Carbon Mapper Airborne System Alternative Test Method (MATM-001) - Aerial Imaging Spectroscopy to Detect, Geolocate, and Quantify Methane (CH_4) Emission Plumes from the Oil and Gas Sector.

Note: This document is a mirror of the approved method found at https://methane.app.cloud.gov/review/58.

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 super emitter program (SEP) requires that a method:

a. can detect super-emitters with sufficient sensitivity to confidently differentiate sources above the
b. 100 kg/hr notification threshold
c. can quantify emission rates including uncertainty bounds
d. can geolocate plumes to within 50 meters of the origin of the emission
e. 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

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[1] Worst case (not to exceed) 90% probability of detection for 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 image pixels (and 1 sigma radial geolocation accuracy) at aircraft at altitudes up to 14 km above ground level

(Cusworth et al., 2021).

Carbon Mapper's analysis workflow combines calibrated radiance data acquired by the spectrometers with measurements of the aircraft attitude and position to retrieve CH4 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 XCH4 (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 XCH4 column mixing ratio. This mixing ratio can be estimated explicitly with a dynamic CH4 absorption spectrum, i.e., the change in radiance for a perturbation of XCH4 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 CH4 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 CH4 and surface wind speed data from third-party weather reanalysis products. Carbon Mapper analysts combine the CH4 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.

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).

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 (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.

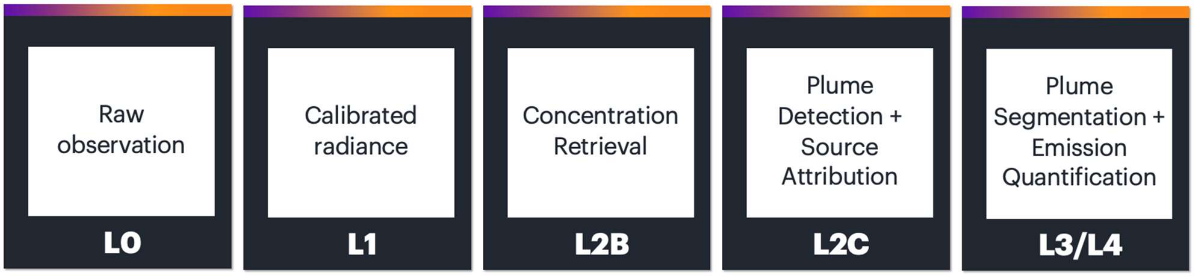

Figure 1. Simplified data flow indicating the Carbon Mapper data processing pipeline and product levels. More details are provided in the Carbon Mapper product guide and algorithm theoretical basis documents included in this application. The most current versions of these documents are available at https://carbonmapper.org

2.3 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.

2.4 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

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

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

3.3.3.2. Flight altitude. The distance between the ground and the sensor.

3.3.3.3. *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

3.3.4.1 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.

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

3.3.4.3 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:

3.3.5.1 Signal to Noise Ratio (SNR). The ratio between sensor optical throughput and all optical and electronic noise sources.

3.3.5.2. 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.

3.3.5.3 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.

3.3.5.4 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.

3.3.5.5 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.

3.3.5.6 Surface wind speed. Methane enhancements in the atmosphere vary directly with near surface wind speed due to dilution.

3.3.5.7. 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. Carbon Mapper uses a columnwise matched filter (CMF) method, for identification and quantification of methane plumes, which is 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 Method Interferences and Envelope of Operation

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 zenith angle	Method requires sunlight for robust detection	Schedule aerial surveys to meet sun-angle constraints (typically 0900-1500 local time)

4.2	Clouds	Dense clouds can reduce surface radiance and/or obscure earth's surface, directly impacting detection and/or quantification impacting detection and/or quantification	Schedule aerial surveys for days with <= 50% average cloud cover; avoid broken to overcast conditions; use cloud gaps and repeat overflights to image priority facilities; QC flag for cloud contamination and/or low SNR.
4.3	Aerosols, smoke	Aerosols, smoke and other atmospheric artifacts can reduce SNR, impacting detection and/or quantification	Schedule aerial surveys for days without excessive Aerosol optical depth. QC flag for evidence of aerosols/smoke in visible band images and/or low SNR.
4.4	High wind speed	Wind speeds in excess of 10 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 bad 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	High wind variability	Rapidly changing wind speeds (gusts) and/or shifting wind directions	Unusually high variability in wind speed or direction can impact quantification (e.g. gusts or swirling winds)
4.8	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
4.9	Surface artifacts	Some surface types can generate artifacts in methane retrievals that could result in a false positive detection or error in emission rate estimate.	Analysis workflow includes multiple retrieval algorithms with various surface controls that can help identify surface artifacts; QC flag for surface artifacts based on visible band images.Where possible, previous overpasses are often checked for the same artifacts.
4.10	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 based on SWIR and visible band images.

4.11	Short flight lines	The column-wise retrieval algorithm can underestimateCH4 enhancements and emission rates without a sufficient number of along-track pixels to constrain background covariance.	Aerial surveys are planned using a minimum flight line length
4.12	Instrument hardware issues	Instrument errors such as thermal control issues or drifts or offsets in instrument calibration or equipment malfunctions can impact spectroscopy or geolocation	Near-continuous on-board calibration procedures of spectrometer instrument and IMU. Periodic surface hangar calibrations of the spectrometer.
4.13	Orthorectification/geolocation Errors	Offsets in scene coordinates relative to ground GPS coordinates	Checked by toggling scene images (RGB layers acquired simultaneously by the spectrometer) with basemaps and looking for significant deviation. QC flag for geolocation errors in standard workflow.

Table 2. Known data collection interferences and mitigations.

Ref #	Title (Class)	Summary	Mitigation
4.14	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
4.15	Ambiguous sources	An amorphous plume shape and/or incomplete facility information may complicate attribution	Attribution quality control and confidence metrics applied
4.16	Uncertainty	Large standard deviations(1-σ uncertainties) in emission rate estimates could lead to reporting a super-emitter that's below the SEP 100 kg/hr threshold	Carbon Mapper computes 1-σ uncertainties for every emission estimate and considers this before reporting to SEP.

Table 3. Known quantification and attribution interferences for Carbon Mapper's method of methane quantification and attribution.

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.

7.0 Regents and Standards

There are no reagents required for this method. Periodic hanger calibrations are done using a NIST-calibrated standard irradiance lamp which 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. Specific details on calibration methods and instrument deployment are presented in Section 10.

8.0 Data Collection and Method Input Sourcing

Imaging Spectrometer 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. Each instrument sensor is supported by an onboard flight computer and redundant data storage systems for recording spectrometer data for post-flight analysis. 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.

Once calibrated radiance files are collected, Carbon Mapper’s column-wise match filter (CMF) algorithms are applied to reduce data volume prior to file ingestion in Carbon Mapper’s data pipeline. This is typically, but not always, done by the aircraft data crew prior to transmission to Carbon Mapper.

After CMF processed files are ingested, Carbon Mapper’s plume identification and quantification algorithm workflow process begins. This workflow generates plume images and quantifications. Table 4 shows the data that is ingested into Carbon Mapper’s pipeline as part of the attribution and quantification process and identifies the source and use of each data type.

Data Inputs	Variables	Use
Spectrometer	Calibrated Radiance Data, SWIR bands (2100-2480 nm)	Radiance data processed to generate the SMF masks used to identify and analyze methane plumes.
Spectrometer	Calibrated Radiance Data, visible bands (RGB) (380-780 nm)	Visible images used analysts to look for activity or new development not visible in basemap imagery.
Aircraft IMU	Altitude (m), latitude, longitude, velocity (m/s)	Orthorectification of calibrated radiance data on a per-pixel basis.

Scene Specific Unit Enhancement Spectrum Database	Unit Absorption Spectra (ppm-m/nm)	Unit absorption spectrum is derived from a database described in Carbon Mapper's L2b ATBD and in Foote et al., 2021. To obtain a copy of the database, contact the authors of Foote et al., 2021.
Pysolar (python library)	Scene specific solar zenith angle (SZA) for use with unit absorption spectrum	SZA is calculated from first principles using python code and libraries.
NASA's MERRA-2 reanalysis product	Scene specific water vapor for use with unit absorption spectrum	This product is available online at: https://gmao.gsfc.nasa.gov/reanalysis/merra-2/
US National Weather Service HRRR 3km 60m Forecast	10 m wind speed (m/s) and wind direction (degrees)	Preliminary meteorological data. Forecast data used for flight planning and initial data work-up for emission rates and plume characterizations. Plumes quantified using forecast products are considered preliminary. Final QC is only performed on plumes once reanalysis meteorological products are available (see next entry). Wind speed standard deviation is calculated by Carbon Mapper using HRRR data.
US National Weather Service HRRR 3km 60m Reanalysis product	10m wind speed (m/s), Wind direction (degrees), standard deviation of wind direction	Final Meteorological data. Wind speed is used to calculate finalized emission rates. Wind speed is used for quality control purposes. Once reanalysis data is ingested, plume emission rates are made available for final QC and publication on the Carbon Mapper data portal.
MapBox, Planet Maps	GIS Base Maps	Base Maps and associated data are often at higher spatial resolution than simultaneous RGB imagery, but may not be as current. Overlays of both are available to analysts in the Carbon Mapper quantification pipeline.
Mapbox, Google Earth, EDF's O&G public infrastructure maps, etc.	Sector Attribution	Public datasets used for attributing detected plumes to the O&G sector.
EPA portal database	Owner or Operator Attribution	EPA provides attribution tools during plume submission which may (best effort) be used to attribute plumes to specific infrastructure owner and/or operator.

Table 4. Data sources used by Carbon Mapper during quantification and attribution of detected methane plumes.

9.0 Quality Control

9.1 Retrieval Quality Control

Radiance data is processed after each flight day to produce calibrated radiance files, using in-flight calibration processes described in section 10. Routine flight decisions relating to safety, meteorological conditions and other environmental factors are made by the flight crew and instrument operators during pre-flight checks. The flight crew processes data collected after each day's flights at the base of operation. Aircraft IMU flight data is used to orthorectify radiance files, extract the channels needed to quantify methane and apply artifact and apply columnwise matched filters (CMF), which are described in more detail in Carbon Mapper's Description of

Technology. At this stage the reduced data is ingested into Carbon Mapper's data portal for detection and quantification of methane. Raw radiance is archived to allow for future reprocessing.

9.2 Carbon Mapper Quality Control Workflow

After data is received by Carbon Mapper, data analysts manually look at each scene's match filters and identify methane plumes for quantification. Once an analyst has marked a plume origin, a plume is automatically delineated, quantified and a plume image is generated. Plume quantification uses the data described in Table 4 above. The automated process is described below and in more detail in Carbon Mapper's public-facing Algorithm Theoretical Basis Documents (ATBDs), which are included in this application. Carbon Mapper most up-to-date ATBDs are available at https://carbonmapper.org/resources/technical-resources.

After a plume image is generated, analysts perform additional plume and scene evaluation and quality assurance using the data quality indicators (DQIs) described in section 9.3. In addition to match filter outputs and plume images, analysts are provided with several different basemaps, meteorological data and have access to infrastructure GIS data layers, which are used to assign a preliminary industrial sector. When analysts complete their work on a plume, they mark each plume done. A full description of the plume marking and assessment is provided in Carbon Mapper's QC Guide available at https://carbonmapper.org/resources/technical-resources.

Carbon Mapper's system automatically reprocesses plume quantification when wind reanalysis products become available, usually in 3-5 days in the United States. Plumes then enter the queue for additional QC by a subject matter expert before they are submitted to SEP or published to Carbon Mapper's Portal. Subject matter experts also review the DQIs in section 3 before making the final decision to publish the plume. For plumes submitted to EPA's SEP this will also include evaluation of SEP-specific criteria for location accuracy and uncertainty.

9.3 Data Quality Indicators

Data Quality Indicators used by Carbon Mapper for each method interference described above (Table 2) are summarized in Table 5 below. Table 6 summarizes additional interferences that are evaluated during the QC process. These criteria are evaluated by analysts at the time of quantification and separately by subject matter experts prior to submission to SEP and publication to Carbon Mapper's data portal.

Ref #	Data Quality Indicator	Optimal Range*	Criteria for SEP reporting
4.1	Solar zenith angle	Solar Zenith Angle: <= 70 degrees	Contributes to SNR assessment in QC process for which a low SNR flag is a binary filter for reporting or not.
4.2	Clouds	Cloud cover <= 50%. Separation between CH4 plume and nearest cloud/cloud shadow > 2 pixels	Detections only reported if the CH4 plume quantification is not affected by intersection with cloud or cloud shadows

4.3	Aerosols, smoke	Aerosol optical depth < 0.9	Contributes to SNR assessment in QC process for which a low SNR flag is a binary filter for reporting or not.
4.4	High wind speed	Surface wind speed: 0.5-10 m/s	If wind speeds are too high, detection will not occur. If speeds are too low, pooling will lower confidence in emission rate quantification. We generally have confidence in plumes observed within this range but wind speed is not an absolute standard for confidence in emission rate quantification.
4.5	Low wind speed	Surface wind speed: 0.5-10 m/s	Detections not reported if plume shape due to low wind speed results in large uncertainties in geolocation or emission rate.
4.6	Wind speed error	<=50%, 1 sigma uncertainty	Wind speed error factors into plume uncertainty calculations. Carbon Mapper will report plumes to SEP only when we are confident that emission rates exceed 100kg/hr.
4.7	High wind direction variability	<= 50% variability in wind direction on short time-scales	In cases where visual evidence of plumes "corkscrewing" preclude geolocation or quantification the source will not be reported.
4.8	Albedo	SWIR albedo >=10%	Not a specific criteria for SEP reporting. Contributes to SNR assessment in QC process for which a low SNR flag is a binary filter for reporting or not.
4.9	Surface artifacts	No surface artifacts (specular reflectors and certain surface materials) intersecting the CH4 plume candidate.	Binary decision: detections not reported in cases where the CH4 plume candidate intersects a surface artifact.
4.10	Flares	CH4 plume length outside the observed flare perimeter >= 10 pixels.	If flare flag is set, only report if CH4 plume length is >= 10 pixels outside the flare perimeter. Wind direction is also evaluated to assure plume extends from source downwind.
4.11	Short flight lines	Flight line lengths should be >= 10 km	Not a specific criteria for SEP reporting. If a flight line is too short, calculated emission rate estimates could be too low (i.e. more conservative).
4.12	Instrument hardware issues	Nominal instrument engineering data and completion of routine calibration procedures. See section 10.	Not a specific criteria for SEP reporting. Data collected in the presence of instrument hardware or calibration issues is not used for CH4 analysis and reporting.

4.13	Orthorectification and geolocation errors	Geolocation errors <= 50 meters radial, 90% circular error probability	Binary decision: detections that include geolocation flags or errors > 50 meters are not reported.

Values outside of the optimal range are not necessarily disqualifiers for SEP reporting purposes. Rather, they indicate the need for further QC evaluation by a Carbon Mapper Subject Matter Expert before submission to assure plumes still meet reporting criteria.

Table 5. Data quality indicators used during Carbon Mapper's QC process.

Ref #	Title (Class)	Optimal Range*	Criteria for SEP reporting
4.14	Multiple emission sources	No optimal range.	Individual source contributions to a plume must clearly exceed 100 kg/hr per source or plume will not be submitted to SEP
4.15	Ambiguous sources	No optimal range. Unambiguous plumes are more gaussian with a clear origin.	Individual source contributions to a plume must clearly exceed 100 kg/hr per source or plume will not be submitted to SEP. Causes of ambiguity include diffuse sources, pooling of plumes and sheared plumes due to wind corkscrewing.
4.16	Emission rate Uncertainty	1 sigma uncertainty	Only report CH4 plumes where the mean emission rate estimate minus the lower 1 sigma uncertainty exceeds 100 kg/hr.

Values outside of the optimal range are not necessarily disqualifiers for SEP reporting purposes. Rather, they indicate the need for further QC evaluation by a Carbon Mapper Subject Matter Expert before submission to assure plumes still meet reporting criteria.

Table 6. Data quality indicators for quantification and attribution interferences evaluated by Carbon Mapper during the QC process.

9.4 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, Ω is the concentration enhancement of that pixel, α 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 CH4 plume. (Ayasse et. al, 2023)

10.0 Calibration and Standardization

Methane column retrievals are derived from processed radiance data using atmospheric inversion methods derived from the Beer-Lambert law which does not require absolute calibration (e.g., using methane standards). However, in order to ensure reliable and repeatable performance, sensors used in this method go through comprehensive factory calibration, followed by field calibration during instrument deployment.

10.1 Sensor Factory Calibration

Every imaging spectrometer sensor undergoes comprehensive radiometric, spectral and spatial calibration in the laboratory during initial assembly, integration and test, prior to initial field deployment.

Instrument calibration occurs in a thermal-vacuum chamber to mimic in-flight conditions, with optical subsystems (telescope, spectrometer, and detector) held at the midpoints of the allowable flight temperature performance ranges, within required thermal stability specifications. The instrument calibration and characterization requirements for each instrument and relevant measurements are as follows:

Spectral

- Spectral Range, Spectral Sampling, Spectral Calibration Knowledge - Laser Sphere
- Spectral Response (SRF) - Scanning monochromator

Spatial

- Spatial Sampling - Broadband Slit
- Cross-track Spatial Response Function (CRF) - Broadband Slit
- Along-track Spatial Response Function (ARF) - Broadband Slit
- Slit (Camera) Model - Broadband Slit

Uniformity

- Spectral Cross-track Uniformity (smile) - Laser Sphere
- Spectral IFOV Uniformity (keystone) - Broadband Slit

Radiometric

- Radiometric Range (maximum reflectance) - NIST Lamp and Panel
- Radiometric Calibration Uncertainty - NIST Lamp and Panel
- Signal-to-Noise Ratio - NIST Lamp and Panel

- Swath Width - NIST Lamp and Panel

Stray Light
- In-field Spectral Scatter - Scanning monochromator
- In-field Spatial Scatter - Scanning monochromator
- Specular Ghosts - Scanning monochromator

These in-lab measurements verify that the instruments meet the mission requirements and are used to generate initial calibration files. These files are an integral part of our data processing pipeline, allowing conversion of instrument Digital Numbers (DNs) to accurate physical units of radiance prior to field deployment.

10.2 Field Calibration

The field calibration procedures are described in more detail in the peer-reviewed literature (Chapman, et al. 2019). In short, the key elements of which are summarized below including: 1) correcting for detector electronic effects such as dark current offset, pedestal shift, and electronic ghosting as well as flat field correction; 2) correcting for optical effects including stray light; and 3) applying radiometric calibration corrections to raw data to obtain absolute spectroradiometry.

10.2.1 Hanger Calibration. Each aerial field campaign begins with a “hangar calibration” of the sensor while fully integrated with the aircraft. The sensor images a Spectralon panel (model SRT-99-120 from Labsphere Inc) illuminated by a NIST-traceable irradiance lamp (model OL200C from Optronic Laboratories) powered by a precision power supply (Model OL83A Variable Power Supply from Optronic Laboratories).The relative response of the detector is then measured using a linear integrating sphere (model QL455-8-2 from Optronic Laboratories) mounted on a swinging track positioned below the sensor at a uniform distance, ensuring each spatial pixel receives the same radiance. The absolute response is then scaled to the relative response, producing the calibration flat field image. Procedures for calibration transfer are further described in Chapman et al., 2019.

10.2.2 In-flight Instrument Checks**.** The conversion from raw digital number (DN) to measured radiance is a function of detector dark current and pedestal shift. These parameters are estimated on an ongoing basis during operations by imaging 1000 “dark” frames with the sensor shutter closed at the start of each flight-line. The dark current represents changes that arise from the thermal environment of the sensor on timescales of minutes or hours, depending on the length of acquisition. Trending of the long-term temporal evolution ensures the dark current level remains stable across multiple flight campaigns.

11.0 Analytic Procedure

Carbon Mapper works with the instrument operators to develop and execute flight plans to meet data collection objectives for deployment campaigns, each typically lasting 2-4 weeks. Operators are responsible for instrument characterization and field calibration as well as flight operation, field calibration (described in section 10.2, above) and data acquisition. Imaging spectrometers are mounted in the aircraft in a downward looking orientation, and collect data in a pushbroom scanning mode. 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.

At the conclusion of each flight day, data from the IMU and imaging spectrometer is removed from the aircraft. A ground-based computer system is used to perform orthorectification and to process data using Carbon Mapper algorithms. Once artifact masks and match filters are applied, processed data is delivered to Carbon Mapper digitally for ingestion into the Carbon Mapper data portal. Calibrated radiance data is archived to allow for future reprocessing as needed.

12.0 Data Analysis and Calculations

12.1 Retrieval Workflow and Calculations. For each scene collected, orthorectified calibrated radiance files are processed by Carbon Mapper's Algorithms. The following list describes Carbon Mapper's processing workflow in chronological order.

12.1.1 Artifact Masks. Carbon Mapper applies a variety of artifact masks to radiance data during radiance data processing. The purpose of these masks is to detect and remove interferences such as clouds, bad pixels, and flare artifacts. The theoretical basis for these masks are described in detail in Carbon Mapper's Description of Technology and L2B ATBD. Artifacts can invalidate plumes or impact confidence in emission rates and invalidated plumes are removed from our workflow.

12.1.2 Columnwise Matched Filters (CMFs). Carbon Mapper's algorithms generate several match filter images, each with slightly different optimizations. These grayscale, high contrast images are overlaid on GIS basemaps and analysts examine these CMFs as they look for, identify and mark detected methane plumes. CMFs are described in detail in Carbon Mapper's Description of Technology and L2B ATBD.

12.1.3 Manual Plume Marking. Analysts mark and QC plumes as described in Section 9. Plumes are then automatically processed by Carbon Mapper's data system through each of the next steps in the process before additional QC is performed by analysts. If a plume origin is moved, this automated process runs again and a new quantification is generated.

12.1.4 Automated Plume Delineation and segmentation. Carbon Mapper algorithms delineate and segment plumes for each marked plume. This process is described in Carbon Mapper's Description of Technology and L3-L4 ATBD documents.

12.1.5 Automated Integrated Mass Enhancement (IME). Once a plume is delineated, an integrated mass enhancement (IME) in units of kilograms is calculated for this plume. Section 9.4 describes this calculation and additional detail is available in Carbon Mapper's Description of Technology and L3-L4 ATBD documents.

12.1.6 Automated Plume Concentration image. For each pixel in a delineated plume, an IME value is generated using equation 1. At this stage, a greyscale concentration plume image is generated that graphically shows pixel-by-pixel IME values used to calculate the emission rate for the plume.

This plume image is the proper product to use to recreate Carbon Mapper's plume quantification.

12.1.7 Automated Determination of Plume Length (L). Carbon Mapper's algorithms calculate a plume length. This process is described in detail in Carbon Mapper's L3-L4 ATBD.

12.1.8 Automated Plume Emission Rate (Q). Wind speed data from the HRRR forecast product and the plume length are used to calculate an emission rate for each plume in units of kg/hr as shown in equation 2. Carbon Mapper describes this process in detail in both our Description of Technology and L3-L4 ATBD.

12.1.9 Automated Plume Uncertainty. The 1 sigma uncertainty associated with each plume is calculated as described in section 13 and in our Description of Technology and L3-L4 ATBD. In most cases, wind speed uncertainty is the major source of uncertainty, but other sources of uncertainty are included in this calculation.

12.1.10 Automated Plume Visualization Image. Carbon Mapper generates an intuitive visualization plume with a color scheme designed to be easily understandable and visually appealing. This is the plume image that is ultimately submitted to EPA's SEP and published on Carbon Mapper's data portal. This image should not be used to recreate Carbon Mapper's plume quantification.

12.1.11 QC and Evaluation of DQIs. After a plume visualization is generated, analysts perform further QC on each marked plume. Plumes visualizations are overlaid on a variety of basemaps. At this stage, analysts perform assessments according to Carbon Mapper DQIs described in section 9.3 and flag any QC issues in their comments. Analysts also identify the most likely origin of observed emissions and attribute plumes to sector of origin (e.g. O&G, waste, agriculture).

12.1.12 Automated Ingestion of HRRR reanalysis wind products. When HRRR reanalysis products are available, Carbon Mapper's system imports final 10m wind speeds and recalculates emission rates (Q). This generates a final quantification value for each plume. This process usually takes about 3-5 days. Submission to EPA SEP requires 15-day turnaround times, and therefore emission rates may still be preliminary at the time of submission.

12.3 Final QC by Subject Matter Expert. Domestic oil and gas sector plumes eligible for submission to SEP are further evaluated by the SEP review team and designated reporter authority. Prior to submission to SEP, a subject matter expert will evaluate each plume individually to make sure each meets SEP requirements for:

- emission rate (>100 kg/hr)
- reporting time deadline (15 days from time of detection)
- geolocation accuracy (60 m or better)

Where possible, plume origins are compared with available infrastructure databases before submissions. Carbon Mapper makes a good faith effort to associate plumes with appropriate, existing infrastructure prior to submission to SEP. Origin locations for submitted plumes are considered final, but quantification estimates are preliminary and may change slightly after final QC, prior to publication on Carbon Mapper's own portal. From time to time, Carbon Mapper may reprocess data that has been submitted to SEP with improved algorithms. Carbon Mapper will preserve a record of plumes submitted to SEP as they existed at the time of submission and can provide documentation of version changes over time if needed.

Plumes that pass all QC assessments and meet submission requirements are submitted to SEP by an EPA-authorized Carbon Mapper employee who has been delegated reporting authority. Additional details regarding data archiving, final quality assessment, and organizational structure have been provided to EPA in the form of a Quality Management plan as part of the Third Party Notifier Certification process.

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 estimated 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 Data Management

15.1 Document Management and Organization

Carbon Mapper's data portal contains a complete record of plumes marked by analysts and their current status. This data system records a version history of all plume IDs, plume locations, quantifications, including information on the identities of staff evaluating plumes, decision history logs, changes to plumes, algorithms used for quantification. Carbon Mapper will preserve version histories as its algorithms improve over time which will allow the recreation of all plumes reported to SEP.

In addition, documents related to Carbon Mapper's Airborne System are maintained according to EPA's Records Policy and Guidance. Carbon Mapper maintains a document database that is detailed in Carbon Mapper's Quality Management Plan.

The database includes the following **categories of documents** used for planning and reporting**.** Additional categories are added as the need arises:

- EPA-specific Records
- Algorithm Theoretical Basis Documents (ATBD)
- Operations (including SOPs and Quality Control Guides)
- Data Platform Documents & Product Guide
- Scientific Study Results

15.2 Document Versioning and Archiving

Carbon Mapper's Chief Operations Officer (COO) and designees, have responsibility for documents and archival processes developed by Carbon Mapper team members. Further, Carbon Mapper's COO:

- Ensures the applicable chain of custody and confidentiality is maintained
- Ensures that the Version Number and Revision Log are updated according to standard procedure
- Ensures compliance with all statutory, contractual, and assistance agreement requirements for records from environmental programs
- Provides adequate preservation of key records necessary to support the mission, by archiving and retaining documents according to the EPA's Record Schedules

16.0 References

16.1 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.

16.2 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.

16.3 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/resources/technical-resources.

16.4 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/resources/technical-resources.

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

16.6 Carbon Mapper QC Guide. Most up-to-date version available at https://carbonmapper.org/resources/technical-resources.

16.7 Cusworth, D.H., *et al.*, 2021. Intermittency of Large Methane Emitters in the Permian Basin. *Environmental Science & Technology Letters* 8 (7): 567–73.

16.8 Cusworth, D.H., *et al.,* 2022, Strong Methane Point Sources Contribute a Disproportionate Fraction of Total Emissions Across Multiple Basins in the United States. *Proceedings of the National Academy of Sciences* 119 (38).

16.9 Cusworth, D.H., *et al.,* 2024, Quantifying methane emissions from United States landfills. Science 383 (6690): 1499-1504. https://doi.org/10.1126/science.adi7735

16.10 Duren, R. M. *et al.,* California's methane super-emitters. Nature 2019, 575, 180−184.

16.11 El Abbadi, S. H., *et al.,* Technological Maturity of Aircraft-Based Methane Sensing for Greenhouse Gas Mitigation, *Environ. Sci. Technol. 2024, 58, 9591−9600.*

16.12 Foote, M.D., *et al.,* 2021. Impact of scene-specific enhancement spectra on matched filter greenhouse gas retrievals from imaging spectroscopy. *Remote Sensing of Environment,* 264, p.112574.

16.13 Hamlin, L., *et al.,* Imaging spectrometer science measurements for terrestrial ecology: AVIRIS and new developments. *Aerospace Conference,* IEEE (2011).

16.14 R. O. Green *et al*., "Airborne Visible/Infrared Imaging Spectrometer 3 (AVIRIS-3)," *2022 IEEE Aerospace Conference (AERO)*, Big Sky, MT, USA, 2022, pp. 1-10, doi: 10.1109/AERO53065.2022.9843565.

16.15 Sherwin, E.D., et al., 2024, US oil and gas system emissions from nearly one million aerial site measurements. *NATURE* 627, 328–334.

16.16 Thompson, D.R., *et al.,* Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane. *Atmos. Meas. Tech.,* ***8*** (10), 4383-4397 (2015).

16.17 Thompson, D.R., et al., On-orbit calibration and performance of the EMIT imaging spectrometer. Remote Sensing of Environment, 303:113986, 2024. https://doi.org/10.1016/j.rse.2023.113986

16.18 Thorpe, A.K., *et al.*, 2021. Improved methane emission estimates using AVIRIS-NG and an Airborne Doppler Wind Lidar. *Remote Sensing of Environment*, *266*, p.112681.