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Novel Mission Concept for global greenhouse gases emissions measurement using small satellite capabilities

E. Armandillo*[a], D. Stepanova [b], V. Lapkovsky [c]
[a]Eventech Ltd., Pulka iela 3, Riga, LV-1007, Latvia, [b]GOS (D), [c]RTU, Riga (Lv)

Abstract

Climate change is one of the biggest challenges of our generation. It is also recognized as one of the challenges where use of Earth Observations (EO) can make the most difference, as EO has the capability to capture environmental and socio-economic data over a range of spatial, spectral, and temporal resolutions. **This highly depends on the amount and quality of data available to provide valuable analytics on carbon and methane footprints.** However, **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.

The goal of **current** project is to establish a network of new data sources for GHG monitoring with high temporal and special resolution to expand the existing monitoring systems and enable new emissions monitoring applications to combat the climate crisis. This is achieved using a small satellite constellation carrying a set of novel instruments for active remote sensing and advanced fusion algorithms. Compared to existing solutions, proposed constellation will improve the temporal revisit over the globe while meeting the high accuracy and spatial resolution requirements. High revisit rate and global coverage will be enabled by 12 satellites on Low Earth Sun Synchronous Orbit. High sensitivity and resolution of 10x10m for 0.9 µm-to-1.7µm bands with 20 km swath will enable new precisions for monitoring of GHGs changing the way emissions are monitored and offset. System will offer single measurements of point sources enabling new applications. The gas loads information per specific area or region will allow development and industrial sites to plan and manage their greenhouse gas emissions, align with current guidance, policies, and trends related to climate change/global warming, calculation of carbon footprints, and the applications of offsets to reduce carbon footprints. Using novel observation technology, satellite constellation will be capable of attributing emissions directly to individual facilities. The emissions data will be later transformed into actionable insights with our in-house analytics, facilitating the optimization of their operations, reduce emissions and uphold environmental standards.

The measurement approach proposed by AIRMO project is powered by fusion of raw data from several instruments. It will enable high resolution emission data retrieval both in day and night while fitting in the small satellite form factor. Detecting weak CO2 and CH4 band is the main target since there are few other gas absorption bands in this area. The chosen observation technique, to be compatible with Small Sats approach, is the SWIR spectrometry performed with a high-resolution Grating-Spectrometer, supplemented by a VIS Camera, for scene recognition & precise geolocation, and a microlidar operating in SWIR.

SWIR Spectrometry is chosen since CO2 has useful absorption bands in the 1.6-micron bands and very sensitive in GaAs array detectors are available. For these reasons, here it is proposed to combine the Spectrometer with an atmospheric LiDAR to add and complement retrieval-important atmospheric information and minimize retrieval errors as seen in similar passive-only VIS-SWIR payload. This paper outlines the optical system design as well as satellite mission description and implementation status at the time of reporting.

Keywords: Cubesats, microLIDAR, Green House Gases, SWIR Spectrometry, Aerosol, Sensor Fusion

*e.armandillo@eventechsite,com

1. Introduction

The European Commission adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net greenhouse gases (GHG) emissions by at least 55% by 2030, compared to 1990 levels. This highly depends on the amount and quality of data available to provide valuable analytics on carbon and methane footprints. Data and knowledge around global greenhouse gas (GHG) emissions, trends and sources are becoming key levers to support national and international climate policymaking. To enable GHG emission reduction, we need a more comprehensive understanding of current national and global GHG emissions contributing to global warming and the overall impact of mitigation efforts. Earth observations is the most powerful tool to provide a synoptic monitoring and reporting on Earth's changing climate over time.

Existing solutions for GHG monitoring[1,2,4] are not meeting these requirements. Ground sensor networks provide accurate but limited coverage on the whole spectrum of gases. Sensors installed on premises require significant investments and maintenance effort while tracking only emissions generated by industrial facilities. Datasets generated by large public satellites such as GOSAT-2, OCO-2 or Sentinel 5 allow middle precision and low revisit rate (up to 7 days revisit rate, 1 km2 for CO2 and CH4). Small satellites can significantly improve the coverage, while the technology still does not allow to reach high accuracy and precision to actually use the data for reporting and validation. While small satellites have proved that such measurements are possible (GHGSat tracks only CH4 for oil & gas industry with 50m average resolution and maximum 25m for conditions with low aerosols concentrations), but the focus area of point sources shrinks the application span and limitations of the technology significantly decrease the sensitivity of measurements. While there are promising projects on the horizon enabling medium precision and higher revisit rate (SCARBO, Planet & Carbon Mapper, Merlin, Methansat) these projects still targeting specific applications (plumes detection for oil and gas sector) or do not provide sufficient data quality. Most of existing spacecrafts can sense the leaks of methane over very large areas but have poor resolution at the local level, at the scale of a leaking pipeline. And those systems that can capture these details will lack the wide-area coverage and the timely return to a particular location.

Currently there is no solution which enables the daily carbon dioxide and methane monitoring with high resolution and high sensitivity. Market demands precision up to 50m, several passes per day and sensitivity of at least 10ppm to allocate emissions to specific facilities, factories, and farms. This paper presents the approach to locate and quantify GHG with high accuracy and precision.

2. High-level service description

AIRMO proposes a novel service that will deliver L01b level data about greenhouse gas emissions concentrations on the predefined location. The goal of the AIRMO is to establish a network of new data sources for GHG monitoring with high temporal and special resolution (50m for CH4 and CO2) with 4 passes per day to expand the existing monitoring systems and enable new emissions monitoring applications to combat the climate crisis. This is achieved using a small satellite constellation (12 satellites) carrying a set of 3 novel instruments LiDAR, spectrometer and camera for active remote sensing and advanced fusion algorithms.

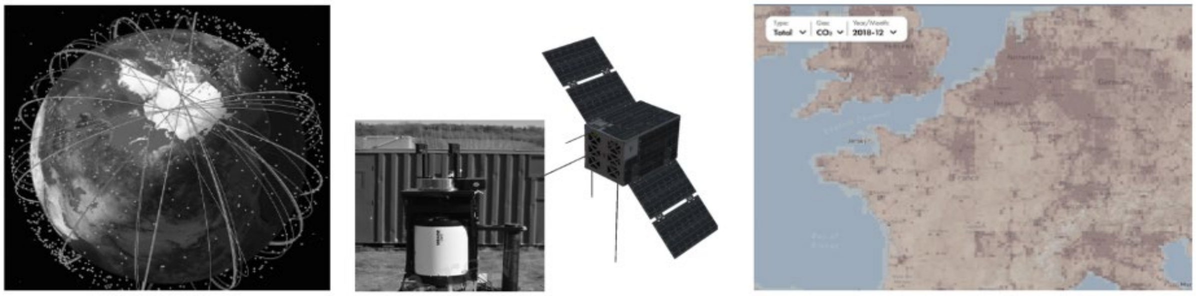
AIRMO will offer single measurements and monthly subscriptions for monitoring of CO2 and CH4 for facilities of different sizes, as this data was requested by the industry (please find LoI's in the ANNEX). The gas loads information per specific area or region will allow development and industrial sites to plan and manage their greenhouse gas emissions, align with current guidance, policies, and trends related to climate change/global warming, calculation of carbon footprints, and the applications of offsets to reduce carbon footprints.

Table 1 AIRMO Services list: The Table provided by you needs update:

Service Name	Description of the product/service	Customers Segments	Level 2 Product	revisit (hrs)	horizontal resolution (m)	height range (km)	uncertainty (%) goal, minimum, target
AIRMO data (L2) from 3 instruments	Data of CO2 and CH4 concentrations over the point sources downloaded from satellites and processed on ground	EO services, Climate solutions and applications	CO2, CH4, Aerosols	6	< 50x50	0-10	1, 10, 2
AIRMO monitoring service	On-demand monitoring of selected	Direct emitters, EO	CO2, CH4, Aerosols	6	<<50x50	0-10	1, 10, 2

	facilities or areas	services, Climate solutions and applications					

The main innovation in AIRMO is in measurement approach and data fusion algorithms. Using novel observation technology, satellite constellation will be capable of attributing emissions directly to individual facilities. The emissions data will be later transformed into actionable insights with our in-house analytics, helping customers to optimise their operations, reduce emissions and uphold environmental standards. The innovative measurement approach powered by a unique combination of proprietary LiDAR developed by AIRMO, Short-Wave Infrared (SWIR) spectrometer and Camera is the core of the proposed service. Fusion of raw data from these novel instruments enables high resolution emission data retrieval both in day and night all over the globe.



Satellite constellation - 12 satellites in 4 orbital planes

Satellite & Payload - CubeSat & Payload assembly: LIDAR, SWIR & VIS Imager

L0 to L2 data preprocessing, analytical tools and mapping

Figure 1 AIRMO service components

A distinct opportunity of the service is powered by the capability of satellite constellation global coverage and high resolution of on-board payloads. This is supplied by the combination of novel instruments and data processing techniques providing information about atmospheric concentrations of GHGs. The service will allow the access to historical and near real time data on atmospheric concentrations of CO2 and CH4 via web platform.

The core of the Product is the retrieval of the atmospheric column concentration and spatial distribution of main GHG, namely CO2 and CH4, with associated H2O & O2 gases which are required for accurate retrieval[3]. This shall be accomplished in the SWIR spectral region between 1 and 2 microns with optimized Radiative Transfer models.

Table 2 Detected gas and their parameters

	CO2	CH4	H2O	O2	Aerosols
Spectral channels, um	1.4- & 1.6-day, 1.6 night	1.6	1.4	1.27	1-2
Spatial resolution, m[1]	50 x 50 m	50 x 50 m	50 x 50 m	50 x 50 m	50 x 50 m
SNR	>500	>500	>1000	>1000	>100
Sensitivity, ppm	≤2	≤2	<2	<2	1.E-7
Concentration uncertainty in the column, %	<10	<10	<5	<5	NA

The picture below shows the service, the overall modules and major interfaces:

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[1] related to detector pixel size & GIFV. limited by satellite pointing stability & precision

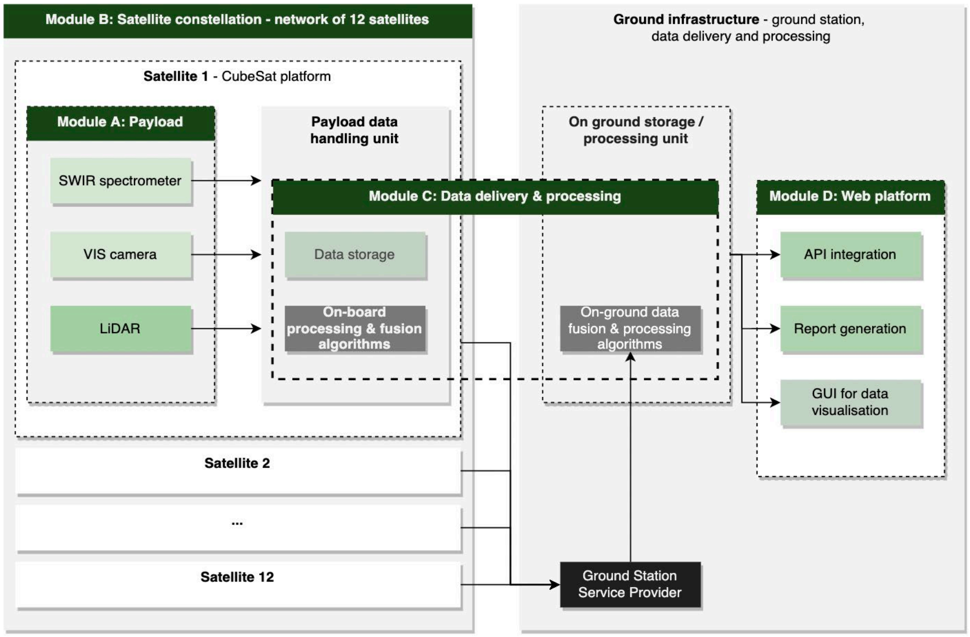

Figure 2 AIRMO service architecture

The Satellite will process Level 0 data from the three instruments into level L01b (Radiance, Irradiance|), and will transmit to Ground together with various instrumental & satellite engineering data & CKD (Calibration Data) and transmit to ground Processor where the L2 products will be generated. The external interfaces of the service are:

- Web platform that is delivering data products to the end customer
- RF interface between satellite and ground station network to deliver dataset from the satellite
- Launch interface that will allow deployment of the satellite into orbit

4, Detailed modules description

The main modules identified in the architecture are described below.

4.1 Payload assembly - measurement approach enabling high precision

Extensive literature exist that provide evidence on the errors incurred by ignoring aerosols, thin clouds and, for CH4 plume measurements, local surface winds. All local information on aerosols loads, cirrus, thin clouds & winds can be obtained by our novel microlidar concept as already reported in the literature (https://spie.org/Publications/Proceedings/Paper/10.1117/12.2599360?SSO=1). A recent paper discussing the retrieval precision on the GHGsat -D1 satellite (D. Jervis et al.: Atmos. Meas. Tech., 14, 2127–2140, 2021), for the CO2 and CH4 gases, clearly shows that by neglecting aerosols (and local winds for Methane) will add an important error in the retrieval accuracy. Our payload and processing retrieval approach will remove these important errors source for GHG gases and mostly important for CH4 plumes emission from local sources by adding local wind information. The basic idea behind the measurement approach goes along these steps:

1. The on-board spectrometer point measurements allow to generate the scene radiance (from the telescope incoming solar irradiance to detector array);
2. The elastic LiDAR inversion algorithm, embedded in the on-board processor, will supply information on vertically resolved aerosols layers, thin & subvisible clouds and backscattering & extinction coefficient
3. The radiative transfer model (RTM) embedded in the on-board processor will incorporate the lidar data and generate the scene corresponding simulated radiance;
4. Tuning the RTM parameters will converge faster & more accurate than previously done towards the measured radiance.

Detecting the weak CO2 and CH4 band is the main target since there are few other gas absorption bands in this area, and it is much easier to separate the band from neighbouring bands. The chosen observation technique, to be compatible with Small Sats approach, is the SWIR spectrometry performed with a high-resolution Grating-Spectrometer, supplemented by a VIS Camera, for scene recognition & precise geolocation. SWIR Spectrometry is chosen since CO2 has useful absorption bands in the 1.6-micron bands and very sensitive in GaAs array detectors are available. This technique relies on analysis of the reflected sunlight and can only be used while the satellite passes over illuminated areas of the planet. For this, solar-based spectroscopy is vulnerable to errors introduced by uncertainties in path length, atmospheric transmission, presence of thin clouds or aerosols, altitude/range errors, etc. For these reasons, here it is proposed to combine the Spectrometer with an atmospheric LiDAR to add and complement retrieval-important atmospheric information and minimize retrieval errors. Although LiDAR techniques exist for spectroscopy measurements of GHGs, within the frame of this project LiDAR is used as a supporting instrument to the SWIR spectrometer to enhance the accuracy and spatial resolution of the SWIR spectrometer. An only-LiDAR solution as is in Ascend or Merlin missions is not implementable on CubeSat in view of the power/mass/size constraints of the required LiDAR specifications for high-altitude orbits as being here considered (≈400-500 km). In fact, 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 fit within a small satellite no larger than 12U-16U therefore minimizing the volume of the instruments within the satellite is of paramount importance. 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.

The proposed setup guarantees, for the first time, the possibility to retrieve CO2 daytime and night time. For daytime, inversion algorithms, via radiative transfer & radiance reconstruction, will be used to determine CO2 and CH4 concentration based on Solar Irradiance as Source whose CO2 absorptions bands provide the “imprint signature” which is then obtained via Radiance measured by the Satellite. Nighttime, the same process will be used but the Target area will be illuminated by an artificial light source, at the exactly the absorption wavelength of CO2 (1.5716 -15730 nm absorption band of CO2): the laser source will be used both as an atmospheric LiDAR and specifically on night times, as the artificial “solar irradiance”. Night measurements for CO2 are feasible with a fiber-laser at 1 W average. For CH4 required absorption sources lie above 1.6 micron (1.645 to 1.655 micron) are difficult to be achieved with fiber lasers: other suitable candidate solid state sources will be considered if night CH4 is required.

The LiDAR is not scanning but steering and generating Point Clouds images of the atmosphere (0 to 10 km): the images shall be processed for Aerosol & subvisible clouds, data that will be fed in the RTM models to match the measured radiances for spectral bands.

For the Data provided in this proposal, we have used designing & verification as provided by our Forward Model for the Grating spectrometer and a LiDAR simulator Tool which contains all system parameters from satellite height, input radiance to telescope, feed optics, detection chain & electronics providing raw Data & SNR for the various situations analyzed.

Table 3 Budgets for payload elements

Budgets	Value or range of values	Units	Additional information
MicroLiDAR			
Configuration	Elastic Point Cloud Imaging		
Power	< 10	W	total wall plug, with thermal control & electronics
Mass	< 5	kg	
Volume	2-4 U	U	
GSD target	10<X<50	m	can be adjusted to meet Customer objectives
Swath	< 20	km	As above
Camera			
spectral range	0.4-2	micron	
GSD	10	m	Typical
Volume	2	U	
Swath	10	km	
Spectrometer			
configuration	grating spectrometer		
spectral range	0.4 to 2.1	micron	
FOV	0.02	degree	
Volume	2	U	

Detector	1x256 or 1x1200 picels InGaAs array	elements	

4.2 Satellite constellation deployment

Since global coverage is required for GHG emissions monitoring, a CubeSat constellation of at least 12 satellites is selected in the sun synchronous orbit in 4 different orbital planes with separation of 45 degrees between planes. Spacecrafts will be launched in several launches while passive or active orbital phasing will deliver them to the dedicated orbital spots. The propulsion decision is to be made in the scope of the activity.

The emissions monitoring of GHGs 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 3-4 years maximum lifetime for the constellation to generate enough data, the altitude is fixed initially set at 450 km. The constellation altitude is 450 km as this gives each satellite enough room, both above and below the normal operations altitude. Most of the Satellites that historically have monitored GHG 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 a limiting factor. Thus, the base size of one satellite shall be coherent with 12U or 16U CubeSat. It will require deployable solar panels and an active attitude control system with low jitter to enable high pointing stability for image acquisition. During preliminary mission study the available satellite volume was assessed, and a sample CAD modelling allowed evaluation of satellite positioning and places for apertures. Besides that, data, power, mass and link budgets were evaluated, and satellite subsystems were selected. Table below outlines the satellite baseline design. It includes the main subsystems as well as their parameters.

Some of the initial findings for mission results are outlined below. The mission is composed of three segments, the space, ground and launch segment.

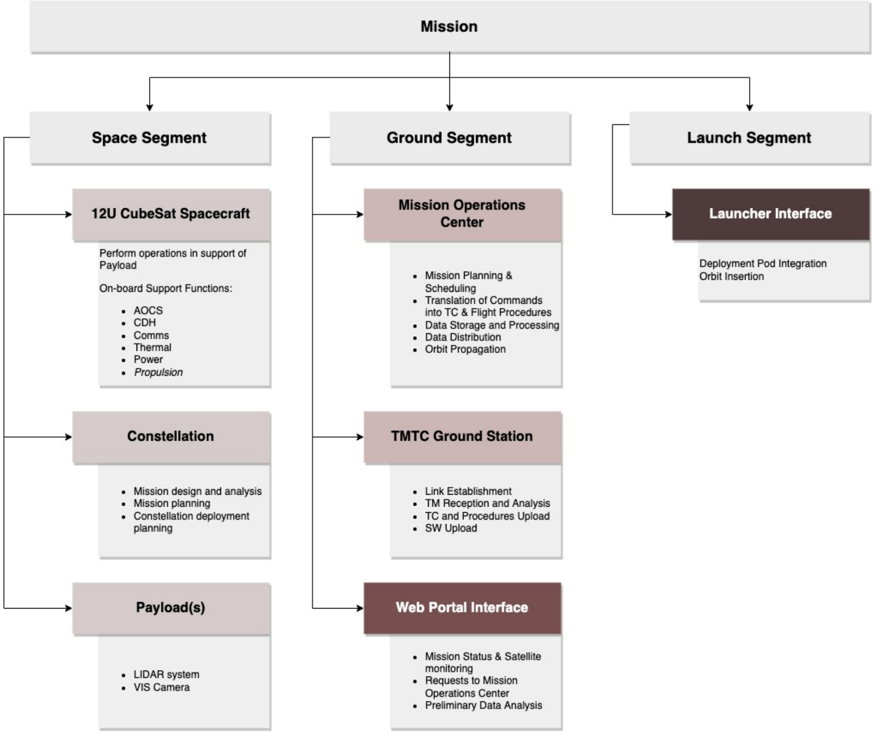

Figure 3 Mission Architecture

The satellite platform is a 12U platform based on the CubeSat form factor. From the 12 CubeSat Units, 8 will be occupied by the multiple payloads and the remaining 4 will be used by the bus.

Table 4 Budgets for satellite element

Budgets	Value or range of values	Units	Additional information

Mission/Constellation Level			
Launch date	Q4 2023		
Lifetime	3-4 years		
Launcher/deployer	Exolaunch, Falcon 9		
Number of satellites	12		
Orbital description	SSO, 98 degrees inclination		
System/Satellite Level			
Satellite mass	Up to 30	Kg	
Continuous payload power	Up to 45	W	
Dimensions (stowed deployed)	12U – 16U CubeSat	U	
AOCS Description	Axis stabilized, 0.05 deg pointing requirements, star tracker integrated		
OB Computer/Architecture	Up to 10 Gb of storage memory	Gb	
Downlinking	Up to 100	Mbps	
OB processing	Pre-processing, calibration and filtering		

4.3 Data processing block

The retrieval of the desired species concentration is based on three steps algorithms:

- Reconstruct the actual scene Radiance
- End-to-end simulation of the instrument function.
- Inverse methods to obtain the species volume mixing ratio (vmr)

During this process there are many sources of errors during computation of Step 1 & 3: primarily associated with poor knowledge of the atmospheric conditions, and mostly presence of thin clouds and Aerosols which are undetected by the VIS Camera, and which can lead to large errors in the vmr's values. For this, in this Mission proposal, the Spectrometer & Camera are supported by a cloud/aerosol LiDAR, which is the simplest of all active LiDAR instruments, but will be able to detect and characterize with high vertical resolution and accuracy the presence of Aerosols and (subvisible) clouds & cirrus. The effect of this additional data, which is proposed for the 1st time for the CO2 CubeSat mission, will improve the measurement accuracy which will be then independent from the atmospheric conditions.

The AIRMO Level 1B product list are calibrated and geo-located spectral radiances. Each Level 1B product will contain a unique record for every sounding that the payload instruments acquire while viewing the Earth during a single spacecraft orbit, consisting of atmospheric column spectra. The Level 1B product also includes error measures and indicators that assess the quality of each acquired spectrum. These indicators denote which spectra are suitable for subsequent processing. The full Constellation of AIRMO small satellites will be correspondingly generating thousands of Gbs of data daily. Certain pre-processing algorithms will enable on board compression and pre-processing (L01b) while the final intelligence products (L2) will be processed on the Ground segment. AIRMO shall develop a set of visualization, analysis, and processing tools for the exploitation of the L0 to L2 data from the mission. The Lidar and SWIR spectrometer produce a relative low data rate, major Data volume are generated by the RGB camera. For raw unprocessed instrumental Data, assuming each pixel # (from each instrument) being sampled at 10MH/sec with 12 Bit/sec, total ground "Tile" Data rate is calculated approximately as: 12x10E6 giving order of 10Gb

4.4 Lidar Impact on GHG gases Climatology

In this paragraph, we show the impact of Lidar-acquired Data on CO2 Climatology. A simple compact lidar of the type presented at ICSO 2020 (Ref.) supplements the RTM models with information about presence of aerosols layers, cirrus clouds, presence of sub-visible clouds, which are not otherwise detected by the on board SWIR Camera. This added information remove the inaccuracy in the retrieval of GHG concentrations from the Spectrometer measured Radiances. Additional important contribution provided by this lidar concept is that it can provides the local surface winds (see Paper 009_Armandillo in this Conference) which will allow to determine without error the local CO2 or CH4 out flow rates from industrial sites.

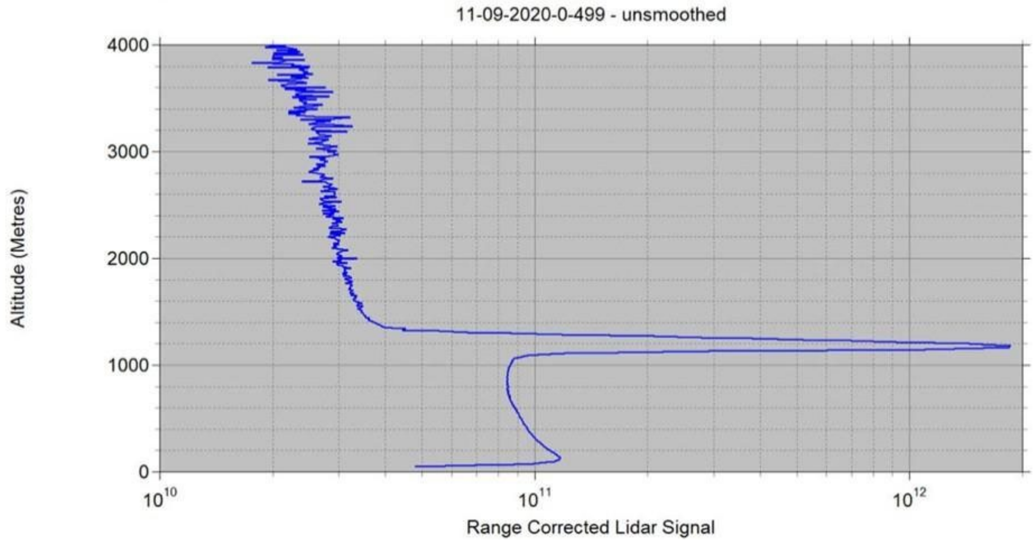

Fig. 4a

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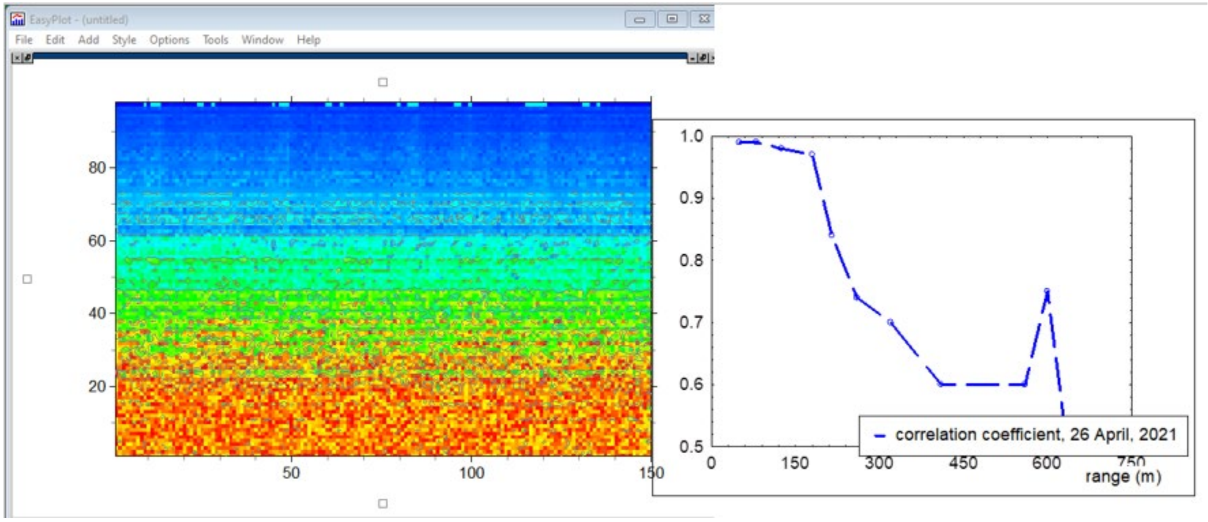

Fig, 4b

Figure 4 shows typical profiles from the lidar: Fig. 4a shows vertical atmospheric profile. Fig. 4b shows the typical Point-Cloud pattern which is then processed for information retrieval.

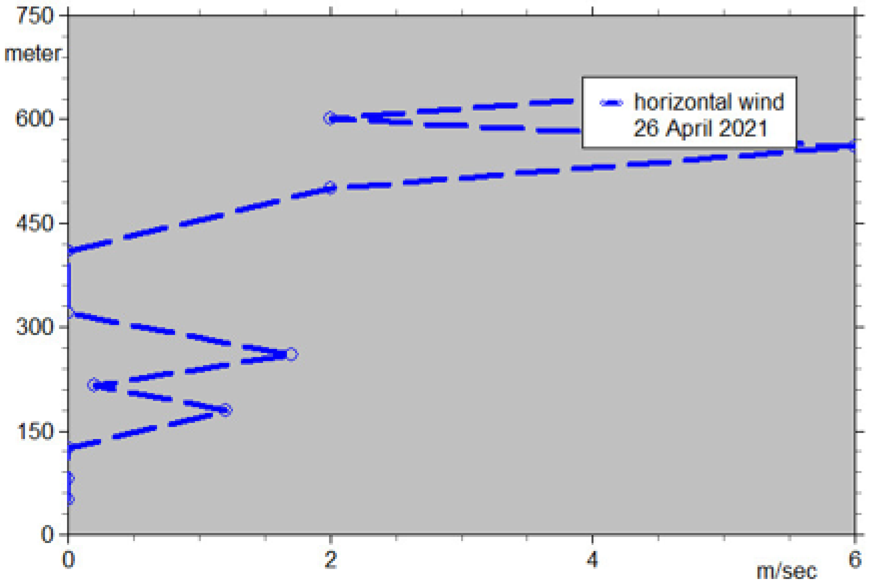

Fig. 5: local winds processed by the Point-Clouds pattern of Fig. 4b

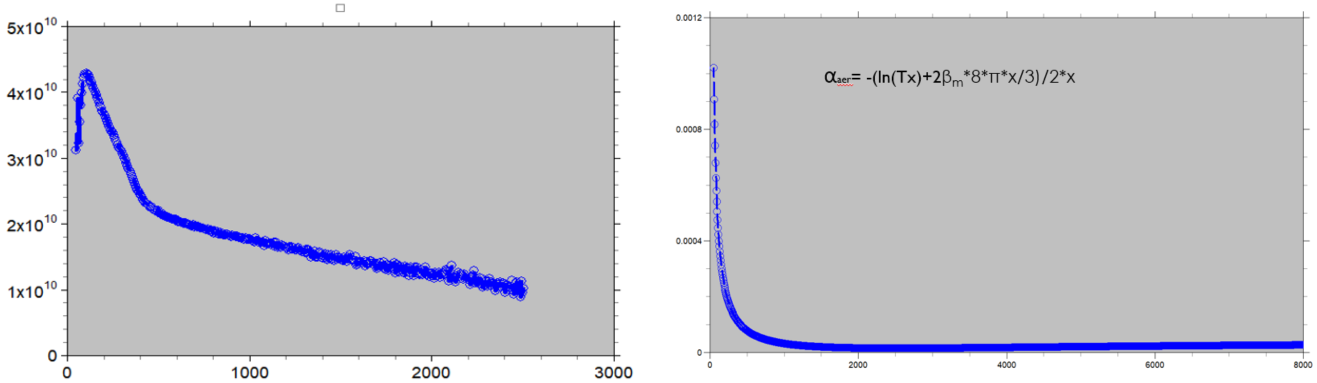

Fig. 6: Backscattering & extinction coefficients retrieved from the Point-cloud pattern of Fig. 4

Fig. 7 below shows clearly the impact of lidar data on Radiance measurements. For these Aerosols AOD values:

-
- high load -> AOD 440 nm = 0.7
- medium load -> AOD 440 nm = 0.3
- low load -> AOD 440 nm = 0.03

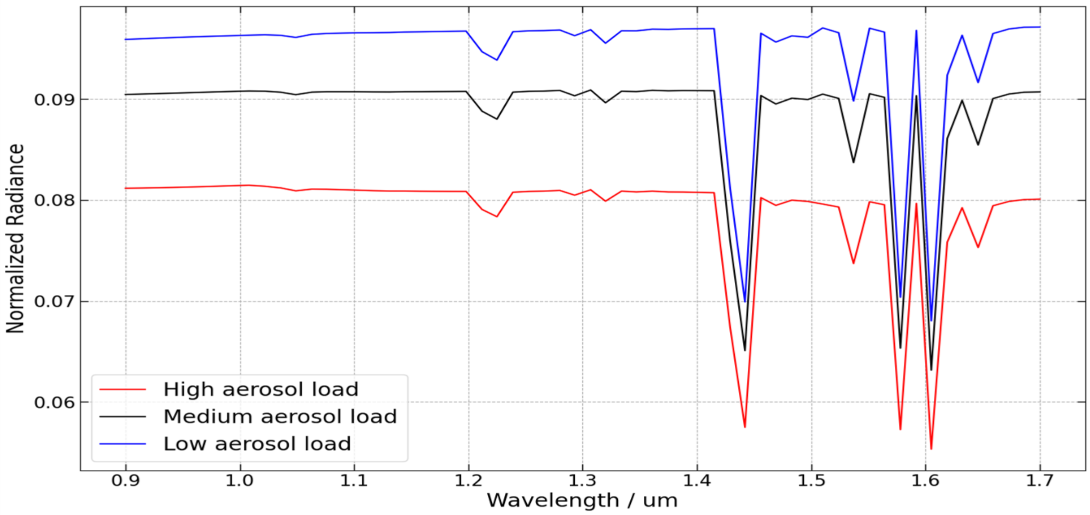

Fig. 7: Effect of aerosols of varying optical density on the Absolute radiance retrieval from Spectrometer.

5. Conclusion

Using novel observation technology, satellite constellation will be capable of attributing emissions directly to individual facilities. The emissions data will be later transformed into actionable insights with our in-house analytics, helping customers to optimize their operations, reduce emissions and uphold environmental standards. The innovative measurement approach powered by LiDAR and Short-wave infrared (SWIR) spectrometer proposed by AIRMO is the core of the proposed service. Fusion of raw data from these novel instruments enables high resolution emission data retrieval both in day and night all over the globe.

6. References

[1] https://ghgsat.com
[2] Meznsat, MeznSat—A 3U CubeSat for Monitoring Greenhouse Gases Using ShortWave Infra-Red Spectrometry:Mission Concept and Analysis, 2019
[3] SRON, 2021, Algorithm Theoretical Baseline Document for Sentinel-5 Precursor Methane Retrieval
[4[Clouds effect on the Atmospheric Total Column Carbon Dioxide Retrieval by Space Orbiting Argus 1000 Micro-spectrometer: Introductory Study