Remote Sensing of Atmospheric Methane: A Primer for Policymakers
November 2024
DRAFT

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1. Introduction

> This paper provides an accessible introduction to the science and technology of methane remote sensing, focusing especially on new satellite-borne methane detection instruments. It aims to help support and build capacity for legal and policy officials concerned with control of methane emissions in diverse national and subnational jurisdictions in the Global North and South.

Reducing methane emissions is one of the most effective near-term climate change mitigation tools. Because of methane's high contribution to global heating over a relatively short

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atmospheric lifetime, cutting emissions today will achieve a reduction in heating that is concentrated over the next ten years or so.

Effective control of methane emissions has been hindered, however, by the limited information available about how much is emitted, when, where, and from what sources. Emissions estimates have typically used "bottom-up" methods, in which an observed level of some emissions-producing activity – e.g., volume of oil production or number of cows – is multiplied by an "emissions factor" derived from prior research – e.g., methane emitted per barrel of oil produced or per cow – to yield an estimate of total methane emitted.[2]

It is clear that these estimates are inadequate. They are incomplete. They rely on emissions factors that are in many cases old and unrepresentative. They neglect variation over time, location, and activity. And they are too coarse-grained and fixed over time to support effective monitoring and control. These limitations grow more severe as estimates are scaled up to produce large-regional, national, or global estimates. Many field studies to observe atmospheric methane have shown bottom-up emissions estimates to be widely inaccurate, in most cases to seriously under-estimate actual emissions.

Recent advances are transforming the ability to observe atmospheric methane. Where earlier direct observations of methane required costly, limited-duration field campaigns with airborne or ground-based instruments,[3] current advances are mainly from satellite-borne instruments. These are enabling more precise, complete, and reliable estimates of emissions at scales ranging from individual point sources to the world.

Notable advances already achieved from these satellite observations include the following:

- Imaging the plume of the large 2015 leak at the Aliso Canyon gas storage reservoir in California, confirming an initial measurement from aircraft.4

- Identifying and quantifying emissions from multiple subsequent large point-source releases, including leaks and well blowouts in Turkmenistan, Kazakhstan, Algeria, and several US states, coal mines in Russia and Australia, and landfills in Spain and Bangladesh.[5]

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2 IPCC emissions inventory methodology at: https://www.ipcc.ch/2019/05/13/ipcc-2019-refinement/

3 Notable advances prior to current satellite instruments include: Alvarez et al, "Assessment of methane emissions from the US oil and gas supply chain," Science 21 June 2018, https://www.science.org/doi/10.1126/science.aar7204; and Duren et al, "California's super-emitters," Nature 6 November 2019, https://www.nature.com/articles/s41586-019-1720-3.

4 Thompson, D. R. et al, Space-based remote imaging spectroscopy of the Aliso Canyon CH4 superemitter. Geophys. Res. Lett. 2016, 43, 6571– 6578, DOI: 10.1002/2016GL069079

5 Pandey, S. Satellite observations reveal extreme methane leakage from a natural gas well blowout. Proc. Natl. Acad. Sci. U.S.A. 2019, 116, 26376– 26381, DOI: 10.1073/pnas.1908712116 16; Maasakkers, J. D. Reconstructing and quantifying methane emissions from the full duration of a 38-day natural gas well blowout using space-based observations. Remote Sensing of Environment 2022, 270, 112755, DOI:

- Quantifying emissions from major oil and gas production basins, including studies identifying point-source "ultra-emitters" emitting more than 25 tonnes per hour, and a detailed analysis of the Permian, the largest in the United States with separate analysis of basin-wide emissions (showing them more than double those from prior bottom-up methods) and identifying extreme point sources within it.[6]
- Quantifying national-level emissions from the oil, gas, and coal production sectors.[7]

Capabilities are now advancing rapidly, with the recent launch of two new satellite instruments specifically designed for methane detection and the ongoing development of systems to calculate methane emissions from satellite observations, integrate methane data from multiple sources, and make it widely accessible. Together, these advances will represent a revolution in the ability to identify and monitor methane emissions worldwide, nearly continuously, at spatial scales ranging from point sources to nations and the world. In turn, these advances will both empower current approaches to methane control, and enable new mechanisms not previously available or considered. At same time, the new data present various novel limitations and challenges, and many policy-makers are unfamiliar with the new data sources, their scientific and technical foundations, and their strengths and limitations – in jurisdictions that face significant capacity constraints, and also in many well-resourced jurisdictions.

The UCLA Emmett Institute methane project explores how these new observational capabilities can expand the ability to control methane emissions, under existing regulatory frameworks in diverse jurisdictional settings, and potential new ones. This briefing note supports the project goals by providing an accessible introduction to the science and technology of methane remote sensing for policy and legal officials, including the basics of how current and planned instruments work, what scientific principles they rely on, what information they can provide in what form and on what timeframe, with what accompanying limitations and challenges. It aims to help support and build capacity for legislators, officials, and others concerned with control of methane emissions in diverse national and subnational settings in the Global North and South.

10.1016/j.rse.2021.112755; Cusworth, D. H. Multisatellite imaging of a gas well blowout enables quantification of total methane emissions. Geophys. Res. Lett. 2021, 48, e2020GL090864, DOI: 10.1029/2020GL090864; Varon, D. J. et al, High-frequency monitoring of anomalous methane point sources with multispectral Sentinel-2 satellite observations, Atmos. Meas. Tech., 14, 2771–2785, https://doi.org/10.5194; Guanter et al, En and Climate, June 30, 2024; World Geospatial Industry Council, "Methane emissions from pipelines and landfills, https://wgicouncil.org/methane-emissions-from-pipelines-and-landfills/; GHGsat press release on Russian coal mine releases, June 15, 2022. https://www.ghgsat.com/en/newsroom/russian-mine-produces-biggest-methane-leak-ever-seen-by-ghgsat/; Sadavarte et al EST 2021, coal superemitters in Australia

6 Schneising, Oliver; Buchwitz, Michael; Reuter, Maximilian; Vanselow, Steffen; Bovensmann, Heinrich; Burrows, John P. Atmospheric Chemistry and Physics (2020), 20 (15), 9169-9182; Zhang et al, Quantifying methane emissions from the largest oil-producing basin in the United States from space, Sci. Adv 6 (2020), https://www.science.org/doi/pdf/10.1126/sciadv.aaz5120; Irakulis-Loitxate et al., Sci. Adv. 2021; 7 : eabf4507 30 June 2021; Lauvaux et al, Science, 3 Feb 2022, DOI: 10.1126/science.abj4351.

7 Lu Shen et al, Quantifying National Emissions, Nature 2023, https://www.nature.com/articles/s41467-023-40671-6

2. Basics of remote sensing: What it is and how it works

Remote sensing is the process of gathering information (sensing) about an object of interest at a distance (remote) from the object. Remote sensing (RS) can be used to observe a wide range of objects at a distance – a speeding automobile, an aircraft approaching a landing, a school of fish in the ocean, and many aspects of the Earth and its atmosphere, including pollutants in the air. Human vision is an example of remote sensing, because we see distant objects by sensing the light that originated in the sun or a light bulb and scattered off the object into our eyes.

Like human eyes, RS instruments operate by sensing light that travels to the instrument from the thing being observed. But RS can see much more than human eyes – partly because RS instruments can go places that human observers cannot, but mainly because human eyes are sensitive to only a thin slice of all the light that is available to observe. As we explain in more detail in the text box, human eyes can see light with wavelengths between 0.4 and 0.7 micrometers or microns. Within this narrow range, human eyes see different wavelengths as different colors, from red with the longest wavelengths (~ 0.7 microns) to violet with the shortest (~0.4 microns).

RS instruments, by contrast, can be designed to see light of one particular wavelength, or several different wavelengths, or a wide continuous range of wavelengths, which may overlap with the wavelengths visible to human eyes or be longer or shorter, depending on the purpose.

Remote sensing instruments are used to observe many aspects of the Earth's surface, oceans, and atmosphere. Instruments can be carried on a wide range of platforms. They can be fixed in place, hand-held, or carried on vehicles, but most important environmental remote sensing is done from aircraft, drones, or satellites.

Different flavors/colors of light

Light, or electromagnetic radiation (these are equivalent terms – one informal, one scientific), comes in a vast range of different varieties.

In some respects, light acts like waves, similar to waves on the surface of a body of water. All waves are described by their speed of travel, their wavelength (the distance between the top of one wave and the next) and by their frequency (the number of complete waves that pass a fixed observation point each second). Because all light travels at the same speed, describing light by its wavelength and by its frequency are equivalent: light with shorter wavelength has higher frequency. In this note, we will speak in terms of wavelength, because that is most common in discussions of RS.

Only a small slice of light is visible to the human eye, with wavelengths between about 0.4 and 0.7 micrometers (μm), or microns. A micron is one millionth of a meter or 10^{-6} meters. For comparison, a human hair is roughly 50 to 100 microns in diameter, so visible light has a wavelength about one hundred times smaller than a human hair.

Light of different wavelength ranges, both longer and shorter than visible light, is called by different names for convenience of reference. Light with wavelengths slightly longer than visible light, from about one micron to a few hundred, is called "infrared." As we explain below, the most important wavelengths for observing methane lie in the "near infrared" with wavelengths of a few microns, slightly longer than visible light. Light with still longer wavelengths is called microwaves (with wavelengths from about 1 mm to 1 m) or radio waves (from 1 m to hundreds of kilometers). Light with wavelengths shorter than visible light is called ultraviolet (UV), X-rays, or gamma rays. Its wavelengths are usually stated in units smaller than microns such as nanometers (nm), one billionth of a meter or 10^{-9} meters. These different names do not denote fundamentally different things; they simply refer to light with wavelengths in different ranges, often emitted by different sources and used in different ways. It is reasonable to think of these different varieties of light as being different colors, although of course with a vastly wider range of colors than human eyes can see.

While some light sources emit light of just one wavelength, light sources often combine light of many different wavelengths. A description of light that specifies the mix of different wavelengths present – what specific wavelengths are present, how brightly – is called its "spectrum." We can speak of the spectrum of sunlight, or the spectrum of a particular type of light bulb. Similarly, the spectrum of an instrument is a description of how sensitive it is to light of different wavelengths. The term "the electromagnetic spectrum" describes the totality of all wavelengths of light and their division into different named ranges, as shown in Figure 1.

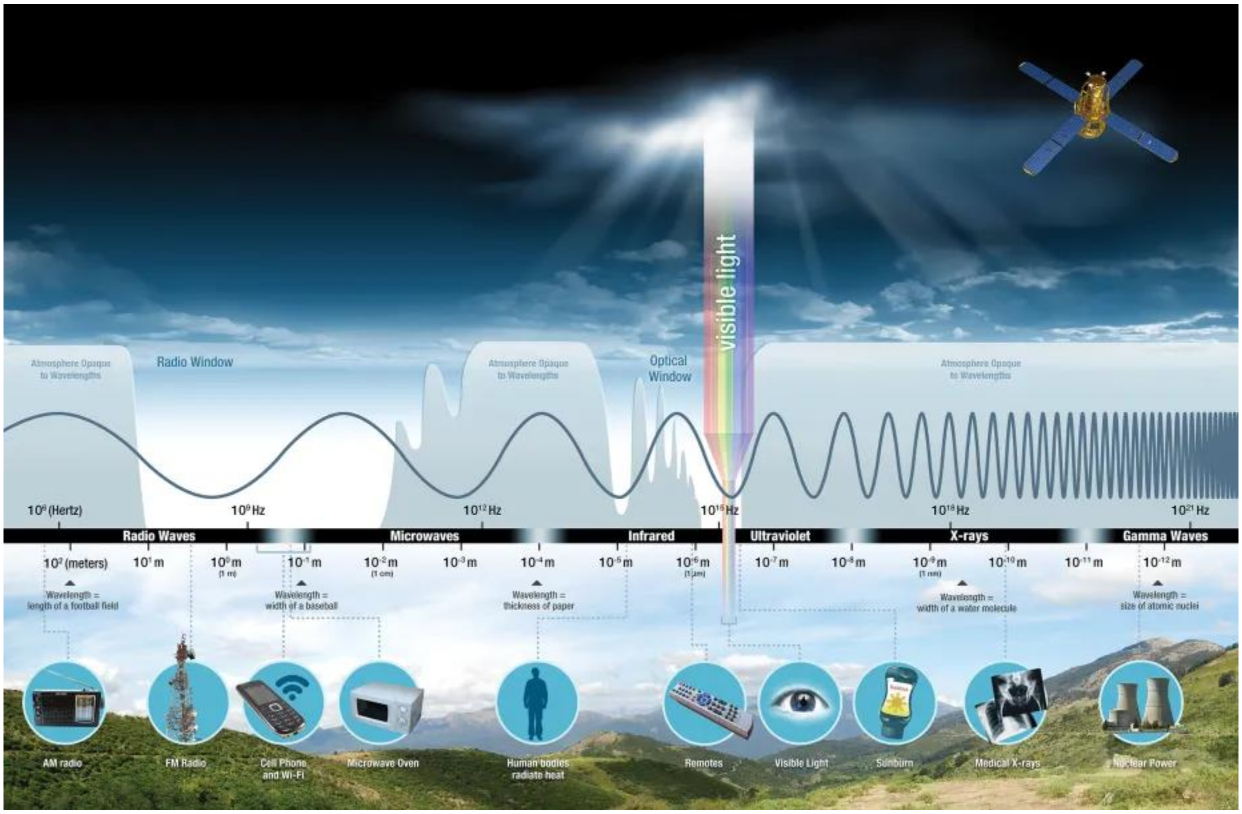

Figure 1: The electromagnetic spectrum, with the visible region represented by the rainbow colors between the longer-wave infrared radiation (IR) to the left, and the shorter-wave ultraviolet radiation (UV) to the right. (Source: NASA)

Satellite instruments measure the brightness (or "radiance") of light reaching the instrument at specific wavelengths that the instrument is able to see. For an instrument to observe anything remotely, the target of observation must interact with wavelengths of light that the instrument can detect. Much RS for environmental and earth-science purposes, and nearly all RS of atmospheric methane, relies on passive observation of sunlight scattered from the target to the instrument. Methane and other atmospheric constituents can be seen by this method because their molecules interact strongly with light at highly specific wavelengths, so the brightness of light scattered back to the instrument at these wavelengths differs from that in the incoming sunlight.

Any chemical compound present in the atmosphere – whether water vapor, carbon dioxide, or methane – consists of molecules made up of specific combinations of atoms held together in a specific shape by chemical bonds. For example, a molecule of methane consists of one carbon atom joined by chemical bonds to four hydrogen atoms making a tetrahedral shape. These bonds stretch, wobble, and vibrate like tiny springs, and their movement can be excited by specific wavelengths of light, rather like a bell has a specific characteristic frequency that can be excited by striking the bell, or by exposing the bell to sound of that frequency.

Because each molecule of methane is identical, each interacts with different wavelengths of light in the same way. But these interactions are different for each chemical species, due to differences in the length, shape, and stiffness of their chemical bonds. Every species present in the atmosphere thus has a highly specific set of stronger or weaker interactions with light at different wavelengths. This pattern of interactions is called the molecule's absorption spectrum, because the interactions begin with the molecule absorbing incoming light. Because these spectra are such uniquely identifying properties of specific molecules, they are also sometimes called the molecule's spectral signature or spectral fingerprint. RS instruments can identify how abundant specific molecules are in the atmosphere by seeing their spectral fingerprints in the mix of wavelengths scattered back to the instrument, using methods that we discuss further below.

3. Remote Sensing of Methane: How do RS instruments observe methane specifically?

Satellite instruments see methane in the atmosphere by taking advantage of its spectral fingerprint, in particular its strong interaction with light of two specific wavelengths in the near-Infrared, 1.65 and 2.3 microns, as shown in Figure 2 below.

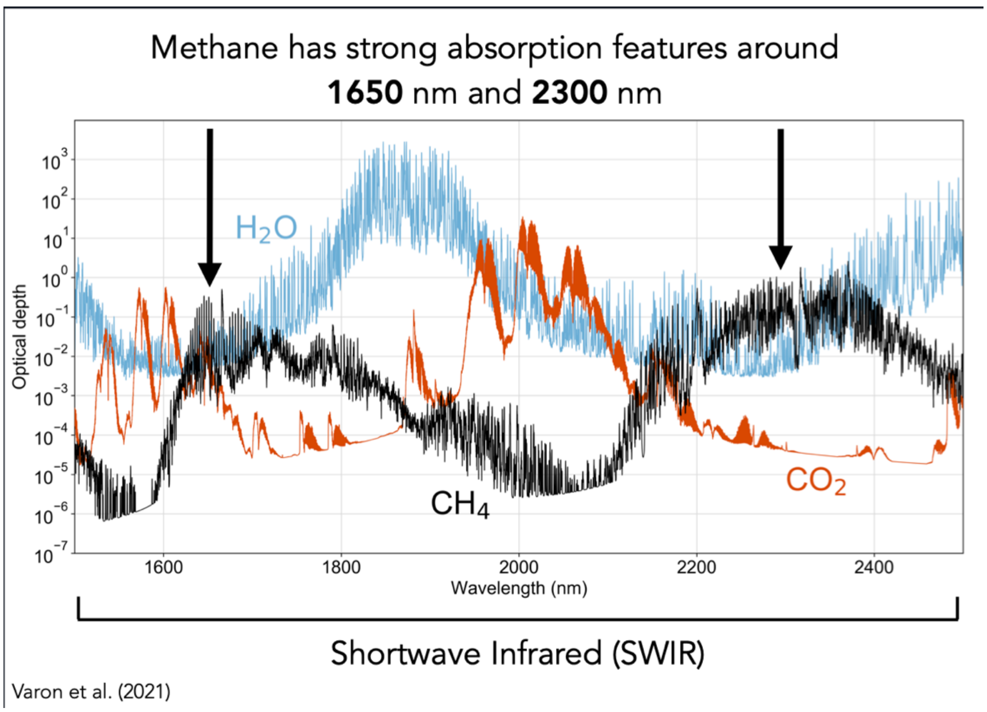

Figure 2: Methane IR absorption spectrum.

As Figure 2 shows, methane's spectrum has two regions of strong absorption in the near-IR at 1.65 and 2.3 microns. Although these are not the only wavelengths where methane interacts with light, they have the advantage that these strong regions of methane absorption correspond with relatively weak absorption by other chemical species in the atmosphere. They are thus good places to look specifically for methane. All currently operational and planned RS methane instruments observe at one or both of these wavelengths.

While RS instruments can be carried on various observation platforms, each with advantages and limitations for specific observational tasks, current excitement about methane observation is mainly driven by recent and continuing deployment of new satellite-borne instruments. There are more than a dozen satellite-based instruments observing methane, including both instruments specifically designed to detect methane and multi-purpose instruments that have shown the capacity to do so. Two important methane-specific instruments were launched in 2024 and are now working on the validation and dissemination of their data and several more are scheduled or planned. Collectively, these satellites are expected to achieve fine-grained, near-global daily coverage within the next few years. A list of operating and planned methane satellite instruments is in Appendix 1.

These new satellite instruments for the first time allow practical global or near-global observation of atmospheric methane, at low cost, with rapid worldwide availability of data, and with consistent, high-quality measurements. Although there are strengths and weaknesses of every data source and continued importance of other data sources, this briefing note concentrates mainly on satellite RS methane measurements in account of their rapid expansion and their potentially transformative impact on methane monitoring and control.

Developing a satellite instrument to observe methane requires several basic design decisions with tradeoffs among various advantages and limitations for specific observational aims. The next section discusses the major design choices, how current and planned satellite instruments have resolved them, and their implications for the data produced and its uses.

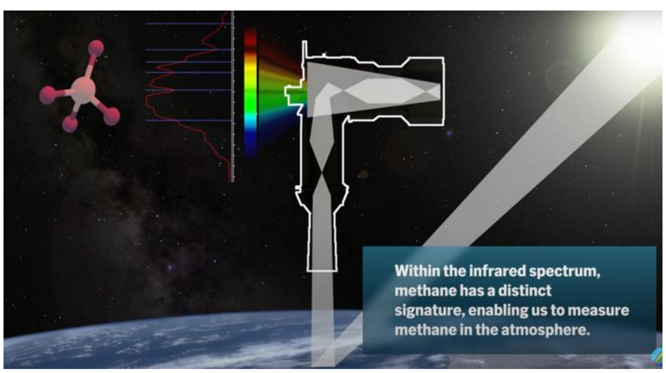

Figure 3: Source EDF MethaneSAT page

4. Design of a methane RS instrument: Major design choices and their implications

Current and planned instruments reflect a range of decisions on four major design characteristics: whether the instrument operates passively or actively; spatial coverage and resolution; spectral coverage and resolution; and return time. The first three of these are properties of the instrument itself, while the fourth depends on the orbit of the satellite carrying the instrument.

Active versus Passive Detection

RS instruments can be either active or passive, meaning they either carry their own light source or depend on light that originated in a different source. In general, the choice of active versus passive detection affects the ability to see under different conditions, as well as what information can be gathered about the target. Although active observation has certain advantages, all current and planned methane instruments except for one are passive.

Active RS instruments shine light on the target to observe the light scattered back, like using a flashlight to illuminate objects in a dark room. Two well-known active RS methods are Radar, which reflects radio waves off target objects, and LiDAR (Light Detection and Ranging), which reflects a laser off a target to observe its distance, movement, or other characteristics. Just one proposed methane instrument will use an active sensor – MERLIN, a French-German LiDAR mission planned to launch in 2027. Because LiDAR does not require sunlight, it can observe at night and in polar winter. It is also less disrupted by aerosols and fine clouds in the atmosphere than instruments that rely on scattered sunlight. LiDAR is better suited for aircraft and ground-based use than on satellites, however, mainly due to satellites' tight constraints on instrument mass, volume, and energy use.

Lacking its own light source, a passive RS instrument observes light that comes to it from the target. That light can be emitted by the target in a way that depends on its temperature, like the "thermal" infrared that night-vision goggles use to distinguish (warmer) people from their (cooler) surroundings in the dark. Or it can be light that was initially emitted by some other source, usually the sun, and then scattered or reflected from the target into the instrument. Nearly all RS of atmospheric methane is passive, relying on sunlight scattered back from the target to the instrument.

Spatial Coverage and Resolution

Spatial coverage and resolution pertain to how large an area of the Earth's surface an instrument can see at one time, with how fine detail. These characteristics affect instruments' ability to detect sources of different sizes and emissions rates.

Spatial coverage, also called swath or field of view, describes how much total surface area the instrument can see at one time. Spatial resolution, also called pixel size, describes the smallest areas within this field of view that the instrument observes separately and thus can distinguish.

These two characteristics correspond to the total field of view and the pixel size in a digital camera – and in fact, a remote sensing instrument is just a special type of digital camera, albeit one that sees different light wavelengths than the camera on your mobile phone.

On spatial coverage and resolution, satellite methane instruments have made a range of choices that are usually grouped into two broad classes: area flux mappers and point source imagers. As their names suggest, area flux mappers aim to estimate total methane emissions over larger areas, from regional up to global scale. They achieve this through large fields of view and large, relatively coarse pixels within their field of view. A single pixel on an area flux mapper can have an edge length of 1 to 10 kilometers. Sources smaller than this cannot be distinguished, but instead are averaged into a single observation of the whole pixel. Point source imagers aim to identify and quantify individual point sources, often defined as sources smaller than 30 by 30 meters that emit more than 10 kilograms per hour. They achieve this through small pixel sizes, with edge lengths of 60 meters to as small as 20 meters. One instrument – MethaneSAT, launched in March 2024 – has intermediate spatial resolution, between the point-source and the other area instruments, with pixels of ~ 100 by 400 meters. This intermediate resolution enables it to capture both large point sources and clusters of multiple smaller sources within relatively concentrated areas of scale kilometers to tens of kilometers, as are often found in areas with concentrated oil and gas production, large coal mines, or large livestock operations.

These different instrument designs have distinct advantages that make them suited for different purposes. Point source imagers can support monitoring and control of individual sources, including identifying leaks, accidents, or previously unidentified sources. They can thus be used to direct maintenance crews or enforcement authorities to respond to particular sources. Area flux mappers can capture the total emissions flow over relatively large areas, ranging from large livestock operations or oil and gas production basins to entire nations or regions. They can thus be used to estimate organizational or jurisdictional emissions inventories, or to detect aggregate changes in emissions in response to changes in policy, management, or other factors.

An advantage of area flux mappers is that their estimates of emissions rates have high precision – meaning small variation over repeated observations of the same scene. They achieve high precision in part because many of the random factors that introduce error in measurements tend to average out over larger observed areas. Some area flux mappers claim precision of 1% or less, meaning repeated observations of the same scene would be expected to vary (have a standard deviation or RMS error) by less than 1% of the reported emissions rate. The meaning and importance of observational precision is well understood in scientific research, as it provides a quantitative estimate of the uncertainty in any observation. For use of methane in regulatory and policy settings, the implications of greater or lesser precision, and the value of higher precision relative to other valued characteristics of emissions estimates, is thus far largely unexplored.

Spectral Coverage and Resolution

Spectral coverage and resolution describe what range of wavelengths an instrument can see, and how finely within that range it can distinguish different wavelengths from each other. These characteristics affect instruments' ability to distinguish methane from other atmospheric species and the precision of their observations.

Spectral coverage and resolution correspond to spatial coverage and resolution, in that they describe how much the instrument can see and how finely it can distinguish within what it sees, but these spectral concepts can appear less intuitive than their spatial counterparts because they lack a direct analogue in ordinary consumer cameras. A more intuitive analogy to understand spectral coverage and resolution is human vision. Human vision has spectral coverage of 0.4 to 0.7 microns, the total range of wavelengths human eyes can see, while its spectral resolution is the smallest difference in wavelength that people can identify as distinct colors.

To reliably distinguish methane from other atmospheric species, fine spectral resolution is crucial. A close look at the picture of methane's absorption spectrum in Figure 2 shows why this is so. As we have noted, methane has regions of strong interaction around 1.65 and 2.3 microns. But these are not single values with total absorption at exactly these wavelengths and none at any other. Rather, they are regions of generally high absorption, with a lot of fine-scale variation over small changes in wavelength and a large decline as you move toward more distant wavelengths. The precisely identifying spectral fingerprint of methane is found not just in the fact that it absorbs strongly at these two wavelengths, but also in this fine-grained variation over small changes in wavelength around these values, similar to the way you can recognize a particular mountain range by local differences in the height of specific peaks, passes, and valleys.

This fine-scale variation in absorption at specific wavelengths is crucial because, while these two wavelength regions are good places to observe methane, they do not absolutely distinguish methane from other atmospheric species. For example, CO_2 has an absorption band at 1.61 microns, just beside and overlapping with methane's 1.65-micron band, as you can see in Figure 2. Observations that don't distinguish different wavelengths finely enough can thus confound methane with other species, just as a fingerprint that smudges nearby lines together can impair the ability to attribute the fingerprint to a particular person.

Among current and planned methane instruments, instrument engineering and satellite payload limits impose a tradeoff between spatial and spectral resolution. The point-source imagers that prioritize fine spatial resolution with pixel sizes of 10s of meters or smaller have relatively coarse spectral resolution, from 10 to 200 nanometers, while the area flux mappers with kilometer-scale pixels, achieve spectral resolution of less than 1 nm. One consequence of this is that satellites that are best at seeing relatively small methane sources are not, at least for the moment, as well able to distinguish methane molecules from other molecules.

A couple of instruments use compromises or special abilities related to spectral resolution to maximize their ability to resolve methane. MethaneSAT uses intermediate spatial resolution with still sub-nm spectral resolution (0.3 nm) while CarbonMapper has 6 nm spectral resolution, a significant advance over the 10 nm more typical of small-pixel point-source imagers. GHGSat achieves a combination of fine spatial and spectral resolution by being able to point the instrument in specified directions.

Spectral resolution is one characteristic that distinguishes instruments designed for the specific purpose of observing methane from others that are able to see methane but were designed for a different main purpose or multiple purposes. This latter group includes several general-purpose instruments that observe multiple wavelength bands, called “multispectral” or “hyperspectral” instruments. Multispectral instruments typically observe 3 to 10 discrete wavelengths with a spectral resolution of ~ 0.1 microns, while hyperspectral instruments observe hundreds of different wavelengths within a continuous spectral range, with spectral resolution ~ 0.01 microns. These multi-purpose instruments can detect methane because their spectral coverage include wavelengths where methane interacts strongly, but they are not optimized specifically for methane. For example, EMIT and Landsat-8 are hyperspectral and multispectral instruments that were primarily designed for other purposes – EMIT to study the desert dust, Landsat for land surface imaging. These instruments can observe methane because their broad spectral coverage includes regions of strong methane absorption, but they tend to do so with lower precision and a higher observation threshold than specialized methane sensors.

<u>Return Time and Orbital Path</u>

Methane instruments observe places on the Earth’s surface directly below them as they pass over, viewing larger or smaller places at each moment depending on the instrument’s spatial field of view. What places an instrument can see, and how often it returns to observe the same place, are determined by its satellite’s orbit, which – except for small adjustments – is fixed when it is launched.

Orbits are defined by their angle relative to the Earth’s equator as well as by their altitude, with higher orbits circling the Earth more slowly. The large majority of satellites are in low-Earth orbit, where they complete an orbit of the earth in a couple of hours. Most methane instruments are in low-Earth polar orbits, orbits oriented North to South that pass over the North and South poles on each circuit. Polar orbits are favored for many earth-science and environmental applications because they can observe the Earth at all latitudes. Even in polar orbit, whether and how often an instrument will see every place on Earth depends on how its orbit moves in the East-West direction on each successive pass.

The polar orbits of methane instruments are sun-synchronous, meaning their path moves eastward on each orbit just as much as the Earth has rotated in that time, so the instrument passes over every location at the same time each day. Small differences in this orbital movement, along with how wide an East-West view the instrument sees, determine the time between successive views of the same place, or its return time.

An instrument's return time determines its ability to interpret individual readings and estimate trends. More frequent returns allow more accurate estimation of emissions trends and assessment of the effectiveness of actions to cut emissions. A shorter return time also aids in determining whether a single high reading is an error, an anomalous event (such as a brief release due to maintenance), or an indication of sustained high emissions. Current and planned systems have return times ranging from about one day to one week.

There is one satellite that reports methane observations that is not in a low-earth polar orbit, and others have been proposed. The EMIT instrument is carried on the International Space Station in an inclined orbit that ranges between about 50 degrees North and South with a return time over that area of about 3 days. Other methane instruments have been proposed for satellites in geostationary orbit. Geostationary orbits are situated over the Equator, at such high altitude that completing one orbit takes 24 hours. A satellite in geostationary orbit thus appears from the Earth to be standing still over one location, allowing communications equipment to be permanently aimed at that location. This property makes geostationary orbit locations so important that they are allocated to countries around the equator by international agreement. A methane instrument in geostationary orbit, such as a recently cancelled one that would have orbited over the Equator in South America, would always see the same longitude slice, with its view extending as far North and South of the Equator in that region as its spatial field of view and ability to point allowed.

5. From Instrument Data to Useful Information: Generating Emissions Estimates

Most practical applications of methane observations – policy/regulatory, managerial, or other – require estimates of emissions, defined over some relevant scale of space and time. Satellite instruments don't provide these, or at least don't do so directly. Generating estimates of emissions from instrument data requires two computational steps, each of which may incorporate additional sources of information and can introduce new sources of uncertainty.

What instruments actually measure is the brightness (or "radiance") of light reaching the instrument at specific wavelengths (as determined by the specific instrument's spectral scope and resolution), at specific pixels at known locations (as determined by the instrument's spatial scope and resolution), at specific times. From these measurements of wavelength-specific radiance, the first step toward making the data useful involves calculating estimates of how much methane is in the atmospheric column between the instrument and the Earth's surface. This can be expressed as the total number of methane molecules in that column of air (column abundance), or as the fraction (or mixing ratio) of methane in that dry air column. The latter form – the fraction or mixing ratio – is easier to understand and use, because it does not depend on variations in land elevation, air pressure, or humidity.

This calculation depends on knowing how radiation of different wavelengths is repeatedly emitted, absorbed, and re-emitted by all the gases in the vertical column of air the instrument is observing. These processes are represented by quantitative "radiative-transfer models." In their normal use, these models take inputs of how much of each gas is present at each height in the atmosphere and calculate the resultant radiation. For example, if you already knew how much methane was present at every altitude below the instrument, you could use a radiative-transfer model to calculate what brightness the instrument should see at each wavelength it observes.

Here, however, we don't know how much methane is present in the atmosphere but instead must calculate it from the observed radiation. This reversal of model outputs and inputs requires a calculation that runs the model backwards, a process called inverting the model or retrieving the column methane. There are a few different methods to do this. Different retrieval methods have distinct strengths and limitations, but they all depend on statistical estimation, whose success varies with observational conditions. Retrievals tend to do best in dry areas with clear skies, and more often fail when the atmosphere is hazy or cloudy or the surface is complex or too dark.

Turning the map of column methane produced by this retrieval process into an estimate of methane emissions from particular sources requires another calculation step. In this step, there are different methods used for estimating emissions over extended areas with many sources, or for detecting, locating and quantifying concentrated point sources.

Area sources versus point sources

Many discussions of methane emission estimates will distinguish between point sources and area sources. Although point sources aren't fully distinct from diffuse area sources – emissions sources vary widely in their size and how much they cluster together – a point source is often defined as emissions of more than 10 kilograms per hour over an area smaller than 30 meters squared.

For larger areas, ranging from tens of kilometers to continental or global scales, the aim is usually to quantify average emissions and trends over time periods ranging from weeks to years. These estimates can be used to attribute emissions to area sources, to make inventories, or to measure trends at jurisdictional or larger scale to assess effectiveness of emissions-control measures. Since area source emissions are more consistent over time than leaks or point sources, estimates for these larger areas can be based on many repeated observations. Using multiple observations improves the precision of estimates, as random errors in each individual measurement tend to average out. It also lets you fill in locations that are missing in a single overpass due to clouds or other factors that make the column retrieval calculations fail.

As with the prior step of calculating column methane from radiation measurements, going from column methane to emissions estimates requires calculations based on models. Here, the models are atmospheric transport and chemistry models, which calculate the concentration of atmospheric gases over space and time as they move and mix after specified patterns of emissions. Like the previous step, this calculation requires inverting the model via statistical estimation processes, to calculate the pattern of emissions most likely to have led to the observed pattern of column abundances.

For point sources, calculations to estimate emissions rely on the fact that sufficiently large point sources have a plume, a clear trail of highly elevated concentration around or downwind from the source as the air is moved by wind or mixed by turbulence. For point sources, the priority is on fast detection to enable timely response to leaks, accidents, and unexpected or unauthorized emissions. Although quantitative estimates of emissions rates are also important for point sources, there is greater emphasis on simply identifying and locating sources. Instruments with fine spatial resolution can detect plumes, if the increased concentration within the plume is large enough relative to the instrument's sensitivity. It is then possible to estimate the emissions rate even from just one satellite pass, using various methods that map the size and shape of the plume, or observe changes in concentration between nearby pixels. These methods are highly sensitive to wind, which is a major source of uncertainty. Some methods need separate estimates or observations of wind, while others try to estimate wind from observed characteristics of the plume itself.

Data Levels, Availability, and Uses

The various forms of data available from methane instruments are often labeled by a set of numerical levels, ranging from Level 1 data to Level 4 data.

These refer to general data standards established by NASA in the 1990s to organize the then-exploding amount and diversity of data coming from the first generation of earth-observation satellites then being launched. Different levels denote different levels of processing and calculation, with higher levels being more processed to represent quantities useful for management, policy-making, or other practical applications.

In this system, Level 1 data are direct instrument observations, with only minimal processing to map each observation to a precise time and place and add information about instrument performance and calibration. For most instruments as for methane, Level 1 data is some measure of brightness, or radiance, at each wavelength that the instrument sees. Level 1 data are not directly useful for policy or other applications, nor are they often useful for scientific research without further processing.

Level 2 data describe some meaningful physical quantity that can be calculated from the Level 1 instrument observations, often some property of the land surface or vegetation. For methane, Level 2 data describe the total methane in the atmospheric column between the instrument and the surface, at the same spatial scale and resolution as the original instrument observations.

Additional processing then translates these Level 2 data to a uniform spatial and time scale so data from instruments with different resolution can be compared or aggregated (Level 3), then does further calculation – often including additional data from other observations or models – to generate data in forms directly useful for specific applications (Level 4). For methane, Level 4 data are calculated estimates of emissions rates, at time and spatial scales ranging from individual point sources to large regions or jurisdictions, up to the entire world. Level 4 data are thus the most heavily processed data, and the data most directly useful for policy or other applications.

6. Measuring Performance of Instruments and Systems

Just as methods to calculate estimates of emissions differ between point sources and larger areas, so too do ways to measure instrument performance.

For large areas, where emissions estimates are generated by making repeated observations, performance is measured by how long it takes to detect a specified emissions rate over a given area. Detecting emissions is more difficult, and thus takes longer, for low emissions rates, emissions that vary more over time, and smaller areas of interest. With these conditions held fixed, the time needed to detect the emissions – the measure of instrument performance – depends on the combined effects of several instrument characteristics, including its precision, spatial resolution, return time, and rate of successful retrieval of column methane.

For example, for an emissions rate of 5 kilograms per square kilometer per hour over a 10-kilometer square – a pattern typical of a large livestock feeding area (CAFO) – time needed to detect these with current area flux mappers varies from a few weeks to about one year. For more diffuse emissions over larger areas – e.g., a rate of 0.5 kilograms per square kilometer per hour over a 100-kilometer square, typical of a major oil and gas production basin – the time to detect these ranges from a few days to a few weeks. (The larger area makes detection easier, more than offsetting the lower emissions density.) In both examples, we are excluding MethaneSAT from the other area flux mapper with which it is often grouped, because its finer spatial resolution – 100 meters versus kilometers – gives it a substantial advantage in detecting these emissions patterns, identifying either one within a few days.

For point sources, the priority is the ability to detect, locate, and quantify an emissions source rapidly. For these sources, an instrument's performance is measured by its detection threshold, the lowest emissions rate it can detect in one pass. With clear skies, the difficulty of detecting a point source, and thus any instrument's detection threshold, depends on the nearby land surface and the wind speed. Detection is easier over a bright uniform surface with consistent winds of around 2 to 5 meters per second. These moderate winds are easiest because calm conditions can produce complex multi-layered plumes that hinder quantitative emissions estimates, while strong winds can dilute plumes so quickly that they make it hard to see point sources at all. For given conditions, an instrument's detection threshold improves with its precision and its spatial and spectral resolution. Some instruments improve their threshold by adjusting their viewing angle along the direction of travel instead of always looking straight down, so they can focus on a source for longer as they pass over.

There are many estimates of specific instruments' detection thresholds, but these are not fully meaningful or comparable because they are based on a wide range of viewing conditions and there are still relatively few controlled intercomparisons.[8] Absent such precise comparative measurements of detection thresholds, current and planned point-source instruments can be roughly grouped in broad categories, as follows:

- Detection thresholds of about 100 kg/hour (CarbonMapper, GHGSat, and Worldview-3).
- Detection thresholds of about 500 kg/hour (MethaneSAT, EMIT, PRISMA, and EnMAP).
- Detection thresholds of about 1 to 10 tonnes per hour (Sentinel-2 and Landsat).

For comparison, aircraft-borne instruments – which require special missions with limited spatial coverage, but can see sources from much closer than satellite instruments – can identify leaks of about 10 kg per hour. The 100-kilogram per hour detection threshold of the most sensitive satellite instruments is estimated to be able to identify about 75 and 99 percent of total point-source emissions worldwide. Tropomi, the first satellite-borne area-source mapper to provide global daily coverage, can only see very large point sources of more than about 25 tonnes per hour. This compares with the peak emissions rate of about 50 tonnes per hour from the 2015 failure of the Aliso Canyon gas reservoir in California, and the approximate emissions rate of the largest landfills of about 20 tonnes per hour.

7. Current and Projected Advances

The basics of methane remote sensing that we discuss in this note – e.g., the design of instruments, the principles on which they operate, and the methods available to calculate emissions from their observations – do not change fast. But the specifics of currently operating instruments, their capabilities, and the quantity, quality, and terms of availability of data from them – are changing rapidly. Consequently, we can only provide a snapshot of the current state of affairs and plans as they stand in November 2024.

Multiple major advances in methane observations have been reported over the past ten years in scientific papers, drawing on data from several satellite instruments, notably the Tropomi instrument since its launch in 2018, often in conjunction with other observation platforms or data sources. These advances have, however, tended to be effort-intensive and costly case-specific analyses that demonstrate capabilities and draw attention to particular, often overlooked emissions sources, but they have not previously provided a clear path toward more general and practically usable capability. This situation is now being transformed by advances that promise fundamental changes in the comprehensiveness, quality, and usability of satellite-based methane data. We can provide only very brief introductions to these advances, recognizing that the specifics we report will likely soon be out of date.

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[8] Bell, C., et al, Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol, Environ. Sci. Technol., 57, 5794–5805, https://doi.org/10.1021/acs.est.2c09235, 2023; Sherwin, E. D. et al, Single-blind test of nine methane-sensing satellite systems from three continents, Atmos. Meas. Tech., 17, 765–782, https://doi.org/10.5194/amt-17-765-2024, 2024.

Two long-anticipated methane satellite instruments were launched in 2024, by MethaneSAT and Carbon Mapper, and are now in the process of generating and releasing their first emissions estimates. By combining an intermediate, hundred-meter spatial resolution with a wide field of view and high sensitivity, MethaneSAT targets emissions from the oil and gas sector, aiming to capture both high-emitting sources and smaller sources spread over a wide area. Emissions data will be provided free through a portal integrated with Google Earth. Data from spatially targeted airborne observations in 2023 is already available on the portal, with plans to release the first satellite data by early 2025. Carbon Mapper's hyperspectral instrument, carried on the Tanager-1 satellite of the earth observation company Planet, targets emissions sources of more than 100 kilograms per hour in the fossil-fuel, waste, and agriculture sectors, with fine spatial resolution to image plumes. Their data portal, which integrates observations from satellites and aircraft, will provide data on methane plumes and emissions, for free, 30 days after the initial observation. Several other methane instruments are planned, including additional satellites in existing constellations and new independent efforts, including the first active methane sensor, the Merlin LiDAR instrument, planned for 2027 launch.

There are also continuing advances in systems to generate emissions estimates from satellite observations quickly, reliably, and cheaply; and to make the resultant data available in forms that can be used, understood, and trusted by policy-makers and other relevant decision-makers.[9]

These include the following:

- The "Integrated Methane Inversion" (IMI) tool developed by Harvard researchers, a cloud-based tool allowing users to calculate estimated methane emissions for any region and time period of interest from Tropomi data.
- UNEP's International Methane Emissions Observatory (IMEO), which provides a portal for methane point-source data from multiple satellites and other sources that make the data publicly available. IMEO is linked to UNEP's Methane Alert and Response System (MARS), which notifies governments of large methane point-source detections.
- "Methane Watch," a portal provided by the environmental information and analysis company Kayrros, which integrates publicly available methane satellite data with related commercial and energy data and its internally developed estimation algorithms.

8. Conclusions: Advantages, Limitations, and Uses of RS atmospheric methane data

Although application of satellite methane observations is still in early stages, their potentially transformative effect on the ability to manage and control methane emissions is already evident. The new data make it possible to locate and quantify emissions that were previously invisible without costly field campaigns. They are moving toward near-global, near-continuous estimates of emissions at scales from individual point sources to the world, in some cases with

[9] Růžička, V., Mateo-Garcia, G., Gómez-Chova, L. et al. Semantic segmentation of methane plumes with hyperspectral machine learning models. Sci Rep 13, 19999 (2023). https://doi.org/10.1038/s41598-023-44918-6

commitments to free, timely, widely available data. Parallel advances are building the ability to integrate, disseminate, and interpret methane data from multiple instruments and platforms.

At same time, the new data come with certain challenges to their usability, accessibility, or acceptability in certain policy and legal applications: some technical, related to the instruments and how they work; and some socio-political, related to how and by whom they are collected and used. These limits do not weaken the expectation that the new data represent transformative advance in the ability to manage methane, but they do suggest challenges in some applications and highlight the need for policy actors to understand the data and their origins.

Potential challenges include:

- Limited and uncertain spatial coverage. Quality of measurements depends on surface, weather, and sun-angle conditions. Measurements cannot be made at night or in polar winter, and can fail due to clouds or surfaces that are too bright (ice and snow) or too dark (water, except with special viewing techniques). These conditions introduce consistent regional and seasonal limits to reliable observations.
- Intermittency of observations, and related challenges of consistently integrating diverse data sources to reduce intermittency;
- Data availability, timeliness, and cost, as well as policy-makers' capacity to utilize it;
- Policy-makers' willingness to rely on data produced by diverse entities (national governments, IGOs, non-profits, private firms) based in multiple jurisdictions; and
- Reliability of continued availability of data and terms of access.

Present discussions of the new data stress two types of uses, both clearly in line with current and projected capabilities.

- Rapid and precise identification of large or unexpected point sources, to inform the responsible parties, legal and regulatory authorities, or other potentially concerned parties such as government bodies, commercial or financial parties, or community and civil-society groups;
- Improving jurisdictional emissions inventories through well validated measures of area emissions.

Additional uses are possible, including incorporating observations at intermediate scale, between individual point sources and entire jurisdictions, into the design and implementation of regulations within jurisdictions. Rapidly expanding capabilities, both via additional satellite instruments and advancing integration of data from diverse sources, may enable development of new approaches to policy and regulation, support stronger implementation and enforcement of existing approaches, or simply help to identify control priorities and provide feedback on results.

Appendix

<u>Operational Methane Observing Satellites</u>

Satellite / Instrument	**Launch Date** Date/Year	**Notes**
MethaneSAT	March 2024	Useful to detect smaller oil and gas facilities, that may have previously gone undetected, while offering reliable attribution that the detected methane is coming from those identified sources. The satellite will also monitor enough of Earth's surface to cover 80% of oil and gas production areas.
Carbon Mapper	August, 2024	Useful to detect and quantify methane emissions of facilities or pieces of equipment (such as pipelines or flares) emitting over 100 kg of methane per hour, and attribute emissions to their specific source within 50 meters.
GOSAT	January, 2009	Provides global measurements of carbon dioxide and methane concentrations, contributing to improved understanding of greenhouse gas sources and sinks.
TROPOMI	October, 2017	Offers daily global coverage of methane concentrations at high spatial resolution, enabling identification of large methane plumes and regional emission patterns.
Landsat-8	February, 2013	While primarily designed for land imaging, it can detect large methane plumes, aiding in the identification of major emission sources.

WorldView-3	August, 2014	High-resolution imaging capabilities allow for detection of methane plumes from specific facilities, supporting targeted emission reduction efforts.
Sentinel-2	June, 2015 (2A); March, 2017 (2B)	Provides frequent, high-resolution imagery that can be used to detect large methane plumes and monitor land use changes related to emissions.
GHGSat	June, 2016 (Claire); September, 2020 (Iris); January, 2021 (Hugo)	Offers high-resolution methane detection capabilities, allowing for identification and quantification of emissions from individual facilities.
PRISMA	March, 2019	Hyperspectral imaging capabilities enable detailed methane plume detection and characterization, supporting emissions monitoring efforts.
EnMAP	April, 2022	Provides hyperspectral data for methane detection and quantification, contributing to improved understanding of emission sources and patterns.
EMIT	July, 2022	While primarily designed to study mineral dust, it has demonstrated the ability to detect methane plumes, contributing to the identification of "super-emitters"

Planned Methane Observing Satellites

Satellite / Instrument	**Expected Launch** Date/Year	**Notes**
GOSAT-GW	December, 2024	GOSAT-GW satellite will provide the first global space-based measurements of methane in Earth's atmosphere at 1-3 km resolution.
Sentinel-5	2025	This follow-on mission from Sentinel-5P (precursor mission launched in 2017) will advance the detection of methane super emitters.
CO2M	2026	CO2M will combine data sources to distinguish anthropogenic methane emissions from natural sources, such as plants and animals.
MERLIN	TBD (roughly 2028)	As a LiDAR mission, MERLIN will be useful to detect large methane sources over water, such as offshore oil and gas facilities, wastewater facilities, hydroelectric and agricultural reservoirs, and estuaries.
Carbon-I	2030/2032	Carbon-I is a point source imager that will have high enough spatial resolution to allow the detection of natural fluxes and to break through less than 1km cloud gaps in the tropics.
SBG-VSWIR	TBD (2030 +)	Between SBG-VSWIR and CHIME there should be 5-6 day global revisit time which will allow for more reliable and continuous point source detection.
CHIME	2028 - 2030	Between SBG-VSWIR and CHIME there should be 5-6 day global revisit time which will allow for more reliable and continuous point source detection.