Carbon Mapper Quality Control Description Document

Volume 1: Methane and Carbon Dioxide Detection

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Document Owner	Daniel Cusworth
Contributors	Daniel Cusworth, Alana Ayasse, Riley Duren, Judy Lai-Norling, Mackenzie Huffman, Alex Diamond

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Carbon Mapper, Inc.
12 S. Raymond Ave, Suite B
Pasadena, CA 91105
data@carbonmapper.org

1 Background and Scope

Methane (CH4) and Carbon Dioxide (CO2) are greenhouse gasses that have primarily driven anthropogenic warming since the pre-industrial era. High emission CH4 and CO2 point sources make up a disproportionate amount of the anthropogenic budget. Carbon Mapper's mission is to detect, quantify, and publish these sources using airborne and satellite remote sensing platforms. Carbon Mapper supports policy makers and stakeholders by providing decision support tools and analyses that synthesize satellite and airborne remote sensing data into actionable insights.

The Carbon Mapper data platform is a full-scale operational implementation of a science data system that builds on 10+ years of research and development projects led by Carbon Mapper team members, initially at NASA's Jet Propulsion Laboratory supported by funding from NASA, the California Air Resources Board, and the University of Arizona. Those research projects included multiple airborne field campaigns, satellite and surface observations, and development of CH4 retrieval algorithms, machine learning tools, multi-scale analytic frameworks, data pipelines, open data portals and synthesis analysis.

The Carbon Mapper data platform is designed to rapidly processing and publish point-source CH4 and CO2 data from multiple satellite and airborne imaging spectrometers.The platform has been routinely processing data from airborne surveys using NASA JPL'sAVIRIS-NG and the Arizona State University Global Airborne Observatory since 2022 and expanded in early 2023 to include observations from NASA's EMIT mission on the International Space Station. In 2024, the platform will begin operational processing of Planet's first two Tanager satellites which are being launched by the Carbon Mapper Coalition.

Carbon Mapper is dedicated to providing CH4 and CO2 data that is transparent, trusted and actionable. To meet these objectives we have established Quality Control (QC) methods and procedures that govern the various stages of data analysis and internal review prior to release of CH4 and CO2 products. Here we provide an overview of our methods and procedures to detect and geolocate CH4 and CO2 plumes and attribute them to specific point source by equipment type and sector, along with relevant QC review. Other Carbon Mapper Coalition documentation will describe the theoretical basis for key algorithms as well as QC procedures for emissions quantification.

2 Overview of data products and data processing

Figure 1 below lists Carbon Mapper Coalition data products and processing levels. In brief, the L2b data product is an estimate of column CH4 concentrations that are derived from L1b top of the atmospheric calibrated radiance using CH4 and CO2 absorption features at shortwave infrared (SWIR) wavelengths. Each plume is individually segmented (L3) and emission rates are quantified (L4). In this document we describe the quality control methodologies used by our team for detection, geolocation and attribution of CH4 and CO2 plumes.

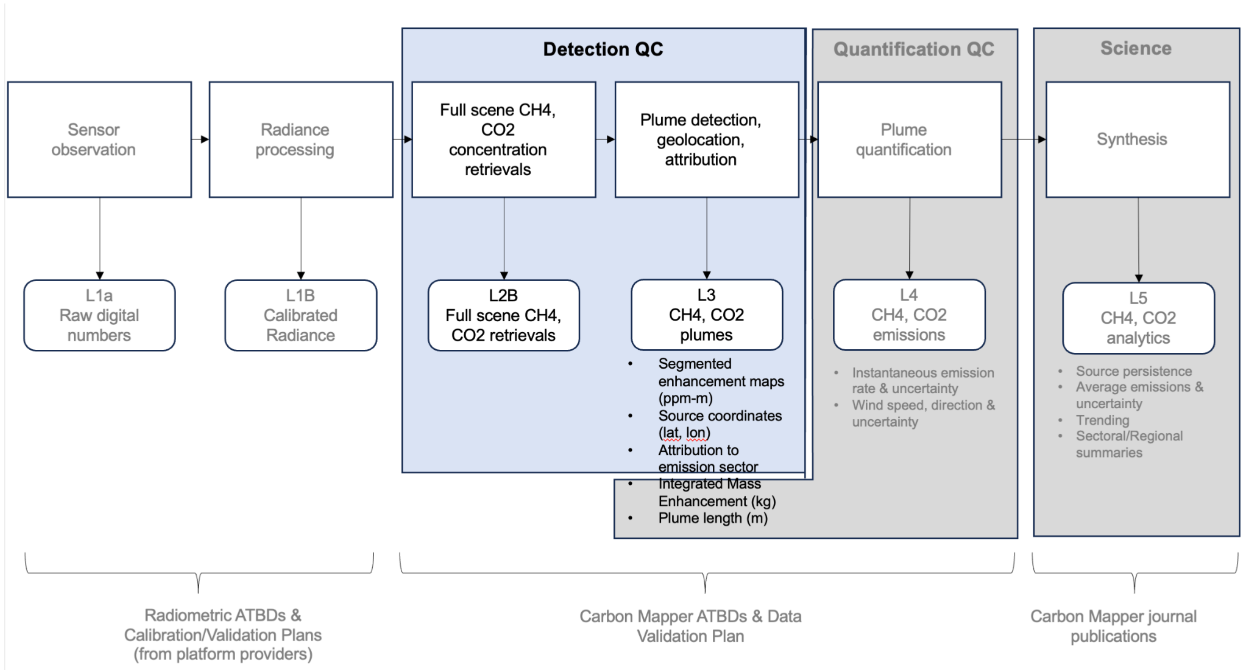

Figure 1: Simplified data flow indicating key QC stages for CH4 and CO2 processing along with the relevant documentation. This document describes Detection QC methods (blue shaded area). Quantification QC, Algorithm Theoretical Basis Documents (ATBDs) and Calibration/Validation Plans will be covered in other documents.

3 Point Source Detection

A **point source** is defined as the geographic location from which emissions originate that results in a highly concentrated plume of CH4 or CO2 gas in the atmosphere. **Plumes** are an excess mass of concentration in the atmosphere produced by a specific source. Plumes are the atmospheric manifestation of emission processes that occur in a variety of economic sectors. Note that point source plumes are a subset of a broader class of CH4 or CO2 **enhancements** that may occur anywhere in the atmosphere as a result of point source and/or diffuse area sources that may or may not be co-located with the enhancements (e.g., a “cloud” of enhanced CH4 can appear in the atmosphere some distance downwind of the actual source). This is a critical concept: not all observed atmospheric enhancements are the result of a point source emission nor can those enhancements always be attributed to a specific emission source. Therefore, Carbon Mapper point source detection and quality control requires that any detected atmospheric plume must be related to a credible point source on the earth’s surface before reporting. Any observed enhancements that fail to meet QC checks are noted for potential follow-up study but do not result in published plumes or emission rate estimates.

The Carbon Mapper point source detection process relies on concentration retrievals (CH4 and CO2 band images), visible red-green-blue (RGB) imagery from various observing systems, GIS databases, and meteorological data. The process begins with automated application of CH4 and CO2 retrieval algorithms to every calibrated radiance scene generated by a satellite or airborne sensor. This results in grayscale CH4 and CO2 band images that first undergo scene level QC review. This review includes determination of systematic scene level issues, including retrieval processing problems, atmospheric artifacts (high haze, clouds, smoke, etc), geolocation issues, and an assessment of scene-level noise.

Each scene's CH4 and CO2 band images are then reviewed to detect potential point source plumes. Figure 2 shows an example of RGB and CH4 imagery from an oil & gas field. In the CH4 band image (right panel), a plume of high concentration is readily visible (here, pixels that appear "white" are high concentration compared to background methane levels). When a plume is identified, a review procedure, which uses a mixture of automated and manual processes that are verified by human analysts in the Carbon Mapper Plume Quality Control Portal, follows the step-by-step process described below:

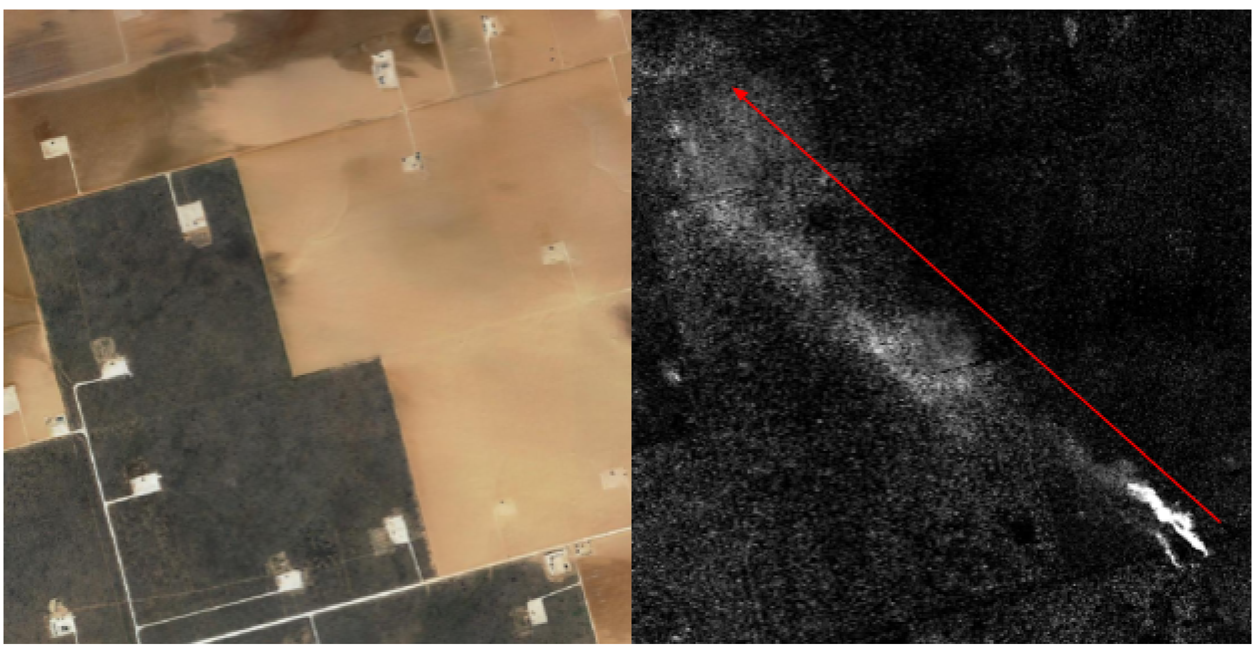

Figure 2. Example imagery of an oil & gas field: RGB imagery (left panel), and plume (white area = high concentration; right panel). The red arrow indicated the wind direction.

1. **Check for RGB Correlation:**

a. For remote sensing instruments, in some cases, certain pixels may falsely appear as areas of high concentration. Certain materials or conditions can predictably result in false positive enhancements, including dark surfaces, water bodies, certain soils, specular reflectors (e.g., solar panels), large thermal sources (e.g., flares), and rooftops.
b. Comparison of CH4 imagery and the contemporaneous RGB imagery is performed to see if any signals in the RGB align very closely with the enhancement. If so, these falsely high concentration areas will not be classified as point sources. See Figure 3 for an example of soil artifacts.

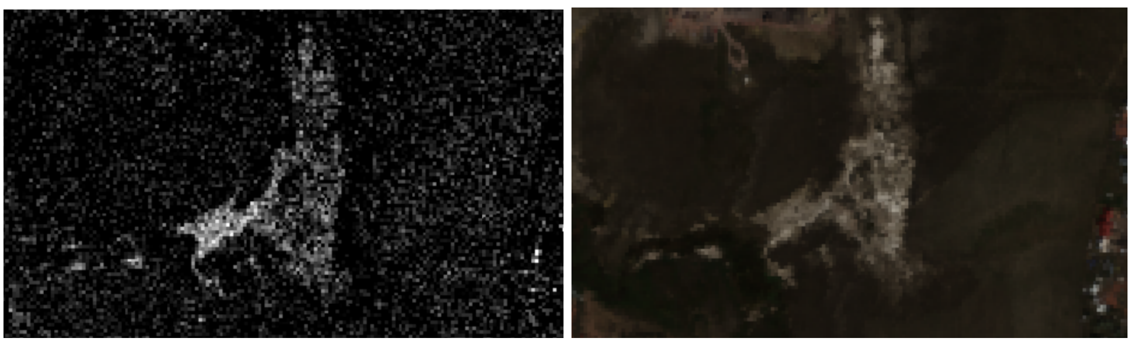

Figure 3. Example of false positive artifacts due to soil. Soil spot visible in the RGB channels of the spectrometer (right panel) also appear as positive concentration enhancements (left panel). The analyst would not mark this enhancement as a plume.

2. **Origin and sector attribution**:
   a. Basemaps, which are high resolution images often taken at a different time with a different instrument, do not only confirm presence or lack of potential artifacts, but serve the function of determining if an enhancement can be considered a point source - i.e., it is connected to some infrastructure and attributable to a sector. Figure 4 shows examples of infrastructure types known to potentially be sources of point source emissions
   b. A combination of RGB imagery from the imaging spectrometer, available basemaps, including MapBox, the most recent monthly PlanetScope basemap, any potentially high resolution imagery taken near contemporaneously (e.g., SkySat) are used to corroborate a CH4/CO2 concentration enhancement to an origin. Other layers from global information system (GIS) databases, like the Greenhouse Gas Reporting Program (GHGRP), the Oil and Gas Infrastructure Mapping (OGIM) database, MEthane Tracking Emissions Reference (METER) database, etc are used for corroboration.
   c. Plumes are attributed to sector based on corroborating basemap and GIS information (oil & gas, waste, electricity, livestock, etc)
   d. The origin of the point source is determined using a combination of two criteria: (1) high concentration - typically a spatially tightly constrained area of maximal

concentration, indicative of a large gas release. (2) plausible RGB/GIS infrastructure.

e. If no determination of an origin is possible from basemaps or GIS database information, the plume will not be classified as a point source.

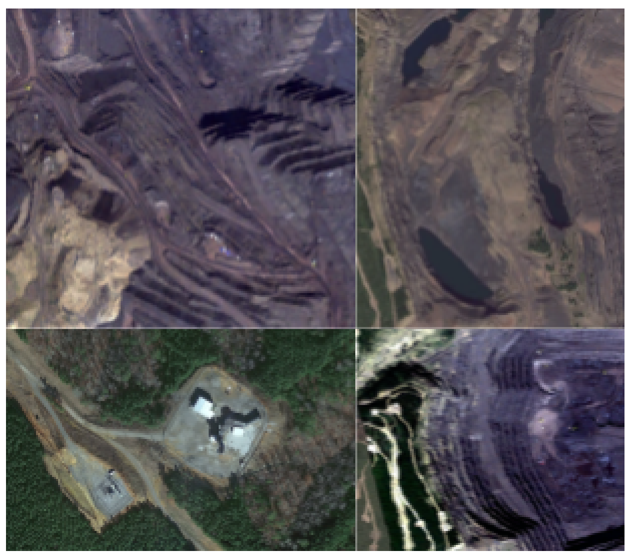

Figure 4. Typical aerial appearance of common infrastructure types known to be sources of CH4 point sources. Top panel: Confined Animal Feeding Operations (CAFOs). Second panel: Surface coal mines and coal mine ventilation shafts. Third panel: Upstream oil&gas operations. Bottom panel: Solid waste management (landfills).

3. **Consult Additional Overpasses**:
    a. In cases where a plume may be marginal in size, odd in shape, or have some other attribute that makes clear detection complicated, previous data acquisitions over the same site are used as evidence.
    b. As atmospheric gasses, the shapes of CH4/CO2 follow the dynamics of atmospheric transport, meaning that a unique plume shape should be anticipated in every scene due to variability in meteorology, turbulence etc.
    c. If a candidate plume has a consistent shape across many scenes, it is likely the result of a surface artifact (see point 1), and will not be classified as a detection.
4. **Compare against wind speed and direction**:
    a. The Carbon Mapper Plume Quality Control Portal has the ability to dynamically query reanalysis (e.g., HRRR, ERA5) wind speed and direction of reanalysis wind products on demand.
    b. The morphology of a candidate point source is checked against reanalysis wind direction (and its uncertainties). Cases where there is large divergence in

reanalysis wind direction and plume morphology are marked for additional manual review.

5. **Final decision**
    a. For point sources that are marked as true detection following steps 1-4, additional attributes are determined for each plume, including:
        i. Plume quality
            1. "Good": unambiguous point source that is not corrupted by artifacts, shape, noise, etc.
            2. "Questionable": unambiguous point source that may suffer from some artifact corruption, shape, etc.
            3. "Bad": unable to make a determination of a true point source. Additional manual review will be needed by an analyst. Note: "Bad" is not a terminal state: either another analyst will remove entirely or reclassify as "questionable"
        ii. Other Plume Attributes: other metadata associated with the plume that is helpful for assessing quality (checkboxes).
            1. Plume Shape: The plume's shape diverges from standard quasi-gaussian appearance (e.g., has gaps, swirls, "blobs," etc)
            2. Intersect Artifacts: The plume intersects obvious artifacts
            3. Intersect Flare: The plume intersects a flaring artifact
            4. High Background Enhancement: The plume is embedded within a region of high noise / high background making delineation, or separation from foreground and background pixels complicated
        iii. Other notes
            1. An analyst can choose to leave a custom note for each plume describing any additional thought processes that went into plume determination

After detection is complete for a scene, all identified plumes will be automatically delineated and quantified for emissions. A final QC round is performed by an alternate analyst to check detection attributes as well as check for consistency in emission rates before publication to the Carbon Mapper Open Data Portal. This process is described in forthcoming (Volume II) quality control documentation.