The VIBES Program: Revolutionizing Earth Observation through Consumer Electronics

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Abstract

The satellite research program VIBES (Visionary Ingenuity Boosting European Spacecraft) was established in 2021 at the Institute of Aerospace Technology (IAT) of the City University of Applied Sciences Bremen. VIBES aims at bringing the consumer electronics revolution to space to improve the performance of spacecraft, and to connect education, research and industry to foster the development of talent and technologies for the future of spaceflight. In 2022, work was begun on the program's first spacecraft, VIBES Pioneer. VIBES Pioneer is a 3U CubeSat that carries a MEMS-based microvibration measurement system (MVMS). It will launch on the second flight of RFA ONE and will be deployed into a 500 km circular sun-synchronous orbit for a nominal mission duration of 12 weeks. Building upon the VIBES Pioneer mission is SENSORIS, a constellation that is being developed by the IAT, ZARM Center of Applied Space Technology and Microgravity and the DLR Institute for Satellite Geodesy and Inertial Sensing. The purpose of the constellation is to measure the Earth's gravity field using a NewSpace approach for faster, cheaper and more flexible data acquisition for research, security and resource management. It consists of twelve 3U CubeSats which are an evolution of the VIBES Pioneer spacecraft. The concept will be demonstrated with the VIBES Pathfinder mission. The paper at hand provides an update on the VIBES Pioneer mission and outlines the strategic roadmaps for VIBES Pathfinder and the SENSORIS constellation. Together, these missions support the aim of the VIBES research program of bringing the Consumer Electronics Revolution to space.

Keywords: CubeSat, microvibrations, consumer electronics, miniaturization, Earth observation, GNSS

Acronyms/Abbreviations

ADCS	Attitude Determination and Control System
COTS	Commercial-off-the-shelf
EO	Earth Observation
FPGA	Field-programmable Gate Array
GNSS	Global Navigation Satellite System
HL-SST	High-Low Satellite-to-Satellite Tracking
LEO	Low Earth Orbit
LL-SST	Low-Low Satellite-to-Satellite Tracking
VLEO	Very Low Earth Orbit
MEMS	Micro-electromechanical System
MVMS	Microvibration Measurement System
PCDU	Power Control and Distribution Unit
SDR	Software-Defined Radio
SoC	System-on-Chip
STM	Structural Thermal Model

1. Introduction

The VIBES research program, established in 2021 at the Institute of Aerospace Technology (IAT) of the City University of Applied Sciences Bremen, aims to revolutionize Earth observation missions through the innovative use of consumer electronics to enable more agile and cost-effective spacecraft. The paper at hand explores the potential of integrating consumer-grade technology into spacecraft, highlighting the significant advancements in computing power, cost-efficiency, and accessibility that these components offer. The paper is divided as follows: Firstly, a general overview is provided on why consumer electronics are a relevant field of study for future space missions in Section 2. Next, the VIBES program is introduced in section Section 3, followed by a presentation of the VIBES Pioneer mission and how consumer electronics are incorporated wherever possible (Section 4). Building upon VIBES Pioneer, the development of a 12-satellite constellation was begun. This constellation is called SENSORIS and aims at conducting measurements of the Earth's gravity field more frequently than currently pos-

sible. An overview on SENSORIS is provided in Section 5. Lastly, a brief outlook on the far future is given in Section 6.

2. Consumer Electronics in Space

Over the past years, there has been substantial progress in consumer electronics: it is nowadays possible to have video chats with friends from all around the globe, vacuums are independently cleaning homes, and cars are driving increasingly autonomous. These advancements have been primarily enabled by improvements in computing power. Thirty years ago, home computers were limited to basic tasks such as word processing. Today, everyone can carry a small yet powerful computer in their pocket or on their wrist. The chips used in these devices are energy-efficient and capable of handling increasingly complex tasks.

While this technological progress has affected our daily lives, spacecraft designs have been much slower at incorporating these advancements. An average flight computer for a CubeSat still costs more than 5000 Euros, whereas a flagship phone equipped with multiple cameras, sensors and a screen can be purchased for 1000 Euros or even less[1].

This underscores the potential consumer electronics house: Being smaller, more powerful and significantly less expensive than traditional components, they are attractive for projects with limited funding or for innovative approaches. The mars helicopter Ingenuity (Fig. 1) is a fascinating example of such a mission: Even though major components of its avionics architecture were taken from a smartphone and other household items, the helicopter survived a six-month long journey to Mars and performed 72 flights in almost three years. At one point, sensors commonly used in smartphones even saved the mission when another component failed. The first Martian helicopter could only be stopped by a mechanical failure, grounding the craft permanently in 2023; however, the electronic components are still functioning, allowing Ingenuity to have a second life as a Martian weather station[2][3].



Fig. 1. Ingenuity Mars helicopter – 72 flights on another planet using consumer electronics[4]

In addition to the performance and cost improvements, the implementation of consumer electronics can significantly shorten development times due to their wide availability. The growth of the launch services market is further reducing overall mission costs, allowing more agile, iterative approaches and the launch of multiple, inexpensive spacecraft rather than a single expensive one.

3. VIBES Research Program

Missions such as Ingenuity clearly show that consumer electronics not only work in space but can actually enable new types of missions. To study how consumer electronics can be used for a variety of space applications, the VIBES research program was established in 2021 at the Institute of Aerospace Technology (IAT) of the City University of Applied Sciences Bremen (HSB). The IAT has almost 30 years of experience with space projects with a specific focus on the study of future technologies. With VIBES, the IAT wants to further expand its portfolio. VIBES is short for Visionary Ingenuity Boosting European Spacecraft and aims at bringing the consumer electronics revolution to space, and to connect education, research and industry to foster talent and technologies for the future of spaceflight. With this emphasis on miniaturization and the integration of consumer electronics, the VIBES program is in line with the German federal government's space strategy [5]. Students are actively involved in the on-going research from their first semester onwards, enabling them to work on real space projects as part of their studies. At the same time, researchers get valuable resources and fresh minds for their projects (Fig. 2). Through cooperations with industry, a constant exchange of ideas and concepts is generated that benefits all stakeholders.



Fig. 2. University of Applied Sciences: with VIBES, the Institute of Aerospace Technology Bremen (IAT) is exploring new ways to build and test spacecraft using components designed for our daily lives while providing students with hands-on learning opportunities

With VIBES, the IAT is also flying for the first time their own spacecraft. Presently, two missions incorporating consumer electronics are in the works: VIBES Pioneer and SENSORIS.

4. VIBES Pioneer

The development of VIBES Pioneer was begun in 2022. It is the first ever spacecraft built in-house at the IAT. In Fig. 3, an overview of the spacecraft elements is provided. The 3U CubeSat uses consumer electronics wherever possible: The batteries of the Electrical Power Subsystem are LiFePo4 battery cells which are usually found in all types of household electronic devices. The Power Control and Distribution Unit (PCDU) is purchased from an aircraft electronics manufacturer. The flight computer of VIBES Pioneer combines ATMega microchip with a modified FPGA-based microcontroller. The structure of the spacecraft is being produced by a local manufacturer. For the thermal control system, polyimide heaters, self-developed heat sinks and COTS sensors are used.

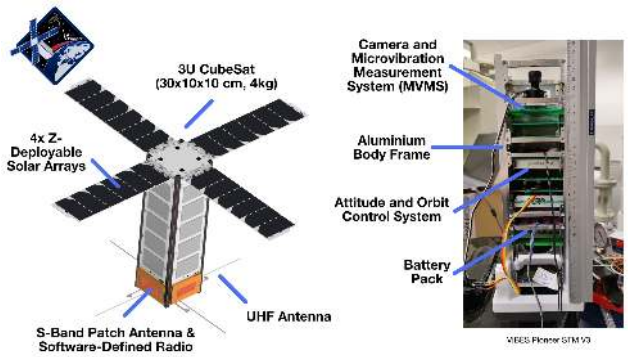


Fig. 3. VIBES Pioneer spacecraft elements

As its main payload, VIBES Pioneer carries an optical instrument and the Microvibration Measurement System (MVMS). The optical instrument is a Raspberry Pi HQ camera with a M12 25mm f/2.5 lens from Edmund Optics while the MVMS has been developed by the VIBES research team. It uses micro-electromechanical systems (MEMS) to measure small mechanical perturbations. These microvibrations are emitted by moving parts of a spacecraft, for instance the reaction wheel of the attitude control system, disturbing optical instruments such as cameras. Using sensors from the automotive industry that cost less than 60 Euros and an FPGA for data processing, the MVMS can create a detailed image of where, how and when the vibrations occur (Fig. 4).

The data can then be used to optimize photos taken by a camera in post-processing, and to optimize the operational modes of the spacecraft to reduce the impact of the vibrations. The demonstrated performance of the MVMS achieves similar results to heavier and more expensive measurement systems such industry standard dynamometers[6].

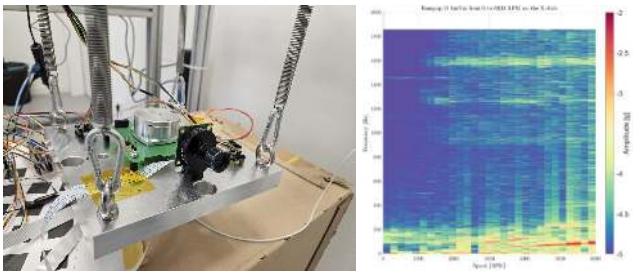


Fig. 4. MVMS test setup (left) and plot of microvibrations measured using MEMS sensors (right)

In the long term, the processing of the images shall happen directly on the computer of the spacecraft, so that only the polished data has to be downlinked, significantly optimizing the use of restricted downlink times.

In addition to the MVMS, the communication link for the mission will be evaluated as a secondary mission objective. The main mission downlink uses S-Band and is implemented as a software-defined radio (SDR) system (Fig. 5). At the core of the system lies a Zynq-7020 System-on-Chip (SoC), which provides both flexible signal processing capabilities and programmable logic. This is coupled with a fully self-developed RF front-end board that covers a wide frequency range from 70 MHz to 4000 MHz (Fig. 6). The front-end includes an integrated 2 W power amplifier and supports high-speed vector modulation with data rates of up to 20 Mbit/s. The signal is transmitted using an array of circularly polarized patch antennas to ensure robust communication, even under dynamic orientation conditions in orbit.



Fig. 5. Software-Defined Radio for VIBES Pioneer

For telemetry and command purposes, a dedicated UHF communication link operating in the 430 MHz to 440 MHz band is used. The UHF link is designed to provide continuous low-rate telemetry, while the S-Band SDR system focuses on high-speed data downlink, for instance, for payload data transmission. The SDR-based architecture allows for in-orbit reconfiguration, enabling future protocol adaptations and performance optimization. This architecture demonstrates a flexible and scalable communication solution, particularly suitable for CubeSat-class missions with demanding downlink requirements.



Fig. 6. S-Band antenna for VIBES Pioneer

Among the only components that are not consumer electronics is the Attitude Determination and Control System (ADCS). It consists of a magnetorquer board supplied by ZARM Technik and a magnetometer, a gyroscope and sun sensors as well as a reaction wheel made by Astrofein. The other major element not made from consumer electronics are the solar arrays, which use space-graded cells from an established manufacturer. However, the IAT has recently begun multiple research projects with industry partners to develop consumer-electronics-based solutions for the components (Fig. 7).

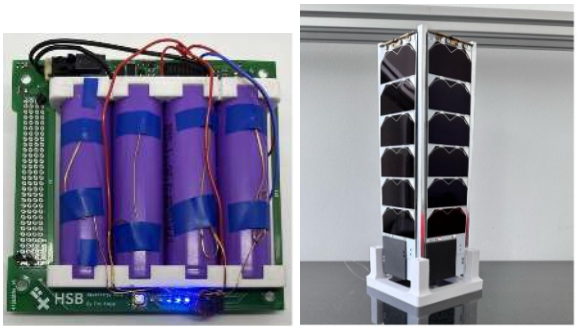


Fig. 7. Consumer Electronics are used in all subsystems. Future research projects will further advance these solutions

As a result of the implementation of consumer electronics, it was possible to build an ultra-low-cost spacecraft that delivers a high performance for its size. Presently, functional and qualification tests of all subsystems are carried out. Selected milestones of the on-going development include:

- Multiple test campaigns of the MVMS under microgravity conditions at the GraviTower Bremen Pro of ZARM
- Qualification of the spacecraft structure at ESA's CubeSat Support Facility (CSF) in May 2024 (Fig. 8)
- Vacuum deployment tests of the solar array and antenna release mechanisms
- Tests of the Attitude Determination and Control System (ADCS), of which key components are supplied by ZARM Technik AG
- Establishment of the VIBES Ground Control Center at the IAT in Bremen, with S-band and UHF ground stations being located at OHB Bremen and DLR Institute of Space Systems

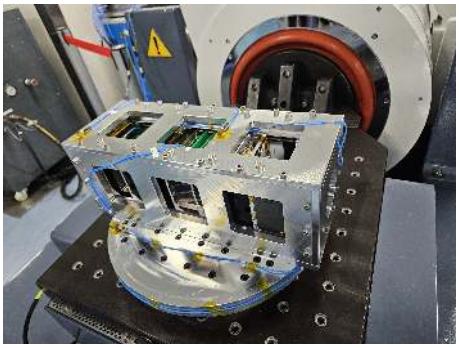


Fig. 8. Structural qualification of VIBES Pioneer at ESA CFS

The launch of VIBES Pioneer is currently foreseen for no earlier than the end of 2025 on the second launch of RFA ONE, a microlauncher under development by Rocket Factory Augsburg. This launch opportunity was secured through the Microlauncher Payload Competition of the German Space Agency, which selected the VIBES Pioneer mission in 2023 as one of eight European projects. The launch will occur from the SaxaVord Spaceport on the Shetland Islands in northern Scotland and will place VIBES Pioneer in a circular sun-synchronous orbit with an altitude of 500 km. VIBES Pioneer is designed to complete its primary mission objectives – the measurement of microvibrations and the implementation of an improved operation mode to reduce microvibrations based on the generated data – within 12 weeks (Fig. 9). The mission duration and profile have been designed with flexibility in mind, acknowledging the use of an untested launch vehicle

and the associated risk of not achieving a perfectly circular orbit. This flexibility ensures that the mission can be adapted to variations in the launch and orbital conditions, thereby maximizing the chances of meeting all mission objectives.

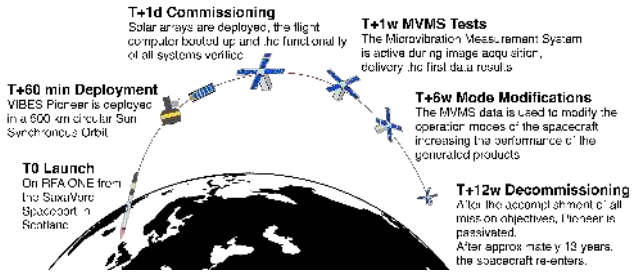


Fig. 9. VIBES Pioneer mission profile

5. SENSORIS

The second mission currently under development as part of the VIBES program is SENSORIS, a constellation of 12 identical 3U CubeSats that shall provide global coverage of the Earth's gravity field once per day. The name SENSORIS comes from the Latin *menoris*, meaning "the surveyors". It is being developed by the IAT together with the Center of Applied Space Technology and Microgravity (ZARM) and is supported by the DLR Institute for Satellite Geodesy and Inertial Sensing (DLR-SI).

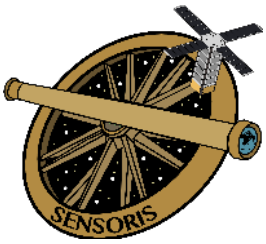


Fig. 10. SENSORIS mission patch

The primary objectives of the SENSORIS mission are:

- providing daily and thus phased high-resolution gravity field scans,
- to increase the added value of the future GRACE-C and NGGM missions by addressing the problem of limited background modelling,
- generating redundancy in gravity field determination and thus increasing resilience to failures, and
- the utilisation of consumer electronics for space applications to build smaller, lighter and more cost-effective satellites.

The SENSORIS spacecraft will utilize the same general architecture as VIBES Pioneer. However, the flight computer will be replaced by a new, consumer-electronics-based design that is being developed with DSI Aerospace GmbH. This computer, referred to as VIBES-OBC, will be capable of managing all operational tasks while further enabling the on-board processing of data generated by the MVMS. In addition, the magnetorquer board of the ADCS will also be replaced with a new development that is utilizing COTS components. The so-called Magnetic Attitude Control System (MACS) is being designed with ZARM Technik AG and the ZARM research institute of the University of Bremen. The VIBES team is also looking at incorporating consumer electronics into the solar arrays of the spacecraft.

The main payload of the SENSORIS spacecraft will be GNSS sensors. These will be used to determine temporal variations in the gravity field using the concept of high-low satellite-to-satellite tracking (HL-SST). It was recently shown that it is sufficient to equip individual satellites with GNSS receivers and accelerometers[7]: the absolute position is measured, from which gravity fields up to about degree and order 15, i.e. a spatial resolution of about 1200 to 1500 km, can be determined. The lower spatial resolution is deliberately accepted, as the significantly lower costs mean that a large number of satellites can be launched into space, thus producing data more frequently.

While SENSORIS will not be able to achieve the higher spatial resolution of GRACE-type missions, it represents a unique product on its own. Directly measured gravity field scans with a daily resolution have never been available. This will make it possible to observe large-scale fluctuations in the atmosphere, the ocean and hydrology. Episodic events in particular, but also the increasing intensity within the cycles of the Earth system, cannot yet be covered by models. In fact, the models need precisely these observations to be improved. In addition, AI-based methods are being developed that may allow an increase in spatial resolution. The first direct and global observation of daily tidal signals is also unique. Tidal forces are calculated using models in existing missions. These models are generally based on observations from altimetry missions, whereby aliasing frequencies are used to determine them. The direct and global observation of tidal signals has so far been impossible. This will change with SENSORIS and a significant improvement in tidal modelling can be expected, which in principle will benefit every satellite mission directly or indirectly. Furthermore, the use of additional satellites offers the possibility of scalability, i.e. by doubling the number of satellites, half-day and, if quadrupled, quarter-day tides can be observed globally. This would make large parts of the tidal spectrum fully observable for the first time, all while the cost for the SENSORIS constellation are significantly lower than other GRACE-type missions (Table 1).

Table 1. EO missions studying Earth's gravity field

Mission	GRACE [8]	GOCE [9]	GRACE-FO [10]	MAGIC [11]	SENSORIS
# of S/C	2	1	2	4	12
Mission Cost [M€]	115	250	465	unk.	30
Days per global coverage	30	240	30	5	1
Launch	2002	2009	2018	2028	2028

The roadmap for SENSORIS foresees an initial nine-month study to determine the requirements as well as technological feasibility of the mission architecture. While the mission definition phase has only just begun, three main constraints have been defined as a baseline:

- Low Earth Orbit: The mission takes place in LEO. The lower the altitude, the greater the influence of the gravitational field on the satellites, which leads to better measurement of the gravitational field. This is countered by a faster lowering of the satellites due to external forces such as drag.
- Polar orbit: A polar orbit, or an inclination of approx. 90° (inclination of GRACE and GRACE Follow-On is 89°) is necessary to achieve coverage of the entire Earth.
- CubeSat satellite platform, size 3U: The SENSORIS constellation will use the CubeSat architecture, as it offers great flexibility at low cost and are a widely used standard.

Succeeding the study, a fast-paced, test-rich development phase will follow, leading up to a demonstrator mission named VIBES Pathfinder. VIBES Pathfinder was originally planned as an independent successor to the VIBES Pioneer mission, upscaling the spacecraft architecture from 3U to 12U to incorporate a more capable MVMS and a propulsion system. As the development of VIBES Pioneer and the MVMS progressed, it became evident that this size increase was not necessary to accommodate the more powerful systems. At the same time, many of the components of VIBES Pioneer can be reused in modified form for SENSORIS. Hence, it was decided in early 2025 to merge the two developments. VIBES Pathfinder will now retain the 3U form factor and will not gain a propulsion system as neither is necessary for the SENSORIS mission. Further, not one but two VIBES Pathfinder spacecraft will be built and launched to demonstrate the SENSORIS concept. Once operational, the two satellites will be joined by 10 identical spacecraft to form the full SENSORIS constellation. The mission concept also allows adding additional spacecraft to the constellation, further increasing the performance and range of capabilities of SENSORIS.

6. A Look to the Future

The development of the SENSORIS constellation will not end with its full deployment. The consortium is already looking at a potential follow-/add-on project to further increase the capabilities of the constellation. This concept foresees the addition of technologies such as a micro-propulsion system and inter-satellite laser links to the spacecraft architecture. This would allow a lowering to a VLEO orbit of close to 200 km, and a low-low satellite to satellite (LL-SST) configuration, further improving the quality of the generated data as well as potentially reducing the time per full scan down to 6 hours. As it is planned with the VIBES Pathfinder mission, these upgrades will first be tested as part of a demonstration mission. While this mission will not launch before 2030, the VIBES team and its partners are already taking the future upgrades into account for the design of the initial SENSORIS spacecraft.

Beyond Earth Observation, the VIBES team is currently studying a spacecraft concept that would utilize consumer electronics for a mission on the Moon. The details of this study shall not be discussed in this paper, but the promising results of the ongoing work provide a positive outlook on the future of consumer electronics in space (Fig. 11).

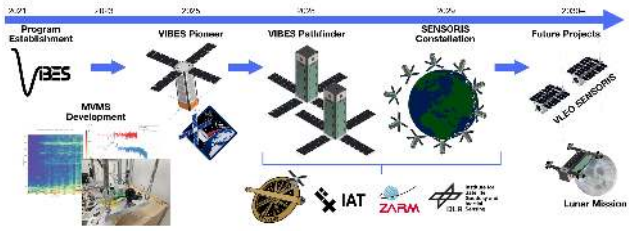


Fig. 11. The VIBES roadmap: from the MVMS to Pioneer, Pathfinder, SENSORIS and beyond

7. Summary

The VIBES research program of the Institute of Aerospace Technology Bremen is working on ways to bring the consumer electronics revolution to space. With its first mission – VIBES Pioneer – the VIBES research team is demonstrating the potential of consumer electronics in space. Together with their partners at ZARM and DLR-SI, the VIBES team is building

upon the VIBES Pioneer mission to create the SENSORIS constellation which will be capable of delivering global coverage of the Earth's gravity field once per day, a never before available frequency. Beyond the SENSORIS mission, the VIBES team is already looking at further increasing the capabilities of their spacecraft by using consumer electronics. The capabilities of the SENSORIS constellation will be expanded to provide even more frequent data on the Earth's gravity field. In addition, mission concepts beyond Low Earth Orbit are also being studied.

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