PILOT STUDY ON THE IMPACT ASSESSMENT OF ESA EARLY R&D ACTIVITIES

An ultra-compact mass spectrometer that enables the reliable analysis of complex molecules

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Monitoring the chemical composition of Earth’s atmosphere helps understand natural and anthropogenic changes …

The risks of climate change are well-documented, and adverse effects are already being experienced across Europe. As the fastest warming continent in the world (European land temperatures have increased 2.04°C to 2.10°C between 2013 and 2022 compared to pre-industrial levels[i]), European regions are facing more frequent and more potent extreme weather events, such as heatwaves, storm surges, droughts, and floods[ii]. Weather- and climate-related extreme events have caused economic losses of assets estimated at €738 billion between 1980 and 2023 in the European Union (EU), with over €162 billion (22%) between 2021 and 2023 alone[iii]. Looking ahead, climate-related risks endanger our energy, water and food security, financial stability, and public health[iv].

Studying the Earth’s atmosphere is a crucial step to better understanding climate change, and to be better able to mitigate its consequences effectively: monitoring greenhouse gases such as carbon dioxide and methane allows scientists to assess the causes of climate change and forecast its future impact; tracking pollutants such as nitrogen oxides, sulphur dioxide, and particulate matter is vital for managing air quality and protecting public health, as these pollutants are linked to respiratory and cardiovascular disorders; and monitoring atmospheric ozone levels helps preserve the ozone layer, which shields us from harmful UV radiation. Overall, this continuous monitoring is key to maintaining the balance of Earth's ecosystems.

Additionally, by studying atmospheres of other planets, scientists gain valuable perspectives that test and refine our understanding of fundamental atmospheric processes – such as the greenhouse effect, aerosol and cloud physics, as well as atmospheric chemistry and dynamics[v,vi]. This can help identify potential flaws in our Earth climate models and improve our understanding of how Earth's climate systems operate.

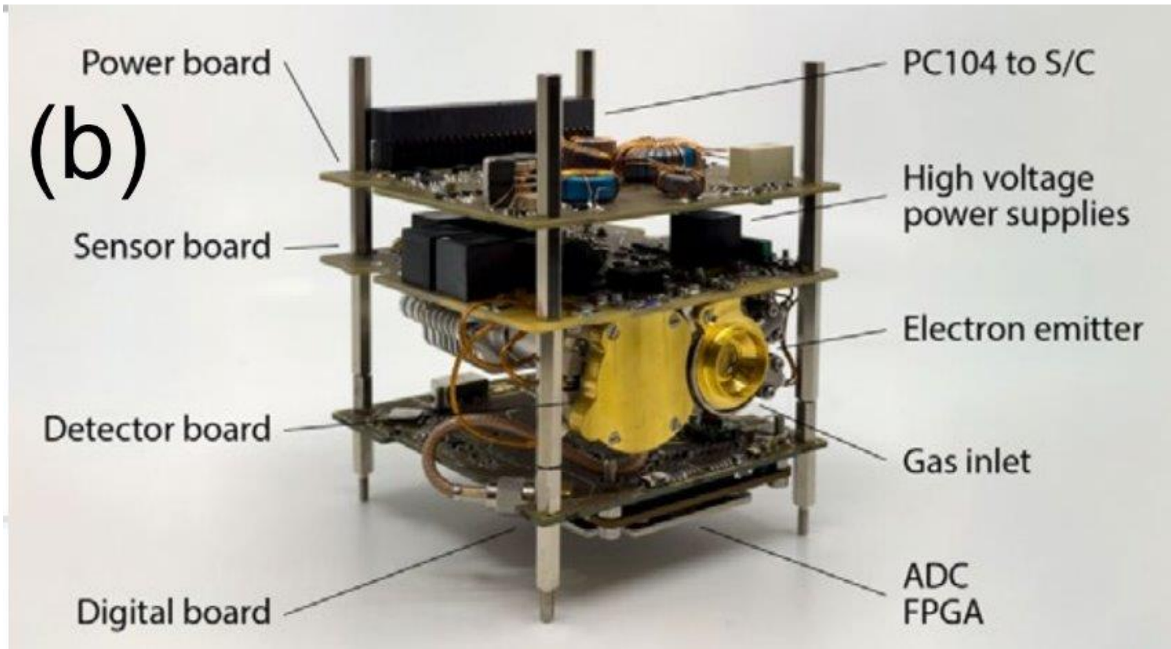
… which is enhanced by a molecule-preserving compact mass spectrometer, developed with ESA funding …

'CubeSatTOF (Time-of-Flight)' is a completed project funded by ESA's Discovery Programme[1] that is seeking to investigate the adverse impacts of high-speed planetary flybys on molecular structures. Traditional mass spectrometers have limitations when encountering speeds higher than 5 km/s, where the molecular structure of gases is altered through fragmentation, reducing accurate scientific analyses due to measurements with limited reliability. The CubeSatTOF instrument addresses these limitations through its novel ion-optical and gas inlet system. The contactless gas intake system preserves molecular structures, resulting in enhanced reliability and data accuracy from high-speed terrestrial and extraterrestrial samples.

The CubeSatTOF project is pioneering the Time-of-Flight mass spectrometer, and is CubeSat-compatible having achieved the 1U form factor.[vii] It is capable of handling encounter velocities of up to 10 km/s in the small 1-liter version (i.e., the compact 1U form). The full-scale 3U form factor will be able to handle encounter velocities of up to 20 km/s in a typical deep-space mass spectrometer scale. The CubeSatTOF instrument is engineered to deliver enhanced mass resolution 20 times higher than the currently available technology, while at the same time maintaining molecular integrity across mass ranges. The instrument currently weighs only 1kg and fits within a 1U volume, removing the need for bulky and potentially risky high-voltage connectors and harness.

[1] The Discovery Programme, as part of ESA's innovation pipeline, explores new ideas and disruptive technologies by funding early-stage research and development in space technology. Through an open and competitive approach, it encourages risk-taking and collaboration with academia, industry, and innovative SMEs, aiming to identify game-changing concepts for future space missions.

Overview of CubeSatTOF with novel gas inlet system which has already achieved appropriate form factor (1U)



Source: University of Bern

The miniaturisation of CubeSatTOF and the processes used to develop this instrument have been closely aligned with NewSpace techniques. The miniaturisation of technology, agile development processes and lower costs are hallmark features of NewSpace[viii]. These NewSpace approaches have been leveraged by the University of Bern (prime contractor of this activity) for efficient resource-use, precise measurements and enhanced data processing, making missions and space exploration more cost-effective and accessible.

This project is led by the University of Bern, who has extensive experience in developing space exploration technologies, specifically mass spectrometers. The project began with an overall average Technology Readiness Level (TRL) of 3 – 4 and, due to ESA Discovery funding, was able to increase to an average TRL level of 4 – 5. Some of the hardware subsystems used to develop CubeSatTOF were already at TRL 9 prior to receiving ESA funding, meaning the project team used the funding to transfer the technology from other deep-space projects the University of Bern have been involved in to Earth Observation (EO) applications.

The technological maturity of CubeSatTOF, advanced thanks to the Discovery-funded activity, has led to its selection as the primary payload on board ESA's Constellation of

High-Performance Exospheric Science Satellites (CHESS) mission. The mission (anticipated to launch in 2028) aims to enhance our understanding of the Earth's upper atmosphere through direct measurements using two twin 3U CubeSats: Pathfinder 1 & 2.[ix]

… enabling robust and reliable analysis and modelling of the Earth's upper atmosphere …

The main purpose of a spectrometer, including CubeSatTOF, is to analyse the composition of the atmosphere. Whilst most EO activities are focused on optical observations of the Earth, this technology is concerned with understanding chemical dynamics of Earth's upper atmosphere.

Spectrometer data can help understand long-term atmospheric changes due to natural and anthropogenic factors. As part of follow-on work from this Discovery-funded activity, CubeSatTOF is demonstrating its capability to analyse the chemical composition of the thermosphere and exosphere of the Earth while in orbit through ESA's CHESS mission. It will measure the absolute number densities of various molecules, their dynamics, and, depending on the orbit, their altitude profiles. These measurements are crucial for exploring atmospheric escape, tracking long-term trends in the upper atmosphere, and studying the effects of space weather and their underlying drivers. This data will also support an atmospheric chemistry-based approach to modelling processes in Earth's upper atmosphere, essential for understanding climate change and other environmental phenomena. Additionally, thanks to the CubeSatTOF's unprecedented 1 km lateral resolution, the applications can also extend to space traffic management in cooperation with a GNSS device onboard the satellite. As the mass spectrometer can only provide relative measurements number densities used for space traffic, using it with a GNSS device could provide absolute measurements, significantly increasing the accuracy and reliability of the data.

The applications of this technology are versatile across sectors. In industry, it can enable commercial organisations to monitor processes to optimise emission control. In defence and environmental management, it can be used by governments to monitor the chemical compositions of the atmosphere for pollution control and potentially check for chemical warfare.

…and possible future applications in deep-space missions…

ESA's Discovery funding served as the catalyst for CubeSatTOF to achieve the necessary level of technological maturity to be selected as one of the primary payloads of ESA's CHESS mission. The in-orbit demonstration of CubeSatTOF through the ESA CHESS mission will help validate the technology, acting as a first step towards other future applications. For example, in the future, the payload could be part of a descent probe, where the host spacecraft could deploy a nanosatellite equipped with CubeSatTOF, enabling it to descend and analyse the chemical composition of the object in detail. The full-scale version of the CubeSatTOF technology will be designed to meet the demanding conditions of deep space (e.g., low levels of contamination, rapid changes in temperature, radiation), enhancing the potential for scientific discovery in challenging extraterrestrial environments. This instrument's capabilities may significantly increase our understanding of volatile compounds on celestial bodies and assess atmospheric escape dynamics.

Deep space mass spectrometers currently in operation are designed for encounter velocities of 20 km/s. The instruments slow down incoming gas streams through collisions with chamber walls. This leads to molecular fragmentation, which limits accurate scientific assessment. The novel ion-optical systems of the full-scale CubeSatTOF, which can handle the same 20 km/s encounter speeds, enhances the reliability of these analyses by use of a contactless gas intake and avoiding molecular fragmentation. This allows for critical advancements in accuracy and applicability in analysing high-speed extraterrestrial and terrestrial samples.

… delivering potentially valuable socio-economic benefits …

While the technology needs to be matured further and commercialised before the most significant benefits are realised, **some important benefits have already been realised at this early stage** through this Discovery-funded activity.

Fostering growth for students and early-career professionals

This activity allowed ~120 students per year to be involved in mission design, supported the research of 6 students' theses (up to a Master's level) and upskilling of early-career scientists, equipping them with valuable experience and technical know-how.

ESA Discovery funding has enabled the project team at the University of Bern to support the growth and development of students and early-career professionals in physics, electronics engineering, mechanical engineering, thermal engineering and systems engineering. 6 students were involved in the project directly as part of their theses (up to a Master's level), supervised by experienced engineers and scientists. Around 120 students were also involved over the duration of the project in mission design. Early-career scientists developed advanced skills in working in highly technical areas, focusing on hardware and software aspects of the project, improving their efficiency for subsequent projects. These skills are not readily available on the job market, meaning the project helped develop highly-skilled workers with desired profiles for future employers.

Up-skilling and supporting the workforce

The University of Bern's project team were able to advance existing capabilities in the development of ultra-compact mass spectrometers through the use of NewSpace techniques.

This project has enabled skills development in the architecture of the mass spectrometer – miniaturising size and weight while also improving performance. One of the University of Bern's main achievement lies in the removal of high-voltage connectors, which otherwise cause significant risks to spaceflight. This Discovery-funded activity enhanced skills across the team in rapid prototyping, a key technical skill, as they had to create many iterations of this technology as quick as possible. Other skills including analogue electronics, increased software abilities, high-voltage power supplies were also acquired in a short period of time. The University of Bern's team had to also develop ways to meet the high requirements for space technologies (e.g. radiation resilience) while keeping costs low and development cycles short – fitting the NewSpace paradigm[x]. While the University already has extensive expertise in deep space projects, this activity has enabled them to gain valuable transferable capabilities that can be leveraged for future NewSpace opportunities.

Across the duration of the project, the team have been able to hire and support 1 FTE (full-time equivalent): a senior engineer, whose role and skills developed by working on CubeSatTOF will be kept in-house to further the development of the Laser ablation Ionization Mass Spectrometer (LIMS). The LIMS device is being designed and built by the University of Bern to study the chemical make-up of lunar soil and will be launched in 2028 as part of the NASA Commercial Lunar Payload Services initiative. The type of skills taught on this project are also not readily available on the job market. The applicability of these skills from one project to another highlight the value of the Discovery-funded activity in training and upskilling new hires to the standards of the space industry, enabling them to work on other deep-space projects, increasing overall efficiency.

Strengthening reputation and heritage

The University of Bern has an established reputation in developing mass spectrometers. Discovery-funded activities led to the publication of papers and allowed the team to attend conferences, overall enhancing the university's global visibility.

The University of Bern is a key player in the field of mass spectroscopy. Most recently, it has contributed the NIM mass spectrometer[xi] (part of the Particle Environment Package) flying on ESA's Jupiter's Icy Moons Explorer (JUICE) mission, and has also been involved in the development of two other instruments on the same mission: the SWI Sub-millimetre Wave Instrument and the GALA Laser Altimeter[xii]. The University of Bern also leads the Characterising Exoplanets Satellite (CHEOPS) mission, a Switzerland-led joint mission with ESA[xiii]. Its contribution to these missions highlights its expertise in building mass spectrometers, driving innovation in space and expanding our understanding of the Earth and the cosmos.

The development of CubeSatTOF has allowed the University of Bern to strengthen its position in the field and further enhance it by demonstrating its capabilities in developing NewSpace devices/instruments. The project has led to increases in visibility within ESA and across the wider community, for both the University of Bern and the novel CubeSatTOF technology. The activity notably generated three papers[xiv,xv,xvi] and 9 presentations at conferences and workshops. Additionally, the project lead was optimistic about potential future partnerships and collaborations, having received interest from industry and government. CubeSatTOF's potential defense applications have also been investigated. Overall, through this increased visibility and strengthened reputation, the Discovery-funded project has enhanced the university's competitiveness to secure high profile mission contracts and further funding, including within the NewSpace realm.

Enhancing market access and potential collaboration interest

Considering the growing spectrometry market and advanced capabilities of CubeSatTOF, the contractor is keen to explore future collaborations and partnerships driven by the availability of atmospheric monitoring data.

One of the main areas of application for this technology is juncture between Space Weather and Earth Observation – more specifically, the monitoring and analysis of the dynamics in the upper atmosphere. The global spectrometry market is expected to grow at a compound annual growth rate (CAGR) of 5.9% from 2022 – 2030[xvii], with the demand for a modular structure, high-performance and cheaper payloads rising alongside it. This miniaturisation of a mass spectrometer, in CubeSatTOF, enhances the feasibility of deploying this technology in mobile terrestrial applications, at a lower cost – for example, to monitor volcanic emissions or track chemical pollutants.

The project lead reported that new collaborations and partnerships (e.g. scientific or commercial in nature) will be enabled once the data from the in-orbit demonstration on the ESA CHESS mission is available – with the team already receiving interest from government and industry, specifically the defence and public-private sectors, scoping potential future collaboration.

The project team is also seeking ESA PRODEX funding as a follow-on to this activity. This would enable them to collaborate with an industrial partner to further the design and development of this instrument and in turn, increase market access within the field of mass spectrometry.

Spillover to other sectors

Miniaturisation processes and lighter component development demonstrated by CubeSatTOF can benefit wide-ranging sectors by improving efficiency and reducing costs.

Innovations resulting from the Discovery-funded development of CubeSatTOF, particularly in areas like miniaturisation and the development of lighter components, can lead to spillover benefits (e.g., increased efficiency and cost reductions) in other sectors such as electronics, aerospace, and manufacturing.

Would these benefits have been realised without ESA?

Although the funding value was small, ESA's Discovery support came at a crucial point in the technology development process, helping de-risk and mature the ultra-compact mass spectrometer solution. Without ESA's funding, the project team would have been unable to advance from a laboratory prototype to accessing an in-orbit LEO demonstration, as they reported that funding opportunities for early TRL hardware R&D are significantly limited. The main impact of the funding has been the CubeSatTOF mass spectrometer being selected as one of the main scientific payloads to launch on ESA's CHESS mission in 2028.

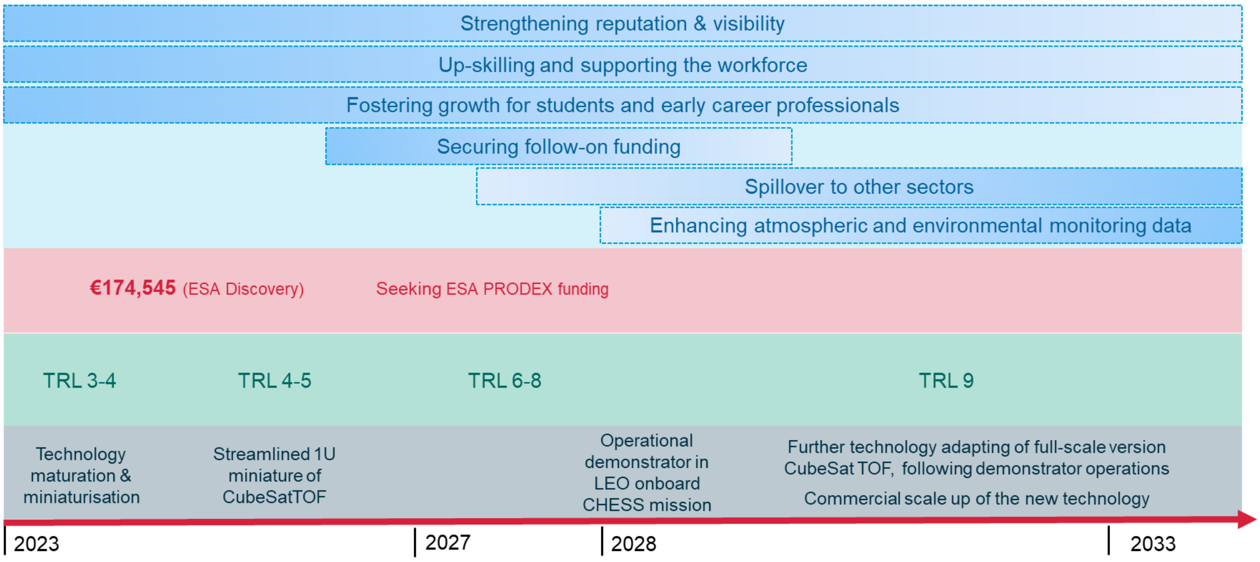
"Without ESA, it would have been really difficult to develop this technology from a lab prototype to now flying a LEO demonstration, as it is hard to get early R&D funding such as this. The funding came at the right moment to reduce risk." – Dr. Rico Fausch, University of Bern

Next steps: Further development, further benefits

Once CubeSatTOF demonstrates its capabilities in LEO as part of the CHESS mission, new partnerships will be enabled for the use of that data, as there is already interest from industry and government.

A preliminary timeline overview of the Discovery-funded 'ultra-compact mass spectrometer' project and associated potential benefits is provided below. However, these next steps and their impact are entirely dependent on the availability and timeliness of funding.

Overview of the timeline of the ultra-compact mass spectrometer project and the potential associated benefits



Source: know.space based on University of Bern data

Key priority indicators

Programme	Discovery
Country	Switzerland (CH)
Activity cost	€174,545
Duration	18 months
Lead contractor	University of Bern
Sub-contractors	-
TRL progression	Started at TRL 3-4 on average and increase +1, hardware now TRL 4-5. Some subsystems were already at TRL 9.
Spin-in into the space sector	-
Jobs supported	1 job created (senior engineer) + 6 students working on this project (as part of their theses) and ~120 students involved over the duration of the project (1.5-year project duration)
New collaboration with ESA	Previously worked with ESA.
Partnerships created	-
Follow-on funding applied/secured	In-orbit demonstration on the CHESS mission + seeking ESA PRODEX funding (award decision pending)

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