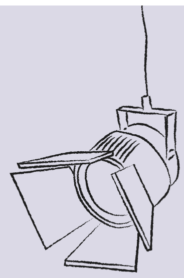


INSPIRE

From Teaching Tools to Sun and Earth Observation Satellites

[Mustapha Meftah *(CNRS-LATMOS, France)*,
Amal Chandran *(Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, USA)*, Loren Chang *(National Central University, China: Academy of Sciences Located in Taipei)*,
Leigh Fergus *(COSPAR, France)*, Jean-Claude Worms *(COSPAR, France)* and
Dan Baker *(Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, USA)*]

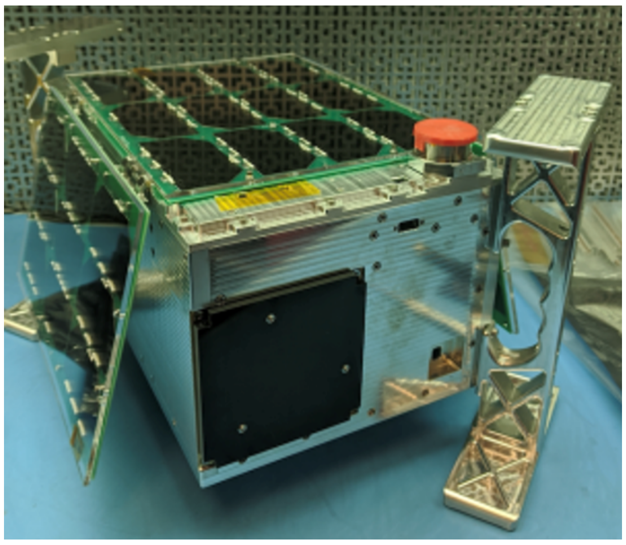
The INSPIRE programme aims to provide a constellation of Earth and space weather observing satellites

The International Satellite Program in Research and Education (INSPIRE) is a global consortium of space universities formed to advance space science and engineering, spearheaded by the Laboratory for Atmospheric and Space Physics of the University of Colorado at Boulder (CU Boulder-LASP) and its international academic partners. Each **INSPIRE** small satellite (Figure 1) typically proceeds from concept to flight in three years, providing the opportunity for undergraduate and graduate student involvement in small satellite design, implementation, testing, and operations. **INSPIRE** brings science, engineering, and management to campuses across the globe. The **INSPIRE** program aims to provide a constellation of Earth and space weather observing satellites. To date, eight satellites are part of this program.

INSPIRE universities involved in this program are:

- The University of Colorado at Boulder (CU Boulder), USA
- The University of Versailles (UVSQ), France
- The National Central University (NCU), China: Academy of Sciences Located in Taipei
- Nanyang Technological University (NTU), Singapore
- The Indian Institute of Space Science and Technology (IIST), India
- The University of Iowa, USA
- The University of Alberta (UoA), Canada
- Sultan Qaboos University at Muscat (SQU), Oman
- Kyushu Institute of Technology (Kyutech), Japan
- Research Centre Jülich, Wuppertal University, Germany

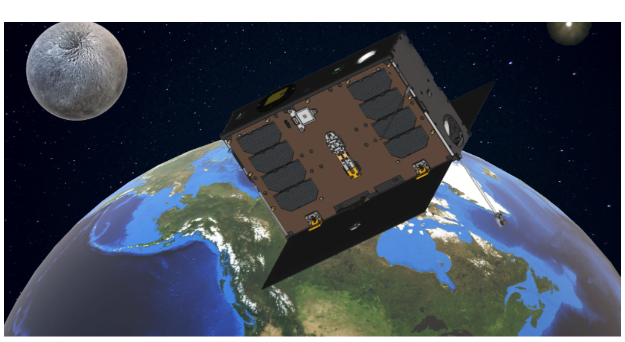
Figure 1



(a) *Inspire-Sat 1 spacecraft undergoing testing at LASP.*

(b) *Inspire-Sat 5 (Uvsq-Sat) spacecraft dedicated to Earth Radiation Budget (ERB) observations.*

(c) *Inspire-Sat 7 spacecraft dedicated to ERB observations.*



(d) *Inspire-Sat X (Uvsq-Sat NG), a spacecraft for monitoring ERB and Greenhouse Gases (GHGs).*

The Space Age began in 1957 with small satellites, particularly marked by the launch of the Sputnik satellite into orbit. Since then, thousands of small satellites have been launched into orbit. Their mass varies, ranging from subgram levels up to 500 kg for minisatellites (Branz et al., 2023), as specified in Table 1.

The year 1999 marked the beginning of the CubeSat era. CubeSats are small, cube-shaped satellites that have revolutionized access to space, making space exploration more accessible and less costly. The CubeSat concept was introduced in the 1990s by Professors Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University in the USA.
They developed this concept with the goal of allowing their students to design, build, test, and operate small satellites capable of performing scientific missions in space, all within the frame of a graduate study cycle. These small satellites typically have a volume of 1 litre (10 cm x 10 cm x 10 cm), and their modular design allows the assembly of multiple units to create satellites of various sizes.

Table 1. *Small satellite classes by mass.*

Small satellite classes	Mass
Minisatellite	300 - 500 kg
Super-microsatellite	100 - 300 kg
Microsatellite	10 - 100 kg
Nanosatellite	1 - 10 kg
Picosatellite	0.1 - 1 kg
Femtosatellite	10 - 100 g
Attosatellite	1 - 10
Zeptosatellite	0.1 - 1 g
Yoctosatellite	Less than 100 mg

Today, CubeSats have proven their versatility for a wide range of scientific applications. They have also demonstrated that it is possible to develop space programs that can work within cost, schedule and performance constraints, while setting themselves apart from traditional space missions.

> The Global Climate Observing System currently identifies 54 Essential Climate Variables

CubeSats open up new perspectives and force the space industry to reinvent itself, focusing on the real challenges. One of the major advantages of CubeSats is that they can be used in constellations, particularly to meet the challenges of climate change. The miniaturization of electronic components and the reduction in costs make it possible to envisage the deployment of a constellation of CubeSats dedicated to Earth Observation. Furthermore, artificial intelligence is redefining the limits of the space sector, offering unprecedented capacity to analyse scientific data – particularly climate variables from Earth. After the era of large satellites in geostationary orbit, launched by telecommunications satellites, we are now witnessing the rise of small satellites (CubeSats, nanosatellites, microsatellites) deployed in large numbers in low or medium orbit. They can cover the entire surface of the Earth, including high-latitude areas poorly served by satellites in geostationary orbit. A constellation with multiple satellites, orbiting on the same sun-synchronous path—known as a trailing constellation—presents the potential for significantly reduced revisit periods, allowing for observations of Essential Climate Variables (ECVs) at varying local solar times of identical scenes. This implies the availability of real-time observational data on diurnal scales for every global location, encompassing hard-to-reach areas like the polar regions. Achieving this level of detailed, variable observational data is impossible with a singular satellite in a sun-synchronous orbit, as it is constrained to sample specific locations at consistent local solar times, thereby offering no insight into the diurnal variations of emissions, a significant limitation for understanding various emission sources. Additionally, the versatile and interconnected measurements from these smaller, 'agile' satellites could be calibrated in-flight by referencing the more precise measurements obtained from larger satellites. In practical terms, every coincidence where smaller and larger satellites observe the same scenes provides an opportunity to cross-verify the calibration of the smaller satellites using the accurate data from larger satellite platforms. In reciprocity, the constellation can convey critical information, including diurnal emission components, back to the larger satellites for more extensive scrutiny and comprehensive analysis. This collaboration between CubeSat constellations and substantial satellite platforms is indicative of an evolving paradigm in Earth Observation, offering a synergistic approach that leverages the strengths of both satellite types to enhance our understanding and monitoring of Earth's diverse and dynamic environments.

> They can be used in constellations, particularly to meet the challenges of climate change

The Global Climate Observing System (GCOS) currently identifies 54 Essential Climate Variables (ECVs). Approximately 60% of these variables can be addressed using satellite data, establishing satellites as a crucial element in observing and comprehending the climatic transformations of our planet.

Global satellite broadband connectivity is also important for surveillance, crisis management and critical infrastructure connectivity and protection. It connects any location on the planet to the Internet, reducing data transmission times thanks to the greater proximity of satellites. This ability to respond rapidly to diverse, fast-growing needs, such as the Internet of Things, autonomous driving, telehealth, aviation and maritime connectivity, smart farming, financial services, education and research, is crucial. It also plays an essential role in combating global warming more effectively.

CubeSats also play a key role in demonstrating innovative technologies. They enable us to test new materials, electronic components, new-generation sensors, disruptive instruments, revolutionary attitude control systems, on-board computers, radio-frequency communication systems and innovative propulsion systems. Validating these technologies in orbit is a crucial step in preparing for more complex space missions. This paves the way for the development of new satellite constellations dedicated to Earth observation.

CubeSats play a key role in demonstrating innovative technologies

From a pedagogical point of view, CubeSats are an excellent learning tool. They meet higher education needs by providing students with scientific and technical knowledge. By using concrete examples linked to different engineering disciplines, CubeSats stimulate young people's interest in space exploration and inspire new generations of space enthusiasts. The INSPIRE program demonstrates the multiple possibilities and objectives that can be achieved through the use of CubeSats. Five satellites of the INSPIRE program have been launched into orbit since January 2021. The small satellites developed under the INSPIRE program have masses ranging between 1 kg and several tens of kilograms. The following chapters provide a description of the various INSPIRE satellites.

CubeSats are an excellent learning tool

1. Inspire-Sat 1, a new type of satellite developed in universities – launched in February 2022

The scientific objectives of Inspire-Sat 1 encompass two primary goals.

The initial objective involves the utilization of the Compact Ionosphere Probe (CIP), a comprehensive plasma sensor, to investigate ion composition, density, velocity, and temperature of the ionosphere in eclipse. CIP is expected to provide ionospheric measurements, which will advance our understanding of ionosphere dynamics and plasma transport.
The secondary objective is to capture the soft X-ray (SXR) spectrum emitted by the Sun during periods of solar quiescence through to the solar maximums, employing the Dual Aperture X-ray Solar Spectrometer (DAXSS). This undertaking aims to yield valuable data for the examination of solar flares, solar cycles, elemental abundances in the solar corona during flares and the enhancement of our comprehension of the process responsible for the Sun's coronal heating.

The first annual INSPIRE workshop was held at NCU in July 2016

The first annual INSPIRE workshop was held at NCU in July 2016. The initial design phase for Inspire-Sat 1, the program's inaugural CubeSat, started towards the end of 2017, and the necessary funding was secured in 2018. The inaugural mission of INSPIRE was marked by the collaborative development of a small satellite by LASP, IIST and NCU. This satellite was equipped with the CIP instrument developed by NCU and the Taiwan Space Agency (TASA). The DAXSS instrument, was funded by the National Aeronautics and Space Administration (NASA) Heliophysics division.
The launch service for this satellite was provided by

the Indian Space Research Organization (ISRO). The program has a unique organizational structure with verticals at the three main university partners and principal investigators, program managers and system engineers at each university. Student, program managers and systems engineers at each university held weekly meetings and escalated action items to the faculty principal investigators for management decisions and to student subsystem leads for action item resolution.

In 2017, LASP hosted 11 students from three universities (CU Boulder, NCU, and IIST) for an eight-week summer training program, at the end of which the students had the preliminary design review (a 3U CubeSat). In 2018, CU Boulder-LASP and CU's Department of Aerospace Engineering Sciences (AES) hosted 17 students from six universities (CU Boulder, NCU, IIST, SQU, NTU, and UoA) for an eight-week training program (also a six-credit graduate course in AES) at the end of which the students had critical design review in July 2018.

The satellite had changed to a ~ 9U satellite with the addition of DAXSS and to be deployed from a ring deployer. The spacecraft category fit micro-sat better than CubeSat since it was ring deployed rather than from a canister. By end of summer 2019, the Engineering Model (EM) integration and testing was completed and Flight Model (FM) build had started.

Inspire-Sat 1 was launched on 14 February 2022 on the ISRO PSLV C52 mission.

2. Inspire-Sat 2, a satellite for the observation of the ionosphere – launched in January 2021

Ionospheric Dynamics Explorer and Attitude Subsystem Satellite (IDEASSat) – named also Inspire-Sat 2 – is a CubeSat project led by TASA. Its primary objective was to measure ionospheric activity, which has implications for both satellite and terrestrial communication, while also providing a hand-on learning opportunity for students. It complements and forms a constellation with Inspire-Sat 1 to gather data on ionospheric structure and plasma irregularities, essential for monitoring radio communications. The scientific instrument aboard IDEASSat is the CIP instrument, an all-in-one in-situ plasma sensor developed at NCU and built upon the heritage of the Advanced Ionosphere Probe (AIP) used on FORMOSAT-5. The CIP is designed to monitor the thermal, chemical, and electro-dynamic properties of the ionosphere, enabling the detection of plasma irregularities that can disrupt satellite and terrestrial radio communications through scintillation. IDEASSat was successfully deployed into a Low Earth Orbit (LEO) on 24 January 2021, initiating mission operations.

> The satellite showcased its capabilities in three-axis attitude stabilization

The satellite effectively showcased its capabilities in three-axis attitude stabilization and control, tracking, telemetry, and command (TT&C), along with demonstrating the functionality of flight software and ground systems to support autonomous operation.

However, the mission encountered a critical anomaly approximately 22 days after launch, followed by a communications blackout lasting 1.5 months (Chiu et al., 2022). During a brief recovery period from the blackout, flight data was replayed, leading to the identification of the root cause behind the blackout.

It was determined that the blackout resulted from the electrical power subsystem reset circuit's inability to recover from a single-event latch-up induced by ionizing radiation.

While the mission was not fully accomplished, the data collected during the mission will contribute to enhancing the designs of upcoming spacecraft projects under development at NCU.

3. Inspire-Sat 3, a satellite for education and research – under development

Inspire-Sat 3 is a MicroSat mission being developed for launch in 2025. It involves collaboration primarily between LASP, IIST, UoA and FZ Jülich to provide opportunities for students and researchers to gain hands-on experience in satellite development and research. Inspire-Sat 3, like its predecessors, is designed to serve as an educational and research platform. The spacecraft will carry the NASA Heliophysics funded Occultation of Wave Limb Sounder (OWLS) instrument from LASP for Thermospheric Gravity Wave (GW) studies, a flux gate magnetometer for studying auroral magnetic fields from UoA and thermospheric gravity waves using the AtmoLite infra-red imager from FZ Jülich on a 30x30x30 (27U) MicroSat being built by IIST and designated for launch on board an ISRO launch vehicle.

Inspire-Sat 3 is designed to serve as an educational and research platform

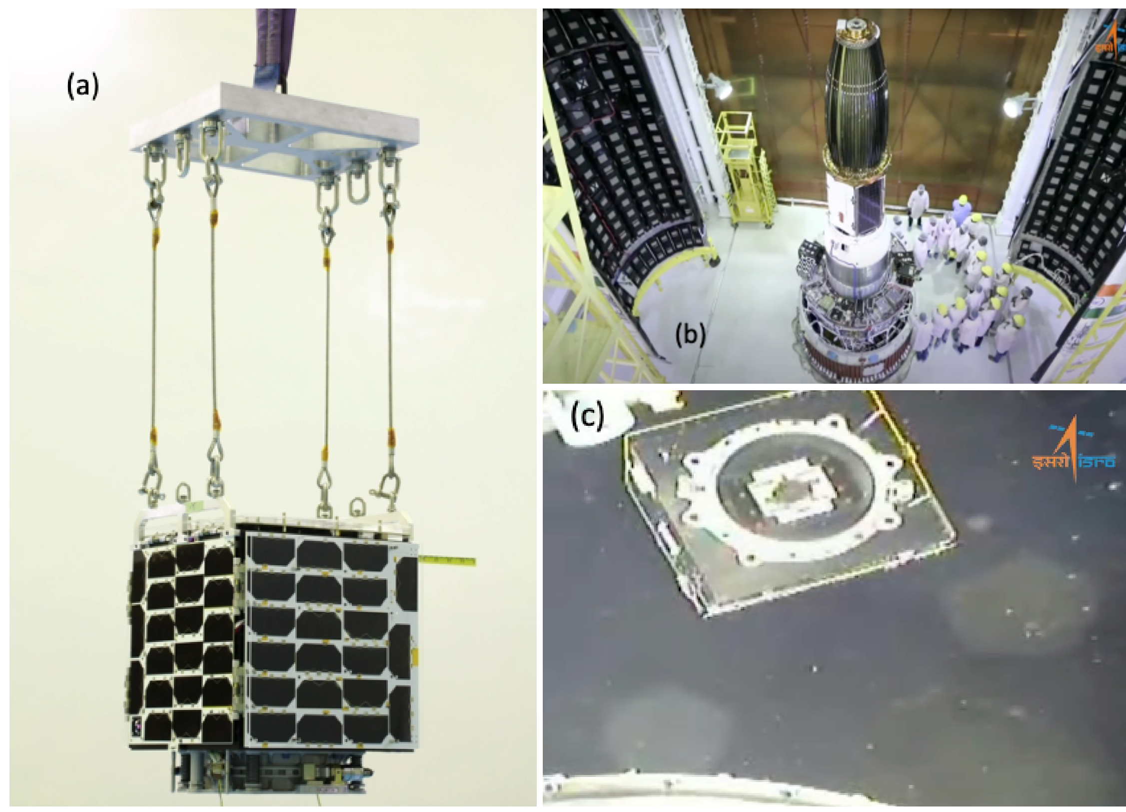
4. Inspire-Sat 4, a satellite for observing the atmosphere – launched in July 2023

The Atmospheric Coupling and Dynamics Explorer (ARCADE), also known as Inspire-Sat 4 (Figure 2), is an experimental microsatellite mission initiated by Singapore. This project is an integral part of NTU's Undergraduate Satellite Program, providing engineering students with a valuable opportunity to engage in a hands-on, multidisciplinary space project.

Most nano-satellite and small satellite missions are typically designed for altitudes of 400 km or higher. This is due to the limitations imposed by the mass, volume, and power constraints of small satellites, which hinder their ability to counteract the significant aerodynamic drag experienced at lower altitudes. Consequently, there has been a lack of in-situ scientific data collection within the altitude range of 200 to 300 km by small satellite missions.

It offers a unique opportunity to study the equatorial ionosphere at low altitudes

Inspire-Sat 4, is a 27U CubeSat spacecraft (30x30x30 cm) deployed in a ring configuration. Its primary mission objective is to carry an ionospheric plasma payload capable of conducting measurements related to ion temperature, velocity, density, and electron temperature. This mission is particularly significant as it offers a unique opportunity to study the equatorial ionosphere at low altitudes, where ion and electron density are considerably higher. The ionosphere, situated around the Earth at altitudes between 100-700 km, consists mainly of charged particles and electrons. In-situ measurements of ions below 400 km altitude are limited, and such measurements can provide valuable insights into the composition and dynamics of ion generation and evolution within this region of Earth's atmosphere. This knowledge is crucial for understanding the impact of the ionosphere on phenomena such as Global Positioning System (GPS) signal scintillation, electromagnetic wave propagation, and communication disruptions caused by ionospheric effects. The ion plasma payload, known as the CIP instrument, has been developed by NCU. Additionally, the mission incorporates a Spatial Heterodyne Interferometer (SHI) Infra-Red Imager designed for imaging the Mesosphere and Lower Thermosphere (MLT) region, spanning altitudes from 60 to 120 km. The SHI instrument provides temperature data critical for understanding MLT dynamics. This instrument was developed in collaboration with Forschungszentrum Jülich, affiliated with the University of Wuppertal in Germany. Combined with CIP, Atmolite measurements will contribute to our understanding of the lower atmosphere's impact on the ionosphere and the structures observed within the equatorial ionosphere. Furthermore, the spacecraft will carry a third payload from NTU, aimed at studying the effects of atomic oxygen on material degradation and perovskite solar cells in Very Low Earth Orbit (VLEO). ARCADE will also employ an electric propulsion hall effect thruster developed by the French company 'Thrust Me' to transit the spacecraft from its initial orbit to VLEO, as well as for Earth imaging purposes. This ambitious project has involved the dedicated efforts of a team of 15 NTU students, both undergraduate and graduate, over a span of five years in collaboration with the School of Electrical and Electronic Engineering (EEE).



The satellites VELOX-AM, ARCADE and SCOOB-II serve as demonstrations of NTU's leading capabilities in satellite engineering and undergraduate space engineer training. Since 2011, NTU has successfully built, launched and operated 13 satellites, including these three launched in July 2023 by ISRO on the Polar Satellite Launch Vehicle. Inspire-Sat 4 was successfully launched by an ISRO PSLV-C56 rocket on 30 July 2023.

Figure 2

(a) Inspire-Sat-4 (ARCADE) being integrated with the launch vehicle.
(b) Inspire-Sat-4 on the ISRO Polar Satellite Launch Vehicle (PSLV).
(c) Spacecraft being deployed in space.

5. Inspire-Sat 5, a satellite for observing the Earth – launched in January 2021

UltraViolet & Infrared Sensors at High Quantum Efficiency Onboard a Small Satellite (Uvsq-Sat), also known as Inspire-Sat 5, is a mission developed by Laboratoire Atmosphères, Observations Spatiales (LATMOS) of UVSQ with support from the INSPIRE consortium (Meftah et al., 2020). It aims to showcase advanced technologies for measuring the Earth Radiation Budget and Solar Spectral Irradiance (SSI) in the Herzberg continuum (200 – 242 nm). Uvsq-Sat (Figure 3) is a nanosatellite project following the CubeSat standard, specifically designed as a 1U CubeSat. The LATMOS team serves as the project owner and primary contractor for the 1U CubeSat project, with collaboration from the manufacturer, Isispace, responsible for building dedicated satellite subsystems. The main scientific goals of the mission encompass the measurement of incoming solar radiation (total solar irradiance) and outgoing terrestrial radiations (the outgoing longwave and shortwave radiations at the top of the atmosphere) utilizing twelve compact thermopile sensors. Additionally, monitoring the Herzberg solar continuum at 215 nm of solar spectral irradiance is another pivotal objective. Beyond these scientific objectives, the project also seeks to validate the space-worthiness of a medical device designed for utilization by astronauts. Uvsq-Sat was designed, manufactured, and tested by LATMOS in collaboration with its academic and industrial partners, as well as the French-speaking amateur radio community.

It is outfitted with multiple photodiodes and Earth Radiation Sensors

This satellite, comparable in size to a Rubik's Cube and weighing around 2 kg, was successfully launched into orbit in January 2021 via the SpaceX Falcon 9 launch vehicle. Since February 2021, Uvsq-Sat has been performing various measurements, including assessing the reflection of solar radiation from Earth and measuring Outgoing Longwave Radiation (OLR). The satellite does not possess an active attitude control system; instead, it is outfitted with multiple photodiodes and Earth Radiation Sensors (ERS) on every side to conduct scientific measurements.

Six photodiodes facilitate the measurement of both Total Solar Irradiance (TSI) and Outgoing Solar Radiation (OSR). Albedo is calculated from these measurements, with TSI considered a known parameter, measured by other instruments in space. For just under three years, the satellite has been fully operational and conducting its observations from space.

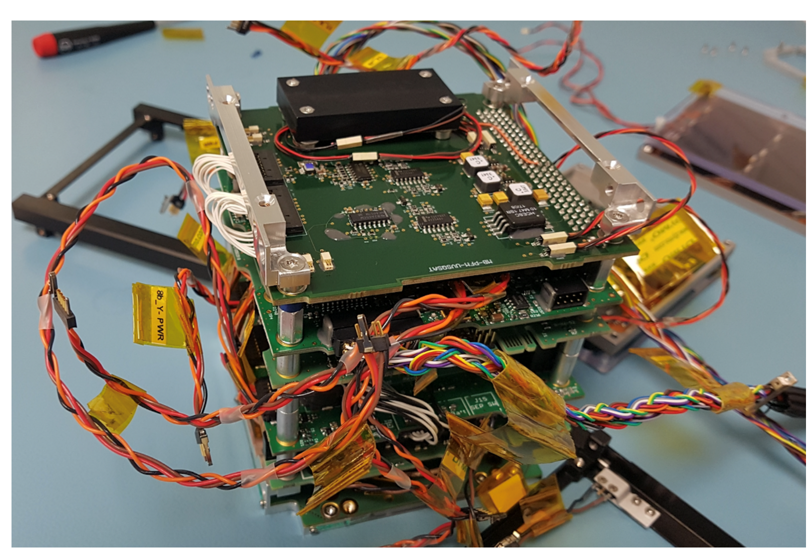


Figure 3

Inspire-Sat-5 (Uvsq-Sat) during integration in May 2020.

6. Inspire-Sat 6, a satellite for atmospheric and ionospheric science – under development

Small satellites offer a practical platform for various scientific investigations, the testing of new scientific instruments, and can serve as precursors for future extensive missions or satellite constellations. We introduce the mission concept and initial design of the SCintillation and IONosphere eXtended mission (SCION-X), a project currently in development at NCU in collaboration with partners within the INSPIRE consortium as its sixth spacecraft. SCION-X aims to provide in-situ sampling of the ionosphere using the CIP instrument, as well as measurements of thermospheric optical depth using a Solar Extreme Ultraviolet Probe (SEUV).

SCION-X aims to provide in-situ sampling of the ionosphere

This will yield valuable data for understanding how the ionosphere affects satellite navigation and communication systems. Furthermore, the mission will serve as a platform for the flight qualification and calibration of a hyperspectral imager developed at NCU. This imager will be used to identify the sources and composition of PM2.5 aerosols in the lower atmosphere, contributing to air quality studies. In summary, SCION-X will enhance our knowledge of both ionospheric and upper atmospheric conditions, as well as facilitate the development of remote sensing instruments for air quality research. UVSQ-LATMOS is interested in SCION-X, which could deliver vertical profiles and direct sampling of the ionosphere using the CIP instrument, along with a possible Global Navigation Satellite System radio occultation (GNSS RO). The Inspire-Sat 6 satellite is currently under development.

7. Inspire-Sat 7, a new INSPIRE program satellite placed in orbit in April 2023

Inspire-Sat 7 (Meftah, Boust et al., 2022) is a French nanosatellite based on the CubeSat standard (Twiggs, 2000), a satellite format defined in 1999 by California Polytechnic State University and Stanford University (USA). This CubeSat 2U satellite (11.5 × 11.5 × 22.7 cm) is an educational, technological and scientific demonstrator dedicated to Earth and Sun observation. It was conceived, designed, built and tested by LATMOS and the Office National d'Études et de Recherches Aérospatiales (ONERA), in collaboration with their academic and industrial partners, and the French-speaking amateur radio community. This space mission is an integral part of the INSPIRE programme, an initiative that brings together several universities including CU Boulder-LASP, NTU, NCU, and UVSQ, among others. Weighing just 3 kg, Inspire-Sat 7 was placed in orbit on 15 April 2023 from the US military base at Vandenberg, California, aboard SpaceX's Falcon 9 launch vehicle–the Transporter 7 "sherpa" mission (Figure 4).

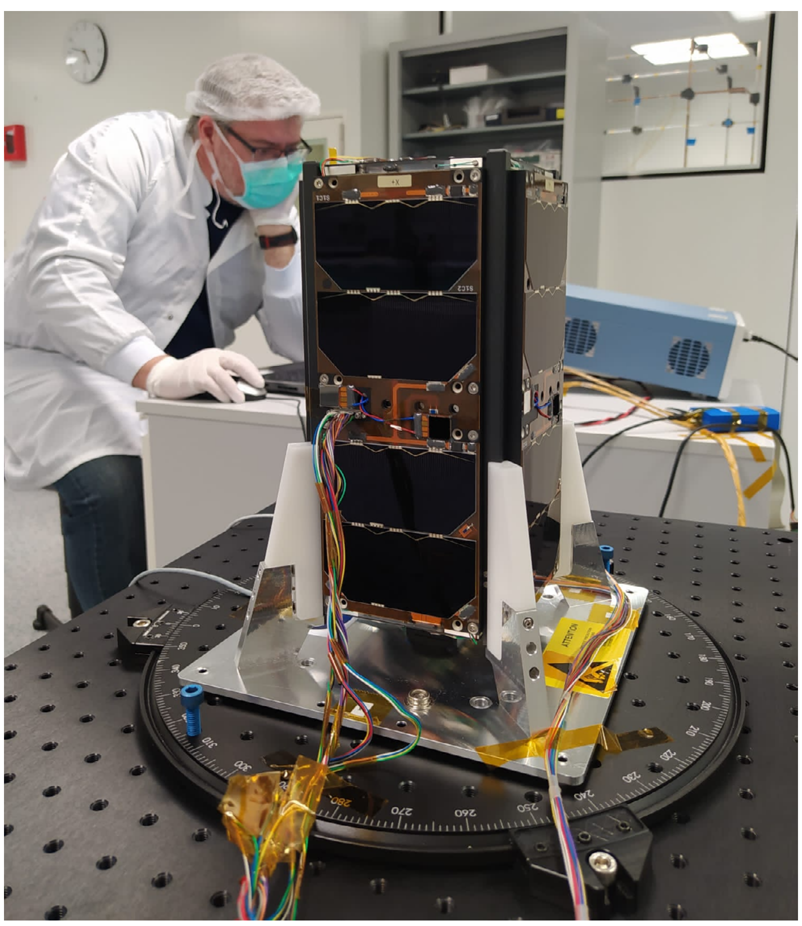
This space mission is an integral part of the INSPIRE programme

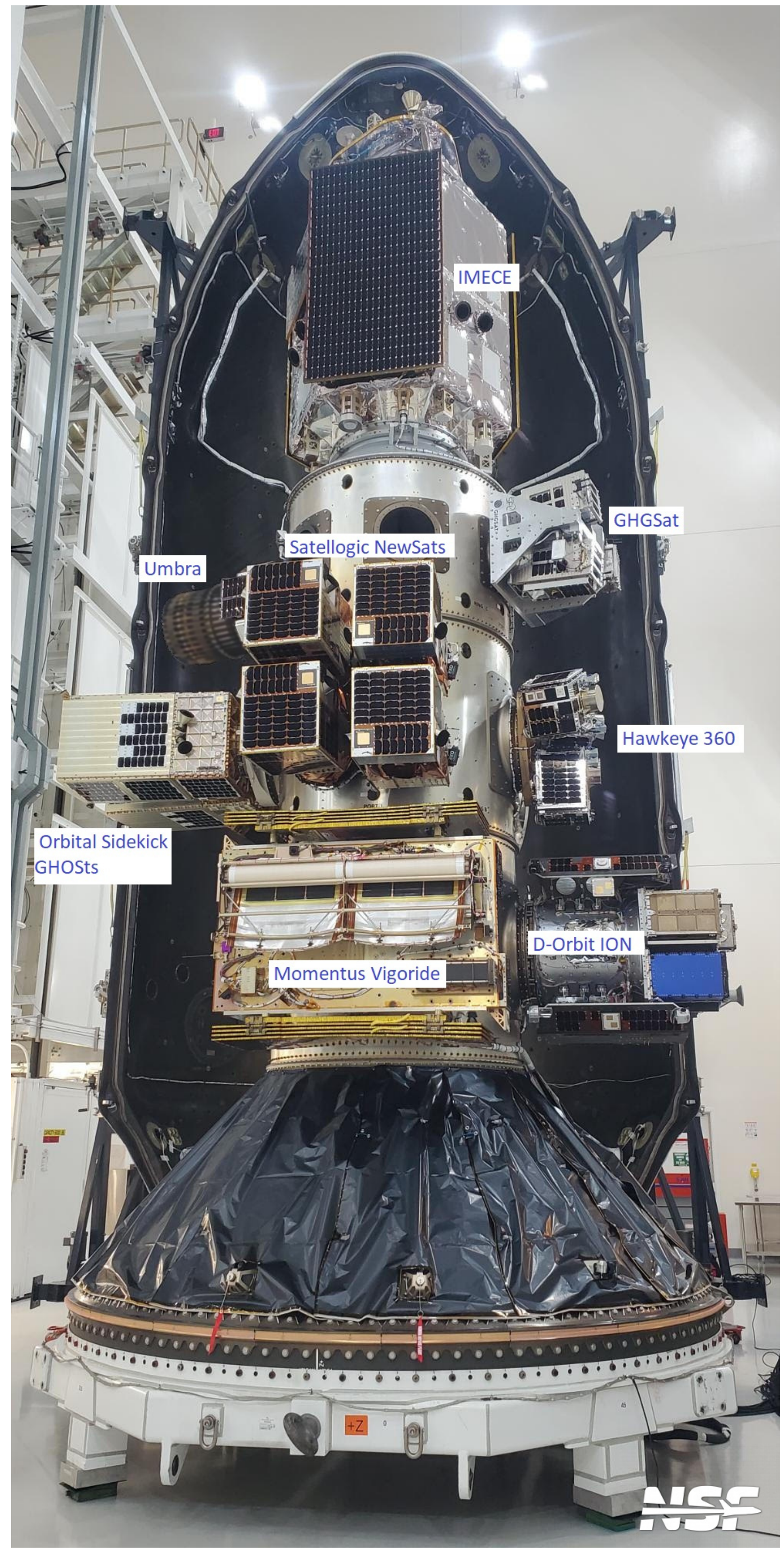
The Inspire-Sat 7 space programme bears many similarities to that of FR-1, the very first French scientific satellite, which was successfully launched from Vandenberg by an American Scout rocket on 6 December 1965.

Figure 4:

(left) *Validation tests on the Inspire-Sat 7 satellite.*

(right) *Transporter 7 space ride-sharing mission with 51 commercial and government satellites on board, including Inspire-Sat 7.*

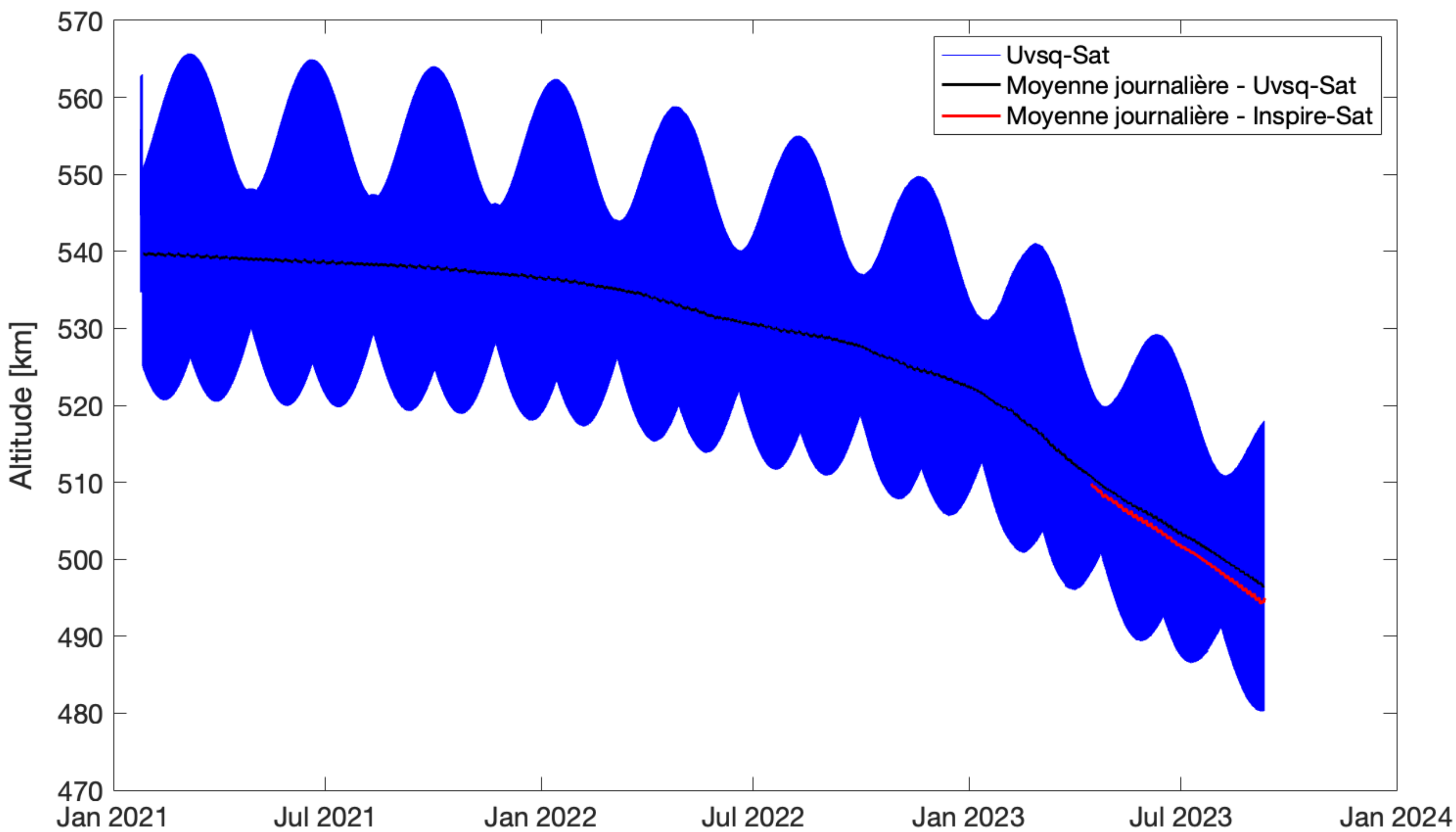




Since April 2023, Inspire-Sat 7 has joined Uvsq-Sat (Meftah, Damé et al., 2020), another INSPIRE satellite already at an altitude of around 500 km (Figure 5), creating one of the first university constellations of CubeSats dedicated to observing essential climate variables.

In sun-synchronous orbit, these two satellites observe from space: solar radiation; solar radiation reflected at the top of the Earth's atmosphere at short wavelengths (UV, VIS, NIR); OLR, OSR; as well as the Earth's magnetic field.
Inspire-Sat 7 can also measure ionospheric disturbances at high frequencies (HF) from 10 to 20 MHz. Three frequencies have been successfully tested during the first five months in orbit.

Figure 5: Altitude of Uvsq-Sat and Inspire-Sat 7 satellites since their launch.



Program organisation and key dates

LATMOS acts as both prime contractor and owner of the satellite, with responsibility for designing, building and managing the entire space programme. This project has been built around a simplified organizational structure, favouring an 'Agile' approach, while avoiding the vertical management model, which often proves ineffective for rapidly driving a space programme from its definition and analysis phase (Phase 0/A) through to its exploitation phase (Phase E). The mission's Principal Investigator encouraged the active participation of the scientific team throughout the project, emphasizing flexibility when facing possible changes and minimizing the importance of traditional procedures.

The organization of the Inspire-Sat 7 programme is a complex process that nevertheless requires meticulous planning, precise coordination and the consideration of many variables. The scientific objectives of the programme were determined as early as 2020. Several phases were then undertaken to develop the various space mission concepts, including the ground segment (comprising the mission operation centre, UHF/VHF ground stations and data processing systems, the scientific operation centre) and the space segment (encompassing the satellite platform and its scientific instruments). The technical, financial and time feasibility of the project was rapidly assessed. In mid-2020, the first financing arrangements were put in place. The design and engineering of the programme got off to a very early start, involving numerous partners from a wide variety of fields, including LATMOS, ONERA, CNES, Belgium's Royal Institute for Space Aeronomy (IASB), ESA, AMSAT-F, F6KRK, Electrolab, ACRI-ST, Adrelys, Oledcomm, Nanovation, and Institut Lafayette, Mecano Id, among others. Each has contributed its own specific scientific, technological and educational expertise to the project. In mid-2021, the choice of launcher was made, so that the satellite could take to the skies as early as 2023. At the end of 2021, integration and environmental testing of the satellite began. The resources of the Plateforme d'Intégration et de Tests (PIT) at the Observatoire de Versailles Saint-Quentin-en-Yvelines (OVSQ) and LATMOS were used (clean rooms, shaker table for testing, thermal vacuum tank, ground stations, etc.). Tests were also carried out at Centre National d'Études Spatiales (CNES) in Toulouse (France) to characterize the satellite's magnetic field. Calibration of the satellite's instruments was carried out at LATMOS and in Belgium at the Institut d'Aéronomie Spatiale de Belgique (IASB). By the end of 2022, the satellite was ready for launch—all the necessary checks, tests and preparations had been successfully completed, confirming that the satellite was in good working order and could be safely deployed in space. Inspire-Sat 7 was ready for flight. The satellite's in-orbit operations planning and ground control procedures were ready by January 2023. On 7 February 2023, Inspire-Sat 7 was integrated into its ejection device used to deploy satellites in orbit. This was the final step before integration into the launcher fairing. A large number of students from various disciplines and backgrounds (ESTACA, SupOptique, IUT de Mantes-en-Yvelines, Master NewSpace) took part in this programme, which is supported in particular by the French town of Saint-Quentin-en-Yvelines (SQY) and the département of Yvelines (78).

Satellite description

The main objective is to quantify the Earth's energy imbalance

The platform of the Inspire-Sat 7 satellite includes various essential systems such as the physical structure, solar panels, power supply and batteries, communication with its antennas, attitude control, telemetry and commands, on-board computer, scientific instruments, thermal control, as well as radiation protection devices. The satellite's payload comprises several scientific instruments. Inspire-Sat 7 is equipped with miniaturized ERS sensors, which are used to measure the ERB components (reflected solar radiation, OLR, OSR). The main objective is to quantify the Earth's energy imbalance, which is the main driver of global warming and is fueled by the increase in greenhouse gases. Inspire-Sat 7 is equipped with photodiodes specially designed to observe the Sun in the Herzberg continuum (200 – 242 nm), enabling solar radiation to be measured in the UV. This innovative technology was developed by LATMOS, Nanovation and their industrial partners. Inspire-Sat 7 is also equipped with an HF receiving antenna and SDR card (CU-IONO1) developed by ONERA in collaboration with LATMOS. CU-IONO1 is an HF receiver able to pick up signals emitted from the ground by ONERA equipment, in particular a vertical probe and an HF radar. These measurements will help to improve ionospheric modelling and to quantify more precisely ionospheric disturbances which are not yet well understood. These disturbances can then be correlated with observations made by a network of magnetometers and other orbiting satellites.

On another note, Inspire-Sat 7 carries the first LiFi module aboard a CubeSat. Oledcomm and LATMOS aim to demonstrate that light-based wireless communication is a credible alternative to traditional copper harnesses. Finally, an amateur radio payload (SPINO) is part of the Inspire-Sat 7 satellite.

An amateur radio payload is part of the Inspire-Sat 7 satellite

This is a device designed for all radio amateurs on the planet. Adrelys, Electrolab, AMSAT-F and LATMOS decided to design a complete "free" bidirectional telemetry card for CubeSats. This device (SPINO) is associated with the audio transponder already validated on board UVSQ-SAT, and which already offers the possibility of communication between radio amateurs. Since its launch, the audio transponder of INSPIRE has been activated on multiple occasions, similar to the one on Uvsq-Sat, which has been in operation since February 2021.

Launch and orbit operations

After several days of weather-related delays, the Inspire-Sat 7 satellite was finally put into orbit on 15 April 2023 at 09:52 (Paris time). The satellite was successfully deployed at an altitude of 508 km. It was placed in the orbit requested by the LATMOS scientific team (inclination 97.71 ±0.5°, eccentricity less than 0.004, local time at the descending node 10:00 ±00:30). LATMOS teams quickly took control of the satellite. The first signal emitted by Inspire-Sat 7 was picked up by amateur radio operators (Fredy Damkalis, PE0SAT). On 15 April 2023, Inspire-Sat 7 began its mission to observe the Earth and the Sun.

A team from LATMOS manages in-orbit operations. It manages the mission in progress, monitors systems and collects scientific data. It reacts to potential problems and makes adjustments in real time. Data reception is handled by LATMOS ground stations (Hermes and Elsa), as well as by ACRI-ST and the amateur radio community. Data analysis is carried out by LATMOS (all observations) and ONERA (ionospheric observations) teams.

Data reception is handled by LATMOS ground stations

First observations and results

Inspire-Sat 7 has been operational since its launch. Its functional life is at least two years. Inspire-Sat 7 is a passive satellite, meaning it cannot actively adjust its orientation or position in space. Using several sensors on board the satellite, the LATMOS team has developed methods for measuring reference vectors in space, such as the Sun-Earth and Magnetometer-Earth vectors. By using the TRIAD method in conjunction with the Kalman filter (MKF), precise estimates of the satellite's attitude are obtained, which is essential for restoring the satellite's attitude in space. The TRIAD method is a common algorithm used for attitude determination, where the attitude of a spacecraft is found using vector observations, typically of the magnetic field and gravity vectors. The Kalman filter, on the other hand, is a mathematical method to estimate the state of a system based on measurements and statistical noise models.

Solar radiation reflected by the Earth and the outgoing radiation (IR) data are obtained based on knowledge of the satellite's attitude and the measurements made by the ERS detectors (Figure 6).

The map of OSR at the top of the atmosphere during August 2023 shows the presence of surfaces that strongly reflect solar radiation (snow, ice, sand and deserts). Areas that are generally cloudy tend to reflect

These maps provide an excellent tool for monitoring global cloud cover

more energy, while the land surface reflects less than clouds, and the ocean reflects less than land and forests. Atmospheric aerosols, such as dust, soot or pollution particles, can interact with solar radiation. They can act as "condensation points" for water, forming clouds or water droplets. As these clouds are highly reflective, these maps provide an excellent tool for monitoring global cloud cover, which plays a major role in the Earth's radiation budget. For over 20 years, solar radiation reflected at the top of the atmosphere has been decreasing (by at least 1 Wm-2). This is one of the variables to be monitored over time. OLR at the top of the atmosphere also represents a variable to be monitored over time. It is latitude-dependent (Figure 6). High latitudes are colder and emit less IR radiation. Humid tropical regions are clearly visible. In tropical and equatorial regions, the weak radiation emerging at the top of the atmosphere is due to the presence of high-altitude clouds. These clouds absorb the radiation emitted by the Earth's surface. Consequently, because they are cold, they emit little outgoing radiation into space. Outgoing radiation data centred on equatorial zones, from 160°E to 160°W longitude, can be converted into a standardized anomaly index. Negative (positive) values of OLR indicate increased (suppressed) convection and therefore more (less) cloud cover, typical of El Niño (La Niña) episodes. Greater (lesser) convective activity in the central and eastern equatorial Pacific implies higher (lower), colder (warmer) cloud tops, which emit much less (more) infrared radiation into space. Since May 2023, outgoing radiation (IR) anomaly values at the top of the atmosphere have been negative (decreasing), indicating the link with the arrival of the El Niño phenomenon in the tropical Pacific for the first time in seven years. This could lead to a rise in global temperatures and disrupt weather and climate conditions.

Figure 6: *Observations carried out by Inspire-Sat 7 in August 2023.*

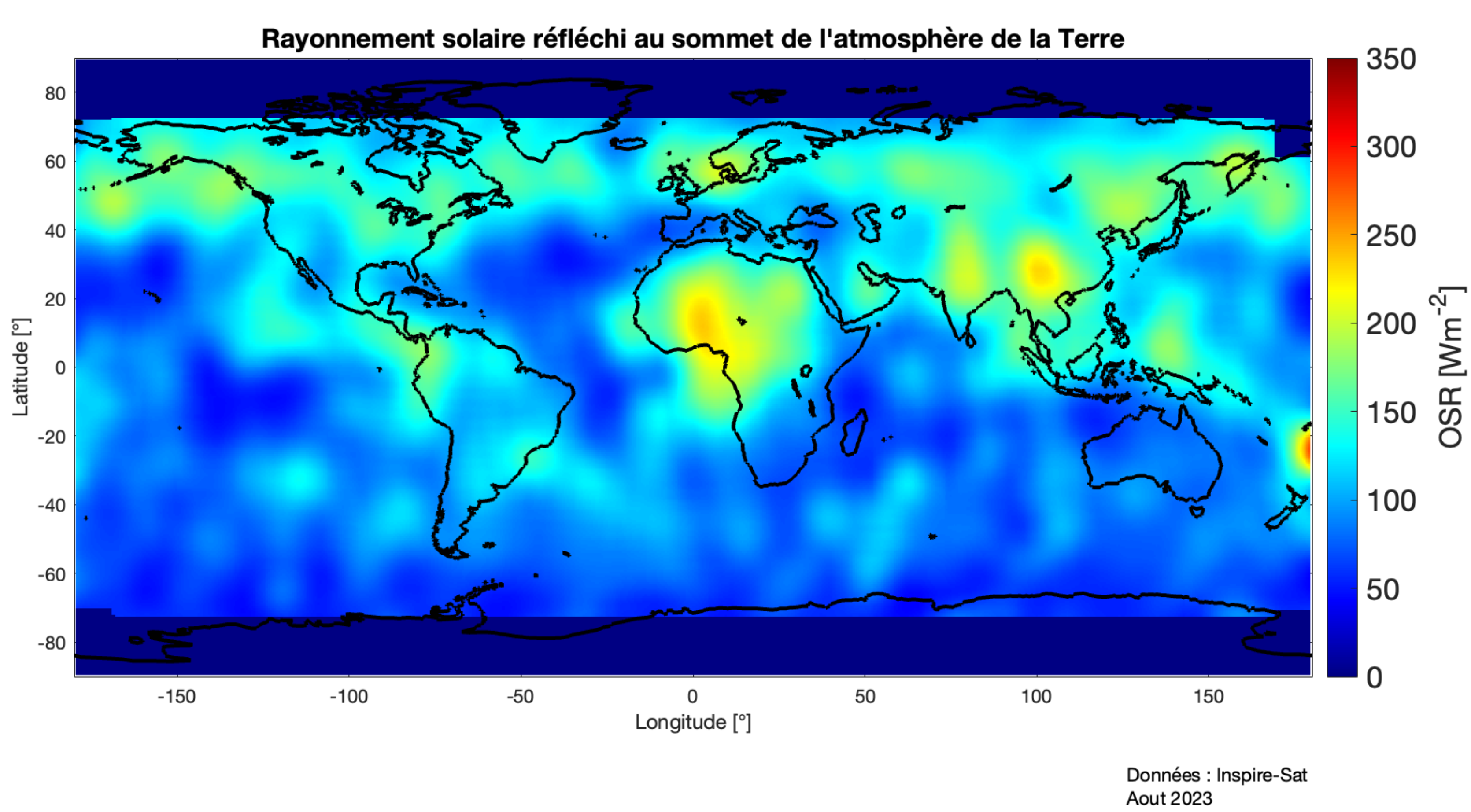
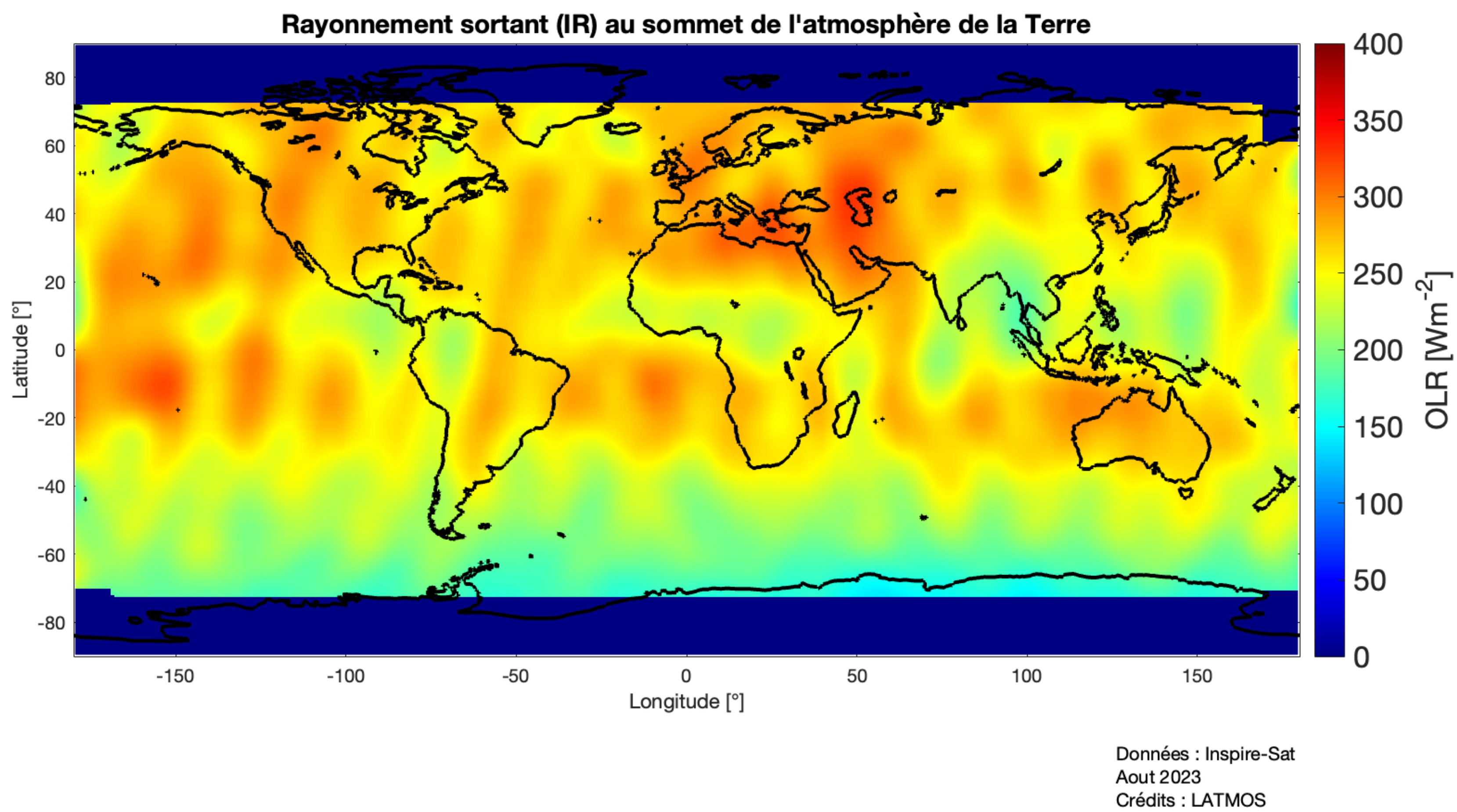


Figure 6: Observations carried out by Inspire-Sat 7 in August 2023.



Since April 2023, all the satellite's scientific instruments have been tested. The UV detectors are working. The HF receiver (CU-IONO1) is able to pick up signals emitted from the ground. The amateur radio payload (SPINO) has been activated very frequently.

A future constellation of nanosatellites?

A large fleet of small, low-orbiting satellites (Gaïa Y78) would enable observation of any changes on Earth with an unprecedented level of detail, both in spatial and temporal resolution (Meftah, 2023a). Several variables would then be simultaneously observed by this armada, such as the Earth's radiation balance and spectral solar irradiance. Monitoring CO2 and CH4 from space is also very important for characterizing the spatiotemporal distribution of these main greenhouse gases and quantifying their sources and sinks, in order to better understand global warming.

> A large fleet of small, low-orbiting satellites would enable observation of any changes on Earth

While we have a sound understanding of the greenhouse effect mechanism and the contributions of various man-made greenhouse gases (GHGs) to global warming, certain interactions and feedback involving clouds, polar ice and oceans remain less well understood. As GHG concentrations rise, less infrared radiation is able to escape to space, leading to a decrease in outgoing infrared radiation (OLR), a build-up of energy in the climate system, and ultimately a warming of the Earth's surface. Observations and model simulations reveal that the direct impact of GHGs on warming is amplified by climatic feedbacks, such as the melting of Arctic ice, which exposes more ocean, thereby enhancing the absorption of solar radiation. It is therefore becoming essential to observe several key climate variables simultaneously in order to better characterize climate change.

8. Inspire-Sat X, a satellite to observe climate change

Climate change stands as one of the most urgent and critical challenges confronting humanity in the 21st century. Within this context, the monitoring of Earth's Energy Imbalance (EEI) is of paramount importance, in conjunction with greenhouse gases (GHGs), to gain a comprehensive understanding of climate change and devise effective solutions.

The pioneering Uvsq-Sat NG mission (Meftah, Clavier et al., 2023b), led by LATMOS and supported by INSPIRE, addresses this imperative. This mission will be launched in 2025 and centres on a 6-Unit CubeSat with dimensions of 111.3 cm x 36.6 cm x 38.8 cm in its unstowed configuration.

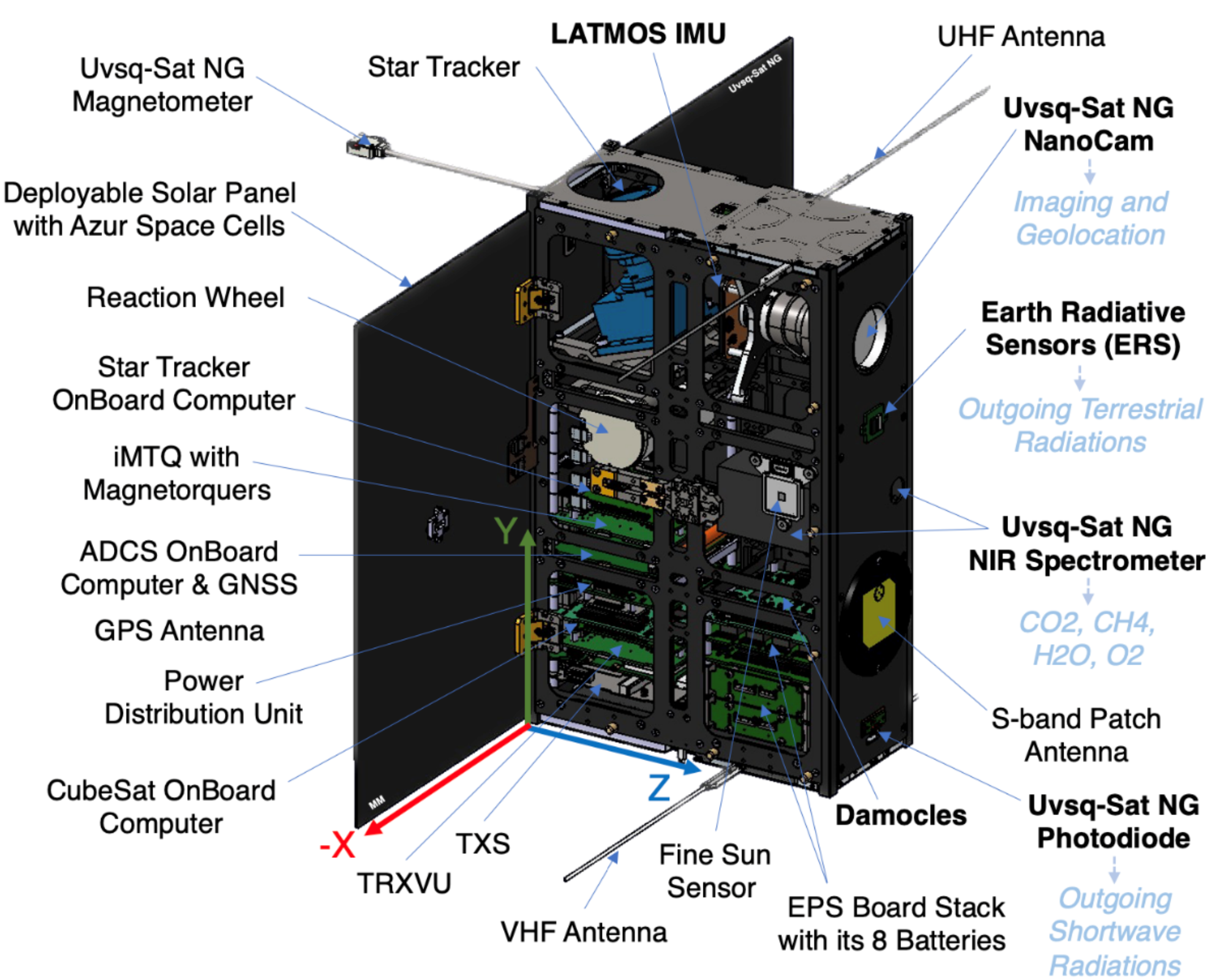


Figure 7: Computer-aided design of the Uvsq-Sat NG satellite with its platform and its scientific payloads (NIR Spectrometer, NanoCam, Earth Radiative Sensors, Photodiodes).

Uvsq-Sat NG, also known as Inspire-Sat X, aims to ensure the seamless continuation of ERB measurements, building upon the groundwork laid by the Uvsq-Sat and Inspire-Sat satellites.

The monitoring of Earth's Energy Imbalance is of paramount importance

One of its primary objectives is to conduct broadband ERB measurements, leveraging state-of-the-art yet user-friendly technologies. Furthermore, the Uvsq-Sat NG mission seeks to conduct precise and comprehensive monitoring of global atmospheric gas concentrations, focusing on CO_2 and CH_4, and examining their correlation with Earth's Outgoing Longwave Radiation.

The satellite (Figure 7) carries multiple payloads, including ERS sensors for monitoring incoming solar radiation and outgoing terrestrial radiation.

Uvsq-Sat NG is equipped with a high-definition camera to capturing visible range images of Earth

Additionally, it incorporates a Near-InfraRed (NIR) Spectrometer designed to assess GHGs atmospheric concentrations through observations in the wavelength range of 1200 to 2000 nm. A new method was developed for retrieving atmospheric gas column data (CO_2, CH_4, O_2, H_2O) from the Uvsq-Sat NG NIR Spectrometer. These retrievals are based on simulated spectra encompassing various environmental conditions (surface pressure, surface reflectance, vertical temperature profile, gas mixing ratios, water vapour levels, other trace gases, cloud and aerosol optical depth distributions) and spectrometer parameters (Signal-to-Noise Ratio (SNR) and spectral resolution ranging from 1 to 6 nm). Moreover, Uvsq-Sat NG is equipped with a high-definition camera, NanoCam, dedicated to capturing visible range images of Earth. This capability aids in post-processing spectrometer data by ensuring precise geolocation of observed scenes. NanoCam also offers the potential to observe the Earth's limb, enabling rough estimations of the vertical temperature profile of the atmosphere. UVSQ-LATMOS acts both as the prime contractor and owner of the satellite, and it receives invaluable assistance from its INSPIRE partners. This satellite is currently under development (Figure 8) and will be launched in 2025 or 2026.

Figure 8: *Inspire-Sat X (Uvsq-Sat NG) during integration in October 2023.*

One of the objectives of the Uvsq-Sat NG mission is to measure incoming solar radiation, solar radiation reflected by Earth, as well as outgoing infrared (IR) radiation at the top of our planet's atmosphere (Meftah, Clavier et al., 2023b). Moreover, this mission aims to enhance the detection, tracking, and understanding of human-made greenhouse gases through space observations.
One of the aspirations is to perform global monitoring of atmospheric gas concentrations

(CO_2 and CH_4) on a planetary scale and to study their relationship with Earth's outgoing radiation.
The simultaneous observation of these vital climate variables is crucial as it provides a better assessment of the various stages of the global warming mechanism and, consequently, a deeper understanding of climate change.
A constellation of small satellites is garnering increased interest in the context of climate change observation, as it allows for a more global and continuous spatio-temporal coverage of the Earth than what a single large satellite can provide. This setup would ensure real-time observations (revisiting the same point every hour) for all areas of the globe, including those hard to access from the ground, such as polar regions. This is crucial for better monitoring of climate variations.
Uvsq-Sat NG is an INSPIRE mission that seeks to bring the scientific teams of the programme closer together.

***Committee on Space Research (COSPAR)** ought to initiate a mechanism where International Teams can collaborate to set science objectives and guidelines for a modular, global small satellite constellation for Earth observations. The role of **COSPAR** is one of an honest broker, focusing on orchestration rather than financing. The outcome of a collective endeavour to construct small satellite constellations would benefit all involved parties and prove more significant than the sum of its parts. **COSPAR** is in a position to help foster this international collaboration, creating a precedent for setting up community science in a very open way.*

To learn more...

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