PRODEX PROJECT APPLICATION

(Version 1.6, June 2022)

to be submitted to:	space@sbfi.admin.ch
or:	State Secretariat for Education, Research and Innovation SERI Swiss Space Office, PRODEX Einsteinstrasse 2 3003 Bern

Name of the proposal:

CHESS pathfinder 1 - A CubeSat Constellation for High-Performance Time-of-Flight Mass Spectrometry to study the Earth's Exosphere

Name of the experiment/instrument:

Instrument Suite for Exploration of Earth's exosphere and ionosphere (ISEE)

Primary payload: CubeSatTOF: the next generation of mass spectrometers

Secondary payload: A precise and power-efficient multi-GNSS receiver module with real-time density calibration capability

Name of the mission or platform:

The CHESS pathfinder 1 a 3U nanosatellite platform for exploration of Earth's upper atmosphere.

Phase:

Implementation Phase (C-D)

Swiss Principal Investigator for this proposal:

Name and first name:	Prof. Jean-Paul Kneib
Affiliation and position:	Director of the EPFL Space Center
Address:	route Cantonale, 1005 Lausanne
Phone number:	+41 79 733 2111

to be submitted to:
State Secretariat for Education, Research and Innovation SERI
Swiss Space Office, PRODEX
Einsteinstrasse 2, 3003 Bern
space@sbfi.admin.ch

1 Summary

1.1 Abstract

CHESS is a Swiss space initiative federating academia and industry partners to drive multiple space experiments by developing Swiss-made scientific instruments. The primary science objective of this request is to improve the understanding of the upper atmospheres of planets by in-situ measurements. Taking advantage of the cost-effective CubeSat standard, we hereby propose a nanosatellite-compatible instrument suite to study the chemical composition of the terrestrial exosphere and its density in situ. The suite consists of a miniaturised time-of-flight mass spectrometer led by the University of Bern as the main payload, and a high-precision multi-GNSS payload board with four receivers conceived by ETHZ. These payloads will provide unique, long-awaited data from Earth’s upper atmosphere, namely the number density of species, altitude profiles of them, total electron content, ion population, and its dynamics. This dataset will be used for atmospheric sciences, Earth observation and planetology, updating 40-year-old measurements in many international and national institutions. EPFL leads the platform and management. Other contributors such as HE-Arc, HES-SO, HSLU, and RUAG provide avionics and devices for testing. The multiple space heritage of those actors paves the way for a successful mission regarding science, technological development, and education inside the Swiss space ecosystem.

1.2 Discipline

Atmospheric Sciences	Solar Observations	Life Sciences
Earth Observations	Astronomy	Materials Sciences
Space Plasma Physics	Technology	....

Experiment type:
- Hardware
- Software
- Science operations

1.3 Timeline

Starting date of experiment/instrument development	March 1, 2023
Starting date of this request	March 1, 2023*
Completion date of this request	December 31, 2025
Expected launch date	March 1, 2026

*: earlier if possible. Completion date and expected launch dated shift accordingly.

1.4 Requested PRODEX funding (in Euros)

Applied exchange rate: 1.10 CHF/EUR

This request (Phase C,D)	**~~2’657’466~~2’657’445.76**	**Euro**
Previous requests (Phase …)	0.00	Euro
Potential future requests (Phase …)	0.00	Euro
Total	**~~2’657’466~~2’657’445.76**	Euro

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1.5 Expected yearly budget for this request (in Euros)

Total

Year	**2023**	**2024**	**2025**	Total (€)
Budget	407’916.82	1’023’090.58	1’226’459.36	2’657’445~~66~~.76

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EPFL share

Year	**2023**	**2024**	**2025**	Total (€)
Budget	36’333.82	43’600.58	127’168.36	207’102.76

ETHZ share

Year	**2023**	**2024**	**2025**	Total (€)
Budget	67’313.00	163’009.00	113’889.00	344’211.00

UBE share

Year	**2023**	**2024**	**2025**	Total (€)
Budget	304’270.00	816’47~~81~~2.00	985’390~~402~~.00	2’106’132~~53~~.00

Table 1: PRODEX yearly budgets

2 Signatures

Swiss Principal Investigator
Prof. Jean-Paul Kneib
EPFL Laboratory of Astrophysics
Lausanne, Nov 1, 2022

Endorsement by the department/university
Prof. Jean-Paul Kneib
Director of the EPFL Space Center
Lausanne, Nov 1, 2022

Co-Investigators

Dr. Gregor Moeller
Eidgenössische Technische Hochschule Zürich (ETHZ)
GNSS Receiver Instrument Lead
Zurich, 31/10/2022

Dr. Rico Fausch
University of Bern (UBE)
Co-PI of the CubeSatTOF Instrument
Bern, 31/10/2022

Prof. Peter Wurz
University of Bern (UBE)
Co-PI of the CubeSatTOF Instrument
Bern, 1/11/2022

Mr. Aziz Belkhiria
École Polytechnique Fédérale de Lausanne (EPFL)
President of the EPFL Spacecraft Team
Lausanne, 31/10/2022

3 Experiment description and development plan

3.1 Scientific background of the mission and objectives of the Swiss experiment

The objective of this experiment is to improve our understanding of Earth's upper atmosphere. The science case for this mission was summarised in reference (Fausch et al., 2022):

Our detailed understanding of Earth's atmosphere becomes limited at the exobase. In the last decades, Earth's atmosphere has attracted considerable attention, especially regarding weather and climate change. Chemical composition, number density, and temperature influence these phenomena. Depending on the altitude and the measurement itself (for example, temperature, pressure, chemical composition such as humidity, ozone concentration, particulate matter pollution in cities, and more), there is a low latency between the actual measurement and the time of availability of the data. In fact, most Earth observation systems provide almost real-time data of measurements from the lower and middle atmosphere these days. This status contrasts the upper region of our atmosphere, which completely lacks real-time measurements or, even more recently published, reliable data of the chemical composition and exospheric temperature.

Measurements of the chemical composition of Earth's upper atmosphere led to the currently available models of the exosphere. Mass spectrometers analyzed species up to an upper mass limit of about m/z 50 (Hedin et al., 1973; Nier et al., 1973; Pelz et al., 1973; Carignan et al., 1981) covering the mass range of the major species in the upper atmosphere (H, N, O, N_2, CO, NO, O_2, Ar; H^+, He^+, N^+, O^+, N_2^+). Measurements in this mass range were ceased after the successful measurements of the Dynamics Explorer launched in 1981 (Carignan et al., 1981). The resulting data provided updates to the Jacchia-70 type models using total mass density (inferred from orbital decay) (Jacchia, 1970) leading to the empirical (US) Naval Research Laboratory (NRL) – mass spectrometer and incoherent scatter radar models of the atmosphere (MSIS) MSIS-86 (Hedin, 1987) and MSISE-90 (Hedin, 1991). COSPAR International Reference Atmosphere (CIRA) models have also been used, especially in climate modelling (see discussion in (Picone et al., 2002)) but were mostly replaced by the International Reference Ionosphere (IRI) model of the ionosphere (Bilitza, 2018). NRLMSISE-00 (Picone et al., 2002) became the standard model for the chemical composition of species in the upper atmosphere for years (Figure 1, right panel). It was more recently upgraded with the NRLMSISE 2.0 (Emmert et al., 2021) but both models still rely mostly on measurements of the lower thermosphere or mass spectrometric data of the 1980s. Although several groups have identified this gap, both missions and instruments designed to fill it either failed, or considerable vary in scientific performance, or are scheduled for launch in the (far) future (Cutler, Ridley and Nicholas, 2011; Rodriguez et al., 2015; Kepko et al., 2017; Guo et al., 2018; Paschalidis et al., 2019; Agathanggelou et al., 2020; Klenzing et al., 2020; Sarris et al., 2020; Attrill et al., 2021). However, the desire for updated data is persistent as illustrated by NASA science mission directorate's recent announcement on its planning for a Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) mission and the solicitation for the Geospace Dynamics Constellation (GDC) mission. Both missions will address the dynamics of the atmosphere.

Above about 200 km altitude, the atmosphere is strongly driven by electromagnetic forces resulting from the interaction of the solar wind with the Earth's magnetosphere. Thus, the dynamics in the upper atmosphere cannot solely be described by measurements of the neutral species but requires a profound understanding of the coupling processes between the thermosphere and ionosphere. Ionospheric models such as the latest release of the International Reference Ionosphere model (IRI-2016, (Bilitza, 2018)) can capture large parts of these dynamics but strongly depend on the synthesis of available and reliable measurements, for example, from ionosondes, incoherent scatter radars, rockets, topside sounders, and in-situ satellites. Further improvements in ionospheric modelling require a further densification of existing observing networks in critically under-sampled regions in the ionosphere, for example, in the form of global navigation satellite system (GNSS) based electron maps or topside profiles (Bilitza, 2018).

The understanding of Earth's upper atmosphere directly connects to numerous research fields related to both basic research and applied science. This selection of topics provides insights into how society relies on this under-estimated dataset.

Earth's Upper Atmosphere

Earth's upper atmosphere is a complex region, as it has multiple drivers whose influences remain unclear. Depending on the usage, either the ionosphere or thermosphere-exosphere are considered. Parameters of interest are the chemical composition, number density, temperature, and total electron content. Whereas the ionosphere has significant amounts of ions and electrons, the thermosphere and exosphere mostly contain neutral species, as the abundance of the ions is about two decades lower. The thermosphere is characterised by the region in which many collisions of species statistically determine the particle trajectories and the macroscopic physical parameters (Knudson number $\ll 1$). The higher the altitude, the more the density decreases. Above the exobase, the particle trajectories of species are dominated by ballistic trajectories rather than by statistical collisions as observed in the thermosphere (Knudson number $\gg 1$). The transition from the thermospheric to the exospheric regions is the exobase that is estimated to be located at about 300 km altitude, where the Knudson number, i.e., the ratio of the mean free path to the characteristic length scale, is about 1. The Sun and other drivers influence the altitude of the exobase (Emmert, 2009; J. T. Emmert, 2015a). Although all the drivers are thought to be identified (see e.g. (Emmert, 2009; Prölss, 2011; J.T. Emmert, 2015b; Laštovička and Jelínek, 2017) and references), their exact influence remains largely unconstrained. Only new, highly sensitive and in situ measurements of the chemical composition, the number density, and the total electron content may advance this enduring debate.

Exospheres in Comparative Planetology

Exospheres represent the interface between interplanetary space and the celestial object. A fraction of the species present in the exosphere constantly leaves Earth into space. As the extent of these atmospheric escape processes is species dependent, atmospheres may evolve over their lifetime. A planet's atmosphere may evolve from a toxic atmosphere as found on present Venus to a life-bearing atmosphere as found on present Earth. Venus, Earth, and Mars are shown to have a very similar composition (rocky planets) and similar initial atmospheres during the times of the early Solar System (Füri and Marty, 2015). Modelling the evolution of the Earth with these initial conditions and with the currently assumed atmospheric loss rates leads to a version of Earth that severely contradicts our today's observation, for example, a habitable planet (Lammer et al., 2020). As the difference in chemical composition of the atmospheres of three siblings cannot solely be explained by enhanced Jeans escape, a unique evolution of Earth has to be considered. In situ investigation of Mars' and Venus' atmospheres (Mars Express, Venus Express, and Mars Atmosphere and Volatile Evolution MAVEN) found a considerable non-thermal (ion) contribution to the atmospheric escape that could explain this inconsistency. However, no sufficiently accurate data of Earth's exosphere are available to conclude on this issue.

Currently, two methods exist to determine Earth's thermal escape: 1) Thermal escape can be modelled from the temperature and the density profiles of species by subtracting the superthermal contribution, which is inferred from velocity distributions of the species of present in the exosphere (Brinkmann, 1970). This approach requires a neutral and ion mass spectrometer for in situ measurements. 2) Plasma instruments are used to cover the complete energy range of ionic species to determine the energy distribution of them as well. The latter approach is currently not feasible given the size of the required instrumentation, especially for CubeSats.

Earth Observation, Space Weather, and Climate Change

Objects orbiting Earth as satellites constantly interact with energetic particles of the tenuous exosphere causing drag. Drag is beneficial as it causes space debris to decelerate and ultimately re-enter into Earth's atmosphere. Especially, CubeSat designers are encouraged to meet the Inter-Agency Space Debris Coordination Committee (IADC) orbit lifetime policy stating that objects shall re-enter 25 years upon end of life. The lifetime of satellites is modelled using the density (and chemical composition) of the exosphere, the geometry of the satellites, and orbital parameters. Forward propagation of orbital elements is already challenging in a short time scale, for example, for re-entry into Earth's atmosphere, but almost impossible in the requested lifespan as the density models are poorly constrained. Another issue for satellite designers is the largely unknown chemical composition of the exosphere. On a microscopic scale, drag is caused by the constant bombardment of particles on a satellite's surface. This chemical sputtering degrades solar cells considerably, limiting their lifetime. Unfortunately, as the chemical composition has to be estimated and might be off by factors (e.g., Krall et al., 2018), designing appropriate surfaces remains an inefficient task.

The short-, medium-, and long-term dynamics of the upper atmosphere (human timescales) provide opportunities for humankind but may also involve threats. There is an ongoing discussion on the long-term trends and variations of the parameters defining the upper atmosphere as of anthropogenic origin (Laštovička et al., 2006; Laštovička and Jelínek, 2017, 2019; Solomon et al., 2018, 2019; Danilov and Berbeneva, 2021). A cooling of the exosphere is shown, causing the exobase to contract to lower latitudes. The reduced drag at a given altitude implies an increased lifetime of objects in space. An increased lifetime of space debris may threaten both the access to space in the future and projects such as the international space station (ISS). In the medium-term, satellite operators depend on space weather forecasts. These forecasts are substantially complicated, as, among other reasons, not even the current status of the exosphere is exactly known. In short-term, possibilities to capture earthquake precursors have been suggested by identifying disturbances in the chemical composition and in the density (e.g., (Doda et al., 2011; Skorokhod and Lizunov, 2012; Jin, Occhipinti and Jin, 2015; Korepanov, 2016) and references). Further sophisticated, sensitive in situ measurements are needed to provide evidence for such a speculative hypothesis.

Objectives

We conceived the constellation of high-performance exospheric science satellites (CHESS) mission to provide updated data conducted with state-of-the-art, high-performance instrumentation. At a later stage, with more units, low latency of data collection will be realised. The CHESS missions will fill the gap of space-time degeneracy in chemical composition, number density measurements of the exosphere and electron density measurements of the ionosphere.

The roadmap of the CHESS mission foresees a stepwise implementation as part of a 3-step plan. Step-1 (this request) consists of flying the CHESS pathfinder 1 payloads. In the framework of both CHESS and the payloads, the mission serves as a technology demonstrator. Despite this mission and its payloads will be carefully implemented to reduce risks (see section/annex 5.1~~TDB~~), the follow-up constellation will benefit from lessons learned during the pathfinder mission. It is foreseen to place the CHESS pathfinder 1 satellite into an elliptical orbit with a perigee of 1000 km and an apogee between 180 and 400 km (Figure 1, left panel). In the framework of science, measurements of the CHESS pathfinder 1 payloads will already provide reliable, valuable in situ data. These data will already solve top priority science questions.

~~In the framework of the anticipated constellation, the objective of this request is to build instrumentation to fly the CHESS pathfinder 1 payloads. This mission foresees a perigee of 1000 km and an apogee between 180 and 400 km.~~ The three primary mission objectives are:

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A—Create an inventory of chemical species and determine the total electron content present in the exosphere and upper ionosphere to serve as a data archive for Earth observation including space weather and climate change, comparative planetology including astrobiology, and space mission design of satellites. In addition to the inventory itself, the selected payload will provide number densities (partial pressures) of species and altitude profiles of them for providing insights into the origin and evolution of the Solar System (see also Figure 1).

B—Analyse the dynamics of the chemical composition of the species and the total electron content. To determine both the drivers themselves and their influence on the upper atmosphere in detail, we measure these variables each at an instance, locality (in the orbital plane) and along the line-of-sight to the GNSS satellites in view.

C—We use these data to couple them with data from other Earth observation services to establish a real-time monitoring system of Earth's upper atmosphere. This CHESS pathfinder 1 mission will determine the parameters of the follow-up CHESS missions, for example, constellation parameters such as number of needed satellites and orbit parameters, instruments on board the satellites, their parameters, and, especially, the need for further space-time-locking of the measurements.

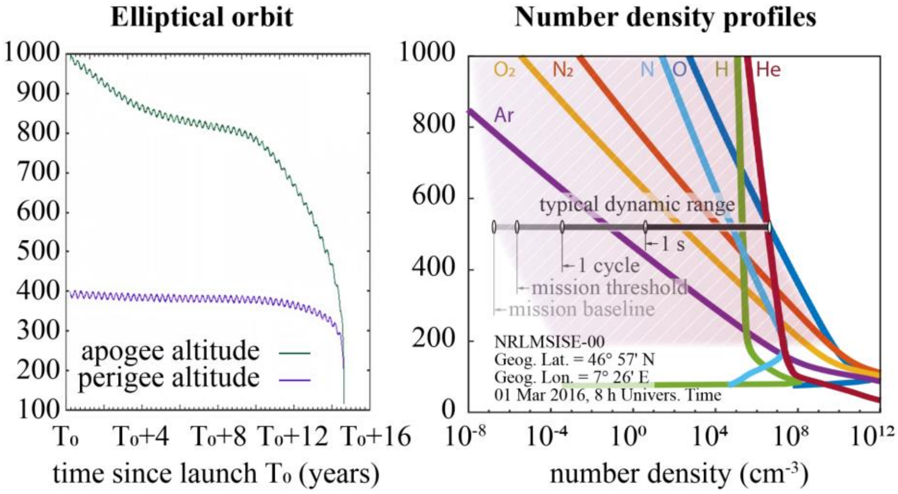

Figure 1: The altitude profile of the CHESS pathfinder 1 satellite is indicated in case of 400 km perigee orbit (worst case). Despite the apogee will decrease over time (left panel), there is sufficient time for performing measurements, especially at the lower altitudes to investigate the lower thermosphere-ionosphere region. The dynamic range of the CubeSatTOF mass spectrometer (red highlighted region, right panel) in combination with the capabilities of the GNSS payload board empower the satellite to measure the theoreticized altitude profiles of the number density of species in situ, with the highest currently feasible accuracy (right panel).

Step-2 foresees flying at least one other satellite in a similar, circular, or polar orbit. The current mission architecture of Step-2 will be adapted according to the lessons learned in Step-1 (goal C). If identified in the CHESS pathfinder 1 mission, a second mass spectrometer and GNSS will be selected as payloads, which likely will be the case, to fly on the CHESS pathfinder 2 satellite (or maybe more satellites). We anticipate that the next step for the scientific community will be to overcome space-time degeneracy, i.e., measure with two platforms on different locations at the same instance. CHESS pathfinder 1 (Step-1) is already designed to anticipate this follow-up mission. However, upon passing the technology demonstration level, funding of such a mission is considered to be shifted towards

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ESA. Programs sharing the vision of CHESS include Scout missions and FutureEO. Given that the Scout missions require payloads to be delivered within 3 three years, from kick-off to launch, this mission could be launched in about 2030.

Step-3 foresees implementing a network of satellites to constantly monitor Earth's upper atmosphere and understand its dynamics in more detail overcoming spatially-sparse measurements. Step-2 will finally conclude on constellation parameters to be implemented in Step-3. About 24 satellites could be reasonable. Its funding will be channelled preferably into a COPERNICUS programme element. Such a shift of responsibilities will improve data quality of a constellation, as it will benefit from a better coordination of measurements with other satellites and/or ground-based measurements. A constellation is anticipated for 2035 or later.

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3.2 Detailed description of the instrument, parts of instruments and/or software to be developed

The CHESS pathfinder 1 satellite carries two major scientific instruments namely the mass spectrometer, CubeSatTOF, and the GNSS receiver payload board. CubeSatTOF provides the chemical composition of both the neutral particles and ions and provides altitude profiles of number density data for each species, from which exospheric temperatures will be derived. These measurements are improved by GNSS estimates of total electron content, which can be converted to the number density. In addition, the GNSS receivers enable precise determination of each satellite's orbit, and the drag, from which estimates of atmospheric density can be derived. Combining these data, this instrument suite uniquely provides absolute values for the number density of species, and their altitude profiles. To the best knowledge of the authors, even recently outlined projects in the early concept phase lack this valuable opportunity.

The CubeSatTOF Instrument

The CubeSatTOF instrument is a neutral and ion mass spectrometer of 1U size (1 l; 10x10x10 cm^3) for quantitative chemical composition analysis of tenuous atmospheres. It is described and characterised in detail in the references (Fausch et al., 2019, 2020, 2022, submitted-A). This instrument uses the time-of-flight (TOF) technique to analyse species. TOF mass spectrometers have been widely used for the analysis of planetary atmospheres (Scherer et al., 2006; Abplanalp et al., 2009; Wurz, Abplanalp, Tulej and Lammer, 2012; Föhn et al., 2021) since they measure the complete mass range simultaneously in about 100 ms translating at low Earth orbit (LEO) to a spatial resolution of about 1 km, depending on orbital parameters.

Atmospheric processes include chemical reactions, the formation and destruction of molecular species. As we cannot observe the reactions themselves, we analyse the reactant and the product of such reactions statistically with a high sensitivity, allowing for identification of both major and minor processes. To do so, the CubeSatTOF instrument is designed to analyse species in a mass range m/z of about 1 to 200. The mass resolution which is necessary to achieve this mass range was recently demonstrated (Fausch et al., 2020, 2022), outperforming comparable instrumentation by at least an order of magnitude (e.g., Rodriguez et al., 2015).

The CubeSatTOF instrument measures the stream of gas incoming into the mass spectrometer directly. Thanks to this novel direct open source mass spectrometry technique (DOeS-MS), radicals and even heavy species preserve their chemical identity while entering the instrument. Thus, it can measure even complex (bio) molecules in its extended mass range. This allows for measurements of fragile, reactive and complex molecules such as O_3 and N_xO_y. A typical dynamic range of about 10^6 in 1 s can be reached by the CubeSatTOF instrument thanks to its heritage from the Neutral Gas Mass Spectrometer (NGMS) on board Luna-Resurs (Abplanalp et al., 2009; Wurz, Abplanalp, Tulej and Lammer, 2012; Fausch et al., 2018) and the Neutral and Ion Mass Spectrometer (NIM) on board the Jupiter Icy Moon Explorer (JUICE) (Föhn et al., 2021), both approx. 25 cm instruments. The longer the instrument measures in space, the higher the dynamic range will be, as the measurements can be accumulated (see also Figure 1; e.g., reference (Wurz, Abplanalp, Tulej, Iakovleva, et al., 2012)).

Achieving this dynamic range with the necessary sensitivity is possible thanks to the carefully designed, sensitive read-out electronics. The electronics draw substantial heritage from the NGMS/Luna-Resurs and NIM/JUICE design, and the currently developed Mass Analyzer for Neutrals and Ions at Comets *(*MANIaC) / Comet Interceptor instrument. In fact, the currently anticipated flight design of CubeSatTOF inherits almost all concepts of NGMS / NIM. However, CubeSatTOF is simpler, as the complicated connection to a gas chromatograph (NGMS) is omitted and it does not require space-grade high reliability (Hi-Rel) components (NGMS / NIM). This design freedom allows for using Commercial Off-The-Shelf (COTS), hence drastically increases the availability of components, reduces costs of them, and condenses schedule. To partially compensate for the lack of reliability, military grade components will be used where reasonable (we nevertheless refer to them as COTS components) and extensive testing will be conducted. In addition, the instrument benefits from technological advancements, though the underlying concept remains the same.

The orbits designed for only require only limited use of radiation mitigation techniques (Fausch et al., 2018), especially given the CubeSat nature of this project. We decided to use spot shielding, for example, with Ta or W, on selected components and subsystems where necessary (Fausch et al., 2022). The electronics are enclosed with about 0.5 mm Ta additionally.

Since the first tests with this ion-optical system in 2019, the instrument underwent extensive prototyping and concept proofing (Fausch et al., 2019, 2020, 2022, submitted). The instrument successfully passed all relevant milestones regarding testing of the subunits, corresponding to about the end of phase B. The tests included, for example, performing background measurements in a vacuum chamber (see Figure 2, left panel (Fausch et al., 2020)) and testing the instrument exposed to neutral gas beams, representing measurements in orbit (right panel, see (Fausch et al. 2022) for a detailed description), and electronics and mechanical tests.

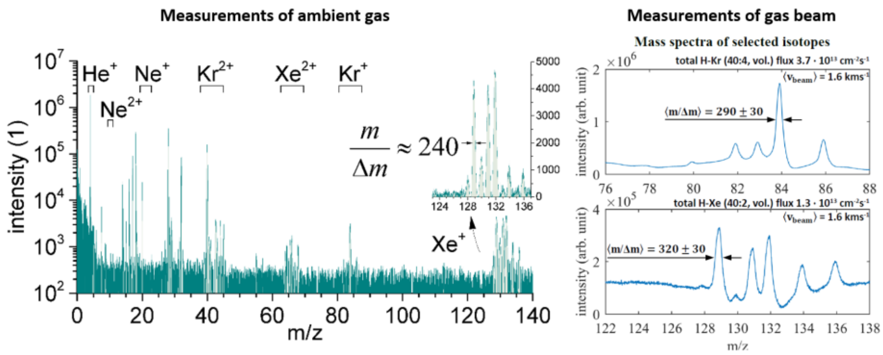

Figure 2: Typical mass spectra from prototypes of CubeSatTOF. The mass range would be about 1 to 200 as enabled by the mass resolution of about 240 full width at half maximum, (left panel) if the gas has thermal velocities (ambient gas). The mass range is clipped at m/z 140 for clarity purposes. Measurements with accelerated gas provide reference measurements once in low Earth orbit (right panel). References are provided in the text.

The proposed flight design includes four boards namely the sensor board, the detector board, the digital board, and the power board. The digital, sensor and power board are stacked representing a card rack, as usual for CubeSats (see section 3.5.1, WP1.1.2 for more detail). Figure 3 shows the ion-optical system mounted on top of the sensor board (panel A) with the detector including its proximity electronics, and the Data Processing Unit (DPU) stacked on top of the sensor board for electronics front-end testing and testing of the DPU (Fausch et al., submitted-A). This instrument achieved superior performance to its competitors while maintaining an ultra-compact form factor.

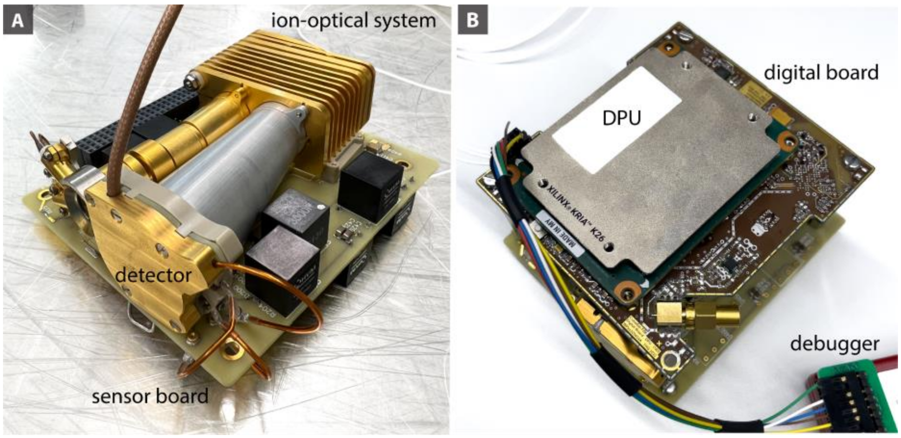

Figure 3: Breadboards allow for testing of the subsystems. The ion-optical system is directly mounted on the sensor board printed circuit board (PCB) (A). The detector board will be connected to the front-end electronics on the digital board with a SubMiniature version A (SMA) connector simplifying the commissioning phase (B). References are provided in the text.

Besides that COTS components enable this miniaturisation, the CubeSat nature of this instrument comes along with other benefits. Interfaces and units are standardised. This framework is in stark contrast to the typically customised space hardware. As interfaces are defined, concepts relating to the mass spectrometer are approved, and we were able to end the extensive prototyping phase, implementing a flight design of the CubeSatTOF instrument is considerably simplified as compared to its predecessors.

The instrument is miniaturised for two reasons: first, its scientific performance is sufficient for an application in, on one hand, Earth's upper atmosphere. Its mass range allows for a detailed investigation of present species in the exosphere. In addition, it is capable of performing measurements of the ions present in this region. Its sensitivity is state-of-the-art and comparable to other major instrumentation. Hence, relying on CubeSat standards increases the chance of being selected given this rapidly growing market. On the other hand, an application as a descent probe during a flyby of a major spacecraft of, for example, Uranus and Neptune, is enabled. The high-end scientific performance and the low size, weight, and power consumption considerably increase the selectability of such a concept. In addition, providing a flight-proven instrument further eases selection. As of yet, no comparable flight-proven instrument could be found in the literature. Moreover, it is imaginable that we are able to include the partners of this consortium in such a project thanks to future heritage.

Second, a bigger version of this instrument is considered for investigation of complex (bio) molecules during flybys on board major spacecraft, similar to NIM. Mission scenarios addressing the analysis of complex molecules have been limited by current instrumentation. Up to now, the maximal relative encounter velocity of current mass spectrometers has been a major constraint for design of their flight trajectories. Analysis of complex molecules is preferably done in open source mode. Due to the poorly understood chemical mechanisms, i.e., hypervelocity induced bond-dissociation and related inhibition of deriving meaningful data, ideal relative encounter velocities between 3 and 5 km/s were recommended for, for example, measuring bare amino and fatty acids to prevent fragmentation of the molecules. For higher velocities, the use of an antechamber leaves room for interpretation of the results given the chemical alteration caused by the interaction with the walls. CubeSatTOF will be upscaled to increase its mass range for deep space missions on board major spacecraft. Such an upscaled instrument overcomes this limitation and provides direct measurements at hypervelocity of up to about

20 km/s enabling mission concepts to analyse complex species during flybys reliably (Fausch et al., submitted-B). In addition, volcanic worlds also represent a possible target, for example, to Io. This bigger instrument serves as the baseline for the Io Volcano Observer (IVO) mission concept (McEwen et al., 2021), which will be submitted to answer the upcoming NASA New Frontiers call.

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The GNSS payload board

For satellites in LEO, aerodynamic forces are acting on the surfaces of a satellite as non-gravitational accelerations. These accelerations can be estimated together with the orbital parameters from GNSS measurements on board the satellite (Fong et al. 2008; von Engeln et al. 2011, Vallado and Finkleman, 2013; Schreiner et al. 2020). The temporal resolution of the estimates is dependent on the GNSS position accuracy and the satellite's altitude. For example, a GNSS position accuracy of 1 dm allows for estimating the atmospheric density twice per satellite revolution. Thereby, we assume that the atmospheric drag in the suggested LEO can be separated well from the other perturbing forces (solar radiation pressure, albedo, etc.). To reach this high level of accuracy, one of the preconditions is that the GNSS receiver is dual-frequency. On the one hand, this allows for mitigating dispersive atmospheric effects; on the other hand, this also enables the study of these effects by estimating the total electron content (TEC) along the signal paths to more than a hundred active GNSS satellites (Moeller, 2022b).

Since the beginning of 2022, a prototype of the GNSS payload board has been available (see Figure 4). With a size of 95 x 90 x 11 mm³, a weight of 65 g (without aluminium case) and a power consumption of about 0.5 W, it is designed for the operation on nano- and picosatellites. The motivation is to equip large nanosatellite constellations with these boards and therefore enable new observation concepts, e.g., for sensing medium-scale structures in the atmosphere using tomographic principles (Moeller et al., 2019; Moeller et al., 2021).

The GNSS prototype in its current state is based on four u-blox ZED-F9P dual-frequency multi-GNSS modules (www.u-blox.com/en/product/zed-f9p-module) and therefore, is, in principle, suited for centimetre positioning accuracy. For data handling and communication, we use a STM32L4 microcontroller with an external watchdog, an MRAM for storage of critical data and a NOR flash for the recording of the GNSS raw data. Additional bandpass filters, LNAs, and signal splitters are implemented directly on the board for interference mitigation, signal amplification and signal splitting to the four GNSS receivers. For signal reception, the GNSS receiver is connected to a passive GNSS antenna. So far, two antenna options have been tested: the CubeSat GNSS antenna from the Frauenhofer Institute in Germany (https://www.iis.fraunhofer.de/de/ff/lv/lok/gnss/) and the smaller commercial taoglas GPSF.36.A patch antenna. The Frauenhofer antenna generates a slightly stronger GNSS signal but in principle, both antennas can support the frequencies of the u-blox ZED-F9P receiver.


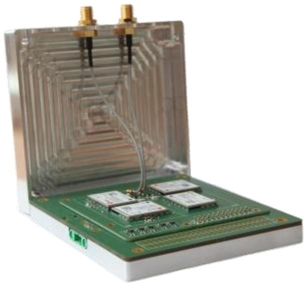

Figure 4: Prototype of the GNSS payload board developed at ETH Zurich together with Swiss industry partners

~~The up-screening of the existing GNSS module for the operation on nanosatellite missions has been conducted in a series of environmental tests at Beyond Gravity, Zurich, ETH Zurich, as well as the Paul Scherrer Institute, Villingen in 2021 (Moeller et al., 2022a). In summer 2022, the board was integrated into the Precursor satellite (http://precursor.space) for in-orbit validation. In addition, first experiences under orbital conditions have been obtained by operating the GNSS module with a Spirent GS900 GNSS signal simulator at EPFL, Lausanne and at the University of Stuttgart. Based on these experiments, a reasonable number of GNSS raw data was collected. It can be concluded that this power-efficient and low-weight GNSS receiver module is in principle suited for the operation in space but further development is necessary so that the functional requirements for the CHESS mission can be fulfilled.~~

~~In a feasibility study, a specification and requirement report has been compiled, which serves in the following as a guideline to define the development goals. They will allow us to convert the existing prototype GNSS payload board into a scientific instrument for studies of the Earth's exosphere~~

~~onboard the CHESS pathfinder mission. The developed instrument will function in the CHESS mission as a calibration source for the CubeSatTOF Instrument but can be also operated as a stand-alone instrument.~~

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In the CHESS pathfinder 1 mission, this GNSS board will be used as the basis for further development. In a dedicated feasibility study, a specification and requirement report has been compiled, which serves in the following as a guideline to define the development goals. They will allow us to convert the existing prototype GNSS payload board into a scientific instrument for studies of the Earth's exosphere onboard the CHESS pathfinder mission. The developed instrument will function in the CHESS mission as a calibration source for the CubeSatTOF Instrument but can be also operated as a stand-alone instrument

Development goals:

In addition to the existing functionalities of the prototype for precise orbit determination, the following features shall be implemented:

GNSS modes and states:

- The GNSS receiver shall be able to execute predefined scientific scenarios for radio occultation, atmospheric density estimation and electron density monitoring in coordination with the CubeSatTOF instrument
- Therefore, the GNSS board shall be operable in a PVT mode (for real-time Positioning, Velocity determination and Timing), scientific modes (GNSS raw data collection in varying receiver-antenna combinations and configurations) and maintenance mode (for firmware updates and configuration changes). In addition, the GNSS board shall be operable in user-defined scenarios uploaded from ground
- The GNSS board shall forward the undistorted time pulse for a precise time synchronisation of all subsystems involved in the coordination of the scientific measurements

Hardware modifications

- The Doppler search range shall be adaptable to the expected radial velocities between the CHESS satellite and the GNSS satellites in view
- The signal tracking loops of the u-blox ZED-F9P module shall be optimised for the tracking of dual-frequency multi-GNSS signals under high dynamics
- The signal tracking loops of the u-blox ZED-F9P module shall be optimised for the tracking of dual-frequency multi-GNSS signals affected by atmospheric refraction
- The GNSS antenna phase centre variations and code biases shall be known by calibration on a satellite mockup (GCM)
- All components > 0.1 W shall be well connected to a thermal dissipating PCB layer

Software modifications

- A boot loader shall be implemented into the payload software to allow for installation of software updates in form of images or image patches
- A scheduler shall be implemented to allow the GNSS receiver to sample the signals of specific GNSS satellites with 20 Hz (radio occultation)
- Appropriate receiver-antenna configurations shall be automatically identified by the payload software (by monitoring the GNSS signal quality) and selected accordingly
- The GNSS payload shall provide an event log and a housekeeping message informing about passed events, e.g. for problem analysis

Reliability and redundancy

- The GNSS payload shall have redundancy in all critical hardware components
- All components on the GNSS board shall be protected against latch-up events
- All important data shall be protected with a checksum or an appropriate hashing function
- The GNSS payload shall be functioning within a temperature range of ± 40°C with a temperature gradient of less than 2°C/min
- The GNSS payload shall withstand a total radiation dose of 20 krad and the average flux of the high-energy protons (> 1MeV) shall be below 4.8 x 10^8 p/cm² (leading to about one single event effect (SEE) every 12 days under quite conditions or one SEE every 6 hours during solar storms)
- The GNSS antennas shall be protected against corrosion by atomic oxygen by using a protective film

Interfaces

- The GNSS payload shall comply with the standards foreseen for the CHESS pathfinder mission in terms of connectors, hole positions, dimensions and power supply
- A voltage filter shall be installed to reduce the impact of strong variations in the power supply
- In addition to UART, the SPI interface shall be an assembly option
- The main supply shall be disconnected in case of overcurrent
- The GNSS payload shall support the communication protocol defined for the CHESS pathfinder mission
- The GNSS payload shall be able to receive, process and reply to commands from the ground system

Autonomous failure management

- The GNSS payload shall implement autonomous failure management
- On regular intervals, the GNSS board shall perform a set of self tests
- If a specific scenario fails, the receiver shall automatically switch to another receiver-antenna configuration
- If a specific scenario fails for all relevant receiver-antenna configurations, the receiver shall automatically switch to a default scenario
- The GNSS board shall implement watchdogs to ensure its functionality

Validation

- The GNSS orbit solution shall be validatable against an independent technique, preferably satellite laser ranging

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Code de champ modifié

3.3 Experimental techniques and technology to be developed

CubeSatTOF

The experimental technique to be used in the CubeSatTOF is a ultra-compact, fully-operational, spaceborne time-of-flight mass spectrometer. It benefits from the capability of directly measuring the incoming molecules without hypervelocity impact induced bond dissociation, which allows for reliably measuring complex molecules, radicals, isotopes, and atoms present in the exosphere, simultaneously. The existing prototypes answered their purpose of providing a flight design, which can now be realised in this project.

The GNSS payload board

A critical part in the development of the GNSS instrument is related to the signal tracking capabilities of the receiver module for signals at low elevation angles (~0 degrees and below). These signals are important for a proper projection of the ion concentration in flight direction so that a combination with the CubeSatTOF measurements becomes feasible.

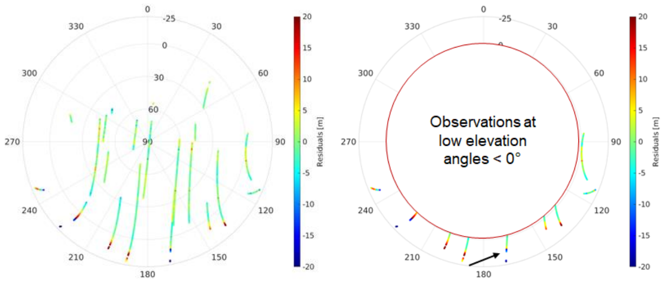


Figure 5: Carrier phase residuals [m] from a reduced-dynamic orbit fit. Left: The full skyplot with all signals tracked by a u-blox M8T receiver connected to a GNSS antenna pointing in flight-direction. Right: The same skyplot but with an elevation mask for signal above 0° elevation angle. Analysed data: 20 min of GPS L1 carrier phase measurements, recorded with 1Hz sampling rate on the Astrocast satellite P01S02 in the beginning of 2022

Based on the experiments with the u-blox M8T receiver onboard the Astrocast satellites, we are confident that a tracking of low-elevation signals is possible on GPS L1 (see Figure 5). We have to make sure that a similar performance can be obtained for the other signals (GPS L2C, Galileo E1/E5b, Glonass L1/L2). Only this will allow to fully exploit the capabilities of the dual-frequency GNSS receiver. Therefore, a series of optimization strategies shall be developed and tested to protect the GNSS antennas against environmental influences, reduce signal losses between antenna and receiver, minimise interferences with other subsystems (e.g., the ADCS system) and improve signal tracking in the receiver by defining an optimal Doppler search space. The challenge is that the optimization strategies for the GNSS receiver module have to be in the form of firmware updates so that it remains applicable to the available COTS components.

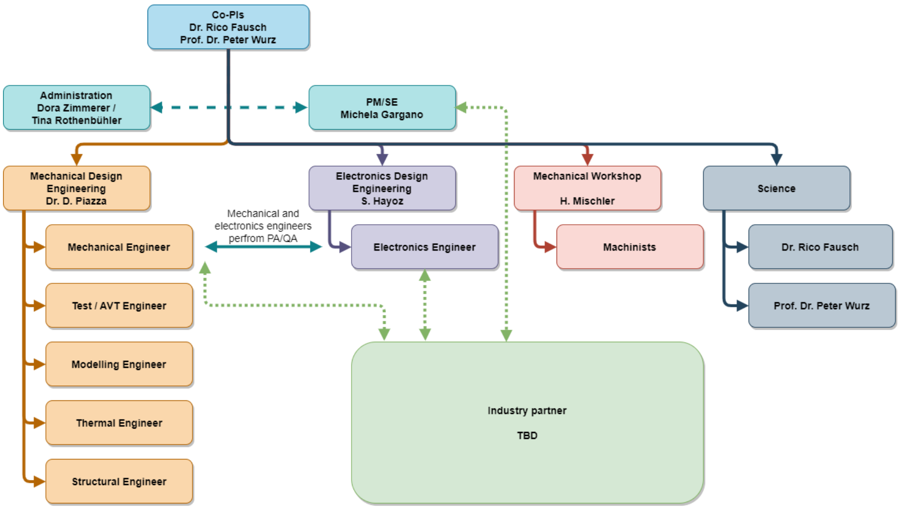
In addition, we have to deal with the fact that the tracking with highest sampling rate (~ 20 Hz), as needed for a detailed ionospheric profiling, will be possible for a limited number of satellites only (giving the available resources in the GNSS receiver module and download bandwidth). Thus, we have to develop a strategy to optimise the signal tracking so that the distribution of satellites remains sufficient for a proper mapping of the ion concentration in flight direction. This will help to reduce the data volume so that the download of the GNSS raw data from continuous tracking remains at an acceptable level (target 20 MB/day).

To further increase the accuracy of the orbit solution and therefore, the quality of the atmospheric density retrievals, a proper knowledge about the GNSS antenna reference point is crucial. In contrast to geodetic GNSS antennas, the phase centre variations of patch antennas are significantly higher and the antennas are more affected by multipath. Thus, a proper calibration of the GNSS antennas on a satellite mockup is seen as very beneficial for the success of the mission. From previous calibrations of GNSS patch antennas the calibration protocol and software routines are available at ETH Zurich. However, the calibration of an entire satellite will require additional adaptations of the mounting system and a refinement of the calibration procedure.

3.4 Involvement of Swiss industry and proposed collaboration scheme

Collaborations planned for the development of the CubeSatTOF

The following organisational chart presents the structure of UBE and provides an overview of key personnel and its interaction with industry.



The industrial collaboration of this project has two pillars. First, there will be an Invitation To Tenders (ITT) of ESA. Those work packages that stimulate innovation in industry will be outsourced. We believe that work related to miniaturising electronics necessary for operation of mass spectrometers will provide such a stimulus. More than 50% of the total cost is guided to industry. The industrial partner will be selected via an ITT of ESA. UBE will provide the required specification, documentation, and other input, as necessary. The industrial partner and its personnel are required to be well-experienced in executing such projects. Project Management and Systems Engineering (PM/SE) with the engineering team members of UBE will supervise industry. Close interaction is especially necessary in an early phase of the project, to iterate interfaces between in the mechanical and electronic design simultaneously. At an early stage, major electrical components, in particular their weight and their location, need to be defined on a currently best estimate basis allowing to continue with structural and thermal design and related testing. Minor iterations are acceptable (and even anticipated) enabling some flexibility in the design of the electronics.

Second, although the majority of the parts of the ion-optical system will be designed and manufactured at UBE, parts of it will be manufactured or further processed by local industry. A list of considered companies is provided in Section 8. The developments will take place at UBE given the required specific knowhow necessary for the development of ion-optical systems. Designing these spaceflight compatible vacuum-electronic devices requires highly trained engineering teams. The detailed requirements for an operational device commonly summarized as “knowhow” are challenging to specify in an ITT, as compared to electronics, which already is time consuming. Outsourcing this development would lead to significantly increased costs. In addition to the engineers that specify the instrument, which has also to be accounted for at a development at UBE, additional engineering FTEs would be required for knowhow transfer and even more detailed PA/QA.

Collaborations planned for the development of the GNSS payload board

~~The commercial off-the-shelf GNSS modules selected for the first prototype GNSS payload board were provided by the Swiss company u-blox. Based on the existing agreement with u-blox it can be guaranteed that the relevant hardware and minimal firmware modifications can be provided for the CHESS mission. However, this agreement does not include the project specific optimizations in signal tracking and payload software development. Thus, ETHZ has planned to involve *u-blox* in Thalwil (CH) and in Espoo (FI) as a strategic industry partner in the project for optimising the GNSS receiver tracking performance. For the integration of the refined GNSS modules into the GNSS payload, an extension of the existing payload software is foreseen. The development of the GNSS payload software shall be carried out by one industry partner selected in an open *ITT process*. Once chosen, the industrial contractor will join the consortium as a member. In addition, a collaboration with the *Fraunhofer Institute for Integrated Circuits IIS* in Erlangen (D) is foreseen as a potential provider of the GNSS antenna. For the qualification of the subsystems, the *Paul Scherrer Institute* in Villingen (CH) is considered as an optional partner for the radiation tests, in case additional infrastructure is needed. For the soldering of the components on the prototype board we have *Minel AG* (www.minel.ch) as a potential industry partner, which already contributed to the development of the prototype GNSS payload board.~~

The commercial off-the-shelf GNSS modules selected for the first prototype GNSS payload board were provided by the Swiss company u-blox. Based on the existing agreement (see letter of support in the attachment) with u-blox it can be guaranteed that the relevant hardware and minimal firmware modifications can be provided for the CHESS mission. However, this agreement does not include the project specific optimizations in signal tracking and payload software development. Thus, ETHZ has planned to involve *u-blox* in Thalwil (CH) as a strategic industry partner in the project for optimising the GNSS receiver tracking performance. For the integration of the refined GNSS modules into the GNSS payload, an extension of the existing payload software is foreseen. The development of the GNSS payload software shall be carried out by one industry partner selected according to ESA’s procurement rules. Once chosen, the industrial contractor will join the consortium as a member. In addition, a collaboration with the *Fraunhofer Institute for Integrated Circuits IIS* in Erlangen (D) is foreseen as a potential provider of the GNSS antenna. The material cost for the antenna development are specified in Section 6.4. Additional personal costs are provided as in-kind contributions. For the qualification of the subsystems, the *Paul Scherrer Institute* in Villingen (CH) is considered as an optional partner for the radiation tests, in case additional infrastructure is needed. For the soldering of the components on the prototype board we have *Minel AG* (www.minel.ch) as a potential industry partner, which already contributed to the development of the prototype GNSS payload board.

As a member of *Space Innovation* (https://space-innovation.ch/) and the *Swiss Aerospace Cluster* (https://swiss-aerospace-cluster.ch/) the application ETH Zurich has established a close network with industry partners in the Swiss space domain. A list of considered companies for this project is provided in Section 8. These partners will give us the capacity to generate a tailored solution for our specific needs and quickly react to unforeseen events, where necessary.

3.5 Work breakdown structure and description of all work packages

The work in this project is organised in three major work packages (WP) namely to i) realise the development of a mass spectrometer; ii) realise the development of a GNSS instrument; iii) perform AVT on satellite level. Despite the proposed payloads providing a unique output only when applied together, from an engineering perspective, the instruments are two fully independent instruments.

3.5.1 WP1 CubeSatTOF

The development of the CubeSatTOF mass spectrometer is lead by UBE and organised into three major sub-work packages (WP1.X) namely to i) develop the CubeSatTOF electronics (WP1.1); ii) develop the ion-optical system including structure, referred to as CubeSatTOF sensor (WP1.2); iii) perform assembly, verification, and testing (AVT) on instrument level and provide support on higher levels (WP1.3). In the following Gantt chart, the overall schedule of the work packages of the instrument are provided.

Schedule

Year		2023				2024				2025			
Quarters		**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
WP1.1 CubeSatTOF Electronics	**WP1.1.1**		x	x	x	x	x	x	x	x	x	x	x
	WP1.1.2					x	x	x	x	x	x	x	x
	WP1.1.3					x	x	x	x	x	x	x	x
	WP1.1.4					x	x	x	x	x	x	x	x
WP1.2 CubeSatTOF Sensor	**WP1.2.1**		x	x									
	WP1.2.2			x	x	x	x	x	x	x	x		
	WP1.2.3			x	x	x	x	x	x	x	x		
WP1.3 CubeSatTOF AVT	**WP1.3.1**										x	x	x
	WP1.3.2											x	x

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Table-2: Work package 1 organisation

Milestones (detailed; not all of them are listed in the provided schedule in section 3.7)

Abbrv.	Description	Purpose	Date*
KOM-P	Kick-Off Meeting of this project	Start of project	1 March 2023**
RRR	Requirements Readiness Review	Initiate ITT, development of mechanics	1 August 2023
KOM-I	Kick-Off Meeting with industry	Start industry collaboration	1 January 2024
PRR-C	Production Readiness Review Phase C	Design freeze phase C on subsystem level	1 May 2024
SCDR	Critical Design Review on subsystem level	Subsystem level tested instrument	1 July 2024

Abbrv.	Description	Purpose	Date*
KOM-P	Kick-Off Meeting of this project	Start of project	1 March 2023**
RRR	Requirements Readiness Review	Initiate ITT, development of mechanics	1 August 2023
KOM-I	Kick-Off Meeting with industry	Start industry collaboration	1 January 2024
ICDR	Instrument Critical Design Review	System level tested instrument; closes phase C on instrument level.	1 October 2024
PRR-D	Production Readiness Review Phase D	Design freeze phase D on subsystem level	1 February 2025
SIR	System Integration Review	Subsystem level tested instrument	1 May 2025
SAR	System Acceptance Review	Instrument delivery to EPFL	1 August 2025
ORR	Operational Readiness Review	AVT at EPFL completed	1 November 2025
MRR	Mission Readiness Review	AVT at launch provider completed; project close out	31 December 2025

Table ~~3~~1: WP1 Milestones

*: Note that the presented dates are TBC, because of working days, public holidays, etc. The exact date will be fixed on a rolling basis.**: Given T_0 of this request is on 1 March 2023.
The industrial partner will have full responsibility for their work package and they are expected to deliver the hardware fully tested and qualified for space flight, including the complete set of documentation, as it will be described in the Statement of Work (SoW).

The CubeSatTOF electronics and the CubeSatTOF sensor will be integrated at the University of Bern representing the CubeSatTOF instrument. At UBE, functional testing of the integrated system, final environmental testing, and calibration will be performed before delivery to EPFL partners. Details on the testing requirements and the deliveries are provided in section 3.6.

The work packages WP 1.1 and 1.2 share the input, namely the documentation including SoW for previous developments such as, for example, NIM/JUICE, NGMS/Luna Resurs, and MANIaC/Comet Interceptor.

WP1.1: CubeSatTOF Electronics (leader: UBE, systems engineer and project management)
The CubeSatTOF instrument is a standalone instrument. The electronics shall fulfil the whole control and operation of the instrument.

WP1.1.1 Management and systems engineering (leader: UBE, systems engineer)

Goal: Preparation of the industrial activities for Phase C/D (ITT process, WP1.1.1.1). Assist and supervise the industrial activities including ITT process, interface the communication between industry and UBE, and perform related management and systems engineering (WP1.1.1.2).

Task description: The concepts for operation of a spaceborne mass spectrometer need to be adapted given the opportunity of extensively using COTS components, allowing for implementing simpler, more power efficient, and miniaturised concepts. These concepts were already successfully tested during earlier phases of the instrument development. The selected industry partner will either use these concepts as a reference design or invent novel solutions better suiting the need for providing the instrument according to the specified requirements. In the first weeks, the existing SoWs of many preceding mass spectrometers are adapted to output an updated, simplified SoW. The high heritage of this instrument allows for a rapid completion of this initial task of the work package. Upon completion, the ITT is prepared. Given the highly integrated nature of this instrument, a close collaboration between electronics and mechanics is indispensable, requiring a frequent iteration of interfaces during the complete design phase of this project.

Output: SoW, Preparing the documentation for the ITT process including electronics SoW and participation in the ESA's ITT process. Hardware, software, and documentation deliverables according to the SoW.

WP1.1.2 Instrument electronics (leader: industry; supervised by UBE, electronics engineer)
Goal: Provide an electronic system to operate CubeSatTOF including design, testing, and validation, including management and systems engineering thereof.

Task description: The electronics of the CubeSatTOF is accommodated on several PCBs. The baseline design foresees four PCBs, though the industry contractor may decide to implement more if complying with the volumetric and power specifications, i.e. a denser packaging (see Figure 2). Three of them are stacked forming a card rack and the detector board is mounted orthogonally to the sensor board.

The sensor board (WP1.1.2.1) supports the ion-optical system. It is mounted on the PCB. The electrodes comprising the ion-optical system are directly connected to the PCB circuit through the screws fixing those electrodes in place. We found that placing the high voltage power supplies (HVPS) on this PCB is simpler, as compared to previous instruments, bulky high voltage connectors and stiff harnesses are not necessary. This architecture reduces risks, shortens both development time and budget, and allows for a considerable miniaturisation.

Mostly, COTS components are used for the HVPS. CubeSatTOF relies on seven HVPS, of which one has a minimum voltage of nominally –1800 V, two –900 V, and three below +400 V. Another power supply floats on the detector bias voltage. They are likely controlled with an analogue 0 to 5 V input voltage each and connected via the serial peripheral interface (SPI bus) to the data processing unit (DPU).

An additional subsystem that benefits from omitting the transmission line is the high voltage pulser. The high voltage pulser rises from about 0 V to nominally +220 V with a rise time of about 2 ns. The high voltage pulse is created on the opposite side of the ion source on the PCB, i.e., directly at the location where it is needed.

Using fast high voltage pulsers usually creates a noisy electronic environment contrasting single ion measurement. Therefore, the detector board is mounted on the second drift tube of the ion-optical system. This PCB also supports the multi-channel plates (MCP) chevron stack, the anode collecting the electrons created by the MCPs, and limited detector proximity electronics. Most supporting electronics, i.e., filters and power supplies, are placed on the sensor board to save space on the detector board. The detector proximity electronics is connected with simple metal luges to the sensor board, and to the DPU via a coaxial cable with SMA connector, accelerating the commissioning phase.

Whereas the design of the sensor board is well guided, there is flexibility for providing the input for the design of the digital board (WP1.1.2.2). The digital board incorporates two subunits namely the DPU with FPGA and the front-end electronics. The front-end electronics includes the high-speed analog-to-digital converter (ADC). We propose using a commercially available 12-bit 1.6GHz ADC, e.g., ADC12SJ1600 from Texas Instruments, Inc. The definitive selection of the ADC will be delegated to the industry partner, as they might benefit from tailoring the ADC to existing front-ends and/or DPU interfaces. The DPU controls the consumers, performs housekeeping, communicates with the Electrical Ground Support Equipment (EGSE) or the spacecraft, triggers the measurements, and records them. In analogy, we baseline a Xilinx, Inc. Kria K26 as a DPU given its system on module approach. An Ethernet connection in addition to the usually implemented RS-422 interface will provide communication during commissioning and during spacecraft operation. A universal asynchronous receiver transmitter (UART) console allows for direct communication with the DPU for debugging. The industry partner is encouraged to choose a chip set with which they are familiar to use synergies.

The power for consumers is prepared on the power board (WP1.1.2.3). Either the EGSE or the spacecraft inputs 12 VDC. An additional circuitry for filtering and current limiting protects the instrument. The stabilised voltage is either distributed directly, or converted to +5V and +3.3V via DC/DC converters to provide input voltages for the consumers. We anticipate placing the low voltage power supplies (LVPS) on this board and connecting them to the sensor board with a miniaturised board-to-board connector. The ion-optical system requires two variable LVPS providing ±12 V and three providing –100 V. In addition, the filament controller is located on the power board. The baseline for heating the filament is a low power consumption, AC driver.

This WP includes assistance for AVT, as needed by the testing entities, in particular, but not exclusively, UBE and EPFL.

Output: Electronics design, verified hardware, and documentation.

WP1.1.3 EGSE (leader: industry; supervised by UBE, electronics engineer)
Goal: Provide an EGSE to support the operation of CubeSatTOF including design, testing, and validation, including management and systems engineering thereof.

Input: SoW, reference designs, ITT contract.

Task description: To emulate the spacecraft during testing, commissioning, and upon launch for calibration, an EGSE is required. The EGSE is designed following its predecessors NIM/JUICE and NGMS/Luna Resurs. The requirements for communication and interfaces are provided from UBE to the industry partner, though prepared by the platform provided (EPFL). The EGSE shall allow for an operation of all features on the ground, i.e., full functional testing. Each EM, PFM, and flightspares require their own EGSE, of which the EM might be an early version and all others are replicas of each other. This WP includes assistance for AVT, as needed by the testing entities, in particular, but not exclusively, UBE and EPFL.

Output: Qualified EGSEs
WP1.1.4 Software (leader: industry; supervised by UBE, electronics engineer)
Goal: Provide software of the CubeSatTOF instrument and the EGSE including design, testing, and validation, including management and systems engineering thereof.

Input: SoW, reference designs, ITT contract.

Task description: The application software (WP1.1.4.1) on top of the firmware (WP1.1.4.2) depends on the architecture of the chip set. For both, concepts and an according implementation need to be provided by an industrial partner. Both work packages are responsible that the complete instrument can be controlled and communicated with. State machines used in previous instrumentation serve as a baseline. Although low level commandos are required for debugging, simple, top level commands operate the instrument once in orbit. The same software shall be used for AVT and operation in space. Both software updates and firmware updates shall be possible in space, or have to be duly justified otherwise. The data is transmitted to the on-board computer of the spacecraft, where packaging of the data is performed for transmission. Data compression for downloading is necessary with a compression factor of about 6. It can be performed subsequent to recording the measurements. This WP closely interacts with WP1.3 (AVT) providing the necessary assistance and solutions. This WP includes software assistance for AVT, as needed by the testing entities, in particular, but not exclusively, UBE and EPFL.

Output: EGSE software, CubeSatTOF software and firmware, specifications of algorithms for CubeSatTOF.

The CubeSatTOF electronics and software (WP1.1.2, WP1.1.3, and WP1.1.4) shall be delivered to the University of Bern fully tested at system level (flight configuration) and subsystems level, with the detailed test requirements. The list of required tests is given in the following table.

A: acceptance levels; Q: qualification levels; -: not performed unless necessary; TBD: to be defined.

Verification / Test	Configuration	Location	Responsibility	EM	EQM	FM	FS1	FS2
Visual Inspection	Subsystem	TBD	Industry	Q	Q	A	A	A
Performance Test over Operational Temperature	Subsystem	TBD	Industry	TBD	Q	A	A	-
Functional Test over Operational Temperature	Subsystem	TBD	Industry	TBD	Q	A	A	-
Preliminary EMC Test	Subsystem	TBD	Industry	Q	(Q)		-	-
Functional Test	System	UBE	Industry (UBE)	Q	Q	A	A	A
S/C Interface Test	System	EPFL / UBE	UBE (Industry)	Q	Q	(A)	(A)	-
EMC Test	System	TBD	Industry (UBE)	-	Q	TBD	TBD	-
Overall Software Test	System	TBD	Industry (UBE)	-	Q	(A)	(A)	-

Thermal Vacuum Test	System	UBE	Industry (UBE)	-	Q	A	A	-
Vibration Test	Subsystem	UBE	Industry (UBE)	-	Q	A	A	-

Table ~~1~~4: CubeSatTOF required tests

The deliverables of this work package by the contractor are:

Reference	Description	Quantity
EM	Engineering Model: • Electronics design accepting dummy consumers • Layout • PCB manufacturing • EEE parts procurement • PCB population • Cable harness excluding cables to detector and filament • Assembly of electrical parts that are necessary for testing with the spacecraft • Integration into Cube (i.e., electronics box) • Conformal coating • Software • Testing • Documentation	1x CubeSatTOF Electronics
EQM	Engineering Qualification Model: • Electronics design • Layout • PCB manufacturing • EEE parts procurement • PCB population • Cable harness including cables to detector and filament • Assembly of all electrical parts • Integration into Cube (i.e. electronics box) • Conformal coating • Software • Testing • Documentation	1x CubeSatTOF Electronics

FM	Flight Model: • Electronics design • Layout • PCB manufacturing • EEE parts procurement • PCB population • Cable harness including cables to detector and filament • Assembly of all electrical parts • Integration into Cube (i.e. electronics box) • Conformal coating • Software • Testing • Documentation	1x CubeSatTOF Electronics
FS1	Flight Spare: • Copy of FM • Testing • Documentation	1x CubeSatTOF Electronics
FS2	Flight Spare: • Copy of FM (besides testing levels) • Testing • Documentation	1x CubeSatTOF Electronics
EGSE-CubeSatTOF-EM	EGSE EM (FS) CubeSatTOF: • Testing • Documentation • Shall be upgraded to be usable for EM / EQM / FM / FS once FS1 is delivered	1 unit
EGSE-CubeSatTOF-FM/FS	EGSE FM CubeSatTOF: • Compatible with EQM / FM / FS1 / FS2 • Testing • Documentation	2 units

Table ~~1~~5: WP1 Deliverables

WP1.2: CubeSatTOF Sensor (leader: UBE, systems engineer and project management)
The CubeSatTOF sensor represents the mechanical implementation of the ion-optical system and the structure necessary to house the CubeSatTOF electronics.

WP1.2.1 Finalise the SoW for the CubeSatTOF Sensor (leader: UBE, mechanical engineer)
Goal: Provide the final design of the ion-optical system of the instrument.

Input: CubeSatTOF EM ion-optical system and sample documentation from phase C/D instrumentation.

Task description: Adapt the existing documentation to tailor it to the instrument's needs regarding specifications, requirements, and statement of work.

Output: SoW and documentation.

WP1.2.2 Design of the ion-optical system of CubeSatTOF (leader: UBE, mechanical engineer)
Goal: Provide the final design of the ion-optical system of the instrument.

Input: CubeSatTOF EM ion-optical system and SoW.

Task description: Modify the EM of the ion-optical system to provide the ion source and the reflectron including drift tubes. Manufacture them, test them, and verify them on EM, STM and flight instrument level, including integration. The ion-optical system is directly mounted on top of the PCB (sensor board). Therefore, there will be a frequent iteration with the industry partner. Although interfaces are defined before industry starts with their work, some minor iterations are foreseen to fit the industry's needs in case of duly justified issues.

The ion-optical system of CubeSatTOF consists of an ion source, emitters with support, a reflectron (ion-mirror) including drift tubes, and a detector. Although the scientific technique regarding how the ion-optical system is used considerably differs from what has been implemented in previous instrumentation, i.e., the novel gas inlet system via direct open source, most of the subsystems draw significant heritage from their predecessors regarding engineering. This allows for adaptation of previous successfully tested concepts to implement them into this ion-optical system.

Output: Hardware and documentation.

WP1.2.3 Design of the structure of CubeSatTOF (leader: UBE, mechanical engineer)
Goal: Provide a supporting structure of CubeSatTOF

Input: CubeSatTOF EM structure, SoW and structure provided by the platform in phase C.

Task description: The main structure is defined by the platform provider (EPFL). EPFL provides the concept for mounting the instrument into the satellite, which will itself likely be part of the instrument's structure. Current design will be adapted to comply with environmental requirements

Output: Hardware and documentation.

A: acceptance levels; Q: qualification levels; -: not performed unless necessary; TBD: to be defined. *: UBE is responsible for at least one qualification shock testing (TBC).

Verification / Test	Configuration	Location	Responsibility	STM	EQM	FM	FS1	FS2	GCM
Visual Inspection	Subsystem	UBE	UBE	Q	Q	A	A	A	A
Dimension Verification Test	Subsystem	UBE	UBE	Q	Q	A	A	A	A
Functional Test	System	UBE	UBE	-	Q	A	A	A	-

Partial Discharge Test	Subsystem	UBE	UBE	TBD	Q	A	A	-	-
Thermal Vacuum Test (Thermal Cycling)	System	UBE	UBE	Q	Q	A	A	-	-
Vibration Test	System	UBE	UBE	Q	Q	A	A	-	-
Shock Test	System	TBD	EPFL	Q*	TBD	A	TBD	-	-
GNSS phase centre calibration	System	ETH	ETH	-	-	-	-	-	A

Table 5~~1~~: CubeSatTOF structural tests

The deliverables of this work package by UBE are:

Pos.	Description	Quantity				
		STM	EQM	FM	FS1,2	GCM
1	Ion Source	1	1	1	2	1
2	Ion Source manufacturing documentation: ● Datasheets, etc. ● Verification protocols	1	1	1	1	0
3	Emitters (all models use similar emitters, qualified from NIM/JUICE)	15				
4	Reflectron including drift tubes	1	1	1	2	0
5	Reflectron including drift tubes manufacturing documentation ● Datasheets, etc. ● Verification protocols	1	1	1	1	0
6	Detector	1	2	3	3	0
8	Detector manufacturing documentation ● Datasheets, etc. ● Verification protocols	1	1	1	1	0

Table 6~~1~~: Deliverables of WP 1.2.3

WP1.3: CubeSatTOF AVT (leader: UBE, systems engineer and project management)

WP1.3.1 Assembly, integration, verification, and testing of the instrument (leader: UBE, mechanical engineer)

Goal: Provide an operational instrument and verify its compliance to the requirements.

Input: Phase C/D EM, EQM, FM and flight spares: hardware and software deliverables of both UBE and industry.

Task description: Integration of CubeSatTOF industry deliverables and UBE deliverables into the complete CubeSatTOF instrument. Provide support for CubeSatTOF integration of the electronics with the sensor. Support (at subsystem level for industry's provided items) and performance (at system level) of (qualification and acceptance) test plans for STM, EM, EQM, FM and flight spares.

Output: Verified EM and Flight Hardware and Software.

WP1.3.2 Post-delivery and spacecraft integration support (leader: UBE, electronics engineer)
Goal: Provide support for AVT of CubeSatTOF on spacecraft level to ensure compliance to the requirements and adapt system or subsystem if necessary.

Input: All other WP1.X input this work packages, i.e., verified flight hardware and software.

Task description: Provide post-delivery support for flight hardware and software to EPFL. Provide support for the integration of CubeSatTOF at the launch provider, likely being D-Orbit (TBC). Manage software support until launch.

Output: Integrated flight module on the spacecraft.

3.5.2 WP2 - The GNSS payload board

The development of the GNSS payload board is led by ETH Zurich and is organised in three major sub-work packages (WP2.X). This includes i) the optimization of the GNSS tracking performance (WP2.1), ii) the GNSS payload software development (WP2.2) and iii) the assembly, verification and testing (AVT) of the GNSS payload board on instrument level (WP2.3). In the following Gantt chart, the overall schedule of the work packages is provided.

Year		**2023**				**2024**				**2025**			
Quarters		**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
WP2.1 GNSS receiver optimization	**WP2.1.1**		x	x	x	x							
	WP2.1.2				x	x							
WP2.2 GNSS payload software	**WP2.2.1**		x	x	x	x	x	x	x	x	x		
	WP2.2.2				x	x	x	x	x	x	x		
WP2.3 Manu-facturing and testing	**WP2.3.1**						x	x					
	WP2.3.2							x	x				
	WP2.3.3									x	x		
	WP2.3.4									x	x	x	
	WP2.3.5											x	x
Milestones			**K1**		**K2**	**M1**	**M2**			**M3**	**M4**		**M5**

Table ~~1~~7: Work package 2 organisation

ETH Zurich will be responsible for the overall coordination of WP2, supervision of the industry contributions, the timely delivery of the agreed hardware, software and documentation to project partners and ESA. In addition, ETHZ will have the full responsibility for WP2.1.1 as well as WP2.3 with

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its five sub-work packages (WP2.3.1-5). The industry partners will be responsible for the work packages WP2.1.1 (GNSS receiver firmware) and WP2.2.2 (GNSS payload software development). The total industry contribution to the development of the GNSS payload is expected to be 52.2% (179’833 kCHF).

Detailed work package description:

WP2.1. GNSS receiver optimization

WP2.1.1 GNSS receiver firmware (leader: industry, supervised by ETHZ)
Goal: A firmware update for the u-blox ZED-F9P module

Input: Firmware FW 1.00 HPG 1.2 of the u-blox ZED-F9P module

Task description: The current firmware of the u-blox ZED-F9P module (FW 1.00 HPG 1.2) requires further modification for the extraction of all relevant information needed in subsequent work packages (e.g. the almanach for all visible GNSS satellites). In addition, the GNSS firmware shall be able to process tracking requests for individual satellites. For faster signal tracking on GPS L2, Galileo E1/E5b (and optional Glonass L1/L2 and Beidou B2/B7) the Doppler search range shall be adaptable and specific models designed for the operation in near-earth applications shall be replaced. In addition, the configurable parameters of the code and phase tracking loops shall be optimised for the operation under high orbital dynamics.

Output: Firmware update as image or directly flashed on the ZED-F9P receivers, including a release note.

WP2.1.2: Observation scenarios (leader: ETHZ)
Goal: Provide a set of preconfigured receiver settings to be implemented in the GNSS payload board as scientific scenarios.

Input: The modified u-blox GNSS receiver with the firmware developed in WP2.1.1

Task description: For the operation of the GNSS payload five observation scenarios have been identified: nominal PVT (for real-time positioning, velocity determination and timing using code observations), three scientific modes (for precise orbit determination, radio occultation and SLR validation of GNSS orbits) and a maintenance mode (for firmware updates and configuration changes). Each scenario is a predefined set of configurations executed for a measurement. Further, a scenario consists of a unique scenario ID, the receiver-antenna assignments and the channel configuration. In case of the nominal PVT mode, an onboard PVT solution shall be computed and an undistorted time pulse for a precise time synchronisation of all satellite subsystems shall be generated. In the scientific modes the raw GNSS code and carrier phase measurements shall be recorded and stored on the NOR-flash until requested by the onboard computer, e.g. for download to the ground. To start a measurement, one instructs the GNSS-board (e.g. by a specific command) to initialise the measurement tasks with its unique scenario ID. The individual settings for each scenario will be carefully set up and tested in ground-based open sky tests using an engineering model (see deliveries) as well as a GNSS signal generator.

Output: The configured GNSS receiver, including a set of observation scenarios files to be saved in the MRAM onboard storage of the GNSS payload board. These files will be provided together with a list of scenario commands to fetch the configurations, start/stop a measurement or upload a custom scenario with a unique scenario identity.

WP2.2: GNSS payload software development

The development of the GNSS payload software shall be carried out by one industry partner selected in an open ITT process. The entire process will be initiated and coordinated by ETHZ. Therefore, in addition to the payload software development a management and systems engineering work package is defined.

WP2.2.1 Management and systems engineering (leader: ETHZ)
Goal: Preparation of the industrial activities for the development of the GNSS payload software. Assist and supervise the industrial activities including the invitation to tender (ITT) and perform related management and systems engineering activities.

Input: Statement of Work for the industry partner(s)

Task description: For the preparation of the industrial activities a Statement of Work (SoW) shall be provided and the entire process assisted. Once the development process has been initiated, the source code and documentation of the existing payload software is provided so that a direct continuation will be possible. During the development process of the payload software, which will be in parallel to the other work packages, an integration of the industry partner into the project is foreseen to the level possible and accepted by the project partners. About six months before delivery, access to an engineering model will be granted so that an intensive testing of the payload software functionalities can be carried out. For quality assessment, we will guide the implementation of a test driven development (TDD) and continuous integration (CI) approach to ensure a high test coverage.

Outcome: Documentations for the ITT process. Hardware, software and documentation deliverables according to the SoW.

WP2.2.2 Payload software development (leader: industry, supervised by ETHZ)
Goal: Development of the payload software for the GNSS payload board with all functionalities and documentation described in the SoW. The industry partners shall have full responsibility for this work package. Thus, it is expected that the software is delivered fully tested and qualified for space flight.

Input: Hardware, software and documentation deliverables according to the SoW

Task description: The payload software will act as an intermediary between the GNSS receivers and the other hardware components and thus, will enable most of the core functionalities of the GNSS payload board. It is expected that all software modifications are implemented into the existing source code using a test-driven development and continuous integration approach. Code formatting and variable naming shall be according to the coding guidelines. All software modules shall be fully tested and delivered with a complete set of documentation.

The basic functionality of the payload software is described as follows: It allows to receive, process and reply to commands from the ground system, act as an observation scheduler, i.e. to load specific observation scenarios based on well-defined criteria, perform a set of self-tests, provide event logs and a housekeeping message, and shall include an autonomous failure management system.

Specific requirements:

- A boot loader shall be implemented into the payload software to allow for installation of software updates in form of images or image patches
- An observation scheduler shall be implemented to allow the GNSS receiver to sample the signals of specific GNSS satellites according to well defined criteria
- The software shall be able to receive, process and reply to commands from the ground system
- In addition to UART, the SPI interface shall be an assembly option
- All important data shall be protected with a checksum or an appropriate hashing function
- The software shall support the communication protocol defined for the CHESS mission
- Appropriate receiver-antenna configurations shall be automatically identified by the payload software (by monitoring the GNSS signal quality)
- On regular intervals, the GNSS board shall perform a set of self-tests
- The GNSS payload shall provide an event log and a housekeeping message informing about passed events, e.g. for problem analysis
- If a specific scenario fails, the software shall allow to automatically switch to another configuration
- The GNSS payload shall implement autonomous failure management

Output: The source code, documentation and an image of the payload software ready for the integration into the FM-GNSS (see deliveries).

WP2.3: Manufacturing and testing

WP2.3.1: Hardware modifications (leader: ETHZ)
Goal: Selection of the hardware components for the GNSS payload and redesign of the printed circuit boards according to CHESS standards.

Input: The prototype GNSS payload board design

Task description: The GNSS payload consists of two printed circuit boards (PCB), the main board and the GNSS receiver board (see Figure 6). The main board provides the processing and storage capabilities and serves as a coordinator for all measurement tasks. The GNSS receiver board consists of a set of (four) GNSS receivers, signal amplifiers, filters and splitter for GNSS signal reception, amplification and tracking.

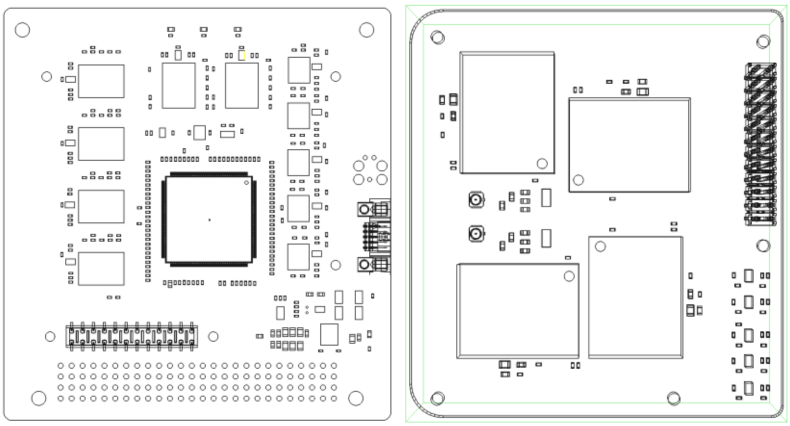


Figure 6: Preliminary design of the main board (left) and the GNSS receiver board (right).

For the operation on the CHESS pathfinder satellite the existing prototype has to be further extended. The suggested modifications include:

- The adaption of the board to the CHESS standards in terms of connectors, hole positions, dimensions and power supply
- Connection of all components > 0.1 W to the thermal dissipating PCB layer
- Redundancy in all critical hardware components
- Protection of all components against latch-up events
- Installation of a voltage filter to reduce the impact of strong variations in the power supply
- Implementation of a SPI interface as an assembly option (in addition to UART)

Disconnection functionalities from the main supply in case of overcurrent

Output: The hardware for the GNSS payload board and a documentation for the integration into the Engineering Model (EM-GNSS). The hardware design and components will be provided by ETHZ. The fabrication of the PCBs and soldering by industry partners will be commissioned.

WP2.3.2: Initial environmental and functional testing (leader: ETHZ)

Goal: Initial environmental testing (vacuum, temperature, radiation) of the EM-GNSS model and of relevant subsystems.

Input: The Engineering Model (EM-GNSS) of the GNSS payload board

Task description: After fabrication of the EM-GNSS model the qualification of the selected hardware components shall be tested under realistic environmental conditions. For the vacuum and temperature tests, the existing facilities at ETH Zurich will be utilised. The radiation test will be coordinated together with UBE and EPFL. Based on initial simulations, the framework for the testing (temperature range, temperature gradient, radiation dose, etc.) will be defined. For a proper signal tracking it will be crucial that the number of resets in the electronics, especially in the GNSS receiver, is below one event per revolution. Otherwise, a significant loss in GNSS measurements is expected. Planning the initial environmental tests as separate tasks will give us the flexibility for further modifications in hardware design about seven months prior to the delivery date of the flight model.

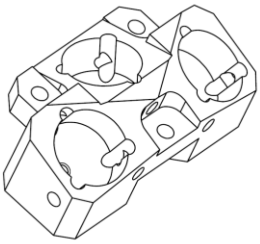
Output: A qualified Engineering Model, including qualification report for the hardware components selected.

WP2.3.3: Manufacturing and assembly of the SLR reflector (leader: ETHZ)

Goal: Provide an alternative technique for validation of the GNSS orbits

Input: JGS1 corner cubes

Task description: For validation of the satellite orbits, an inter-comparison with Satellite Laser Ranging (SLR) is foreseen. Therefore, the CHESS satellite will be equipped with a laser retro-reflector. The necessary JGS1 corner cubes are available and tested. This work package comprises the production of the mounting structures, the preparation for assembly and the clueing in a clean room. The preliminary design of the retro-reflectors is shown in Figure 7.



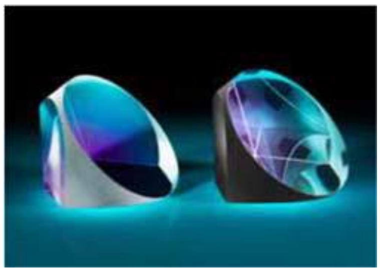


Figure 5: Preliminary design of the SLR reflectors. Left: The mounting structure for three corner cubes (36 x 20 x 10 mm). Right: The JGS1 corner cubes (10 mm)

Output: The laser retro-reflector and documentation for the integration into the FM.

WP2.3.4: GNSS antenna calibration (leader: ETHZ)
Goal: Calibration of the GNSS antennas on a satellite mockup, referred to as the GNSS phase centre calibration model (GCM), to further improve the orbit accuracy.

Input: A full-scale satellite mockup (GCM)

Task description: In an initial study, the GNSS antenna type for the CHESS mission is selected. Potential candidates are the taoglas GPSF.36.A, the AMO ASPA-A28A or the Frauenhofer CubeSat antenna. Since in orbit determination the position of the satellites is defined with respect to the centre of mass (CoM), the position of the antenna as well as the frequency-dependent phase centre corrections have to be determined. Since the antenna performance is influenced by the mounting position and materials in the environment of the antenna, a calibration on a GCM is requested. For the calibration procedure, the satellite is mounted on an industrial robot and rotated around the expected antenna phase centre. The collected GNSS raw data are combined with measurements of a reference antenna nearby to compute the position of the antenna phase centre on the satellite as a function of frequency and incidence angle (expected accuracy: 1-2 mm).

Output: A calibrated GNSS antenna, including the calibration files for the frequency-dependent phase centre offsets and variations with respect to an antenna reference point.

WP2.3.5: AVT support and modification (leader: ETHZ)
Goal: Provide support for the assembly, verification and testing of the GNSS payload on the CHESS satellite models to ensure compliance with the system requirements.

Input: Phase C/D EM, FM and flight spares: Hardware and software deliverables of both ETHZ and industry.

Task description: Provide post-delivery support for flight hardware and software to EPFL. Provide support for the integration of GNSS payload into the launch vehicle. Manage software support until launch.

Output: Verified flight hardware and software.

WP2 Milestones

Overview about the milestones defined for the development of the GNSS payload board

M	Date	Description	Purpose
K1	1. March 2023	Kick-Off Meeting of this project	Start of project
K2	November 2023	Kick-Off Meeting with industry	Start ITT-based industry collaboration
M1	January 2024	Instrument Critical Design Review	Design freeze phase C on instrument level
M2	April 2024	Production Readiness Review	EM-GNSS ready for internal testing and delivery to EPFL

M3	January 2025	System Integration Review	Design freeze phase D on instrument level
M4	April 2025	System Acceptance Review	FM-GNSS delivery to EPFL
M5	November 2025	Operational Readiness Review	AVT at EPFL completed
M6	December 2025	Mission Readiness Review	AVT at launch provider completed

*: Note that the presented dates are TBC, because of working days, public holidays, etc. The exact date will be fixed on a rolling basis.**: Given T_0 of this request is on 1 March 2023.

Table ~~81~~: WP2 Milestones

3.5.3 WP3 Project Management, Payload interaction, AVT

This work package encompasses overall management and coordination of the CHESS Project as well as System Engineering (Payload integration, Assembly Verification and Testing).

The development of the two payloads, the CubeSatToF and the GNSS payload board, constitute two different work items conducted by UBE and ETHZ. However these two WPs share a common objective which is the constitution of one relevant scientific experiment enabled by the successful integration and verification of the payloads onto the CHESS satellites.

We therefore identified the need for this work package decomposed as follow:

WP3.1: Project Management

Goal: Ensure the development of the TOF Spectrometer and GNSS payload board are on time, on budget and within scope with respect to the overall objectives of the space mission.

Input: Updated statuses of WP1 and WP2. CHESS mission budgets and timelines.

Tasks: Conduct regular progress Meetings, identify and take actions regarding potential deviations from the timeline or budget, identify and take actions regarding any blocking points on WP1 & 2, keep track of project milestones, ensure proper flow of information between the members of the consortium throughout the duration of the project.

Output: Project reporting to PRODEX and stakeholders.

WP3.2: Systems engineering

Goal: Verify that the design and developments of the CubeSatTOF and the GNSS payload remains aligned and compatible with the CHESS satellites platform. Provide a persistent technical overview of the project throughout its duration. Ensure functionality of the payloads in the mission environment before handing them over for scientific use.

Inputs: CubeSatTOF and GNSS payload board development status, in close collaboration with WP1 and WP2 systems engineers.

Tasks: Continuously assess the design of the two payloads, perform regular reviews, ensure technical budgets are updated, ensure compatibility of the payloads with the platform. Manage Integration and Testing activities for the two payloads at CHESS system level.

Output: TRL 8 space scientific experiment as supported by test reports, reviews reports.

Staff member	**Split of WP 3**	
	2023-2024	*2025-2026 (Q1)*
WP 3.1: Project Management	60%	40%
WP 3.2: Systems Engineering	40%	60%

Table ~~1~~9: Work package 3 organisation

3.5.4 Deliverables

UBE

The main internal deliverables are described in detail in section 3.5.1 broken down by work package. This section provides an overview of the delivered models and discusses the model philosophy, which is inferred from previous experience, risk analysis, and the needs of the consortium. The figure down below shows an overview of the model flow.

The preliminary flight design inputs the STM. The STM will be built for reducing risks regarding structural and thermal integrity, especially regarding the novel design of the ion-optical system (see section 5.1). These test outputs will prepare to unlock the gate to phase C. Meanwhile, the EM is provided by electronics. University of Bern will deliver an EM to EFPL provided by the industry partner for testing purposes. As usual, the EM serves for electrical and software (interface) testing of the satellite at an early stage.

Both models provide input for the EQM. Once the EQM will successfully be tested at UBE, and ICDR will have been passed to close out phase C, the EQM replaces the EM for more representative testing at EFPL. The exact time of delivery to EPFL remains TBC. It remains TBD if the EM will return either to industry or to UBE after the EQM is available at EPFL. The EQM will remain at EPFL for post-launch satellite reference modelling.

The FM will be delivered to EPFL for space flight. Given the low cost of the COTS components, risks are reduced when flying an FM instead of a (potentially) overtested PFM. FS1 is stored at UBE in a clean environment or at vacuum conditions preventing degradation. This model serves as a flight spare model including limited ground reference activities. For all non-clean and risky activities, the EQM has to be preferred. FS2 represents a pre-assembled spare kit anticipating unexpected events given the extensive use of COTS components. This approach allows for providing limited support of UBE, especially during phase E, regarding the COTS approach. In addition, FS2 will be used for extensive calibration campaigns at UBE, enabling the scientific use case of the instrument.

Additionally, a GNSS phase centre calibration model (GCM) will be produced for testing purposes of ETH. Goal is to deliver this by Q1 (preferred) or Q2 2025. This model will provide a mechanically representative envelope including the outer parts of the gas inlet system, but no electronics or other parts inside are needed. If possible, STM spare parts are recycled for this model with updates on the envelope.

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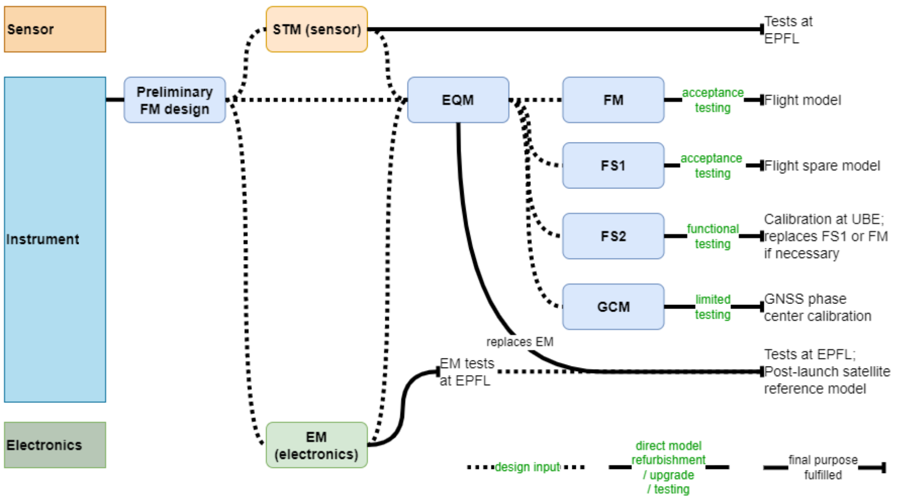


ETH Zurich

ETHZ will produce two engineering models (EM-GNSS) for testing at EPFL and internally. Once the EM-GNSS is tested and phase C is closed out, ETHZ will start with the development of the flight model (FM-GNSS). In April 2025 the FM-GNSS will be delivered to EPFL for AVT. In addition, two flight spares (FS-GNSS) will be built as copies of the FM. One FS is stored at ETHZ in clean conditions preventing degradation. This model serves as a ground reference model. The second FS represents a pre-assembled spare kit in case of any unexpected event and serves for ground testing and implementation of new features before upload to the satellite.

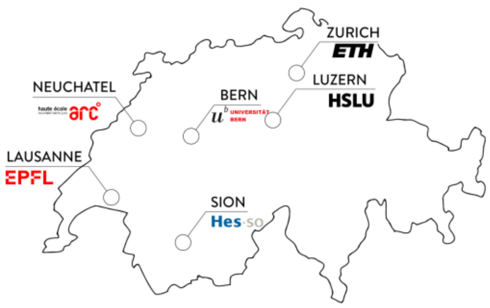
Reference	Description	Purpose
Engineering Model of the GNSS payload board (**EM-GNSS**) Quantity: 2 Availability: Q2/2024 (together with M2)	Components • 1 Printed Circuit Main Board including all hardware modifications • 1 Printed Circuit GNSS Receiver Board including all hardware modifications • Cable harness including cables to the GNSS antennas • Integration into an aluminium structure • Firmware updates • Documentation	Dimensional verification Functional verification Interface verification Firmware tests Power consumption test EMC test

Flight Model of the GNSS payload board (**FM-GNSS**) Quantity: 1 Availability: Q2/2025 (together with M4)	Components • 1 Printed Circuit Main Board including all components foreseen for the final delivery • 1 Printed Circuit Receiver Board including all components foreseen for the final delivery • Layout • Cable harness including cables to the GNSS antennas • Integration into an the final aluminium structure • Conformal coating • Payload software • Firmware updates • Documentation	Dimensional verification Functional verification Interface verification Firmware and payload software tests Environmental tests (TV, radiation, vibration, shock)
Flight Spares of the GNSS payload board (**FS-GNSS**) Quantity: 2 Availability: Q2/2025 (together with M4)	Components • Copies of FM (excl. testing)	Ground testing Implementation of new features before upload to the satellite

Table 10: Deliverables for the GNSS payload

3.6 International collaboration

The project consortium is composed of internationally renowned Swiss institutions whose comprehensive combined expertise in the fields of atmospheric physics, precise orbit determination, system engineering, nanosatellite technology and metrology set a solid foundation for a successful project outcome.



3.6.1 Entities and internal collaboration scheme

In the following section, a brief description of the project partners and their involvement in international collaborations is highlighted:

ETH Zurich

Key personnel: Gregor Moeller, Alexander Wolf, Markus Rothacher

The Institute of Geodesy and Photogrammetry (IGP) at ETHZ brings in the complementary expertise in precise orbit determination, atmospheric remote sensing, satellite mission design and GNSS receiver development. IGP has vast experience in processing geodetic GNSS data to the highest standards, e.g. for GNSS orbit and clock determination, complex parameter estimation approaches and real-time processing algorithms as well as parameter prediction. In the context of this proposal, the capability to design, manufacture, test, fly and operate GNSS hardware will be essential for the success of this mission. Key personnel at IGP have extensive knowledge in space geodesy and the development of satellite technology. IGP pioneered the use of commercial off-the-shelf GNSS components for the operation on nanosatellite missions. Furthermore, IGP has extensive experience in development and testing of innovative GNSS hardware solutions in various research projects. The most relevant collaborations for this activity are shortly summarised in the following:

- At TU Berlin a picosatellite swarm mission was developed consisting of the four quarter-unit CubeSats BEESAT-5 to BEESAT-8 with a mass of 375 grams each. The picosatellites were designed fully redundant and almost completely single-fault tolerant. The primary mission objective is to demonstrate a newly developed communications subsystem in the UHF band and an experimental GNSS receiver. MPG supports this mission with a modified GNSS receiver for precise orbit determination. The satellites are operational from March 2021. (Q1/2019 - now)

- Precise orbit determination based on low-cost GNSS receivers on-board the Astrocast nanosatellites: Prototypes of the GNSS positioning module have been launched on board twelve Astrocast 3-unit cube satellites for precise orbit determination and manoeuvre analysis. The satellites are also equipped with a small array of three laser retro-reflectors enabling orbit validation with Satellite Laser Ranging. (Q4/2018 - now)

- Demonstration of Galileo capabilities in-orbit using low-cost receivers on a CubeSat: This project financed by ESA’s Galileo Science Support Center had the goal to demonstrate the capabilities of Galileo in orbit. Therefore, the two Astrocast satellites at an altitude of 575 and 500 km, respectively, have been selected for further analysis. The performance of various single-system and multi-GNSS solutions has been analysed putting a special emphasis on solutions including observation data from the Galileo system. (Q2/2017 - Q2/2019)

Once the scientific payload has been launched, an involvement of NASA's Jet Propulsion Laboratory (JPL), Pasadena (USA) ist planned for a joint analysis of the GNSS raw data collected from the CHESS mission. A cooperation letter from JPL can be found in the Appendix. Neither hardware nor software will be delivered to those entities.

UBE

The Space Science Group of University of Bern has profound experience in the analysis of tenuous exospheres of celestial objects with mass spectrometers. It provides a major instrument, NIM, for ESA’s flagship mission, JUICE. In addition it was involved in many former space missions, and is currently involved in the early design phase of novel flyby missions to analyse upper atmospheres of deep space objects. Most of them share the scientific goals namely to find signatures of life, identify objects that provide conditions to do so and provide insights into the origin and evolution of Solar System objects, in particular the evolution of atmospheres.

Scientific exchange will be performed with many institutes, including, but not limited to the following list. Neither hardware nor software will be delivered to those entities:

- Alfred McEwen; Lunar and Planetary Laboratory, The University of Arizona, USA (LPL)
- Olivier Mousis; Institut Origines, Observatoire des Sciences de l'Univers, Aix-Marseille Université, France (AMU)
- Helmut Lammer; Space Research Institute, Austrian Academy of Sciences, Austria (IWF-ÖAW)
- Kathy Mandt; Applied Physics Laboratory, Johns Hopkins University, USA (APL)
- Christina Plainaki, Agenzia Spaziale Italiana, Italy (ASI)
- Ben Teolis; Southwest Research Institute, USA (SWRI)
- Dana Hurley; Applied Physics Laboratory, Johns Hopkins University, USA (APL)
- Cesare Grava; Southwest Research Institute, USA (SWRI)
- Iannis Dandouras; Institut de Recherche en Astrophysique et Planétologie, CNRS, France (IRAP-CNRS)
- Kurt Retherford; Southwest Research Institute, USA (SWRI)
- Joachim Saur; Institute of Geophysics and Meteorology, University of Köln, Germany
- Alice Lucchetti; National Institute of Astrophysics, Italy (INAF)
- Lorenz Roth; Division for Space and Plasma Physics, KTH Royal Institute of Technology, Sweden (KTH)
- Valeria Mangano; National Institute of Astrophysics, Institute for Space Astrophysics and Planetology, Italy (INAF-IAPS)
- Alessandro Mura; INAF-IAPS
- Tim Cassidy; Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, USA (LASP)
- Masaki Nishino; JAXA, Japan (JAXA)

EPFL

On the platform level, EPFL partners with the Italian industry partner D-Orbit SA to perform the in-orbit demonstrations of the platform subsystems. The partnership consists of a reduction in the prices of launch of hosted payloads as well as direct contact with D-Orbit engineers for an exchange of expertise on spacecraft development.
The EPFL Spacecraft Team also partners with the Bulgarian industry partner Endurosat, specialising in CubeSat development, to educate students about the state of the art in satellite design and benefit from the accumulated expertise in this industry.

By building the project consortium we have focussed our attention on the potential offered by Swiss academia and industry. Naturally, in phases where the satellite is to be put in orbit and operated, the international science community must be involved. We will constitute an advisory board of national experts to pragmatically progress in this approach. Their role will be, on the one hand, to periodically review the evolution of the project and ensure its compliance with the scientific requirements, and, on the other hand, identify items of technical interests, competences and financial contributions by national agencies.

~~3.6.2 Deliverables~~

~~UBE~~

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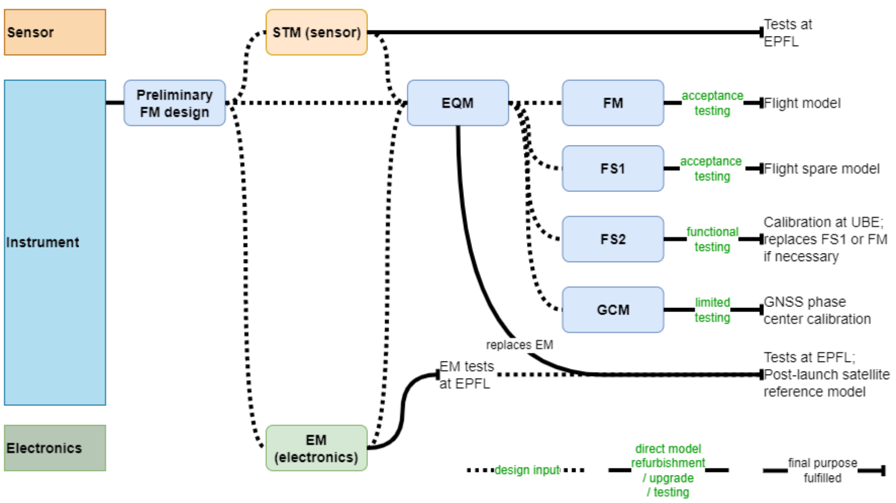

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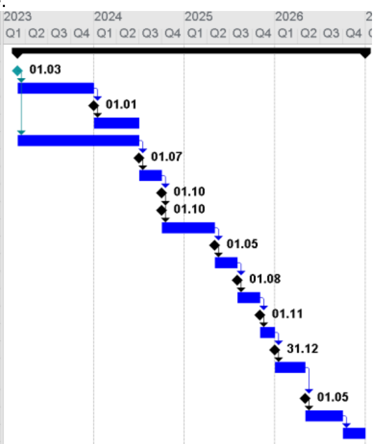
3.7 Status of the mission and schedules at mission and instrument level

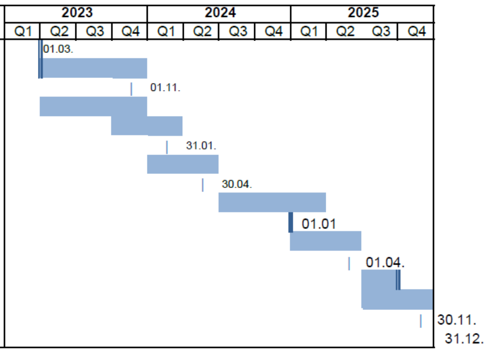
The top-level schedule of UBE is provided below. It aligns with the requirements of the platform and ensures sufficient time for development, as discussed above.

	Task Name	Duration	Start	Finish
1	**Top level schedule UBE**	**1003 dys**	**Wed 01.03.23**	**Fri 01.01.27**
2	KOM-P	0 dys	Wed 01.03.23	Wed 01.03.23
3	ITT and related preparation	306 edys	Wed 01.03.23	Mon 01.01.24
4	KOM-I	0 dys	Mon 01.01.24	Mon 01.01.24
5	Phase C Electronics (Industry)	182 edys	Mon 01.01.24	Mon 01.07.24
6	Phase C Sensor (UBE)	488 edys	Wed 01.03.23	Mon 01.07.24
7	SCDR	0 dys	Mon 01.07.24	Mon 01.07.24
8	Phase C AVT	67 dys	Mon 01.07.24	Tue 01.10.24
9	ICDR	0 dys	Tue 01.10.24	Tue 01.10.24
10	CDR	0 dys	Tue 01.10.24	Tue 01.10.24
11	Phase D Sensor and Electronics	152 dys	Wed 02.10.24	Thu 01.05.25
12	SIR	0 dys	Thu 01.05.25	Thu 01.05.25
13	Phase D AVT	66 dys	Fri 02.05.25	Fri 01.08.25
14	SAR - Instrument delivery to EPFL	0 dys	Fri 01.08.25	Fri 01.08.25
15	AVT at EPFL	92 edys	Fri 01.08.25	Sat 01.11.25
16	ORR	0 dys	Sat 01.11.25	Sat 01.11.25
17	Satellite delivery to launch provider	43 dys	Mon 03.11.25	Wed 31.12.25
18	MRR	0 dys	Wed 31.12.25	Wed 31.12.25
19	Shipping, integration on S/C (no staffing required)	121 edys	Wed 31.12.25	Fri 01.05.26
20	Launch	0 dys	Fri 01.05.26	Fri 01.05.26
21	De-tumbling	153 edys	Fri 01.05.26	Thu 01.10.26
22	Post-launch commissioning	92 edys	Thu 01.10.26	Fri 01.01.27



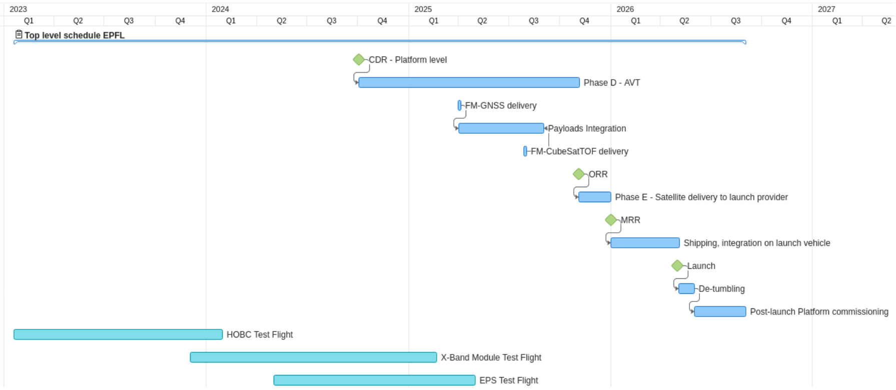
The top level schedule of ETHZ is provided below. It aligns with the requirements of the platform and ensures sufficient time for development, as discussed above.

Task name	Duration	Start	Finish
KOM-P	0 dys	01.03.2023	01.03.2023
ITT and related prep.	240 dys	01.03.2023	30.10.2023
KOM-I	0 dys	01.11.2023	01.11.2023
Phase C - Hardware	304 dys	01.03.2023	01.01.2024
Phase C - Software	93 dys	01.11.2023	31.01.2024
ICDR	0 dys	31.01.2024	31.01.2024
EM model develop.	425 dys	01.02.2024	01.04.2025
PRR	0 dys	30.04.2024	30.04.2024
EM model qualification	245 dys	01.05.2024	01.01.2025
SIR	0 dys	01.01.2025	01.01.2025
FM model development	123 dys	01.01.2025	30.04.2025
SAR	0 dys	01.04.2025	01.04.2025
FM model delivery	0 dys	30.04.2025	30.04.2025
AVT phase	121 dys	01.08.2025	01.11.2025
ORR	0 dys	01.11.2025	01.11.2025
MRR	0 dys	31.12.2025	31.12.2025



From an EPFL point of view, the project is scheduled as shown next. The project is currently in Phase C, the first milestone (CDR) is expected on 01.10.24. This milestone shall synchronise the work on the platform level given the performed in-orbit demonstrations for the various subsystems.

The integration of the payloads is shifted such that the EPFL team can integrate the GNSS and perform functional testing and calibration prior to the reception of the CubeSat TOF. The shift in the calendars of both payloads allows for a sequential integration rather than parallel work.



4 Scientific context and experience of the institute

4.1 Scientific benefits for the institute and the Swiss research community

The proposed project will help to consolidate the Swiss position considering research of Earth's upper atmosphere, expand the Swiss heritage of analysis of extra-terrestrial exospheres to perform analysis of Earth's upper atmosphere. Switzerland has a broad research community regarding atmospheric physics regarding both the modelling and the measurement thereof. Enhancing and verifying the models with in-situ measurements will serve as a baseline in comparative planetology, exoplanetary research, aeronomy, and astronomy. It would also improve the science of climate change by confirming the latest research, which suggests a cooling of the upper atmosphere. The related increase in the lifetime of satellites would exacerbate the space debris issue. Accurate data about such effects aim to establish a reliable foundation for decision-making committees such as the Scientific and Technical Subcommittee (STSC) of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), where Switzerland has a leading role in building awareness towards issues concerning space debris.

A potential benefit of the data collected in applied research is a deeper comprehension of the chemical sputtering that takes place on solar panels. This knowledge could lead to improvements in the products of the solar industry. To achieve this, the chemical components measured by the scientific payloads are compared to the solar panel telemetry data collected by the platform, which falls outside the scope of PRODEX.~~In applied research, a better understanding of the chemical sputtering occurring on solar panels would contribute to improving products of this industry.~~ Additionally, current research foreshadows that density variations of the exosphere could be pre-warnings for earthquakes. This mission will further investigate this phenomenon. A positive result might lead to a closer collaboration between atmospheric science and classical geophysics, in which Switzerland has a widespread research community.

Validation of a novel small-scaled GNSS receiver with multiple space applications

Together with the company *u-blox*, ETH Zürich will produce a very versatile low-cost multi-GNSS satellite payload which requires extremely low resources of power, space, and weight. It can be used on any future satellite for positioning, timing, as well as for Earth system monitoring. Flown in a constellation, this payload will enable 4D-ionosphere monitoring: a crucial benefit to space weather and climate research, atmospheric science, as well as air density measurements useful for satellite re-entry studies.

Provide Switzerland with a long term competitive ground station

Today Switzerland's expertise in the design and realisation of space and ground segment systems is limited to sub-6 GHz. The CHESS project is an ideal opportunity to extend the knowledge and competence to higher frequency bands. The outcome will impact education and high-speed communications. At HSLU, it will be incorporated in engineering courses. It will also allow the university to handle projects in the areas of 5G telecommunications and perform cutting edge satellite communications.

A consortium of space actors to strengthen the Swiss space community

CHESS is at the centre of a growing space community connected with strong and interdependent expertise in Switzerland. Today all actors of the project are heavily promoting knowledge transfer between researchers and industry, and provide advanced technology knowledge to students. Our collaboration is already strengthening the relations between Swiss space actors, and there is a strong will to commit to the perennity of this project. CHESS is also a solid educational project initiated by the EPFL Spacecraft Team association. With 60 fully dedicated students, the association has been selected as one of the 13 interdisciplinary projects promoting academic excellence at EPFL, thus gaining financial and technical support from the university.

The pole of knowledge emerging from this project can be an excellent contributor to the rising trend of the nanosatellites market. A major long-term objective of CHESS is indeed to give birth to sister space initiatives to periodically undertake in-orbit demonstration or in-orbit validation of Swiss scientific instruments.

The CHESS project enables students within the consortium to apply hands-on training on the development of space flight instrumentation through the multiple in-orbit demonstrations of the platform subsystems as well as the development of the science payloads. The project will benefit many young scientists including BSc, MSc, and PhD students evaluating the data

4.2 Relation of the project to the institute strategy, other activities of the institute and experience of the institute with handling projects of similar size

All of the three major contributors of the proposing consortium provide an excellent track record regarding the development of hardware for space flight and the management thereof, including management of missions.

First, the Space Science and Planetology division of the Physics Institute of the University of Bern has continuously been committed to experimental space research related to the Sun, the planets including Earth, comets, and the space environment for more than 50 years, almost since the beginning of the space age. As attested by their publication record, our researchers are recognised in the worldwide scientific community for their contributions to space research. Research of the upper atmosphere is an ongoing research endeavour of the division of Space Research and Planetology, starting with the participation in the GEOS 1 and 2 mission, to which the institute contributed mass spectrometers. Lateron, tenuous exospheres of comets were analysed with mass spectrometers on board, for example, the Giotto mission 1985 and ROSETTA mission during 2004-2016. Besides other major contributions, the Bernese institute leads the development of the NIM instrument on board ESA's flagship mission JUICE to analyse the exospheres of Juiter's icy moons. On this instrument, it also provides the Co-PI of the particle environment package (PEP) designed to analyse the particle environment of the same region. The recently launched CHEOPS mission, which is led by the institute, will be investigating extraterrestrial planets of about Earth size, thus will support the search for possible places for life outside the Solar System. Considering the increased interest in the search for life or signatures of it, spacecraft flybys through plumes provide an easy access to subsurface oceans as present on, for example, Enceladus. The development of this instrument and its related achievements provide opportunities for reliably analysing such plumes as part of unprecedented mission concepts.

Second, the intended proposal is well aligned with the core competencies of ETH Zurich's Institute of Geodesy and Photogrammetry (IGP). Key personnel at IGP have extensive knowledge in the development of satellite technology, including a precise GNSS payload board for orbit determination. Dr. Gregor Moeller, senior scientist and lecturer at IGP, has dedicated his scientific career to the development of high-precision GNSS applications, e.g. for precise orbit determination of dense nanosatellite constellations and atmospheric remote sensing. Thus, he is seen as a perfect candidate for leading the ETHZ developments in this project. He will be supported by Alexander Wolf, leader of the electronic lab at IGP and Prof. em. Markus Rothacher (head of IGP until 07/2022). Markus Rothacher brings in his broad experience in precise orbit determination, mission planning and project management. As PI of the CHAMP and Co-PI of the GRACE mission as well as the current Chair of the ESA Galileo Science Advisory Board he has the necessary experiences in handling large ESA projects. Current involvements into space missions such as Astrocast, Beesat (lead: TU Berlin), SAGE (lead: ARIS) and Precursor (lead: Uni Würzburg) guarantee continuity in this field of research and show that geodetic metrology, satellite geodesy and remote sensing are an integral part of the institute`s research activities.

Third, The missions of EPFL eSpace are: to inspire, educate, boost the next generation of top talents in space science and engineering, and to promote and support space research in laboratories, developing synergies through innovative and visionary projects. Based on eSpace's missions, the activities of the center are focused around three main areas: education, research, and communication and outreach.

eSpace current activities are dominantly research initiatives on Sustainable Space Logistics,which can include missions such as removal of space debris, and technologies such asRelative Navigation and Space Robotics. Example of outcomes of these initiatives are:

- The partnership with the eSpace's commercial spin-off Clearspace SA which will launch the first satellite removal mission in 2025, following the recent selection of the mission ClearSpace-1 by ESA
- The hosting and operation of the space sustainability rating launched in early 2022
- Activities in the domain of space logistics optimisation.

In addition, eSpace has a long history of being involved in space system development, the most striking achievement of eSpace being without any doubt the launch and decade-long operation of Swisscube, the first Swiss satellite. Notable eSpace contributions to the Swiss space sector also include the Cleanspace-one concept which later became Clearspace and later Innosuisse projects contributing to Clearspace such as Capture system Validation or Relative Navigation design, as well as contributions to CHEOPS, SOLVE and CASSIS missions.
eSpace is also in charge of the coordination of award-winning EPFL space-related student projects such as the EPFL Rocket Team or Xplore rover team. This is related to the educational role of eSpace within EPFL. eSpace is indeed responsible for the EPFL minor in space technology, which provides cutting-edge education for tomorrow's Swiss space engineers.

4.3 Concept for securing data analysis at the institute

The project concerns the development of two scientific instruments, the CubeSatTOF and a GNSS payload board for the exploration of Earth's upper atmosphere and ionosphere. Integrated into the CHESS pathfinder mission, an inventory of chemical species and GNSS raw data is generated, which serves as a data archive for Earth observation including space weather, climate change, as well as space mission design of satellites. Data produced through the course of this project and later during the operational phase fall into three categories: model simulation, test data on the ground and observations from the in-flight experiments.

The anticipated amount of simulations and observations is quite significant and shall be organised as a database with a proper and clear structure, complemented also with metadata. As a part of a convenient processing scheme related to this project, routines for automatic data transfer and storage shall be established to record as much data as possible within project duration and the operational phase afterwards. The calibrated, quality-controlled files will be annotated on a timely basis and stored accordingly on the group's computers at UBE, ETHZ and EPFL. The quality of collected data will be guaranteed mostly through the calibration of devices, repetition of experiments, comparison with literature, internal standards, previous data, and during the anticipated in-house tests. This shall assure a high compliance of the measurement instruments (CubeSatTOF and GNSS payload board) with the mission requirements.

According to the data policy of the investigators, no data will be stored on a public cloud hosted outside Switzerland. Any confidential (or sensitive) data, which may be produced due to the nature of the anticipated cooperation with other research facilities from science and industry, will be managed by the authorised participants of this project. The access to the laboratories/offices will be also restricted based on general regulations present at the involved institutes.

It is expected that the scientific output of this project will be presented and expressed in accordance with existing common standards and practices of the scientific community related to the investigated topic. Data publication will be conducted with the use of a well-established and non-commercial repository with a long-term preservation plan of the archived data. Each published dataset will have its own persistent and globally unique identifier. In addition, the licence for the data is clearly visible in this system. Some of the code connected to this project might be also shared on gitLab repositories belonging to the researchers involved in this project.

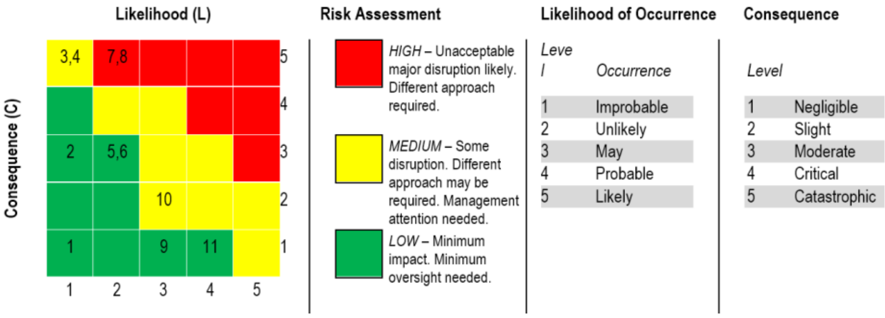
The immediate publication at the end of the project aims to minimise the data loss risk. Data (derived products, models) that underpins any related prospective publication will be therefore made available at the time of publication. ~~The main dataset (raw observations, auxiliary satellite-related files) will be disseminated but with an embargo of 2 years for priority of exploitation reasons.~~ The main dataset (raw observations, auxiliary satellite-related files) will be disseminated but with an embargo of 2 years for priority of exploitation reasons. During this period, access to the main dataset will be limited to the project consortium and selected partners involved in the instrument development as well as to ESA on request.

To guarantee that the necessary resources are available for the exploration of the generated data, financial assistance will be requested during the upcoming calls of SNSF. Providing these data is of high interest to the scientific community, thus increasing the risk of selection of such a project. The task will likely be performed by students on BSc, MSc, or PhD level supervised by the PIs and other PostDocs. At UBE, the computer infrastructure is provided by the University/Kanton, and the corresponding staffing provides limited support in copying existing databases from previous projects, i.e., for example, ROSINA/ROSETTA. Additionally, both strategy and base funding of the University will likely be available to support accomplishing this task. Moreover, international collaboration is strongly intended to share costs and increase the scientific output.

5 Risks assessment

5.1 Identified risks

CubeSatTOF instrument



Risk	L x C	Description	Mitigation strategy
1	1,1	Chip crisis causes delay during manufacturing of hardware	Given the simplicity of the ion-optical parts, several similar manufacturers exist. Thus, they can easily be replaced.
2	1,3	Hardware components of the mass analyser break during testing	As exceptional for CubeSat-type projects, we will execute a dedicated testing campaign to derive the limitations of the implemented design, in analogy to the development process of major space instrumentation (see also model philosophy and risk #8). The personnel necessary to perform actions is available until a late stage of AVT. This ensures the very capability to act during this most important phase.
3	1,5	Industry fails to adapt Phase B design of electronics and does not pass SCDR	This event is improbable, as we demonstrated with dedicated breadboards the functionality and feasibility of the outlined project. Concepts, schematics, and layouts are provided for the industry partner where necessary. Multiple reference designs exist for the complete instrument, though the CubeSatTOF is a simpler version of all of the recently successfully built and tested instrumentation. Additionally, a well-experienced, agile company has to be selected to be compliant with schedule.
4	1,5	Novel gas introduction system fails	This is improbable, as we extensively tested the instrument during dedicated laboratory test campaigns, and published the results in the literature (references see above). As the current ion-optical system is fully representative of the flight ion-optical system with respect to functionality, risks were reduced before starting the project.

5	2,3	Electronics fails to meet expected power consumption	We provide baseline designs for which the power consumption of the instrument is achievable. These concepts were derived for NGMS/Luna-Resurs and NIM/JUICE and further developed for this instrument. Despite industry being encouraged to implement their own solutions to the quest, we provide reference designs.
6	2,3	Delays in the delivery of the electronics and mechanics subsystems	Subsequently after subsystem SCDR, we perform rigorous testing of the instrument before we close out phase C in the instrument ICDR. SCDR can, in principle, be postponed by a few weeks, if the ICDR-date is maintained.
7	2,5	Baselined COTS components cannot be used as a high-voltage power supply	Unlikely as we tested some COTS components during phase A and B. If they turn out to be unreliable during further testing, then other suppliers can be selected, likely accepting a moderately increased power consumption. Alternatively, the previous project outline foresaw a customisation of the high voltage power supplies, encapsulate them, and therefore provide a custom solution. There is some both space in the instrument and time in this request reserved for such a modification, if necessary, thus allowing for a reliable planning of the project.~~.~~
8	2,5	Structural integrity of the instrument is compromised	Despite this spaceborne mass spectrometer providing unique advantages, it aligns with the constantly ongoing development of similar mass spectrometers, where mechanical innovation is limited given the simplicity of these instruments. From a mechanical (and electrical) engineering point of view, the most considerable innovation is the direct mounting of the ion-optical system on the PCB. To ensure a reliable system, we partially deviated from the modern PFM model philosophy to the EQM-FM philosophy (see discussion above). Including an early STM allows for representative testing and risks. A typical issue of modern CubeSat design is on one hand the lack of testing and on the other hand latently pre-damaged (overtested) systems, as the COTS components might not withstand equal levels to regular Hi-Rel, space-grade components. Thus, acceptance testing for the FM reduces risks as it mitigates identification of structural and thermal deficits at a late state of the project. Furthermore, UBE has profound experience in designing such systems.

9	3,1	Industry fails to hire well-trained personnel (if needed)	Currently, the labour market is dry. We provide reference designs for feasible solutions, but the company has to adapt them to be compatible with their own ecosystem to implement their software. We consider this as feasible for an experienced, successful company.
10	3,2	Delays in the delivery of the software	The testing functionality of the instrument has to be ensured during the testing phase. Limited performance restriction can be accepted during early AVT, as long as the feasibility of qualification (and acceptance) testing is maintained with a reasonable effort. Therefore, software updates shall be possible at all stages of the project, including phase E. To further mitigate this issue, industry may implement their own chipset, allowing for usage of reusable, well-tested libraries.
11	4,1	MCP breaks during testing	Rapid testing iterations induce stress on the MCPs in the detector. Frequent failure of this consumable is anticipated. We will establish a stock of this long lead item. As the anticipated type of MCPs are considerably more robust regarding mechanical stability as compared to, for example, NIM MCPs, these MCPs can easily be changed inside the detector, allowing for, in principle, frequent maintenance.

Table 11: CubeSatTOF identified risks

The GNSS payload board

Critically matrix used for risk identification

		Consequence (C)				
		1	2	3	4	5
Likelihood (O)	1	1	1	1	2	2
	2	1	2	2	3	3
	3	2	3	4	5	6
	4	3	5	7	8	9
	5	5	8	10	11	12

Risk Assessment

8-12: High - Unacceptable major disruption likely. Different approach required

4-7: Medium - Some disruption. Different approach may be required. Management attention needed

1-3: Low - Minimum impact. Minimum oversight needed

Identified risks:

Risk	L x C	Description	Mitigation strategy
1	2,5	The tracking performance of the COST GNSS receiver is not sufficient for the intended application	Early in-orbit validation of the GNSS receiver performance onboard the Precursor mission (Q2/2023) and Astrocast (Q2/2023). Early integration of the receiver manufacturer into the project. Enable the possibility for the installation of firmware updates from ground.
2	1,4	No industry partner can be identified for the development of the GNSS payload software	Early start of the ITT. Integration of the former software engineer responsible for the development of the basic version of the payload software into the process.
3	1,3	Chip crisis causes delay during manufacturing of hardware	Given the simplicity of the GNSS payload board, several similar manufacturers exist. Thus, they can easily be replaced.
4	2,4	Selected COTS components not qualified for space operation	Scheduling of an early environmental and functional testing so that damage hardware can be identified and replaced by other components
5	2,3	Antenna calibration on a satellite mockup not possible	Measuring of the antenna positions on a workbench with lower but acceptable accuracy. Determination of the phase centre variations on a 1U mockup or PCB.

Table 12: GNSS identified risks

Platform

Note: The risks in the following section are related to the platform which is not covered by the PRODEX funding.

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Identified risks:

Risk	L x C		Description	Mitigation strategy

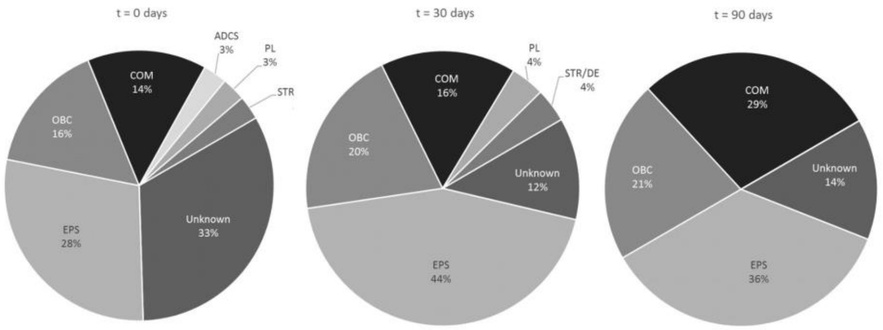
		Subsystem		
1	1,1	Structure	The structure is not able to withstand the loads during launch.	Identification of the right materials and perform qualification in lab to model the highest loads from the launch vehicle
2	4,4	Telecom	Platform cannot communicate with the ground station. Data cannot be downlinked. Commands cannot be uplinked.	Use flight heritage subsystem Redundancy of communication link (UHF and X-Band) and exhaustive testing (in lab and in orbit). Guarantee attitude-independent UHF link.
3	2,3	Power System	Not enough power is stored Not enough power is delivered to the subsystems	Redundancy Test exhaustively / manufacturer responsibility.
4	4,2	Attitude Control	ADCS is not providing the right pointing and manoeuvring, ADCS cannot compute the satellite attitude	Test sensors, test actuators, test power connections, test deployment of magnetometers. Use flight heritage subsystem
5	4,2	OBC	Commands cannot be executed Longer time to upload commands and updates	Use flight heritage subsystem and in-orbit testing

Table 13: Platform identified risks (Not funded by PRODEX)

5.2 Risk mitigation plan

Risks and their mitigation strategies of the payloads are discussed in section 5.1 where risks were identified. This section provides insights into ensuring a mission reliable platform.

Regarding the platform, the risk assessment analysis was performed on two levels. The first one consists in reviewing the current state of failures' occurrence and severity impacting past and current cubesats missions. Most cases failures are caused by the inability to communicate with the satellite (dead-on-arrival satellites). The second largest contributor in the early phases and the largest one in later phases is the Electrical Power System, with more than 40% of all failures caused after 30 days. After 90 days, 30% of failures originate in the communication subsystem whereas the attitude determination and control system, payload and structure contribute the 10% to the failure of the satellite.



CubeSat failure per subsystem (Langer and Bouwmeester, 2016)

The EPFL Spacecraft Team is thus aware of the common failures modes encountered by active actors of the sector and has set up a risk management framework with analysis methods for the technical, cost, schedule and management aspect of the project (which is especially relevant as the workforce is continually changing because of the nature of the group). Making sure that the project is robust of those changes is essential for the well-being of the team and the final product's reliability. A detailed summary of potential failure on a subsystem level is available in the annex. To emphasise the education and the development dimensions of the project, an iterative strategy is being implemented for the development of all subsystems. Hence the series of in-orbit demonstrations of the platform's most critical subsystems.

1. On-Board Computer (OBC)

The In-house designed on-board computer from the EPFL Spacecraft Team is scheduled for launch no earlier than the 19th of January 2023 on the ION orbital transfer vehicle from D-Orbit as a hosted payload. The mission aims at performing a functional testing of the OBC in an environment similar to the CHESS mission. The mission will have a minimal duration of 1 year and enables the analysis of component degradation as a function of time.

At the time of writing, the OBC is integrated on the ION spacecraft and delivered to the United States of America for integration and launch on Falcon 9 - Starlink Rideshare.

2. X-Band Telecommunication Module

The EPFL Spacecraft Team is in final discussions with Armasuisse to sponsor the development of the X-Band transmitter and antenna and the following in-orbit demonstration in Q1 2024 as a hosted payload. The contract with Armasuisse shall cover the development of an engineering model in Q1 2023, flight model in Q3 2023 and launch in Q1 2024.

The overall goal of the strategy presented above is to increase the technology readiness level of the platform before the CHESS mission in 2026. As such, the platform should have in-house designed and COTS subsystems already space-proven.

This strategy from the Spacecraft Team attracts more sponsors to the project, to the example of Armasuisse, whose goal is to contribute to hands-on work directly impacting students' education. A sponsoring campaign is currently being conducted to secure additional funding for the rest of the subsystems of the platform.

6 Requested PRODEX funds

6.1 Overview of costs per category and year

- Total

Category	2023	2024	2025	Total (€)	% of overall costs
Salary costs at institute	311'127.82	~~434'896~~430'896.58	478'224.36	1'220'248.76	45.9 %
Travel costs	1'868.00	4'068.00	10'820.00	16'756.00	0.6 %
Other costs at institute	51'588.00	17'959.00	21'082.00	90'629.00	3.4 %
Industry costs	43'333.00	570'167.00	~~716'333~~716'321.00	~~1'329'833~~1'329'812.00	**50.0 %**
Total (€)	407'916.82	1'027'090.58	~~1'226'459~~1'226'447.36	~~2'657'466~~2'657'445.76	

Table 14: Total requested PRODEX funds

- UBE share

Category	2023	2024	2025	Total (€)	% of overall costs
Salary costs at institute	254'167	325'000	295'000	874'167	41.5%
Travel costs	788	2'628	5'760	9'177	0.4%
Other costs at institute	49'315	9'686	13'809	72'810	3.5%
Industry costs	-	479'158~~67~~	670'821~~33~~	1'149'978~~50'000~~	**54.6%**
Total (€)	**304'270**	**816'47~~8~~1**	**985'390~~402~~**	**2'106'132~~53~~**	

Table 15: UBE requested funds

- ETHZ share

Category	2023	2024	2025	Total (€)	% of overall costs

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Salary costs at institute	20'627	62'296	56'056	138'979	40.4%
Travel costs	1'080	1'440	5'060	7'580	2.2%
Other costs at institute	2'273	8'273	7'273	17'819	5.2%
Industry costs	43'333	91'000	45'500	179'833	**52.2%**
Total (€)	**67'313**	**163'009**	**113'889**	**344'211**	

Table 16: ETHZ requested funds

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- EPFL share

Category	**2023**	**2024**	**2025**	**Total (€)**	**% of overall costs**
Salary costs at institute	36'333.82	43'600.58	127'168.36	207'102.76	100
Travel costs	NA	NA	NA	NA	0
Other costs at institute	NA	NA	NA	NA	0
Industry costs	NA	NA	NA	NA	0
Total (€)	**36'333.82**	**43'600.58**	**127'168.36**	**207'102.76**	

Table 17: EPFL Requested funds

6.2 Salary costs at institute

UBE

The need for additional staff to be funded by PRODEX is given in the following table, detailed to several categories: System engineer and project manager, mechanical engineer, and electronics engineer. These positions are described further in the text below.

Year	Phase	Months	System Engineer / Project Manager	Mechanical Engineer	Mechanical Modelling and Test Engineer	Electrical Engineer	Total personnel (FTE)
2023	C	2	0%	0%	0%	0%	0.00
2023	C	10	50%	100%	0%	100%	2.08

2024	C/D	12	50%	100%	17%	100%	2.67
2025	D	12	50%	75%	17%	100%	2.42

Table 18: Salary costs at UBE

Systems Engineer and Project Manager: This position will be filled with Ms Michela Gargano. She will be hired at 50% level for this project. She already holds a similar position (50%) at the institute for managing hardware contributions to IMAP, another PRODEX funded project. This optimises resources and omits the training period, reducing costs. She is experienced in the processes related to both PRODEX and hardware development. In her position, she will work at UBE and will interface the mechanical engineering of UBE, electronics engineering of UBE, assist the contact with the industry partner (responsibility of electronics engineer), act as a point of contract for other partners from the CHESS consortium. She will supervise all tests and AVT, is responsible for schedule, documentation in particular numbering and administration structure, and will participate in technical, management, and in science team meetings.

Mechanical Engineer: He/she will be hired at 100%, will be reporting to the UBE lead mechanical engineer Dr. D. Piazza, and will be responsible for the mechanical design of the structure, the ion-optical system and the EGSE, lead AVT on subsystem and assist it on system level, perform and assist AVT on the platform and on the satellite, if necessary. He/she adapts the previously existing designs to and adapts the SoW to provide the according implementations. He/she will assist the technical interface with industrial partners, provides and adapts interfaces on the instrument, prepares the required documentation, performs and leads QA/PA, and participates in technical meetings. We consider hiring a mechanical engineer that has already profound experience with the design of similar mass spectrometers.

Mechanical Modelling and Test Engineer: FTEs related to these positions are shared within the institute with other projects. During the design phase, limited time is allocated for thermal and structural simulation of the instrument to ensure thermal and structural integrity of the system. In addition, test engineers are used when necessary for the dedicated testing campaigns minimising FTE consumption. All engineers will report to the UBE lead mechanical engineer Dr. D. Piazza, participate in technical meetings, prepare the required documentation, and interface with other members of the consortium for limited consultancy, if necessary.

Electronics Engineer: He/she will be hired at 100%, will be reporting to the UBE lead electronics engineer S. Hayoz, and will be responsible for the preparation and implementation of the ITT including all relevant documentation, adapt the SoW regarding electronics, supervise industry collaboration, provide assistance for questions from industry and other members of the consortium during all phases of the project, assist AVT on subsystem and lead it on system level, perform and assist AVT on the platform and on the satellite. He/she will perform QA/PA, and participate in technical meetings.

- ETH Zurich

Descriptions of duties and expected workload for each staff member at ETH Zurich to be paid by PRODEX and as described in the work packages in section 3.5.

Year	System Engineer / Project Manager (Months)	Mechanical Engineer (Months)	Electrical Engineer (Months)	System Engineer (Months)

2023	10%	(10 M)	0%	(0 M)	0%	(0 M)	10%	(3 M)
2024	10%	(12 M)	10%	(3 M)	20%	(4 M)	20%	(12 M)
2025	10%	(12 M)	10%	(3 M)	20%	(2 M)	20%	(12 M)

Table 19: Salary costs at ETHZ

Overview about ETHZ staff members and their contributions to the project

Staff member	Duties	Months	Workload	Hourly rate
Gregor Moeller (System Engineer / Project Manager)	Overall project management and coordination of WP2.1.2, WP2.2.1, WP2.3.2 and WP2.3.5	32	413 hours (FTE = 0.1)	110 €
Alexander Wolf (Electrical Engineer)	Coordination and development in WP2.3.1	6	208 hours (FTE = 0.2)	90 €
Robert Presl (Mechanical Engineer)	Coordination and development in WP2.3.3 and WP2.3.4	6	104 hours (FTE = 0.2)	90 €
Andreas Brown (System Engineer)	Developments in WP2.1.2, WP2.2.1, WP2.3.2 and WP2.3.5	27	936 hours (FTE = 0.2)	70 €

Table 20: ETHZ staff organisation~~1~~

Gregor Moeller is a senior scientist and lecturer at ETH Zurich's Institute of Geodesy and Photogrammetry, with focus on high-precision GNSS, precise orbit determination for dense nanosatellite constellations and atmospheric remote sensing. In 2020, he was initiating the development of the current prototype GNSS payload board and is leading this activity since July 2022.

Alexander Wolf is an electronics engineer at IGP and leader of the electronics lab, where he is involved in various high-precision GNSS instrument developments. His expertise was crucial for the design of the current GNSS board. Thus, in this project he will be responsible for the hardware modifications and testing of the new integrations.

Robert Presl is a hardware engineer at IGP and leader of the metrology lab. In this project he is contributing his expertise to the manufacturing of the SLR retro-reflectors and will be responsible for the mounting of the satellite mockup for antenna calibration.

Andreas Brown is currently a student assistant at IGP. He joined ETH Zurich in 2021 with the prestigious Excellence Scholarship from ETH Zurich. Since September 2022, he is a project assistant under the supervision of Prof. Benedikt Soja and Gregor Moeller in the field of high-precision GNSS.

- EPFL

Summary of WP3 Workload

Staff member	Duties	Yearly FTE in 2023 (03/2023-12/2023)	Yearly FTEs in 2024	Yearly FTEs in 2025
TBD	WP3.1	0.25 (0.3 FTE over 10 months)	0.3	0.875
	WP3.2			

Table 21: Salary costs at EPFL~~1~~

This workload has been estimated with the feedback from the SwissCube project conducted by EPFL

Breakdown of EPFL salary cost for WP3 (WP3.1 and WP3.2):
0.3 FTE during the development phase (March 2023 to Q4 2024) and 0.7 FTE during AIT of the CHESS satellites. (Q1 2025 to Q1 2026)

- Est. maximal gross hourly rate : 97.6 CHF/h (rate defined between EPFL and ESA[1]). This is used in this proposal because the actual EPFL staff in charge of the work package has not yet been defined
    - This is **88.87 €/h**r given current SERI exchange rate of 1.10 CHF/EUR[2].
    - It is important to note that this is a *maximal* case estimate for this proposal. The effective reimbursable hourly rate will most likely be lower and will depend on staff selection.
- Sellable yearly hours per FTE : **1638**[3] h,
- Yearly cost of one FTE :**145 335,27** €/year.

    - Total salary cost for EPFL : **207'102.76 €**

6.3 Travel costs

UBE

The expected travel expenses to be funded by this request are presented in the table below. They base on estimates of previous projects. Despite most meetings being held virtually, limited travel remains necessary. Travels are grouped into international trips and trips within Switzerland. CH trips are necessary for team meetings with the industry, EPFL and ETH. Only selected personnel will likely be part of these meetings to reduce costs. Supporting the AVT phase at EPFL will require frequent travel within Switzerland for some or all engineers. International trips include support of AVT at the launch provider, if necessary. We baselined an average travel cost of 130 € for national trips, and 1820 € for international trips.

Year	Phase	Months	Trips Int.	Trips CH	Travel (Euro)
2023	C	2	-	-	0

[1] ESA-IPL-IAA-LE-2020-5615-KMS
[2]https://www.sbfi.admin.ch/sbfi/en/home/research-and-innovation/space/informations-for-experts/prodex.html
[3] ESA-IPL-IAA-LE-2020-5615-KMS

2023	C	10	-	6	788
2024	C/D	12	-	20	2’628
2025	D	12	1	30	5’760
Travel total			**1**	**56**	**9’177**

Table 22: Travel costs at UBE~~1~~

ETH Zurich

The expected travel expenses to be funded by this request are grouped into international trips and trips within Switzerland. CH trips are necessary for team meetings with the industry, UBE and EPFL. Only selected personnel will likely be part of these meetings to reduce costs. Supporting the AVT phase at EPFL will require frequent travel within Switzerland for some or all engineers. International trips include support of AVT at the launch provider, if necessary. We baselined an average travel cost of 180 € for national trips per person, and 1820 € for international trips.

Year	Phase	Months	Trips Int.	Trips CH	Travel (Euro)
2023	C	9	-	6	1’080
2024	C/D	12	-	8	1’440
2025	D	12	1	18	5’060
Travel total			**1**	**32**	**7’580**

Table 23: Travel costs at ETHZ~~1~~

6.4 Other costs at institute

UBE

The expected cost in category 1 and 2 to be funded by this request are presented in the table below. The costs are driven by the consumables of the CubeSatTOF instrument, coatings and other hardware treatment necessary for the ion-optical system and the structure, complemented by small parts for both mechanics and electronics and minor computer-related infrastructure (licences, computer, etc.).

Consumables of CubeSatTOF include the microchannel plates (MCPs) for the detector and thermionic emitters, also referred to as filament (or cathode). For the filament, we use the same item that we space-qualified, enabled by funding of previous PRODEX grants, reducing both costs and risks. However, experience has shown that testing of the electronics during AVT can be accelerated if a representative filament can be used for testing, as the filament represents a non-linear resistor, and designing a representative model is challenging. Based on previous orders, an item costs about € 600 per item, of which two are necessary upon AVT for space flight.

For the MCPs of this instrument, no previously tested item can be used. Despite the design and characteristics of this detector and detectors from previous instrumentation are very similar, it has an increased diameter. This minor modification will require some testing during AVT. In addition, the MCPs are very sensitive parts with respect to air exposure. MCPs require a dedicated outgassing and commissioning process upon air exposure. Experience from NIM/JUICE and NGMS/Luna-Resurs baseline a time for outgassing of about 5 to 7 days once in a reasonable vacuum. This considerably prolongs AVT phase, as iterations consume about 2 weeks. To accelerate these iterations, we accept more risk for the MCPs (and hence the detector) during AVT, drastically shortening this process. As the mechanical design is optimised for rapid outgassing and the electronics design is capable of handling malfunction of the MCPs, we anticipate replacing them more frequently than in previously built instrumentation. This reduces the time necessary for the AVT phase at the cost of some MCPs. As they are long-lead items, they will be ordered in an early phase of this request. Based on orders for the prototypes, the currently anticipated item costs about € 3200 per item including shipping and fees.

Small parts and coatings are based on both instrument elegant breadboards and experience from previous instrumentation.

Category	**2023**	**2024**	**2025**	**Total (€)**
Cat 1 (equipment to be procured)	45’192	3’500	3’500	**52’192**
Cat 2 (equipment to be developed/built by the institute)	4’124	6’186	10’309	**20’619**
Total (€)	**49’315**	**9’686**	**13’809**	**72’810**

Table 24: ~~1~~ Equipment costs at UBE

ETH Zurich

The costs for the GNSS payload board can be divided into *material costs* to build the printed circuit boards (GNSS receivers, microcontrollers, MRAM, NOR-Flash, LNAs, splitters, filters, transistors, etc.) and the *material costs* to build the four GNSS payload models (structures, antennas, cables, connectors, etc.). Additional *material costs* are expected for the SLR retro-reflectors, the mounting of the satellite mockup on the calibration robot and the preparation of the environmental tests. *External production* costs are expected for the production and soldering of the PCBs, the production of the SLR mounting structures and the assembly in the clean room. *Facility costs* are expected for the environmental tests. Some costs are also allocated for *transport and insurance*.

Category	**2023**	**2024**	**2025**	**Total (€)**
Material costs (Cat 1)	2`273	3’182	3’727	**9’182**
External production (Cat 2)	-	1`636	2`182	**3’818**

Facility costs (Cat 2)	-	3’455	1`364	**4’818**
Total (€)	**2’273**	**8’273**	**7’273**	**17’819**

Table 25: Material and production cost at ETHZ~~1~~

6.5 Industry costs

UBE

Realising CubeSatTOF in this project includes sub-WPs summarised in WP1.1 that is recommended to invite tenders as one single, inclusive WP (1.1) given the highly integrated nature and inherent structure of CubeSatTOF.

In 2020, for the first version of this proposal, we received an informal sales quotation (private communication with Jürg Jost, CEO of SpaceTek Technology AG, Gümligen, Switzerland, on 5 March 2020). Presented numbers represent estimates to comply with the signed non-disclosure agreement that UBE and SpaceTek Technology AG signed exclusively.

The initial relevant firm-fixed price for this request was about 1 M€. Neither an EQM nor a tested FS was included at this price. Since providing the initial sales quotation,

- model philosophy has changed given the updated both mission design and testing philosophy;
- inflation increased prices of electronics;
- chip shortage increased prices of electronics;
- inflation increased prices of labour;
- chip shortage compromised availability of components and increased lead time.

Current model philosophy adapts the needs of this mission. A detailed justification of the model philosophy is provided above. Especially FS2 represents a special approach for electronics. This model shall be fully functional regarding, i.e., pass the full functional test, but is not acceptance tested. As explained above, this model will be fully qualified (acceptance levels), if the FM breaks and cannot be repaired with reasonable effort given the COTS component approach. In this case, acceptance testing of FS2 will be finalised replacing FS1, and the FS replaces the FM.

Manufacturing of the FS2 will consume some costs for labour and components, but improves schedule reliability. Given the COTS components approach, we estimate actual additional hardware costs for FS2 to be about 15 k€ based on the baseline, internal design, given scaling effects. This estimation enabled by the CubeSat approach is in stark contrast to instruments relying on Hi-Rel components. Once the FM is tested, FS1 and FS2 will be commissioned rapidly, as long as both the knowhow and routines of the team remain available. On the other hand, if the FM or FS1 is irreparably damaged during late AVT, manufacturing another FS could be very expensive, and schedule cannot be met given the current market situation.

The initial timeline in the study logic foresaw completion of the project within 1 year. This time was tailored to this very industry partner, and we doubt that others might be as quick as the initially proposed partner. Independent of the industrial partner, the chip crisis hit the industry hard. Back in 2020 and in later discussions, we had the agreement with SpaceTek Technology AG that enough crucial chips were available and could be used for this project. To provide fair conditions for an ITT, to increase the reliability on the milestones regarding the chip crises, reflect trends on the labour market, ensure schedule integrity, and adapt to the updated model philosophy, we increased the duration of the study plan logic from 1 year (preliminary development plan) to 1 year and 4 months.

Given these conditions presented above and NGMS/Luna-Resurs baseline sales quotations, we estimate the following labour hours for this request. Using a gross hourly rate ~~between 110 and~~of 132.70 € is reasonable, based on previous sales quotations, resulting in € 1'149'978.

WP	Description	Estimated labour force in hours	In FTEs
1.1.2	Provide the electronics of CubeSatTOF	5'260	3.1
1.1.3	Provide the EGSE of CubeSatTOF	400	0.2
1.1.4	Provide the software of CubeSatTOF	3'006	1.8
Total		**8'666**	**5.1**

Table 26: UBE industry costs~~1~~

ETH Zurich

~~Realising this project includes the integration of industry partners in the following two work packages: GNSS receiver optimization (WP2.1.1) and payload software development (WP2.2.2). Given the highly integrated nature and inherent structure of the GNSS payload board it is recommended to invite tenders as one single. Based on the given heritage, we recommend u-blox as an integration partner for the first WP 2.1.1. The industry partner for the second work package shall be identified in an ITT process. To provide fair conditions for an ITT, the start date of the second work package was set to T0+8 months and the entire project duration is defined as 21 months. For the labour costs a gross hourly rate of 125 € is foreseen. The FTE computation is based on an expected workload of 1650 hours per year.~~

Realising this project includes the integration of industry partners in the following two work packages: GNSS receiver optimization (WP2.1.1) and payload software development (WP2.2.2). Based on the given heritage, we recommend u-blox as an integration partner for the first WP 2.1.1. The industry partner for the second work package shall be selected during the project phase according to ESA's procurement rules. Given the highly integrated nature of the GNSS payload board, we recommended having the payload software developed by a single collaboration partner. A potential list of partners can be found in Section 8. To provide fair conditions for a potential ITT, the start date of the second work package was set to T0+8 months and the entire project duration is defined as 21 months. For the labour costs a gross hourly rate of 125 € is foreseen. The FTE computation is based on an expected workload of 1650 hours per year.

WP	Description	Estimated labour force in hours	In FTEs
2.1.1	GNSS receiver optimization	347 (over 10 M)	0.25
2.2.2	Payload software development	1092 (over 21 M)	0.35
Total		**1439**	**0.6**

Table 27: ETHZ industry costs~~1~~

7 Other funding sources

7.1 Third-party funding

UBE

Funding organisation	Status of application	Amount and purpose	Duration
ESA OSIP / selected for implementation in the ESA Discovery Programme	Accepted	*Title*: An ultra-compact mass spectrometer that enables the reliable analysis of complex molecules: from a real time monitoring system of Earth's exosphere towards analyses on airborne platforms. *Purpose*: The goal of this project is to investigate both commercial and deep space applications of a miniaturised time-of-flight mass spectrometer, referred to as CubeSatTOF. As of yet, mass spectrometers are either too bulky or lack performance to reliably use them on portable platforms such as uncrewed aerial vehicles (drones) flying on Earth or on descent probes for spacecraft flybys. A miniaturised version of the neutral and ion mass spectrometer (NIM) flying on board ESA's JUICE mission could fill this gap. We will test the instrument on breadboard level in real world applications on Earth. Enclosed in a vacuum system, which we will design, it will fit on uncrewed aerial vehicles for unknown gas cloud monitoring (e.g., on volcanoes and upon military attacks), or for disaster control. These applications complement the future goal of establishing a high-performance technology for the detection of complex signatures of life in plumes of celestial objects in deep space. *Total amount*: 174'545 €.	1 Jan 2023 to 31 Jan 2024

Table 28: UBE third-party funding~~1~~

ETH Zurich

Funding organisation	Status of application	Amount and purpose	Duration
ETH ORD Program	Accepted	*30k CHF for Mitigating spaceborne radio frequency interference*	6 months
ESA PRODEX	Pending	*3,2M EUR for vANCESTOR - bringing absolute optical reference to the astronomical observatories of the world*	1 Jan 2023 to 1 Apr 2025
SNSF project funding	Pending	*465k CHF for Machine Learning for Ionospheric GNSS and VLBI Data Assimilation*	48 months

Swiss Polar Institute Technogrant	Pending	*45k CHF for GNSS sensor for high-altitude and polar science*	24 months

Table 29: ETHZ third-party funding~~1~~

7.2 In-kind contributions

UBE

In preparation of our participation in the CHESS mission, UBE provides funds from the Kanton dedicated to the general laboratory activities. The total funding provided in kind for the duration of this request is estimated to be about 300 to 500 kCHF based on previous projects.

- Engineering kick-off support, 0.5 FTE total in 2023 (University strategy funding/Kanton)
- Laboratory infrastructure, per year (University/Kanton)
    - Vacuum test stand #4 for ion source development and testing
    - Modified vacuum test stand #4 for neutral gas beam testing
    - MEFISTO laboratory for testing and calibration
    - Thermal vacuum chamber
    - Vibration test facilities
- Clean room facilities
- Engineering infrastructure
- Large mechanical machine shop
- Electronics shop
- Travel for CHESS, per year (SNSF)
- Travel for CHESS, per year (University/Kanton)
- Maintenance of test equipment, per year (University/Kanton)
- Maintenance and infrastructure personnel, prorated, per year (SNSF)
- Maintenance and infrastructure personnel, prorated, per year (University/Kanton)

These facilities are used on demand. For example, the vacuum test infrastructure will be available permanently over the project duration contrasting, for example, the vibration facilities, which are shared with other projects.

An impactful share of the total cost is covered by the university as in-kind contribution. UBE offers funding for personnel costs for manufacturing the vast majority of the ion-optical system in its mechanical machine shop, as tools from the shop allow it to do so (cf. costs of the ion-optical system of previous requests). This considerably reduces costs in Category 2 (see above). In addition, this ensures rapid availability of the parts once ordered, condensing schedule.

Moreover, UBE provides in-kind contributions for testing the subsystems of the CHESS platform and related subsystems. Support includes personnel support for both testing and consultancy, facilities, reference documentation. UBE has already successfully performed tests with the subsystems of the platform.

ETH Zurich
Mentoring of experienced staff, e.g., from Prof. em. Markus Rothacher (100 hours, ~17k EUR) is provided in kind. Infrastructure in the form of office space, computing facilities, group shares, vacuum and temperature test facilities, electrical and mechanical engineering infrastructure, industrial robot and the geodetic GNSS equipment needed for the calibration of the GNSS antennas is provided in kind by the Institute of Geodesy and Photogrammetry. The students participating in the project are either:

- Project or student assistants
- Master & Bachelor students performing a semester project equivalent to 12 ECTS.
- Master students performing a master thesis equivalent of 30 ECTS.

Supervision is provided by the p~~P~~rofessors and various experts at the Institute.

EPFL

The EPFL provides the platform hardware and software as well as the student work force dedicated to platform specific system engineering and subsystem design.
The students participating in the project are either:
- Members of the association EPFL Spacecraft Team.
- Master & Bachelor students performing a semester project equivalent to 10 or 12 ECTS.
- Master students performing a master thesis equivalent of 30 ECTS.

The students are thus also supervised by professors and various experts who help, guide and give a clear overview of the specific technical aspects of the projects. In addition, the team is in constant relation with alumni-students who are now working in the industry and able to offer advice.

EPFL also contributes an amount of CHF 20'000 per semester in direct funding for the platform development in the scope of MAKE projects. The funding is renewable every year until the end of the mission.

The facilities of EPFL including the Discovery Learning Laboratory (The SPOT) is made available for MAKE projects for all prototyping and manufacturing related activities. The cleanrooms in EPFL Space Center (ISO8) are also available on demand.

Finally, EPFL covers the launch cost through the partnerships established between the Spacecraft Team and industry partners to secure reduced cost offers.

8 Potentially interested industrial partners

UBE

Collini-Flühmann AG
Ringstrasse 9, 8600 Dübendorf
Mr. H.A. Braun

Cosylab Switzerland GmbH
Badenerstrasse 13, 5200 Brugg
Hr. Diego Casadei

Heinz Baumgartner AG
Schuetzenstrasse 29, 8902 Urdorf
Mr. S. Murbach

Kaltbrunner AG
Sportstrasse 1, 2540 Grenchen
Mr. D. Oertle

Klein L. SA/AG
Längfeldweg 110, 2501 Biel

Linktronix AG
Zürcherstrasse 66, 8800 Thalwil
Mr. Pietro Bianco

Mecha AG
Stockmattstrasse 12, 3123 Belp
Mr. C. Rohr

Meier Schutzgastechnik
Landstrasse 5, 5426 Lengnau
Mr. F. Meier

PinPlus AG
Zentweg 17a, 3006 Bern
Mr. M. Züger

Retero GmbH
Stadtweg 24, 8245 Feuerthalen
Mr. Retter

Rickli Micromécanique S.A.

a mis en forme : Français (France)

Route de Romont 27, 2537 Vauffelin
Mr. P. Rickli

Signer Titanium AG
Kantonsstrasse 1, 8807 Freienbach SZ
Mr. Signer

Spacetek Technology AG
Brüggliweg 18, 3073 Gümligen
Mr. J. Jost

<u>ETH Zurich</u>
beyond gravity
Schaffhauserstrasse 580, 8052 Zurich
Michael Fisler

CYSEC
EPFL Innivation Park A, 1015 Lausanne

ERNI Switzerland
Casinoplatz 2, 3011 Bern
Flavio Sonnenberg

Exolabs
Hegibachstrasse 48, 8032 Zurich

Steiger AG
Rue de Pra de Plan 18, 1618 Châtel-St-Denis
Mr. J.-C. Puippe

Surcotec SA
Chemin du Pont-du-Centenaire 109, 1228 Plan-les-Ouates
Ms. V. Prieux

Thyssen (Schweiz) AG
Industriestrasse, 9501 Wil

Saphyrion
Strada Regina 16, 6934 Bioggio

SpacePNT
Rue du Puits-Godet 8, 2000 Neuchâtel
Cyril Botteron

Syderal Swiss
Rue du Puits-Godet 6, 200 Neuchâtel

u-Blox AG
Züricherstrasse 68, 8800 Thalwil

Etienne Favey

a mis en forme : Français (France)

9 List of acronyms

A	Acceptance levels
ADCS	Attitude Determination and Control System
ADC	Analogue to Digital Converter
AVT	Assembly, Verification and Testing
CaSSIS	Colour and Stereo Surface Imaging System
CH	Switzerland
CHEOPS	CHaracterising ExOPlanet Satellite
CI	Continuous Integration
CIRA	COSPAR International Reference AtmospherE
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research
COTS	Commercial Off-The-Shelf
D	Germany
DOeS-MS	Direct Open Source Mass Spectrometry
DPU	Data Processing Unit
DYNAMIC	Dynamical Neutral Atmosphere-Ionosphere Coupling
ECTS	European Credit Transfer System
EEE	Electrical, Electronic and Electro-mechanical (components)
EGSE	Electronic Ground Support Equipment
EM	Engineering Model
EMC	ElectroMagnetic Compatibility
EPFL	Swiss Federal Institute of Technology in Lausanne
EQM	Engineering Qualification Model
ESA	European Space Agency
ETHZ	Swiss Federal Institute of Technology in Zürich
FI	Finland
FM	Flight Model
FS	Flight Spare model
FTE	Full-Time Equivalent
GCM	GNSS phase centre calibration model
GDC	Geospace Dynamics Constellation
GEOS	Geostationary Earth Orbit Satellite
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Hi-Rel	High-Reliability (component)
HSLU	Lucerne University of Applied Sciences and Arts
IADC	Inter-Agency space debris Coordination committee
ICDR	Instrument Critical Design Review
IGP	Institute of Geodesy and Photogrammetry
IMAP	Interstellar Mapping and Acceleration Probe
IRI	International Reference Ionosphere model
ISS	International Space Station
ITT	Invitation To Tenders
IVO	Io Volcano Observer
JPL	Jet Propulsion Laboratory
JUICE	JUpiter ICy moon Explorer
KOM	Kick-Off Meeting
KOM-I	Kick-Off Meeting with industry
KOM-P	Kick-Off Meeting of this project
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LVPS	Low Voltage Power Supply
M	Milestone
m/z	Mass per charge ratio
m/Δm	Mass resolution
MANIaC	Mass Analyzer for Neutrals and Ions at Comets
MAVEN	Mars Express, Venus Express, and Mars Atmosphere and Volatile Evolution
MCP	Multi-Channel Plate
MCU	Microcontroller Unit
MEFISTO	MEsskammer für FlugzeitInStrumente und Time-Of-Flight (Measurement chamber for TOF instruments)
MRAM	Magnetoresistive Random Access Memory
MRR	Mission Readiness Review
MSIS	Mass-Spectrometer-Incoherent-Scatter (model)
NA	Not Applicable
NGMS	Neutral Gas Mass Spectrometer
NIM	Neutral and Ion Mass spectrometer
NOR	Not OR flash memory
NRL	Naval Research Laboratory
NRLMSISE	Naval Research Laboratory - Mass-Spectrometer-Incoherent-Scatter (model)
OBC	On Board Computer
ORR	Operational Readiness Review
PA	Product Assurance
PCB	Printed Circuit Board
PEP	Particle Environment Package
PFM	Proto-Flight Model
PRODEX	PROgramme de Développement d'Expériences scientifiques
PRR-C	Production Readiness Review phase C
PRR-D	Production Readiness Review phase D
PVT	Positioning, Velocity determination and Timing
Q	Qualification levels
QA	Quality Assurance
ROSETTA	A name
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RRR	Requirements Readiness Review
S/C	Spacecraft
SAR	System Acceptance Review
SCDR	Subsystem Critical Design Review
SIR	System Integration Review
SLR	Satellite Laser Ranging
SMA	SubMiniature version A
SNSF	Swiss National Science Foundation
SoW	Statement of Work
SPI	Serial Peripheral Interface
STM	Structural Thermal Model
STSC	Scientific and Technical Subcommittee
TBC	To Be Confirmed
TBD	To Be Defined
TDD	Test Driven Development
TEC	Total Electron Content
TV	Thermal Vacuum
U	Unit (measure for the volume of a CubeSat), corresponding to 1 l
UART	Universal Asynchronous Receiver Transmitter
US	United States of America
USA	United States of America
WP	Work Package

10 Attachments

- Letter of Scientific Support
  - NASA's Jet Propulsion Laboratory
  - O. Mousis
  - A. McEwen
  - H. Lammer[4]
- Risk analysis on the platform level based on the NASA Risk Management Handbook

[4] Absences due to prolonged vacation lead and short notice of the needs of such a letter will lead to the submission of this letter, soon. We were promised to receive it by 3 November 2022.