Noctua: Compact single site emission monitoring from space

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Summary

"Information Made in Space" has clear added value through low-cost, repetitive, independent, and homogenous pinpointing of world-wide emissions to individual assets. Our atmosphere is like an open sewer, forcing over 80 countries to set net-zero emission targets. Emitted Methane is cleared from the atmosphere within about a decade, making cuts a quick way to slow down climate change. The single site level Methane emission regulation that is being drafted is a first concrete step towards global measuring and monitoring of emissions. Regulation of other emissions will follow in the near future. In 2021 the ADSN/ SRON team delivered their first compact high-end/lean-approach aerosol monitoring instrument SPEXone to NASA for the PACE mission. Re-use of the SPEXone concept lays the foundation for the *Noctua family* of emission monitoring space instrument solutions. The first new member of the family is a Methane monitoring instrument. The target is to reach detection thresholds (well) below 100 kg/hr for single sources, with a localization better than 2500 m^2. We will be are able to pinpoint 90% of the Methane leakages to individual assets from space. We intend to expand the Noctua capabilities by continuously improving Methane pinpointing, and making versions for other gases.

1 CHALLENGE OF CONTROLING AND REGULATING EMISSIONS

Our atmosphere is like an open sewer. All kinds of pollutants are discharged by everyone with major consequences for the climate, health and biodiversity. The OECD environmental outlook for 2050 in case of in-action is as follows [1]:

> Climate change is the challenge of the 21st century. Without targeted action, the global average temperature will be 3 – 6 degrees Celsius above pre-industrial levels by the end of the century. Precipitation patterns will change, glaciers and permafrost will melt, sea levels will rise and the frequency of extreme weather will increase. People and ecosystems will struggle to adapt. At the end of the 21st century, economic damage in Europe could amount to 2% of GDP per year (200 billion euros per year). The Paris Agreement of 2015 wants to prevent this and states that the temperature should not rise more than 2 degrees Celsius. To achieve this, net-zero emissions, primarily from greenhouse gases such as CO_2 and Methane, in 2050 are essential.
>
> Premature death and illness are the result of breathing bad air. Without targeted action, air pollution (and no longer drinking dirty water and lack of sanitation) will be the leading environmental cause of premature death. The number of premature deaths from exposure to particulate matter (aerosol) in outdoor air is now 4.2 million annually, according to the WHO and will double worldwide by 2050, with most of the deaths occurring in China and India. RIVM indicates that, in addition to the reduction in quality of life, the Dutch live on average

one year shorter by breathing bad air. The social economic damage amounts to more than USD 5,000 billion per year, according to the World Bank, about USD 700 per inhabitant of the Earth.

Climate change and the precipitation of these emissions have a major impact on biodiversity. Globally, terrestrial biodiversity is expected to decline by a further 10% by 2050, with significant losses in Asia, Europe and Southern Africa. And forest areas are expected to shrink by 13%. In addition to pollution and climate change, other factors such as land use change (e.g. agriculture), expansion of commercial forestry, infrastructure development and human degradation of natural habitats play a role. Agriculture is the main cause of biodiversity loss, but climate change will become the fastest growing driver of biodiversity loss until 2050.

That these are the greatest challenges of our time are underlined by the diverse plans and activities that are being initiated worldwide to achieve the ambitious Sustainable Development Goals. With the main goal of a net zero emission society by 2050. The measures defined globally, at European and national level are a good starting point. The question, however, is how policymakers and governments can manage policy, compliance and results. How do we ensure that we are and remain on track in the coming decades?

The containment of harmful emissions requires a reliable solution that equips governments with a monitoring tool that leaves no room for so-called "free-rider" behavior - where polluters can evade their responsibility - while at the same time giving industries and investment funds the opportunity to themselves fulfill their social task.

2 ADDED VALUE OF INFORMATION MADE IN SPACE

The current state-of-the-art can best be illustrated with Copernicus. With the Copernicus satellite system, which will measure global CO_2 emissions from 2026 onwards, Europe is taking an important first step in independent and homogeneous emission monitoring. The data from space will soon make it possible to make reliable statements about harmful emissions from countries, regions and cities. Copernicus thus provides insight into the effectiveness of policy measures and progress towards national emission reduction targets.

However, the core of the worldwide problem often lies with the individual polluter, and Copernicus does not allow to monitor and control at the level of the polluter. With constellations of small satellites, it is possible to zoom in to the level of the causer, which enables governments to measure at source level and thus actually detect and address the responsible ship, farm or gas source.

Typically a small satellite (16U) is able to carry one compact high end atmospheric monitoring instrument. As a consequence, a single small satellite can target not all greenhouse gases at the same time. So, choices have to be made. In contrast to CO_2, emitted Methane is cleared from the atmosphere within about a decade. This makes Methane emission cuts the low hanging fruit to slow down climate change. The single site level Methane emission regulation that is being drafted by the Oil & Gas Monitoring Platform is the first concrete step towards global measuring and monitoring of emissions. In addition, it is foreseen that the regulation of other emissions will follow in near future.

In thirty years of refining the measurement of Methane from space we have progressed from scientific discovery to providing a compass towards net-zero emission, as is shown below:

2002 – 2012: Global Methane concentrations turn out to be significantly higher than expected, as shown by the global homogeneous measurements obtained with SCIAMACHY on board ESA EnviSat. This indicates that the Methane emissions are higher than expected. Large-scale sources are identified: fossil energy mines, wetlands, industrial areas, and melting permafrost.

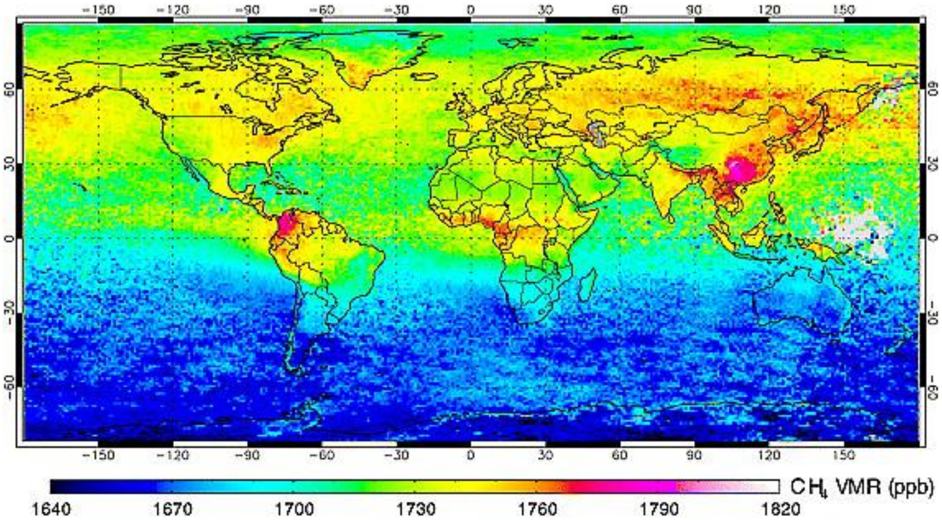

Figure 1: Bi-annual average Methane concentrations from SCIAMACHY (2003 en 2004), ref [2].

2017 – now: Major Methane leaks are discovered by TROPOMI on the ESA Sentinel-5 Precursor mission [3]. To give an example, Australia's coal mines appear to be emitting far more Methane than the country reports. This is especially true for the open coal mine. This means that Australia is contributing more to climate change than it is giving up, as Methane is a potent greenhouse gas. TROPOMI is able to detect major Methane leaks worldwide.

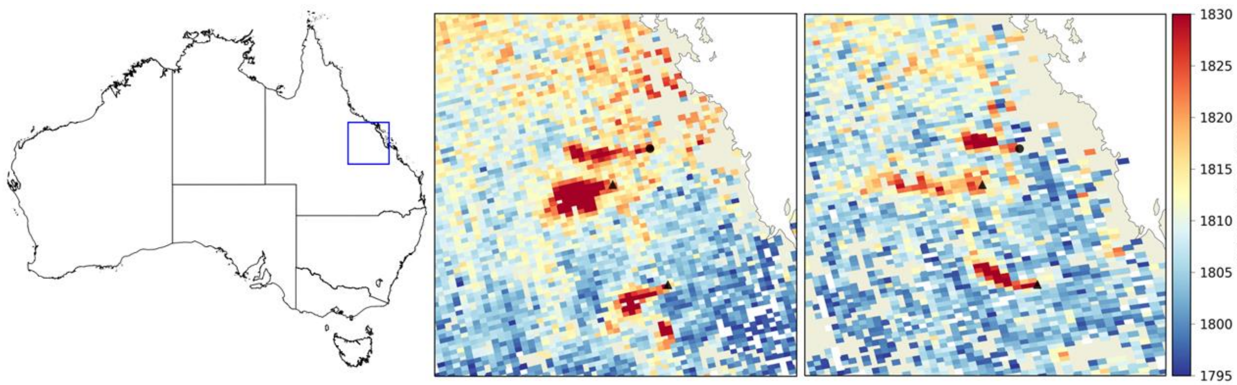

Figure 2: TROPOMI Methane observations on two different days clearly show three coalmine locations. Top: Hail Creek. Middle: Broadmeadow, Moranbah North en Grosvenor. Bottom: Grasstree en Oaky North.[3]

Within 3 years from now (our vision): All the elements are in place to enable monitoring of 90% of the currently reported Methane emissions worldwide homogeneously and objectively. In this way, it is possible to point the way to net-zero emissions (who should reduce emissions and is that successful). The climate constellation is a system of small high-tech satellites in low Earth orbit that measures 50x more finely than TROPOMI where Methane is emitted. This makes it possible to monitor and control emissions at asset level.

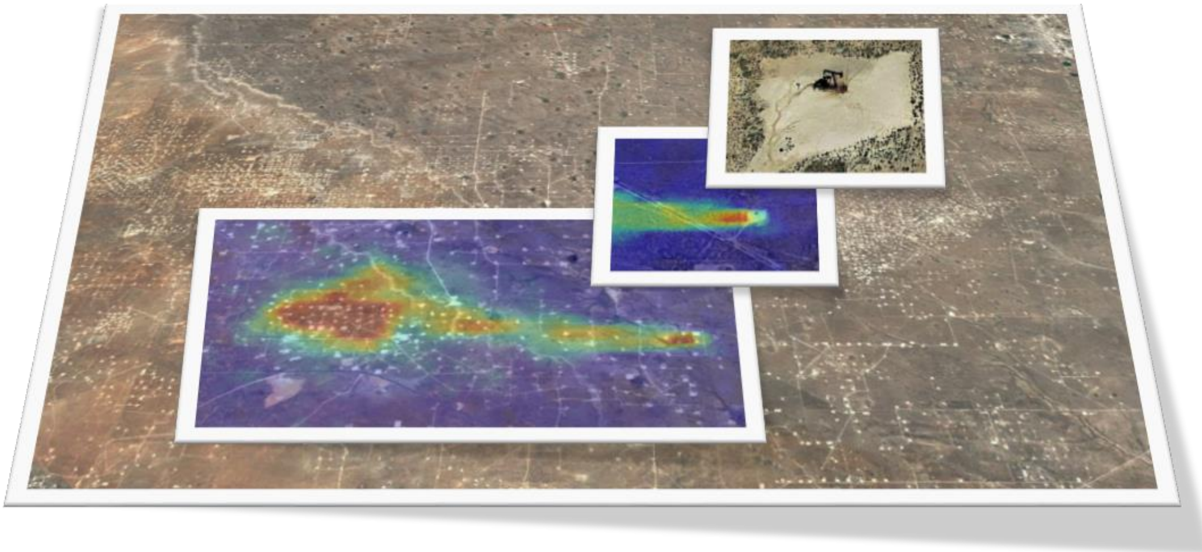

Figure 3: Simulated Methane emission map.

The single site level Methane emission regulation that is being drafted by the Oil & Gas Monitoring Platform requires the monitoring of a sheer number of wells and pipelines as illustrated in Figure 4 and Figure 5.

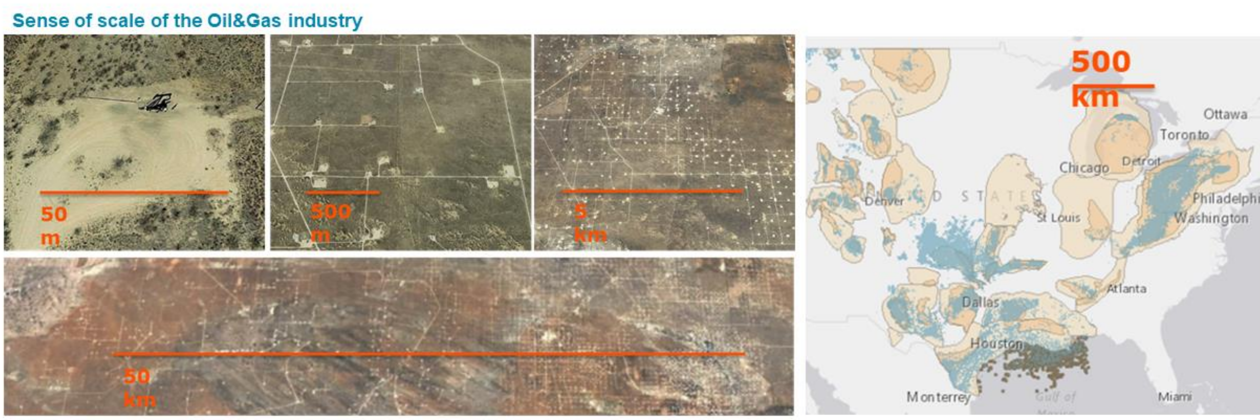

Figure 4: A sense of scale for oil wells

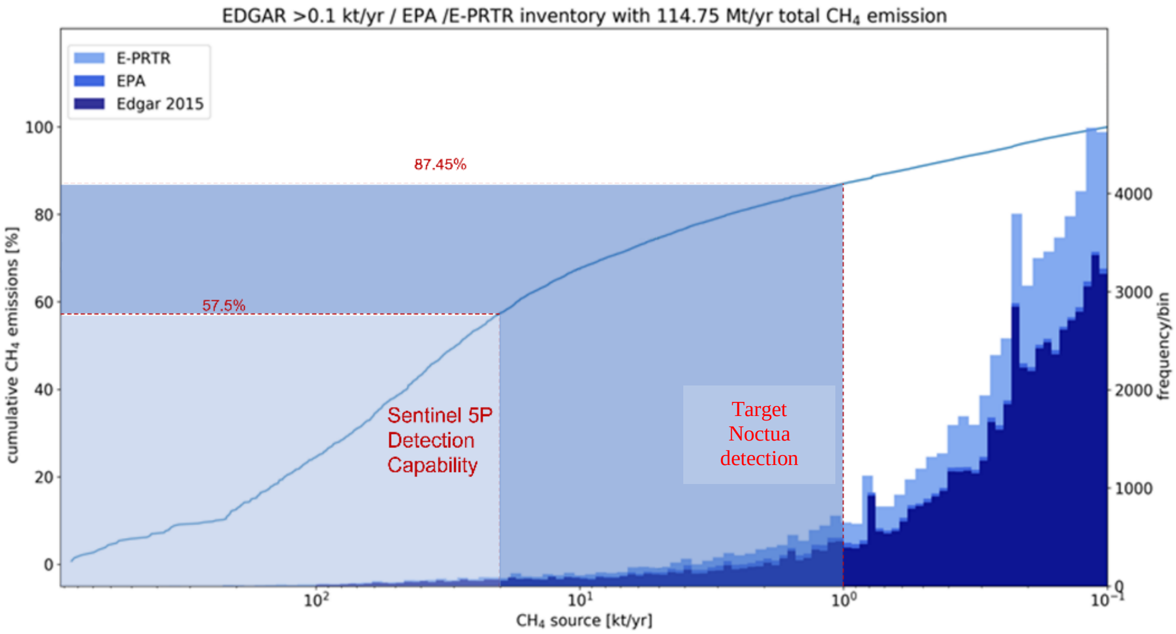

Figure 5: Methane emission due to gas leaks

Emission monitoring from space solves fundamental problems associated with in-situ measurements: Gas leaks can occur – and suddenly increase – at any time and at any place. In order to pinpoint the emitter, either a measurement device is needed at each potential source, or follow-on dedicated measurements are needed, often at poorly accessible locations. In addition, each of these devices needs to be calibrated regularly and protected against mis-use.

Monitoring from air is an incomplete solution. Planes and even High Altitude Pseudo Satellites have limited range, only provide snapshots, and need to comply with national regulations. This makes the price-per-measurement large. Monitoring from space does not have these drawbacks. Yes, the initial costs are high, but this is offset by global access on a regular basis with measurements that are of high quality. This makes the price-per-image lower than air-based measurements.

Measurements from space do have their limits. Better sensitivity, larger swaths, and higher resolution result in large instruments. Detection of multiple gases require larger spectral ranges and therefore multiple detectors. This leads to large instruments like TROPOMI, which has a mass of 200 kg, and uses 120 W of power. TROPOMI has successfully measured large Methane emissions (Figure 2), but is not well suited for localizing small emitters (Figure 5).

The alternative is to have small instruments dedicated to a single – smaller – wavelength range, i.e. most of the time to a single greenhouse gas. Revisit time is considered to be less of a design driver than localization. A much better sampling distance (less than 20 m) than TROPOMI can be implemented, at the cost of swath: tens of km as opposed to 2600 km. In fact, the sensitivity and resolution are mainly limited by the available volume for the telescope.

From extensive interviews with potential customers for greenhouse gas data, ranging from oil and gas companies to regulatory authorities, we have derived a primary use case for a Methane detection service:

- Find Methane leakages below 100kg/hour (at 1.5 m/ wind speed), and quantify them below 250kg/hour
- Localize Methane leakages better than 50x50 m^2.
- Deliver information within 2 days after a measurement
- Have a service that includes the first in-house developed space segment available by 2024 or earlier

As can be seen in Figure 5, the 100 kg/hour limit (= 8.5 kton/year) shows a significant improvement in cumulative Methane leak detection over TROPOMI. How does this fit with existing or planned similar instruments? Figure 6 below shows an overview of the expected performance of other missions compared to $Noctua^{CH4}$.

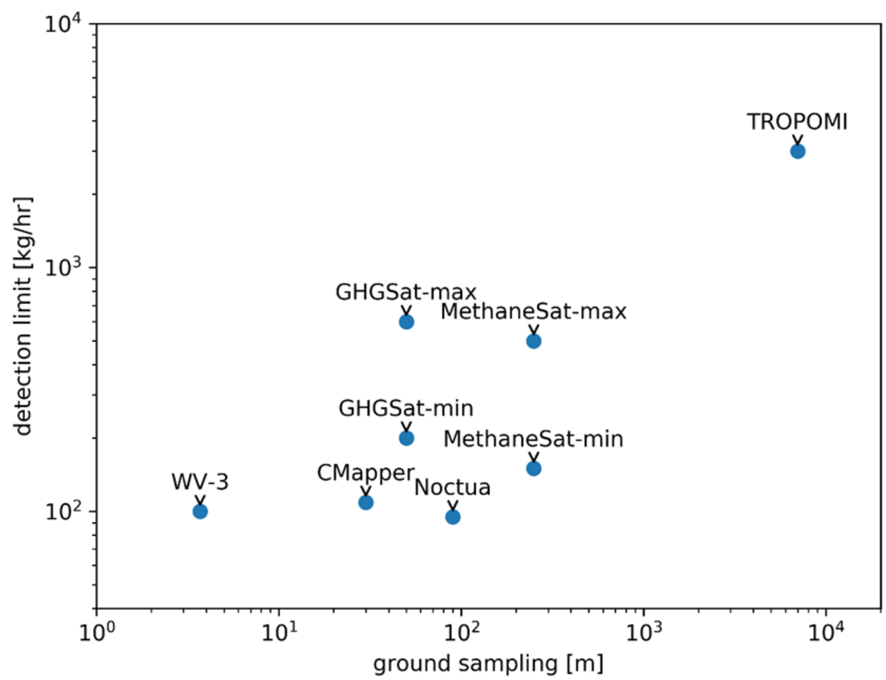

Figure 6: Overview ground sampling distance and detection limit capabilities of other Methane missions.

The figure shows that there are certainly missions with better performance Carbon Mapper (CMapper), World View 3 (WV-3), but these are not compact instruments that can easily form larger constellations. Significantly better sensitivity will lead to an exponentially higher number of detectable sources, but in our current estimates this would require telescopes that exceed the current volume capabilities of mature CubeSat sizes (16U, of which 8U is available for an instrument).

3 FROM LARGE TO COMPACT, A 25-YEAR EVOLUTION

For this type of measurements, two basic opto-mechanical designs are in use, push-broom spectrometers and Fabry-Perot imaging spectrometers. In the Netherlands, Airbus DS NL and partners have over 25 years of experience with the former type, as illustrated in Figure 7.

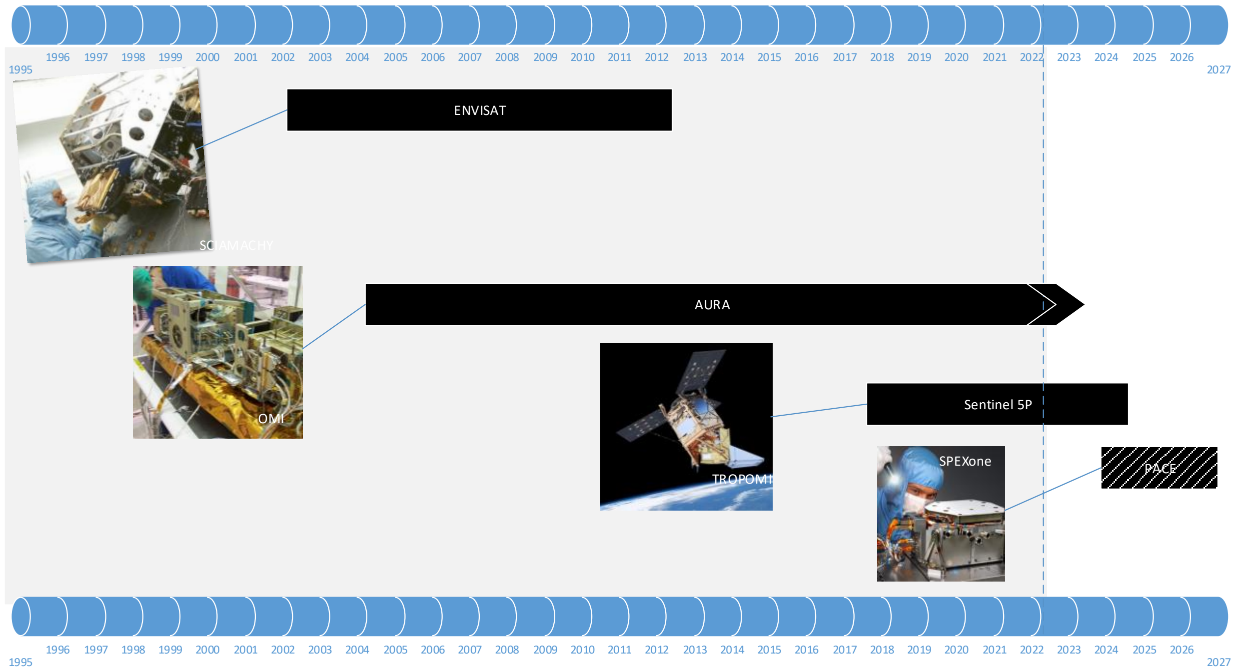

Figure 7: 25 years of push-broom instruments

Sciamachy on Envisat (2002-2012), OMI on AURA (launched in 2004) and TROPOMI on Sentinel 5P (launched in 2017) were all large multi-purpose instruments. In 2018, Airbus DS NL switched to a compact (8.5U) instrument, SPEXone (see Figure 8). SPEXone is a compact, optical satellite instrument that will characterize aerosols from low Earth orbit as part of the NASA PACE mission. SPEXone has been developed by a Dutch consortium consisting of SRON Netherlands Institute for Space Research and Airbus DS NL, supported by opto-mechanical expertise from TNO [5]. SRON and Airbus DS NL are responsible for the design, manufacturing and testing of the instrument. The scientific lead is in the hands of SRON. SPEXone is a public-private initiative, funded by the Netherlands Space Office (NSO), the Netherlands Organization of Scientific Research (NWO), SRON and Airbus DS NL Although this is an instrument with science objectives, the design and AIT approach of this instrument incorporated many elements of what now is termed Next Space:

- A joint design, AIT, and science team that knows the essence of the requirements, and can adapt them based on well-informed trades (performance to cost).
- Focus on the essentials, constantly reminding ourselves why we are doing things, and how they can be done more effectively. This includes documentation.

The instrument was delivered, fully calibrated, to NASA within 40 months after Kick-Off, in spite of the ongoing CoVid19 pandemic. A larger swath, lower resolution version for the ESA CO2M mission has just passed PDR.

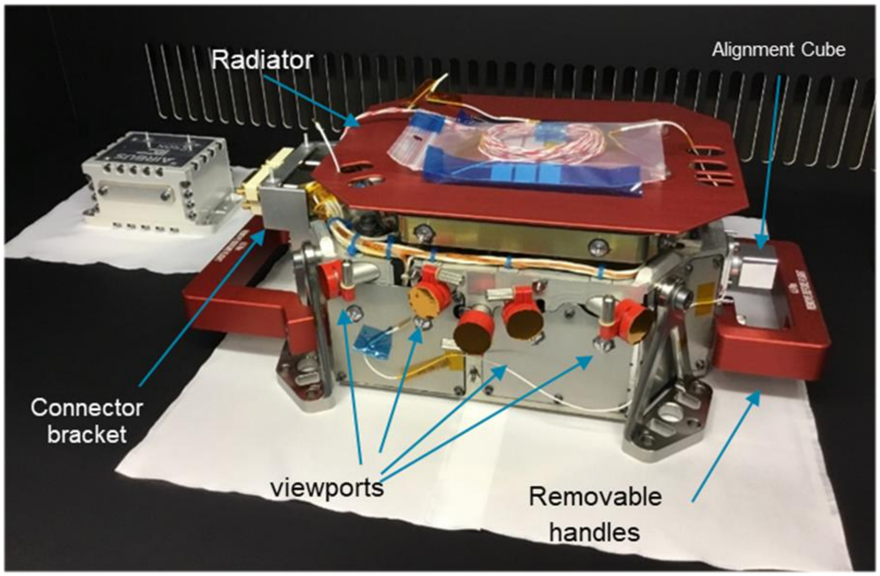

Figure 8: SPEXone for the NASA PACE mission

4 FROM SPEXONE TO THE NOCTUA FAMILY

The step from SPEXone to a compact greenhouse gas monitoring instrument is a natural one. Its mass and power consumption are already well compatible with the CubeSat boundary conditions, and its volume (which was not a constraint for PACE and CO2M) is already close. And because of the need for only one viewing angle (SPEXone has five), and the absence of polarization detection requirements, its volume can be easily be reduced. This has led to the realization that SPEXone can form a solid basis for the type of compact monitoring instruments that is fit for the future. We have chosen the brand name Noctua (named after the owl of Athena, the godess of wisdom), of which SPEXone is the precursor for Noctua^{PM}. Similarly, Noctua^{CH4} is suited for measuring Methane emissions at single asset level from space.

The essential conceptual difference with earlier – science driven – instruments is that we make different choices for the family:

- We keep the SPEXone spectrometer design as-is, using the available volume to create more room for small variations (e.g. detector)
- In general, we focus on easy manufacturability, to make sure that series production is efficient without compromising on quality
- We take optimal advantage of the capabilities of the platform. Specifically, as the only instrument on a CubeSat we can increase performance by using the attitude control system to perform staring maneuvers (i.e. changing the pitch direction such that the same strip on Earth is within the Field of Regard for a longer time).

With the 8U volume as a hard constraint (which in turn limits the light collection capabilities), we have made a trade to determine the best balance between detection capabilities and localization. This has resulted in a rather narrow swatch and small ground pixels. Sufficient SNR per pixel is obtained by implementing a fairly long staring law. By transmitting the data unbinned, we can tune the localization capabilities on ground per target. Tabel 1 below shows our solution, compared to two other missions (based on the publically available data).

Tabel 1: Noctua instrument characteristics vs. expected customer needs and two other missions

Parameter	Localization (ACTxALT) [mxm]	Swath [km]	Detection limit [kg/hr	Comment
Customer need	<50x50	NA	< 100	Swath has to satisfy revisit time < 1 month
Noctua^{CH4}	17x17 to 90x90	17	95	@500km altitude Lref = 6.0e12 photons.s-1.nm-1.cm-2.sr-1) SZA = 50 deg FMC=50 Wind 3 m/s Using Jacob et al. 2016
GHGsat	30x30 to 50x50	12	200	@514km altitude grassy scene; wind 3 m/s
CarbonMapper	30x30 to 30x30	18	109*	@400km altitude point source, 4500m2 plume, single-detection, 5 m/s wind

Our analysis has shown that the size of the telescope is indeed the constraining factor, especially for localization. Further optimization may be possible, but to be able to make the step to < 25 kg/hr emission detection and/or localization to 10m, it is necessary to either increase the available volume (i.e. increase the size of CubeSats, thereby increasing the launch costs), or to move away from push-broom systems to new technologies.

5 CONCLUSIONS

We are at the dawn of an age of environmental regulation. The social impact of emissions has become too great to rely on that the problem resolves itself. Environmental monitoring from space provides a useful guide to net-zero emission and support the implementation of the upcoming regulations. The current large space missions are an essential component in monitoring from space, but insufficient to fulfill the goals of detecting and pinpointing emitters. The number and density of sources is so large that there is a need for a fleet of simple, compact replenishable and constantly improving instrument solutions.

The Netherlands has always been at the front line of science driven climate monitoring (Sciamachy, OMI, TROPOMI). In addition, with SPEXone Airbus DS NL, in a teaming with SRON, has made a successful transition to compact instruments. This gives us the ideal starting point to develop a new line of compact atmospheric monitoring instruments that can be built into 16U CubesSats. Airbus DS NL is now in a position that a commercially high ranking prototype flight model of a CH_4 compact measuring instrument can definitely be built in two years.

6 ACKNOWLEDGEMENTS

The work presented on this paper builds on the lessons learned from the TROPOMI and SPEXone projects. The Authors are grateful to the many persons working on these projects.

7 REFERENCES

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