# Carbon Mapper
# Airborne System

## Formal Alternative Test Method

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# 1.0 Scope and Application

This document describes Carbon Mapper's Method Protocol (how is technology applied in the field) for using aerial imaging spectroscopy to detect, geolocate, and quantify methane ($CH_4$) emission plumes in support of EPA's Super Emitter Program under 40 CFR part 60 subparts OOOO, OOOOa, OOOOb and OOOOc as defined in § 60.5471b of part 60. The document summarizes the instrumentation, observational approach, and analytic workflow used for mapping large regions to identify $CH_4$ super-emitter events.

| Analyte | CAS Number | Matrix | Method Sensitivity[1] | Method Resolution[2] |
|---|---|---|---|---|
| Methane ($CH_4$) | 74-82-8 | Ambient Air | <100 kg/hr | 14 meters |

**Table 1.** Scope of Method.

# 2.0 Summary of Method

This method describes Carbon Mapper's airborne deployments in the context of meeting EPA Superemitter detection and quantification thresholds. In this context EPA's superemitter program (SEP) requires that a method:

1) can detect super-emitters with sufficient sensitivity to confidently differentiate sources above the
2) 100 kg/hr notification threshold
3) can quantify emission rates including uncertainty bounds
4) can geolocate plumes to within 50 meters of the origin of the emission
5) can deliver a digital image of methane plumes

All aerial deployment of imaging spectrometers based on design criteria developed by NASA's Jet Propulsion Laboratory allow for detection of methane plumes during aircraft campaigns. While detection limits vary based on operational and environmental variables, the quantification algorithms developed by Carbon Mapper are sensor agnostic and do not vary with aircraft flight altitude. As such, for all airborne applications, Carbon Mapper's methods meet both SEP criteria.

Carbon Mapper methods and findings have been demonstrated in multiple aerial surveys spanning the majority of US oil and gas production basins and published in peer-reviewed journals (Duren et al., 2019; Cusworth et al., 2022; Sherwin et al., 2024) including citation in EPA's 40 CFR part 60 (Cusworth et al., 2021).

Carbon Mapper continues to refine algorithms as more controlled release experiments are performed. Any modifications to Carbon Mapper algorithms from L2-L4 are only undertaken when they significantly improve correlation and bias against controlled validation datasets and other independent benchmarks (e.g., cross-comparison with other instrument platforms).

Documents included in this application are current at the time of submission. The most up-to-date versions of these documents can be found at https://carbonmapper.org.

## 2.1 Data Collection

Carbon Mapper commissions wide-area aerial surveys of oil and gas operations and other methane emitting regions with high precision imaging spectrometer instruments designed by NASA's Jet Propulsion Laboratory (JPL) that are calibrated and operated on various aircraft by JPL and other partners such as Arizona State University. These instruments, collectively referred to as the Airborne Visible Infrared Imaging Spectrometer

[1] Worst case (not to exceed) 90% probability of detection methane plumes for 25% albedo scene, 45 deg solar zenith angle, 3 m/s wind speed, and aircraft altitudes up to 14 km above ground level

[2] Worst case (not to exceed) spatial resolution of plume images pixels (and 1 sigma radial geolocation accuracy) at aircraft at altitudes up to 14 km above ground level

(AVIRIS) series, measure ground-reflected solar radiation with fields of view, spatial resolution, and detection limit that vary with aircraft altitude.

## 2.2 Data Processing and Analysis

Carbon Mapper's workflow analyzes spectrometer and aircraft navigation data to retrieve atmospheric CH4 concentrations, generate geospatially resolved CH4 plume images and combines those results with ancillary visible band imagery and 3rd party wind data, respectively, to geolocate plume origins and estimate emission rates.

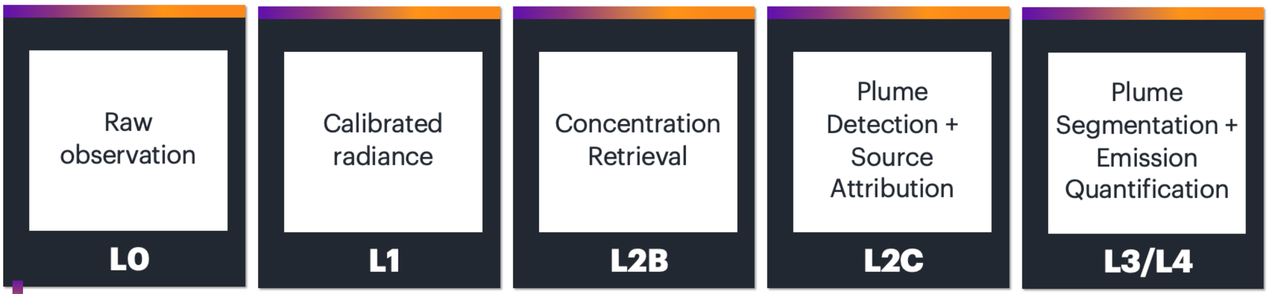


**Figure 1.** Simplified data flow indicating the Carbon Mapper data processing pipeline and product levels. More details are provided in the Carbon Mapper product guide and algorithm theoretical basis documents included in this application. The most current versions of these documents are available at https://carbonmapper.org

## 2.2 Quality Control, Reporting and Publication

Carbon Mapper analysts review the resulting CH4 products to reject false alarms, correct or remove questionable emission estimates, and add attribution meta-data before publication. Quick-look CH4 detection products are available for direct notification to operators and regulators within 72 hours of observation while final fully quality controlled (QC'd) products are published to the Carbon Mapper data portal, typically after 30 days.

# 3.0 Definitions of Method

## 3.1 General Definitions of Method

**3.1.1 Plume:** A spatially resolvable enhancement of gas concentration in the atmosphere that originates from an identifiable location.

**3.1.2 Plume origin:** Best estimate of the lat/lon of the localized source based on a single plume observation.

**3.1.3 Attribution:** the process of relating a plume origin to a facility or infrastructure, and where sufficient

ancillary information is available, including owner/operator name, emission sector and/or facility, equipment or process type.

**3.1.4 Source:** A geographic feature on the earth's surface from which emissions originate. The point or extended area system or site that emits the analyte and is the subject of the measurement.

**3.1.5 Analyte:** The air pollutant species emitted by the source that is detected or retrieved by the method; methane.

**3.1.6 Background Spectrum:** An average or typical spectrum of solar backscattered and reflected radiance within the instrument's viewing capability.

**3.1.7 Background Concentration (BC):** The ambient concentration of the analyte with no local source present.

**3.1.8 Enhancement:** connected region of gas concentrations that are elevated above the background concentration. Enhancements may result from area sources, single localized source, complex of multiple localized sources, downwind manifestation of an unobserved localized source(s).

**3.1.9 Delineated Plume Boundary:** Geospatial boundary of a region of enhancement that through method inference is ascribed to the Source.

**3.1.12 Atmospheric Parameters:** The measure of atmospheric stability, wind speed and direction, and other parameters necessary to conduct the method.

**3.1.13 Super Emitter:** Facilities, equipment, and other infrastructure, typically in the fossil-fuel and waste that emit methane at high rates. EPA's definition of a super emitter for the oil and gas sector is a source having an instantaneous emission rate of methane of 100 kg/hr or greater.

## 3.2 Airborne Platform: The crewed aircraft used to execute the method

**3.2.1 Imaging Spectrometer:** Passive remote sensing instrument that measures solar backscattered and reflected radiance across multiple wavelengths, including wavelengths where the analyte has known rovibrational absorption features. The instrument must possess optimum radiometric accuracy, signal-to-noise, and spectral response to be sensitive to enhanced analyte concentration.

**3.2.2 Navigation Instrumentation:** The equipment or techniques that provide information necessary for manned aircraft or satellite that provides operational data required to execute the method and other platform-specific operational parameters. Includes the aircraft Inertial Measurement Unit (IMU) which records the aircraft attitude, altitude, air speed, geospatial position system (GPS) data and velocity at >100 Hz to support post flight analysis including reconstruction of observing geometry and orthorectification of spectrometer images.

**3.2.3 Off-platform Measurements or Methods:** Supporting measurement data or meteorological model outputs that support execution and quality assurance of the method.

## 3.3 Flight Path Metrics

This section includes a collection of observing platform flight path descriptions and associated data with source location and size parameters that characterize the specific method application.

**3.3.1 Radiance:** A measure of the light or heat reflected or emitted from a target. typical units are W/m2-sr.

**3.3.2 Field-of-Regard:** The total area that can be observed by a sensor, including its pointing capabilities. For non-movable sensors, the field-of-regard is equal to the field of view. For pointing sensors, the field-of-regard is larger than the field of view.

### 3.3.3. Definitions that determine Pixel size

**3.3.3a. Viewing angle:** The viewing angle (in degrees) measured from nadir with which a sensor captures data.

**3.3.3.b. Flight altitude:** The distance between the ground and the sensor.

**3.3.3.c.** Instantaneous Field of View (iFOV). The solid angle through which a single detector element is sensitive to radiation.

### 3.3.4. Factors that determine Area Coverage

**3.3.4.a. Swath Width (cross track):** The spatial extent (distance) on Earth's surface in the direction orthogonal to the flight direction that is measured by one pass of the sensor. Swath width is a function of field of view and altitude.

**3.3.4.b. Field-of-View (FOV):** The solid angle through which the entire sensor is sensitive to radiation or the angular extent of the observable area.

**3.3.4.c. Swath Length (long track):** The spatial extent (distance) on Earth's surface in the direction of the flight direction that is measured by one pass of the sensor.

### 3.3.5 Factors that determine Method Sensitivity:

**3.3.5.a Signal to Noise Ratio (SNR):** The ratio between sensor optical throughput and all optical and electronic noise sources.

**3.3.5.b. Integration time:** A metric that combines exposure interval and potential oversampling (multiple exposures per ground image footprint) which can increase effective SNR; where oversampling is a function of imaging mode, platform altitude and ground speed.

**3.3.5.c. Albedo:** the proportion or percent of radiation received by the surface that is reflected by the surface. Also known as the ratio of reflected to incident light.

**3.3.5.d. Solar Zenith Angle:** The angle between the sun's rays and the vertical direction. This is the complement angle to the solar altitude or solar elevation.

**3.3.5.e Spectral Resolution:** The wavelength intervals and width of the spectral bands in a sensor system. Higher spectral resolution has more frequent wavelength intervals and narrower bandwidths.

**3.3.5.f Surface wind speed:** Methane enhancements in the atmosphere vary directly with near surface wind speed due to dilution.

**3.3.5.g. Pixel size:** Projected extent of a single detector element on the earth's surface. Larger pixel size results in more methane dilution in a pixel (and vice-versa).

## 3.4 Primary Method Calculations

**3.4.1. Concentration Retrieval:** The method by which column-averaged concentrations of analyte are estimated from measured radiance. Two retrieval methods are deployed for concentration estimation: (1) columnwise matched filter (CMF), . Both explained in detail in Section 12. These methods use either physical radiance spectrum, such that an impulse concentration of an analyte corresponds to anticipated transmission response manifested in a radiance spectrum. The relationship between concentration enhancement to transmission is used to estimate concentration enhancements across imaged scenes.

**3.4.2. Background Calculation:** Each concentration retrieval and emission quantification approach requires an estimate of a background to determine emission rates. A Background Spectrum is estimated using some sampling of scene-level spectra. And deviation from the mean and covariance of this explicitly used to estimate an Enhancement.

**3.4.3. Plume detection:** Identification of Source Enhanced Concentrations pertaining to a localized Source. The method results in identification of a Plume whose origin is attributable to geographic coordinates of the Source.

**3.4.4. Source geolocation attribution:** Method that uses the geographic information of a Plume in conjunction with other ancillary information (near-contemporaneous red-green-blue (RGB) imagery, geographic information system (GIS) data, etc) to associate a Plume with a Source.

**3.4.5. Plume Segmentation:** Method to isolate Source Enhanced Concentrations associated with a Plume from other background concentration signals estimated from the Concentration Retrieval. The result of this method is a Delineated Plume Boundary that is used to assess extent, shape, and geographic locations of Source Enhanced Concentrations associated with a Plume.

**3.4.6. Mass emission rate quantification:** Method to estimate emission rates from Plume Source Enhanced Concentrations, segmentation plume maps, along with other ancillary information (wind speed). This method relies on quantifying the mass of the plume (kg) and the lifetime of the plume (1/s). The mass of the plume is calculated (details in Section 12) by integrating some portion of the plume (e.g., Integrated Mass Enhancement - IME; units kg). The lifetime of the plume is calculated through estimation of the plume's inverse length or fetch (units 1/m) and the wind speed (units m/s).

**3.4.7. Plume length (m) & fetch (m):** Method to calculate the length of the plume using Delineated Plume Boundary. This value is used for emission rate quantification.

**3.4.8. Integrated Mass Enhancement (kg):** Method to estimate the mass of a Plume using retrieved concentrations. Assuming retrieved concentration units of kg/m2, the IME is calculated for some subset of a plume by multiplication of concentration units with the area of a pixel (units m2), then summation of all subset pixels - this results in units kg for that subset of pixels.

## 3.5. Definitions related to Method Characterization

**3.5.1. Minimum Detection Limit:** the lowest level emission rate that can be detected by the method. Corresponds to about 10% probability of detection.

**3.5.2. 90% probability of detection:** emission rate threshold above which 90% of sources emitting at or above that threshold are detectable by an observing system for a specified range of test conditions (such as average surface wind speed, surface albedo, sensor altitude, sensor viewing angle, and atmospheric stability).

**3.5.3 Quantification Uncertainty:** 1 sigma uncertainty (1 standard deviation) for emission rates are calculated by summation in quadrature of independent terms that cause variability in emission rate quantification, primarily by wind and by IME quantification method.

**3.5.4 Geolocation precision:** The variability in identification of the source of a plume across multiple observations can be determined in cases where methane source locations are known with a high degree of certainty. The error in distance of marked plume origins from a known emission source are summed in quadrature to produce a metric that characterizes 1-sigma variability in plume placement.

## 3.6 Emission Rate Validation

**3.6.1 Controlled release experiment:** Ground-based analyte releases that serve to challenge, validate and characterize emission rate quantification under particular environmental conditions. Carbon Mapper has participated in blinded and unblinded controlled release testing (El Abbadi, et al., 2024) to constrain and validate its emission rate calculation methodology. These studies have shown that airborne platforms reliably detect emissions well below 100 kg/h (minimum detection limits for 3 m/s winds ranging from 10 to 45 kg/h) and show low bias against metered emission rates (Figure 12; El Abbadi et al., 2024).

# 4.0 Interferences

Carbon Mapper has identified the following method interferences and mitigations through a combination of blinded and unblinded controlled release testing (El Abbadi, et al., 2024), simultaneous observations with independent measurement methods such as *in-situ* mass balance flights (Cusworth et at., 2024), and years of application in field surveys including feedback from regulators and operators following site-level inspections. Mitigation methods range from adjusting aerial surveys to work around environmental conditions to algorithmic features and Quality Control (QC) procedures in the data analysis workflow.

| Ref # | Title (Class) | Summary | Mitigation |
|---|---|---|---|
| 4.1 | Solar illumination | Method requires sunlight for robust detection | Schedule flights to meet sun-angle constraints (typically 1000-1500 local time) |
| 4.2 | Clouds | Dense clouds can reduce surface radiance and/or obscure earth's surface, impacting detection and/or quantification impacting detection and/or quantification | Schedule flights for conditions with better than broken sky cover; use cloud gaps and repeat overflights to image priority facilities; QC flag for cloud contamination and low SNR. |
| 4.3 | Aerosols, smoke | Aerosols, smoke and other atmospheric artifacts can reduce SNR, impacting detection and/or quantification | Schedule flights to avoid dense smoke plumes. QC flag for evidence of aerosols in visible band images or low SNR. |
| 4.4 | High wind speed | Wind speeds in excess of 20 m/s dilute $CH4$ concentrations, complicating detection | Schedule flights to avoid high wind conditions. QC flag in analysis workflow for high winds reported in reanalysis product. |
| 4.5 | Low wind speed | Calm/no wind conditions do not impede detection but can impact accurate geolocation or emission rate estimation. | QC flag in analysis workflow for plume shape suggesting calm/no wind (e.g., blob rather than gaussian shape). |
| 4.6 | Wind speed error | Differences between actual surface wind speed at source location and wind speed from 3rd party reanalysis products can result in over- or under-estimate of emission rate. | Periodic validation of reanalysis wind products against surface meteorological observations |
| 4.7 | Low albedo | Surfaces that appear dark in the SWIR bands can result in lower SNR, impacting detection and quantification | QC flag in analysis workflow for low SNR |
| 4.8 | Surface artifacts | Some surface types can generate artifacts in methane retrievals | Analysis workflow includes multiple retrieval algorithms with various surface controls that can help identify surface artifacts; QC flag for surface artifacts. |
| 4.9 | Flares | Flares produce highly specular radiance that in some cases can trigger false methane detections | QC flag for flares in vicinity of potential methane plumes |
| 4.10 | Short flight lines | Column-wise retrieval algorithm can have a low bias in emission rate estimate for short flight lines | Enforce a minimum line length flight rule for aircraft survey operations |
| 4.11 | Instrument hardware issues | Drifts or offsets in instrument calibration or equipment malfunctions can impact spectroscopy or geolocation | Near-continuous on-board calibration procedures of spectrometer instrument and periodic surface hangar calibrations of spectrometer and inflight maneuvers to calibrate IMU. |

**Table 2.** Known Collection Interferences in and Mitigations

| Ref # | Title (Class) | Summary | Mitigation |
|---|---|---|---|
| 4.12 | Multiple emission sources | Localized sources may be in close proximity to one another based on operational conditions | Quality control decisions made with greatest confidence possible |
| 4.13 | Ambiguous plume sources | Shape of a plume and attribution data make localization lead to low confidence attribution | Attribution quality control and confidence metrics applied |
| 4.14 | Diffuse sources, pooling sources | Emission source may emit across a distributed area that is still localized or wind stagnation or topographic conditions cause analyte pooling | Plume delineation quality control process. In cases where confidence is low in quantification, plumes may be deleted or quantifications may not be published. |

**Table 3.** Known Quantification and Attribution Interferences

# 5.0 Safety

Safety of aerial methane mapping missions used by Carbon Mapper is governed by standard FAA requirements on aircraft operations and additional safety procedures mandated by the operating institutions (NASA JPL and Arizona State University).

# 6.0 Equipment and Supplies

Carbon Mapper's aerial methane mapping programs use a suite of imaging spectrometer instruments designed by NASA's Jet Propulsion Laboratory (JPL), referred to here as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) series of instruments. The AVIRIS-series covered by this ATM includes the Next Generation AVIRIS (AVIRIS-ng), AVIRIS-3, and AVIRIS-5 operated by JPL and the Global Airborne Observatory (GAO) operated by Arizona State University.

These instruments measure ground-reflected solar radiation from the visible to infrared spectral regions (380 to 2,500 nm). A subset of bands in the shortwave infrared (SWIR) bands are used for $CH_4$ detection. The instruments all feature high signal to noise ratio and high spatial and spectral uniformity at all wavelengths (Hamlin et al., 2011; Asner et al., 2012; Green et al., 2022). The instruments operate as pushbroom sensors deployed on high performance aircraft, allowing for efficient mapping of large regions at altitudes ranging from 1,000 to nearly 14,000 meters above ground level. Increasing flight altitude affects the ground resolution, i.e., the size of each image pixel increases while the image swath increases.

Each instrument sensor is supported by an onboard flight computer and redundant data storage systems for recording spectrometer data for post-flight analysis. Most aircraft configurations have some variant of onboard methane detection software providing real-time feedback for the flight crew including the potential for rapid repeat flyovers of super-emitters. For complete instrument descriptions, refer to Carbon Mapper's Description of Technology Document and the references cited therein.

Each aircraft is also equipped with an Inertial Measurement Unit (IMU) co-located with the imaging spectrometer sensor that records the aircraft attitude, position and velocity at >100 Hz to support post flight analysis including reconstruction of observing geometry and orthorectification of spectrometer images.

# 7.0 Regents and Standards

There are no reagents required for this method. A NIST-calibrated standard irradiance lamp is used to irradiate a Spectralon standard reflectance panel to assess detector performance during flight campaigns. Power supplies for the lamp are regularly factory calibrated.

# 8.0 Sample Collection, Preservation and Storage

Imaging spectrometers operate using a passive spectroscopic measurement technique. Radiant light is the only directly measured quantity and no sample is collected.

# 9.0 Quality Control

## 9.1 Data Collection

Data quality is evaluated as it is collected in real time by the team operating the instrument. Troubleshooting of instrument performance is done in real time as data is collected. Any instrumental issues are either corrected during flight, or, in extreme cases, the aircraft returns to the hangar to service the instrument.

## 9.2 Retrieval

Radiance data is processed after each flight day using the most current algorithmic methods which standardize detector responses. Additional algorithms process calibrated and corrected radiance cubes applying artifact correction and data masking. In order to make data easier to work with, Carbon Mapper algorithms also trim raw radiance cubes to only the spectral bands needed to quantify analytes. Data quality is assessed by Carbon Mapper's science team at each step of the process leading up to quantification and publication. Current versions of public facing Carbon Mapper Algorithm Theoretical Basis Documents (ATBDs) are included in this application. The most up-to-date ATBDs are available at https://carbonmapper.org/.

## 9.3 Plume Delineation and Quantification

Plume masks applied during data processing are evaluated by analysts trained to identify and mark plume origins. Once an analyst has marked a plume origin, processing algorithms automatically perform plume delineation and apply atmospheric column inversions to generate methane column concentrations for each pixel in units of parts per million-meter (ppm-m). The Integrated Mass Enhancement (IME; units kg; Thompson et al., 2016) approach is used to calculate the excess mass emitted to the atmosphere from a source:

$$IME = \alpha \sum_{i=1} \Omega_i A_i \quad (1)$$

Where *i* refers to a single plume pixel, $\Omega$ is the concentration enhancement of that pixel, $\alpha$ is a unit conversion scalar (from ppm-m to kg $m^{-2}$), and *A* is the area of that pixel ($m^2$). Delineated IMEs are also called concentration plumes. Wind reanalysis products are combined with concentration plumes to calculate plume mass emission rates.

Carbon Mapper calculates emission rates via the integrated methane enhancement (IME) method:

$$Q = \frac{IME}{L} U \quad (2)$$

where Q is the emissions rate in kg/hr, IME is the integrated mass enhancement in kilograms, and L is the length in meters. U is the 10 meter wind speed. In the absence of a 10m anemometer wind observation at the site of the plume, High-Resolution Rapid Refresh (HRRR) reanalysis products are used to estimate the 10m wind speed at the time and location of the observed $CH_4$ plume. (Ayasse et. al, 2023)

## 9.4 Plume Visualization

Algorithms developed by Carbon Mapper are applied to concentration plumes to generate visually compelling and easy-to-interpret images of each plume published on Carbon Mapper's data portal. It should be noted that these visualizations are not the same as the concentration plumes described above, which are used to quantify methane emission rates. Users interested in recreating and evaluating Carbon Mapper plume mass emission rates in a pixel-wise manner, should download concentration plumes rather than plume visualizations. Concentration plumes can be downloaded using Carbon Mapper Application Program Interfaces (APIs) at https://api.carbonmapper.org/api/v1/docs

# 10.0 Calibration and Standardization

Radiance data is collected during flight campaigns by imaging spectrometers mounted in a downward looking orientation inside aircraft. Calibration and characterization of instrument radiometric and spectral performance is done during instrument commissioning and periodically during field deployments.

Calibration of detector performance is done in the field using a NIST-calibrated standard irradiance lamp. The procedure is described in much more detail in the peer-reviewed literature (Chapman, et al. 2019). Methane column retrievals are derived from processed radiance data which does not require direct calibration using methane standards using atmospheric inversion methods derived from the Beer-Lambert law.

# 11.0 Procedure

## 11.1 Flight Planning

Flights campaigns are planned by identifying potential methane point source targets across sectors. Flights are scheduled within the nominal range of acceptable local solar zenith angles and weather conditions. Weather is assessed each morning and adjusted to avoid significant cloud and other interferences. Under typical flight conditions, a raster, lawn-mower type pattern is flown with some overlap between adjacent transacts. For methane use cases, aircraft crew see large plumes in real time displays and can optionally spend extra time reimaging large emissions that are identified.

## 11.2 Aircraft Integration

Imaging spectrometers can be installed in specially equipped survey aircraft provided that mass and power specifications are met and appropriate downward facing optical windows are installed. During a typical deployment, the instrument is installed in the aircraft prior to a field campaign and uninstalled after the end of the campaign.

## 11.3 Data Collection

Data is collected on instrument computer hard drives aboard the aircraft and removed after each flight day for processing. After processing, both raw and processed data are archived.

## 11.4 Post processing and delivery

Post flight data processing is done after data is removed from the instrument hard drive, typically each evening after an individual flight. Algorithms described in Carbon Mapper's attached Algorithm Theoretical Basis Documents (ATBDs), perform orthorectification and plume masking and reduce data size. Processed data is delivered electronically to Carbon Mapper the next day. Raw data is delivered later for archiving and is available for future reprocessing as needed.

# 12.0 Data Analysis and Calculations

Carbon Mapper's analysis workflow combines calibrated radiance data acquired by the spectrometers with measurements of the aircraft attitude and position to retrieve $CH_4$ dry column mean mixing ratios in the strong methane absorption band between 2200-2400 nm. We apply a linearized matched filter to radiances to infer $XCH_4$ (Thompson et al., 2015). The matched filter approach models background radiance as a multivariate Gaussian with the mean spectrum and its covariance estimated from the data. Each pixel is compared to the background, and the difference between the mean radiance and a pixel spectra (normalized by the covariance) is proportional to the $XCH_4$ column mixing ratio. This mixing ratio can be estimated explicitly with a dynamic $CH_4$ absorption spectrum, i.e., the change in radiance for a perturbation of $XCH_4$ given a scene's solar angle, surface altitude, and water vapor concentration. Matched filters can perform full-scene retrievals on CarbonMapper collects within minutes, allowing for fast analysis and visualization of plumes.

The resulting spatially resolved $CH_4$ band images are first analyzed to identify emission plume candidates and assign quality control flags. Automated algorithms then generate delineated plume images, source origin coordinates and emission rate estimates and uncertainties using the retrieved $CH_4$ and surface wind speed data from third-party weather reanalysis products. Carbon Mapper analysts combine the $CH_4$ plume images, visible band surface reflectance images from the spectrometer and 3rd party high resolution satellite imagery and databases of oil and gas infrastructure to attribute plumes to emission sector, nearest equipment type and (where possible) nearest owner/operator.

# 13.0 Method Performance

For this ATM we summarize performance for an aircraft reference altitude of 14 kilometers (approximately 46,000 feet) above ground level representing "worst-case" performance: the highest 90% methane detection limit and coarsest spatial resolution and geolocation accuracy covering all instruments. The instruments used in this ATM all have improved detection limits and spatial resolution at lower altitudes (with a trade-off of reduced area coverage). Imaging swath widths range from 0.5 to nearly 10 kilometers depending on specific flight altitude and instrument configuration.

## 13.1 Uncertainty Quantification

All published plumes include both a mass emission rate estimate and a quantification uncertainty. Carbon Mapper reports a 1-sigma standard deviation.

Uncertainties in emission estimates are calculated by summing in quadrature elements that contribute to variability in emissions:

$$\sigma_q = \sqrt{\left(\frac{\partial Q}{\partial U}\sigma_U\right)^2 + \left(\frac{\partial Q}{\partial IME}\sigma_{IME}\right)^2 + \left(\frac{\partial Q}{\partial L}\sigma_L\right)^2} \quad (3)$$

Where

$$\sigma_{IME} = \frac{\partial Q}{\partial IME}\sigma_N + \frac{\partial Q}{\partial \Omega}\sigma_\Omega \quad (4)$$

In Equation 4 - the $\left(\frac{\partial Q}{\partial U}\sigma_U\right)$term represents the uncertainty due to wind speed, which we estimate by computing the standard deviation of 10-m wind estimates across the hour before and after the plume detection. The $(\frac{\partial Q}{\partial IME}\sigma_{IME})$ term is decomposed into two components, first uncertainty due to masking, which we parameterize as the standard deviation of IME estimates across all segmented plume masks calculated for optimal candidate crop/percentile masks (black curve in Figure 3), and second uncertainty due to the retrieval, which was estimate as the standard deviation of concentration enhancements outside of the segmented plume mask. Finally, the $\left(\frac{\partial Q}{\partial L}\sigma_L\right)$ represents an irreducible uncertainty term due to the pixel resolution of the instrument and how it affects the estimate of plume length *L*.

## 13.2 Detection limit and Probability of Detection

Carbon Mapper assesses both minimum detection limit and 90% probability of detection (90% POD) for methane emission rates. For individual plumes, both metrics are highly dependent on surface reflectance (albedo), solar zenith angle at time of collection, flight altitude and meteorological conditions (especially wind speed). Ayasse et. al (2023) reported a MDL of 10 kg/hr CH4 and a 90% probability of detection of 45 kg/hr CH4 for deployments of ASU's GAO instrument during real world controlled release experiments spanning 2021-2022. Controlled release experiments have also shown that Carbon Mapper quantification accuracy ensures the ability to differentiate emissions above and below SEP thresholds (>100 kg/h).

Carbon Mapper detection and quantification methods are not dependent on an MDL or 90% POD for any particular campaign or set of environmental conditions. All detected plumes are quantified in a similar manner regardless of emission rate. Methods for calculating uncertainty are also independent of flight and environmental conditions.

## 13.3 Validation

### 13.3.1 Controlled Release Experiments

The best validation for method quantification of methane by imaging spectroscopy is blinded controlled releases of carefully metered methane at surface sites. Carbon Mapper has participated in multiple blinded controlled release experiments conducted byStanford University. These experiments allow side by side comparisons of multiple techniques for methane quantification. Carbon Mapper consistently scores well in these studies. For more details on the results of past controlled release experiments, please see peer reviewed publications from Ayasse, et. al, 2019 and El Abbadi, *et al.*,2024. Carbon Mapper will continue to participate in controlled release experiments conducted under a variety of environmental conditions to expand understanding of how our mass emission rate quantifications depend on environmental variables. Many controlled release publications provide comparisons with other simultaneous methane quantification efforts.

### 13.3.2 Comparison with other emission rate measurements

Carbon Mapper has participated in comparison studies with Scientific Aviation, which conducts airborne in-situ concentration based sampling and mass-balance methodologies to determine methane emission rates. Some of these comparisons have been published in peer reviewed journals (Duren et al., 2019 and Cusworth et al., 2024).

# 14.0 Pollution Prevention

Associated emissions from aircraft fuel combustion, staff travel and other operational processes have non-negligible carbon footprints, but are similar to those other scientific field deployment efforts.

# 15.0 Waste Management

No waste is generated by imaging spectrometer instruments and therefore no management process is needed.

# 16.0 References

Asner, G. P., et al., Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. Remote Sensing of Environment 2012, 124, 454−465.

Ayasse, A., *et al.,*, 2023. Performance and Sensitivity of Column-Wise and Pixel-Wise Methane Retrievals for Imaging Spectrometers. *Atmospheric Measurement Techniques* 16 (24): 6065–74.

Carbon Mapper L2b: Methane and Carbon Dioxide Emission Quantification for Satellites Algorithm Theoretical Basis Document. Most up-to-date version available at https://carbonmapper.org.

Carbon Mapper L3/L4: Methane and Carbon Dioxide Emission Quantification for Satellites Algorithm Theoretical Basis Document. Most up-to-date version available at https://carbonmapper.org.

Carbon Mapper Product Guide: Data Definition & Specification document. Most up-to-date version available at https://carbonmapper.org.

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