Atmospheric Imaging Mission for Northern Regions (AIM-North)

Mission Objectives Document

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EXECUTIVE SUMMARY

This Mission Objectives Document (MOD) describes the objectives for the Atmospheric Imaging Mission for Northern Regions (AIM-North, www.aim-north.ca). The broad mission objectives are to:

- Monitor greenhouse gas (GHG) and air quality (AQ) species over northern regions to quantify natural and anthropogenic sources/sinks in support of Government of Canada (GoC) policies to mitigate climate change and improve air quality
- Address the gap in northern AQ and GHG spatial and temporal coverage from the emerging international virtual constellation and provide overlap with geostationary (GEO) observations over North America, Europe and Asia.

A number of more specific and detailed mission science objectives are also provided in this MOD. All objectives are consistent with the mandate of Environment and Climate Change Canada (ECCC) and key GoC programs and priorities that include environmental prediction, emission reporting, monitoring of pollution hotspots and policies to reduce emissions. AIM-North could help to meet objectives in these areas by providing GHG, AQ, solar induced fluorescence (SIF) and cloud observations over northern land (~40-80°N) from a pair of satellites in a highly elliptical orbit (HEO) formation. Furthermore, AIM-North would offer a unique opportunity for Canada to demonstrate international leadership in earth observation with a focus on northern latitudes.

Observations of CO_2, CH_4, CO and SIF would be made with a high spectral resolution instrument in the near-infrared (NIR) and shortwave-infrared (SWIR) regions. Observations of NO_2, O_3, aerosol optical depth (AOD) and a number of other air quality species would be made with a moderate resolution ultraviolet-visible (UV-vis) spectrometer. Imaging column quantities of the AQ species and GHGs, along with SIF at ~3x3 km^2 with a revisit of 60-90 minutes during daylight would yield observations of unprecedented density and frequency over northern land, when clouds permit. A high spatial resolution cloud imager could enable intelligent pointing to optimize the proportion of cloud-free observations, while also providing near-real-time cloud data with a number of applications.

Precision and accuracy goal and threshold requirements are provided for individual species such that the observations could be used to meet stated mission and science objectives. A justification primarily relying on peer-reviewed literature is provided for each key requirement, where available. Finally, a preliminary estimate of the instrument requirements necessary to meet the mission and science objectives is provided.

In addition to the primary industrial mission feasibility study in Phase 0, science studies will help to refine the instrument requirements for achieving the desired precision and accuracy using realistic GHG/SIF and AQ retrieval algorithms, with other studies geared toward demonstrating the value of AIM-North data in applications in support of ECCC scientific research, operations and policy objectives.

REVISION HISTORY

Rev.	**Description**	**Initials**	**Date**
Draft 0.1	Empty URD template	HvM	2018 July 02
Draft 0.2	Modified format and added content	RN	2018 Aug 20
Draft 0.3	First nearly complete draft	RN	2018 Aug 24
Draft 0.4	First complete draft	RN	2018 Aug 28
Ver. 1.0	Version for public release	RN	2018 Aug 30
Ver 1.1	Minor corrections, slightly expanded text, streamlined objectives and figures added	RN	2018 Sep 26
Ver 2.0	Updates in response to industry team’s request for clarification	RN	2019 Mar 22

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This Mission Objectives Document (MOD) summarizes the mission objectives for the Atmospheric Imaging Mission for Northern Regions (AIM-North). It has been prepared by the core AIM-North team at ECCC at the start of Phase 0 (Feasibility Study) according to instructions given by the Canada Space Agency (CSA). The purpose of this document is to record the objectives for this proposed satellite mission, which are driven by the needs of Environment and Climate Change Canada (ECCC). These objectives are fundamental to the industrial feasibility studies in Phase 0. The most recent update to this document (v2.0) addresses areas where requests for clarification have been made by the Phase 0 industry team.

This document also forms the basis for a future User Requirements Document (URD). The URD will provide a detailed view of the AIM-North user requirements from the broader User and Science Team perspective, which in addition to ECCC scientists, includes members from other government departments and academia, both within Canada and internationally.

1.2 BACKGROUND

ECCC is the federal government department responsible for protecting and conserving Canada’s natural heritage and ensuring a clean, safe and sustainable environment for present and future generations. ECCC is the largest user of Earth observation (EO) data within the Government of Canada (GoC), as it works to fulfill this broad mandate.

In March 2015, the CSA solicited ideas for satellite mission concept studies from ECCC. A mission concept for air quality (AQ) and greenhouse gas (GHG) observations over northern regions was proposed and was one of only two ideas selected. In early 2016, a request for proposals (RFP) was prepared jointly by CSA and ECCC and issued publicly for this concept study. An industry team was selected from multiple proposals and awarded the contract. The AQ-GHG mission concept study commenced in July 2016 and successfully concluded at the end of March 2018 as the “Atmospheric Imaging Mission for Northern Regions (AIM-North)”. In May 2018, ECCC Deputy Minister Stephen Lucas sent a letter to CSA President Sylvain Laporte reaffirming ECCC interest in AIM-North and conveying support for it to advance to Phase 0.

The idea for AQ and GHG observations focused on the North was not entirely new. Earlier Phase 0 and A studies had already occurred from 2010-2012 for the “Weather, Climate and Air quality (WCA)” instrument suite [R01] under the CSA’s Polar Highly Elliptical Orbit Science (PHEOS) program, which considered small payloads (< 50 kg) as enhancements to the proposed Polar Communications and Weather (PCW) mission [R02]. The PCW concept consisted of two satellites in a highly elliptical orbit (HEO) configuration. PHEOS-WCA Phase 0 and A studies were led by Principal Investigator (PI) Professor Jack McConnell of York University. The science team included members from academia and government, including Environment Canada.

The needs and priorities of every government department evolve over time. From the time of the PHEOS-WCA studies to present, Environment Canada was renamed Environment and Climate Change Canada to emphasize the Government of Canada's commitment to addressing climate change. The department's use of EO data has also increased as EO capabilities have continually improved. Internationally, direct links between EO data and environmental monitoring for policy, which were only theoretical just a few years ago, have now become the new driving force for the upcoming generation GHG and AQ missions. To remain competitive and at the forefront of these fields, Canada must also explore the development of policy-driven monitoring missions.

As the observing requirements for GHG and AQ missions evolve toward meeting policy needs, monitoring anthropogenic emissions and acquiring a more detailed scientific understanding of atmospheric and surface processes, the required density of observations has increased significantly relative to requirements from just a few years ago. Internationally, a number of geostationary (GEO) air quality and GHG missions are planned for the early 2020s to image atmospheric constituents with multiple revisits per day. GEO satellites are a highly efficient method of achieving rapid revisit over the tropics and mid-latitudes, but viewing zenith angles become too large at latitudes higher than ~50-60°N/S, depending on the quantity being measured.

This gap in northern hemisphere high latitude coverage is unacceptable considering that the Arctic is showing temperature increases three times as large as the tropics, as a result of climate change. Amplified warming in the North has the potential to further accelerate climate change due to feedback processes. As warming occurs in the North, resource extraction, transport of cargo and passengers, and wildfires in the North are all increasing, which is changing the atmospheric composition and vegetation of the region. These impacts are already being seen across Canada and other high latitude countries. Remote sensing from Earth observation satellites in HEO is an innovative and efficient method of addressing the emerging high latitude coverage gap to enable quasi-geostationary observations of GHG and AQ species over Canada and other high latitude countries that span the Arctic, sub-Arctic and boreal regions.

AIM-North would address this gap in high latitude observations, providing data for scientific research, operations and policy that would be of value to Canada and internationally. Therefore, for the purpose of defining a baseline, AIM-North will commonly be discussed as a standalone Canadian satellite mission; however, other means of implementation are possible such as a hosted payload approach with a Canadian or international partner or other potential partnership scenarios.

2 MISSION MOTIVATION AND JUSTIFICATION

2.1 OVERVIEW

Air quality and greenhouse gas species are exchanged between the Earth's surface and atmosphere, but the direct measurement of emissions or uptake is not possible, only the instantaneous concentrations of species in the atmosphere can be measured. At the same time, the atmosphere is dynamic, as it is in constant motion with the spatial distribution of gases in the atmosphere continually changing at a rate that is much more rapid than changes that occur to Earth surface properties. With multiple atmospheric measurements over time and/or the use of models, emissions of air quality and greenhouse gas species can be inferred from either in situ measurements or remote sensing observations. A satellite remote sensing mission offers a unique opportunity for large scale coverage over a period of many years at an observation density that would be impractical to achieve using in situ methods.

Inferring emissions/uptake related to natural and anthropogenic processes helps to improve our scientific understanding of these processes and links to policies for reducing emissions that impact air quality, climate or other aspects of the Earth system. Accuracy, precision, geographic coverage and spatial and temporal resolution are all extremely important data quality considerations that relate to the ability to quantify emissions or uptake. For GHGs like carbon dioxide (CO_2) and methane (CH_4), which are very long-lived in the atmosphere, perturbations due to uptake/emission are relatively small compared to background concentrations, hence these considerations are especially important. Satellite missions that measure column CO_2 and CH_4, typically also measure the solar induced fluorescence (SIF) from vegetation as a by-product from one spectral band. SIF is of growing interest for studying vegetation health, productivity and processes for both climate science and policy purposes.

In addition to investigating and quantifying sources and sinks, observations of the atmosphere can also be used for near real-time monitoring and to help forecast future conditions. ECCC is the federal department responsible for weather forecasting and these forecasts have widespread value to the economy and the daily life of Canadians. ECCC also forecasts air quality, thereby benefiting the health of Canadians, especially the most susceptible. Monitoring air quality in near real time is a priority of ECCC in order to inform Canadians of potential risks from exposure to pollution events, such as major forest fires.

AIM-North (www.aim-north.ca) would provide GHG, AQ and SIF observations of unprecedented frequency, density and quality over northern land (~40-80°N) over a span of multiple years. The retrievals of these quantities are all sensitive to clouds to varying degrees. CO_2 is the most sensitive to clouds with ~90% of CO_2 observations rejected from current leading missions due to cloud or related factors. If pointing is intelligently planned to focus on regions with less cloud, the yield of "good" observations could increase substantially. This would require near real-time cloud observations over the high latitudes, which would also be of interest for applications such as weather forecasting.

2.2 GREENHOUSE GASES AND THE CARBON CYCLE

2.2.1 Background and Motivation

CO_2 and CH_4 are the two most important anthropogenic GHGs in terms of direct radiative forcing (estimated at 1.68 Wm^{-2} and 0.64 Wm^{-2} for 1750-2011, respectively [R03]) and overall climate impact. CO_2 and CH_4 both have active natural cycles with uptake and emission occurring through multiple processes. For example, terrestrial vegetation engages in emission and uptake of CO_2 to and from the atmosphere that nearly balance one another on a global annual scale, but the spatial and temporal distribution of source/sink regions remains poorly understood. A better understanding of current vegetation source/sink capacity would enable better predictions of its behavior in the future and enable better projections of future climate.

The boreal forests are currently a net CO_2 sink that cover much of Canada, but large uncertainties remain in the magnitude, timing and spatial distribution of their uptake, which are also changing with climate. The amplitude of the CO_2 seasonal cycle over boreal forests is increasing, while the prevalence of wildfires and insect infestations is also increasing and it is unclear how such factors will alter the boreal forest carbon balance in the future.

Permafrost is a large carbon reservoir (~1672 PgC [R04]) and as it warms, microbial decomposition in the soil breaks down large organic molecules to release CO_2 and CH_4. Although most carbon is released as CO_2, the ratio of CH_4 to CO_2 strongly depends on a number of local factors. Due to uncertainties in the fraction of vulnerable carbon and the partitioning of its release between CO_2 and CH_4, the magnitude and timing of future CO_2 and CH_4 emissions from permafrost is highly uncertain, but important to future climate.

Anthropogenic emission of CO_2 and CH_4 related to fossil fuel extraction, combustion or leakage and emissions due to land use change, have perturbed the natural carbon cycle elevating atmospheric CO_2 and CH_4 concentrations above pre-industrial levels. International discussions to reduce these emissions led to the United Nations Framework Convention on Climate Change (UNFCCC), which was signed in 1992. Developed countries have since been obliged to report their emissions annually under the UNFCCC. The self-reporting is done according to internationally agreed upon guidelines [R05] for estimating emissions. In the case of fossil fuel combustion, emissions are calculated using statistical activity data and emission factors. Atmospheric concentration measurements currently have an extremely limited role in national inventory reporting, but there is a growing interest in the inclusion of observation-based estimates to provide complementary data on emissions, with the potential inclusion in National Inventory Reports. In December 2015, 197 countries signed the UNFCCC Paris Agreement. Quantification of anthropogenic CO_2 and CH_4 emissions using observations from space has the potential to support national emission reduction goals and the transparency framework of the Paris Agreement. Over 60 space and related member agencies of the Committee on Earth Observation Satellites (CEOS) agreed to the Declaration of New Delhi in 2016, which identified the need for better space-based greenhouse gas observations to support emissions monitoring for the Paris Agreement.

Although the earliest space-based observations of CO_2 and CH_4 were based on thermal infrared (TIR) emission spectra, these observations are most sensitive to the middle and upper troposphere, therefore have been shown to have only limited information on surface fluxes [R06]. Observations of solar radiation in the near-infrared (NIR) and shortwave infrared (SWIR) reflected from the Earth's surface are sensitive to the whole atmospheric vertical column, including the surface, thus contain more information on surface sources and sinks. Missions observing in the NIR-SWIR typically measure the oxygen (O_2) *A* band to account for scattering and convert the column density of the GHGs to their column-averaged mole fractions, which are denoted as XCO_2 and XCH_4. The *A* band is also impacted by SIF from vegetation and failing to account for the fluorescence leads to small biases in XCO_2 and XCH_4. By including some solar *Fraunhofer* lines that are isolated from O_2 lines in this band window, SIF can be retrieved to remove the bias from XCO_2 and XCH_4 retrievals [R07]. SIF is also a product of high interest for monitoring vegetation.

2.2.2 Needs

GHGs and the carbon cycle are priority areas of study at ECCC in order to better understand vegetation processes and their impact on the climate and to support policies to reduce our anthropogenic GHG emissions.

CO_2 and CH_4 Precision and Accuracy

The precision requirements for space-based XCO_2 observations to provide information on regional scale source/sink processes were first established almost two decades ago [R08] suggesting a precision goal of ~1.0 ppm. This translates to a precision of ~0.25% relative to the current global annual average background value of ~408 ppm. While single-observation precision is important, the standard error of the mean improves with averaging, therefore regional/continental scale source/sink inversion has shown that spatially-dependent XCO_2 biases are actually more problematic than reduced precision [R09, R10], since they cause biases in surface fluxes.

Based on studies such as those above, the Global Climate Observing System (GCOS) has set requirements for Essential Climate Variables (ECVs), which can be used as an international standard to assist in defining requirements for future missions. GCOS [R11] suggests a combined bias and precision (referred to as accuracy) of 1.0 ppm XCO_2 and 10 ppb XCH_4. Appendix C shows the breakdown of precision and bias goals from a coordinated space agency response to GCOS, for example, suggesting an XCO_2 single observation precision goal of 1.0 ppm and XCO_2 bias of < 0.2 ppm (after bias correction). Future missions under consideration have adopted variations of these requirements, for example, the European Sentinel-7 candidate CO_2 Monitoring Mission single observation precision goal of 0.5 ppm (threshold 0.7 ppm) and bias goal of < 0.5 ppm [R12]. The GCOS standards and requirements for other future missions have been used in determining the AIM-North accuracy and precision requirements for GHG observations.

Anthropogenic CO_2 and CH_4 emissions

Anthropogenic CO_2 and CH_4 emissions, which tend to be more concentrated and localized than natural sources, drive the requirements for spatial resolution or image pixel size. The ability to quantify CO_2 emissions from individual power plants has been demonstrated with data from NASA's Orbiting Carbon Observatory 2 (OCO-2) [R13], which has parallelogram-shaped pixels of $\leq 1.3 \times 2.25\ km^2$. More recent simulated studies [R14] suggest that the 2x2 km^2 to 4x4 km^2 range would provide appropriate data for effectively quantifying large CO_2 point source emissions like fossil fuel burning power plants. Other simulation studies [R15] showed that this resolution was also preferred for the study of CO_2 fluxes from large urban areas.

A review comparing satellite observations of atmospheric methane and their value for quantifying methane emissions [R16] investigated footprint sizes from XCH_4 missions that range from very coarse (30x60 km^2) to very fine (~30x30 m^2). High spatial resolution is preferred for point source *detection*, but precision and accuracy are essential for emission *quantification*. They found that with high precision, spatial resolutions on the order of 2x2 to 3x3 km^2 have a point source detection threshold (0.61-0.80 tCH_4/h) approaching that of the high spatial resolution but lower precision approach (0.25 tCH_4/h). These theoretical numbers were based on multiple assumptions, but it is clear that spatial resolution, accuracy, precision and revisit are all important factors for CH_4 point source quantification, however, the very high resolution data is more challenging to model due to very turbulent behaviour of plumes at those scales [R17].

Canada and the Paris Agreement

The Pan-Canadian Framework on Clean Growth and Climate Change is the Government of Canada’s current plan – developed with the provinces and territories and through engagement with Indigenous peoples – to meet Canada’s emissions reduction targets, grow the economy, and build resilience to a changing climate. The plan includes a pan-Canadian approach to pricing carbon pollution, and measures to achieve reductions across all sectors of the economy. It aims to drive innovation and growth by increasing technology development and adoption to ensure Canadian businesses are competitive in the global low-carbon economy. It also includes actions to advance climate change adaptation and build resilience to climate impacts across the country.

While Canada’s national reporting under the Paris Agreement will continue in accordance with approved best practices, satellite observations of XCO_2 and XCH_4 can play a key role in understanding the spatial, temporal and sectoral distribution of Canada’s CO_2 and CH_4 emissions and in tracking evidence of emission reductions or the effectiveness of policies to reduce emissions on the scale of large facilities, municipalities or provinces/territories. The use of alternative methods such as space-based data is consistent with the transparency framework of the Paris Agreement could support the Global Stocktake, intended to tracking progress towards achieving the goals of the agreement both in Canada and abroad. The link between space-based observations and emission reduction strategies is of high interest in Europe, with the European Commission actively studying the value of space-based observations [R18, R19] and considering development of an ambitious multi-satellite constellation. In Canada, the Climate Research Division of ECCC is engaged in research to understand how similar methods and observations can support Canada’s emission reduction efforts.

Temporal Requirements

It is well-known that biospheric CO_2 emissions vary with seasonal cycles and throughout the day, due to factors such as temperature and sunlight. Anthropogenic CO_2 emissions vary with seasonal and diurnal cycles too, but also exhibit a weekly cycle with lower emissions on weekends due to reduced economic activity and societal norms [R20]. As a result, determining the net annual fluxes or understanding processes requires observations that sample across all of these temporal scales. Using hourly emission data from 187 US power plants, a past study [R21] found that ~15-35 clear-sky overpasses would give annual emissions within ~12.4% for 90% of US power plants. Using a similar approach, a more recent study [R14] determined a matrix of values for the number of overpasses needed to quantify annual CO_2 emissions from a power plant at a given accuracy based on the accuracy of the emission estimate from a single overpass. For example, if a single overpass can yield an emission estimate with 10% accuracy, then 38 clear-sky overpasses are needed to quantify annual emissions at 10% accuracy given the expected temporal variations throughout a year. With most observations lost due to clouds, this implies a much more frequent revisit is actually required. Satellite imaging observations that span the diurnal cycle can theoretically also be used to help separate biospheric and anthropogenic emissions or separate different source sectors since each will have a different diurnal emission profile. Biospheric CO_2 uptake peaks in the midday to late afternoon, while anthropogenic power consumption and thus fossil fuel CO_2 emissions peak during this time, but emissions from transportation have peaks during morning and afternoon rush hour.

CO, NO_2 and SIF

Carbon monoxide (CO) is not considered a GHG since it is reactive and thus has a shorter atmospheric lifetime than GHGs. It is an air pollutant and a tracer for incomplete combustion, for example vegetation burning either by humans or wildfires. CO is grouped with CO_2 and CH_4 here since it is the third most abundant carbon species in the atmosphere, thus also a significant part of the carbon cycle and it can be measured using the same spectral region as chosen for CH_4. The ratio of CO/CO_2 has been suggested as a tracer for fossil fuel combustion [e.g. R22, R23], thus CO observations could help to separate anthropogenic and biospheric signals, but recent European work [R12] has suggested that this is only effective for developing countries, since the most developed countries also have AQ standards requiring low CO emission. Related studies showed that NO_2 was a more valuable tracer overall than CO for identifying anthropogenic CO_2 emission plumes or enhancements. Although use of NO_2/CO_2 ratios was not recommended for quantifying CO_2 emissions, column NO_2 observations, which are less sensitive to cloud than XCO_2 and have a higher enhancement above the background due to a shorter tropospheric lifetime, are an excellent tracer for wind direction and plume shape in the presence of complicated terrain or other conditions leading to non-Gaussian plume behaviour. It should be noted that the NO_2 observations could be from a separate instrument, but are expected to be most effective when the temporal co-registration with CO_2 is shortest, thus the temporal co-registration goal for the Sentinel-7 candidate is 30 seconds. Longer co-registration times are likely tolerable, but the value of NO_2 observations for CO_2 plume tracking would be reduced and at present, we do not have a quantitative understanding of the impacts of a temporal offset of a few minutes between CO_2 and NO_2 observations.

SIF can be used as an indicator of the start, end, and intensity of the growing season, can provide information on vegetation stress and can correlate to gross primary production (GPP). Diurnal SIF observations of the boreal and Arctic regions are desired to enhance our ability to assess the health of forests and other vegetation types, including their net carbon balance at various space and time scales. Such observations are of interest to government departments beyond ECCC that deal with forestry at both the federal and provincial level. Since changes to atmospheric CO_2 provides information on the sum of CO_2 emission and uptake from vegetation, SIF can theoretically help to separate the contributions from photosynthesis and respiration, when used in conjunction with CO_2 observations in a joint inversion context. SIF also has the potential to help separate biospheric and anthropogenic CO_2 fluxes. For example, using SIF to account for the photosynthetic uptake from urban vegetation could give a better quantitative estimate of anthropogenic emissions from an urban area.

2.2.3 Context

The first generation of XCO_2 and XCH_4 satellite missions includes SCIAMACHY on ENVISAT (2003-2012), GOSAT (2009-present), OCO-2 (2014-present, XCO_2 only), TanSat (2016-present, XCO_2 only), and TROPOMI (2017-present, XCH_4 only), which are all LEO missions. Multiple other LEO missions are on the horizon such as GOSAT-2 (scheduled to launch by the end of 2018), OCO-3 to launch in early 2019, CNES MicroCarb in 2020 and a list of others. Most notable are proposed LEO constellations from Europe and China. The European Commission (EC) in partnership with ESA, is considering a constellation of 3 to 4 LEO satellites under the Copernicus program. The proposed “Sentinel 7 Anthropogenic CO_2 Monitoring Mission” (mentioned earlier), would actually measure CO_2, CH_4, NO_2 and aerosols. It would image CO_2 and CH_4 at 2x2 km^2 from a wide-swath (> 200 km) to give a better than weekly revisit rate (before loss of data due to cloud). The Chinese Academy of Science (CAS) in partnership with other Chinese organizations, is considering a constellation of up to 6 LEO satellites. Each would observe CO_2, CH_4 and CO with 2x2 km^2 pixels and >100 km swaths and observe O_3, NO_2 and SO_2 with ~1x1 km^2 pixels and > 600 km swaths. These ambitious European and Chinese programs are strongly motivated by the objective of quantifying anthropogenic CO_2 emissions from space related to national polices and the transparency framework for the Paris Agreement on climate change.

Although the upcoming generation of CO_2 and CH_4 missions continues to be predominantly LEO-based, GEO constellation components are also emerging with NASA’s GeoCarb scheduled for launch in 2022 and ARRHENIUS, which was considered under the ESA Earth Explorer 10 program. GeoCarb is a hosted payload concept that will observe CO_2, CH_4 and CO over North, South and Central America from 50°N-50°S. GeoCarb will observe 3x6 km^2 pixels at the sub-satellite point, which will be oversampled to yield 3x3 km^2 horizontal resolution, although after factoring in viewing angle and pixel growth due to the curvature of the Earth, it will give ~5x5 km resolution at 30°N/S with a revisit of 1-3 times/day (prior to data loss due to cloud). GEO is a more efficient method than LEO for obtaining frequent revisits over a limited region of interest, equatorward of ~50°N/S. From GEO, revisit rate is flexible and can be increased directly by reducing the field of regard. ARRHENIUS proposed to take advantage of this fact with a truly flexible and intelligent pointing approach to determine when and where clouds are present from real-time external GEO cloud data and point to cloud-free regions with 2x2 km^2 pixels. ARRHENIUS would be able to obtain cloud-free observations over Africa, Europe and the Middle East, from frequently cloudy regions that are poorly observed with current LEO satellites. These frequent revisits will also complement Sentinel-7 by observing with diurnal and sub-weekly sampling, which could lead to a better understanding of processes from vegetation or anthropogenic activity.

As mentioned earlier, LEO satellites provide some observations of northern latitudes, but with a limited revisit rate, while GEO observations cannot reach latitudes beyond ~50°N for GHGs. An Observing System Simulation Experiment (OSSE) study [R24] has shown that even CO_2 observations from HEO with a precision about a factor of two worse than GOSAT and a footprint size similar to GOSAT, provided improved constraints on monthly biospheric CO_2 surface fluxes in the Arctic and boreal regions about the size of a large Canadian province or territory. After this first introduction of HEO XCO_2 observations in the peer-reviewed literature, international interest in HEO GHG observations has steadily grown. Although there was no mention of HEO CO_2 or CH_4 observations in the 2010 GEO Carbon Strategy [R25], in the 2014 CEOS Strategy for Carbon Observations from Space [R26] developed in response to the GEO Carbon Strategy, a vision for a future LEO and GEO CO_2 and CH_4 constellation was put forth, while HEO observations were mentioned as a complementary observing approach. In the 2017 European Commission CO_2 Monitoring Report [R19], Canada's longstanding interest in CO_2 and CH_4 from HEO is recognized and HEO is briefly mentioned as part of their long-term vision for future global constellation. In the 2018 CEOS Report *A Constellation Architecture for Monitoring CO_2 and CH_4 from Space* [R27], HEO is mentioned over 20 times and HEO satellites are suggested alongside LEO and GEO as key elements of the envisioned constellation. Updated studies of simulated HEO CO_2 observations with the AIM-North, precision, accuracy, spatial resolution and revisit requirements (and improved data assimilation methods) are currently planned to assess the ability of these improved HEO observations to quantify Arctic and boreal CO_2 surface fluxes, including the detection and quantification of permafrost CO_2 emissions.

2.3 AIR QUALITY

2.3.1 Background and Motivation

Canadian air quality is generally excellent. Ground-level ozone in Canada [R28] is well within Canadian Ambient Air Quality Standards (CAAQS) [http://airquality-qualitedelair.ccme.ca/en/]. Air quality has been improving over North America over the past decade, particularly in eastern North America, where the use of flue-gas desulfurization units have decreased SO_2 emissions by >80% (2005-2015) [e.g. R29]. As a result, there is a decreasing trend in sulfate aerosol that can be detected from satellite observations of aerosol optical depth over southern Quebec [e.g. R30]. The changes in sulfate aerosol have led to significant health-related improvements for Canadians (2000-2011) [R31]. Meanwhile, trends in ground-level ozone vary from region to region but tend to be small [R32].

Nonetheless, exposure to air pollution in Canada is responsible for a large number of premature mortalities. A 2008 study from the Canadian Medical Association estimates that 21,000 deaths can be attributed to air pollution annually, with an associated cost of $8B [R33]. By 2030 the accumulated cost is forecast to be $250B. The compounds thought to be responsible for the majority of these deaths are ground level ozone, nitrogen dioxide, and particulate matter (PM). It is this realization that prompted Canada to formulate an Air Quality Health Index (AQHI) [R31] which uses the concentrations of these three pollutants to define a scale (ranging from 0 to 10+) to help Canadians understand what the air quality around them means to their health. These pollutants, along with others such as sulfur dioxide, formaldehyde, and carbon monoxide, result (directly or indirectly) from combustion of fossil fuels. Natural sources include forest fires and volcanic eruptions, while anthropogenic sources include automobiles and industrial operations.

Forest fires are particularly intense sources of air pollution in the spring and summer. While variable from year to year, there has been an increase in the number and severity of fires in Canada over the past half century and this is expected to continue with the warming climate [R34, R35]. Forecasting the air quality from these events using state-of-the-science models remains challenging and additional and detailed observations are required to guide and verify improvements.

In the Arctic, air pollution is primarily the result of long-range transport from natural and anthropogenic sources. Modelling studies show that European sources are important for near-surface pollution, while transport from Asia and North America may occur at higher altitudes through lofting by warm conveyor belts. Arctic Haze is a pan-Arctic pollution phenomenon lasting from late winter to early spring [e.g. R36]. Further, with the accelerating disappearance of multi-year ice, the Northwest Passage and other Arctic sea routes are more readily negotiated by large container ships. In the coming years there may be heavy marine traffic through the Polar region in an attempt to reduce fuel used in long journeys. This will impact AQ in the whole Polar region, increasing ozone and increasing the abundance of aerosols which will likely affect cloud formation.

2.3.2 Needs

The highest priorities are measurements of ozone (O_3), NO_2 and aerosols. These three species are used to calculate the AQHI. Near-real-time measurements of these constituents could be fed into ECCC’s data assimilation systems with a goal of forecasting hourly AQHI national. However, ground-level ozone is difficult to resolve from free tropospheric ozone with UV/visible satellite-nadir measurements. Of secondary importance are sulfur dioxide (SO_2), a sulfate aerosol precursor, and formaldehyde (HCHO), which serves as a qualitative indicator of volatile organic compounds (VOCs), which are precursory to ozone. Formaldehyde is also a product of isoprene oxidation, and thus linked to secondary aerosol formation [R37]. Carbon monoxide emissions from automobiles have been decreasing in recent decades but like formaldehyde, CO is emitted by forest fires, particularly those of the smoldering variety.

There is also a need to monitor the stratospheric ozone layer. There are signs of recovery but these signs vary with latitude and altitude. Profile measurements of ozone, including separation of tropospheric and stratospheric column abundances will assist in understanding changes in total column ozone. Bromine is capable of catalytic ozone destruction and leads to ozone depletion both near the surface and in the stratosphere. BrO (bromine monoxide) is formed during the catalytic destruction of ozone. It is important to monitor bromine, and specifically inorganic bromine via BrO, into the future to ascertain whether atmospheric abundances of this halogen are truly decreasing as expected following the Montreal Protocol and subsequent amendments.

2.3.3 Context

Space-based air quality observations of the stratosphere began in the in 1970s, but it was not until the 1990s that instruments designed to probe tropospheric composition were launched. In the ensuing 2+ decades, spatial resolution has improved by more than an order of magnitude from 100+ km to less than 10 km. With a few exceptions such as ammonia (NH_3) and CO, the majority of the air quality species of interest (O_3, NO_2, SO_2, HCHO, aerosol) are sensed using back-scattered light from the near-UV, visible, and just into the near-IR (roughly 280 to 700 nm), although deriving aerosol size information generally requires the addition of longer wavelengths.

GOME (1996; ~300 km resolution) was the first UV-visible spectrometer launched capable of deriving total column O_3, NO_2, SO_2, and HCHO (in units of molecules/cm^2). It was followed by SCIAMACHY (2003; ~50 km) and GOME-2 (2006, 60 km). Owing to its superior spatial resolution of about 20 km, OMI, launched in 2004, has proven to be the workhorse for air quality monitoring for over a decade. Most recently, its successor, TropOMI (~7 km) was launched and the early results reveal details in the spatial distribution of pollution down to the sub-urban level. All these AQ instruments to date have been placed in LEO. However, the next 2-5 years will see the launch of a geostationary constellation of AQ instruments, to be placed at longitudes centered over North America (TEMPO), Europe (Sentinel-4), and East Asia (GEMS). The spatial resolution will be comparable to or better than TropOMI, with TEMPO the best at 2 x 4.5 km^2. The hourly repeat cycle of these sensors will enable, for the first time, tracking of pollution events in near-real time and quantifying the rapidly changing emissions and chemistry throughout the day. As with the GHG GEO instruments, the quality and spatial resolution of these degrade above 50°, and are useless above 60°.

The utility of satellite observations for detecting and quantifying emission sources has been established previously [e.g., R38]. However, the single-overpass time provided by a LEO sensor leads to biases due to its inability to capture the diurnal cycle. GEO, with its rapid repeat, means not only more accurate emissions, but improved detection limits. Considering a spatial resolution similar to TEMPO, deriving emissions from individual facilities should be possible.

2.4 CLOUDS

At any given moment, ~70% of the Earth is covered by cloud [R39]. The clearest regions of the world tend to be dry desert regions like the Sahara, much of the Middle East and the interior of Australia, with the northern mid- and high latitudes cloudier than the global average probability of ~70%. Measurements of atmospheric GHGs and AQ are sensitive to clouds to varying degrees. Retrieval of CO_2 with its high precision and accuracy requirements is the most sensitive and thus aggressive filtering is done to remove data that are contaminated by clouds. Clouds can have a direct effect if they are in the light path, but other cloud effects (scattering into the light path, shadows, etc.) can also interfere with observations. In OCO-2, only 7-12% of observations in a given month pass all of the cloud screens and other data quality filters [R40], meaning that ~90% of observations are lost due to cloud and related factors. For GOSAT, with a larger footprint, ~93% of observations are rejected. GOSAT-2 will use an intelligent pointing approach where a cloud imager will provide real time information on clear locations within the field of regard, where the GHG observations have the best chance of success. GOSAT-2's intelligent pointing approach will improve the yield of cloud-free data from partially cloudy regions. However, a cloud-informed intelligent pointing approach is expected to be much more powerful from GEO or HEO, since with the larger instantaneous field of regard due to a much higher satellite vantage point, more pointing options are available at any given instant. A cloud imager with the capability to observe the entire Earth disk north of 40°N, hourly or better during daylight, could provide sufficient information to inform pointing, which would greatly improve the yield of clear-sky observations of GHG and AQ species. Studies are planned to quantify the impact of intelligent pointing from HEO, compared with a simple pointing approach.

Clouds are of course also important for both weather and climate. Observations of cloud coverage and potentially also cloud-top height, with frequent revisit and good spatial resolution would have a number of applications related to weather and climate. Cloud data could be of use for weather and climate model evaluation, process studies or for initialization of forecasts in numerical weather prediction or solar irradiance forecasts for the rapidly expanding renewable energy industry [R41].

2.5 OTHER METEOROLOGICAL AND ATMOSPHERIC PARAMETERS

GHG and air quality observations are the primary observing objectives of AIM-North. However, an enhancement to the mission above the baseline is also possible by adding bands in the longwave and mid-wave infrared. These bands would enable measurements of temperature, water vapour and atmospheric motion vectors in northern regions (for weather forecasting) along with numerous AQ species and CO_2 and CH_4 with mid- to upper tropospheric sensitivity during days, nights and all seasons. Preliminary analysis for AIM-North and past studies (for the PHEOS-WCA instrument suite) suggest that the enhancement would require the addition of one or more additional detector arrays and a cryo-cooler system to one of the spectrometers.

3 MISSION OBJECTIVES

The *Overarching Mission Objectives* of AIM-North are stated, which closely relate to the ECCC and wider Government of Canada (GoC) priorities and mandates. More specific *Mission Science Objectives* are also presented, which are divided into 3 categories on the following page.

3.1 OVERARCHING OBJECTIVES AND ALIGNMENT WITH PRIORITIES AND MANDATE

Overarching Mission Objectives	
M-1	Monitor greenhouse gas (GHG) and air quality (AQ) species over northern regions to quantify natural and anthropogenic sources/sinks in support of Government of Canada (GoC) policies to mitigate climate change and improve air quality
M-2	Address the gap in northern AQ and GHG spatial and temporal coverage from the emerging international virtual constellation and provide overlap with geostationary (GEO) observations over North America, Europe and Asia

ECCC and Government of Canada Priorities and Mandate	
GoC-1	Enhance Canada's weather, climate, air quality and environmental services in order to protect Canadians' health, safety, security and economic prosperity
GoC-2	Contribute to an enhanced understanding of natural and anthropogenic sources and sinks, emissions quantification, and improved air quality forecasts
GoC-3	Improve the GoC's capacity to monitor greenhouse gas emission reduction efforts and inform climate change mitigation strategies
GoC-4	Monitor air quality pollutants over Canada, especially key hotspots like urban areas and the Oil Sands and remote regions including the Arctic

3.2 SPECIFIC MISSION SCIENCE OBJECTIVES

Greenhouse Gas and Carbon Cycle Objectives	
GHG-1	Improve our ability to quantify natural and anthropogenic CO_2 and CH_4 sources and sinks in the Arctic and northern mid-latitudes (~40-80°N) using imaging observations of column CO_2 and CH_4
	a) Improve our understanding of forest CO_2 fluxes and the net carbon balance of northern forests
	b) Reduce uncertainties in the spatial, temporal and sectoral attribution of CH_4 surface emissions
	c) Detect and quantify potential acceleration in CO_2 and CH_4 emission from permafrost
	d) Improve estimation of northern anthropogenic CO_2 and CH_4 emissions at the scale of a municipality or large industrial source
GHG-2	Improve our understanding of northern vegetation health, processes and carbon flux in a changing climate using solar induced fluorescence (SIF) observations
GHG-3	Better quantify emissions and separate CO_2 emissions from anthropogenic versus biospheric sources (respiration and wildfires) with the help of CO, NO_2, SIF or other supporting observations
GHG-4	Improve representation of the carbon cycle in climate prediction models through an improved knowledge of current carbon fluxes and processes
Air Quality Objectives	
AQ-1	Better quantify anthropogenic (including agricultural) and wildfire emissions and their impact on northern air quality (~40-80°N), including understanding the relative contribution from local sources versus long range transport
AQ-2	Better monitor and predict surface air quality (including UV) over Canada, including understanding how episodic events impact air quality and in particular the Air Quality Health Index (AQHI)
AQ-3	Understand how air pollution influences climate change in the Arctic/Subarctic and the extent to which climate change impacts Arctic/Subarctic pollution
AQ-4	Monitor stratospheric ozone and ozone-related compounds in the North
Cloud Objectives	
C-1	Obtain observations of clouds to inform the pointing of the Greenhouse Gas and Air Quality instruments
C-2	Obtain high spatial resolution cloud information to be used in determining cloud fractions for trace gas retrievals and to identify small clouds to allow for more accurate aerosol retrievals

3.3 OBSERVING REQUIREMENTS

Area of interest (AoI)

All land area north of 40°N is of interest, which includes all of Canada along with these latitudes on other continents. Observations over ice sheets (i.e. most of Greenland) are expected to be unlikely due to the surface albedo, so Greenland will be excluded from the baseline observing plan. Observing north of 50°N would address the gap left by upcoming GEO AQ and GHG missions, but overlapping coverage with GEO between (~40-50°N) is also essential since the GEO missions do not overlap with each other. AIM-North would thus enable intercomparisons with GEO across the diurnal cycle, which would not be possible with 3 GEO and a small number of LEO satellites.

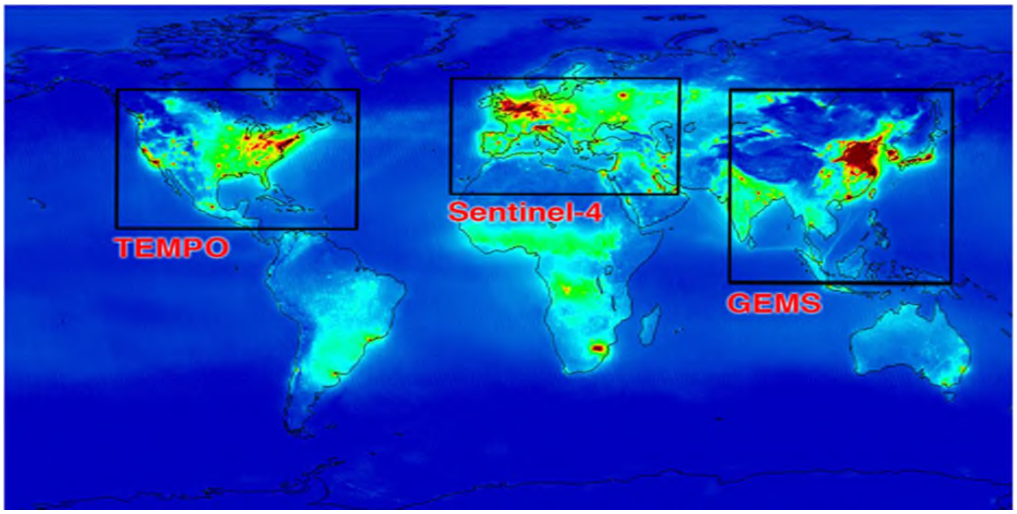

Figure 3.1. Approximate coverage of air quality monitoring from GEO shown on a map of NO_2 concentrations. These 3 GEO systems planned for the 2020s will leave an observation gap at higher latitudes where viewing angles are too large. (Image credit: CEOS AC-VC).

A highly elliptical orbit (HEO) could address the reduced observation density and lack of diurnal sampling that would occur with a virtual constellation based only on LEO and GEO satellites. Earth observation from HEO was first offered as a potential solution to the lack of GEO coverage at high latitudes at least as far back as 1989 [R42], in which a HEO with a 12-hour period (Molniya orbit) was considered, since it had previously been used for Soviet communication satellites as far back as 1965. In recent years, Canada has studied numerous HEO variations and their advantages and disadvantages as options for the Polar Communications and Weather Mission (PCW) [R02, R43, R44, R45, R46]. These studies varied the orbital period and other parameters of the orbit to investigate issues such as coverage, revisit and exposure to radiation and are relevant to AIM-North, but new studies giving special consideration the needs of GHG and AQ observations will also be required to determine the optimal HEO parameters. Figure 3.2 provides a simple illustration of the improved viewing angle offered by HEO relative to GEO northern regions.

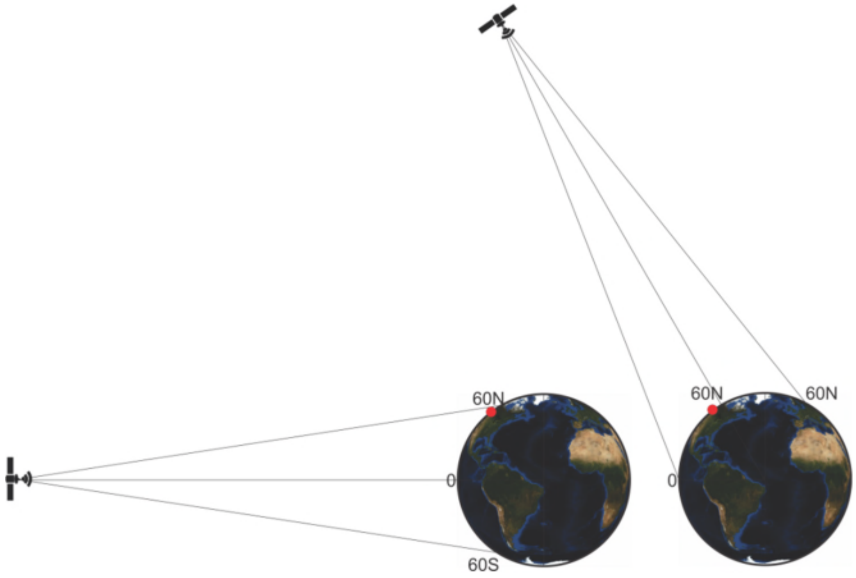

Figure 3.2. The lines show the nadir and ±60° from the nadir for GEO (left) and HEO (right). The red dot is a high latitude point of interest (Alberta Oil Sands) ~57°N. From a HEO near the critical inclination (*i*=63.4°N), the point is viewed with a favourable viewing angle from near apogee, while from GEO the viewing angle is very large and far from vertical. Longitude offset (not shown) compounds the effect.

Viewing zenith angles (VZA) and Solar Zenith Angles (SZA)

The observable area from a satellite (whether LEO, GEO or HEO) is restricted by VZA considerations. For observations that require reflected sunlight, the predominant observing method of AIM-North, SZA is also a relevant factor. VZA and SZA restrictions that are expected for AIM-North observations are given in Table 3.0; however, AIM-North should still have capability to point beyond the typical VZA limit assumed for normal operations, by some margin of at least 10°.

Table 3.0. SZA and VZA Requirements

Parameter	**SZA_{max}**	**VZA_{max} (normal operations)**	**VZA_{max} (design)**
GHG observations	80°	60°	75°
AQ Observations	80°	70°	80°

For atmospheric observations, VZA and SZA are sometimes considered together in a combined quantity called the airmass, which indicates a relative length of the light path through the atmosphere:

$$airmass = \frac{1}{\cos(SZA)} + \frac{1}{\cos(VZA)}$$

An airmass limit may also be imposed as an additional constraint during data processing.

Spatial and Temporal Requirements

Required imaging pixel sizes are shown in Table 3.1. The size should be interpreted to correspond to the equivalent angular distance for a nadir observation at a nominal HEO observing altitude of 40,000 km. Potential observations from higher altitudes and off nadir (i.e. VZA > 0°) will have slightly larger pixels, while observations from lower altitudes could have smaller pixels. The spatial sampling distance is expected to be the same as the pixel size and gapless imagery is desired with minimal overlap between adjacent images. Of course, clouds or insufficient surface albedo (i.e. water bodies) will result in gaps in coverage.

The number of observations per day possible using solar reflectance (UV to SWIR) will vary with season, especially at the highest latitudes. The threshold for GHGs, AQ species and SIF is based on ~4 observations spanning the diurnal cycle for a mean daylight length of 12 hours. Revisit rate requirements do not need to be met for cloud-covered areas or periods when solar illumination is insufficient (night and polar winter).

Table 3.1. Pixel Size and Revisit Requirements

Parameter	**Pixel Size**	**Temporal Revisit**
AQ and GHGs species, SIF	2x2 km^2 (G), 4x4 km^2 (T)	60 min. (G), 180 min. (T)
Clouds for pointing	2x2 km^2 (G), 10x10 km^2 (T)	30 min. (G), 120 min. (T)
Clouds for AQ retrievals	0.25x0.25 km^2 (G), 1x1 km^2 (T)	15 min. (G), 60 min. (T)

(G) = Goal (An ideal requirement above which further improvements are not necessary)
(T) = Threshold (The minimum requirement to ensure mission/science objectives can be met)

Data Level Definition

Table 3.1.1 Definition of Data Levels for AIM-North

Data Level	**Description**
Level 0	Interferograms or other raw data
Level 1a	Raw spectra
Level 1b	Calibrated, corrected and geolocated spectra
Level 2	Retrieved gas/aerosol concentrations, SIF or cloud information
Level 3 & 4	Specialized science data products (e.g. gap-filled maps or surface flux estimates) that are not directly related to instrument requirements

Precision and Accuracy Requirements

Table 3.2. Precision and Accuracy Requirements for Level 2 Data

Species	**Mission Objectives**	**Single Observation Precision (1σ)**	**Accuracy (1 σ maximum allowed bias)**	**Nominal Spectral Region**
Primary				
CO$_2$ (X)[1]	GHG-1, GHG-3, GHG-4	0.25% (1 ppm) (G), 0.75% (3 ppm) (T)	0.05% (0.2 ppm) (G), 0.15% (0.6 ppm) (T) [2]	~1600 nm ~2060 nm ~760 nm[6]
CH$_4$ (X)[1]	GHG-1, GHG-4	0.5% (9 ppb) (G), 1.5% (27 ppb) (T)	0.1% (2 ppb) (G), 0.3% (6 ppb) (T) [2]	~2340 nm ~760 nm
CO (C or X)[1]	AQ-1,2, GHG-3	5% (G) 15% (T)	5% (G) 15% (T)	~2340 nm ~760 nm[6]
O$_3$ (SC)	AQ-1,3	3% (G) 5% (T)	2% (G) 3% (T)	290-345 nm 540-650 nm
O$_3$ (TC)	AQ-1,2	3% (G) 5% (T)	20% (G) 30% (T)	290-345 nm 540-650 nm
NO$_2$ (SC)	AQ-1,3	3% (G) 5% (T)	10% (G) 15% (T)	400-470 nm
NO$_2$ (TC)	AQ-1,2	10^{15} cm^{-2} (G)[3] 1.5x10^{15} cm^{-2} (T)	15% (G) 20% (T)	400-470 nm
Aerosol AOD (C)	AQ-1,2	0.03 + 15% (G) 0.05 + 20% (T)	0.03 (G) 0.05 (T)	(1) 354, 388, 440, 555, 675 nm (2) O$_2$ A-band[6]
Cloud (day)	All	NR	NR	Vis/NIR/SWIR (day)
Secondary				
Solar Induced Fluorescence (SIF)	GHG-3	0.30 Wm^{-2} sr^{-1} μm^{-1} (G) 0.90 Wm^{-2} sr^{-1} μm^{-1} (T) – requires averaging	NR	~758 nm (high res)[6] 500-780 nm[4]
SO$_2$ (C)	AQ-2	10^{16} cm^{-2} (G)[3] 1.5x10^{16} cm^{-2} (T)	2×10^{15} cm^{-2} (G) 3×10^{15} cm^{-2} (T)	305-345 nm
HCHO (C)	AQ-2	TBD	TBD	325-360 nm
BrO (C)	AQ-3	TBD	TBD	340-370 nm
OClO (C)	AQ-3	TBD	TBD	360-390 nm
CHOCHO (C)	AQ-2	TBD	TBD	420-465 nm
Cloud (night)[5]	Other	NR	NR	IR (day/night)

Shading denotes species may be required in near real time
(X) = column-averaged dry air mole fraction
(C) = total vertical column (TC+SC)
(TC) = tropospheric vertical column density
(SC) = stratospheric vertical column density

NR = no requirement
TBD = to be determined

[1] Column-averaged CO_2, CH_4 and CO dry air mole fractions (denoted XCO_2, XCH_4 and XCO) are based on the gas column density divided by the total air column density, the latter of which can be derived from measurement of the O_2 *A* band.
[2] To a very large extent, this observation requirement is a retrieval challenge and not an instrument requirement, but the necessary SNR, spectral sampling, spectral calibration, knowledge of lineshape etc. must be provided by the instrument design. Filtering and bias correction can be applied to meet the requirements.
[3] Vertical column density units (molecules/cm^2, or cm^{-2})
[4] ESA's FLEX spans 500-650 nm for the Photochemical Reflectance Index (PRI), and 650-800 nm for Photosystems I and II
[5] For some applications of cloud data, observations of both day and night would be of value, however, night-time data (from thermal IR bands) is an observable of secondary interest at best

[6] Simultaneous O_2 *A* band measurements concomitant with the other spectral bands are needed for XCO_2, XCH_4 and XCO retrievals as well as aerosol information to for AQ retrievals

In Table 3.2 only nominal spectral regions are given, since for the NIR-SWIR CO_2, CH_4, CO and O_2 bands, the exact start and end points of the band will depend on the instrument technology (interferometric or dispersive), which will be investigated and determined during Phase 0 studies.

Cloud data for pointing will require some limited onboard capability for processing in real-time. Air quality species that are needed for forecasting will have a latency requirement of ~1-2 hours, which is currently estimated based on requirements for TEMPO (2 hours). Data latency for GHG observations on the order of weeks should suffice.

Instrument Level Requirements

Preliminary values for the Signal-to-Noise Ratio (SNR) required to achieve the precision requirements (G and T) were determined in the pre-Phase 0 mission concept study. The approach involved radiative transfer simulations and a simplified retrieval algorithm. This approach accounted only for the impact of instrument noise (Gaussian distribution) on precision and thus should be interpreted as a preliminary estimate for the lower limit on the required SNR. Accounting for other factors relevant to the precision of key Level 2 data products is planned in Phase 0 science activities, using more sophisticated methods, such as full physics retrieval algorithms.

The required SNRs determined correspond to the specified instrument technology, spectral bands and spectral sampling interval. Changing any of these factors will impact the SNR requirement. While SNRs are strongly dependent on surface albedo and solar zenith angle (SZA), SNR requirements are only weakly dependent on surface albedo and SZA. SZA was 45° and albedo was set to a spectrally constant value of 0.2 for the air quality simulations and to that of pine forest for the GHG simulations (according to MODTRAN5.2).

Greenhouse Gas Instrument

The following preliminary minimum SNRs related to the single observation precision requirements are based on an Imaging FTS instrument with 0.25 cm^{-1} spectral sampling at all of the specified bands. Coarser spectral sampling for the O_2 *A* band (0.5 cm^{-1}) has been considered, but accomplishing this from the same IFTS involves either scanning for half the time or degrading the spectral resolution afterward to increase SNR. Past studies have indicated that both of these options result in decreases to the resulting retrieval precision rather than gains.

Table 3.3. NIR and SWIR Spectral Bands, Species and Requirements

Species	Wavelength range (nm)	Wavenumber range (cm^{-1})	Wavenumber (cm^{-1}) for SNR requirement	SNR Goal	SNR Threshold
O_2	758-762	13118-13192	13185	88	30
CO_2	1570-1587	6300-6370	6305	119	40
CO_2	2042-2079	4810-4897	4897	116	40
CO (CH_4)[a]	2301-2380	4195-4345	4324	130	43

[a] CO and CH_4 are both retrieved from this band, but the SNR requirements are driven by the CO precision requirements.

Optimization of spectral bands will differ for FTS and dispersive instruments due to a number of factors such as noise considerations and different methods of spectral sampling. Realistic potential bands for each type of instrument are provided in Table 3.3.1. The FTS bands are mostly based on earlier AIM-North studies, while the dispersive bands are based on NASA's GeoCarb mission [RD47]. SNR requirements for these two configurations, along with a dispersive instrument using identical bands to the FTS will be determined in Phase 0 science studies.

The capability of an instrument configuration to meet SNR requirements depends on assumptions about the reference spectral albedo in each band. Table 3.3.1 provides reference albedos to be assumed in Phase 0, based on a more detailed study than was carried out for previous work. Reference albedos should be used with a solar zenith angle of 60° and a Lambertian profile of reflectivity. The minimum scene albedo represents a barely detectable scene, in which case the precision/accuracy requirements would not be expected to be met. The saturation scene albedo is an approximate brightest scene that could be encountered during Earth observation for which the GHG instrument should be designed to accommodate.

Table 3.3.1. Recommended GHG Instrument Spectral Bands for Phase 0 along with NIR and SWIR Reference (a_{Ref}), Minimum (a_{Min}) and Saturation (a_{Sat}) Spectral Albedos

Species	FTS Band (nm)	FTS Resolution (nm)[a]	Dispersive Band (nm)	Dispersive Resolution (nm)[b]	a_{Ref}	a_{Min}	a_{Sat}
O_2	758.0 - 762.3	~0.0174	757.9 - 772.0	0.0474	0.23	0.02	1
CO_2	1598 - 1618[c]	~0.078	1591.5 - 1621.2	0.101	0.16	0.01	1
CO_2	2042 - 2079	~0.127	2045.0 - 2085.0	0.136	0.17	0.01	1
CO & CH_4	2301 - 2380	~0.167	2300.6 - 2345.6	0.153	0.12	0.01	1

[a] Approximate values for FTS spectral resolution are obtained by applying a factor of 1.2 to the 0.25 cm^{-1} spectral sampling and converting this width to wavelength near each band center for comparison with the dispersive values

[b] Spectral sampling for GeoCarb is based on a polynomial for each band with the function and coefficients provided in [RD47]

[c] The recommended CO_2 band differs from that in the mission concept studies, since it uses a spectral range with a higher albedo over snow and better consistency with the GeoCarb band

Air Quality Instrument

The following preliminary minimum SNRs relate to precision requirements based on a dispersive instrument with 0.40 nm spectral sampling at the specified bands from the mission concept study. Design considerations for TEMPO suggest that spectral sampling beyond the Nyquist sampling criterion is likely necessary, with TEMPO oversampling by a factor of ~5. Although, this high degree of oversampling may not be required, the Phase 0 goal for the air quality instrument is now 0.25 nm spectral sampling.

Table 3.4. UV-vis Spectral Bands, Species and Requirements

Species	Fitting Window Wavelength (nm)	Wavelength (nm) for SNR requirement	SNR Goal	SNR Threshold
Primary Species (single observation SNR requirements are given)				
O_3	290-345	330	239	144
NO_2	400-470	416.4	765	536
O_3	540-650	544 650	177 123	106 74
AOD	675	675	36	12
Secondary Species (SNRs can be achieved by binning in space and/or time)				
SO_2	305-321	320.8	2090	1447
HCHO	325-360	330	2394	1596
BrO	340-370	366	3084	2159

For the UV-vis, the reference, minimum and saturation spectral albedos are provided in Table 3.5, defined as for the GHG instrument. Similarly, reference albedos should be used with a solar zenith angle of 60° and a Lambertian profile of reflectivity.

Table 3.5. UV-vis Reference (a_{Ref}), Minimum (a_{Min}) and Saturation (a_{Sat}) Spectral Albedos

Species	Dispersive Band (nm)	a_{Ref}	a_{Min}	a_{Sat}
O_3	290-345	0.03	0.01	1
O_3	540-650	0.033	0.01	1
NO_2	400-470	0.03	0.02	1
AOD	675	0.03	0.01	1
HCHO	325-360	0.03	0.01	1
BrO	340-370	0.03	0.01	1

Mission Duration

We propose a design lifetime goal for the mission of 5 years and threshold of 3 years. A 3-year mission would provide the minimum duration for studies on interannual variability of carbon cycle or air quality emissions and processes. A 5-year mission would enable a better assessment of interannual variability related to factors such as the El Nino Southern Oscillation (ENSO) and would provide the minimum duration for investigating trends.

3.4 CONCLUSION

AIM-North would provide GHG, AQ and SIF observations of unprecedented frequency, density and quality over northern land (~40-80°N) over a period of multiple years. A small cloud imager would enable intelligent pointing to focus on regions with less cloud, substantially increasing the yield of cloud-free observations, while also generating real-time cloud data over the high latitudes with various applications.

The current baseline approach would use two satellites in a HEO formation, each equipped with spectroscopic instrumentation to measure reflected solar radiation spanning the UV-visible and at carefully selected windows in the NIR and SWIR. The mission science objectives for AIM-North are outlined in this document. The region of interest, precision, accuracy, spatial resolution and revisit rate requirements for the species of interest that would enable the fulfillment of the mission and science objectives are provided. Preliminary estimates of the required instrument level requirements (spectral bands, spectral sampling/resolution and SNRs) are also provided to meet the observing requirements, but retrieval studies during the early stages of Phase 0 will provide a more detailed assessment of these requirements.

AIM-North is supported by ECCC and links directly to climate and air quality research and operations priorities within the departmental mandate. The mission would provide data that could improve ECCC air quality forecasting and would provide data that would enhance Canada's ability to quantify our natural and anthropogenic emissions of GHG and AQ species. SIF observations would also help in understanding the carbon balance and health of Canada's forests. This improved capacity could support GoC efforts to reduce GHG and AQ emissions and other GoC policy objectives. AIM-North would provide data that is consistent with the upcoming GEO AQ constellation coordinated through CEOS and address the upcoming gap in high latitude AQ observations. AIM-North GHG observing plans are consistent with international plans for a CO_2 and CH_4 constellation recommended by CEOS and with the aspirations of the New Delhi Declaration, calling for an improved capacity to provide GHG measurements from space to enable emission monitoring in support of the Paris Agreement.

4 CORE TEAM DESCRIPTION

AIM-North has a core team at ECCC and a large User and Science Team consisting of members from government and academia, both within Canada and internationally. This MOD was prepared by the core team. The User Requirements Document (URD) will represent the requirements of the full User and Science Team.

TABLE 4-1 – CORE TEAM MEMBERS

Name	Organization	Role(s)
Nassar, Ray	ECCC	AIM-North Principal Investigator GHG Lead
McLinden, Chris	ECCC	AQ Lead
Sioris, Chris	ECCC	AQ and GHG Technical Support, Radiative Transfer and Instrument Specialist

Appendix A ACRONYMS AND ABBREVIATIONS

TABLE A-1 – ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AIM-North	The Atmospheric Imaging Mission for Northern Regions
AOD	Aerosol Optical Depth
AoI	Area of Interest
AQ	Air Quality
AQHI	Air Quality Health Index
ARRHENIUS	AbsoRption spectRometric patHfindEr for carboN regIonal flUx dynamicS
BrO	Bromine Oxide
CAAQS	Canadian Ambient Air Quality Standard
CEOS	Committee on Earth Observation Satellites
CH_4	Methane
CMA	Canadian Medical Association
CNES	Centre National d’Etudes Spatiale
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSA	Canadian Space Agency
ECCC	Environment and Climate Change Canada
ECV	Essential Climate Variable
EE	Earth Explorer
ENVISAT	Environmental Satellite
ENSO	El Nino Southern Oscillation
ESA	European Space Agency
FTS	Fourier Transform Spectrometer
GCOS	Global Climate Observing System
GEMS	Geostationary Environment Monitoring Spectrometer
GEO	Geostationary
GEO	Group on Earth Observations
GHG	Greenhouse Gas
GoC	Government of Canada

Acronym	Definition
GOME	Global Ozone Monitoring Experiment
GOSAT	Greenhouse Gases Observing Satellite
GPP	Gross Primary Production
HCHO	Formaldehyde
HEO	Highly Elliptical Orbit
IFTS	Imaging Fourier Transform Spectrometer
IPCC	Intergovernmental Panel on Climate Change
IPCC-TFI	IPCC Task Force on National Emission Inventories
IR	Infrared
LEO	Low Earth Orbit
MOD	Mission Objectives Document
MRD	Mission Requirements Document
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
NO_2	Nitrous Oxide
O_3	Ozone
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
OSSE	Observing System Simulation Experiment
PCW	Polar Communications and Weather
PHEOS	Polar Highly Elliptical Orbit Science
PI	Principal Investigator
PM	Particulate Matter
ppb	Parts per billion
ppm	Parts per million
RFP	Request for Proposals
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SIF	Solar Induced Fluorescence
SNR	Signal-to-Noise Ratio
SO_2	Sulfur Dioxide
SWIR	Shortwave Infrared
TEMPO	Tropospheric Emissions: Monitoring of Pollution

Acronym	Definition
TIR	Thermal Infrared
TROPOMI	Tropospheric Monitoring Instrument
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
UVS	UV-Visible Spectrometer
vis	Visible
WCA	Weather, Climate and Air quality
XCH_4	Column-averaged methane
XCO	Column-averaged carbon monoxide
XCO_2	Column-averaged carbon dioxide

Appendix B REFERENCES

TABLE B-1 – REFERENCES

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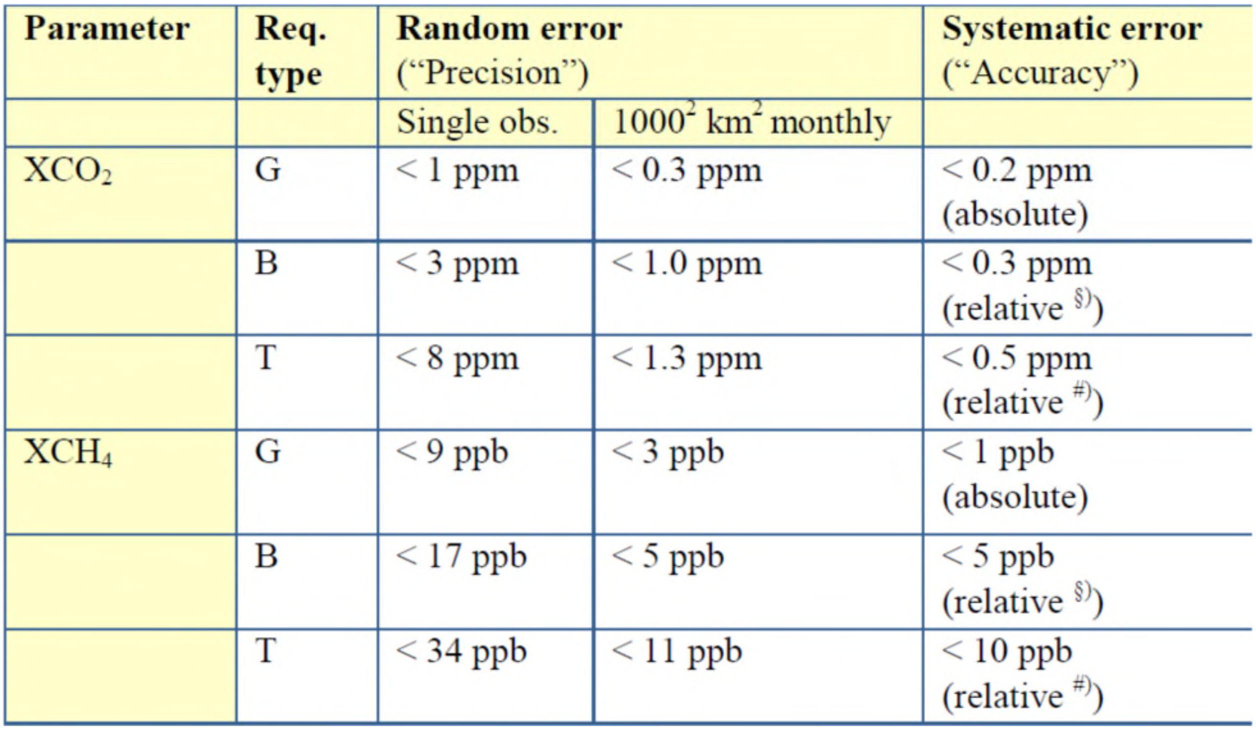
Appendix C SUPPLEMENTARY INFORMATION FOR OBSERVING REQUIREMENTS

The 2015 Update of Actions in the Response of the Committee on Earth Observation Satellites (CEOS) to the Global Climate Observing System Implementation Plan 2010 (GCOS IP-10), specifies requirements for random and systematic errors for XCO_2 and XCH_4. These requirements were specified as guidelines for retrievals of the species from existing international missions to be of sufficient quality as Essential Climate Variables (ECVs); however, these internationally-recognized requirements are also useful in guiding the requirements for future missions and have been considered for AIM-North.



Parameter	**Req. type**	**Random error** ("Precision")		**Systematic error** ("Accuracy")
		Single obs.	1000^2 km^2 monthly	
XCO_2	G	< 1 ppm	< 0.3 ppm	< 0.2 ppm (absolute)
	B	< 3 ppm	< 1.0 ppm	< 0.3 ppm (relative §))
	T	< 8 ppm	< 1.3 ppm	< 0.5 ppm (relative #))
XCH_4	G	< 9 ppb	< 3 ppb	< 1 ppb (absolute)
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative §))
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative #))

Abbreviations: G=Goal, B=Breakthrough, T=Threshold

§) Required systematic error after bias correction, where only the application of a constant offset / scaling factor, independent of time and location is permitted for bias correction

#) Required systematic error after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor.

The Level 2 XCO_2 requirements for the Copernicus Sentinel 7 candidate “CO_2 Monitoring Mission” from the ESA Mission Requirements Document (MRD, v1.0, issued 2018-04-18) are provided below. These requirements have also been considered in derivation of the AIM-North requirements.

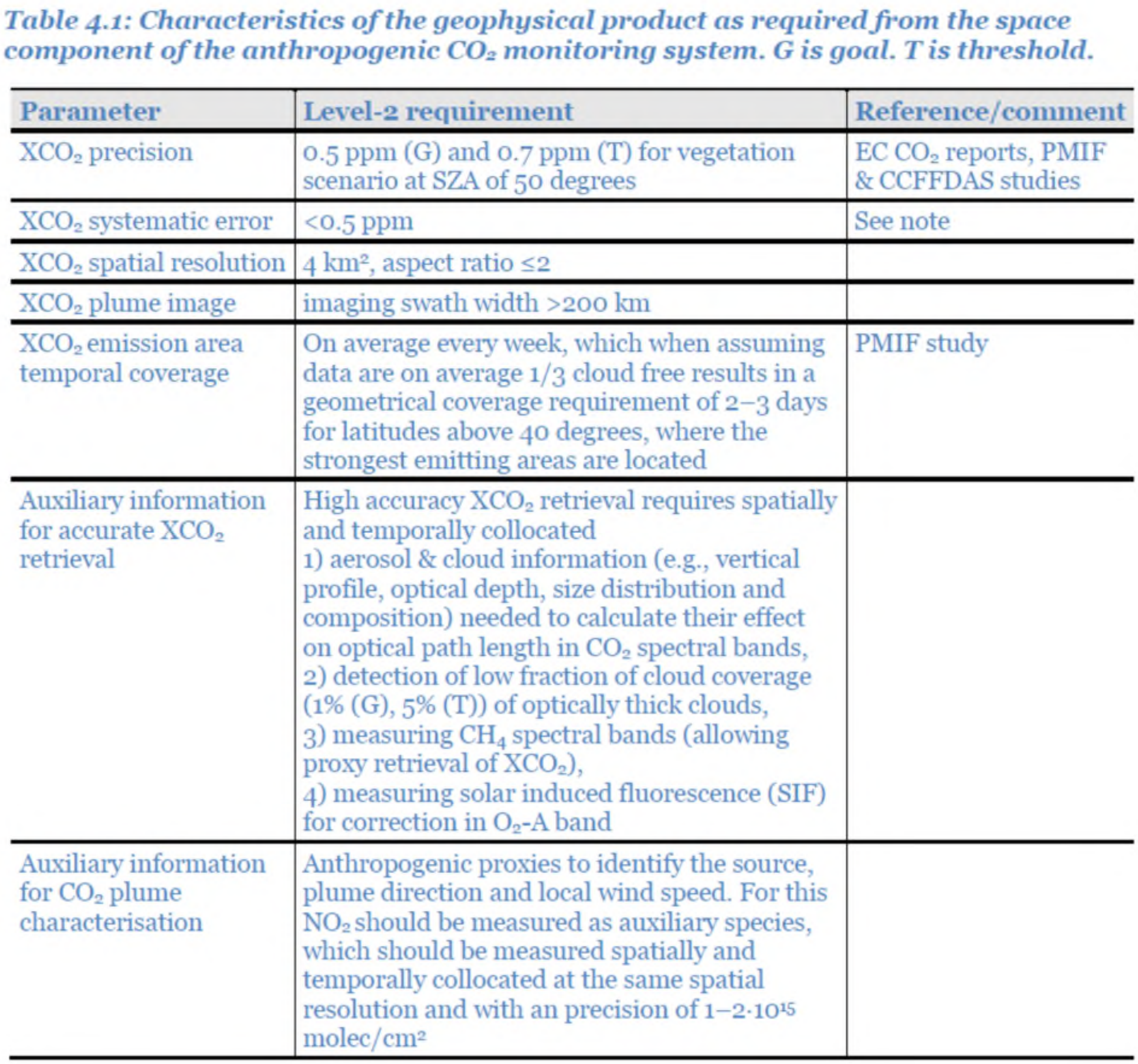


Table 4.1: Characteristics of the geophysical product as required from the space component of the anthropogenic CO_2 monitoring system. G is goal. T is threshold.

Parameter	**Level-2 requirement**	**Reference/comment**
XCO_2 precision	0.5 ppm (G) and 0.7 ppm (T) for vegetation scenario at SZA of 50 degrees	EC CO_2 reports, PMIF & CCFFDAS studies
XCO_2 systematic error	<0.5 ppm	See note
XCO_2 spatial resolution	4 km², aspect ratio ≤2	
XCO_2 plume image	imaging swath width >200 km	
XCO_2 emission area temporal coverage	On average every week, which when assuming data are on average 1/3 cloud free results in a geometrical coverage requirement of 2–3 days for latitudes above 40 degrees, where the strongest emitting areas are located	PMIF study
Auxiliary information for accurate XCO_2 retrieval	High accuracy XCO_2 retrieval requires spatially and temporally collocated 1) aerosol & cloud information (e.g., vertical profile, optical depth, size distribution and composition) needed to calculate their effect on optical path length in CO_2 spectral bands, 2) detection of low fraction of cloud coverage (1% (G), 5% (T)) of optically thick clouds, 3) measuring CH_4 spectral bands (allowing proxy retrieval of XCO_2), 4) measuring solar induced fluorescence (SIF) for correction in O_2-A band	
Auxiliary information for CO_2 plume characterisation	Anthropogenic proxies to identify the source, plume direction and local wind speed. For this NO_2 should be measured as auxiliary species, which should be measured spatially and temporally collocated at the same spatial resolution and with an precision of $1–2{\cdot}10^{15}$ molec/cm²	

Note: XCO_2 systematic error is assumed to be after bias correction.