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French Report to COSPAR 2024

45th Scientific Assembly
13-21 July 2024
Bexco, Busan, Korea

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FRENCH REPORT TO **COSPAR 2024**

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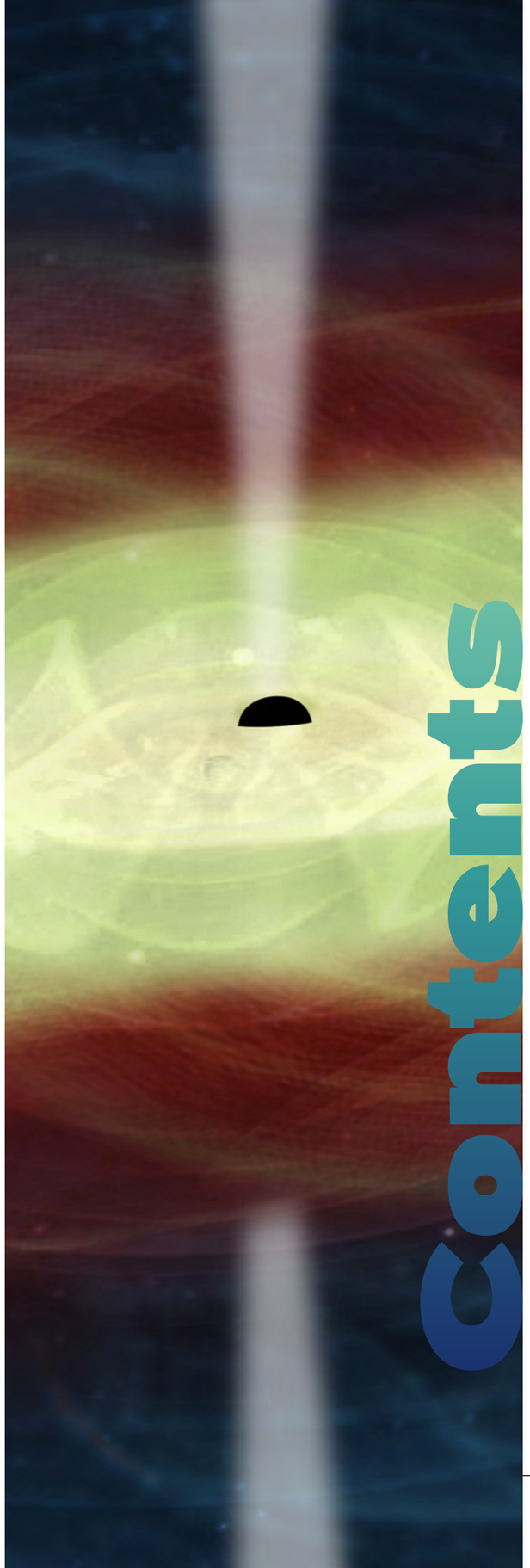

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Editorial

Mioara Mandea
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Deputy Director for Programmes

Space has a huge impact on France's scientific community and economy. CNES is involved in a broad range of activities, advancing our understanding of how Earth works or gaining new insights into our solar system and beyond. New space data are vital for public sector services (e.g. weather services, emergency services and civil protection departments), the economy (e.g. fishing, aviation, agriculture and transport) and citizens (e.g. geo-location, pollution alerts and disaster management).
Here, we would like to highlight CNES's role in French space science.

CNES's partnership with the scientific community, which dates back more than half a century, has proven extremely fruitful and effective. But the landscape has evolved significantly in recent years. The sophistication of spaceborne instruments has increased, as has the volume and complexity of data to be processed. The national research landscape has also changed, with for example greater autonomy for universities and new laboratories. CNES, which lends its financial and technical support to the research efforts of French space scientists, will in the future have to play a growing role in accompanying both the development of innovative space instruments and the processing, archiving and updating of spatial data.

CNES's last COSPAR report already mirrored the scientific structure of COSPAR. Working along the same lines, this report looks at CNES stand-outs in space science, particularly for Earth observation, universe science, condensed matter and life sciences in microgravity. The task of summarizing the agency's achievements in space-based Earth and planetary science and astrophysics observations is a daunting one, as there is a vast amount of information. To take just one example: on 5 July 2023, Ariane 5, operated by Arianespace, completed a flawless launch on its 117th flight from the Guiana Space Centre, adding a final success to its storied history.

Our changing planet is under the constant watch of satellites taking its pulse and helping us to anticipate its likely evolution. This report underlines results obtained in France over the last two years:

- On 16 December 2022, a Falcon 9 launch vehicle operated by SpaceX successfully orbited the Surface Water and Ocean Topography (**SWOT**) satellite. **SWOT**, a joint mission between CNES and NASA, with contributions from the Canadian Space Agency (CSA) and the UK Space Agency (UKSA), is dedicated to measuring surface water levels in lakes and rivers and river discharges, and to acquiring highly precise and innovative measurements of ocean dynamics. The **SWOT** mission is able to measure and survey waters on over 90% of Earth's surface, providing a high-resolution map of our planet's water resources for the first time ever. The satellite's measurements of freshwater and ocean masses are set to deliver new insights into the global ocean cycle impacted by climate change. Given the **SWOT** system's complexity and the giant leap in technology afforded by employing radar interferometry from space, the satellite's results and performance are already unbelievably good and look very promising.

- January 2024, the first European mission ever designed to monitor carbon fluxes by precisely measuring carbon dioxide, the **MicroCarb** satellite (developed with UKSA), reached a key milestone in its development with the completion of assembly and qualification. With its compact technology packed inside a small form factor, **MicroCarb** marks a major step for Europe towards establishing a system to monitor global CO_2 fluxes. CNES is overseeing developments.

- CARIOQA partners—CNES, the German space agency DLR, the European Commission, Airbus Defence & Space, GMV and FORTH/PRAXI—came together to officially kick off phase A of the project. This marks a key milestone in the development of this technology demonstration mission to space-rate a quantum sensor capable of measuring accelerations using cold atoms. This new technology holds huge potential for measuring Earth's gravity field and monitoring the water cycle or seismic risks, for example. Future space geodesy missions will benefit from it to advance scientific knowledge in hydrology, oceanography and glaciology, delivering deeper insights into the water cycle and Earth's interior structure.

More broadly, CNES is implementing innovative space missions to gain a better understanding of the major cycles that govern our environment and planet, such as the water, carbon and methane cycles, while developing ever more accurate measurements from space that will enable us to gain a better understanding and control of our planet's resources.

As example we can cite **Trishna** a French-Indian mission dedicated to acquire imagery of Earth's surface in the visible and thermal infrared with a resolution and revisit frequency never seen before (launch in 2025) or **MERLIN** a scientific minisatellite developed by the French and German and French space agencies which must measure with unequaled precision the spatial and temporal distribution of methane emissions for the entire planet.

CNES is striving to develop science-driven systems that also offer easy access to Earth-observation data, to meet the scientific and societal challenges that lie ahead.

In the field of space science and exploration, we also note a few key results:

- In June 2022, CNES signed the Artemis Accords, making France the 20th nation to join this space exploration programme led by the United States. The Artemis Accords offer a wealth of opportunities for industry and scientific research in France and Europe. French firms in the space sector are already actively contributing to the Artemis programme. France's signature will thus extend and deepen such mutually beneficial partnerships.

- Since the start of the **InSight** mission, the SEIS seismometer has been collecting high-quality science data about Mars on a daily basis. The latest release from InSight, in October 2022, is of special importance as it contains data on the largest marsquake detected by SEIS: a magnitude 4.7 temblor, "the big one" that scientists had been hoping for since the start of the mission. This quake, which yielded high-quality seismic data with an excellent signal-to-noise ratio, has refined our knowledge of Mars' deep interior.

- In April 2023, the **JUICE** space mission (JUpiter ICy moons Explorer) was launched on its voyage of more than seven years to the planet Jupiter. **JUICE** is the first European space probe to venture this far out into the solar system. On reaching its destination in 2031, **JUICE** will spend three and a half years studying Jupiter and its three icy moons: Ganymede, Callisto and Europa. The mission's main goals are to investigate the moons' potential habitability, i.e., to determine whether the conditions to support life might exist there, to acquire new data on how the solar system and planets formed, and to characterize Jupiter's magnetosphere and how it interacts with its moons. **JUICE** is carrying 10 scientific instruments. France is contributing to six through laboratories affiliated to the French national scientific centre CNRS and its partners.

- In July 2023, the **Euclid** mission developed by the European Space Agency (ESA) and the Euclid Consortium was launched. CNES engineers and French scientists are involved in this mission. **Euclid**'s main objectives are to better understand dark energy and dark matter by accurately measuring the accelerating expansion of the universe. On 7 November 2023, ESA revealed the mission's first full-colour images of the cosmos. The telescope has created razor-sharp astronomical images across a large patch of the sky, looking far into the distant universe. The first five images indicate the full potential to create the most extensive 3D map ever of the universe.

We also note developments in other research fields. For space plasmas in the solar system, including planetary magnetospheres, the **Solar Orbiter** mission is continuing its observations with an important rendezvous in 2025, when it will change inclination to observe the Sun from its poles. In the field of life sciences related to space, emergency medicine is an active field of research at CNES, with an eye on future long-duration spaceflight missions (LDSM). During recent parabolic flight campaigns, French medical research teams tested different intubation configurations designed to improve medical procedures in spaceflight conditions. Concerning the field of materials sciences, CNES was responsible for developing the **FLUIDICS** instrument to study fluid behaviour when subjected to mechanical excitation, and the **DECLIC** small physics laboratory to study transparent materials, equipped with high-definition imagery and precise thermal control capabilities. In fundamental physics, the final results of the **Microscope** mission were published in Physical Review Letters in 2022. Also, final preparations for ACES/PHARAO will ensure a launch in 2025. From a programmatic perspective, the **LISA** mission was given the go-ahead at the dedicated meeting of ESA's Science Programme Committee in January 2024. A number of member states are contributing to this ESA-led mission, with France focusing on performance tests and data processing, both supervised by CNES.

The last two years have been very busy for CNES and France, with numerous events and rendezvous throughout the year. In October 2022, CNES organized the very first 'Science Day' in Paris, and the second one in 2023. These annual events—excepting the year of the agency's Science Survey Seminar—offer opportunities to discuss the remarkable results obtained in space science. In June 2023, during the Paris Air Show, there were many significant events, one being the signing of a trilateral agreement between CNES, the Japan Aerospace Exploration Agency (JAXA) and the German space agency DLR to supply JAXA with a rover co-developed by CNES and DLR for the MMX mission. During the meeting, we also organized a full day for our early career scientists. CNES is also engaging in several initiatives to support and develop French and European space industry efforts to meet New Space challenges. For example, the Connect by CNES programme encourages exchanges between space and other sectors, continuing to support the downstream sector and the environment, mobility and health domains.
The development of space science research is an essential mission of CNES. As an agency and field centre, CNES does not have its own research laboratories but works in partnership with major public research organizations. To implement its scientific programmes, CNES relies on a Scientific Programmes Committee (CPS), which assists the Board of Directors in prioritizing projects with respect to their scientific objectives.

Finally, let us note that 2024 is a crucial moment with the CNES Science Propsective Seminar, an event held every five years. The work done by the community of French scientists is a great aid to the agency in defining our space strategy and priorities at both national and European levels. Preparations for this seminar are undertaken by the scientists themselves, working within committees and thematic working groups: TOSCA (Land, Ocean, Surfaces Continental, Atmosphere) for Earth observation and CERES (Space Science Research and Exploration Committee) for the study and exploration of the universe as well as two thematic working groups devoted to life and material sciences. Other working groups have also been set up to tackle cross-functional issues and more general questions, such as links with our international partners or the environmental responsibility of space activities. We would like to thank all members of these committees for their unfailing support and dedication.

We would like to take the opportunity to thank the Heads of CNES programmes involved in producing this report. We also thank Orianne Arnould, Michele Dupire, Karine Priselkow and Boyd Vincent for assistance with editing.

1 Space Studies of Earth's surface, meteorology and climate

© GettyImages

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Observations of the Earth system—the lithosphere, hydrosphere, atmosphere and biosphere—from space are crucial to understanding our planet's inner workings and climate. These observations have a dual dimension: exploratory, by gathering unprecedented data on the different compartments of the Earth system, and thematic, by answering precise scientific questions such as changes in continental ice, rising sea levels or variations in greenhouse gases. They are an invaluable tool for tackling many of the challenges associated with the United Nation's Sustainable Development Goals (SDGs), from preserving biodiversity to improving water management and supporting local agriculture. These data, combined with field observations and numerical models, can help people anticipate future risks, while promoting social transformation and more sustainable lifestyles.

CNES's Earth-observation programme is dedicated to addressing these urgent needs through a consistent set of actions: increased collaborations and partnerships at all scales, improved combination of satellite, in-situ and model data from upstream (R&T) to downstream (applications) processes, and provision of guidance on strategy and funding support to scientific committees (CPS and TOSCA). We are also supporting and promoting studies on cross-cutting challenges such as climate science, coastal zones, the cryosphere, the water and carbon cycles, health-related issues, risks and the urban environment, to cite a few.

Among the major missions currently under development in which CNES is actively involved are: **MicroCarb**, in partnership with the UK, to monitor carbon dioxide; **MERLIN**, in collaboration with Germany, to measure methane; the sophisticated **IASI-NG** (Infrared Atmospheric Sounding Interferometer New Generation) forecasting instrument that will set

[...]

[...]
new standards of accuracy in short-term weather prediction; and **Trishna**, in partnership with India, to study plant evapotranspiration and the temperature of complex surfaces such as coastal, urban or volcanic zones in the thermal infrared. More recently, CNES has also started development of a new mission in partnership with Israel, **C3IEL** (Cluster for Cloud evolution, ClimatE and Lightning), to address challenges related to cloud convection and numerical weather prediction.

CNES also operates 15 missions currently in orbit, including the Surface Water and Ocean Topography (**SWOT**) satellite, a wide-swath altimetry mission launched in December 2022, a fine example of successful international cooperation (NASA/CNES/CSA/UKSA) and instrumental innovation. **SWOT**'s initial results are promising, notably for measuring ocean levels on unprecedented scales, studying coastal zones and monitoring rivers and lakes. Other recent scientific achievements in the field of oceanography include the outstanding results from the China-France **CFOSat mission**, launched in 2018, which has enabled considerable advances in our understanding of ocean waves, wind-wave interactions and ocean modelling.

These advances will stimulate new research in oceanography and altimetry, paving the way for new applications in water resource management. In the field of infrared sounding, where CNES has a long record of excellence, observations from the **IASI instruments** on the European Meteorological Satellites Programme's Metop satellites reveal atmospheric and climate phenomena thanks to their reliability and operational measurements of atmospheric composition. As regularly emphasized by our community's scientists, long time-series and continuity of Earth observations are key to monitoring essential climate variables (ECVs).

We are committed to working across the entire value chain of Earth-observation data, from space to ground, and in collaboration with a range of partners, from national and international institutions to aerospace industry leaders and private sector players. The development of Earth-observation applications and services can only be secured with close support from space agencies, who are able to deliver free, high-quality data through their various programmes—like the European Commission's Copernicus programme—and platforms. In this domain, CNES provides funding and technical support to thousands of data users through downstream services (e.g. Hydroweb.next for the water cycle) and develops new downstream services related to the water, carbon or methane cycles, all hosted by the Data Terra infrastructure. Under the French government's France 2030 investment plan, four innovative services will be developed to address the needs of the hydrology sector (monitoring of freshwater volumes in dams, surface water quality and irrigated agricultural surfaces, and visualization and distribution of these services). These services have been developed through an extensive R&D effort supported by CNES for the **SWOT** early adopters programme, working closely with long-time players and scientists from research laboratories, as well as New Space players, all serving France's public policy in the space sector. Indeed, while continuing to support its traditional partners, CNES's mission is to accompany these new players to ensure their projects' success and to help them to become established in the market. Today, Earth-observation data are mainly used by scientists and institutions to meet public policy requirements. The private market currently relies essentially on data suppliers whose main customers are governments. Non-institutional applications and services are still in their infancy and our mission is to help new entrepreneurs develop new services and meet growing societal needs.

Finally, this year will be marked by our five-yearly Science Survey Seminar, where the scientific communities and CNES executive members will gather to reflect on achievements since the last edition and to outline their roadmap and research priorities for the next five years. This will be a key milestone to engage our programmes in continuing to develop cutting-edge space missions and delivering high-quality data and science to advance understanding and ensure the sustainability of our planet.

TRISHNA

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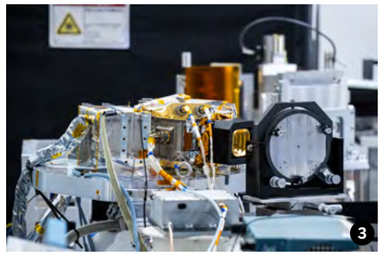
TRISHNA (Thermal infraRed Imaging Satellite for High-Resolution Natural resource Assessment) is a CNES/ISRO cross-purpose thermal-infrared (TIR) Earth-observation mission designed to deliver images at high spatial (60 metres) and temporal (three days) resolutions. Its launch is foreseen in 2026 with a nominal mission duration of five years, and a possible extension for two more years.

This Indo-French polar-orbiting mission will overcome the limitations of existing thermal-optical observations from Landsat satellites and ASTER: low-revisit observations or MODIS and Sentinel-3/SLSTR kilometric resolution.

TRISHNA scenes will be fully harnessed to pioneer the first cutting-edge high-resolution global maps of land surface temperature (LST) and land surface emissivity (LSE) of natural and managed agro-ecosystems, man-made structures, water bodies, bare soils, rocks, snow, ice and sea. The quality of pre-processing—radiometric calibration, atmospheric and directional corrections—is mandatory to satisfy the specifications with an expected precision of 1 K on LST in order to meet the mission's goals.

TRISHNA's design drivers are the detection and monitoring of water stress, radiative and heat transfer processes over marine and terrestrial ecosystems, paving the way for impactful applications in water resources, urban climate, cryosphere and biogeochemical cycles.



FIGURES
1) Artist's view of TRISHNA (Thermal infraRed Imaging Satellite for High-Resolution Natural resource Assessment).
© CNES/ill.Michel Regy, 2021
2) View of entrance to the EM model of the cryostat in the French thermal infrared (TIR) instrument for the TRISHNA programme during integration and testing at Airbus Defence & Space in Toulouse, 12 July 2023. .
© CNES/Frédéric Lancelot, 2023
3) View of the EM model of the TRISHNA programme's TIR instrument during integration and testing at Airbus Defence & Space in Toulouse, 12 July 2023..
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IASI Climate Trends over 17 years

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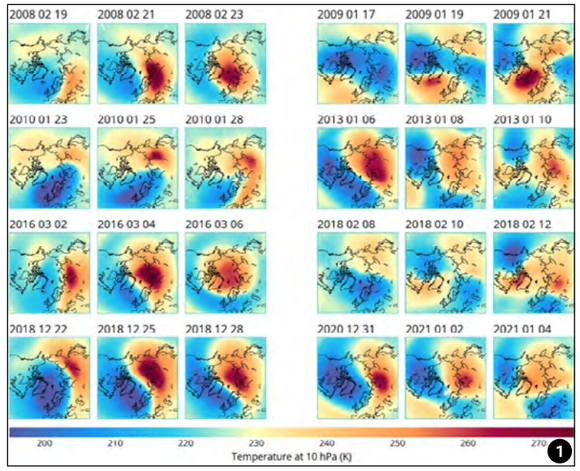
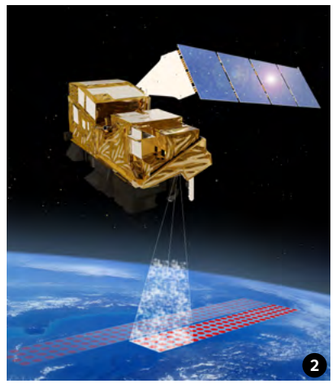
The IASI instruments on Eumetsat's Metop low-Earth-orbit satellites have been monitoring atmospheric temperature and composition since 2007, allowing scientists to construct long and stable records of several atmospheric variables and to study disruptive phenomena which may have a strong impact on climate change.



Sudden Stratospheric Warming events (SSW) are extreme phenomena during which stratospheric temperature can increase by tens of degrees in a few days. They are due to the propagation and breaking of planetary waves, disrupting the polar vortex and influencing polar ozone depletion.

IASI has observed eight major SSWs since 2007 and displacement or split of the vortex were analysed split events. Scientists showed that temperature anomalies vary over the years, but on average there are positive anomalies over Canada and Greenland, and negative anomalies over Europe and Russia. Winters with major SSWs tend to have larger ozone concentrations in March than those without. Most notably, average ozone concentrations in March are strongly correlated to the duration of the positive temperature anomaly at 10 hPa, except for the winters of 2010-2011 and 2019-2020 that had very low ozone concentrations due to very stable vortex conditions.
https://doi.org/10.1029/2023JD038692

This shows the potential of the **IASI instruments** for studying unusual atmospheric phenomena in the future, as they are planned to be operational until at least 2027, and will be continued with the **IASI-New Generation instruments** until at least 2040.



FIGURES

1) Zonal wind (orange, from ERA5) and North-South temperature gradient (blue, from IASI) at 60°N and 10 hPa between 1 December and 31 March..
2) Artist's view of the Metop-SG satellite.
© CNES/ill./Michel Regy, 2021

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C3IEL

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CNES recently confirmed the development of a new joint Earth-observation mission in partnership with the Israel Space Agency (ISA). This mission, named C3IEL (for Cluster for Cloud evolution, ClimatE and Lightning), will enable us to observe clouds in a completely innovative way. It should not only improve our understanding of the mechanisms behind cloud formation, but also our weather models.

For the first time, clouds will be viewed from space in three dimensions using CLOUD cameras, while their electrical activity will be recorded using LOIP photometers and water vapour measured using WaterVapor radiometers.

Two identical satellites, flying one behind the other, will carry these instruments, so that the same scene is observed simultaneously from different angles. Data from this mission will be made available to the scientific community on Data Terra through the AERIS atmospheric science data and services centre. Created in 2014, AERIS federates atmospheric data management activities and scientific expertise at national level, as is the case for IASI, Calipso, Megha-Tropiques and Parasol.

In this partnership, CNES is responsible for developing and operating the two **C3IEL satellites**, as well as the innovative geometric processing that will enable these scientific advances.

ISA will be in charge of developing the three instruments and radiometric processing. Various French and Israeli research laboratories are also working on this mission, in particular the LOA atmospheric optics laboratory, the LAERO aerology laboratory and CNRM, the national meteorological research centre.

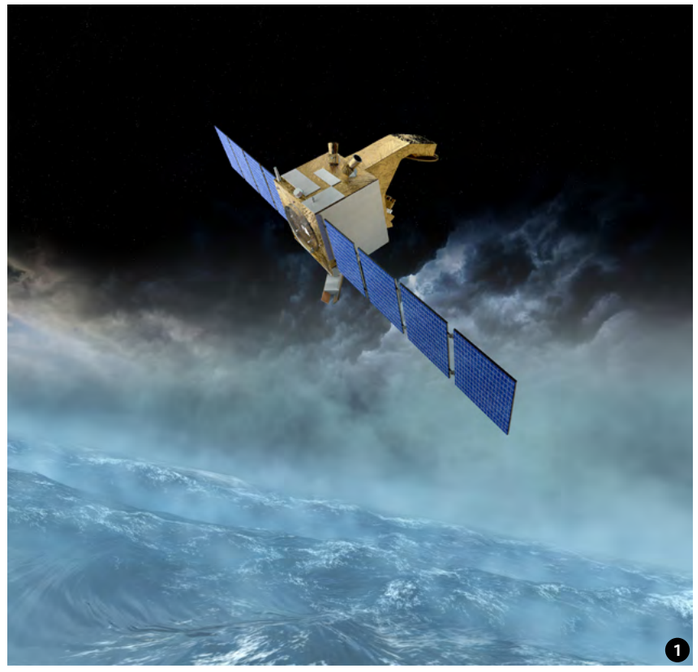
The launch of these two satellites is scheduled for early 2027, and the mission is planned to last two to three years.

FIGURES

Artist's view of the two C3IEL satellites observing a convective system.
© CNES – Olivier Sattler, 2021.

CFOSAT

Authors:
A. SYLVESTRE-BARON and Y. FAUGERE
Ocean Programme Managers

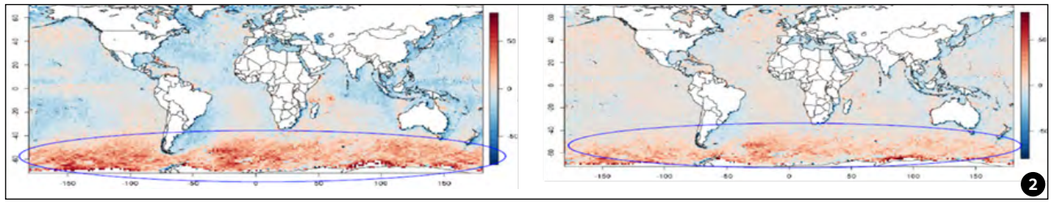


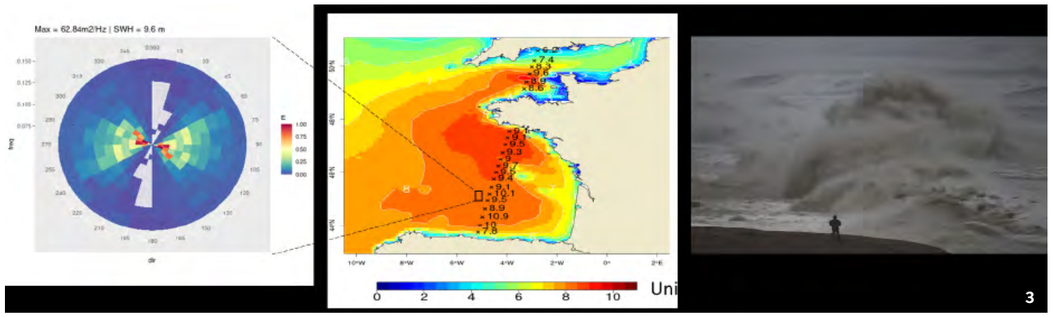
CFOSat (China France Oceanography Satellite) is an innovative mission from the Chinese and French space agencies (CNSA and CNES), launched on 29 October 2018 and carrying two K_u-band active instruments:
SWIM, measuring ocean surface wave direction, and SCAT, measuring wind vectors. In 2023, CFOSat completed its fifth year in operation. During this period, it has contributed to global surface wind field observations alongside existing scatterometer missions (e.g. ASCAT on Metop, SCAT on HY-2A, HY-2B and HY2C) and significant wave height measurements alongside other altimeter missions (like Jason-3, Altika, Sentinel-3a and 3b, 6-MF and HY-2).

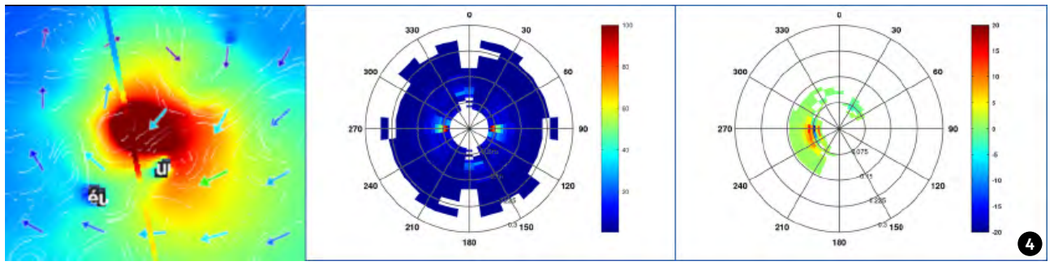
But what makes **CFOSat** unique compared to other satellite missions is that it provides continuous, co-located surface wind vector fields and directional spectra of ocean waves for wavelengths in the range of about 30-500 metres. The SWIM instrument provides wave properties not only for long swells, but also for wind-waves and mixed sea conditions, making CFOSat very complementary to SAR missions (like Sentinel-1).

The **CFOSat Science Team**, renewed in 2023, has been very active in exploiting these unique capabilities, producing a wealth of scientific results and publications. Notable advances have been made on various topics related to our understanding of the wave field, wind-wave analysis, wave/ocean coupling, Stokes drift, sea-ice and more.

Besides the high-level scientific results obtained these last years, a great achievement of the mission is the positive impact of the assimilation of its wave measurements, SWH and wave spectra in numerical wave models (Fig1). After some first positive Ocean Simulation Experiments (OSE), the operational assimilation of CFOSat products in near-real-time (NRT) models such as MFWAM was rapidly implemented. While **CFOSat SWH measurements** are assimilated operationally since 2020, the directional wave spectra are used in the NRT wave models of the national weather service Meteo-France and the Copernicus Marine Service since February 2021, with major benefits for wave forecasts. These additional directional observations induce better scaling of wave energy and dominant wave period, particularly on storm tracks in the North-East Atlantic, markedly improving initial wind-wave conditions during the growth phase of storm events (Fig 2). Assimilation of **CFOSat data** also impacts wave forecasts near cyclones (Fig 3). This kind of improvement is of the utmost importance for applications such as marine safety and wave submersion prediction along coasts. Five years after its launch, **CFOSat** is thus bringing direct benefits to citizens, in a context of increasingly frequent severe weather events.







FIGURES
1) Illustration du satellite CFOSat.
© CNES/ill./Olivier Sattler, 2017)
2) Illustration of the benefit of CFOSat SWH and wave spectra assimilation with notably strong impacts on the circumpolar area. SWH bias between model and observations (cm) without CFOSat assimilation (left panel), and with CFOSat assimilation (right panel).
3) Illustration of a severe storm captured by CFOSat. Storm Ciaran occurred on 2 November 2023 in the North-East Atlantic and generated strong waves along the coast (right panel). The middle panel shows a snapshot of the SWH forecast from the MFWAM model on this date at 06:00. CFOSat SWH measurements, capturing the storm with values between 7 and 10 metres, are very consistent. An example of wave spectra measured in the middle of the Bay of Biscay is also shown (left panel). Both SWH and wave spectra are assimilated in the model, contributing to better forecasting of such events.
4) Illustration of Cyclone Freddy (Feb. 2023) captured by CFOSat north of La Reunion (left panel). The directional wave spectrum is observed by SWIM at the front of the cyclone on 20 February 2023 at 15:00 UTC (middle panel), showing long swell at ~80° and a wavelength of ~350 m, with wind-wave partition in the same direction, and other winds/waves in a perpendicular direction. The figure on the left shows the difference between wave spectra with and without assimilation. CFOSat captured some interesting wind-wave information near the eye of the cyclone, significantly improving the modelled wave spectra.

SWOT

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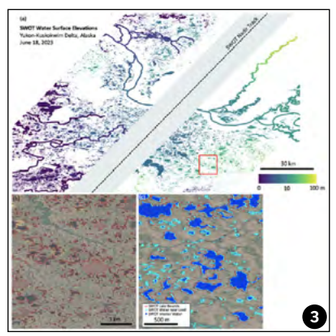
Ocean Programme Managers

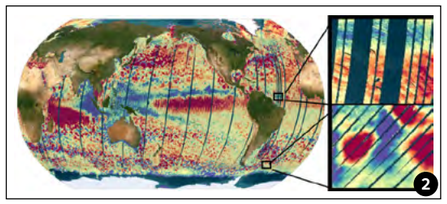
The innovative Surface Water and Ocean Topography (SWOT) altimetry satellite mission developed jointly by NASA and CNES, the French space agency, in partnership with the Canadian Space Agency (CSA) and UK Space Agency (UKSA), was successfully launched on 18 November 2022. The objectives of this mission are to complete the first global survey of Earth's surface water, to observe the fine details of the ocean surface topography and to measure how land surface water bodies change over time. SWOT's innovation consists in measuring 2D images of the surface topography, thanks to a 120-kilometre wide swath with a 20-kilometre nadir gap sampled with coarse resolution along the centreline by a conventional altimeter.



After a few weeks the satellite reached a specific orbit on 29 March with a one-day repeat cycle, dedicated to CALVAL activities. Although limited in terms of spatial coverage due to the wide separation between the satellite ground tracks, the high revisit frequency proved valuable in interpreting such an innovative kind of measurement, and notably for separating true signals from errors in KaRIn images. Statistical analysis over the ocean demonstrated the very good performance of the KaRIn instrument, exceeding the mission requirement by an order of magnitude.

These outstanding results confirm **SWOT** as a game-changer for space oceanography (Fu et al, 2024). One of the keys of the data quality has been the work over several years on advanced algorithms to handle this new type of measurements, and notably the robust calibration process (Dibarboure et al 2023). On 21 July 2023, SWOT transitioned to a global mapping phase in which the satellite covers the globe in approximately 21 days, revealing an unprecedented view of global sea level. As for the one-day repeat phase, KaRIn is able to capture a wide range of ocean phenomena from the new orbit, from large-scale signals like El Niño to high-resolution structures (Fig 1).

SWOT measurements over land surface waters are also revealing unprecedented details of rivers and lakes. Preliminary results suggest that it will enable robust, simultaneous observation of changes in water surface elevation and flood extent in the world's lakes, rivers, floodplains and reservoirs (Fig 2). As for the ocean, **SWOT** will fill substantial gaps in monitoring of inland waters, allowing global estimation of variables such as variations in reservoir storage and river discharge that are important to both the global water balance and water resource management.



FIGURES

1) Artist's view of the SWOT satellite.
© CNES/ill./David Ducros, 2022
2) Sea level anomaly as measured by SWOT in November 2023 (left panel) showing various oceanographic features, from large scales (El Niño, Indian Ocean Dipole) to mesoscale signals in the western boundary currents or the Circumpolar Current (bottom-right panel), and even smaller features like internal solitary waves in the Amazon shelf (top-right panel).
3) SWOT water surface elevation data from SWOT River and Lake data products. Zoom for 18 June 2023 over a portion of the Yukon River Delta in Alaska (from Fu et al, 2024).

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DATA CENTRES

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Data Terra Research Infrastructure Technical Director

To be able to answer societies' questions about their environment, research needs to address the "Earth system" as a whole, from its core to the edge of the atmosphere, taking into account the interactions of its various components, and to explore all aspects ranging from the physical environment to the living environment.

Observation occurs at different stages of the scientific process: description, understanding, modelling and forecasting. Technical advances are providing us with increasingly diverse capabilities generating ever-richer **datasets**. However, using or accessing these datasets can be made difficult by the variety of data types, their volume, the complexity of their underlying processing, and their distribution and location. In order to make the most of this unprecedented supply of data for the benefit of knowledge and society, all **data centre policies** need to be aligned and appropriate approaches must be defined to process, archive and distribute the validated **data** and products derived from them.

The **Data Terra** research infrastructure was designed with this goal in mind.

Data Terra is part of the Ministry for Higher Education and Research roadmap. Its main mission is to develop a structure for accessing and processing data, products and services geared towards observing, understanding and predicting in an integrated manner the history, mechanisms and evolution of the Earth system in response to global changes. While aimed chiefly at the scientific community, it also serves public and socio-economic stakeholders and its multi-source data are accessible via coherent, one-stop portals.

As a digital infrastructure in the field of environmental science, **Data Terra** works closely with Earth-observation research infrastructures and space agencies. It is backed by a continuum of distributed and interconnected platforms, proposing services that span the full **data cycle** from access to value-added processing, thus enabling cross-correlation, exploitation of large volumes of **data**—notably satellite data—and generation of information on demand combining multi-source, multi-disciplinary products. At national, European and international levels, it is advancing the development of open science, implementation of FAIR approaches, contributing to space missions and applications and to the initiative to generate digital twins of the Earth.

Data Terra encompasses a collection of data and services hubs. Each of these hubs covers a major compartment of the Earth system (solid Earth, ocean, land surfaces and atmosphere):
- **FORM@TER:** solid Earth
- **ODATIS:** oceans
- **THEIA:** land surfaces
- **AERIS:** atmosphere

A new data and services centre joined Data Terra at the beginning of 2024: PNDB, **the National Biodiversity Data Centre.**

Data Terra also encompasses DINAMIS (Dispositif Institutionnel National d'Approvisionnement Mutualisé en Imagerie Satellitaire), a recently created tool affording one-stop access to high- and very-high-resolution satellite imagery for a broad spectrum of non-commercial users (scientists and public stakeholders) in France.

Each **data** and **services centre** aims to facilitate access to satellite, aerial and in-situ (ground) data acquired and managed by research laboratories, distributed structures (universe science observatories (OSUs), research federations (FRs), etc.) or national infrastructures such as the national observation services (SNOs), environmental research observation and experimentation systems (SOEREs), the French oceanographic fleet, airplanes and space missions. They combine scientific disciplines related to a terrestrial compartment, offer value-added services and products, provide scientific expertise, and promote tools and methods developed within the relevant French scientific research community.

FIGURE

Bordeaux seen by the Sentinel-2 satellite.
© Copernicus Sentinel Data, 2020

2 Space studies of the Earth-Moon system, planets and bodies of the solar system

© GettyImages

Authors:
F. ROCARD and C. MUSTIN
Solar System Programme Managers

“The French space agency CNES is involved in numerous missions to explore the solar system, in addition to DORN on Chang’e 6 with CNSA and SEIS on InSight with NASA. CNES is a key partner on JUICE, an ESA mission to study Jupiter’s icy moons, Ganymede, Europa and Callisto, launched in April 2023. MAJIS is an infrared mapping spectrometer under the responsibility of the IAS space astrophysics institute that will study the mineral composition of the surfaces of the icy moons and Jupiter’s atmosphere. France is also involved at various levels in the overall payload, providing technical contributions to the PEP, RIME, RPWI, SWI and UVS instruments.

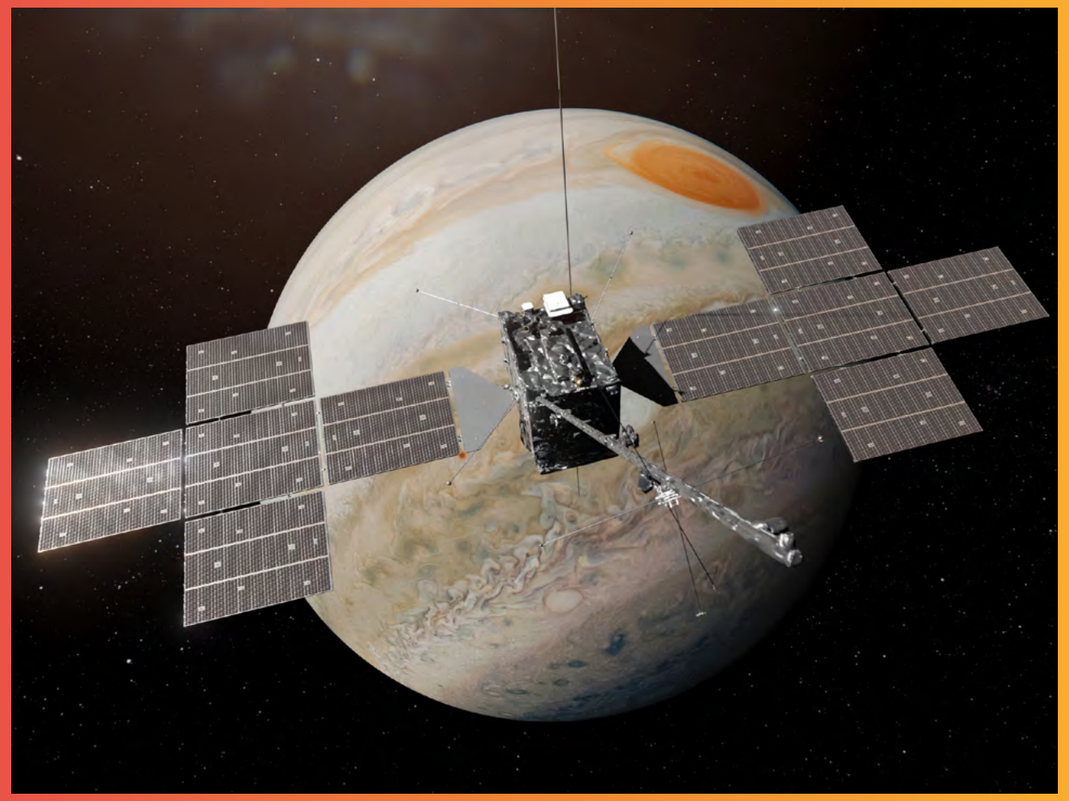
France is leading the PHEBUS ultraviolet instrument on the ESA-JAXA **BepiColombo mission**, which is set to arrive at Mercury by the end of 2025. The PI for this instrument is from the LATMOS atmospheres, environments and space observations laboratory. French scientists are also contributing to Simbio-Sys and SERENA on ESA’s MPO planetary orbiter, as well as providing sensors for MPPE and PWI on the Japanese Mio mission (Mercury Magnetospheric Orbiter, MMO).

France is contributing to the main instrument suite on the Mars rovers: SuperCam on Perseverance and ChemCam, and SAM on **Curiosity**. In addition, on JAXA’s MMX mission, which aims to return samples from the Martian moon Phobos, France is in charge of the IR mapping spectrometer (MIRS) and is jointly responsible with the German space agency DLR for the rover that will explore the surface of Phobos. Our contribution to Venus exploration is focused on the VenSpec-U UV spectrometer and Radio Science Experiment (RSE) of ESA’s EnVision mission, led by French scientists. We are also involved in the VenSpec-M NIR mapping spectrometer.

[...]

[...]
For NASA's VERITAS mission, we are contributing to the VEM spectrometer and providing the K_a-band transponders. The VBB seismometer will be integrated into the JPL FSS (Farside Seismic Suite) autonomous package, which will be launched on a Commercial Lunar Payload Services (CLPS) flight in 2025 to the Moon. Additionally, we will supply CMOS cameras for a reflight of the Emirati Rashid rover, which was lost in 2023.

FIGURE
Artist's view of the JUICE satellite.
© NASA/JPL-Caltech/SwRI/MSSS/
Kevin M.Gill/VR2Planets, 2023



INSIGHT

Author:
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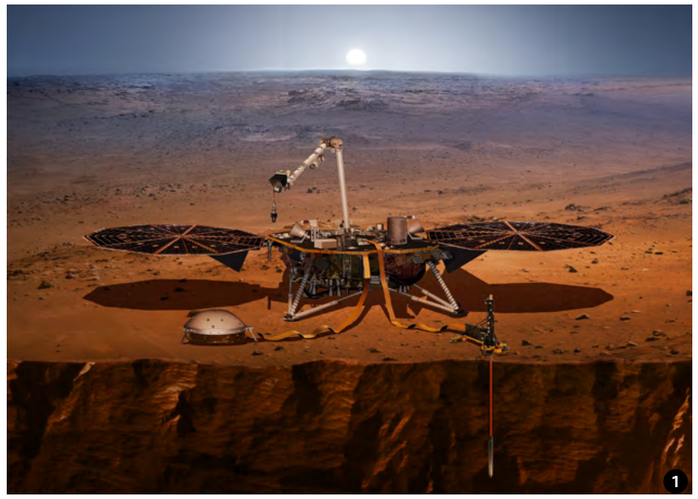
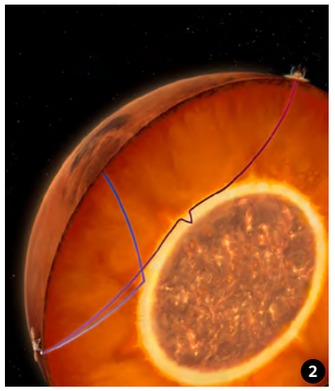
Solar System Programme Manager

InSight is a NASA-led Discovery mission that landed in November 2018 in the Elysium Planitia lowland region south-west of the large volcano Elysium Mons. InSight is carrying SEIS, the ultra-sensitive very-broad-band seismometer built by CNES and the IPGP Earth physics institute in Paris. For more than four years, SEIS has recorded the tiny movements of the Martian surface. More than 1,000 events have been recorded, the most significant having a magnitude of 4.



In 2021, analysis of these signals led for the first time to the determination of the internal structure of Mars: a large liquid core with a radius of 1,830 ± 40 kilometres and a low density, meaning it is composed of iron and nickel plus other light elements. The crust is 20-35 kilometres thick with an altered region in the first 10 kilometres.

SEIS has been able to determine the heat flux at 14-29 mW/m^2, which is quite a low value. Globally, seismic activity on Mars falls somewhere between that on Earth and the Moon, and the Cerberus Fossae region is particularly active. Recent impact events due to meteorites have been detected.



In 2023, a new publication revealed the presence of a layer of molten silicates at the base of the Martian mantle overhanging the metallic core. The presence of such a basal layer implies a metallic core 150-170 kilometres smaller (i.e. a radius of 1,650 ± 20 kilometres) and 5% to 8% denser (i.e. 6.5 g/cm^3) than previous seismic estimates. In December 2022, due to the accumulation of dust on the solar panels, the mission stopped communicating.

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FIGURES
1) Artist's view of the InSight mission.
© NASA/JPL Caltech, 2018
2) SEIS's dome-shaped shield is deployed on the surface of Mars.
© NASA/JPL Caltech, 2019
3) Artist's impression of the internal structure of Mars showing wave propagation diffracted images from the meteorite impact of September 2021 to the InSight mission's SEIS seismometer. Their trajectory passes in the lower part and completely melted silicate layer at the base of the mantle, where seismic velocities are weak.
© IPGP – CNES - N. Sarter

DORN on Chang'e 6

Author:
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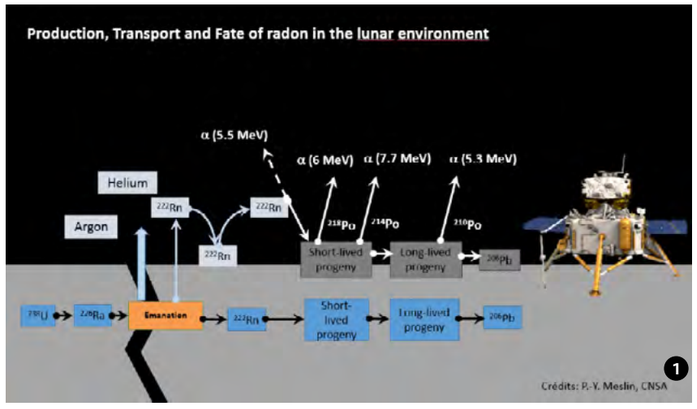
Solar System Programme Manager

The IRAP astrophysics and planetology research institute has built the DORN experiment, with the support of CNES. DORN (Detection of Outgassing Radon) aims to measure ^{222}Rn, ^{220}Rn and their progeny at the surface of the Moon by alpha spectroscopy in the 5–10 MeV energy range.

DORN's science goals are:

- Study lunar outgassing and transport of gases through the lunar regolith; Is the release of radon mostly continuous or due to sporadic venting from the lunar interior? constrain the transport/structural properties of the regolith.
- Study the transport of volatiles in the lunar exosphere; Constrain the rate of diffusion of radon in the lunar exosphere: benchmark tracers for other gases.
- Study the efficiency of the transport of lunar dust; surface churning rate over several decades.
- Improve uranium mapping of the Moon.
- Establish ground truth for orbital measurements (Apollo 15-16, Lunar Prospector, Kaguya).



DORN was delivered to China in August 2023 for integration on board CNSA's Chang'e 6 lunar lander. The mission is slated for launch in early May 2024.

DORN is expected to measure radon for 24-48 hours up to lift-off of the lander to bring back samples back to Earth from the South Pole-Aitken (SPA) basin on the far side of the Moon.

FIGURES

1) Diagram illustrating the production, transport and fate of lunar radon.
2) Flight model of the DORN instrument at IRAP during mechanical tests.
© CNES/MALIGNE Frédéric, 2023

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ExoMars 2028
Follow on

Author:
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For many years, CNES has been guiding and supporting French research laboratories involved in the ExoMars programme. This programme aims to establish whether life ever existed on Mars and to demonstrate key technologies underpinning European ambitions for future exploration missions in the solar system. For CNES, the ExoMars and Mars Sample Return (MSR) missions are key stepping stones to future international missions to Mars.

The **ExoMars mission** comprises an orbiter (2016) and rover (2022), initially conceived in 2009 as part of the Aurora Exploration Programme. In 2012, following the descoping of NASA's involvement, **ExoMars** became a cooperative programme between ESA and the Russian federal space agency Roscosmos. This collaboration led to the development and launch of a Trace Gas Orbiter (TGO) in 2016 and a rover named Rosalind Franklin in 2022.

TGO, launched in 2016, continues to deliver high-quality science data on stereoimaging and atmospheric trace gases of Mars, while also providing a powerful data relay service for NASA's Mars rovers, Curiosity and Perseverance. Unfortunately, due to Russia's invasion of Ukraine, the **ExoMars 2022 mission** was postponed, and in November 2022 ESA decided to terminate its cooperation with Roscosmos. **The ExoMars 2028** mission, named Rosalind Franklin, will now be accomplished through a collaboration between ESA and NASA. The launch window is set for the end of September 2028, with the goal of landing a refurbished rover on Mars in 2030. Under the new partnership scheme, NASA will provide a launcher, braking engines for the new European Descent Landing Module (EDLM) and Light Weight Radio Isotope Heating Units (LWRHUs) for rover thermal control during surface mission operations. Additionally, NASA will provide support for accommodating a new ESA-developed prototype of an Americium-based radioisotope heater unit (RHU).

The Rosalind Franklin rover is currently undergoing refurbishment at Thales Alenia Space-Italy, as shown in the photographs below. It will carry five French instruments or instrumental contributions, including a WISDOM ground-penetrating radar and a MicroMEGA IR spectro-imager at the PI level, and the GC gas chromatograph of the MOMA instrument, the ICEU electronic box of the RLS Raman spectrometer, and the detector of the CLUPI high-resolution colour imager at the Co-I level.

It will also carry one of the two autonomous navigation software packages developed by CNES. Additionally, there are plans to continue DLR-CNES cooperation on the COMARS+ experiment and to supply ICOTOM narrow-band infrared radiometers to measure the temperature of the plasma around the EDLM's shield during the descent phase.

The change of partnership at ESA level does not affect the scope of CNES and laboratory activities. Currently, the objective is to upgrade the rover's instruments with a French contribution, maintain them and participate in system tests. Disassembly of the Analytical Laboratory Drawer (ALD) will begin in 2024, and refurbished payload instruments will be required no later than June 2025.

FIGURES

The ALD flight model is removed from the Rosalind Franklin rover at Thales Alenia Space-Italy.
© ESA

Supercam on Perseverance

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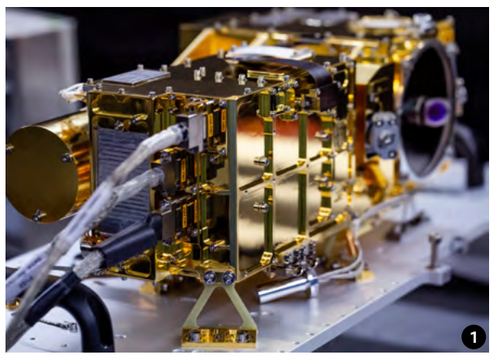
On 18 February 2021, NASA's Perseverance rover landed in Mars' Jezero crater. Currently, the majority of Perseverance's subsystems are functioning perfectly, including the sample caching system, which is the heart of the mission.

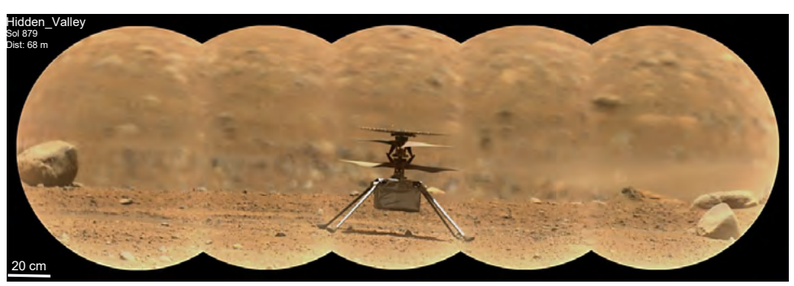
The rover initially explored the floor of Jezero crater, followed by the slopes of its delta. In three years, it has covered almost 26 kilometres, nearly as much as Curiosity (31 km), which has been surveying Gale Crater and Mount Sharp for 12 years.
In January 2023, the rover deposited 10 back-up tubes containing duplicate samples from the first part of the campaign. **Perseverance** currently holds 15 rock or regolith samples in its payload bay and requires 12 more tubes to complete its sample collection. The sample collection will be handed over to the Sample Retrieval Lander (SRL) for return to Earth in a few years' time.

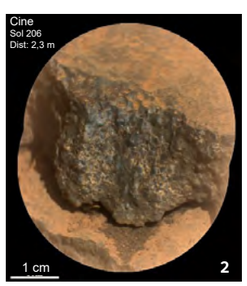
Perseverance's French-U.S. **SuperCam instrument** has already fired over 350,000 laser shots to measure the chemical and mineral composition of Martian outcrops. Using laser-induced spectroscopy techniques (LIBS and Raman), it is possible to analyse rocks, regolith, grains, the fresh inner face of boreholes, cuttings and abraded zones at ranges of 2 to 10 metres.
In comparison, Curiosity and ChemCam are on course to fire millions of laser shots this year. SuperCam has acquired thousands of high-resolution images (RMI) and infrared signatures (Vis-IR) of rocks, providing valuable information on the past habitability of Mars.
The RMI instrument was used to study the geomorphological context, while the Vis-IR spectrometer was used for mineralogical analysis of long-range targets.

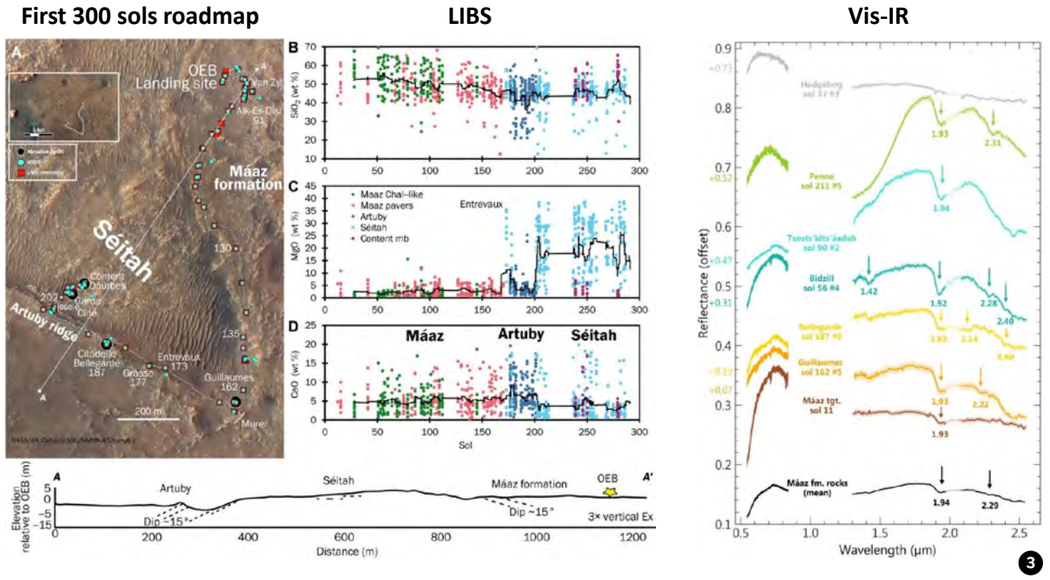
The **SuperCam spectrometer** suite is a crucial tool for daily prospecting of areas of interest and preparing geochemical analyses for other rover instruments. Without **SuperCam**'s long-range elemental and molecular analyses, sample collection would be less relevant and the rover would be prospecting samples blindly. Thorough observations and spectroscopic analysis can help the science team understand volcanic rocks and sedimentary deposits. Volcanic rocks provide insight into the formation of the surface crust, while sedimentary deposits offer information about the rivers and lakes that existed billions of years ago.

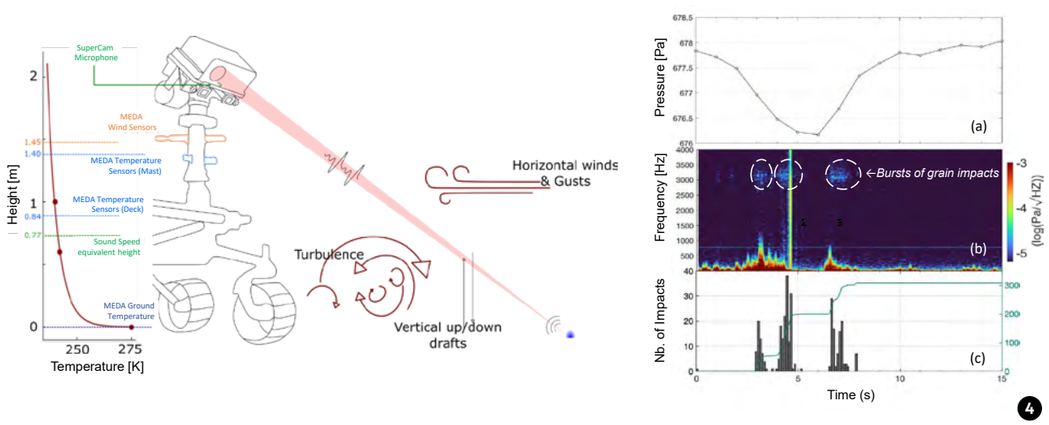
SuperCam's microphone provided the first estimate of sound speed on Mars. The system's high sampling rate (up to 100 kHz) allows for detailed analysis of sound wave propagation and turbulence previously unobserved on Mars. This unique collection of Martian sounds is growing daily and includes over 21 hours of wind, turbulence and artificial noise from the impacts of LIBS laser shots and the rover's internal mechanisms. This soundscape is truly unique, but **Perseverance**'s journey has only just begun.











FIGURES

1) Instrument Supercam de Mars 2020.
© CNES/Gwenewan Le Bras, 2019
2) Long range (Ingenuity Mars helicopter) and close-up (Texture of Olivine Cumulat) imaging with SuperCam Remote Micro-Imager (RMI).
© NASA/JPL-Caltech/LANL/CNES/CNRS
3) Detailed LIBS and Vis-IR analysis of Martian geology: Discovery of exposed intrusive igneous body at Seitah (Wiens et al. 2022).
4) SuperCam microphone: Study of microscale turbulence at Mars surface - (a) MEDA pressure data; (b) Spectrogram of the microphone sound amplitude; (c) Histogram and cumulative histogram of grain impacts (Chide et al, 2022).

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(c) Murdoch et al.,(2022) The Sound of a Martian Dust Devil. Nat Com. 13, 7505

3 Space studies in the solar system

Author:
M. MANDEA
Head of Science Coordination Department

“The main studies promoted by this commission are investigating specific aspects of the properties and structure of the upper atmospheres of the Earth and planets. The commission is also developing comprehensive reference atmospheres and ionospheres for the Earth and planets.

CNES undertook extensive efforts in preparing the TARANIS (Tool for the Analysis of Radiation from lightning and Sprites) mission, unfortunately lost when the launch vehicle failed shortly after launch. Despite this crushing disappointment, the French scientific community, supported by CNES programmes, is pursuing a range of studies related to the commission’s interests, such as Earth’s middle and upper atmosphere and ionosphere, as well planetary atmospheres and aeronomy.

4 Space plasmas in the solar system including planetary magnetospheres

Author:
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Heliophysics Programme Manager

“The French Sun, Heliosphere, Magnetospheres (SHM) community is closely involved in several projects covering the broad domain of the heliosphere, including solar physics, Earth’s magnetosphere and environment, and couplings between the Sun, solar wind, magnetosphere, ionosphere and thermosphere. Space weather is also part of this programme.

SOLAR ORBITER

Author:
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Heliophysics Programme Manager

Solar Orbiter is an ESA-led solar physics mission with strong participation from NASA. The spacecraft's combined in-situ and remote-sensing instruments are delivering new insights into the solar wind, heliospheric magnetic field, solar energetic particles, interplanetary disturbances and the Sun's magnetic field. Launched on 10 February 2020, the mission has since provided close observations of excellent quality and images of the Sun with unprecedented resolution. Also, during 2025 a series of gravity assist manoeuvres at Earth and Venus will enable **Solar Orbiter** to change its inclination and observe the Sun from its poles.

Since its launch, the satellite has acquired science data of such quality that the first results gave rise to a wealth of articles and a special issue of Astronomy and Astrophysics, with 50 articles dedicated to the mission. Among the ten instruments on board, French research laboratories and CNES were closely involved in developing five of them and provided one complete instrument, Radio & Plasma Waves (RPW). RPW acquires in-situ and remote-sensing measurements of both electrostatic and electromagnetic fields and waves over a broad frequency range.

FIGURE

The Sun as seen by the ESA/NASA Solar Orbiter spacecraft on 25 March 2022, one day before its closest approach of about 0.32 AU, which brought it inside the orbit of planet Mercury.
The central image was taken by the Extreme Ultraviolet Imager (EUI) instrument. The outer image was taken by the coronagraph Metis, an instrument that blocks out the bright light of the Sun's surface in order to see the Sun's faint outer atmosphere, known as the corona. The Metis image has been processed to bring out structures in the corona. This revealed the switchback (the prominent white/light blue feature at the roughly 8 o'clock position in the lower left). It appears to trace back to the active region on the surface of the Sun, where loops of magnetism have broken through the Sun's surface.
© ESA

PARKER SOLAR PROBE

Author:
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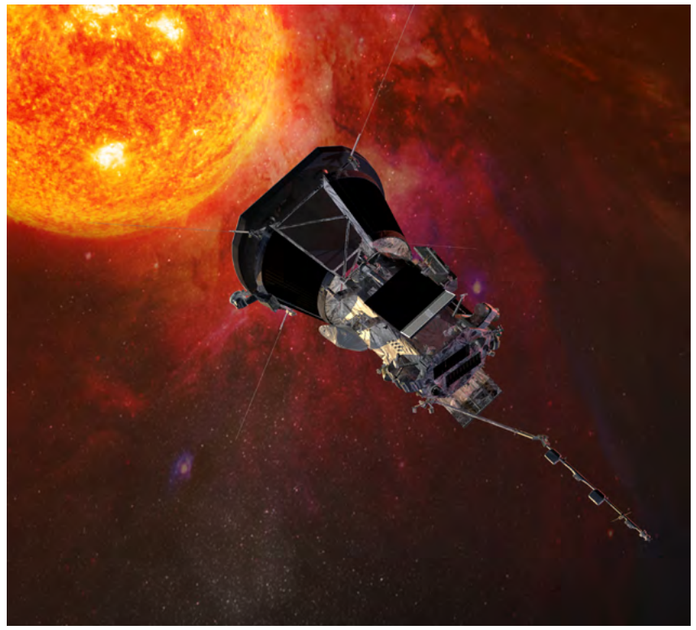
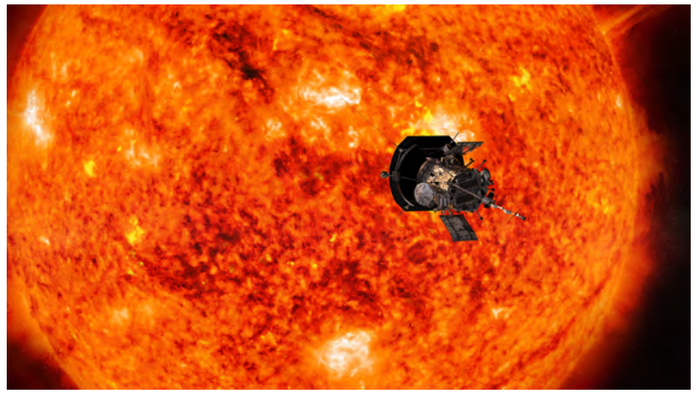
Heliophysics Programme Manager

Launched in August 2018, NASA's Parker Solar Probe (PSP) is on a mission to approach the Sun to within 9.86 solar radii and make in-situ observations of its outer atmosphere, also called the solar corona.

PSP will help to answer two key questions in solar physics: Why is the solar corona so much hotter than the photosphere? And how is the solar wind accelerated? Since 2018, **PSP** is getting closer and closer to our star. During its 18th encounter on 28 December last, it acquired observations of the corona down to 10.5 solar radii (7.26 million kilometres) of the solar surface. The closest approach, within 9 solar radii, is expected to arrive by the end of 2024.

Four French research laboratories and CNES are involved in two of the four instrument suites on **PSP**. They contributed not only expertise and design input for some instruments, but also to the complete search coil magnetometer instrument (SCM), a sensor to measure magnetic field variations.





FIGURES

1) PSP observing the Sun.
@ Nasa
2) Solar Orbiter.
@ Nasa

5 Research in astrophysics from space

Author:
O. LA MARLE
Head of Space Science Programme

“CNES is pursuing an ambitious astrophysics programme. The main questions being addressed derive from the agency’s Science Survey Seminar held in Le Havre in 2019. Understanding the origin and evolution of the universe, as well as the formation of planets and the appearance of life, are major drivers for this programme. In cooperation with research institutes and universities, the agency and its technical field centre are developing space instruments for cutting-edge international astrophysics missions, and contributing to processing of the respective science data.

GAIA

Author:
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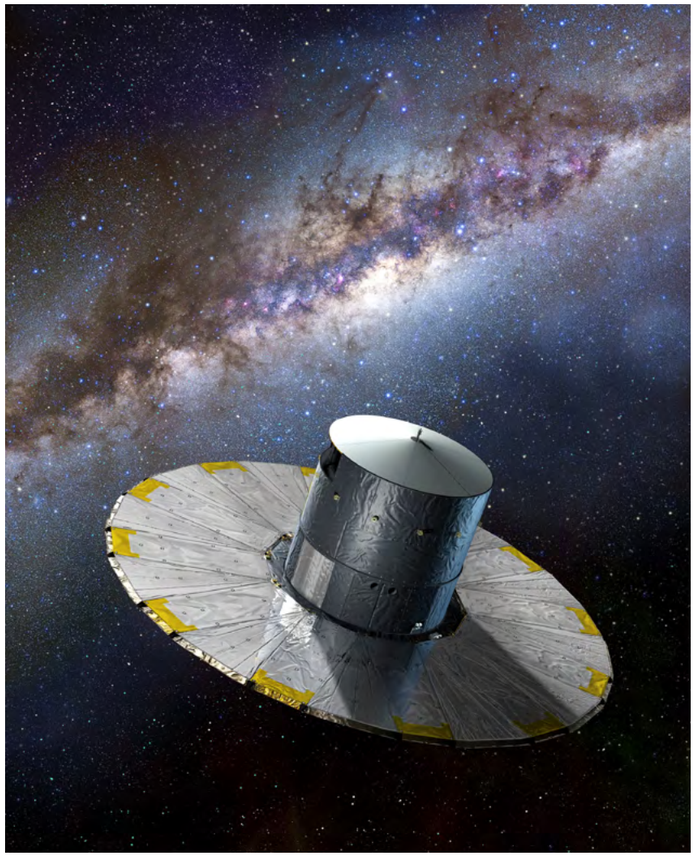
Gaia is an ambitious ESA mission to chart a three-dimensional map of the Milky Way, in the process revealing the composition, formation and evolution of our galaxy. Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our galaxy and throughout the Local Group. This amounts to about one percent of the galactic stellar population. Gaia's payload consists of three main instruments:

- The Astro astrometry instrument precisely determines the position of all stars brighter than magnitude 20 by measuring their angular position.
- The BP/RP photometric instrument acquires brightness measurements of stars over the 320-1,000 nm spectral band, of all stars brighter than magnitude 20.
- The Radial Velocity Spectrometer (RVS).

Several **Gaia catalogues** have been released over the years, each one with more information and better astrometry; the first data release, Gaia DR1, based on only 14 months of observations, was on 14 September 2016. The second data release (DR2) came on 25 April 2018. The third release is composed of Gaia Early Data Release 3 (Gaia EDR3) published on 3 December 2020, and the full Gaia DR3 released on 13 June 2022.



Gaia Focused Product Release (FPR) was released on 10 October 2023 and Gaia DR4, based on 66 months of data, is scheduled for the end of 2025 at the earliest.

In addition to France's contribution to ESA programmes, it is involved in **Gaia** via CNES through the DPC-C (CNES Data Processing Centre), which works on calculation and development of data releases, and supports the French scientific community for data analysis.

FIGURE
Artist's impression of the Gaia satellite.
© ESA/David Ducros, 2013

Euclid

Author:
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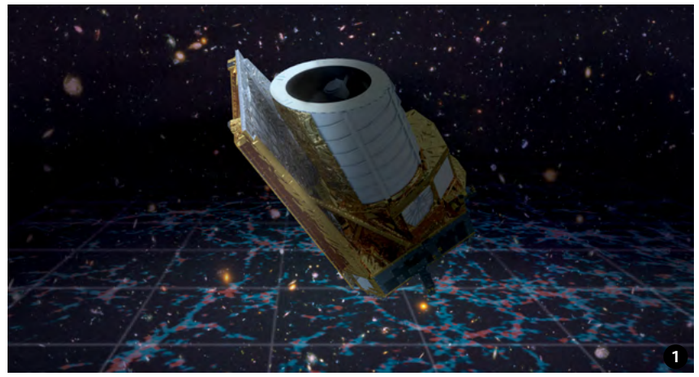
Head of Space Science Programme

Euclid is a medium-class science mission, launched on 1 July 2023 from Cape Canaveral by a SpaceX Falcon 9 launcher. It arrived at its L2 Lagrange point two weeks later. In-orbit commissioning was successfully completed on 9 February 2024.

This high-performance 1.2 metre telescope plans to perform a six-year survey of a large part of the sky in the visible and near-infrared spectrum. This survey started on 14 February 2024. The resulting galaxy catalogue will provide high-resolution images and redshifts of billions of galaxies. Specially designed to address the dark energy question, these products will be a treasure trove for the whole astronomy community.

The **Euclid consortium**, with more than 1,500 scientists and engineers from three continents, developed both focal plane instruments and is in charge of the highly challenging data processing. CNES, in addition to supporting the **Euclid Consortium** Lead at the IAP astrophysics institute in Paris, is also responsible for the infrared spectro-photometer, for parts of the visible instrument and for a large share of the science ground segment.

France is also responsible for the VIS instrument data processing pipeline, which will be the first to work to calibrate the instrument data. Astrometric calibration of the images, aimed at precisely aligning the satellite's pointing with a maximum precision of 10 thousandths of an arcsecond, naturally relies on the Gaia DR3 catalogue.



FIGURES
1) Euclid key visual.
2) The Horsehead Nebula seen by the Euclid space telescope.
© ESA/Euclid/Euclid Consortium/NASA/J-C Cuillandre (CEA Paris-Saclay), G. Anselmi, 2023

ATHENA

Author:
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Athena is ESA's next flagship science mission. One of the largest space-observatories ever built, this X-ray telescope will address unanswered questions surrounding the aggregation of ordinary matter into large-scale structures, and the growth of black holes and their role in shaping the universe. X-ray emissions from hot gas forming the bulk of ordinary matter will be mapped and spectroscopically analysed with unprecedented accuracy by a wide-field imager and a revolutionary X-ray integral field spectrometer, X-IFU.

X-IFU is being developed by an international consortium led by the IRAP astrophysics and planetology research institute and CNES. The instrument will be the workhorse for physical and chemical diagnostics of the hot gas that pervades large structures, of accretion disks around black holes, and of many other objects. Its focal plane populated with several thousand TES-based micro-calorimeters cooled to 50 mK delivers exquisite spectral resolution (4 eV at 7 keV).

Athena is currently in phase B. Go-ahead for the mission is foreseen in 2027 for a launch in 2037.

FIGURE
ATHENA.
© ESA/IRAP/CNRS/UT3/CNES/Fab&Fab

SVOM

Author:
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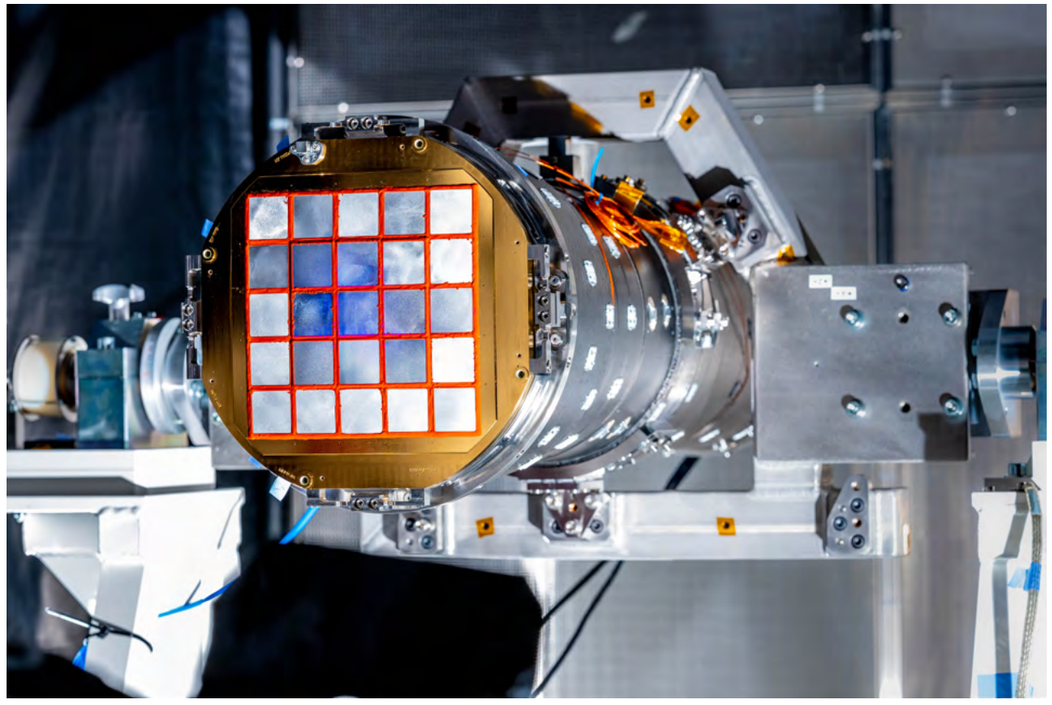

SVOM (Space-based multiband astronomical Variable Objects Monitor) is a French-Chinese mission dedicated to studying gamma-ray bursts, the most distant star explosions. It is to be launched on 24 June 2024 by a Chinese Long March 2C from the Xichang launch centre.

SVOM is a collaboration between CNSA (China National Space Administration) and CNES, with the main instrument contributions provided by the IRFU institute of research into the fundamental laws of the universe and the IRAP astrophysics and planetology research institute in France, and the National Astronomical Observatory (NAO) and the Beijing High Energy Institute (IHEP) in China.

Two of the four main instruments are French (ECLAIRs and MXT) and two are Chinese (GRM and VT):

- The ECLAIRs telescope to detect and locate gamma-ray bursts in the X-ray band and low-energy gamma rays (from 4 to 250 keV).
- The Microchannel X-ray Telescope (MXT) to observe gamma-ray bursts in the soft X-ray range (0.2 to 10 keV).
- GRM to measure the spectrum of high-energy bursts (from 15 keV to 5,000 keV).
- The Visible Telescope (VT) to detect and observe visible emissions produced immediately after a gamma-ray burst.

In addition to coordinating the French contribution and funding the ECLAIRs and MXT instruments, CNES is supporting the French scientific community for data analysis and ground monitoring of GRB alerts.

FIGURE
The SVOM satellite's MXT telescope.
© CNES/Thierry de Prada, 2021

6 Life sciences related to space

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“I believe every human has a finite number of heartbeats and I don’t intend to waste any of mine.” Neil Armstrong, first man to walk on the Moon.

This quote from arguably the most famous astronaut of all time reflects humankind’s desire to discover and conquer new horizons. Since ancient times and the discovery of the North African coasts, or the first circumnavigation of the globe by Magellan around 1520, the rapid development of science and technology has offered new perspectives leading to social advances, resulting in a deeper understanding of biology, astronomy, engineering and many other disciplines.

After exploring low Earth orbit with the ISS for more than 50 years, scientists now want to go further: the Moon and Mars will be their next playground. Lunar exploration missions leading to the establishment of a permanent settlement are planned in the coming years, as early as 2025, and will be followed by missions to Mars.

Experts have estimated that the most significant risks for space exploration missions are trauma, haemorrhagic shock and infections. To some extent, the likelihood of medical events can be estimated from analogue populations here on Earth, both military and civilian, and data gathered from human spaceflight experience. For example, the risk of lower limb fracture has been estimated at 0.046 events per Mars mission (950-day mission for a crew of six). The duration, remoteness and type of activities involved on a Moon or Mars settlement lead to hazard exposure different to what would be expected in low Earth orbit.

[...]

[...]
Exposure to weightlessness—and possibly even to partial gravity—reduces bone density to osteoporotic levels after a few months and exposes astronauts to an increased risk of fractures.
We sought to identify key challenges for a crew on the surface of Mars or the Moon facing a severe surgical emergency such as a major trauma.

This is the purpose of intubation experiments in parabolic flights.

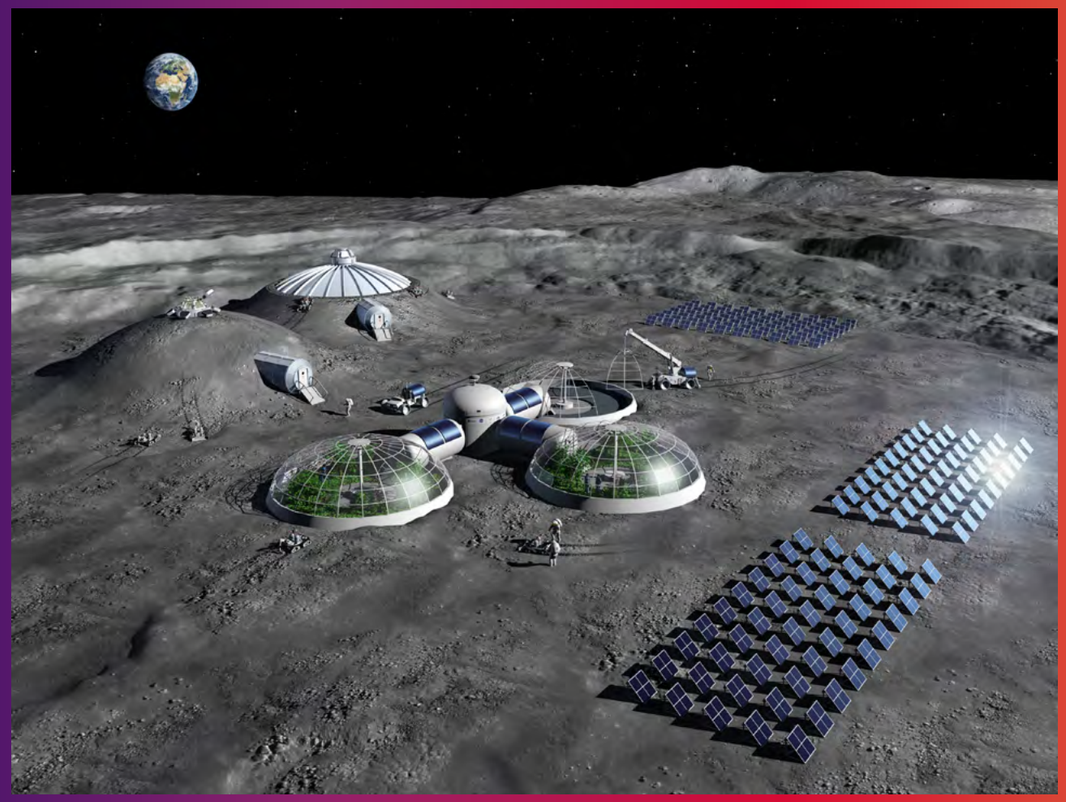

FIGURE
Artist's impression of a Moon Base concept. Solar arrays for energy generation, greenhouses for food production and habitats shielded with regolith.
© ESA - P. Carril

Emergency medicine

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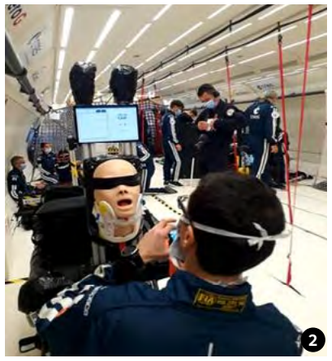
Head of Life Sciences, CNES

Emergency medicine is an active field of research at CNES, with its sights on future long-duration spaceflight missions (LDSM).
The goals are to extend medical capabilities in austere environments, to adapt medical procedures to microgravity and to define their scope and limits with regard to spaceflight constraints.

A good example is tracheal intubation, a specialized and invasive airway procedure used for respiratory support in critically ill patients. This technique secures oxygen supply to the lungs and protects the airway from gastric aspiration. Despite being a life-saving procedure and considered the gold standard in advanced airway management, performing intubation in less-than-optimal conditions is dangerous, such as in pre-hospital settings or with inexperienced operators.


1


2

FIGURES
1) Ice-pick intubation attempt in weightlessness (S. Thierry et al).
2) Modified Aitraq device attempt (R.Birnbaum et al.).

Defining the scope of this medical procedure in spaceflight conditions, especially under the constraint of weightlessness, has been tested in many medical simulations (underwater and parabolic flight studies). Previous results confirm that weightlessness impairs the safety of intubation by lowering the probability of first-pass success, thus delaying the first ventilation.

During parabolic flight campaigns, French medical research teams recently tested numerous intubation configurations. The rationale was to adapt recent terrestrial technical, material and conceptual updates, such as newly developed video-assisted devices, in weightlessness. These results help to refine the scope of this medical procedure in spaceflight conditions, as video-laryngoscopy raised success rates even among novices. Further research on this medical topic is under consideration by CNES and could benefit from cooperation with other scientific fields. Artificial intelligence, augmented reality and cognitive ergonomics show promise for maximizing safety and efficiency of **emergency medicine** in space environments.

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© videolaryngoscope versus McGrath
© videolaryngoscope in a classic approach. Publication under process

7 Materials sciences in space

Author:
T. BRET-DIBAT
Materials Science Programme Manager
Head of Science and Exploration Department

“CNES’s physical sciences programme offers microgravity conditions to French research laboratories. This programme covers airborne weightlessness campaigns, which provide 100 periods of 20 seconds of microgravity.

When longer periods of microgravity are required, after validation of the prototype we look for international opportunities to share our knowledge and access experiments in sounding rockets or on the ISS, most of the time through ESA.

CNES has also been developing some instruments with bilateral partners. The broad goal of physical science in microgravity is to understand the self-organization of matter during phase transitions. Microgravity simplifies problems by removing gravity from the equation, and suppresses the perturbing phenomena it induces such as convection, sedimentation or buoyancy. The fields covered by CNES include fluid physics, complex materials, biophysics, solidification of matter and combustion.

FLUIDICS

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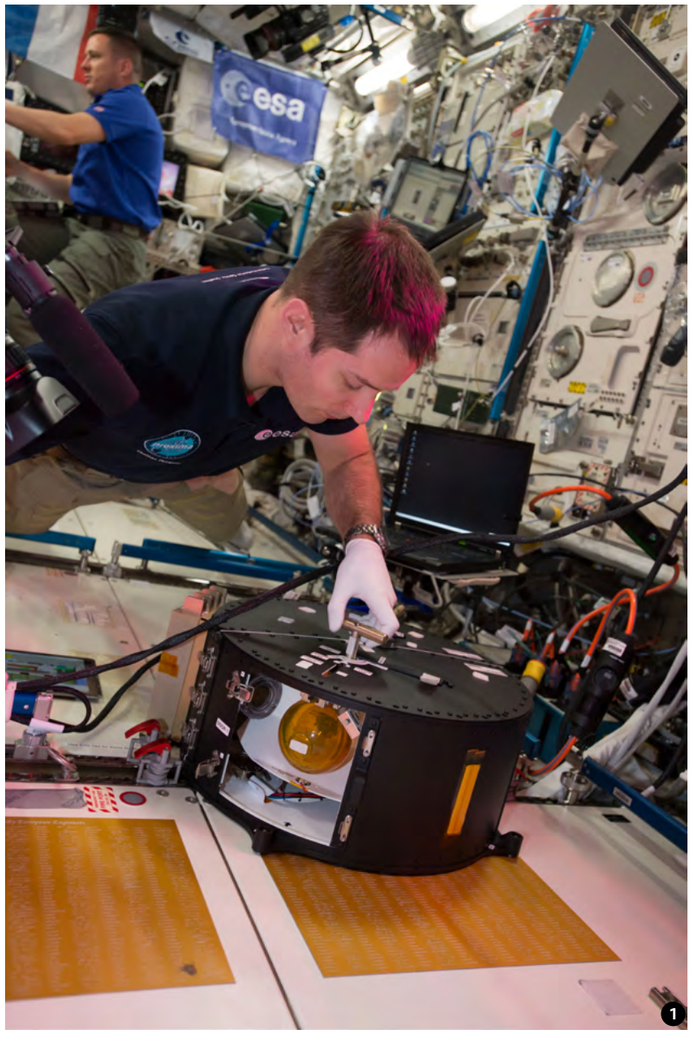
Materials Science Programme Manager / Head of Science and Exploration Department

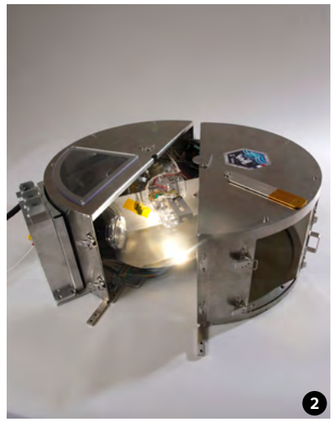
FLUIDICS is an instrument developed by CNES to study the behaviour of fluids subjected to mechanical excitation.

A transparent sphere containing liquid is shaken angularly. In microgravity, the liquid spreads by capillarity over the entire surface of the sphere, thus eliminating the edge effects inevitably encountered in a test pool on the ground. Cameras and liquid film height sensors record the movements of the free surface.

On the ISS, this experiment verified the theory of capillary wave turbulence for the first time. ESA used the instrument aboard the ISS until it reached the end of its life in summer 2023, in particular to simulate sloshing of propellants in the tanks of launchers or satellites.

CNES is currently studying a new instrument incorporating a linear exciter for larger spheres, to overcome angular excitation artefacts and improve research.





FIGURES

1) FLUIDICS.
© ESA/NASA Th Pesquet, 2021
2) The FLUIDICS experiment for the Proxima mission is prepared at CADMOS.
© CNES/Emmanuel Grimault, 2016

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Spontaneous generation of temperature fluctuations in turbulent flows
EPL 141 43002
https://doi: 10.1209/0295-5075/acb732

DECLIC

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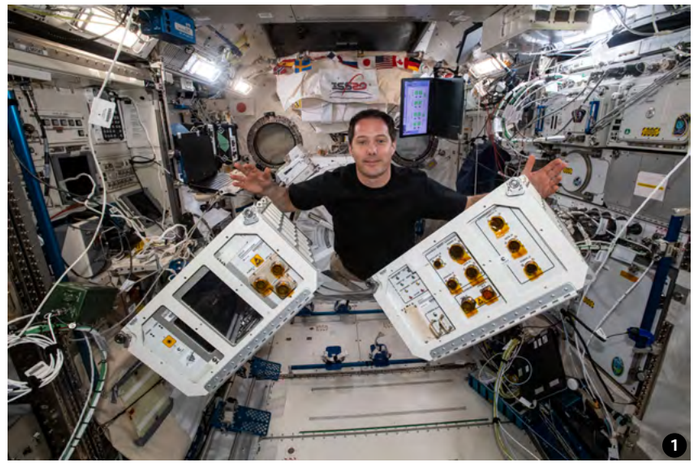
Materials Science Programme Manager / Head of Science and Exploration Department

DECLIC is a small physics laboratory for studying transparent materials, equipped with high-definition imaging and precise thermal regulation capabilities.

Developed by CNES in partnership with NASA, this instrument has been operating on the ISS since 2009 and is still in service today. French and U.S. laboratories are working together to study fluids at the critical point, the chemistry of supercritical water and solidification of transparent model materials. The original experiment inserts have been refurbished over time and have provided improved research results. A particularly recent notable result concerns interpenetration between grains and the solid/liquid interface during directed solidification.

CNES is currently studying a new instrument for research in the fields of the combustion of organic matter and the effects of turbulence on the nucleation of droplets, to gain a better understanding of the microphysics of clouds.



FIGURES

1) Expedition 65 Commander Thomas Pesquet of ESA (European Space Agency) gathers fluid physics and materials research hardware inside the International Space Station's Kibo laboratory module. Also called DECLIC, or Device for the Study of Critical Liquids and Crystallization, the science gear allows researchers to study ambient temperature critical point fluids, high temperature super-critical fluids, and the dynamics and morphology of the fronts that form as a liquid material solidifies.
© NASA/ESA
2) DECLIC installation.
© ESA/NASA Th.Pesquet, 2021
3) Teams at CADMOS receive data from the DECLIC fundamental physics mini-laboratory operating on the International Space Station.
© CNES/Emmanuel Grimault, 2010

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Cell invasion during competitive growth of polycrystalline solidification patterns
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https://doi.org/10.1038/s41467-023-37458-0

8 Fundamental physics in space

Author:
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Fundamental Physics Programme Manager

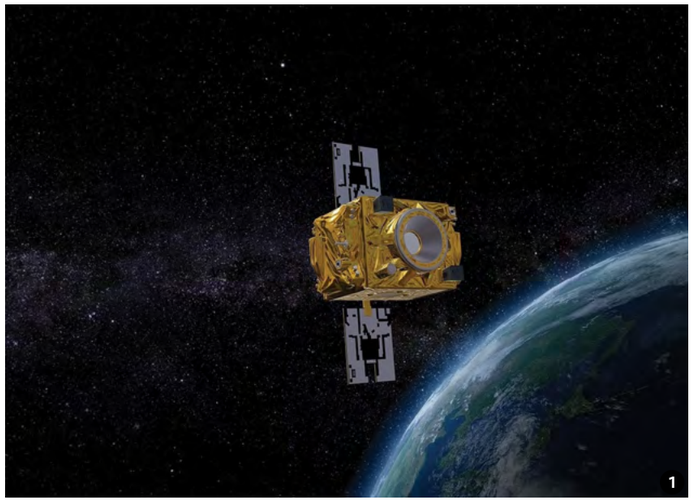
“Space and microgravity offer a unique laboratory for testing the physical laws that govern the universe. Far from Earth’s perturbing environment, fundamental physics experiments in space can measure the structure of space and time with unprecedented accuracy, yielding new insights into ground experiments.

As the French space agency, CNES is closely involved in fundamental physics in space and raising awareness among the French science community about how space missions can contribute to this field. Its programme is mainly focused on the way forward for reconciling gravity with quantum theories and describing the main elements of the universe at a large scale.

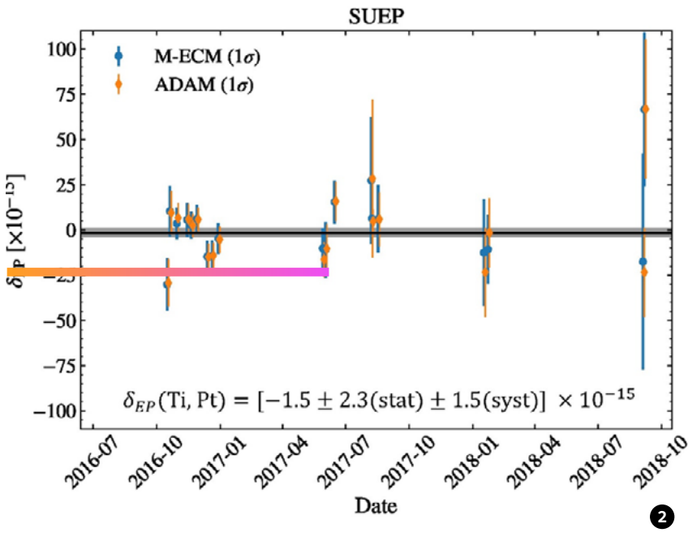
MICROSCOPE

Author:
M. BOUTELIER
Fundamental Physics Programme Manager

Launched in 2016, the CNES Microscope microsatellite (MICRO-Satellite à trainée Compensée pour l'Observation du Principe d'Equivalence) has tested the universality of free fall for the first time in space using an experiment 100 times more precise than anything on Earth.



The first scientific results of Microscope were published in Physical Review Letters (PRL) in December 2017, based on about 10% of the science data collected. After complete analysis of the full data set, representing ~1,900 orbits, the final results were published in Physical Review Letters in 2022 with more than 10 other publications on general quantum gravity.



These results confirm the validity of the equivalence principle with an uncertainty around 10^{-15} for platinum and titanium. To obtain these results, the scientific community—with support from CNES—succeeded in estimating and correcting very accurately systematic errors induced by temperature or the effects of satellite material cracks on the data.

FIGURES
1) Artist's view of the Microscope satellite.
© CNES/Virtual-IT, 2017
2) Source: Touboul et al.

REFERENCE
https://doi.org/10.1103/PhysRevLett.129.121102

ACES/PHARAO

Author:
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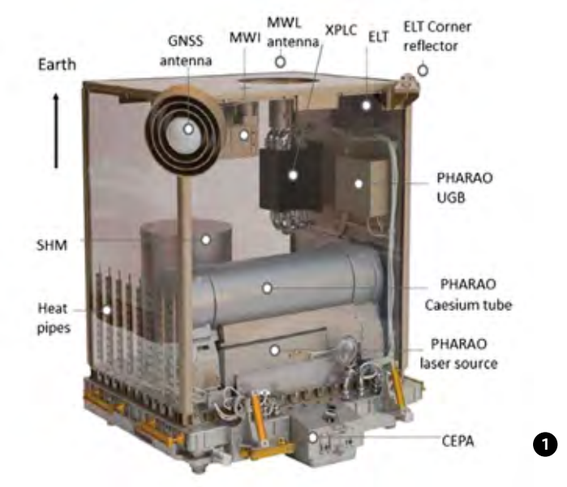
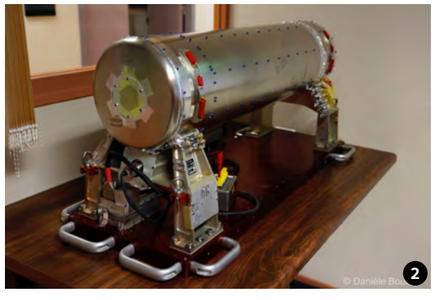
Proposed in 1997, the ACES experiment is a fundamental physics space mission with two atomic clocks on the International Space Station (ISS), a network of ultrastable clocks on the ground and space-to-ground time-transfer systems. The aim of the mission is to construct a time scale on board the ISS and compare it with time scales on the ground using the most accurate clocks in metrological institutes around the world. This will enable many experimental tests of fundamental physics, like the general relativity test of gravitational redshift or Lorentz invariance, with unprecedented accuracy.



A key element of the satellite payload is **PHARAO**, a cold-atom clock designed for microgravity, operating with laser-cooled caesium atoms. The frequency stability target in space is $10^{-13}\tau^{-1/2}$, where τ is the integration time, with an accuracy of 2.10^{-16}. While the flight model was fully tested and delivered to ESA by France under CNES supervision in 2014, the **ACES mission** is still pending completion of other subsystems, mainly the second atomic clock—a space hydrogen maser—and the microwave time-transfer system.

Since 2022, considerable progress has been made towards overcoming technical and quality obstacles. Three milestones have been set to measure and track project achievements. Two of them were successfully reached in summer 2023. A launch date with a SpaceX Falcon 9 is under consolidation and foreseen for the end of January 2025. All subsystems successfully passed integrated system tests at the beginning of 2024 and environmental tests are in preparation and scheduled for summer 2024.

Ten years after delivery to ESA, **PHARAO** is still sustaining the same level of performance and despite some concerns with the second onboard clock, most of the mission's science goals have been preserved.



FIGURES
1) Source: P.Laurent et al. / C.R.Physique16(2015)540–552
2) ACES
© CNES/Daniele Boucon, 2016
3) Artist's impression of PHARAO.
© CNES/ill./Jean Vouillon, 2005

LISA

Author:
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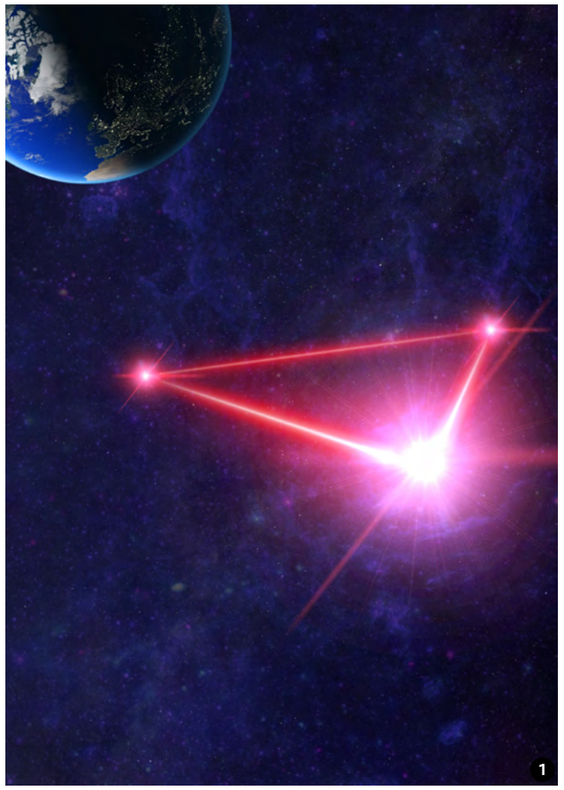
Fundamental Physics Programme Manager



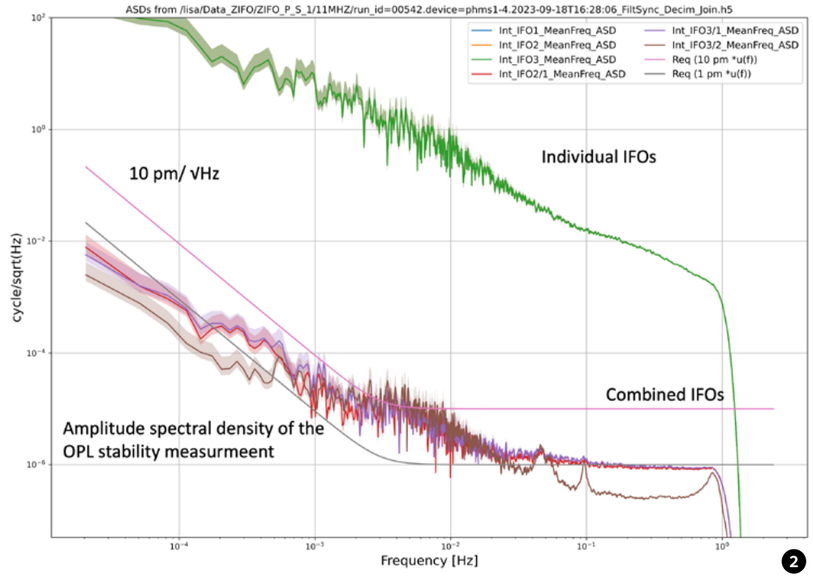
LISA is the third ESA large-class science mission dedicated to the gravitational universe, greatly enlarging the window opened by LIGO-VIRGO and paving the way to new physics. Gravitational waves can probe the early stages of the universe, before decoupling of light and matter and emission of the microwave background. The **LISA** space observatory will operate at low frequencies, from 10^{-4} to 10^{-1} Hz, and observe the whole sky as gravitational waves do not suffer from obscuration. It will be able to detect and study massive objects such as massive black holes, binary or in-spirals of stellar mass objects, thus testing space-time properties in the strong curvature regime.

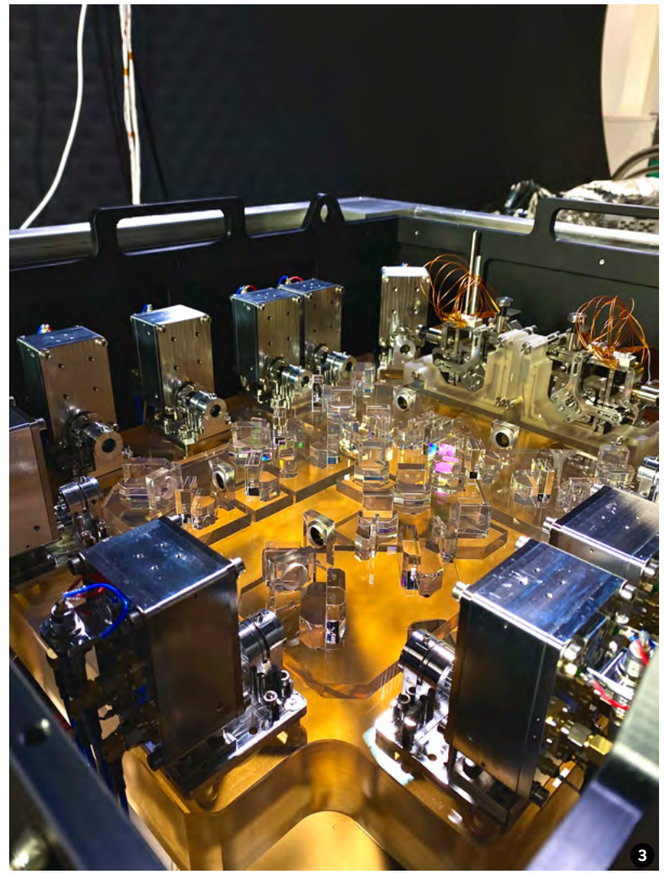
The **LISA space system** is a constellation of three identical satellites trailing the Earth, about 50 million kilometres behind it. The three satellites form an equilateral triangle and a giant optical interferometer, in which each arm is 2.5 million kilometres long. The satellites are linked in pairs by identical and synchronized laser beams to measure any relative movements between free-fall test masses inside each instrument. These test masses are in an environment isolated from external disturbances—solar wind, parasitic forces—in order to detect infinitesimal distortions in space-time. The expected level of sensitivity is a few picometres.

The mission is led by ESA, with NASA as junior partner and contributions from many member states to several onboard subsystems, data processing and, of course, science. France's contributions are focused on performance tests and data processing and are overseen by CNES, the national space agency. France will integrate and verify performance of the interferometric detection system that is the core of the instrument. It will also develop an optical test system that will be used at instrument level and is dedicated to measuring stray light, a key component in the instrument's overall performance. Finally, France is the lead contributor on the scientific data processing centre (DDPC) and is organizing its development with ten other European countries.

Over the last two years, France and CNES have developed technology demonstrators to gain expertise and prove the ability to fulfil their commitments, and in particular the feasibility of measuring optical path length with a stability of a few picometres.

From a programmatic standpoint, **LISA** was given the go-ahead at the meeting of ESA's Science Programme Committee on 25 January 2024. Phase B2 is now ongoing.





FIGURES

1) Front Cover Image Credits:
• Background: a composition of the centre of the Milky Way (custom composition of three different-wavelengths images) and a deep star map by NASA's scientific visualization studio.
• Earth: textures are from NASA blue marble, 3D rendering from Simon Barke.
• LISA constellation: Simon Barke.
2) Optical bench demonstrator used by France to demonstrate the ability to measure stability at picometre level.
© Courtesy M.Vincent, APC laboratory
3) Global performances of the zerodur interferometer developed for the LISA mission. This demonstrator shows the capability to measure stability better than 10 pm/sqrt(Hz).
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