Community Air Monitoring Plan: Appendix C

California Statewide Mobile Monitoring Initiative (SMMI)
Aclima Mobile Platform Quality Assurance System (v4.1)

aclima

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CALIFORNIA AIR RESOURCES BOARD

CALIFORNIA CLIMATE INVESTMENTS
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Table of Contents

1.0 Introduction 4
2.0 Mobile Monitoring Methods and Equipment 6
2.1 Aclima Mobile Measurements 6
2.1.2 Reference equipment and standards used for calibration and performance assessment 10
3.0 Fleet Operations 12
3.1 Sampling Methods and Drive Plan Operations 12
3.1 Mobile Fleet Maintenance and Diagnostics 13
4.0 Measurement Quality Objectives 15
4.1.1 Precision and Bias 17
4.1.2 Data Completeness 18
5.0 Quality Control Procedures 18
5.1 Evaluation during AMN production 18
5.2 Pre-deployment calibration 19
5.2.1 Collocation with Reference Instruments (O3, NO, NO2, and CO2) 20
5.2.2 Peer-to-peer collocation (PM2.5, CO, and TVOC) 20
5.2.3. Black Carbon 21
5.2.4 Reference Gas Calibrations (CH4, C2H6, and TVOC) 21
5.3 Measurement verification during deployment 22
5.4 Mid- and Post-deployment recalibration 23
5.4.1 Drift correction 24
5.4.2 Drift correction: TVOCs 25
5.4.3 Systematic Bias: Ambient Concentration Estimates Data Product 25
5.5 In-field sensor performance 25
5.6 Important Limitations for Specific Sensors 29
5.6.1 Ethane (C2H6) 29
5.6.2 PM2.5 29
5.6.3 Nitric Oxide (NO) 29
5.6.4 Nitrogen Dioxide (NO2) 29
5.6.5 Total Volatile Organic Compounds (TVOC) 30
6.0 Data Stages 30
8.0 Citations 32

1.0 Introduction

Mobile air pollution mapping is a flexible method to measure concentrations of a broad range of air pollutants and greenhouse gases over large geographic areas at high spatial resolution. Aclima has developed a platform (the Aclima Mobile Platform or AMP) for sampling ambient air pollutants at the hyperlocal level. Aclima-operated fleet vehicles are equipped with the custom-designed onboard mobile sensing system), which measures CO, CO_2, NO, NO_2, O_3, CH_4, C_2H_6, TVOC, BC, and $PM_{2.5}$.

The data collected on-road enable a variety of high-resolution spatial analyses that support different use cases. A fundamental output is the creation of maps of typical air pollution concentrations at high spatial resolution that show areas in a community experiencing persistently high or low levels of individual pollutants. The other case study uses time-resolved data from several individual drives of the same location to identify areas where pollution concentrations vary substantially from local levels, indicating a probable local emissions source. Outlined below are Data Quality Objectives (DQOs) for data products based on these two analysis approaches as well as the specific pollutants to which the data product applies.

1. **Show areas that have relatively higher and lower pollution in a geographic region at high spatial-resolution**:
   Data Quality Objectives:
   - Produce estimates of ambient pollution concentrations from measurements balanced over the monitoring time period and at diverse times of day and night, weekdays and weekends, to adequately address seasonal and diurnal variations in the data.
   - Data are spatially distributed throughout the entire user-defined area.
   - Deliver concentration estimates with credible intervals at the desired spatial resolution sufficient to enable assessment of the significance of differences in pollution levels.
   - Support pollution estimates at relevant aggregation scales (e.g. hexbins).
   - Monitor and track the following key data quality indicators: bias, drift, precision

   Typical Pollutants of Interest[1]:
   - O_3, NO_2, $PM_{2.5}$, CO, CO_2, and BC

2. **Identify probable locations of emissions sources of key pollutants**
   Data Quality Objectives:

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[1] The TVOC sensor has two characteristics that make data from the sensor unsuitable to support ambient concentration estimates; (1) the sensor is sensitive to a wide range of VOCs with the sensitivity to different classes of VOCs varying by multiple order of magnitude, (2) the sensor is prone to baseline drift. For more information, see Section 5.6.5.

- Produce geo-located clusters of pollutant source indications by identifying enhancements above background in the form of peaks in the 1-Hz sensor output that have a signal to noise ratio of at least 3.
- Minimize the presence of “false positives” in the determined clusters of pollutant source indications by setting conservative criteria for what defines a source indication, such as the number of repeat enhancement detects in the same location and the signal to noise ratio that defines an enhancement.
- Monitor and track the following key data quality indicators: gain drift and limit of detection

Typical Pollutants of Interest:

- CH_4, C_2H_6, BC, $PM_{2.5}$, NO, CO, TVOC

These DQOs are largely qualitative goals that provide the foundation for the types of insights that the Aclima data products are designed to support. A critical aspect of quality assurance underlying these DQOs is characterizing and maximizing the measurement quality of the sensors, however, our confidence in these data products will depend on a number of additional factors, including but not limited to our sampling strategy, the number of samples collected for features of interest (i.e. road segment or other spatial length scale), and magnitude and variability in pollution concentration and meteorology over the contract period. Therefore, the overall approach to quality assurance must include processes and metrics that address all potential sources of uncertainty, and success in meeting the data quality objectives cannot be measured by a single set of measurement quality objectives (MQOs). Further, many of the factors impacting data quality are subject to real world operational challenges (i.e. driver absences) or outside the control of even a perfectly executed QA plan (i.e. strong wildfire events impacting air quality over short time periods). Therefore, we cannot guarantee any specific maximum confidence interval (or precision) around individual atmospheric concentration estimates, but we can provide data that are high quality with well-characterized performance parameters to support aggregation and analysis of our data products, which can be used to support decision making in various use cases.

With an understanding that the quality of Aclima’s data products involves many complex factors, the measurement quality of the sensors is critical. This document outlines the Quality Assurance processes for the devices, measurement, and sampling that provide the foundation upon which Aclima’s data products are produced. The document covers Aclima mobile monitoring methods, equipment, and sampling methodology from device assembly to 1-Hz time-resolved data verification for each device and vehicle. We also include information on sensor calibration and data review processes.

2.0 Mobile Monitoring Methods and Equipment

This section outlines how vehicles are outfitted with Aclima's custom-designed mobile monitoring platform, as well as the reference equipment and laboratories used to calibrate and assess sensor performance.

2.1 Aclima Mobile Measurements

The Aclima Mobile Platform (AMP) measurement suite includes a core set of criteria pollutants, greenhouse gases, and other pollutants, operating at a collection frequency of every second (1 Hz, with the exception of ozone which is measured at 0.5 Hz): carbon monoxide (CO), carbon dioxide (CO2), nitric oxide (NO), nitrogen dioxide (NO_2), ozone (O_3), methane (CH_4), ethane (C2H6), total volatile organic compounds (TVOC), fine particulate matter (PM2.5), and black carbon (BC). Additionally, the mobile platform is outfitted with high frequency wind measurements (1 Hz). The complete sensor package, supporting hardware infrastructure, and vehicle, is referred to as a single "mobile platform."

At the core of the sensor package is a comprehensive sensor suite integrated into an Aclima-built hardware package, collectively called the Aclima Mobile Node (AMN). The AMN is a low power self-contained device that houses a range of different sensors in a temperature-controlled enclosure (solid state thermoelectric cooling) and includes a high quality GPS system and an LTE cellular router. The AMN is compatible with the DC power available in any vehicle (internal combustion engine, hybrid, and EV) and doesn't require external shore power, generators or additional batteries. The AMN measurements include CO, CO2, NO, NO2, O3, TVOC, and PM2.5. Methane/ethane and BC sensors sit physically alongside the AMN in the vehicle but outside of the AMN enclosure. The wind sensor is mounted outside on the roof of the vehicle. The AMN functions as the communications portal to transfer measurements from all sensors to the cloud and as backup storage in the event of any connectivity issues. The AMN can also serve as a communications platform for additional sensors in custom applications.

The AMN actively samples ambient air from a custom-designed, window-mounted inlet anchored in the rear passenger side window of the vehicle. The Aclima Mobile Node (AMN) has two primary sampling lines that transfer air from the ambient atmosphere to the internal sensors, one for gases and one for $PM_{2.5}$. The methane/ethane and BC sensors each have their own independent sampling inlets.

To minimize changes in concentrations of reactive species (e.g. NO, NO_2, O_3, and TVOC) due to chemical reaction with or loss on tubing surfaces, these gases are sampled through non-reactive PTFE (polytetrafluroethylene) tubing with PFA (perfluoroalkoxy alkane) fittings. These gases are measured within the Aclima Mobile Node (AMN). Sample lines for CH_4 and

C_2H_6, and air toxics consist of PTFE tubing with stainless steel fittings. Methane and C_2H_6 are measured by the same sensor (one sample line). Inlet lines for gases extend straight out from the window and the inlet of the sample lines are perpendicular to the surface of the vehicle. A Nafion™ dryer is placed inline, just inside the window, to help control the water content in the sampled air for CH_4 and C_2H_6, which is particularly important during conditions when the ambient dew point is high (i.e. hot and humid conditions) where condensation could form inside the sampling lines once inside an air conditioned vehicle. A Nafion™ dryer is not used for the primary gas line due to diffusion of VOCs impacting the TVOC measurement.

To minimize particle loss, sample lines for $PM_{2.5}$ and BC are composed of copper and antistatic silicone conductive tubing with brass fittings. The sample lines for $PM_{2.5}$ and BC extend from the inlet mounting surface with its opening situated parallel to the car exterior and facing towards the front of the car. Separate sample lines are used for $PM_{2.5}$ and BC. No size-based removal of particles occurs at the inlet in the $PM_{2.5}$ sample line. A Nafion™ dryer is placed inline for each, just inside the window, to help control the water content in the sampled air for $PM_{2.5}$ and BC. The BC sample line includes a cyclone (sharp-cut 2.5 µm at 150 mL/min) in order to keep larger particles from depositing inside the sensor and deteriorating performance.

The $PM_{2.5}$ sensor reports particle counts in six size ranges based on optical scattering. Aclima uses a standard mass conversion model assuming spherical particles and constant particle density across the different size ranges to convert particle counts to particle mass. Additional details on limitations of the PM sensor are discussed in Section 5.6.2 and in the accompanying "Hyperlocal Ambient Concentration Estimate Validation and Quality Assurance Plan" document (CAMP Appendix D, Section 5.2).

Table 1: Aclima Mobile Monitoring Platform Sensor Operational Characteristics

Parameter	Measurement Method	Measurement Frequency	Operational Range*
O_3	UV Spectroscopy	2 sec	0-100 ppm
NO	Electrochemical	1 sec	0-20 ppm, adjustable
NO_2	Electrochemical	1 sec	0-2 ppm
CO	Electrochemical	1 sec	Adjustable
CO_2	Nondispersive Infrared	1 sec	0-5000 ppm
CH_4	Direct Absorption Spectroscopy	1 sec	1 ppb-1%

C_2H_6	Direct Absorption Spectroscopy	1 sec	1 ppb-1%
TVOC	Photoionization Detection	1 sec	1 ppb - 20 ppm
$PM_{2.5}$[1]	Optical Light Scattering	1 sec	0-300,000 counts/L
BC	Optical Absorption at 880 nm	1 sec	0-1 mg BC/m^3
Wind Speed and Direction	Ultrasonic Anemometer	1 sec	0-60 m/s; 0-359°
Temperature	Diode voltage	NA	-40-85 ℃
Relative Humidity	Resistive	1 sec	0-100%
Pressure	Capacitance	NA	300-1100 hPa
Location (GPS)	Satellite GPS	1 sec	> 5 m
Time	Real-time clock (RTC) via Network Time Protocol	32.768 kHz oscillator	NA

Additional sensor performance metrics are included in Table 5.

* Manufacturers' specification

1. $PM_{2.5}$ is determined from particle number (PN) counts, where PN is measured in six size ranges between 0.3 and 2.5 µm with count concentration (c/L) converted to mass concentration assuming spherical particles and constant density across the six size ranges.

Sensors located within the AMN each record in-line temperature (T), pressure (P), percent relative humidity (RH%), and flow-rate at 1 Hz. These sensors are located close to the respective sensor so environmental conditions are known when the pollutant is measured. The BC and $PM_{2.5}$ sensors also include T, P, RH, and flow rate (at 1 Hz) as part of their measurement system, while the CH_4 and C_2H_6 sensor includes temperature, pressure, and absolute H_2O concentration (at 1 Hz). These environmental measurements provide system state diagnostics or *status indicators* and are used in Aclima's sensor models to convert the sensor signal (e.g., voltage) into a physically meaningful concentration measurement (µg/m^3, ppb, ppm) and to ensure sensor measurements are maintained within their appropriate operating conditions. Because the T, P, and RH measurements are specifically designed to measure internal instrument conditions, they are not representative of ambient atmospheric conditions and are thus not provided as part of Aclima's data products.

To account for differences in transport time between the sample intake and when it reaches the different sensors in the Aclima Mobile Platform, the data for each sensor is time-shifted according to the nominal residence time in the sample tubes In Aclima's current mobile platform, where the inlets are located at the rear passenger window, time shifts range from about 2-10 seconds and have been estimated based on sample tube lengths, inner diameter, and flow rate. Uncertainty around these estimates primarily comes from the uncertainty in flow rates, estimated at approximately ±5%.

The geographic position of each measurement, described using latitude and longitude, is provided by GPS (manufacturer specifications of ±5 m) and is measured at 1 Hz. Evaluation of GPS position during field operations when parked indicated an uncertainty of ±6 to ±12 m depending on location and averaging time of the data, with smaller uncertainty at longer averaging times. Vehicle speed is determined based on change in GPS location and provided at 1-Hz. All measurements are synchronized using Network Time Protocol (NTP), which synchronizes the internal computer to Coordinated Universal Time (UTC), and are reported to the nearest segment in UTC. Individual sensors are tracked throughout by project, serial number, parameter, model, and start and stop time of use.

The measurement method for each of the sensors employed in Aclima's mobile monitoring platform is listed in Table 1, along with the reporting frequency and operational range as reported by the manufacturer.

Table 2: Manufacturer Specifications for Reference Instruments and Gas Standards

Target Pollutant[1]	Detection Principle	Resolution[2]	Range	Response Time	Manufacturer
Reference Instruments					
O_3	UV Absorption	0.1 ppb	0.001-2 ppm	4 sec	2B Technologies, Model 211
NO	Chemiluminescence	0.001 ppm	0-0.5 ppm to 0-100 ppm selectable	<1 sec	Eco Physics AG, Model CLD64
NO_2	Cavity attenuated phase shift spectroscopy	0.010 ppb	0-1 ppm	<10 sec	Teledyne Inc., Model T500U
CO_2	Non-Dispersive Infrared (NDIR)	0.1 ppm	0-20,000 ppm	~1 sec	LiCor Environmental, Models 840A & 850
		a)	a)		
Certified Reference Gas Standards					
Target Pollutant	Standard Gas	Span Values	Standard Gas Uncertainty		
CH_4	NOAA and NIST Certified Reference Gas Standards[3]	~2 ppm ~5 ppm ~50 ppm	NOAA standards: +/-0.2% NIST standards: +/-0.2% (at 2 and 5 ppm) or +/-2% at (50 ppm)		
C_2H_6	NOAA and NIST Certified Reference Gas Standards[3]	~ 1 ppb ~ 50 ppb ~ 5000 ppb	NOAA standards: +/-0.2% NIST standards: +/-0.2% (at 1 and 50 ppb) or +/-2% at (5000 ppb)		
TVOC	NIST Certified Reference Gas Standards[4]	zero and ~1 ppm after dilution	20.00 ppm ± 5%		

[1] Reference methods are not currently used in the Mobile Calibration Laboratory for $PM_{2.5}$, BC, TVOC, and CO sensorsSee section 5 for details on how these sensors are calibrated.

[2] Resolution is the ability to distinguish between two measurements from each other and does not refer to the limit of detection or the ability to distinguish from the baseline single.

[3] A combination of reference standards prepared by NOAA's Central Calibration Laboratory and working standards prepared by NIST are used for CH_4 and C_2H_6 . The latter acts as a transfer standard. The uncertainties for the NIST working standards were characterized against the NOAA standards.

[4] Isobutylene in nitrogen.

2.1.2 Reference equipment and standards used for calibration and performance assessment

Aclima uses laboratory-grade reference equipment in Aclima's location-specific Mobile Calibration Laboratories and at Aclima's location-specific Ambient Calibration Laboratories to calibrate O_3, NO, NO_2, and CO_2 measured by the Aclima mobile platform. Instruments selected for use as reference for calibration are historically tested and widely-used detection methods accepted by the atmospheric science community as a high-quality measurement. For some sensors, NIST certified gas standards were used as a reference for calibration and evaluation. All reference instruments have well defined uncertainty over a wide range of conditions. Table 2 provides a summary of manufacturers' specifications or certifications for all reference instruments or gas standards. (Note that the reference equipment is not operated in a manner that meets the requirements of regulatory reference methods, e.g. mobile sampling uses 1-Hz data rates vs typical gas reference method requirements of a 60-sec averaging time.) NOAA (primary standard) and NIST (transfer standard) traceable gases are used to calibrate the combined CH_4 and C_2H_6 sensor (Section 5.2.4). Individual $PM_{2.5}$ and CO sensor performance (precision and bias) and sensor-versus-sensor comparability are quantified, under real world driving conditions, pre- and post-deployment by peer-to-peer collocation using Aclima's Mobile Calibration Laboratories (Section 5.2.2). Volatile organic compounds (TVOC) undergo an initial calibration using a reference gas (Section 5.2.4) and are validated through the peer-to-peer collocation approach (Section 5.2.2). The BC sensor flow rate is calibrated using a certified flow calibrator provided by the sensor manufacturer specifically for use with the BC sensor. The BC sensor is not routinely collocated with a reference method or with other BC sensors as part of its standard calibration procedure. However, occasional collocation experiments have been performed in order to characterize general sensor performance (see Sections 5.2.3 and 5.5 for more details).

Table 3: Reference instruments[1], quality control, and corrective action

Description	Modalities	Frequency	Acceptable Bounds	Corrective Action[2]
Reference Instrument span using NIST traceable methods	O_3, NO, NO_2, CO_2	Monthly	± 5% (O_3, NO, NO_2); ±10 ppm (CO_2)	Recalibrate the instrument span
Reference Instrument zero checks NIST traceable methods	NO, NO_2, O_3, CO_2	Monthly	±0.5 ppb (O_3, NO_2); -0.3-1.3 ppb (NO)	Recalibrate the instrument offset
O_3 Generator[3] and Gas Calibrator	NO, NO_2, O_3	As needed		Manufacturer service and recalibration
NIST traceable gases (cylinder)[4]	CH_4, C_2H_6 TVOC[5] (isobutylene)	As needed when cylinders reach <25%		Replacement with new cylinder

	NO CO_2	full or certification expires		
Zero Air Generator	NO, NO_2, O_3	As needed		Manufacturer service
Flow Calibrator	BC	Approximately annually, as recommended by mfr		Recalibration performed by manufacturer

1. Reference instruments are not available at this time for use in the Mobile Calibration Laboratories for CO, air toxics, $PM_{2.5}$, and BC. Aclima uses a relative reference or the average of an ensemble of CO, TVOC, or $PM_{2.5}$ sensors of the same make and model as the test sensor as described in Section 5.2.2. BC and $PM_{2.5}$ are currently used as received by the manufacturer.
2. If reference instruments fail to meet acceptance criteria they are sent back to the manufacturer for recalibration or replacement. Instruments are sent back annually for recalibration.
3. The O_3 generator is not routinely sent to the manufacturer for recalibration/certification, but only when service is required and may result in a small source of systematic bias for O3 and NO2.
4. For CH_4 and C_2H_6, Aclima uses a combination of reference standards prepared by NOAA's Central Calibration Laboratory and working standards prepared by NIST. The latter acts as a transfer standard.
5. TVOC - isobutylene certified gas standard in cylinder at ~1 ppm for an initial calibration, which is followed by peer-to-peer collocation in an Aclima Mobile Calibration Laboratory where the slope and R^2 values for bias and precision are obtained from comparison to the relative reference, similar to PM, TVOC, and CO.

Since laboratory-grade reference equipment forms the basis for data quality, Aclima performs a suite of quality control checks that are integrated into our operating protocols to quantify uncertainty in the reference measurements to ensure they are within an acceptable range. Table 3 details the type of checks performed with reference instruments, the frequency at which they are performed, the values triggering corrective action, and the type of corrective action triggered. Internally developed processes and instrument manuals are used to conduct the checks.

3.0 Fleet Operations

This section focuses on driving operations – the planning and operational information about how Aclima maps with a mobile measurement fleet. Details regarding field and laboratory procedures for measurements and data verification and validation are provided in Sections 2.1 and 6.0.

3.1 Sampling Methods and Drive Plan Operations

Aclima's sampling design algorithm ("the algorithm") supplies daily drive (routing) plans to drivers. This algorithm is different from typical survey-based approaches: it is dynamic, making decisions on where to collect additional data based on a near-real-time view of all collected data and available resources. As with traditional survey-based methods (e.g. Apte et al., 2017) the algorithm is built upon the well-established fundamental principle that repeat measurements are required for mobile monitoring outputs to produce temporally representative pollutant concentrations and that error reduction in the resulting data products is driven by increasing the number of repeat measurements; however, it is a substantial improvement on historical survey-based approaches in that it is designed for flexibility and adaptability as data collection proceeds. Functionally, this approach results in a different number of repeat measurements in different locations, with the sampling deliberately distributed to provide higher rates of repeat measurements in locations with higher observed variability. It helps ensure that the measurements generated via Aclima's mobile monitoring adequately and efficiently characterize the spatial and temporal variability in air quality in areas of concern during the monitoring time period.

The drive planning algorithm automatically schedules drive plans on a daily basis. This system updates all internal models and datasets based on most recently performed analyses of data collected to-date. Each of these models is analyzed for mischaracterization or uncertainty across the coverage area, resulting in a prioritization surface that the algorithm uses to optimize vehicle routing before generating the final drive plan. This drive plan, which describes the specific route for the driver for that day, is made available to drivers at the beginning of their shift for display on a tablet computer inside the vehicle.

3.1 Mobile Fleet Maintenance and Diagnostics

Preventative maintenance tasks are implemented at various frequencies as specified by the manufacturer or based on past experience as outlined in internal SOPs[2]. Aclima uses a multi-level approach to mobile platform maintenance to help ensure the successful collection of high quality data while minimizing data loss. A rigorous schedule of system checks and replacements has been established, which includes daily, weekly, and monthly system maintenance tasks. A separate AMN/sensor database links each unique instrument (by serial number) to allow for tracking preventative maintenance due dates for individual sensors and mobile platforms.

Aclima technicians perform a full diagnostic check on the system at each installation of an AMN or sensor into a vehicle and whenever any on-demand maintenance is required. Diagnostic checks are also performed immediately prior to uninstallation in order to verify that the integrity of the system, especially the sampling system, was maintained over the duration of the deployment. The following tasks are performed and logged as part of these diagnostic checks:

[2] Aclima's internal SOPs are for internal use only as they include specific details related to Aclima's operations and are, therefore, considered proprietary.

- gas sample line filter change
- BC sensor sample line cyclone cleaning
- flow checks using an external calibrated flow sensor, with acceptable thresholds specified in SOPs[3]
- PM sample line zero check
- full inspection of all sample line connections
- sample line cleaning using forced air
- checks on integrity of the mounting hardware
- power system and communications checks

Multiple diagnostic tests are also conducted by the drivers on-site with the vehicles and remotely by Aclima staff or when the vehicles report back to one of Aclima's Calibration Facilities. On-site, drivers perform the following on a daily basis:

- visual inspection of the system, including sampling line connections
- PM zero checks (using a filter on the PM sample line),
- visual inspection of sampling lines (e.g., presence of water or disconnection)
- data connectivity checks
- cleaning the BC sensor sample line cyclone
- other system parameters, including flow system status diagnostics

Drivers are trained and guided by Aclima staff to make simple repairs, such as change a filter, or replace or repair a sampling line or leak. Remotely, Aclima staff check various diagnostic variables and make adjustments to account for drift (see section 5.3).

If more advanced maintenance is required, the AMN or other sensor device ($PM_{2.5}$, BC, CH_4 and C_2H_6) is brought back to one of Aclima's Calibration Facilities for recalibration or swapped out in the field with a different sensor. Examples of repairs that may occur at Aclima include replacement of in-line filters for the gas sensors, replacement of PM sheath air filters used to keep internal components clean, and replacement of consumable materials, such as batteries and other filters.

Planned routine car maintenance occurs when cars report to one of the location-specific Calibration Facilities or in the field by drivers (e.g., oil change) during field operations as required or as time permits. Planned preventative car maintenance is tracked in a separate database from the sensor tracking system. If issues occur outside of planned preventative maintenance periods (sensors or vehicle), a system has been established, including inclusion of relevant information in the vehicle tracking database that helps to ensure a quick resolution with minimal loss of data during deployment.

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[3] Aclima's internal SOPs are for internal use only as they include specific details related to Aclima's operations and are, therefore, considered proprietary.

Aclima drive managers and technical staff follow procedures developed to interact with a driver when safety, car, communication, or measurement problems are detected. Based on those procedures, Aclima trains drivers on safe vehicle operations, device operation, route navigation, basic device troubleshooting, and protocols for coordinating with Aclima fleet operations staff at headquarters to address any anomalies. The procedures are designed to maximize the collection of valid data while ensuring driver safety. These procedures continuously evolve with lessons learned in the field.

4.0 Measurement Quality Objectives

Measurement Quality Objectives (MQOs) are quantitative criteria used to assess data quality and ensure that the Data Quality Objectives (DQOs) are achieved. Aclima's MQOs include setting acceptable quantifiable criteria at the device level for the Data Quality Indicators (DQIs) for precision, bias, and completeness. Per USEPA (2002) guidance, the term "accuracy" is not used since it represents both precision and bias. Aclima's MQOs define the performance and acceptance criteria that calibrated and verified sensors must meet before being installed into the Aclima Mobile Platform. MQOs are derived through Aclima calibrations and quality control checks (Section 5.0; Table 4). Data from each sensor is evaluated during and after collection to determine the validity of the 1-Hz data. Data verification includes two multilevel steps, which may lead to data revision and final validated data as described in Section 6.0.

Multiple in-line measurements of T, P, RH, and flow rate are recorded in conjunction with measurements from each sensor. These data provide system state diagnostics or Status Indicators, which are applied to sensor models along with calibration results and to verify that sensors remain within their normal physical operating limits of T, P, RH, flow rate, and concentration. If limits are exceeded, data are flagged at two levels and either excluded from additional aggregation and analysis, maintained but considered suspect (associated with a larger uncertainty), or investigated further (Section 5.3 and 6.0). Consistent exceedance of Status Indicator limits suggests potential issues with the system within the mobile platform that may impact the validity of the pollutant measurements. It may also indicate an issue with one or more of the state diagnostic sensors, which is important to ensure appropriate data for sensor models. In either case, tracking these measurements allows preventative maintenance before sensor or other system failure that might impact the measurement, minimizing loss of data. System state diagnostic limits are based on manufacturer specifications as well as internal evaluations of sensor performance.

Table 4: MQO - Aclima Mobile Node Acceptance Metrics

Pollutant	Acceptance Metric vs. Reference Instrument	
	Precision (± value) (Section 4.1.1)	Bias (Section 4.1.1)

O_3	3 ppb	3 ppb
NO	10 ppb	10 ppb
NO_2 [1]	5 ppb	6 ppb
CO_2	11 ppm	12 ppm
CH_4 [2]	10 ppb	50 ppb
C_2H_6 [2]	10 ppb	15 ppb
	Acceptance Metric using Other Approaches	
	Precision based on R^2	Bias based on Slope
CO	>0.8	0.75 - 1.25
TVOC	>0.75	0.5 - 2.0
PM2.5[4]	>0.8	0.75 - 1.25
BC[5]	Successfully pass internal flow calibration procedure	

1. NO_2 uncertainty is a combination of Ox (NO_2+O_3) and O_3 uncertainty since NO_2 is measured by difference between a sensor that measures Ox and a sensor that measures only O_3. Generally, under the conditions of our data collection, the Ox uncertainty dominates.
2. See Section 5.2.4.
3. See Section 2.1, Table 1, Footnote 1 regarding conversion of counts to mass concentration.
4. The BC sensor is used as delivered from the manufacturer.

Other supporting data include GPS that provide high precision latitude and longitude position, and car speed. Sensor and system state data are used to create single pass mean values, which are used to create the high spatial resolution baseline aggregates. These aggregates are then used to develop spatial maps for Aclima's current mapping products.

Device-level MQOs or acceptance criteria are provided in Table 4; precision and bias are described in Section 4.1.1. These criteria were arrived at after extensive characterization over different phases of development from prototype to the current version of the AMN and other sensors outside the AMN (BC, CH_4 and C_2H_6). These criteria must be met before a sensor is included in the Aclima mobile platform, and thus represent the upper limit (worst case) of what is expected from real-world (on-road) performance for a sensor at the start of deployment. Actual performance, which is characterized in Section 5.5, is typically better than these MQO criteria, but can also degrade over time due to sensor drift.

4.1.1 Precision and Bias

Precision and bias for O_3, NO, NO_2, and CO_2 are calculated based on the methodology used for meeting regulatory quality assurance requirements (Federal Register, 2022). Precision and bias are calculated using ambient, on-road concentration data measured by reference instruments that are collocated with sensors in Aclima's Mobile Calibration Laboratories. Inlets of the reference instruments and sensor are placed in close proximity to each other so both are sampling from similar air parcels. A slightly modified approach is used as the primary comparison statistic for precision and bias, where the difference between the sensor measurement concentration and the reference or target measurement (Equation 1) is used instead of the percent difference (Federal Register, 2022).

$$d_i = (\text{sensor - target}) \qquad \text{(Equation 1)}$$

Precision is expressed as the upper bound (at 90% confidence) of the standard deviation of the difference (d_i) measured over a specified time period.

Bias (AB) is expressed as the upper bound of the mean absolute value of the difference (d_i) over the same time period as given in Equation 2.

$$|AB| = 1/n(\sum_{i=1}^{n} |di|)+t0.95,_{n-1}(AS/\sqrt{n}) \qquad \text{(Equation 2)}$$

where, n is the number of single point checks being aggregated; $t0.95,_{n-1}$ is the 95th quantile of a t-distribution with n–1 degrees of freedom. AS is the standard deviation of the absolute value of the d_i's.

For CO, TVOC, and $PM_{2.5}$, precision and bias are based on regression analysis, where the test sensor (x-axis) is collocated in the Mobile Calibration Laboratory with an ensemble of sensors of the same type (make and model; y-axis). The average of the ensemble of sensors is referred to as a relative reference. While the regression is usually linear, it also may be based on a nonlinear function depending on the pollutant and sensor. Precision is given by the coefficient of determination (R^2) and the bias is based on the slope of the regression line.

The reference for CH_4 and C_2H_6 is based on a two point (~ambient and high concentration span) calibration using NIST traceable calibration gases (training) with a subsequent middle span check (testing), which must pass the acceptance criteria in Table 4 prior to deployment. The same three reference gases are used for periodic calibration checks. The NIST CH_4 and C_2H_6 gas mixture is a working or transfer standard verified by comparison to a gold standard NOAA gas mixture.

The BC sensor is used as provided by the manufacturer. Manufacturer specifications that relate to sensor performance include: flow repeatability ±0.4% in the range of 0-1 L/min; flow accuracy ± 5% at the range of 0-1 L/min. Performance of the sensor has been more directly evaluated through various one-off experiments, including peer-to-peer comparisons and collocations with regulatory measurements. Details on performance are provided in Section 5.5.

Quality control procedures for calibration and quality control checks for gases and particles are described in Section 5.2.

4.1.2 Data Completeness

Data completeness is calculated as the number of final verified 1-Hz data points collected relative to the number of data points expected, based on the amount of time a vehicle is actively driving on the road and the reporting frequency of each instrument (e.g., most gases are 1 Hz, ozone is 0.5 Hz). Aclima's completeness goal for 1-Hz data collection is >95%, with one exception. The completeness goal for the CO_2 sensor is >80% because its internal process results in sporadic drops of 1-second data points. Overall, a lower percent completeness can result, for example, from missing data (not measured because of power or network failure, vehicle or driving issues, calibration, etc) or data flagged as invalid (data excluded from further analysis during the data verification and validation steps, Section 6.0).

5.0 Quality Control Procedures

At Aclima, quality control begins with initial assembly of the AMN and initial testing of all sensors that will be installed into the mobile platform (Section 5.1) and extends through to final data verification (Section 6.0). Aclima staff meet weekly to assess vehicle and sensor performance, data quality, and status of the mapping effort. Automatic Status Indicator flags, which flag data outside specified Status Indicator limits, are established in the database before Aclima staff manually review data. Problems or irregularities are logged, investigated, and suitable corrective actions implemented as soon as possible. This section outlines the procedures implemented by Aclima as part of the quality control efforts. These processes underpin the technical success of the measurements and mapping campaign and help to guarantee Aclima's data are of the highest quality possible, providing critical information to effectively address broader community-level objectives and outputs.

5.1 Evaluation during AMN production

Detailed testing of sensors embedded in the AMN occurs during production and after the AMN is fully built. Checks include verifying voltages, communication, programming, flow rate, leak checks, and a series of visual inspections that include, for example, verifying labels, batteries are installed, and all fasteners are present and tightened. Once AMN production is complete, the checks are repeated on the entire AMN. Sensors external to the AMN also undergo detailed testing. After final verification of the AMN's operation, the AMN and other sensors that are not built into the AMN ($PM_{2.5}$, BC, CH_4 and C_2H_6) are sent for calibration and or verification (pollutant dependent) (Section 5.2) at one of Aclima's Calibration Facilities. All checks are tracked and results are logged into a tracking system designed for this purpose.

In support of AMN production and integration of other sensors into the mobile platform, a series of SOPs[4] have been developed that provide detailed instructions for AMN assembly and installation of the AMN and external AMN sensors into the mobile platform.

5.2 Pre-deployment calibration

A completed AMN along with any external sensor units installed in Aclima's mobile monitoring platform undergo initial calibration for O_3, CO, CO_2, NO, NO_2, CH_4 and C_2H_6, and/or performance verification for $PM_{2.5}$ prior to deployment. The sensors installed in the mobile platform are tested and/or calibrated by one of three approaches, depending on the pollutant: 1) collocation with reference instruments in one of Aclima's Mobile Calibration Laboratories for O_3, NO, NO_2, CO_2; 2) peer-to-peer collocation in one of Aclima's Mobile Calibration Laboratories, between an ensemble of sensors of the same make and model as the test sensor for $PM_{2.5}$, CO, and TVOC (TVOC after initial span and zero with reference gas at a Calibration Facility); and 3) calibration using NIST traceable calibration gases for CH_4 and C_2H_6.

With each of these pre-deployment calibration/verification processes, the performance metrics are quantified from the "test" time period and compared against Aclima's Measurement Quality Objectives or acceptance criteria (Table 4). If a sensor does not meet the stated acceptance criteria, then individual sensors undergo a thorough evaluation to determine the root cause of the issue, replacing the affected sensor if necessary. Regardless of the cause of the problem, sensors must then undergo a repeat calibration and/or verification. Acceptance criteria for all sensors within an AMN as well as those not built into the AMN must be achieved before a sensor is installed into a vehicle for deployment.

These calibration approaches are used to derive and test sensor model input parameters prior to deployment. Sensor models are used to convert the sensor signal (e.g., voltage) into a physically meaningful measurement (μg/m^3, ppb, ppm). The sensor model may also include T, RH, pressure, and other pollutants that may interfere or be related to the measurement of interest.

Where possible, the Mobile Calibration Laboratories is deployed in the same areas where data collection is occurring in order to calibrate under similar environmental conditions as where the AMNs will be deployed. However, this is not always possible and assumptions must be made about performance of the AMNs under different conditions. As part of our data validation processes, we use regulatory reference station data to support mobile-to-stationary

[4] Aclima's internal SOPs are for internal use only as they include specific details related to Aclima's operations and are, therefore, considered proprietary.

comparisons to evaluate and correct for bias in our measurements that may result from differences in environmental conditions from those experienced during calibration, which is outlined in Section 5.0 of the Hyperlocal Ambient Concentration Estimate Validation and Quality Assurance document (CAMP Appendix D). This is particularly important for PM2.5 because chemical composition and size distribution of the particles often vary between geographic regions, and both affect the measurement reported by the sensor.

5.2.1 Collocation with Reference Instruments (O_3, NO, NO_2, and CO_2)

Pre-deployment calibration of the O_3, NO, NO_2, and CO_2 sensors is achieved by collocating sensors with reference methods in one of Aclima's location-specific Mobile Calibration Laboratories. This ensures that these sensors are calibrated over a large dynamic range of analyte concentrations and measured under atmospherically relevant on-road conditions, including variations in pollutant gases and particle concentrations, and varying meteorological conditions. In the mobile calibration laboratory, sensor and reference instrument inlets are situated near each other, essentially measuring pollutants and greenhouse gases from the same air volume. The collocation period for sensor calibration and verification is one week (calibration approaches 1 and 2) and includes a calibration "training" period (4 days) to derive input parameters for the sensor calibration models, followed by a "testing" period (typically 3 days) to verify the input parameters and quantify sensor performance. The performance metrics derived during "testing" are considered to be representative of likely sensor performance when sensors are deployed for Baseline data collection. Regression analysis is applied to determine the gain (slope) and offset (intercept) for use in the sensor calibration model. While the regression is usually linear, it also may be based on a nonlinear function depending on the pollutant and sensor. Collocation ensures that all sensors are providing similar measurements within the expected uncertainty of the measurement and after the calibration model is applied it allows for an estimate of precision and bias relative to the reference method. If sensors meet acceptance criteria, they are installed and used in Aclima's mobile platform. If not, the calibration process is repeated.

The reference instruments used for the calibration of the O_3, NO, NO_2, and CO_2 sensors (Table 2) undergo monthly zero and span checks to confirm that the calibration is stable. Periodically or as needed, for example, if span and zero checks are outside performance specifications (Table 3), the zero and span of the sensor are changed based on manufacturer protocol or they are periodically (yearly unless warranted) returned to the vendor for recalibration.

5.2.2 Peer-to-peer collocation ($PM_{2.5}$, CO, and TVOC)

$PM_{2.5}$, CO, and TVOC (TVOC after initial span and zero with reference gas in an Ambient Calibration Laboratory, see section 5.2.4 for details) sensor performance and sensor-versus-sensor compatibility are quantified pre-deployment by collocating sensors in one of Aclima's location-specific Mobile Calibration Laboratories. During collocation periods, each test sensor is compared to an ensemble of other collocated sensors of the same make and model (minimum of 3, although >10 are possible). Inlets are in close proximity so they are sampling from a similar air parcel. The comparison is analogous to the calibration "testing" period for the sensor-versus-reference collocation, but instead of using a reference instrument, the average of the ensemble of collocated sensors is used as a relative reference for comparison to the test sensor.

$PM_{2.5}$ measurements are used as provided and only the flow rate is evaluated. If the flow rate of a $PM_{2.5}$ sensor does not fall within the expected error threshold of ±5%, the flow rate is calibrated according to manufacturer protocols. No other adjustments are applied for the $PM_{2.5}$ sensors – if a $PM_{2.5}$ sensor does not meet the acceptance criteria it is replaced. Peer-to-peer collocation ensures that all sensors are providing similar measurements within the expected uncertainty of the measurement as well as precision and bias. A discussion of accounting for systematic bias that may result from treating $PM_{2.5}$ and CO in this way is included in Section 5.0 of the accompanying "Hyperlocal Ambient Concentration Estimate Quality Assurance System" document (CAMP Appendix D).

5.2.3. Black Carbon

The BC sensor uses a well accepted detection principle (aethalometry) and as a result the sensor factory calibrations are used as is. As needed or annually, the BC sensor is sent back to the manufacturer for calibration and maintenance. The flow rate of each BC sensor is routinely evaluated, and if it does not fall within the expected error threshold of ±2%, the flow rate is calibrated according to manufacturer recommendations. Currently, BC sensors are not routinely placed in the Mobile Calibration Laboratory for peer-to-peer comparison as part of our standard operating procedures, although periodic collocations in the Ambient Calibration Laboratory have been conducted to confirm agreement among the BC sensors (see Section 5.5 for details). The sensor is operated according to manufacture specifications to ensure no significant impacts from loading effects. No additional processing is performed to smooth the signal.

5.2.4 Reference Gas Calibrations (CH_4, C_2H_6, and TVOC)

The CH_4 and C_2H_6 sensor calibrations are performed using NIST traceable reference gases of accurately known CH_4 and C_2H_6 concentrations. The CH_4 and C_2H_6 sensor offset and gain are adjusted if needed using a low target at approximately ambient concentrations of 2 ppm CH_4 + 1 ppb C_2H_6 and a high target at approximately 50 ppm CH_4 + 5 ppm C_2H_6, and then tested using a mid-range target at 5 ppm CH_4 + 50 ppb C_2H_6. If, after calibration, the difference between the test tank concentration and that reported by the sensor instrument is less than ±50 ppb CH_4 or ±15 ppb C_2H_6 or if the standard deviation of the 1 second data during the low concentration reference measurement is less than 10 ppb, then the acceptance criteria (Table 4) are met and the sensor can be deployed. If not met, then the calibration process is repeated as needed or the sensor is replaced. The current best estimate for total uncertainty of the reference gas concentrations are the larger of 25 ppb or 1% for CH_4 and 5 ppb or 0.2% for C_2H_6. This is based on total uncertainty of our gold standard reference gases obtained from NOAAs Central

Calibration Laboratory and repeatability of characterization experiments of the NIST certified working or transfer standards.

TVOC sensors in the AMN undergo an initial pre-deployment calibration based on a single span using a NIST certified reference cylinder of isobutylene in the concentration range of ~1 ppm (range 0.68 to 1 ppm) and a zero check. The zero and span of the TVOC sensor are not checked in the field. The initial calibration is followed by peer-to-peer collocation in a Mobile Calibration Laboratory where the slope and R^2 values for bias and precision are estimated from the relative reference, similar to $PM_{2.5}$ and CO.

5.3 Measurement verification during deployment

During deployments, Aclima engineers and technical staff are notified of potential sensor performance issues based on the following: 1) notifications from drivers or hardware technicians as they perform their routine system checks; 2) as a result of automated flagging within Aclima's data processing pipeline; and 3) during regular (weekly) device-level reviews by data review analysts.

Automated status indicator flags signal when measurements are collected outside the environmental or physical specifications of the sensors, such as values greater than or less than the acceptable concentration range of the sensor or negative values below the uncertainty of the detection limit, data reported during quality control checks (e.g., zero and span checks), or periods where the flow rate is out of the optimal range. In many cases, status indicator flags are part of normal operation of certain sensors, for example when temperature is changing rapidly at warm-up. In other cases, excessive data flagging can be an indication of a hardware issue that requires a corrective action (i.e. low flow rates due to a failing pump or blocked flow path). In addition to these automated flags, manual data review is conducted on a weekly basis over all deployed sensors. During these weekly reviews, up to six weeks of previously collected measurements can be examined at one time to allow for observation of trends, e.g., drift or erratic behavior, or other behaviors that are not currently automatically flagged. Analysts have access to visualizations of time series data at different temporal aggregation scales of multiple devices deployed in the same geographic area to visually scan for anomalous behavior. Correlations between different pollutants are also visualized, which can provide useful context for understanding whether a particular sensor is behaving abnormally (CO vs CO_2, for example). Diagnostic variables such as temperature, pressure, relative humidity, and flow are also visualized.

For deployments where there are active NAAQS sites established by regulatory agencies in the mapping area, data review can rely on data from these sites for contextualizing large scale trends in different air pollutants over time. This is a useful tool for understanding whether features in Aclima's sensor data are anomalous or consistent with trends detected by the regulatory network. It is often possible to detect systematic bias across the network or identify individual sensors that have drifted substantially between their pre- and post-deployment calibration checks (Section 5.4). There are a number of different factors that can impact these comparisons that must be taken into account, including distance between mobile and stationary measurements, road type, site type (i.e. near-road vs neighborhood scale vs background site), and temporal aggregation. In some cases the type of measurement method used at the site can be important, for example different FEM methods for $PM_{2.5}$ can be biased in different ways in relation to the FRM gravitational measurements.

In addition, customized alerts can be set by the technical team to alert for specific conditions that may indicate atypical behavior for a given sensor that needs to be resolved. For example, prolonged periods of elevated CO_2 may indicate possible sampling from inside the vehicle. This can alert the team to potential issues to trigger an intervention in a more efficient way than the standard weekly data review. These customized alerts do not automatically flag data, but trigger a manual review by an analyst who makes the final decision as to whether data needs to be reviewed or not.

When issues are detected, they are documented and tracked through an internal ticketing system. Each ticket is tied to a specific vehicle, sensor serial number, and AMN ID and contains a description of the symptom, which sensors are impacted, recommendation for intervention, description of how the issue was resolved, and the date resolved. If any manual omissions of data are required as a result of any issue, this is noted in the ticket in a manner that provides traceability in Aclima's database back to the reason for omission.

Some issues can be addressed remotely (i.e. firmware update or settings modification), but most issues rely on a physical intervention by either the driver or a trained hardware technician. Once identified, issues are resolved as soon as possible. When a notification is received, Aclima engineers and technical staff work with drivers to perform simpler repairs in the field (Section 3.2), such as a loose wire or blocked tubing. If fixing the issue in the field is not possible or if in-field service impacts performance, the sensor (AMN if the sensor is within the AMN) is returned to one of Aclima's location-specific Ambient Calibration Laboratories for service and repair or swapped for a newly calibrated sensor (or AMN). The returned device is fixed, recalibrated, and re-deployed when needed.

Issues tracked through this system are limited to those that impact data quality. The drivers and fleet operations team are responsible for routine maintenance of the vehicle itself, including monitoring and resolving any issues.

5.4 Mid- and Post-deployment recalibration

At regular intervals during field deployment, mobile platforms are returned to one of Aclima's Calibration Facilities to receive updated calibrations. Each sensor is recalibrated using the same process as described for pre-deployment calibration (Section 5.2). Since the AMN must be installed in the Mobile Calibration Laboratory for an extended time period to be recalibrated, the AMN to be calibrated is uninstalled and a freshly calibrated AMN is installed while at the Aclima Calibration Facility. The CH_4/C_2H_6 and BC sensors (which are physically separate from the main AMN unit) can undergo recalibration while installed in the mobile platform in a matter of 15-30 minutes typically; calibration of these sensors, therefore, can be completed without uninstalling from the mobile platform.

Calibration events that occur in the middle or end of a deployment serve two purposes: 1) to derive an updated set of calibration parameters and check that the sensors are still performing to specification (i.e. meet the acceptance criteria in Table 4 using the newly derived calibration parameters) and can continue to be deployed and 2) to check whether the previously derived calibration parameters are still valid (i.e. still meet the acceptance criteria in Table 4 using the previously derived calibration parameters). If the prior calibration parameters are no longer valid, the data collected in between the prior and current calibration events are adjusted (see Section 5.4.1 and 5.4.2 for more details). The newly derived calibration parameters are applied to the sensors for future data collection up until the next calibration event. Two calibration events are required in order to finalize and verify data collected in between. The frequency of calibration events determines how soon after the start of a field deployment verified data can be generated and on what cadence.

For SMMI, the recalibration frequency will be about 6-8 weeks, which will support the required data delivery schedule of monthly verified data deliveries 3 months after collection. Calibration at an 8 week schedule allows for a ~4 week final review period before data delivery is due. We consider data collected within 2 weeks of a calibration event to meet the acceptance criteria without requiring a 2nd calibration event. In other words, a calibration event that takes place in the 3rd week of a given month is sufficient to be able to verify data for that entire month.

5.4.1 Drift correction

If the acceptance criteria are not met and a calibration adjustment is required, Aclima staff review the pre-, mid-, and post-deployment calibrations/verifications with other collocated data available during deployment. Collocated data may include data from stationary regulatory sites or sensors in other Aclima deployed mobile platforms. This evaluation is used to determine whether the sensor calibration change occurred as a step change or drifted over time. Once determined, appropriate calibration adjustments are applied. Certain sensor types are more prone to drift over time (e.g., CO_2 and CH_4) and a linear calibration function is applied based on the pre- and post-deployment calibrations, whereas other sensors (e.g., NO_2) have been found to occasionally experience fast step-changes in calibration during deployment. Once the date and time of the step change is identified, the sensor model parameters are recalculated after that period, applied, and revised concentrations are updated for the period after the step change. Where there is no obvious shift or if other collocated data are not available, the drift is assumed to be linear over time between the pre- and post- deployment calibrations.

Once determined, appropriate calibration adjustments are applied. If the newly applied calibration values allow the sensor to meet the acceptance criteria (Table 4), then, at this point of the review process, the data undergo a final review. If not, the issue is investigated in more detail and data from that sensor may be excluded from further analysis. All changes are tracked as a metric in a built-for-purpose database that documents adjustments identified after post-deployment calibration. This table contains calibration records by device. A history of calibration values and their corresponding date ranges are stored as metadata with the 1-Hz data as well as a record of the value used for each time stamp.

5.4.2 Drift correction: TVOCs

The TVOC sensor may drift outside of the acceptable range based on the MQOs in Table 4; however, since the TVOC sensor is only partially quantitative, given its wide range of sensitivities to different VOC species (over 2 orders of magnitude differences), the TVOC sensor calibration values are typically not adjusted after the fact. It is assumed that other uncertainties are much higher than the sensitivity of the sensor. If the precision criteria fails during a post-deployment calibration check, indicating a failed sensor, then manual omissions are applied starting at the likely time of failure.

5.4.3 Systematic Bias: Ambient Concentration Estimates Data Product

Systematic bias can be defined as the difference between Aclima's ambient concentration measurements and measurement that can be considered a suitable representation of the true concentration. This bias is always a possibility when comparing two different measurement networks that may use different primary standards, detection methods, and levels of data quality. Sensors in the platform that are not routinely calibrated using a reference instrument (CO, PM2.5, and Black Carbon) may be particularly prone to systematic bias. We use regulatory reference station data to perform mobile-to-stationary comparisons to evaluate and, if necessary, to correct for bias in our measurements. More detail on this process can be found in Section 5.0 of the Hyperlocal Ambient Concentration Estimate Validation and Quality Assurance document (CAMP Appendix D).

5.5 In-field sensor performance

The performance of all Aclima sensors that have been deployed have been evaluated for sensor bias, precision, limit of detection, and drift using different approaches (i.e. performance metric) depending on the relevant data products associated with each sensor type. This analysis, performed over many devices over 3 years of calibration events, indicates typical performance expected for each sensor while deployed in vehicles and mapping.

Monitoring Objective 1 aims to show areas that have relatively higher and lower pollution in a geographic region at high spatial-resolution through the aggregation of data into ambient concentration estimates. . For this type of data analysis, it is important to characterize sensor bias and drift at typical ambient concentrations and to estimate precision and limits of detection at relevant temporal scales (e.g., seconds to minutes).

The relevant approaches for performance evaluation are different for Monitoring Objective 2, which aims to identify probable locations of emissions sources of key pollutants through the detection of enhancement events. This type of analysis aims to detect and localize large enhancements (with respect to the ambient background) in pollutant concentrations over short time periods (typically on the order of seconds to minutes). Sensor bias is important only as it relates to measurements of the magnitude of these enhancements above the ambient background rather than in the absolute magnitude of the ambient background. Since this analysis relies on detecting concentration differences from the same sensor, bias and drift in the sensor gain are more important than bias and drift in the sensor offset. Precision for these pollutants is characterized at 1-Hz defining the lower limit at which a fast enhancement (~seconds) can reliably be discerned from random noise. Baseline instability and sensor drift can impact precision and bias at longer timescales (minutes to hours and up) but can be largely ignored for the sensors exclusively used in the enhancement data analyses.

The following tables contain results for the Data Quality Indicators (DQIs) for each sensor, representing the device-level uncertainty contributions to our two monitoring objectives(Tables 5 and 6). The DQIs used to describe sensor performance are: bias, drift, precision, and limit of detection. The metrics and experiments used to quantify these indicators vary by how they are calculated, sensor, and data product, and these details are given below for each data product. The following provides a general description of each of the DQIs as applied to Aclima's two general data product types:

- Ambient Measurement Bias: Typical errors in accuracy for sensors immediately following a calibration event and evaluated for pre-deployment calibration checks.
- Ambient Measurement Drift: Typical errors in accuracy for sensors at the end of their deployment relative to pre-deployment evaluations.
- Enhancement Measurement Gain Drift: For TVOCs, CO, NO, Blackcarbon, PM2.5, CH_4, and C_2H_6, typical errors in accuracy (as a percent) at the end of their deployment relative to pre-deployment evaluations
- Ambient Measurement Precision: Random differences in agreement between two sensors of the same type at typical ambient concentrations, defined at specific time aggregations and evaluated for pre- and post-deployments.
- Limit of detection
    - Ambient concentration estimates (Table 5): Random differences in agreement between two collocated sensors of the same type evaluated at ambient background concentrations (as defined by the lowest 15th percentile

concentrations and below) and calculated as the standard deviation (2σ) of differences between the two sensors. Note: These calculations are derived from ambient data and not from traditional laboratory evaluations with zero air. For pollutants that typically do not reach zero concentration in the atmosphere (e.g. CO_2, CH_4, CO, O_3), these values should be interpreted as the minimum detectable values above typical background concentrations.

- Enhancement measurements (Table 6): Minimum detectable peak above background at a 1-second sampling frequency determined as the standard deviation (3σ) of reported values while sampling a constant concentration reference gas.

Table 5: Ambient concentration data product - Typical In-field Performance[1]

Pollutant	Bias[2]	Drift[3]	Precision			Limit of Detection (2σ)		
			1 s	8 s	170 s	1 s	8 s	170 s
NO (ppb)[4]	19%	22%	9.7	4.0	1.0	15.6	9.6	2.2
NO_2 (ppb)	2.4	4.6	4	3.1	2.1	6.4	5.2	3.4
O_3 (ppb)	1.5	1.5	1.8	1.8	1.2	3	2.8	1.8
CO (ppm)	0.03	0.03	0.028	0.026	0.023	0.028	0.02	0.012
CO_2 (ppm)	5.5	18.1	3.4	3.3	3	2.4	2.2	2
CH_4 (ppb)	21	41	37	34	27	68	74	60
C_2H_6 (ppb)[5]	2	4	2.5	2.4	2.3	5.2	5.0	2.8
$PM_{2.5}$ (ug/m3)	0.6	0.6	1.4	0.9	0.5	1.6	1.0	0.4
BC (ug/m3)	0.23	TBD	1.7	0.6	0.26	2.8	1.2	0.72

1. These values are our best estimates to-date of "typical" sensor performance and may change in the future as additional data are evaluated. Typical is defined as the median value across all sensors tested, and is not meant to be a performance specification.
2. This bias does not account for systematic bias that can arise from differences in sensor response when mapping in different environmental conditions from those occurring during calibration. See Section 5.2 in the Hyperlocal Ambient Concentration Estimate Validation and Quality Assurance System document.
3. Drift values are based on changes over approximately 1 year of use based on the time between pre- and post-deployment calibrations used in previous deployments.

4. For the NO sensor: as a result of how data is processed from this sensor, bias and drift are only expected to manifest in the gain of the sensor, so values are represented as a percent based on errors in the slope vs reference.
5. See description of limitations of the ethane sensor in Section 5.6.1

The temporal aggregation used to characterize precision and limit of detection impacts the calculated value and is specified for each case. As is typically seen, lower values (indicating higher precision and improved LOD) are observed at longer integration times. For the ambient concentration monitoring objective, the relevant time scales for aggregation are at 1 second (corresponding to the sensor sampling rate), 8 seconds (which is the typical time it takes a mobile platform to travel 100 m), and 170 seconds, which is the number of seconds aggregated into an ambient concentration estimate for a 100m length of road that is visited 20 times. The precision and LOD estimates at 170 seconds, therefore is an approximation of the contribution of random sensor precision to the overall uncertainty in segment level aggregations, but does not include other sources of uncertainty such as drift or sensor-to-sensor variability across all 20 visits, which are collected non-contiguously over the duration of the Ambient Concentration Estimate collection period. As described in the Hyperlocal Ambient Concentration Estimate Validation and Quality Assurance System document, each spatial aggregate in the Ambient Concentration Estimate receives a confidence interval that better describes the true precision uncertainty, which includes a combination of measurement uncertainty and atmospheric variability over time. Note that depending on the implementation of the spatial and temporal aggregation approach as well as the monitoring approach, the number of seconds aggregated may be different from this example base case, but this provides a general approximation of how measurement uncertainty folds up into ambient concentration estimates.

Table 6: Enhancement products In-field Performance

Pollutant	Gain Drift	Limit of Detection (3σ)
TVOC (ppb)	32%	0.6
CH_4 (ppb)	1%	7.5
C_2H_6 (ppb)	1%	1.2
BC (ug/m3)	3%	5.1
NO (ppb)	22%	29.1
CO (ppb)	6%	85
PM2.5 (ug/m3)	10%	4.2

5.6 Important Limitations for Specific Sensors

5.6.1 Ethane (C_2H_6)

Ethane measurements can exhibit significant baseline instability on hourly time scales and the degree of drift can vary quite a bit between individual sensors. These artifacts are significant relative to ambient concentrations of ethane (typically around 1 ppb or less), thus, Aclima does not recommend using C_2H_6 in the typical use cases for the ambient concentration data product. The ethane data is primarily useful where CH_4 enhancements are high (~above the reported precision limits) in order to determine whether the source of methane is biogenic or thermogenic in nature.

5.6.2 $PM_{2.5}$

The $PM_{2.5}$ sensor operates based on sizing and counting particles in six distinct channels between 0.3 and 2.5 μm in diameter and converting to mass using a sensor model that includes assumptions about particle density, optical properties, and shape. These parameters are known to vary depending on the size distribution and chemical composition of the aerosol, resulting in differing optimal sensor model parameters that are location-specific. As part of deployments in new geographies, we evaluate any potential systematic bias as a whole, rather than at the individual sensor level, using comparisons to local regulatory monitors where available. The accompanying "Hyperlocal Ambient Concentration Estimate Quality Assurance System" document discusses how this is handled in more detail (CAMP Appendix D).

5.6.3 Nitric Oxide (NO)

The NO sensor is prone to baseline drift, which we account for by performing a baseline adjustment as part of data processing. As a result, the final measurements can obscure some of the larger spatial and longer temporal trends in ambient NO concentrations. Additionally, the detection limit for the NO sensor is high (at 1 second and 8 second measurement frequency), relative to typical ambient concentrations under clean conditions. Therefore, the NO measurements primarily indicate locations and times when NO is present at high concentrations and close to sources, resulting in sharp spikes in the time series on timescales of seconds to minutes.

5.6.4 Nitrogen Dioxide (NO_2)

The NO_2 sensor requires the use of the O_3 sensor in deriving an NO_2 measurement because the sensor is sensitive to both NO_2 and O_3. As a result, bias in either the O_3 sensor or the NO_2 sensor can impact the derived NO_2 measurement and the magnitude of error can vary as the relative concentrations of the two pollutants vary. The uncertainty values reported in Table 5 reflect the uncertainty from both sensors and are a realistic description of uncertainty during deployments resulting from this source of error.

5.6.5 Total Volatile Organic Compounds (TVOC)

The TVOC sensor operates on the principle of photo-ionization, which permits detection of most VOCs but does not report information on the specific compounds detected. While the TVOC sensor is sensitive to a wide range of VOCs, the sensor has variable sensitivity to different classes of VOCs spanning multiple orders of magnitude. The sensor is calibrated using isobutylene, so the units reported actually represent isobutylene-equivalent concentrations. The response factors for many compounds relative to isobutylene, can vary significantly; for example, benzene has a response factor of about 2x that of isobutylene while ethylene has a response of about 0.1x that of isobutylene.

The TVOC sensor is also prone to baseline drift on various timescales. However, rather than attempting to approximate ambient concentrations the air toxics data product uses enhancements (on the order of seconds to minutes) in the signal with respect to the baseline to detect localized hotspots. For this reason, baseline drift is not a critical aspect of the sensor's performance for its intended use case.

The acceptance criteria for r^2 and slope are more tolerant for the VOC sensors compared to CO and PM. In part this is due to baseline instability between different sensors, but there are also likely differences in the response factors to different VOCs from sensor to sensor. As a result, when sampling real-world mixtures of ambient VOCs, the agreement from sensor to sensor can vary depending on the exact mixture, and therefore the sensor-to-sensor variability during deployments can be large (-50% to +100%) in some cases. Typical sensor agreement is on the order of +/-30% (as shown in Table 6).

6.0 Data Stages

After raw data from Aclima's sensors are initially ingested, they go through a data processing pipeline that ultimately transforms the collected data into our final data products. While the raw data will never be directly modified or removed in the database, modifications are often made to historical data at various stages throughout the processing pipeline as part of our standard QA operations in order to ensure the highest possible data quality in our final products.

In order to communicate to the user when the underlying 1 Hz data (0.5 Hz for Ozone) are final and will not undergo further changes, Aclima uses a simple data stage system that identifies each individual 1 Hz data point by one of two possible stages: (1) Preliminary (data are likely to change) and (2) Verified (data should be considered final). The data stage for each 1 Hz measurement is propagated downstream into the data products that aggregate the 1 Hz data. For this reason, different data products can be constructed from a combination of preliminary and verified data. Each data product that aggregates this 1 Hz data remains in the Preliminary stage until 100% of the 1 Hz data used is labeled as verified. Note that the data stages only apply to processed data and not the raw data as raw data in the ingestion database are never modified or removed.

Preliminary data are available within 24 hours of collection and have gone through a number of data processing steps. The first step is the conversion from raw measurements into calibrated physical quantities representing pollutant concentrations. Calibration input parameters derived from the most recent pre-deployment calibration are used in this stage. Next, the data go through an automated status indicator flagging step based on predetermined thresholds of concentrations or associated diagnostic variables designed to identify and remove as much poor-quality data as possible without requiring manual intervention. Status indicator flags indicate two basic categories: yellow or red. A yellow flag indicates data that are considered useful but likely have a slightly higher uncertainty, such as if the measured concentration range is outside the optimum concentration range of the sensor. Currently, the only instance where a yellow flag is applied to Aclima data is when the PM sensor is measuring above the manufacturer-specific range. A red flag indicates that data are not valid and are excluded from further analysis but are maintained in the raw data archive. Red flags are applied as a result of standard sensor operations (e.g. during zero checks of the PM sensor), during sensor warm-up periods, or if there was an obvious problem where the integrity of the flow system (versus some slight drift in the pump speed, i.e., within 15% of nominal).

In the Preliminary stage, data are routinely modified and should be considered likely to change. These modifications typically fall into two categories: 1) data are removed as a result of manual omissions stemming from issues found during the routine data review process, or 2) calibration input parameter updates as a result of sensor drift as detected during post-deployment calibration checks. Occasionally, changes to status indicator thresholds or modifications to the underlying sensor calibration model may occur as well, but this is less common and not part of routine operations.

When sensors undergo post-deployment calibration checks, this triggers a manual review of all data collected by that sensor between its pre- and post-deployment calibration. This manual review is similar to the routine weekly mid-deployment review (Section 5.3), but the analyst views the entire deployment at once, rather than only the most recent week's data. Additionally, the analyst reviews additional metadata associated with the deployment, including records of all issues detected during the deployment, any relevant findings from post-deployment servicing that might impact data quality, post-deployment calibration results, and any drift corrections applied.

The reviewer's responsibility is to make sure that all required manual omissions and calibration adjustments have been identified and applied. Once this has been ensured, the reviewer marks that sensor as Verified in a tracking system. Each verification mark is applied to a specific sensor and vehicle with start and end dates associated with the pre- and post-calibration events, respectively. Once this occurs, each 1 Hz data point between the start and end dates from that sensor is marked as Verified in the database. Once data have been marked as Verified they are not expected to undergo any further changes. Data products that use verified 1 Hz data may undergo revisions, changing how the underlying 1 Hz data are processed and aggregated, and these changes are tracked and communicated by software versioning, however, the underlying verified data used as inputs to the data products will not change.

8.0 Citations

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