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Small Satellites Potential for Greenhouse Gases Monitoring

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Abstract

Carbon dioxide (CO2) levels and other greenhouse gases (GHG) in the atmosphere are rising to new records. To address this climate emergency, recovery plans need to trigger long-term systemic shifts that will change the trajectory of CO2 levels in the atmosphere. The efficiency improvement of the emissions monitoring can be driven by advancement in data collection processes and diversification of resources and monitoring tools. Today, data about GHG and CO2 emissions is collected using the big satellite capabilities and on-Earth sensors networks. Small satellites can improve the global emission mapping coverage and image update rates, which will improve the understanding of the CO2 and GHG dynamics. Today there are several small satellite missions carrying hyperspectral Short-Wave Infrared Imaging (SWIR) imaging instrumentation, providing gas emissions data. However, alternative missions, instrumentation combinations and satellite architectures are possible. This paper aims to analyse the requirements for the emission sensing instrumentation for the installation on the small satellite platform. It is reviewed together with small satellite platform architecture and the use cases. From that, the rational mission profile for small satellite utilisation for the monitoring is derived

Keywords: small satellites, CubeSat, GHG monitoring, Earth Observation, Satellite constellation

1. Introduction

Atmospheric concentrations of greenhouse gases (GHG) have risen sharply in recent decades as a result of human activity [1]. An increase in greenhouse gases in the atmosphere accelerates climate change. CO2 and CH4 are the two most prevalent greenhouse gases, monitoring of which is necessary to effectively reduce the impact of climate change. Knowledge of the magnitude and spatial and temporal variability of CO2 emissions at the regional scale is also critical in unravelling the natural sources and sinks of the carbon cycle.

The European Commission has adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels [2]. This highly depends on the amount of quality of data available to provide valuable analytics on carbon footprint. The current GHG measurements methods are not able to satisfy the emerging urgent need for neutral and reliable data. There is and will be massive political pressure to provide favourable measurements based on more precise and neutral approaches.

There are several approaches to gather the GHG emissions data. In situ measurements of CO2 are possible from surface networks, aircraft sensors, and mobile platforms. Those measurements have been used to quantify the emissions from different sources. Emissions observations of the Earth’s surface provide information on land cover, forest biomass, fires, biological productivity, cities and power plants and transportation, and human energy consumption. It can be used to estimate several types of emissions and their spatial distribution. Such networks are deployed mostly in developed regions and point sources only. The cost for maintaining a given network to conduct regular measurement campaigns around a given source limits their deployment.

Satellites are also capable of producing high-resolution global observations of Earth's surface and atmosphere including information about greenhouse gas emissions. Satellites have the unique ability to provide global coverage of the Earth's surface and atmospheric composition that is not possible using ground-based monitoring techniques as well as the activity data for "bottom-up" calculations of greenhouse gas emissions and input for emissions estimates validation. Depending on the CO2 and CH4 bands and application the resolution can achieve up to 30m [3]. The big disadvantage of this approach is that the observations are dependent on the cloud conditions [4].

Current space-based observations are mostly done using large satellite platforms enabling the installation of large instruments. As a result, up to date, there are only 5 satellites generating the necessary emissions data [5]. This approach limits the revisit rate of the measurements over the area of interest and as a result, the scope of applications. Taking the dependency on the clouds, it might take significant time to acquire the required data. Moreover, certain industries require more frequent data samples. Small satellite constellations for GHG monitoring can address this issue thus enabling new applications, diversifying the data streams, and complementing existing methods and increase the mission reliability. There are several projects addressing the topic of small satellite constellation design for GHG monitoring, however, those projects target specific market segments and mostly focus on CH4 emissions monitoring [6].

This paper addresses the topic of satellite constellation design to monitor GHG emissions. Including the limitations and capabilities of small satellite platforms, requirements for GHG emissions data from different industries and regions the mission concept is proposed. The mission objective is to enable GHG monitoring in the shortwave infrared region to detect the emission levels of CH4 and CO2. The approach description is visualized in Figure 1.

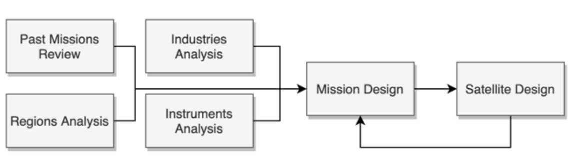

Fig. 1. Research approach

Analysis of imagery parameters such as spatial and spectral resolution, the swath, and data volumes that small satellites can enable is performed to feed the system engineering problem. The analysis of existing missions and available instruments has outlined the current state-of-the-art technology.

2. Literature review

This section outlines the comprehensive literature review and is split between several sections. First, advantages of satellite-based measurements are outlined. Then satellite missions are reviewed together with on board instruments. Later the industries producing the GHG emissions are covered to get an overview of the requirements posted by the industry. Later the limitations of existing approaches are reviewed, and data processing techniques are analysed.

3.1 Advantage of satellite GHG observations

Compared to ground-based measurements, the key advantage of satellite-based measurements is their ability to provide global coverage. Satellite measurements derive atmospheric concentrations of gases using the properties of gases to absorb electromagnetic radiation at specific wavelengths. These instruments primarily use solar radiation that is reflected off the Earth's surface, but some can use radiation emitted by the Earth or from lasers onboard the satellite. The most comfortable orbit for observation based on the historical data - around 500-700 km altitude orbit that pass close to the Earth's poles [7].

Based on previous missions, it can be inferred that only reasonable metrics can be derived from instruments on satellites. No single instrument or collection of satellites can measure every GHG emission, everywhere, all the time. Small but persistent sources, such as those from the nearly infinite gas pipeline connections, can be very difficult to decipher from space. Nevertheless, certain geographies and climatic conditions can inhibit good coverage depending on the satellite sensor system. An example of this might be sensing offshore where poor reflective water surfaces impair satellite measurements, or at times during the day when flames from flares are masked by sunlight. The main goal of this research is to determine the use case for the small satellite based GHG observations.

3.2 Satellites mission review

While ground-based measurement of CO2 and CH4 began in the 1950s, the first satellite mission to measure these gases was ESA's EnviSat mission which hosted the SCIAMACHY instrument [8]. This mission was launched in 2002, and concluded in 2012, and was the first of three prominent missions that focussed on the measurement of atmospheric CO2 and CH4. EnviSat (using the SCIAMACHY instrument) was followed by

GOSAT in 2009 (JAXA) and OCO-2 in 2014 (NASA) [9]. GOSAT received a successor mission GOSAT-2, launched in 2018, with a proposed third successor GOSAT-GW proposed for launch in 2023 [10]. OCO-2 continues to operate approximately seven years after launch, with a successor mission OCO-3 installed aboard the ISS in 2019 [11]. Several Chinese satellites have been launched to pursue the same goal: TanSat, FY-3D and GMI [12]. Most of these satellites were funded by agencies and provide public data on the emissions. As these missions use single satellite setup, the revisit rate is around 3 days and payload mass is more than 100kg.

With the development of small satellites and particularly the advent of the CubeSat architecture, there have been multiple small satellite missions to address the same topic. Meznsat launched in 2020 and GHGSat launched 2016 [13, 14]. There are several more missions planned fort he GHGSat to expand the CH4 measurement update rate to enable fast leakages detections for oil and gas industry.

Of particular note is MERLIN, a joint Franco-German mission for LIDAR observation of atmospheric methane columns [15]. This is the first instance of satellite detection of atmospheric greenhouse gases via LIDAR instead of spectroscopy. Previous LIDAR missions include CALIPSO (2004) which focussed only on the measurement of aerosol concentration and distribution within the atmosphere and ICESat (2003) which measured sheet ice thickness and aerosol height within the atmosphere [16].

MicroCarb is a French space agency (CNES) mission that will observe column CO2 concentrations with a footprint size of 5 x 6 km2 and a narrow swath [17]. The launch is planned for 2022. The gathered information will be used to study climatology and carbon cycle. CarbonSat satellite would combine a small footprint size (2 x 2 km2) with a wide swath (500 km) to provide high-resolution measurements of column CO2 and CH4 with global coverage every 5-6 days38,39. CarbonSat was a candidate mission that was not selected for Earth Explorer 8, but the design may be considered for other missions [18]. The scientific goal of the project is to improve the understanding of the global CO2 distribution and its contribution to climate change, as well as to monitor the CO2 variation on seasonal time scales. ASCENDS is a NASA mission under consideration to transmit and detect pulsed lasers to measure column CO2 concentrations. The launch is not expected until at least 2023 [19]. Received information will permit weekly mapping of CO2 sources and sinks at 1 deg longitude and latitude which will have help in predicting future CO2 concentrations, monitoring CO2 sequestration efforts, and supporting future carbon and energy policies. The satellite initiative Carbon Mapper will use CO2 detection technology with multiple high-resolution imagers and will be built and flown by Planet. The CO2M constellation will consist of two spacecrafts and will track the greenhouse gas across the globe with resolution of 2km^2 [20]. It will help nations assess the scale of their emissions as they must compile CO2 inventories according to the Paris climate accord. Envisat is a large inactive Earth-observing satellite operated by the European Space Agency with an imaging spectrometer on board. The purpose of the satellite was get the information about various trace gases in the troposphere and stratosphere in order to understand their effects on variety of issues such as Antarctic ozone hole, tropospheric pollution arising from industrial activity and biomass burning, troposphere-stratosphere exchange, and different events such as volcanic eruptions, solar proton events, nd related regional and global phenomena.

As it can be observed, in upcoming years there are more missions planned for the CO2 and CH4 measurements. Most of small satellite missions are targeting specific field and adjust the instrumentation for the detection of specific band of GHG emission, while planned large satellite are targeting higher resolutions, larger swath, and broader application ranges, which is beneficial for science and research.

3.3 Review of measurement approaches

Most of the currently operating, planned, and proposed instruments for passive CO2 observations from space measure the reflected shortwave infrared (SWIR) solar radiation in several spectral windows. Satellite-based spectrometers use several wavelengths to measure CO2 and CH4 according to their absorption spectra. They are covering the oxygen A (O2 A) band near 750 nm as well as the weak and strong CO2 absorption bands near 1600 and 2000 nm, respectively [21]. Satellites that observe shorter near-infrared wavelengths are sensitive to CO2 concentrations near the surface and, therefore, these have proved most useful for investigating surface emissions [22]. Additionally, it is also possible to gather data at higher altitudes (6 to 11 km) above the Earth's surface using longer thermal infrared wavelengths (e.g. AIRS and IASI satellites).

Other instruments measure within narrow bands of light, like LIDAR—light detection and ranging sensors—that use a laser to detect emissions. Meanwhile, other hyper-spectral instruments measure across wide-ranging wavelengths and produce fine discrimination between different emissions targets [23].

Microwave radiometer instruments are designed to operate continuously and autonomously often in combination with other atmospheric remote sensors like for example cloud radars and lidars. They allow the derivation of important meteorological quantities such as vertical temperature and humidity profiles, columnar water vapor quantity, and columnar liquid water path with a high temporal resolution on the order of minutes to seconds under nearly all-weather conditions [24].

Microwave radiometers are also used for remote sensing of Earth's ocean and land surfaces, to derive ocean temperature, wind speed, ice characteristics, and soil and vegetation properties.

Another commonly used instrumentation method is Visible/IR imaging multispectral radiometers. They are used to image the Earth's atmosphere and surface, providing accurate spectral information at spatial resolutions of order 100m up to several km, with a swath width generally in the range of several hundred to a few thousand km [25]. Measurements from these multispectral radiometers operating in IR and visible bands are an important source of data on processes in the biosphere, providing information on global vegetation and its variations on sub-seasonal scales. This allows monitoring of natural, anthropogenic, and climate-induced effects on land ecosystems. These instruments also have the ability to make measurements of cloud cover and cloud top temperatures.

Remote sensing data from instruments such as the Advanced Very High-Resolution Radiometer (AVHRR) can assist the process of CO2 monitoring by providing the ability to monitor CO2 concentrations on global scales for longer periods these counties need to examine [26]. These radiometers work hand-in-hand with V/IR radiometers for monitoring land surfaces and clouds. In unison provide the advantage of being able to support weather forecasting and climate monitoring. In the past, several thermal enhanced infrared sounders such as AIRS, TES, IASI, IMG, and CRIS have been launched to monitor the atmospheric state for detailed studies on weather prediction and climate change.

Satellites operate in different observation modes. Global-scanning satellites are almost always surveying. Others are tasked to "point and shoot" at specified targets [27]. Satellite systems that can do both must navigate trade-offs as it focuses on the timely deployment of each instrument. For example, one might choose to sacrifice coverage of a whole region to increase observations over a target known to be a large emitter. However, baseline data on CO2 emissions trends from a sample of cities and power plants can be often gathered.

3.4 Analysis of industries

To analyse greenhouse gas emissions stakeholders, we need to look for the contribution of different industries which are responsible for the rise of GHG levels and define properties for the measurements that can quantity the emissions in specific field [28].

CO2 emission in the energy sector is mostly due to electricity, transportation, and heat. The energy sector alone contributes one-third of the total carbon emission around the world. The transportation sector alone contributes 16% of carbon emissions in total. Whereas the energy used in industry for the manufacturing of various metals, machinery, food processes, and materials contributes 24% of total carbon emission. Energy used in residential and commercial buildings also contributes to carbon emissions.

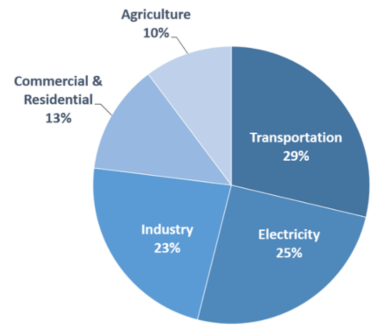

Fig. 2. Total CO2 Emissions distribution in 2019

Another large source of carbon emission comes from agricultural, forestry, and land use. These contribute a total of 18% of carbon emissions. The food system as a whole including refrigeration, transportation, and food processing contributes almost one-quarter of total carbon emission. Livestock and manure, crop burning, and deforestation contribute 16% of total GHG emissions.

The conversion process of cement, chemicals, and petrochemicals produce carbon dioxide as a by-product. And these industrial processes contribute 5% of total CO2 emission. Organic matters and residues from animals, plants, and humans can collect in wastewater systems and due to the decomposition of these materials, they contribute to GHG emission.

Waste is the fourth largest source sector of emissions, accounting for 3% of total greenhouse gas emissions in 2017. Food wastes: About 6%-8% of all human-caused greenhouse gas emissions could be reduced if we stop wasting food. In the US alone, the production of lost or wasted food generates the equivalent of 32.6 million cars' worth of greenhouse gas emissions. Globally, trash released nearly 800 million metric tons (882 million tons) of CO2 equivalent in 2010 — about 11 % of all methane generated by humans. The United States had the highest total quantity of methane emissions from landfills in 2010: almost 130 million metric tons (143 million tons) of CO2 equivalent. China was a distant second, with 47 million (52 million), then Mexico, Russia, Turkey, Indonesia, Canada, the United Kingdom, Brazil, and India, according to the Global Methane Initiative, an international partnership of government and private groups working to reduce methane emissions.

From the analysis of industries and according to references, emission of carbon dioxide from electricity production and industrial productions is contributing more than 30% of the total emission in the energy sector whereas emission from the transportation is also more than 20% of the energy sector. so we can focus on electricity, industrial processes, and transportation industries to monitor emissions from different cities so that we can cover major parts of the emissions.

3.5 Analysis of regions

Different regions emit different amounts of carbon dioxide [29]. According to references, most emissions occur in Asian regions, particularly China accounted for the most carbon emissions, whereas Europe and the US contribute one-third of total carbon emission. The Asia-Pacific region emits 31% of carbon dioxide whereas North America emits 18% of carbon dioxide. South and Central America emit 3.2% of Carbon dioxide from the world's total emission. CO2 emission from Europe is 17% and from Africa, it is 3.5% of the world's total carbon emission. Emission from the Middle East is 5%.

The top 5 countries in the world which contribute to CO2 emission are China, the United States, India, Russia, and Japan. As mentioned earlier China contributes the most CO2 emission in the world. The primary source of CO2 emission in China is the burning of fossil fuels notably from coal burning. The largest sources of CO2 emissions in the U.S. come from transportation, industry, and power generation in 2020. India is the 3rd largest country to produce carbon dioxide emissions, it produces 2.65 billion metric tons in 2018. Russia is the fourth largest country to produce 1.71 billion metric tons of CO2 in 2018. Since Russia has the largest natural gas resources in the world, it is the primary source of energy and power generation in the country and hence it is also the primary source of CO2 emission in Russia. Japan is the 5th largest CO2 emitter in the world, it produces 1.16 billion metric tons of CO2, and its primary source is natural gas and coal burning to generate energy for various industries and the population.

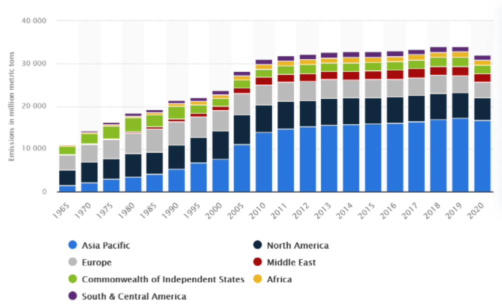

Fig. 3. Total CO2 emissions distribution per region

Out of comprehensive analysis of industries it was defined that analysis of emissions from cities and local points could bring the value in the general assessment of GHGs concentrations observations and can be accomplished by a small satellite mission.

3. Requirement's definition

Some major cities in the world emit a particular amount of carbon dioxide per year. The top 25 cities accounted for 50% of the total urbane GHG emission. The Table 1 shows the cities which emit the most carbon dioxide in their region.

Table 1. Cities analysis with highest footprint

City	Region	CO2 Mt.	Reason
Seoul	Asia	276.1	Industrial processes
Guangzhou	Asia	272.0	Industrial processes, transport
New York	North America	233.5	Industrial processes, transport.
Hong Kong	Asia	208.5	Electricity generation, transportation, & industrial processes
Los Angeles	North America	196.4	Industrial & transport
Shanghai	Asia	181.0	Power plants & transport
Singapore	Asia	161.1	Manufacturing industries
Chicago	North America	152.9	Transport & residential buildings
Tokyo Area	Asia	132.8	Transport
Riyadh	Middle East	118.8	Industrial processes

From the above table, there are so many cities in Asia that have higher carbon emissions. Also, we can see from the above table that these cities have higher carbon footprints due to either transportation or industrial usage. Monitoring global carbon emission we can track some cities which are having higher carbon footprints in their domestic region.

Because of the narrow ground swath and long revisit times, single satellites in LEO are not optimal for monitoring anthropogenic emissions from states in the face of a natural background that is highly variable in space and time. This is a primary reason for a constellation development so that each point of interest can be scanned at least 18 times a day and at most 35 times a day. Observation of megacities may improve with higher resolution measurements, targeting capabilities, and broader swath.

The aim of this satellite mission is to conduct observations of atmospheric carbon dioxide on an intra-city scale. As a result, we require a high resolution and small swath. Additionally, mission requires higher revisit rates to better understand how carbon dioxide sources vary over different timescales and to understand where efforts should be focussed to mitigate excessive concentrations of CO2 within the urban atmosphere. The following mission parameters were used as a guideline for our mission:

- Footprint size: 3.5 km2
- Observation frequency: 3 Hz
- Orbital period of 1 satellite: 90-93 minutes
- Viewpoint: Nadir
- Spectral channels: Weak and Strong CO2 bands (1.61 and 2.06 um)
- Swath - 80 x 80 km

With such parameters it would be possible to target areas of local hot-spot emissions (such as volcanoes) and site of interest such as instrumented field stations. The ability to image features on this scale is crucial to resolving point CO2 sources and gives a positive indication that the imagery can eventually be combined with observations from ground-based monitoring stations.

4. Instruments analysis

The primary gases which will be monitored as part of this mission are CO2 and CH4. The most frequently employed and most successful technique for determining atmospheric concentrations of these gases is spectroscopy which has been used across EnviSat, GOSAT, and both OCO-2 and OCO-3. Spectroscopy relies on detecting reflected sunlight from the Earth's surface which has subsequently passed through the atmosphere. Certain wavelengths of light are absorbed depending on the composition of the atmosphere, and an Earth-observing satellite is then able to measure which of these wavelengths are absent and thus determine the concentration of particular components within the atmosphere. This mission is primarily interested in carrying out measurements at the following wavelengths for CO2: the weak CO2 band at 1.58 µm, the strong CO2 band at 2.06 µm, and the O2 band at 0.76 µm. For measuring the concentration of atmospheric CH4, we require the ability to take measurements of the CH4 absorption wavelengths in the vicinity of 1.67 µm [30].

Detecting the 1.58 µm weak CO2 band is the main target since there are few other gas absorption bands in this area, and it is much easier to separate the CO2 band from neighboring bands. The spectrometer is preferred to have an InGaAs detector because it has a better performance in the SWIR bands since CO2 has absorption bands in the NIR range.

Spectroscopy relies on the presence of reflected sunlight and can only be used while the satellite passes over illuminated areas of the planet. Additionally, spectroscopy is more vulnerable to errors introduced by uncertainties in path length, so data from remote sensing spectroscopy missions must be processed using a coherent and comprehensive validation approach. Alternatively, the spectrometer must be paired with a precision altimetry instrument.

In recent years LIDAR has emerged as a potential alternative to spectroscopy [31] and was to form the basis of NASA's ASCENDS mission following successful in-atmosphere testing [32]. LIDAR is a remote sensing method that uses pulses of laser light in conjunction with a high-precision GPS unit to measure variable distances. In order to detect atmospheric CO2, the laser can be tuned to the absorption wavelengths of CO2, and by aiming at a hard target and measuring the difference between the transmitted and reflected signals the volume of CO2 in the atmosphere can be calculated. As an active remote sensing technique, LIDAR has a significant advantage over SWIR spectroscopy in that it does not rely on reflected sunlight and can therefore operate at night, easing the restrictions on orbital selection. Additionally, it is easier to determine the path length for a laser pulse by simply timing the duration between transmission and reflection. However, LIDAR instrumentation is at a lower technology readiness level than spectroscopy and carries penalties in both size and mass of available instrumentation.

The selection of instrumentation for this mission is tightly constrained. The finalized design of the constellation satellites is subject to a volumetric constraint and must be able to be housed within a small satellite no larger than 12U therefore minimizing the volume of the instruments within the satellite is of paramount importance. In order to ensure that the overall cost of the constellation is not prohibitively expensive, instruments that are commercially available will be selected as a matter of preference.

Since the aim here is not to monitor and produce general full imagery of arbitrary areas around the globe like other CO2 detecting satellites, but to produce highly targeted readings on areas (specific areas based on the urgent need at a certain time), where the readings might be needed in a high rate, or high fidelity for a certain application, the main instrument carried on each satellite in the constellation will be a point spectrometer (one pixel). However, proper coordination of multiple point spectrometers in the constellation will yield equally valuable data for the specific purpose of this mission. To achieve the goal of this mission, specific targets on the ground have to be monitored by the different satellites in the constellation at a specified rate to ensure the coverage is sufficient to produce workable data and readings for CO2 and CH4 emissions.

The table in Appendix A provides a comparative analysis of the instrumentation flown on previous comparable missions, and provides details of physical parameters of the instrumentation to illustrate the difference in form factor between our proposal and previous GHG monitoring missions. Where details are unavailable for a particular instrument, information for comparable instruments that were flown on the same mission has been provided as a reference.

Earth-observing satellite missions can be limited by atmospheric and meteorological conditions. To mitigate the effect that this has on achieving mission success, the spectrometer aboard the satellite can be accompanied by a Cloud and Aerosol Imager which allowed for the detection of atmospheric conditions from accurately measuring the concentration of GHGs, allowing for the measurements to be corrected [33].

As such, satellites within the constellation will carry a secondary instrument. This will be a visible range true-color RGB camera for cloud detection and geolocation. The RGB camera will have a larger footprint than the spectrometer to ensure proper geolocation and target acquisition. Both instruments will be adjusted to ensure the point of detection on the spectrometer is known relative to the RGB camera. That is done to ensure proper cloud detection and more accurate geolocation.

To properly choose the instrument for this mission, we had to look at a sequence of requirements and their parents in order to reach a design that satisfies both the mission requirements and the restrictions presented by the limitations of the satellite design. The starting requirement is to obtain point readings for CO2 emissions at a relatively high rate for a specific location. For that, the spectrometer should be miniature (around 1U) and with a spectral band that covers the CO2 absorption bands. Detecting the 1.58 µm weak band is the main target since there are few other gas absorption bands in this area and it would be much easier to separate the CO2 band from neighboring bands.

5. Instruments Selection

Two potential instruments are discussed: they both have been flight-proven on previous small satellite GHG observation missions. The first one is the Argus 2000 by Thoth, and the second is the NanoQuest mini spectrometer by OceanInsight. These instruments were chosen based on their capability to detect the CO2 bands with high spectral efficiency, as well as their compact size and low power consumption.

The Argus 2000 [34, 35] is a miniature passive grating spectrometer produced by Thoth technologies. It works in the short wave infra-red band 1000nm – 1650nm. It has a size of around 4.5 x 8 x 8 cm which makes it fit in a 1U of the satellite. The resolution is 6 nm making it very efficient for detecting CO2 absorption bands, as has been proved by multiple satellite missions that used the same device (or its predecessor the Argus 1000) in their missions like CanX2, Meznsat, DMsat, and SathyambaSat. It has 100 spectral channels and is equipped with an InGaAs detector with the field of view of 0.15°. The table below provides the main features and specifications of the Argus 2000

The NanoQuest [36] is a miniature MEMS-based grating spectrometer with an 8 or 16 nm spectral resolution. The device is not equipped with an installed lens but with a fiber optics tube and a feed. However, OceanInsight offer the possibility of customizing the instrument for the mission by producing a lens with a 0.20 degree field of view and integrating it with the spectrometer. The device has a spectral range of 1350 – 2500 nm making it highly specific for both CO2 bands, allowing detection at the 1580 nm band like the Argus 2000 as well as the 2060 nm band. This range puts these bands in the high spectral efficiency region of the spectrometer making the reading more accurate. It also separates the CO2 bands from other bands in the spectrum which will improve the quality of the detection. The NanoQuest offers a higher SNR than the Argus 2000 and has a smaller size. However, at time of publication the NanoQuest has not been flight proven.

Fig. 4. Selected instruments for the mission

To satisfy the requirements of this mission, we need the instrument to be compact, efficient, and with low power consumption, which is where the NanoQuest has an advantage over the Argus 2000. That's why we will choose the NanoQuest as our preferred instrument, and the Argus 2000 as the alternative solution. It is important to note that both instruments require the satellite to be pointing to Nadir while the reading is taken. That is to get the minimal path through the atmosphere and to know the reflectance angle. For the second instrument of this mission, we will use an RGB camera for cloud detection and geolocation. The camera will be the Raspberry Pi High-Quality camera [37]. It has a 12.3-megapixel Sony IMX477 sensor providing a 7.9 mm diagonal image size. The lens used will be 50 mm.

5. Mission design

This section is dedicated to the mission requirements definition, design and analysis including constellation design and revisit rates estimation.

5.1 Mission analysis

The mission objective is to provide GHG monitoring in the shortwave infrared region to detect the emission levels of CH4 and CO2.

Since global coverage is required for CO2 and CH4 emissions, a CubeSat constellation of at least 4 satellites is selected primarily in the circular orbits. The emission of CO2 needs to be constantly measured which calls for a satellite constellation to avoid latency while maintaining continuous coverage of areas of interest. The satellite configuration will follow the Walker Delta Pattern- circular orbits with set altitude and inclination for optimal coverage of land area which is the focus of observations to be made based on the literature review to observe mainly industrial areas. Aiming for 5 years maximum lifetime for the constellation to generate enough data, the altitude is fixed initially set at 700 km and mission analysis is done.

The critical outputs of the tests are the final orbital parameters and the exact number of satellites required to meet the needs of the mission. With a walker constellation of 4 satellites at an altitude of 700km circular polar orbit with e=0, i=90 degree analysis is done with a certain point of interest cities which is an attractive target for CO2 and CH4 emissions with maximum populated regions. The 4 satellites are in 4 different orbital planes with RAAN (degrees): 0, 90, 180, -90 (i.e., 270).

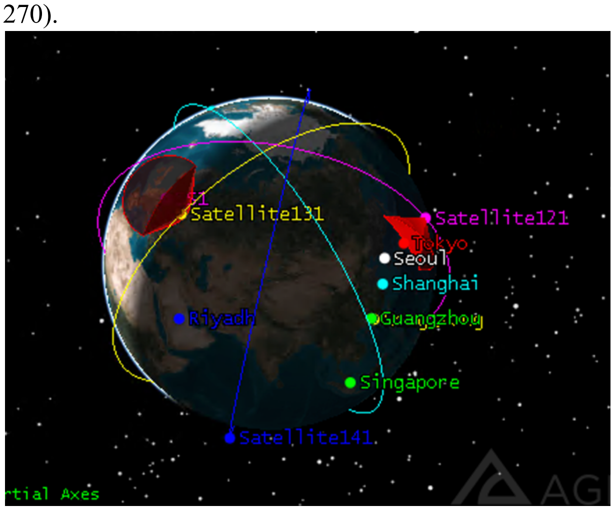

Fig. 5. Constellation design

5.2 Revisit rate analysis

Revisit requires a very accurate repeat of the ground trace. In the case of polar orbit or exceedingly willing low Earth orbit reconnaissance satellites, the sensor has to have the variable swath, to look longitudinally (east west, or sideways) at a target, similarly to direct overflight observation, searching Nadir. The polar constellation is more optimal and efficient as it presents the least value for every satellite. For a sure length of circular coverage, the minimal variety of satellites can acquire entire coverage in a revisit.

The popular Walker constellation notation of i:t/p/f is used, in which i is the inclination; t is the whole range of satellites; p is the range of similarly spaced planes, and f is the relative spacing among satellites in adjoining planes. The range of satellites in step with plane ‘s’ can ultimately be described by dividing the whole range of satellites similarly among the range of planes. The longitude of passes of satellites in more than one plane may be calculated through thinking about the angular separation in RAAN from a reference satellite tv for pc and the relative spacing factor ‘f’ among satellites in every plane. The insurance performances in phrases of most revisit time through Walker, 1 day, 1⁄2 day, and almost 1/3 day frequency revisit may be performed for the carrier region with increasing satellites. The motive for the excessive range of satellites is that each node for sun-synchronous orbits and better inclination orbits typically has an extended revisit time in assessment to decrease inclination orbits. The range of satellites required to offer non-stop international insurance is consequently very excessive. Even with a forty-five satellites constellation, the shortest revisit period is around 3.84 hours.

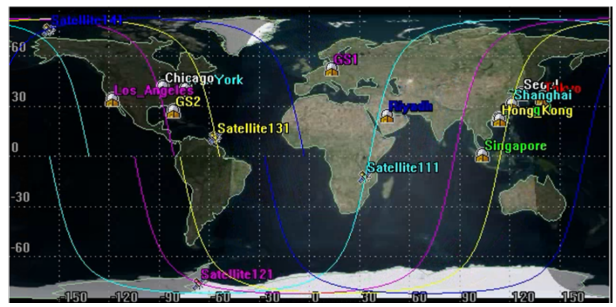

Fig. 6. Constellation coverage overview

Table 2. Cities revisit rates analysis

City	Rev.	Min s.	Max s.	Mean s.	Std. Dev.s.
Seoul	25	365.8	11455.7	2999.3	2821
New York	23	465.5	11509.	3066.4	2847.6
Shangh.	22	167.4	11872	3518	3980.6
Tokyo	23	295.6	11672	2980.3	2915.6
Riyadh	18	6.4	12005.	3969.2	3765.1
Tehran	24	296.8	11599.9	2820.2	2787.7
Mosco	35	336.3	3317.4	1834	1095.9
London	30	818.1	4839	2267.4	1308.5
Benha	20	136.6	11855.	3869.5	4442.2
Cologne	31	804.7	4873.1	2201.8	1265.4
Delhi	22	73	11846	3528.6	3669.7

Ground Stations: TRS (), CLE (Clewiston), TOK (Tokyo), INU (Inuvik), FUC (Fucino), GRI (Grimstad), DUB (Dubai)

Table 3. Ground Station Analysis: Revisit/orbit

Ground Stations	Orbit 1	Orbit 2	Orbit 3	Orbit 4
CLE	5	6	6	5
FUC	8	7	6	7
TOK	7	7	5	7

GRI	11	10	10	11
DUB	6	5	7	5
INU	16	15	15	15
TRS	7	7	7	7

6. Spacecraft design

Most of the Satellites that historically have monitored greenhouse gases and CO2 are known for the fact that they have big dimensions due to hosting several different instruments. For the design of the spacecraft the dimensions were limiting factor. Thus, the base size of one satellite shall be coherent with 6U CubeSat with a maximum mass of 14 kg, from these at least 6 kg would be completely dedicated to the payload.

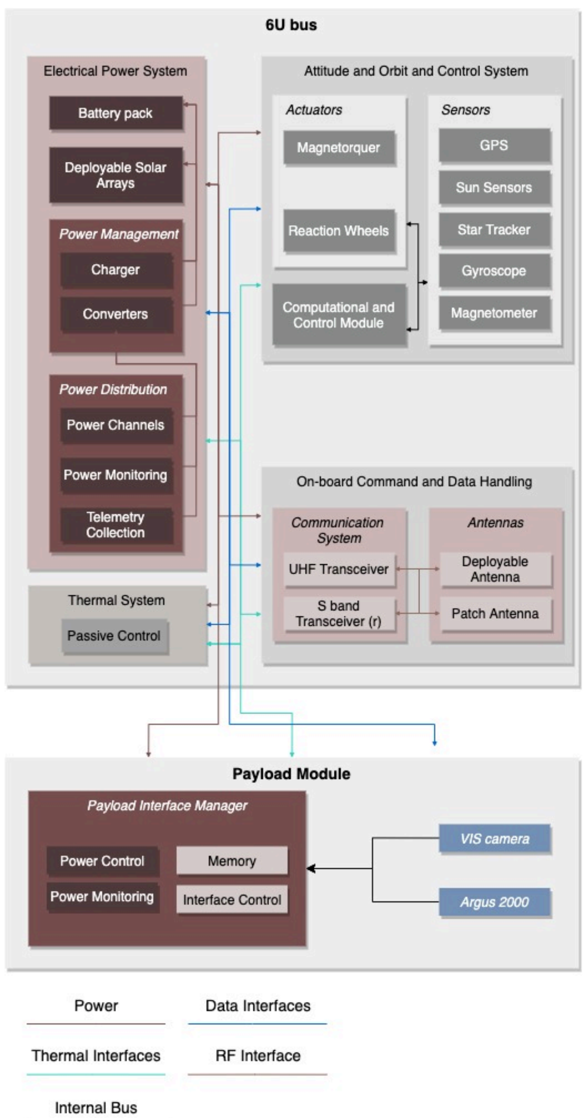

Fig. 7. Satellite architecture

The Table 4 outlines the main systems of the spacecraft.

Table 4. Satellite architecture review

Spacecraft Overview		
Size	Stowed	243 x 106 x 340 mm^3
	Deployed	512 x 415 x 373 mm^3
Mission	Reference Orbit	LEO: 700 km, SSO, 4 years
Mass	Satellite and payload	12 kg
Struct.	6U Structure	
Comms	Band	X-Band, 15.0 Mbps
	Frequency	DL: 8200 MHz
	Antenna	X-band patch
CDH	OBC	180 MHz, 3 GB redundant NAND Flash, 512 Kb of external SRAM
	PDH	1GB RAM, 1.2GHz processor speed, memory 32 GB
TMTC	Band	UHF, 9.6 kbps
	Antenna	Deployable UHF Antennas
AOCS	3-Axis Stabilized	
	Sensor	Sun Sensors, Star tracker, Gyro, GPS, Magnetometers
	Actuator	Magnetorquers, Reaction Wheels
	Determination accuracy	Up to 0.03 deg
	Slew rate	10 deg/sec
	Pointing accuracy	Up to 0.1 deg
	Regimes	Nadir, Sun, Zenith, Target
Therm.	Active	Temperature telemetry, heaters & radiators
Power system	Solar Panels	Deployable panels 72 W
	Batteries	142 Wh

The electrical power system of the spacecraft will include solar panels and a battery pack. These components will permit the normal functioning of all the systems of the satellite.

The spacecraft has an AOCS. The system is divided into sensors and actuators. The sensor subsystem will be composed of a startracker, 4 sun sensors, a GPS receiver with antenna, and magnetometers. For the actuators subsystem, the spacecraft will make use of 3 orthogonal reaction wheels which will assure attitude control. The star tracker works to determine the orientation parameters of the axes of its High-Qualitycoordinate system that is relative to the axes of the inertial system.

The communication systems of the spacecraft will consist of UHF transceiver and X band transmitter including antennas. X band will be used for the downlink of the received data that the spectrometer and camera will provide.

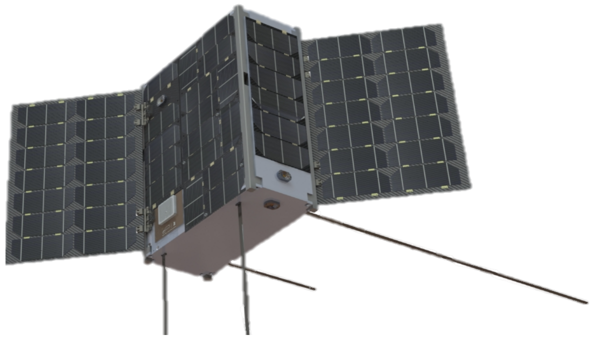

Fig. 8. Satellite 3D model

There is also the need for a thermal control system that assures the proper functionality of the satellite and the central computational and control module that includes the transceivers will be necessary as well for the mission. With that all the components of the satellite are detailed, the Table 5 shows a list of the power, link, and mass budget for the satellite.

7. Results and discussion

While satellite instrumentation has improved significantly and even CubeSats can produce precise measurements, the measurements taken can still be improved by pairing the satellite constellation with a ground based sensor network. This will be particularly necessary in order to determine GHG density within cities, where there are multiple sources across a small area and which may not be distinguishable solely by satellite. Current ground based atmospheric sensor monitoring initiatives include ICOS [Discussion 1] and GAW [Discussion 2] but these stations conduct observations at single points which are generally distant from urban centres. There may be a requirement for individual cities to implement monitoring networks of their own. Obviously, mechanisms to share and combine the data would need to be specified where they do not already exist.

If combining the results with ground based sensor data is impractical or impossible, then consideration should be given to other methods to improve resolution and precision of results. In particular, several efforts and challenges presently exist to incentivize creation of machine learning algorithms to improve the resolution of existing data products produced by, for example, the Copernicus programme [Discussion 3] [Discussion 4].

A long-term and high-quality record of essential climate variables is critical for monitoring and studying criticality related to the earth's climate change.

The data gathered by CO2 monitoring satellites remains of utmost importance to locations that are still experimental but are of growing interest to both technical staff and managers and decision-makers in the public sector. Its relevance and value for detailed interpretation and analysis have also taken higher scale importance with recent efforts for commercialization in the private aerospace sector. Local government planning, management, and operations provide fertile ground for new applications of remote sensing data and information. Since they are responsible for geographically small areas that often have high population densities, city and county governments generally require high-resolution spatial data for several purposes such as cadastral or mapping applications, identification of changes in land use, and maintenance of the transportation infrastructure.

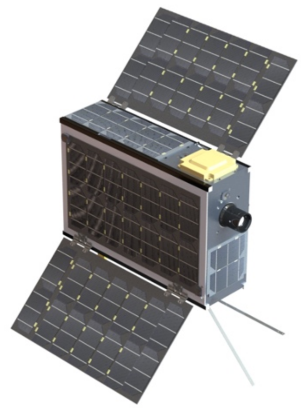

Fig. 9. Satellite 3D model

Previously, although local governments relied on aerial photography for high-resolution data in the past, some are finding that satellite remote sensing data are now available at similar levels of spatial resolution with broader spectral coverage. Many city and county governments already have in-house GIS capabilities; data from satellite remote sensing, like data from some forms of airborne remote sensing, can be used in conjunction with digital data available in existing GIS databases. The possibility of integrating remote sensing data into local GIS databases and using the databases in conjunction with locational GPS data has created opportunities for new types of information applications that were not possible using photographic remote sensing data alone, strengthening detailed analysis that could be performed.

In order to achieve this goal, it is necessary to have a continuity of the observations, which can only be assured when high-quality data collection continues without breach. Having data gaps from multi-instrument data recorded can lead to it being inappropriately interpreted, and the value of the satellite record nearly vanishes. Therefore, it still remains a critical step to mission milestone accomplishment.

Thus, the absolute calibration of each instrument data product and the inter-calibration of multiple pertinent sensors remains critical for success in nearly all objectives of satellite remote sensing. In addition to the calibration of direct observations, the traceability and consistency of the next generation of satellite products to the present-day instrumental suite remains the cornerstone for future analyses.

8. Conclusion

Current study proposes an alternative mission for GHG monitoring including a new instrumentation combination and satellite architecture. In the scope of this paper requirements for the emission sensing instrumentation for the installation on the small satellite platform were analysed. It was reviewed together with small satellite platform architecture, its limitations and the use cases. From that, the rational mission profile for small satellite utilisation for the monitoring was derived. The proposed mission concept addresses the topic of GHG emissions measurement of cities activities including transportation and industrial processes. The base of the mission is a 6U CubeSat with on board spectrometer and VIS camera. The satellite is equipped with on board systems allowing rapid manoeuvring between target points and detection of gases in selected regions.

Appendix A Comparison for different satellite instruments

Satellite	Instruments	Mass (kg)	Power (W)	Resolution	Swath (km, degrees)	Calibration method	Spectral Range (µm)	Sponsor Agency
ENVISAT	MWR	25	23	20 km	20, -	In Flight		ESA
	AATSR	101	100	0.5 km	500, -	In Flight		
	MIPAS	320	210	3 km	3 x 30 km	Pre Flight	4.5 - 14.6	
	MERIS			0.3 km	1150, -	Pre Flight	0.390 – 1.040	
	SCIAMACHY	198	122	2.5 arcsec	950	Pre Flight	2.40 to 17.00	
GOSAT	TANSO-FTS	329	400	10.5	160, 36.1	Irradiance: Solar, Deep space, Diode Laser, Black Body	0.01- 15	JAXA
	TANSO-CAI	42	83	1.5	750-100, 36.1 DEG		0.3 - 1.6	JAXA
GOSAT2	TANSO-FTS	329	400	10.5	160, 36.1 deg	Irradiance: Solar, Deep space, Diode Laser, Black Body	0.01- 15	JAXA
	TANSO-CAI	42	83	1.5	750-100, 36.1 DEG		0.3 - 1.6	JAXA
OCO-2	OCO-2	150	165	1.29 km (cross-track), 2.25 km (along-track)	Cross track 10	In flight	0.76, 1.61, 2.06	HSSS
OCO-3	OCO ISS							
GOSAT-3 (GOSAT-GW)	TANSO-FTS	329	400	10.5	160, 36.1 deg	Irradiance: Solar, Deep space, Diode Laser, Black Body	0.01- 15	JAXA
	TANSO-CAI	42	83	1.5	750-100, 36.1 DEG		0.3 - 1.6	JAXA

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