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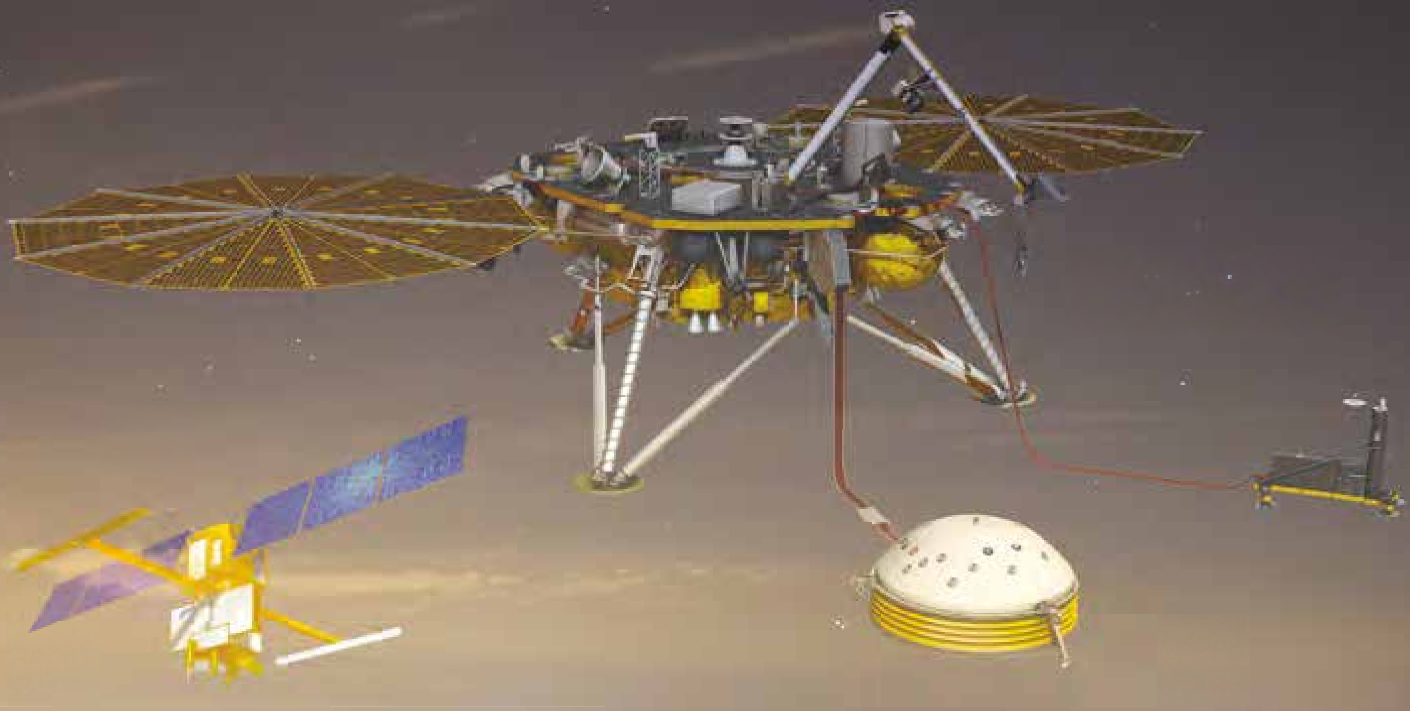

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WORLD COMMITTEE ON SPACE RESEARCH

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Kader Amsif
Benoît Boissin
Cécile Calleya
Selma Cherchali
Christophe Delaroche
Carole Deniel
Guillemette Gauquelin-Koch
Olivier La Marle
Amaury Larue de Tournemine
Mioara Mandea
Isabelle Petitbon
Francis Rocard
Pierre Tabary
Cécile Vignolles
Michel Viso

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TRANSLATION AND EDITING
Romain Dziegielinski

ICONOGRAPHY
Photon Laboratory:
Marie-Claire Fontebasso (CNES Diffusion)
Orianne Arnould (CNES Diffusion)

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Illustration of the InSight mission © NASA
Illustration of the SWOT satellite © CNES/DUCROS David, 2015

CONTENTS


Fig.1

AUTHOR
J.C. SOUYRIS,
Deputy Director, Innovation, Applications and Science
18 avenue Edouard Belin, 31401 Toulouse, France.

This report, drawn up by CNES in collaboration with the French space science community provides highlights on space sciences in France since the last edition of COSPAR report in 2016. It includes both an overview of current research programmes in Earth System, Space Science and Social Science and also a selection of remarkable scientific results obtained over this period. The activities follow the CNES Scientific Prospective Seminar, held in La Rochelle in 2014, the mid-term situation that was drawn up in 2017, and the preparation of the next seminar scheduled for 2019.

First of all, remember that among the missions assigned to CNES by the French government, the French space agency organises national research in the space sciences. It has no research laboratories of its own but works jointly with the French scientific community, especially through public research laboratories and organisations, which it provides with technical and financial support.

There are two sides to the French space programme: i) participation in programmes run by the European Space Agency, with CNES managing the French contribution to ESA, and ii) programmes carried out outside this framework, almost all of which are undertaken through bilateral or multilateral partnerships.

The last 2 years have been rich in programmatic decisions and noteworthy scientific results: CNES has been strongly involved in the space component of the Conferences Of Parties (COP) especially through the French-German MERLIN project and the on-going development of the MICROCARB mission. The deployment of the Spatial Climate Observatory will complete and catalyse all efforts in this area. The 2016-2017 period was also marked by the historic announcement of gravitational-wave detection by ground observatories which now offers the prospect of a new space observation window on the Universe. In the wake of GAIA which released its second star catalogue in April 2018, we are entering the era of high-volume data-driven scientific missions based on digital mass processing.

EARTH SYSTEM

In Earth Science, the space component of the Copernicus European programme has been implemented since the launch of the first SENTINEL missions. CNES is involved at different levels in this operational programme and provides data to national actors via the PEPS platform. JASON-3 is currently the altimetry reference mission of Copernicus. To organise this oceanographic altimetry mission in the long term, which is crucial in the context of monitoring global warming, the JASON-CS-A/SENTINEL-6A and JASON-CS-B/SENTINEL-6B satellites will be equipped with instruments comparable to JASON in order to ensure the continuity of measurements.

CNES supports the exploitation of a dozen missions, and in some cases the corresponding operations, most of which are part of an international collaboration. Moreover, the implementation of 4 data and services centres for space-based and in-situ data distribution and utilisation is almost complete. These data centres are set up by CNES in collaboration with other national research organisations. They operate as a network linked to the European structure.

With CNES' impulse and as an extension of the One Planet Summit held in Paris in December 2017, space agencies linked with international organisations, are preparing for the birth of the Space Climate Observatory which will unite the efforts of international agencies and institutions on this theme in order to provide studies and services solutions at both global and regional scale.

August 2017 saw the launch of the VENµS mission developed in collaboration with Israel. In the meantime, it demonstrated the strong potential of the fine temporal scale analysis for the monitoring of vegetation through its first results. The SWIM instrument on CFOSAT has been delivered to China and is now in the final integration phase. SWOT with NASA is in development. The IASI-NG programme with EUMETSAT will involve 3 identical instruments on the future METOP-SG platforms with both operational and research goals. As for ESA's Earth Explorer programme, the BIOMASS mission – proposed by the French community, and the FLEX mission (selected as the Earth Explorer 8) are also under development.

Several phase 0 and A studies are going forward with top-priority scientific issues. For example: TRISHNA, a thermal infrared Earth observation project currently under discussion with India; WIZA, a concept of large swath altimeter part of an operational system of high resolution measurement of the oceans and continental waters' topography (in collaboration with ESA); and finally, the continuation of SKIM concept studies, pre-selected in November 2017 by ESA within the Earth Explorer 9 programme. This French proposal refers to a novel wide-swath scanning multibeam Doppler radar altimeter to measure ocean-surface currents.

Continuing with the progress made by the CNES balloon programme, 2017 has been particularly fertile, with 2 major missions achieved: EUSO-BALLONS, and PILOT's second flight which made it possible to measure the polarised submillimetric emission of interstellar dust from our Galaxy. The STRATEOLE-2 mission's validation campaign will begin in November 2018.

SPACE SCIENCES AND EXPLORATION

In the field of Space Sciences and exploration, planetology has entered a new golden age. After the glorious epic of ROSETTA and its spectacular epilogue which paved the way for the exploration of small bodies, France is participating in an asteroid sample-return mission with the lander MASCOT launched in 2014 on board Japan's HAYABUSA-2 spacecraft which will reach Ryugu, its final destination between the 21 June and the 5 July 2018. The MMX mission to Phobos will share this ambition to return samples. Mars is still a top priority for the national community and the subject of several ongoing missions: MARS EXPRESS (ESA), NASA's CURIOSITY rover – the operations of the CHEMCAM and SAM instruments are planned from the Toulouse space centre – EXOMARS 2016, the TGO orbiter will begin its active operation phase while the 2 main French contributions of EXOMARS 2020, the MICROMEGA spectrometer and the WISDOM radar are in integration phase. As an extension of this passion for Mars, INSIGHT'S launch (NASA, May 2018), whose main instrument SEIS seismometer is French, arouses a high expectation; just like MARS2020 (NASA), CURIOSITY's successor which will carry the SUPERCAM camera. Over the past 2 years, the CASSINI operations ended but ESA's Large-class JUICE mission (JUpiter ICy moons) is under development with a strong involvment of France.

Milestones in Fundamental Physics in space include the cold-atom clock PHARAO which is awaiting launch to the International Space Station. The publication of MICROSCOPE's firsts results turned this incredible experiment into a global standard for the verification of the equivalence principle. After the success beyond expectation of LISA Pathfinder, ESA's selection of LISA as a L3 mission in June 2017 is a major decision for Europe and its member states. LISA's ambition is to observe gravitational waves from space.

In Solar and Plasma Physics, the exploitation of the SOHO and CLUSTER missions is ongoing while BEPICOLOMBO is almost ready to launch and SOLAR ORBITER is finalising its development. France contributes to the instruments of NASA's MMS mission which was launched in March 2015 and has begun delivering results. Finally, during summer 2018, the American PARKER SOLAR PROBE will begin its journey to the Sun. Its objective is to become the first spacecraft to enter the outer atmosphere of our star. CNES is supporting the participation of several French scientific laboratories.

In Astronomy-Astrophysics, after the success of PLANCK, the French and European cosmology community is expected to continue with EUCLID, under development by ESA. As for high energy, the Franco-Chinese mission SVOM is being developed and is to be launched in 2021. The French teams are also involved in ESA's future large X-ray observatory ATHENA and CNES will be responsible for the development of the spectral and temporal high resolution spectrometer XIFU. After the publication of its second catalogue in April 2018, GAIA data are being exploited. It is the source of unprecedented information on almost 2 billion stars in our galaxy! At last, CNES supports the French scientific contribution to ESA's exoplanet missions, CHEOPS and PLATO as well as the ARIEL mission which just has got selected as a M4 mission within the Cosmic Vision programme.

In November 2016, the French astronaut Thomas Pesquet began a 6-month mission aboard the ISS, within the framework of the PROXIMA mission. Besides, an aircraft from the CNES subsidiary Novespace allows the French and European scientific community to conduct experiments in microgravity during parabolic flight campaigns. There are many scientific themes involved such as neuroscience, the physics of granular materials and various technology experiments.

In Life Sciences, the experiments in development are the BION-M2 mission in collaboration with Russia for monitoring the blood pressure of mice, and the start of the CARDIOSPACE mission's successor elaborated in partnership with China. CNES also supports the MEDES Space Clinic and its dry immersion studies. In 2017, the second campaign of the Bed Rest "Cocktail" study began at MEDES, on the adaptation mechanisms to 60 days of simulated microgravity and the effects of a nutritional countermeasure.

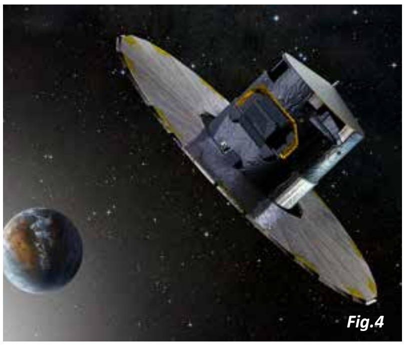
SOCIAL SCIENCE

On Social sciences, CNES continues its reflections for a better understanding of the impact of space activities on societal issues through a unified research programme in collaboration with French laboratories. The current dynamic is part of an opening to a wider variety of disciplines related to the social sciences and encouraging interdisciplinary approaches.

This fruitful period announces a fascinating 2019 Scientific Prospective Seminar. It is positioned at the crossroads of high-level ambitions in Universe Science, in Earth Science, in Condensed-matter Science, in Life Science, in exploration, in new technologies, and acceleration induced by next-generation processing (Big data, artificial intelligence, etc.) applied to ever denser data streams: the proximity of Science and of the digital world has never been so active or so promising!

Fig.2

Fig.3



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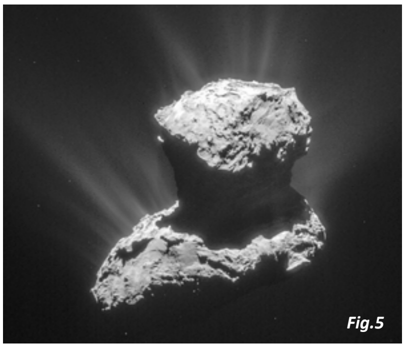

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Fig. 1: Jean-Claude SOUYRIS
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Fig. 2: « One Planet Summit » 11 December 2017. Space agencies worldwide propose the creation of a Space Climate Observatory
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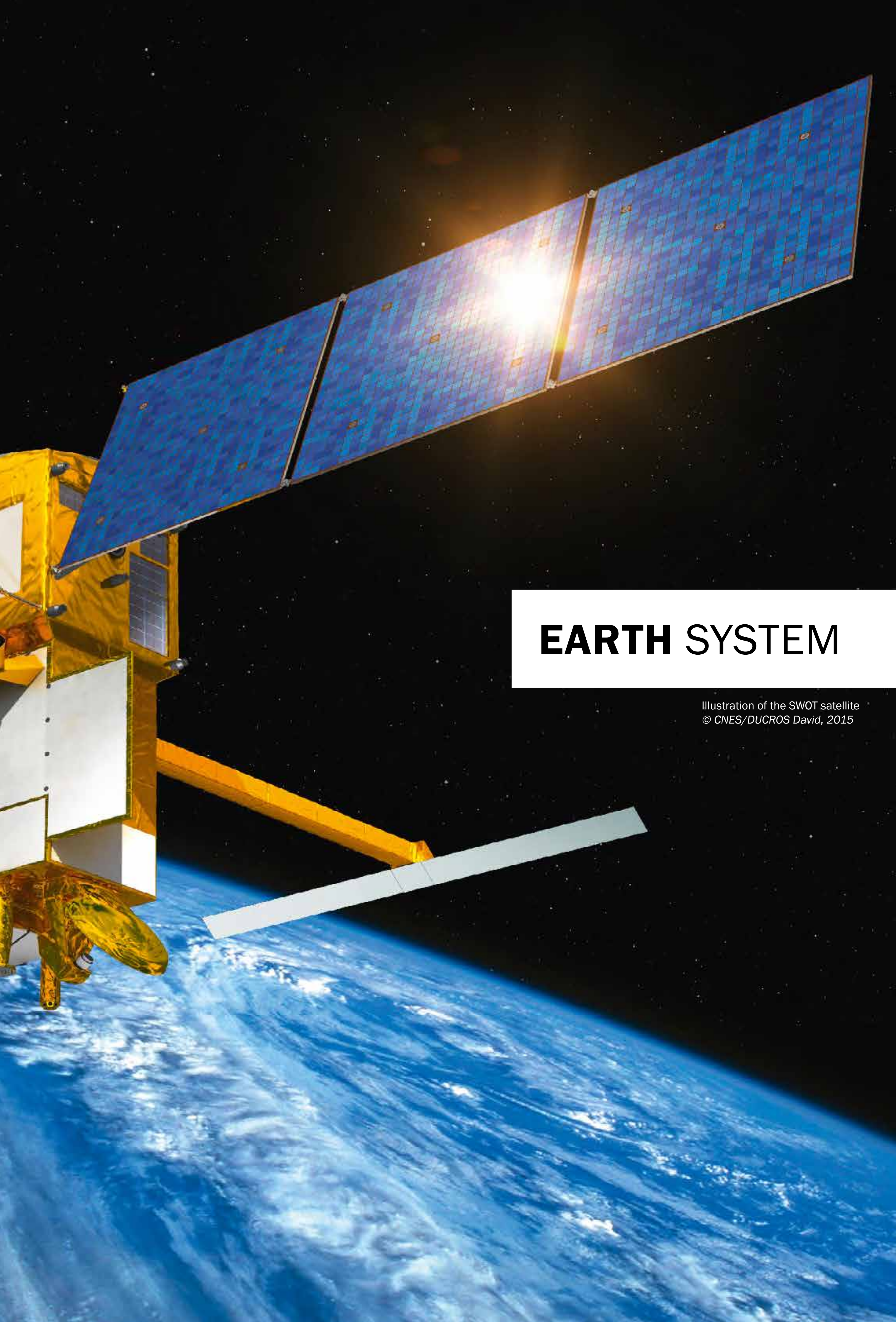
Fig. 3: Artist's view of the MERLIN satellite
© CNES/ill./DUCROS David, 2016

Fig. 4: Artist's view of the GAIA satellite
© ESA/DUCROS David, 2013

Fig. 5: Comet Churyumov-Gerasimenko taken by the ROSETTA probe on 25 March 2015 at a distance of 86,6 km from the centre of comet.*© ESA/ROSETTA/NAVCAM/, 2015*



EARTH SYSTEM

Illustration of the SWOT satellite
© CNES/DUCROS David, 2015

AUTHOR
Juliette Lambin,
Head of the Earth Observation Programme
CNES, 18 avenue Edouard Belin, 31401 Toulouse, France.

Earth – Environment – Climate

The CNES Earth Observation programme covers the full domain of Earth Sciences, from the centre up to the upper atmosphere, a broad range of scientific questions to better understand the Earth System at all temporal and spatial scales.Satellite observation is crucial in this domain, because of its capacity to monitor key Earth parameters at both local and global scale, with great precision and reliability of the measurement, and offering long-term, regular data in a timely and accessible way.

As recommended by the previous Scientific Prospective Seminar held in 2014 and stressed at the mid-term meeting before the 2019 seminar, CNES "Earth – Environment – Climate" programme is supporting Earth system science with a balance of innovative missions exploring new measurements, consolidation of operational programmes such as Copernicus or meteorological programmes, development of ever more innovative applications for operating missions as well as support to fundamental science.

CLIMATE CHANGE

The commitment of CNES towards addressing the environment and climate challenges that our planet faces, already at work through the preparation of COP 21 and 2015 Paris agreement, has been consolidated throughout 2016 and 2017.

At international level, CNES has organised successive meetings of space agencies to encourage and reinforce commitment on this matter and express their determination to give satellites a bigger role informing political decisions at successive COPs. In 2016, space agencies endorsed the New Delhi Declaration, stating that an inclusive global data set would help further global understanding and is a necessary step in establishing an international approach to estimating greenhouse gas emission changes for global use based on internationally accepted data. At COP22 in Marrakesh, space agencies stressed the impact of climate change on water resource management and the importance of past, current and future satellite observations in this domain.

Finally, on 11 December 2017, the Paris declaration "Towards a Space Climate Observatory" was approved by all European space agencies, as well as other countries including China, India, Russia, Mexico, Morocco and the United Arab Emirates. It calls for the creation of a Space Climate Observatory, to act as a hub between space agencies and the international scientific community, providing them with all the space data necessary for monitoring the health of our planet.

At national level, during the 2016-2017 period, CNES has put forward two emblematic missions targeting global monitoring of greenhouse gases fluxes, thanks to financial support of the French government's future investment plan (PIA).

In partnership with UKSA, MicroCarb project is now in phase C/D. Aimed at monitoring atmospheric CO_2 at a global scale, the satellite will be ready for launch in early 2021, giving access to CO_2 satellite data "made in Europe". Along with the preparation of scientific exploitation of the mission, partnerships are being set up with other space agencies in order to share expertise and calibration/validation techniques.

In April 2016, MERLIN satellite, developed through a French-German space cooperation received the green light. To be launched in 2023, Merlin is set *to make major progress in identifying sources and sinks of methane, which are still poorly understood. Methane is the second most potent greenhouse gas in the atmosphere, spreading rapidly and trapping 28 times more heat than carbon. To accomplish the mission's goals, the German space agency DLR is using an innovative LIDAR instrument that will fire laser pulses towards the Earth's surface to measure atmospheric methane concentration day and night, at all latitudes and in all seasons. CNES is supplying its Myriade-Evolutions spacecraft platform with funding from the French government's future investment plan (PIA).*

At European level, France strongly supported the ESA Climate Change Initiative, more than doubling its contribution. This integrated programme is dedicated to Essential Climate Variables (ECV) algorithm development in order to fulfil long-term climate monitoring needs. It is organised into specific projects for each ECV, with a strong involvement of the science user community.

COPERNICUS

As the European Copernicus constellation of SENTINELS progressively began operations from 2014 to 2018, its impact on Earth system science has proven extraordinary. Easy, free and open access to SAR and optical imagery, with a global coverage and systematic revisit has allowed new perspectives for science studies. Through CNES annual call for research proposal, we have witnessed the thriving development of new applications or field of research. In this case, the innovation is not so much about exploring new observables – as SENTINELS are operational missions built on the legacy of previous missions such as Spot and Envisat, but about

Fig.2

transforming the massive amount of data into information at various space and time scales, adding new dimensions to our way of sensing the Earth.

Copernicus missions SENTINEL-3A (launched in February 2016), SENTINEL-3B (launched in April 2018), along with the launch of JASON-3 (in January 2016), put up a constellation of up to 7 altimeters flying at the same time for the strong oceanography community in France. This is almost beyond expectation and it paves the way for more and more progress in our understanding of ocean dynamics and ecosystem. CNES participates in this transition towards operational oceanography by providing support to JASON-3, SENTINEL-3 and the future SENTINEL-6 which will take over from the TOPEX/JASON series.

In the meantime, we are also preparing a bright future for the altimetry community. SWOT mission is now in full development phase. The final authorisation for phase C/D was given by NASA, CNES, CSA and UKSA on 7 July 2016. The international science team co-chaired by 4 lead scientists, 2 French, 2 from the US, one oceanographer and one hydrologist for each, is actively preparing for the exploitation. In addition, a “SWOT-aval” plan is set up to foster downstream applications.

In November 2017, an implementation agreement on hydrology from space has been signed between CICOS (International Commission for the Congo-Oubangui-Sangha basin) and 7 public or private French institutions in the wake of a COP-22 initiative proposed in Marrakech a year earlier. This agreement sets up a pilot programme using satellite data to support strategic orientation in the management of this large trans-boundary hydrology basin. One case of study that particularly crystallises the concerns surrounding climate change and biodiversity is the Congo River and its 204 million hectares of tropical rainforest and 25 000 kilometres of waterways.

EARTH SYSTEM DATA CENTRES

From Earth Science to downstream applications, access to the right data is key. To this end, CNES, along with 30 other French research institutions – that is to say all of Earth-science-related institutions- has initiated a project of “Earth System Research Infrastructure”. This project federated the already existing thematic data centres: Theia for land surfaces, Odatis for ocean, Aeris for atmosphere and Form@ter for solid Earth. Both satellite and ground based data are accessible, and new products merging data from different sources can be made available.

In terms of missions in exploitation, extension of missions beyond their nominal lifetime are subject to review, and their scientific outcome as well as technical feasibility are taken into account. During the summer 2017 mission extension review process, 5 missions were granted a two-year extension: CALIPSO (NASA/CNES, launched in 2006 for the monitoring of clouds an aerosols), JASON-2 (CNES/NASA/EUMETSAT/NOAA, launched in 2008, reference altimetry mission), SMOS (ESA/CNES, launched in 2009, salinity and soil moisture), SARAL (ISRO-CNES, launched in 2013, Ka-band altimetry mission), SWARM (ESA/CNES, launched in 2013, magnetic field measurement).

BALLOONS: STRATEOLE-2 READY TO GO

CNES’s expertise in scientific ballooning is world-renowned. The international STRATEOLE-2 project, which received authorisation in 2016, plans 3 flight campaigns in 2018, 2020 and 2023 with a flotilla of up to 20 stratospheric superpressure balloons that will stay aloft for several months to measure meteorology parameters (temperature, pressure, wind and humidity), carbon gases and ozone, ascending radiative flux and cloud content. They will fly 18-20 kilometres above the intertropical zone to acquire unprecedented records of stratosphere-troposphere exchange processes, which play a critical role in global climate. These data will be especially used to validate meteorological and climate models.

INTERNATIONAL COOPERATION

International cooperation is at the heart of our Earth observation programme.

On 1 August 2017, the VENµS satellite was launched: this joint programme of CNES and Israel Space Agency (ISA) is now observing with a high revisit period specific areas of the planet, targeting applications such as vegetation changes in particular. “Application-ready products” are made available through the Theia land data centre.

Collaboration with China is also reaching a milestone with the CFOSAT project approaching the launch date: in August 2017, the wave-monitoring instrument SWIM, developed by France, was sent to China to be launched with its Chinese wind-monitoring counterpart. Launch is expected in late 2018, providing full sea-state characterisation for marine meteorology and climate studies.

With India the cooperation is now fully mature, as both MEGHA-TROPIQUES and SARAL are still in operations beyond their nominal lifetime. We are now preparing the next generation of ISRO-CNES cooperation, and this time the focus will be on water and resources management with the TRISHNA mission study,

featuring a high-resolution thermal infrared imager.

Closer to us, the successful collaboration with EUMETSAT continues. After the IASI series on METOP, whose contribution to the understanding of our atmosphere is of major importance, CNES is developing IASI-NG which is to be integrated in the future generation of polar meteorological satellites METOP-NG.

KEY SCIENCE RESULTS IN 2016-2017

Only a small sample of these results will be highlighted in the following pages, but science achievements in Earth system space sciences have been following the growth of the user community both in numbers and in excellence. For 2 days, in March 2017, the second "Colloque de restitution du TOSCA" has taken place in Paris, offering an overview of the great science that has been supported by CNES in the recent years. Half-way between 2 Scientific Prospective Seminars, this event was also the opportunity of demonstrating the strong connection between CNES and the research community. Presentations are still available on the conference web site www.tosca2017.fr.

Fig. 1: Juliette Lambin *© CNES/JALBY Pierre, 2016*

Fig. 2: The SWIM instrument of the CFOSat satellite *© CNES/GRIMAULT Emmanuel, 2017*

Fig. 3: Preparing for the flight of the gondola CLIMAT *© CNES/OMP/IRAP/UT3/CNRS/ Sebastien CHASTANET, 2017*

Fig.3

Solid Earth perceived by Form@ter and SENTINEL satellites

The study of the Solid Earth's system is particularly complicated due to the huge spatio-temporal variability of its processes: from the centimetre (fault) to the tens of thousands of kilometres, and from the second (earthquakes) to the millions of years (plate tectonics). A part of the geodynamic processes is studied via satellite data obtained through the Copernicus[1] programme, coordinated by the European Commission.

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SENTINEL-1

SENTINEL-1 is a constellation of 2 satellites with the main objectives of monitoring land and ocean, and ensuring the continuity of the C-band SAR data after the end of the ERS-2 and ENVISAT missions. To this end, satellites carry a C-SAR sensor, which offers medium and high-resolution imaging, with day-and-night capabilities and a reduced repeat cycle. The C-SAR is capable of detecting terrain movements which makes it useful for monitoring geodynamical processes such as volcanoes, seismic activities, and active faults.

PEPS

The CNES' PEPS (Plateforme d'Exploitation des Produits SENTINEL) is the French platform providing access to the products of the SENTINEL S1A and S1B, S2A and S2B, S3A and S3B satellites of the Copernicus programme. Satellite products are generated by ESA, which provides technical coordination of the space component, and are redistributed free of charge by the PEPS platform. Only the products of Level 1, and in some cases of Level 2, are concerned.

FORM@TER

Since 2012, a reflection has been carried out on structuring the French Solid Earth community around a data and services centre. The orientation of the data centre and services ForM@Ter (Forme et Mouvements de la Terre)[2] is driven by a common need to centralise access to data, software resources, and skills that allow access to the observation of the shape of the surface and its kinematics. There is therefore a large interest in several scientific themes of the Solid Earth. There is currently an unprecedented volume of data. To exploit it to the best benefit of research and society, the ForM@Ter is facing the challenges of processing, archiving and making these data available to a greater number of users. This requires the creation of new means of exchange, reflections and collaborative research. ForM@Ter is addressed as a priority to the French scientific community, but does not discard the possibility of serving other user communities (international scientific communities, public policy actors, private sector, education and training, etc.).

SCIENTIFIC PAYLOAD

MISSIONS	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
SENTINEL-1	Land and ocean monitoring via C-band SAR	ISTerre, IPGP, IPGS, OPGC
PLEIADES	The 2 Pleiades satellites have been observing and mapping the Earth's surface at a resolution of only 70 cm every day since December 2011	IPGP, ISTerre, OPGC
GRACE, GRACE-FO, GOCE / BGI	Gravity missions BGI – collecting, validating and redistributing gravimetric data acquired on the surface of the globe	IPGP, GET, GM, GRGS
GNSS /IGS	IGS - based on a global network of receptors	IGN, IPGP, GET, IPGS
DORIS / IDS	Doppler Orbitography and Radiopositionning Integrated by Satellite – French system to ensure a precise orbitography and localisation IDS - International DORIS Service	IGN, IPGP, GRGS

SCIENTIFIC HIGHLIGHTS

The first objective of Form@Ter focuses on surface deformation from SAR and optical imagery data. The associated services are implemented considering the needs expressed by the French scientific community to support the use of huge data volumes like those provided by the SENTINEL missions.

Detailed knowledge of the present-day surface deformation provides a better understanding of the deformation processes affecting the Earth's crust. A recent example shows how radar interferometry offers the possibility of establishing a complete and homogeneous mapping of surface deformations throughout the island of Taiwan thanks to 4 satellites: ALOS-1 (2007-2011), ALOS-2 (since 2015) and SENTINEL-1 A and B (since the end of 2014). To this end, the latest interferometric developments offered by the NSBAS processing chain developed at ISTerre[3] are used. These data are calibrated using the available GPS and leveling measurements. Carrying out this mapping and the associated time series of displacements is a prerequisite and indispensable step in answering several key scientific questions in Taiwan mainly related to the seismic cycle. An example of SENTINEL-1 differential interferogram is given in Fig. 1, showing the co-seismic movements associated with the Meinong earthquake (Mw = 6.3) that reach more than 10 cm vertically.

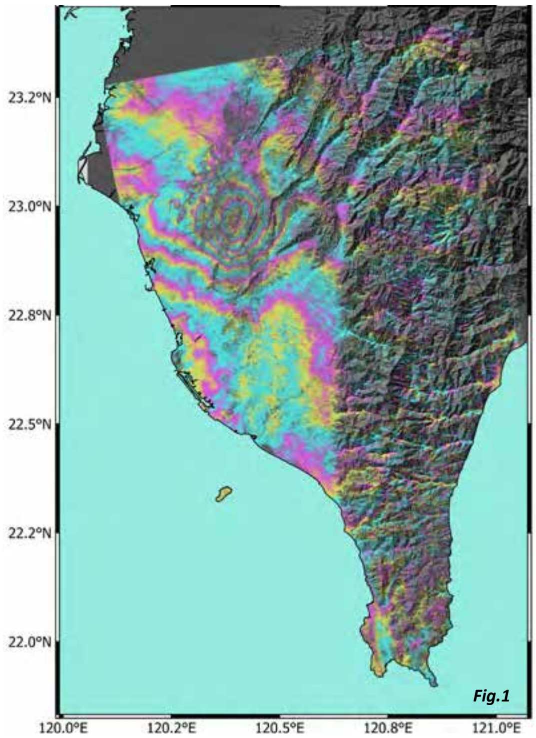

Fig.1

Another example is linked to the monitoring of the crustal deformations on a band of 1100km long by 450km wide along the Mexican subduction over the period 2014-2017 by coupling the measurements of permanent GPS networks and satellite radar interferometry using the SAR data from the new SENTINEL-1 satellite. The main objectives are to measure the surface deformations caused by slow earthquakes, to analyse them and to deduce the spatial and temporal evolution of the slip on the subduction interface. SENTINEL-1 systematic acquisition strategy is crucial to get homogeneous results for such a large area. The improvement of SENTINEL-1 revisits time with respect to previous mission is also crucial to achieve the objective of characterising the spatial variations of interseismic loading and the relation between slow events and seismicity. The launch of the SENTINEL-1B in April 2016, makes it possible to obtain 12-day interferograms over the Mexican subduction, which makes a significant improvement in the quality of interferograms in areas where the phase coherence is rapidly lost (Fig. 2).

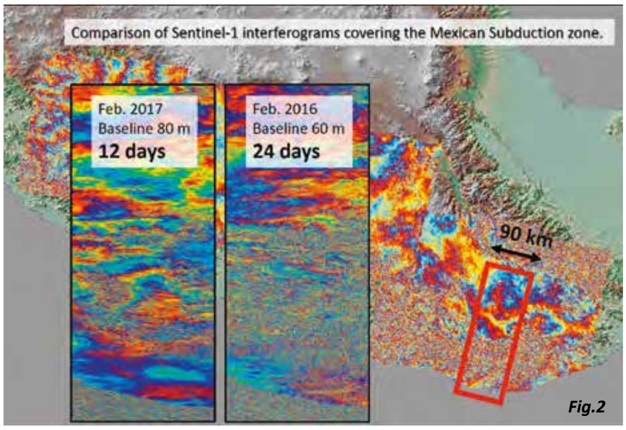

Fig.2

MISSION STATUS

Our understanding of the seismic cycle, in particular of subduction areas, has a strong implication on the estimation of seismic hazard, but also in terms of seismic risk. The same is true for volcanic areas and active faults.

The examples above underline the need to monitor the ground deformations. ForM@Ter currently develops the Ground Deformation Monitoring (GDM) service dedicated to the scientific and private users to facilitate the exploitation of radar and optical data for ground motion monitoring applications. To this end, it will provide a national cooperative platform with a unified access to relevant space based imagery and products (meta-catalogue accessing) to facilitate the access to data, tools, and qualified products for non-expert users.

GDM will provide a storage facility of SENTINEL 1-2-3 products, a catalogue containing the data and products available. Additional such as search, retrieval, computing will be hosted at HPC facilities. The necessary platform will be available for different needs, including massive data processing applications, thematic computational chains, displacements data quality evaluation tools. A user interface will be implemented on the ForM@Ter website. It will then be possible to access to the catalogue and query remote catalogues such as the PEPS catalogue. From this interface, it will be possible to download data, access and use processing tools, make thematic and intermediary products. It will also be possible to use or contribute to web services for data/product visualisation and metadata.

Fig. 1: SENTINEL-1differential interferogram (02/02/2016-02/14/2016) showing the co-seismic movements associated with the Meinong earthquake (Mw = 6.3, 05/02/2016) that reach more than 10 cm vertically (from Fruneau *et al.*, 2017).

Fig. 2: Comparison of 12 days and 24 days SENTINEL-1 differential interferograms with similar baseline in the Mexican subduction zone showing the impact of the improvement of the SENTINEL-1 revisit time on the quality of the interferograms (from Pathier *et al.*, 2017).

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1. http://www.copernicus.eu/ ; 2. http://poleterresolide.fr/ ; 3. https://www.isterre.fr/

AUTHOR
E. Pathier
ISTerre (Institute for Earth Sciences), CNRS UMR 5275, University Grenoble Alpes, CS 40700, 38058 Grenoble Cedex 9, France

Slow earthquakes and seismicity in the mexican subduction: contribution from space geodesy

Earthquakes and slow slip events (SSE) are 2 processes occurring in a subduction zone, where they episodically accommodate tectonic plate convergence. Understanding their interactions can have a significant impact on seismic hazard estimation. GPS and space-borne SAR interferometry techniques are used in the Mexican subduction to understand these interactions. Results shows that a SSE can trigger an earthquake. SENTINEL-1 InSAR will contribute to analyse the 2017 last SSE and earthquake sequence.

Our understanding of the earthquake cycle in subduction zones have strong implications on seismic hazard assessment. Subduction zones are the place of the world's largest earthquakes, which can be very destructive especially when causing large tsunami. Away from tectonic plate's boundaries like subduction zones, tectonic plates move rigidly in relation to the others at steady state, with typical values of a few cm/year. However, at subduction boundaries, the plate convergence is far more irregular in space and in time. Earthquakes and slow slip events (SSE) also called slow earthquakes, are 2 major processes occurring on subduction interface between 2 plates that can episodically accommodate tectonic plate convergence.

Studying interactions between SSE and earthquakes is not easy because the recurrence time of those events can be long, and because SSE are essentially aseismic slips and consequently cannot be monitored through classical seismology. In complement to advanced analysis of low-level seismicity (like tremors or low frequency earthquakes), space geodesy combining GPS continuous records of permanent network and SAR interferometry (InSAR) techniques can be used to study those interactions.

The Mexican subduction zone, where the Coco Plate is subducting below the North American Plate, is a favourable study area to observe such interactions because subduction earthquakes are quite frequent and large slow slip events are occurring regularly in some places of this 1500 km-long subduction zone. For instance, in the Guerrero region, SSE amongst the largest recorded worldwide (with slip amount equivalent to magnitude 7 earthquake) occur with a periodicity of 3-4 years. Furthermore, because of the relatively flat geometry of the subduction interface, those SSE are producing on-land surface displacement of several centimetres, large enough to be recorded by continuous GPS or InSAR.

The CNES is supporting a project from a French Team at ISTerre (Institute for Earth Sciences of Univ. Grenoble Alpes, CNRS and IRD) studying the earthquake cycle in the Mexican subduction zone using space geodesy, in collaboration with Mexican colleagues from the Instituto de geofisica at UNAM.

The project aims to monitor the entire Mexican subduction over the period 2014-2019, using the permanent Mexican GPS network and SENTINEL-1 and ALOS-2 satellite for InSAR. The main objectives are: a) to model the spatial and temporal evolution of the slip on the subduction interface of the largest SSE from surface displacement measured by space geodesy, b) to look for interactions of the SSE with the seismicity (earthquake, non-volcanic tremors, or low frequency earthquakes), c) to map the spatial variation of the tectonic elastic loading for periods in-between significant earthquakes or SSE, and investigate its relation with them.

In 2014, a large SSE occurred in the Guerrero area, which started in February 2014 and lasted until December 2014. Two months after the beginning of the SSE, the Papanoa earthquake (Mw=7.3) occurred nearby on the subduction interface. Using data from the Mexican permanent GPS network (SENTINEL-1 and ALOS-2 satellites were not yet launched at that time), Radiguet *et al.* (2016) [1] have reconstructed the SSE cumulative slip. It turns out that the place where the earthquake rupture started was just in between the SSE slip area and the rupture area of the earthquake. Furthermore, they show that the earthquake ruptured in the upper part of the subduction interface where the SSE did not propagate (Fig. 1a). This spatial and temporal proximity was suggesting that the Papanoa Earthquake has been triggered by the SSE. Radiguet *et al.* were able to confirm that by computing the Coulomb stress change associated to the SSE in the hypocenter area, and showing that the SSE stress change have helped trigger the earthquake (Fig. 1b).

In addition to the large SSE as those of the Guerrero area, smaller SSE occurred on the subduction interface, but are more difficult to detect because they have shorter duration (3 to 40 days) and because they cause surface displacements that are hidden within the noise of individual GPS station records. New methodological developments in GPS time series analysis have been proposed by Rousset *et al.* (2017) [2] to detect them. The idea is to use synthetic models of time series of surface displacement for small slip event that can be computed for every point of the subduction interface and then to correlate the synthetics with the time series of all the GPS stations. By combining the correlation for several stations, one can significantly enhance the detection threshold of SSE in comparison with the analysis of individual time series. By applying their method to the Guerrero area, Rousset *et al.* were able to detect new events not identified before. Those events show a good temporal correlation with the peak of activity of low frequency earthquake, which gives an independent validation of the method.

In 2017, a new significant large SSE occurred in the Guerrero area from May to November. Interestingly the 2017 event was concomitant with a remarkable earthquake sequence in the Mexican subduction zone: the 8 September 2017 (Mw=8.1) earthquake off the coast of the Chiapas region, followed 2 weeks after by the 19 September 2017 (Mw=7.1) earthquake in the Puebla region nearby Mexico City, and the 16 February 2018 (Mw=7.2) earthquake in the Oaxaca region. The project team is currently analysing all these events using GPS and SENTINEL-1 and ALOS-2 InSAR data (Fig. 2), and will investigate the possible interactions between them.

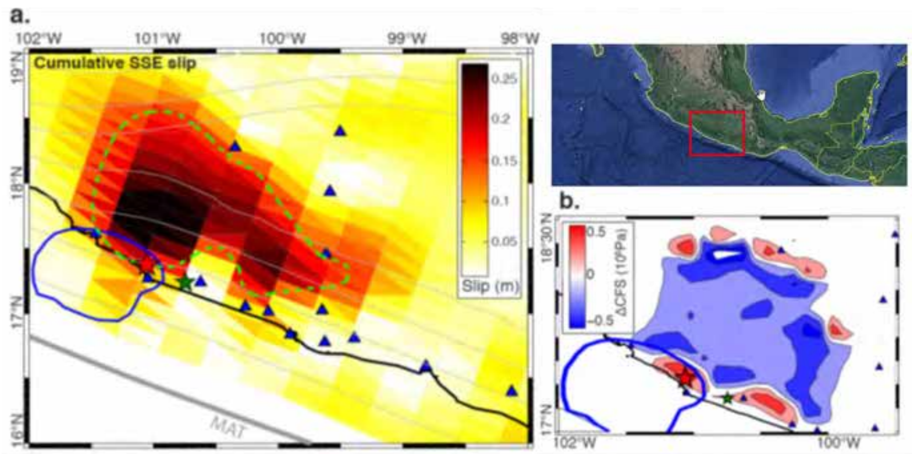

Fig.1

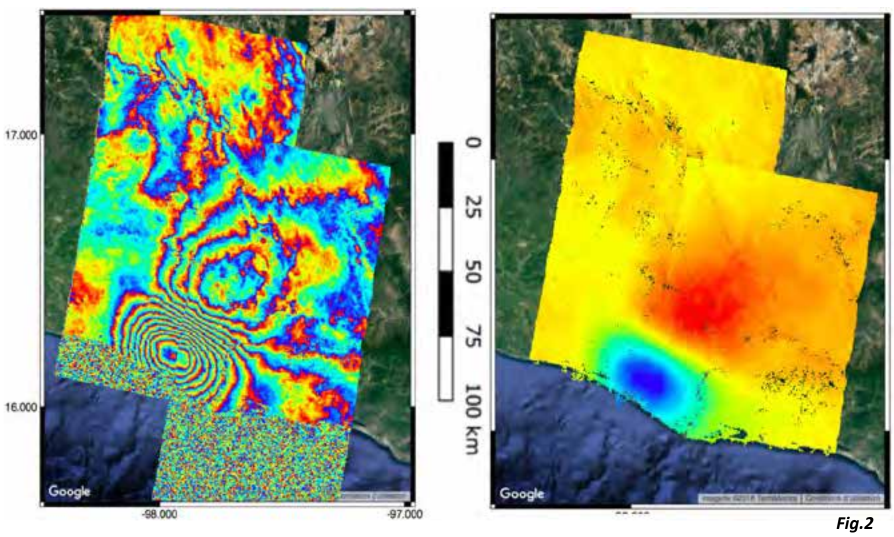

Fig.2

Fig. 1: Triggering of the Papanoa Earthquake (blue line for surface rupture and red star for its initiation point) by the 2014 slow slip event (green dashed line). a) slip distribution of the SSE. b) Coulomb Stress Change of the SSE promoting (red color) earthquake on the subduction interface. (from Radiguet, *et al.* 2017).

Fig. 2: InSAR measurement of the surface displacements due to the 16 February 2018 (Mw 7.1) earthquake in the Oaxaca region of Mexico, captured by 2 tracks of SENTINEL-1. Left: interferogram. Right: unwrapped interferogram showing the coseismic surface displacement (blue 30 cm toward the satellite, red 10 cm away from satellite). © *Louise Maubant (ISTerre).*

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AUTHOR
B. Langlais[1], N. Gillet[2], J.-M. Léger[3], E. Thébault[1]
1 LPG (Laboratory of Planetology and Geodynamics), CNRS UMR 6112, University Nantes, 44322 Nantes, Cedex 3, France
2 ISTerre (Institute for Earth Sciences), CNRS UMR 5275, University Grenoble Alpes, CS 40700, 38058 Grenoble Cedex 9, France
3 CEA/Leti, (Institute for Electronicws and Information Technologies), 17 avenue des Martyrs, 38054 Grenoble, Cedex 9, France

Results of the SWARM magnetic field mission after the first 4 years, a French point of view

The SWARM satellite constellation was launched in November 2013. This mission is the result of the collaboration of several research institutions with national space agencies and the European Space Agency. SWARM consists of 3 identical satellites which are dedicated to the study of the sources and dynamics of the Earth's magnetic field. In this report we review the French contribution to that project, including the first-time flown absolute scalar magnetometer with a vector field mode.

The SWARM mission is the 5th Earth Explorer of ESA. It consists of a constellation of 3 identical satellites in near polar orbit. Two of them (A and C) fly side-by-side with a 1.4° longitudinal separation at about 460 km altitude, and the third one (B) flies about 55 km higher. The local time separation between the lowest pair and the highest satellite progressively evolved, to reach 6 h (or 90°) after 3 years. Among other parameters, the satellites monitor the magnetic field thanks to the combination of several instruments. These are the Vector Fluxgate Magnetometer (VFM), co-mounted with a Star Tracker at the tip of a boom, and the Absolute Scalar Magnetometer (ASM). The latter provides very accurate and stable 1 Hz absolute scalar measurements for calibration and scientific purposes. Each suite of instrument is duplicated for redundancy.

The SWARM mission results from the fruitful collaboration of several institutions. CNES in particular was in charge of providing the ASM developed by the CEA-Leti with the scientific support of IPGP [1, 2]. This new generation instrument is based on the atomic spectroscopy of Helium 4. The novelty lies in the use of 3 orthogonal coils which allows a simultaneous estimate of the projections of the measured field along the 3 directions on top of the total field determination. The performances field model built using only those measurements by the ASM instrument while working in a burst mode [3, 4].

The primary scientific objective of SWARM is related to the characterisation, description and understanding of the Earth's magnetic field and of its temporal variability. The last generation of IGRF models, valid for the time period 2015-2020, directly benefited from the SWARM measurements. In order to ensure the success of the mission, ESA has put forward several dedicated data processing chains, to provide the scientific community with scientific products and outputs of the mission. Researchers at French institutions are responsible for several of them. One is related to the ionospheric field [6, 7], a second one to the lithospheric field [8] (Fig. 1). The objective of these chains is to deliver updates of the scientific models on a regular basis, so that other scientists can use them for their own research.

Some applications of these chains include for instance the first global map of the secular variation measured at constant spacecraft locations, using a virtual observatory scheme [9, 10] (Fig. 2). In this scheme, magnetic field measurements acquired within a limited volume at spacecraft altitude are reduced to a common location through an equivalent source dipole inversion. This allows to reconstruct time series of the temporal evolution of the field, which can be compared to similar series derived from ground-based observatories.

Another example lies in the determination of the electrical conductivity of the Earth mantle using SWARM measurements only. The magnetic signature of the mantle can only be studied provided that other contributions have been identified and subtracted from the measurements. For instance, using the first 14 months of the mission, a 1D conductivity profile of the mantle was estimated, using a Bayesian approach for periods ranging from 2 to 256 days [11]. Results can be interpreted in terms of mantle temperature, which show that the temperature gradient in the lower mantle is close to the adiabatic.

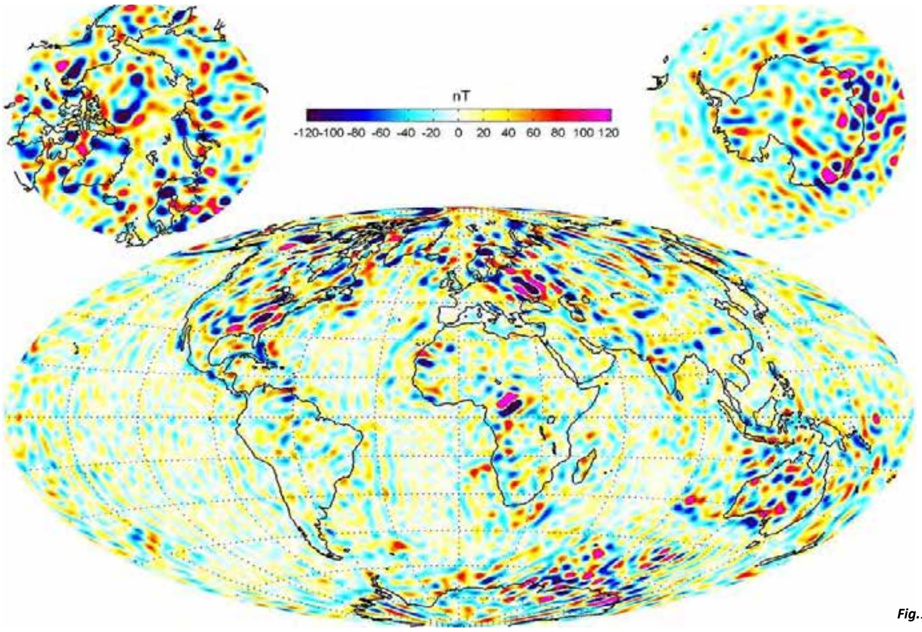

Fig.1

Fig. 1: Model of the radial vector component (the Earth's surface) of the crustal field, between spherical harmonics degrees 16 and 80. Reproduced from [8].

Fig. 2: Temporal variation of the eastward horizontal component of the geomagnetic field, reconstructed from SWARM measurements and estimated at virtual observatories locations. Reproduced from [10].

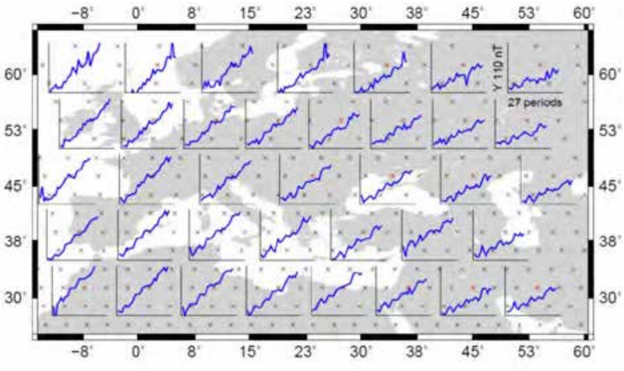

Fig.2

If one goes deeper, it is also possible to derive critical properties of the dynamo processes thanks to the improved quality of the derived geomagnetic field models. Indeed, the SWARM mission comes after more than a decade of spacecraft measurements, which make it now possible to study the temporal evolution of the dynamo. By complementing the information contained in magnetic data with statistical constraints derived from geodynamo numerical simulations, in a data assimilation framework, one retrieves a planetary scale westward gyre at the core surface [12]. Direct inversion from satellite data reveal intense flow acceleration over the past 15 years: an Eastward shift of the meridional circulation around 90E, and the birth of an Eastward flow below the Western equatorial Pacific [13]. We currently lack a physical understanding of such phenomena.

With a little more of 4 years of mission, SWARM is still in its infancy. All the indicators are flashing green except for the ASM sensors on one satellite. Current plans are to maintain SWARM in orbit for many more years, as ensuring the temporal continuity of the measurements is certainly as important as the very accurate description of the field at a given time. Orbit corrections manoeuvers are planned to extend the lifetime of the mission. More (and longer) ASM burst-mode campaigns are planned. And other companion or follow-on missions are under investigation, as the NANOMAGSAT project by CNES.

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VENμS, close eye on vegetation

Not to be confused with its planetary namesake, VENμS is a joint Earth observation project between the Israeli and French governments executed by their respective national space agencies (ISA and CNES). VENμS is designed to provide close and regular monitoring of vegetation on the Earth's surface. It was launched on the 1st August 2017 from Kourou.

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The roots of VENμS' objectives lie in the general concerns for environment monitoring and sustainable development. Monitoring, predicting, and possibly mitigating the impacts of global changes while managing the natural resources in a sustainable way are major issues for our societies. These issues raise a number of scientific and policy making matters that require accurate, consistent, and long-term observations of processes and changes.

For land surfaces, EO satellites should provide measurements from which key information on the dynamics of land cover, land-use, and vegetation functioning can be derived at the various temporal and spatial scales required. Because of the dynamics of vegetation growth and of the short duration of phenological stages, such as flowering, the availability of cloud free and quality data every 5 to 10 days is highly desirable. A spatial resolution better than 20 m is required to capture land surface heterogeneity and to observe rather homogenous targets, such as crop fields.

Given these general objectives, VENμS unique features are to acquire high resolution (5 m), multi-spectral images every 2 days with constant viewing angles over 110 sites of interest worldwide. Every 2 days, the satellite is at the same place, at the same hour. The Equator is crossed by the satellite at 10:30 AM local time. No other sensor currently in orbit combines this kind of revisit rate and resolution for keeping track of vegetation. The trade-off is that VENμS does not offer a global monitoring capability.

By precisely monitoring plant growth and health status, VENμS will help scientists to improve monitoring, to better understand and model the complex interplay between plants, soils, ecosystems, climate and human activities.

The 2.5 years VENμS' science mission will be followed by a one-year technology mission during which its altitude will be lowered to 410 km to gauge the performance of a Hall-effect plasma thruster developed by the Israeli Space Agency (ISA) to counter orbital decay caused by atmospheric drag.

Fig.1

SCIENTIFIC PAYLOAD

The scientific payload requirements were jointly designed by CESBIO (Toulouse University-CNES-CNRS-IRD, France) and the RSL, Jacob Blaustein Institutes for Desert Research (Ben Gurion University of the Negev, Israel).

The VENμS super-spectral camera provides a ground resolution of 5.3 m at nadir over a 27 km swath, for 12 narrow spectral bands from 420 to 910 nm. Most of the bands (565, 620, 670, 702, 742, 782, and 865 nm) are designed to characterise different parts of the chlorophyll spectrum: absorption features, red edge. Some bands are dedicated to atmospheric corrections: 910 nm (water vapour absorption), 420, 443, 490, and 620 nm (aerosol characterisation), while some other bands may be used for water colour studies in coastal or inland water bodies. Finally, the 620 nm band has been duplicated with a slight observation angle difference (1.5°). This enables to determine the altitude of the pixels, with a sufficient accuracy to enable cloud detection.

SCIENTIFIC HIGHLIGHTS

The specifications of VENµS derive from the long record of researches devoted to the monitoring and modelling of vegetation seasonal and interannual cycles that started in the 80's with NOAA/AVHRR and then continued with SPOT-VEGETATION and MODIS for instance. Given this background, the main driver of VENµS specifications was the aim to acquire quality data with a temporal sampling and a ground resolution suitable for monitoring vegetation rapid changes and for driving vegetation and surface process models.

VENµS' unprecedented revisit rate, high spatial resolution, constant viewing angles and rich spectral detail will enable scientists to better understand and model land surface change being driven by climate and human activities. It is expected that VENµS will contribute to the advancement of land sciences and to the testing of new user oriented services based on EO data. VENµS data will also be useful for assessing SENTINEL-2 and LANDSAT 8 pre-processing chains (clouds, atmospheric corrections, etc.) and for sensors cross-calibrations through the monitoring of calibration sites every 2 days. Lastly, VENµS will also contribute to the definition of Europe's future Earth-observation satellites.

VENµS scientific mission relies on the continuous observation of 110 sites. These sites were selected following an international call for proposals. The selection criteria included the scientific merit of the proposals, the technological constraints, and the will to sample a diversity of land ecosystems. VENµS data are freely available to everybody for peaceful and non-commercial uses. The distribution of the data is done by the French THEIA land data centre: http://www.theia-land.fr.

VENµS' ground segment delivers 3 levels of products. The VENµS Level 1 provides geolocated top of the atmosphere reflectance values at 5 m resolution as well as cloud and cloud shadow masks at 200 m resolution. The VENµS Level 2 product provides surface reflectance at 10 m resolution, after cloud masking and atmospheric correction for all spectral bands. Level 3 provides as far as possible cloud free data based on the cloud free pixels of the Level 2 data representative of a short period (7 days).

The progress achieved in terms of understanding and modelling will contribute to various scientific or applied domains, such as an improved vegetation modelling within global carbon cycle models, crop and water resources management, early warning systems for food production.

MISSION STATUS

The first images were acquired in mid-August 2017. The commissioning phase will end in spring 2018. This phase consists in checking the whole system, including the satellite, the camera, the download of the images and data to the Kiruna receiving station, the ground processing chains, as well as the geometric and radiometric calibrations. The image quality requirements for VENµS data are very high and many efforts have been devoted to the radiometric and geometric calibration and performance assessment.

The commissioning phase allowed to test the different radiometric calibration methods used to ensure the highest possible radiometric quality. No onboard calibration device exists on VENµS, its radiometric calibration is accurately performed and monitored using several methods:

- Absolute calibration uses stable reference sites, Rayleigh scattering over the ocean and Moon imaging.
- Desert targets for multi-temporal monitoring and cross calibration with other instruments, including SENTINEL-2. The Moon is also used for monitoring the time evolution of calibration.
- Cross-calibration of spectral bands also uses clouds as grey targets.

The systematic acquisitions of the 110 scientific sites started in January 2018.

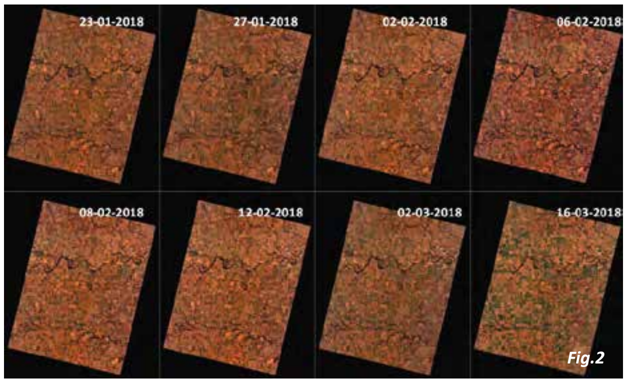

Fig. 1: Artist view of the VENµS satellite © *IDÉ/SARIAN Robin, 2015*

Fig. 2: Time series of VENµS images acquired over Oklahoma (USA) and processed at Level 2A (atmospheric effects correction applied) © *CNES*

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SWOT, a promising hydrology and oceanography mission

The SWOT satellite is set to be a game-changer for hydrology, with its altimeter capable of monitoring the Globe's lakes and rivers from an altitude of 891 km. Launch is scheduled in April 2021.

Fig.1

Satellites have already revolutionised oceanography, and tomorrow they will do the same for hydrology. The French-U.S. SWOT mission (Surface Water and Ocean Topography) will be at the forefront, carrying a wide-swath Ka-band radar interferometer dubbed KARIN that marks a break with today's technologies. Four agencies are joining forces to develop the SWOT project: NASA, CNES, CSA, UKSA.

With its 2 radar antennas perched at the end of a 10-metre boom, KARIN will perform a continuous coverage of a 120-kilometre swath where current radar altimeters are restricted to a strip of a few kilometres directly below the satellite. Thanks to this wide ground track, KARIN will be able to acquire surface water height measurements in more than 100-metre-wide rivers as well as lakes and flood zones with a surface area of 250 m x 250 m, with a 10-metre accuracy, and to quantify slopes with a 1.7 cm/km accuracy (after averaging on a >1 km^2 water surface area).

Combined with high-precision geoid models from the GOCE satellite and precise digital terrain models, SWOT data will radically improve hydrodynamic models used to estimate river discharges. They will also help to determine temporal variations in surface water stocks (lakes, reservoirs and wetlands) covering more than 250 m^2 and in flow dynamics. It is roughly estimated there are more than 30 million lakes larger than 1 hectare in the world.

Oceanographers are also eagerly awaiting SWOT, as KARIN will be able to see mesoscale and sub-mesoscale circulation patterns covering several hundred to several tens of km, like eddies and filaments, to characterise their very dynamic vertical transport, and to study coastal circulation and refine current ocean and climate prediction models, all with centimetre accuracy.

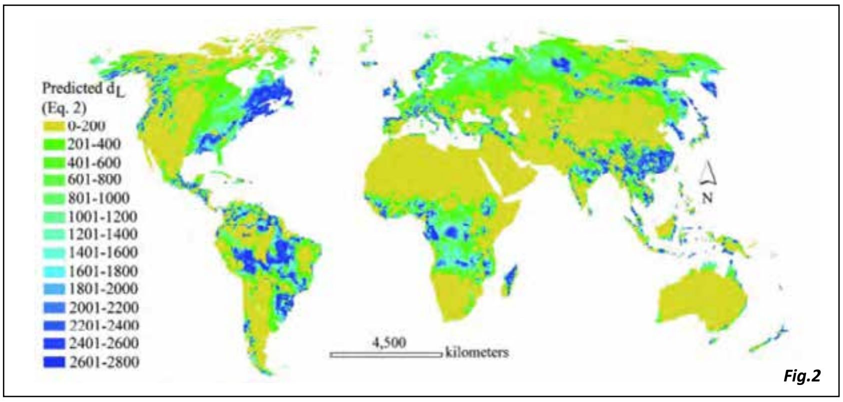

Fig.2

Fig. 1: Illustration of the SWOT satellite *© CNES/DUCROS David, 2015*

Fig. 2: Modelling the number of lakes of between 1 and 10 km² by millions of km² *© NASA/JPL*

Fig. 3: A diagram of the components of the SWOT payload *© NASA/JPL*

The vital technical, scientific and application innovations that SWOT will bring draw on NASA and CNES' joint altimetry legacy going back more than 20 years.

SCIENTIFIC OBJECTIVES

Oceanography

SWOT will provide altimetry data for a 2 x 50 km wide swath with a spatial observation resolution of 15 km, which is a considerable improvement over previous altimeters, which were only capable of along-track nadir measurements. Its main contribution to oceanography consists in precisely characterising mesoscale and sub-mesoscale circulation patterns which play a major role in ocean energy transport. SWOT will also allow us to determine the effects of coastal circulation on marine life, ecosystems, water quality and energy transport and to improve ocean/atmosphere coupling models. It represents a major contribution to operational oceanography (Copernicus, Meteorology).

Hydrology

When investigating the hydrology of continental surface waters, the SWOT mission will provide large-scale measurements of changes in the water stocks of the main wetlands, lakes and reservoirs (it has been estimated that there are more than 30 million lakes in the world with a surface area of more than one hectare; see Fig. 2), and offer a more accurate evaluation of discharge variations in major rivers:

- SWOT will map and monitor water level elevations for all bodies of water greater than 250 m x 250 m irrespective of the weather (limited only by very heavy rainfall), since radar measurements are unaffected by cloud cover.
- SWOT will be able to measure the heights and discharges of rivers over 100 m wide (the ultimate aim being 50 m).

These hydrological observations are extremely important for understanding the global dynamics of terrestrial surface waters and their interaction at estuaries with the coastal area of oceans. This new capability offers the opportunity to monitor the evolution of freshwater reserves in the context of global climate change, particularly in regions for which there are very few observations. In-situ (limnigraph) or airborne measurements only provide a partial picture and at the moment, no other satellite instrument is capable of regularly and globally measuring water bodies worldwide.

Furthermore, SWOT data may be combined with other satellite observation data (such as radar, SAR, InSAR or optical data), weather forecasts and hydrological and hydraulic river models to significantly improve flood forecasting systems. SWOT will also be used to improve the mapping of flood basins after floods.

Secondary objectives

In addition to its unique contributions to high-resolution hydrology and oceanography, the SWOT mission will be used to observe and analyse the dynamic processes in estuaries, the marine geoid, ocean bathymetry and ice over part of the polar icecaps including pack ice.

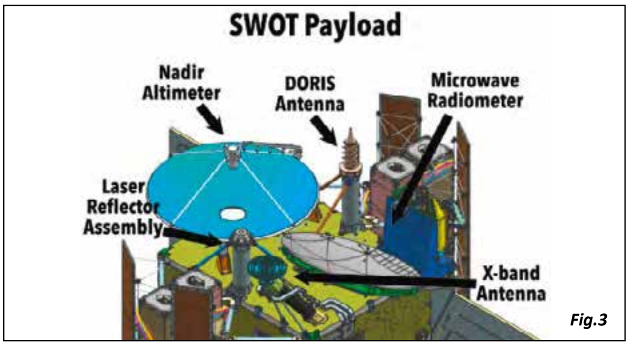

Fig.3

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
KARIN (Ka-band Radar Interferometer)	Plotting in 2D the topography of continental surface waters	SWOT Science Team: international science team. 4 co-chairs: Lee-Lueng fu, JPL Jean-François Crétaux LEGOS Rosemary Morrow, LEGOS Tamlin Pavelsky, Universitu North Carolina More info : https://swot.jpl.nasa.gov/st_projects.htm
Poseidon-3C : nadir radar altimeter in KU/C band	« Nadir » altimetry (1D) for the swath centre and the absolute reference related to the current altimetry constellation	
Microwave radiometer	Troposphere correction (water vapour) for altimetry measurement	
DORIS/GPS/LRA	3-technique precise orbitography payload	

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AUTHOR
N. Martiny[1], J.-F Léon[2], P. Roucou[1], J. Mueller[3], H. Broutin[4]
1 Biogéosciences (Climatology Research Centre), CNRS UMR 6282, Université de Bourgogne Franche Comté, 6 boulervard Gabriel, 21000 Dijon, France
2 Laboratoire d'Aérologie (Laboratory of Aerology), CNRS UMR 5560, Université Paul Sabatier, 14 avenue Edouard Belin, 31400 Toulouse, France
3 Institut Pasteur (Epidemiology of Emerging Diseases), 25-28 rue du Docteur Roux, 75724 Paris, Cedex 15, France
4 MIVEGEC (Infectious Diseases and Vectors: Ecology, Genetics, Evolution and Control), CNRS UMR 5290, IRD 224,
Département de Parasitologie, Faculté de Médecine, Université Cheikh Anta Diop, Dakar, Sénégal

Tele-epidemiology: general approach and specific case of meningitis in Africa

Tele-epidemiology is a recent research field based on the use of remote sensing products to understand climate-environment/health relationships at fine spatial and temporal scales. It is an efficient approach for "climate/environment-sensitive" disease, *i.e.* disease for which ~25% of the variability can be statistically explained by climate and/or environmental factors. The specific case of meningitis is presented here as an example of application. Based on AQUA/MODIS Deep Blue aerosol products and World Health Organisation (WHO) meningitis surveillance bulletins in 15 countries of the meningitis belt, we demonstrate that the area at risk for meningitis epidemics is highly dependent on dry and dusty conditions at the scale of the belt. This paves the way for the definition of an early warning system for meningitis, and further, respiratory diseases in Africa.

Tele-epidemiology is a recent interdisciplinary research field that requires to establish a dialogue between climate and/or environmental sciences and medicine and/or epidemiology. For any given disease, the general approach used is composed of 4 main steps [1].

- Step 1: the biological, societal, environmental and climatic potential determinants of the disease are listed based on epidemiological studies. The determinants may be very different from one disease to another, and for a given disease, the nature of the determinants and the associated spatial/temporal scales may be very heterogeneous. Moreover, only a portion of the determinants comes from climate and/or environment.
- Step 2: a census of remote sensing data for the assessment of the climate/environment risk factor is performed. Data are checked for quality and relevance for health impact studies.
- Step 3: statistical studies linking climate/environment factors and the disease are conducted in order to quantify the degree of influence of these factors on the disease. This is a step forward to make assumptions on the processes behind and define either if the disease is sensitive to the climate/environment factors or not.
- Step 4: simple, efficient and robust climate/environment indicators are defined in order to settle operational early warning systems.

Bacterial meningitis *(meningococcus Neisseria meningitides, Nm)*, that provokes cases or epidemics every year from January to April (JFMA) in the 10-15°N African meningitis belt, has been suspected to be a climate/environment-sensitive disease since the 60's [2]. Climate conditions, and notably the meridional winds in October, November and December, have been shown to explain 25% of the year-to-year variability in the meningitis incidence [3]. This high score enables to classify the disease as a climate-sensitive one, and is promising regarding the settlement of early warning systems. More recent studies have highlighted the specific case of mineral dust versus other climate variables. Indeed, the variability in the weekly number of cases in meningitis has been shown to be statistically related to dust, with a 1- to 2-week time-lag between dust and meningitis at the national and district spatial scales [4, 5]. This result is particularly promising as this time-lag is consistent with the incubation time period of the *Nm* bacteria, *i.e.* <14 days [6].

As a result, tele-epidemiology is a consistent approach for bacterial meningitis which data, methods, and results are presented below as a study case.

DATA AND METHODS

Our study is based on aerosol products from remote sensing and World Health Organisation (WHO) meningitis data sets.

We used the 10-km AQUA/MODIS Deep Blue aerosol products Collection 6 [7] on the 2004-2014 period, notably the land best estimate Deep Blue Aerosol Optical Depth at 550 nm (AOD_{550}), proxy of the aerosol quantity over the atmospheric column, the Angström exponent (α), indicator of the particles size, and the Single Scattering Albedo at 412 nm (SSA_{412}), indicator of the particles absorption properties. These 3 parameters help detecting dust on the images.

The WHO meningitis surveillance bulletins, available in pdf format on the WHO site, and used in Martiny *et al.* (2013) [4], are exploited to calculate the weekly number of cases in meningitis for 15 countries of the African meningitis belt for the AQUA/MODIS period (Sudan is excluded).

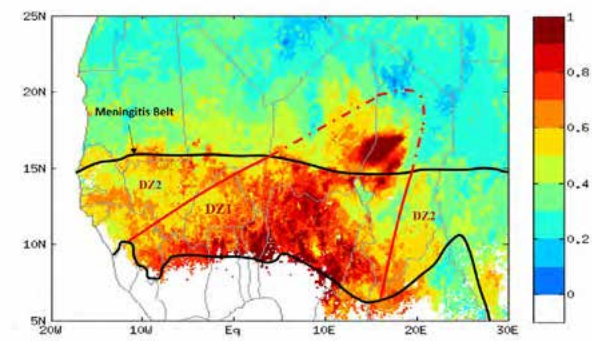
RESULTS

The meningitis belt is traditionally defined between the isohyet 300 to the North (~15°N), corresponding to a critical population size, and the isohyet 1200 to the South (~7°N) corresponding to a humidity threshold (Fig. 1). However, as meningitis is a dry season disease, and considering that dust is highly suspected to play a role on the meningitis development, the contours of the belt may also be related to the dust distribution in the area. Fig. 1 presents the mean AOD_{550} in JFMA. The aerosols observed in the northern part of the belt are mostly pure dust with $AOD_{550} > 0.5$ and $\alpha < 0.5$ [8]. These particles are highly absorbing with SSA_{412} values below 0.96. The aerosols observed in the southern part of the belt are dust mixed with other kinds of aerosols with $AOD_{550} > 0.5$, $\alpha > 0.5$ and SSA_{412} ranging between 0.96 and 0.99 [9]. Beyond the southern limit of the belt, $\alpha > 1$ (Fig. 2) and SSA_{412} is close to 1 (not shown). As a result, the AOD_{550} for which $\alpha < 1$ corresponds to the southern limit of the meningitis belt.

Within the belt, 2 Dust Zones can be defined: DZ1 in the centre, influenced by the Bodele major dust source emissions at this period of the year and experiencing the highest aerosol levels (AOD_{550} ~ 0.5-1) and DZ2 elsewhere in the belt with moderate aerosol levels (AOD_{550} ~ 0.4-0.7). The analysis of the epidemiological dataset reveals that the most affected countries in the belt are Niger, Nigeria, Burkina Faso and Chad with 2000 to 9500 cases/year. These countries are all included in DZ1. The other countries of the belt are less affected by meningitis with a maximum of 1000 cases/year. These countries either experience moderate AOD_{550} (Mali, Senegal, Mauritania, the Gambia, Guinea at the western part of the belt, and the Central African Republic at the eastern part) or high AOD_{550} jointly with high humidity in April (Ivory Coast, Ghana, Togo, Benin and Cameroon). The latter countries are located at the southern limit of the belt and are exclusively affected by meningitis in their northern part. As a result, the meningitis incidence within the belt seems to depend on both aerosol levels and humidity that has been identified as a limiting factor for meningitis [4]. As a summary, the area at high risk for meningitis is shown to be located in the centre of the belt, especially in the countries where the Harmattan regime influence is maximum, with dry conditions and high to very high aerosol levels (~0.7-1).

CONCLUSIONS/PERSPECTIVES

Tele-epidemiology is a research field particularly efficient on « climate/environment-sensitive » diseases, *i.e.* diseases for which climate and/or environment explain at least 25% of the incidence variability. This is the case for different infectious and/or emerging diseases that are of great concern in the context of climate variability and changes at the global scale. Bacterial meningitis is a highly person-to-person contagious infectious disease, and some regions of the world are particularly exposed to epidemic risks, like the African meningitis belt. Even though a mass vaccination campaign has been conducted by WHO since 2010 in this area of the world, global *N. meningitis* incidence may increase again in the future [9] justifying the development of efficient and adapted early warning systems for this disease that represents a major public health problem. Our researches contribute to show the overall influence of climate/environment on meningitis at the scale of the belt, notably through the dust component, which requires to be accurately characterised at the surface. For that purpose, the CALIPSO/CALIOP LIDAR aerosol products can be used as shown in Léon *et al.* [11] and combined to imaging satellite products (e.g. AQUA/MODIS, PARASOL/POLDER, etc.) as actually developed in the frame in the TELEPaF CNES project (2017-2018). Today, our goal is to define high-resolution dust and climate indicators based on imaging and LIDAR satellite products on the one hand, and Regional Climate and Dust simulations on the other hand in order to prevent population from the meningitis cases and epidemics (TELEDM CNES project), but also from Respiratory Infection diseases (TELEPaF CNES project) risks.



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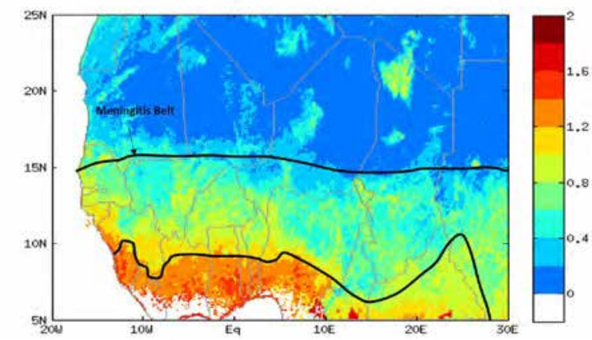

Fig.2

Fig. 1: Seasonal Deep Blue AOD550 for which α < 1 (JFMA season, 2004-2014 period). Black lines indicate the location of the meningitis belt. DZ stands for the dust zones delimited by the red lines © *from Martiny, N., et al. (2017).*

Fig. 2: Seasonal Deep Blue α (JFMA season, 2004-2014 period). Black lines indicate the location of the meningitis belt © *from Martiny, N., et al. (2017).*

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AUTHOR
A. Bégué[1], B. Bellon[1], R. Gaetano[1], V. Lebourgeois[1]
1 TETIS (Land, Environment, Remote Sensing and Spatial Information), CNRS UMR 9000, CIRAD, Maison de la télédection, 500 rue Jean-François Breton, 34093 Montpellier, Cedex 5, France

Mapping agricultural systems using satellite images

Agricultural systems are the key to understand land use in relation to sustainability, and thus, in view of the global challenges, there is an urgent need to better characterise these systems at both the regional and global scales. We present recent methodology developments for multi-scalar agricultural systems' mapping - from the cropping system to the agricultural land use system - such as multi-sensor data combination, expert knowledge-driven methods and land units stratification.

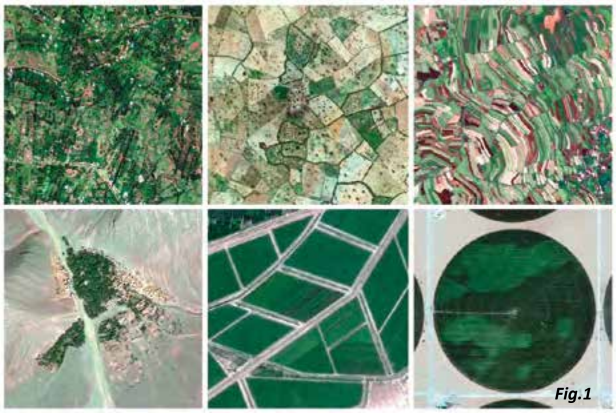
Fig.1

The necessary increase of the world's agricultural production, in response to population growth, will have to cope with climate change, increased competition for land and increasing environmental pressures. The production increase will mainly come from higher yield, but also from higher cropping intensities such as multiple cropping and/or shortening of fallow periods. The agricultural systems are the key to understand land management sustainability, and thus there is an urgent need to better characterise these systems at the regional and global scales, with a particular emphasis on the various pathways toward agricultural intensification. Earth observation data already provide insight into the direction and magnitude of the changes in area under cultivation. However, land cover mapping, with limited consideration of land management, is insufficient to draw a complete picture of coupled human-environment systems, and research must evolve from traditional land cover mapping to land use system mapping [1]. We propose here to illustrate some new methodological advances concerning multi-scalar agricultural systems' mapping, from the field (cropping system) to the agro-landscape unit (agricultural land use system).

CROPPING SYSTEM MAPPING

A cropping system refers to the crop type, sequence, and arrangement, and to the management techniques used on a given field over the years. The first descriptor of an agricultural system is thus the crop type or group. Classifications of crops at the field scale are essentially based on time series of optical or radar images, but their quality depends on the spatial and temporal resolution of the satellite data and on the type of agricultural system in place. To be able to answer to the constraints of the different agricultures of the world (illustrated in Fig. 1), multi-sensor, but also multisource approaches (e.g. satellite, environmental and socio-economic data) are needed.

In France, the national programme THEIA has led to significant advances in the processing of time series of high frequency decametric images for mapping land cover, such as the iota2 chain that produces a land cover map for France on a yearly basis, or the Random Forest classifier/object-based approach applied to multisource spatial data (e.g. decametric resolution image time series, metric resolution image, Digital Elevation Model) that produces land use maps of smallholder agricultural zones at different nomenclature levels. For example, in Madagascar where the small agricultural systems are characterised by high intra- and inter-field variability and where satellite observations are disturbed by cloudy conditions, Lebourgeois *et al.* (2017) [2] showed that classification results were improved by a hierarchical approach (cropland masking prior to classification of more detailed nomenclature levels). The spectral indices derived from the high-resolution time series were shown to be the most discriminating variable, and the very high spatial resolution image was found to be

essential for the segmentation of the area into objects, but its spectral and textural indices did not improve the classification accuracies.

Regarding cropping practices, Bégué *et al.* (2018) [3] reviewed remote sensing studies on crop succession (crop rotation and fallowing), cropping pattern (tree crop planting pattern, sequential cropping, and intercropping/agroforestry), and cropping techniques (irrigation, soil tillage, harvest and post-harvest practices, crop varieties, and agro-ecological infrastructures). They observed that most of the studies carried out exploratory research on a local scale with a high dependence on ground data, and used only one type of remote sensing sensor. Furthermore, most of the methods relied heavily on expert knowledge about local management practices and environment.

AGRICULTURAL LAND USE SYSTEM MAPPING

In response to the need for generic remote sensing tools to support large-scale agricultural monitoring, Bellon *et al.* (2017) [4] presented a new approach for regional-scale mapping of agricultural land use systems based on object-based NDVI time series analysis. The approach first obtains relatively homogeneous land units in terms of phenological patterns, by performing a principal component analysis on an annual MODIS NDVI time series, and automatically segmenting the resulting high-order principal component images. The resulting land units are then classified into cropland or rangeland based on their land-cover characteristics. Finally, the cropland units are further classified into cropping systems based on the correspondence of their NDVI temporal profiles with the phenological patterns of the cropping systems of the study area. With this approach, a map of the main agricultural land-use systems of the Brazilian state of Tocantins was produced for the 2013-2014 growing season (Fig. 2). This map shows the potential of remote sensing to provide valuable baseline spatial information for supporting large-scale land-use systems analysis.

The current spatial technologies, and particularly the SENTINEL constellation, are expected to significantly improve the monitoring of cropping practices in the challenging context of food security and better management of agro-environmental issues. However, the methods will have to cope with the variety of the agricultural systems of the world, through land stratification, multi-sensor data combination, and expert knowledge-driven methods.

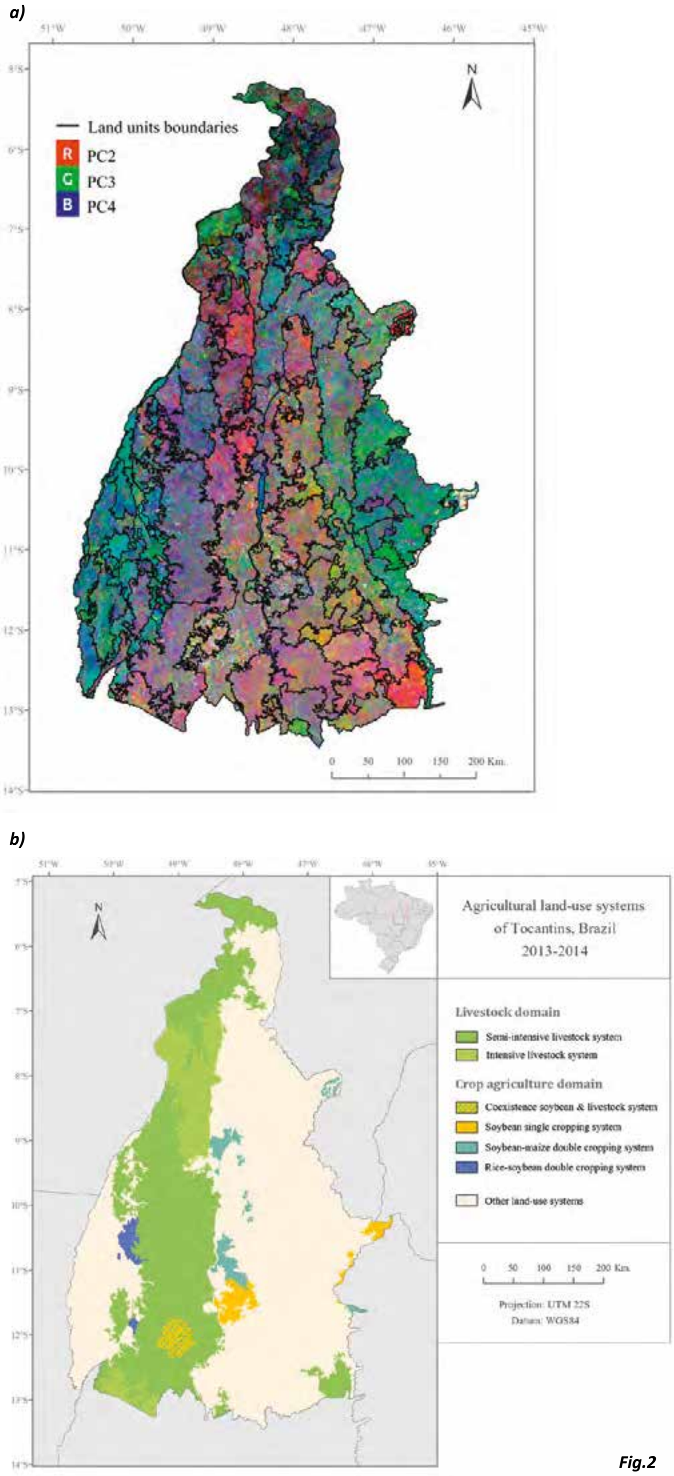

Fig.2

Fig. 1: 1 km² of agricultural land from above (Google Earth images): Top line, from left to right: agroforestry (Tanzania), rainfed annual crop (Senegal), highland rice (Madagascar); Bottom line, from left to right: oasis (Tunisia), sugarcane (Senegal), centre-pivot irrigated crop (Egypt). © *CIRAD/TETIS.*

Fig. 2: Tocantins state (Brazil) in the 2013-2014 growing season: a) land units' boundaries over a colour composition of 3 principal component (PC) images (RGB PC2, PC3, PC4) used as the segmentation variables, b) main agricultural land-use systems, established using MODIS-NDVI time series. © *After [4].*

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AUTHOR
J. Chave[1 2]
1 AIB (Research Federation of Agrobioscience, Interactions and Biodiversity), CNRS FR 3450, INRA, 24 chemin de Borde Rouge, BP 42617, 31326 Castanet Tolosan Cedex
2 EDB (Evolution and Biological Diversity laboratory), CNRS UMR 5174, Université Toulouse Paul Sabatier, Bâtiment 4R1, 118 route de Narbonne, 31062 Toulouse Cedex 9

Carbon stocks in the terrestrial biosphere

The terrestrial biosphere holds some 400 Pg of carbon in live biomass and as much as 2000 PgC in soils. Estimating how these stocks are distributed spatially is key to predict the contribution of land use and land-use change to anthropogenic carbon emissions, and to build more robust environmental policy. Current methods are indirect. Emerging remote sensing capability, better coordination in ground data acquisition, and process-based modelling of the biosphere all offer new perspectives to quantify this important flux with improved accuracy.

The terrestrial biosphere holds massive amounts of carbon in soils and vegetation. One hectare of old-growth forest may hold as much as 300 MgC/ha of aboveground carbon; likewise, boreal peatlands hold up to 400 MgC/ha belowground. One of the most striking trends of the Anthropocene has been a continued conversion of natural lands into agricultural lands [1]. In many regions, this land conversion has been accompanied with the cutting of forests and woodlands, and land conversion has also led to changes in the intensity and frequency of fires. Carbon fluxes associated to land-use drivers often act jointly, and they imply a range of social and economic actors (as for instance in forest degradation and deforestation). The consequences on live carbon compartments and on soil carbon may be delayed.

These processes contribute to the global carbon cycle and current carbon emission estimates due to land use and land-use change are directly based on remote sensing technology. Land pixels are monitored regularly and attributed to a number of land-cover classes. Then, changes from one class to the other are associated with a clear change (gain or loss) of carbon. Changes in carbon stocks depend on the type of transition and on the carbon compartment. This approach is sometimes referred to as carbon-tracking model, or bookkeeping model since it is a simple accounting of gains and losses across pixels [2]. Global estimates of carbon emissions due to land-use change have been estimated around 1.1±0.35 Pg/yr (mean±standard deviation) for the 2006-2015 period, and the method can be extended prior to the LANDSAT/SPOT era of vegetation monitoring [3]. Bookkeeping methods are however facing 3 major limitations: that of attribution, of scale, and of the estimation of carbon conversion factors.

Technology is available to estimate aboveground biomass directly from space using the backscattering properties of vegetation. For low- to medium- biomass forests, the SAR sensor ALOS PALSAR reveals variations in carbon stocks at 25-m resolution at continental scale (Fig. 1) [4]. A new generation of satellite missions are being designed to reduce the problem of attributing a pixel to the improper land-cover class. ESA's Earth Explorer 7 mission BIOMASS will include the first SAR satellite operating at P band, and will provide wall-to-wall aboveground biomass estimates at a resolution of 4 ha [5]. A dual-frequency SAR mission will follow after BIOMASS: operating at L band and S band, and called NISAR, it will be launched by a NASA-ISRO joint venture [6]. Together, these sensors will fill critical knowledge gaps about forest canopy height, and forest carbon density.

Land-cover changes sometimes occur over small spatial scales. New-generation sensors, such as SENTINEL-1 and 2, offer a much higher accuracy, and thus resolve smaller disturbances than previously. Airborne laser-ranging (LIDAR) scanning measures forest canopy height at metric spatial resolution over areas ranging from 10 to 1 000 km^2. Canopy height can be converted into aboveground carbon densities using allometric models using novel methods we have developed in an international collaboration [7]. Airborne LIDAR thus quantifies small-scale carbon stock variability in complex ecosystems, especially forests. Until 2010, a LIDAR called GLAS was on board NASA's ICESAT satellite and this mission provided a large number of forest height data even though this was not the primary aim of the mission. The global forest carbon stock maps available today are largely based on this dataset [8, 9]. A NASA instrument called GEDI and on board the ISS will provide a massive improvement over GLAS: a full-waveform LIDAR will acquire several orders of magnitude and more forest height data than GLAS [10]. The LIDAR shots of GEDI will provide information on canopy height and structure within footprints of ca 25 m in diameter.

Factors used to convert area estimates of deforestation and forest degradation into carbon stock change estimates must be derived from ground observations. The IPCC guidelines (2014) [11] offer several options to estimate the 5 main

Fig. 1: The above-ground biomass map of African savannahs and woodlands at 25 m resolution derived in this study from the 2010 ALOS PALSAR mosaic. Values of biomass greater than 100 Mg/ha cannot be resolved at L band, and have been masked (dense forest in the map). *© From Ref. [4].*

Fig. 2. Changes in carbon stores for African vegetation from 2010 to 2016. Areas with significant negative changes are in red (carbon source), and positive changes in green (carbon sink). *© From Ref [13].*

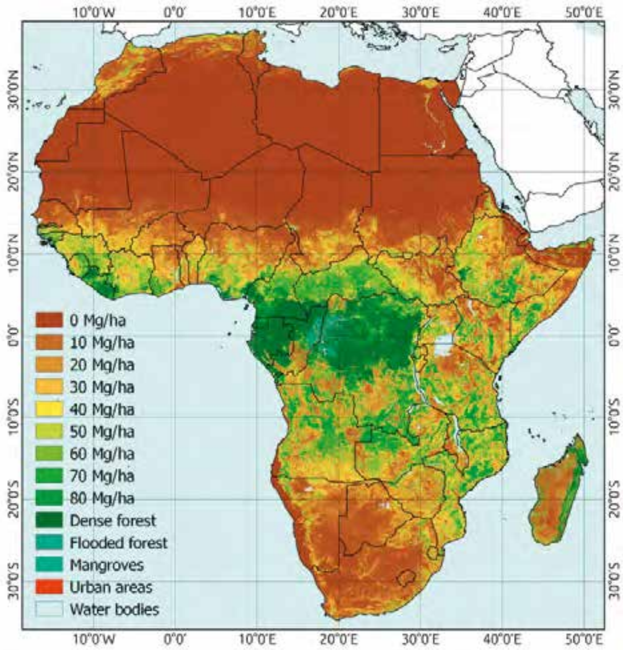

Fig.1

carbon pools (aboveground biomass, belowground biomass, soil organic matter, dead wood, and litter), from prescribed default values (Tier 1) to values computed from national vegetation inventories and calibrated process models (Tier 3). In the tropics, national forest inventories remain rare [12] and initiatives to standardise and report forest carbon stock estimates globally are an important aspect of algorithm training and of the validation of carbon stock map products for all 3 planned mission (BIOMASS, NISAR and GEDI). For instance, the BIOMASS science team has established an online database of in-situ aboveground biomass values (Forest Observation System; http://forest-observation-system.net/).

Another promising approach is to use passive microwave emissions at L band as measured by the SMOS satellite. Recent studies have shown that vegetation optical depth as inferred from SMOS showed a good correlation with biomass temporal fluctuation over pixels of ca 25 km. This was used to assess the trends in changes of biomass from 2010 to 2016 in open woodland vegetation (Fig. 2) [13].

Importantly, even though aboveground carbon stocks and fluxes are increasingly well estimated, belowground carbon components remain difficult to estimate by remote sensing. Soil carbon emission factors are available [13] and global soil carbon maps are now achieving a fairly high spatial resolution [14]. Together, information about the spatial distribution of carbon stores in the terrestrial biosphere is crucial for environmental management, as it helps prioritise land to be set aside in policies intended to avoid to offset carbon emissions.

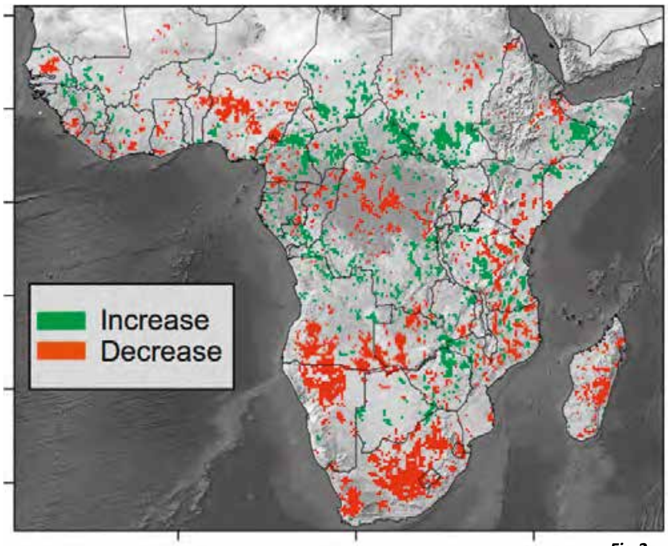

Fig.2

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TRISHNA, quantify water transfers in ecosystems


Fig.1

The Indian-French mission TRISHNA will be dedicated to photographing our entire planet in thermal infrared (TIR) and visible parts of the electromagnetic spectrum at a high spatial scale (50m) every 3 days with 2 main objectives driven by scientific requirements:

- Ecosystem stress and water use monitoring,
- Coastal zone monitoring and management.

TRISHNA is a preoperational mission: it will prepare the future services that Copernicus will provide at the end of the next decade.

SCIENTIFIC OBJECTIVES

Many processes involved in climate change are primarily governed by water and energy budgets where the Land and Sea

Surface Temperatures (LST and SST) appear as key signatures. As they are largely uncorrelated to the other observable surface variables, the surface temperatures provide new information to describe the processes and to create models. Surface temperature is a key component of the surface energy budget and is a direct signature of surface energy flux partitioning, especially latent heat flux (*i.e.* evapotranspiration) and water deficit. The retrieval of EvapoTranspiration (ET) from the surface temperature will provide a direct access to the water cycle, with a particular emphasis on the assessment of the rapid changes in land surface water status (after rainfall or irrigation) at the local scale. The first panel of applications deal with water management in agriculture (70% of water consumption at global scale) in terms of both quantity and quality, and monitoring of crop production and food security. By governing the water cycle and energy transport within the biosphere, atmosphere and hydrosphere, ET plays an important role in hydrology and also in meteorology. In particular ET appears as a key factor in predicting and estimating regional-scale surface run-off, underground water and watershed budgets, which interact with large-scale atmospheric circulation and global climate change.

Sea Surface Temperature (SST) at the ocean-atmosphere interface represents a key variable for understanding, monitoring and predicting flux of heat, momentum and gas as well as ocean dynamics (physics and biogeochemistry) at a large range of scales. In coastal areas, the intense exchanges between ocean, atmosphere and land generate a very large variability of surface temperature both in time and space, which requires SST measurements with fine temporal and spatial resolutions in order to understand the underlying physical and biological processes. Finally, the monitoring of continental water surfaces also represents an important issue for hydrology and water quality.

In addition to those mission objectives, a number of applications are expected to benefit from LST measurements:

- the monitoring of urban climates as the urban population increases (60% of the world's population is expected to live in cities in 2030), to expect the consequences of climate change, in particular the well-known urban heat island (UHI) phenomena, to prioritise both the monitoring of urban environments and the development of adaptation strategies.
- and also geology, volcanology, and cryosphere (sea ice, mountainous areas).

SCIENTIFIC PAYLOAD

TRISHNA is a small satellite (500kg class) that uses an Indian bus derived from the IMS2 bus used on SARAL.
The payload is composed of 2 wide field instruments:

- A thermal infrared scanner supplied by CNES
- A VNIR and SWIR push broom supplied by ISRO.

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
TIR (Thermal InfraRed)	Surface Temperature	INRA
VNIR (Visible and Near InfraRed) & SWIR (Short-Wave InfraRred)	Vegetation index Atmospheric correction	ISRO/SAC

MISSION STATUS

In Phase A
Launch date objective: 2024.

Fig. 1: Illustration of exchanges between ocean and atmosphere
© Getty Images

SENTINEL-3, a pair of multi-instrument Earth-observing satellites

SENTINEL-3 are multi-purpose satellites that provide measurements of great diversity on the oceans and continents: surface temperatures, sea and large lakes level, thickness of pack ice and glaciers, "colour" of the oceans...

Fig.1

Fig.2

The SENTINEL-3 measure the height of the oceans, large lakes and rivers, the thickness of pack ice and glaciers. They provide daily temperatures of land surface with a resolution of 1 km on the ground. They provide information on the "colour" of the oceans, indicating the phytoplankton concentration of the overflew waters with a resolution of 300 m and targeting 21 spectral bands. All these data are made freely available to users (scientists, companies, etc.) on the CNES Internet PEPS platform.

Successor of the ENVISAT mission, SENTINEL-3 is part of the Earth observation and monitoring programme, Copernicus, directed by the European Commission. The European Space Agency (ESA) is responsible for the development of the 2 satellites as well as their successors SENTINEL-3C and D, their instruments and the ground segment. The spacecraft has been designed and manufactured by a consortium of 100 companies under the leadership of Thales Alenia Space. ESA and EUMETSAT manage the mission jointly. ESA processes land products and EUMETSAT the marine products for application through the Copernicus services.

Following a cooperation agreement with ESA, CNES provided the new version of the DORIS instrument, which is essential for deducing the height of the oceans from the radar altimeter data. In addition to DORIS, CNES provides its expertise to a large part of the SENTINEL-3 mission, particularly on the processing and characterisation / validation of the instruments of the altimetry payload (altimeter, radiometry, GNSS and DORIS) but also on the characterisation of the optical instruments (OLCI and SLSTR). The synergy of measurements between optical and radar sensors will be an essential area of work in future years.

Scientific payload

INSTRUMENT	OBJECTIVE
TOPO payload • SRAL (Synthetic aperture Radar ALtimeter) • MWR (MicroWave Radiometer) • GNSS/LRR/DORIS	Measure the height of the sea surface, waves and surface wind speed over the oceans
SLSTR (Sea and Land Surface Temperature Radiometer)	Measure global sea- and land-surface temperatures
OLCI (Ocean and Land Colour Instrument)	Measure ocean and land colour

MISSION STATUS

With a mass of 1250 kg, the SENTINEL-3A satellite was launched on 16 February 2016 from the Russian spaceport Plessetsk on board a Rockot rocket. The in-orbit validation of this first satellite went perfectly and the products of the mission are now available and public.

Its twin, SENTINEL-3B, joined it on 25 April 2018 in the same 814 km orbit.

Fig. 1: SENTINEL-3 placed on a Breeze upper stage of the ROCKOT launcher © *ESA/Pierre Carril*

Fig. 2: The very first image of SENTINEL-3B, captured on 7 May at 10:33 GMT (12:33 CEST), less than 2 weeks after it was launched. It shows the transition between day and night over the Weddell Sea in Antarctica
© contains modified Copernicus SENTINEL data (2018), processed by EUMETSAT, CC BY-SA 3.0 IGO.

CFOSAT, a French-Chinese satellite surveying the oceans

In 2018, CFOSAT (China-France Oceanography SATellite) will be placed into Earth orbit to measure ocean surface winds and waves. These data will enable more reliable sea-state forecasts and yield new insights into ocean-atmosphere interactions.

Developed jointly by CNES and CNSA (China National Space Administration), CFOSAT will carry 2 radar instruments: SWIM (Surface Waves Investigation and Monitoring), a wave scatterometer supplied by CNES; and SCAT a wind-scatterometer supplied by CNSA. The SWIM's 6 rotating beams will measure wave properties (energy, direction, wavelength), while SCAT will measure the surface wind intensity and direction. The data will be downlinked to French and Chinese receiving stations.

These data will allow scientists to achieve more accurate ocean forecasts and give earlier warning of severe weather events like storms and cyclones. CFOSAT will also help climatologists to learn more about exchanges between the oceans and atmosphere, which play a key role in climate. Conceived by LATMOS laboratory (CNRS/UVSQ/Sorbonne University), the SWIM instrument is being developed by Thales Alenia Space with oversight and funding from CNES. Other mission partners include the French institute of marine research and exploration IFREMER, the French national weather service METEO-FRANCE, and research laboratories.

SCIENTIFIC OBJECTIVES

CFOSAT is designed to provide, at a global scale, joint observations of the ocean surface wind and of the spectral properties of surface ocean waves. It will serve both operational needs for the surface wind and wave forecast (marine meteorology and climatology), and research needs by improving our knowledge on the wave hydrodynamics, of the interactions between waves and the atmospheric or oceanic layers close to the surface, and of the interactions between electromagnetic signals and the ocean surface.

These main objectives can be detailed as follows:
- Modelling and predicting ocean surface wind and waves
- Physical processes of wind and waves
- Interactions between surface waves, atmosphere and ocean
- Interactions between electromagnetic signals and the ocean surface
- Wave evolution in coastal regions.

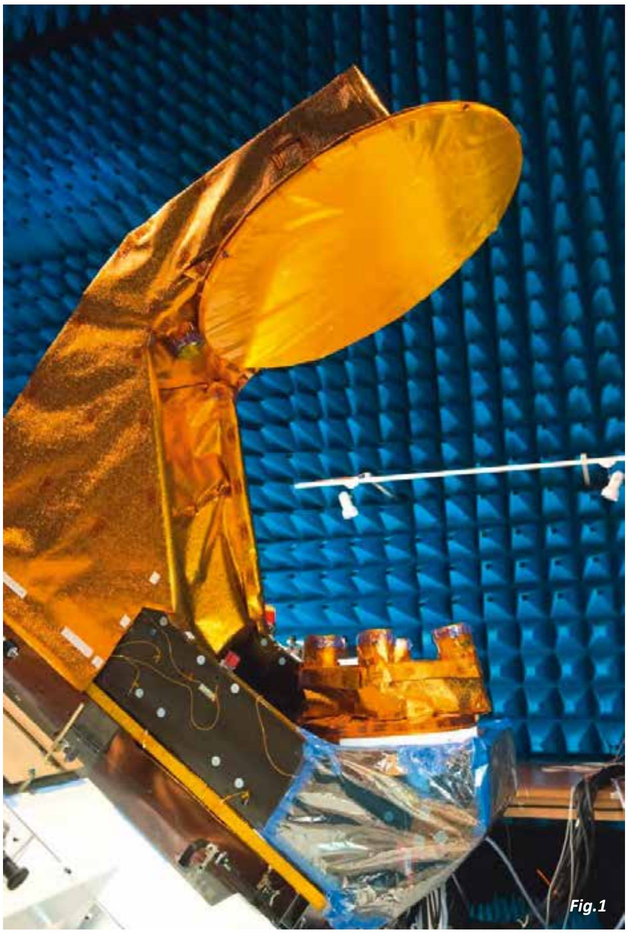

Fig.1

The objectives listed below are secondary objectives to the CFOSAT mission, and specifications related to these goals are to be met on a best effort basis.
- Polar ice sheet
- Land surfaces.

Fig.2

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
SWIM	Wave scatterometer Ku-band real aperture radar for the measurement of ocean wave 2D directional spectra. SWIM is a 6-beam radar at near-nadir incidence (0 to 10°). The main products are: 2D wave spectra, backscattering coefficient profiles, significant wave height and wind speed from nadir beam.	LATMOS, LOPS, METEO-FRANCE
SCAT	Wind scatterometer Ku-band real aperture radar for the measurement of wind vector. SCAT is a rotating fan-beam radar with incidence angles in the range (18~50°).	NSSC (China), NSOAS (China)

MISSION STATUS

The satellite in now under integration and test in DFH facilities (Beijing, China). The assembly and functional tests have been successfully done. The sequence starts now the environment tests. The end of the sequence is expected for August 2018. At this date, the satellite should move to the launch pad in the Gobi Desert.

Meanwhile, the mission ground segment is under development both in China and in France. On the French side, the ground segment is divided in a near-real time mission centre at CNES and a differed time mission centre at IFREMER. For both centres, the algorithms are defined and the operational centres are following their nominal development plan. The CAL/VAL activities are getting organised and supported by CNES, IFREMER/LOPS, LATMOS and METEO-FRANCE. They will be crucial for the commissioning phase and the validation of all these very innovative products.

Fig. 1: SWIM antenna © *Thales Alenia Space*

Fig. 2: Scientific and project teams in Huairou (China, Beijing district) © *DFH/CNSA/NSOAS*

JASON-3, measuring ocean surface height until 2020

JASON-3 is the third in the French-American line of JASON satellites. It ensures the continuity of ocean level data from its orbital viewpoint, 1 336 km above Earth.

//

For oceanographers from around the world, the JASON series of altimetry satellites is a vital resource. TOPEX/POSEIDON, launched in 1992, JASON-1 in 2001, and then JASON-2 in 2008 have revealed that the global sea level is rising at an average rate of 3 mm per year. They have also helped scientists to better understand the vast system of deep and surface ocean currents. Today, they have become a benchmark for other altimetry satellites like SARAL, CRYOSAT, HY-2A and SWOT, and their operational applications are burgeoning.

JASON-3 ensures the vital continuity of the ocean data record in the current context of global warming until at least 2020, while also developing operational services. Like its predecessors, it operates in a high-inclination 1 336-km orbit from which it covers 95% of the globe's ice-free oceans every 10 days. Its instruments are installed on a Proteus spacecraft bus supplied by CNES. In 2020 and 2026, 2 new JASON satellites—respectively JASON-CS-A/SENTINEL-6A and JASON-CS-B/SENTINEL-6B—will join it in the same orbit.

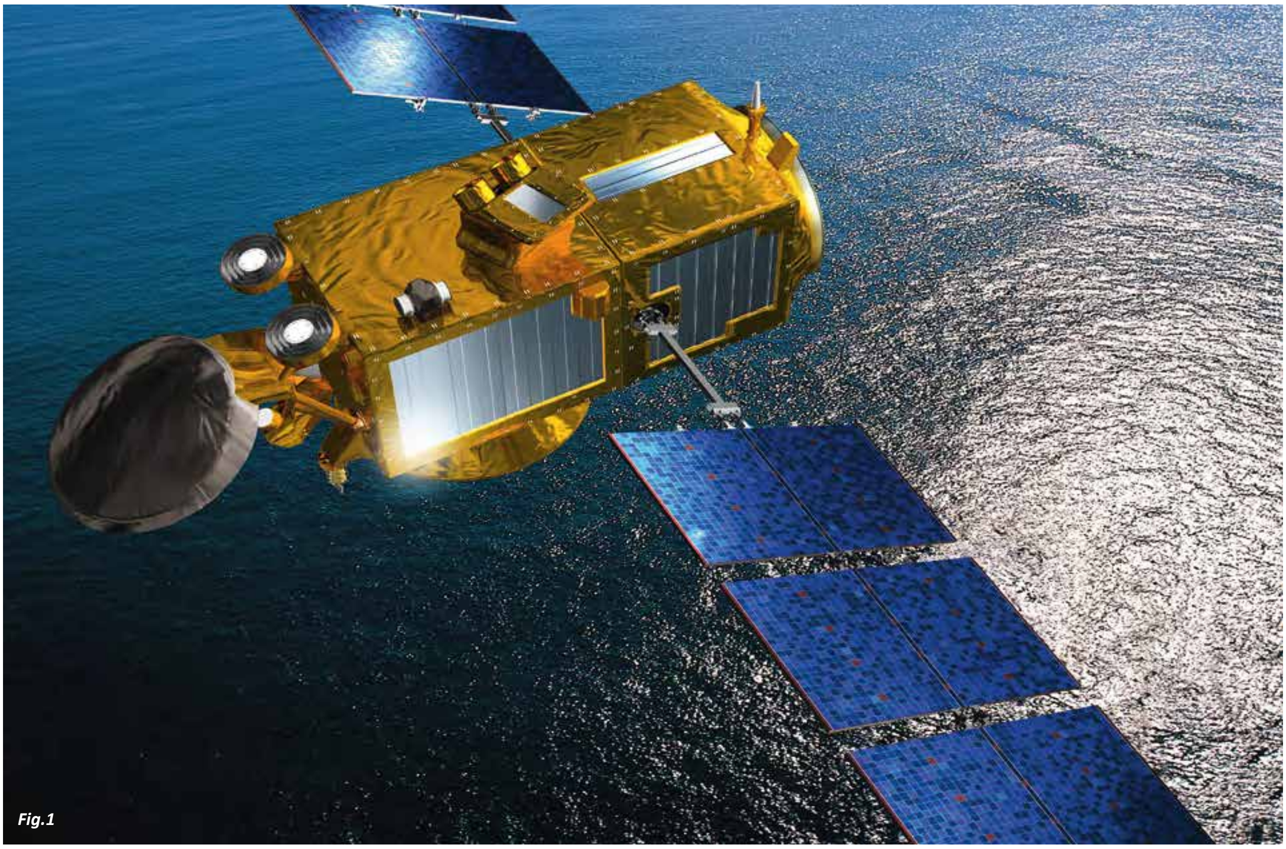

Fig.1

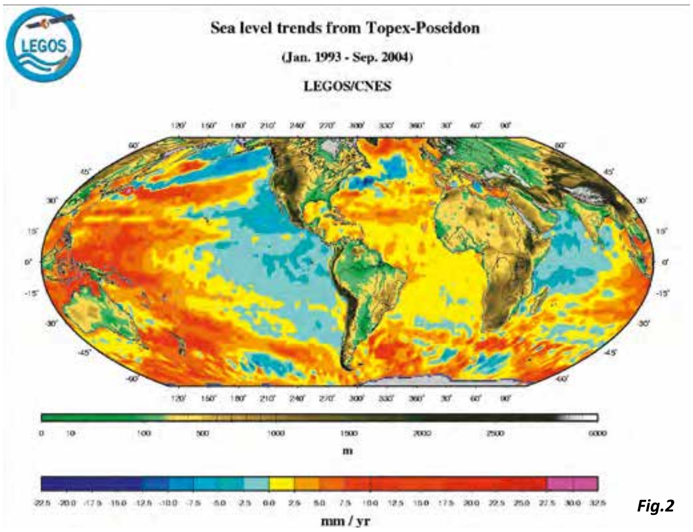

Fig.2

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
POSEIDON	Sea level measurement	CNES
AMR (Advanced Microwave Radiometer)	Water content in the troposphere for tropospheric correction on POSEIDON measurements	NASA/JPL
DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite)	Orbit determination	CNES
GPS (Global Positioning System)	Orbit determination	NASA/JPL
LRA (Laser Retroreflector Array)	Passive / Orbit determination	NASA/JPL
CARMEN 3 (CARactérisation et Modélisation de l'ENvironnement)	Dosimeter	CNES
LPT (Light Particle Telescope)	Dosimeter	JAXA

SCIENTIFIC HIGHLIGHTS

JASON-3 (Fig. 1) was launched 17 January 2017 from California's Vandenberg Air Force Base. Its nominal 3-year mission will continue nearly a quarter-century record of monitoring changes in global sea level. By measuring the changing levels of the ocean, JASON-2 and its predecessors have built one of the clearest records we have of our changing climate (Fig. 2). That record began with the 1992 launch of the NASA/CNES TOPEX/POSEIDON mission and was continued by JASON-1, launched in 2001 and JASON-2, launched in 2008. Data from JASON-3's predecessor missions show that mean sea level has been rising by about 0.12 inches (3 millimetres) a year since 1993.

These measurements of ocean surface topography are also used by scientists to calculate the speed and direction of ocean surface currents and inform scientists about the distribution of solar energy stored in the ocean. This information is used to monitor climate change and track phenomena like El Niño. It will also enable more accurate weather, ocean and climate forecasts, including helping global weather and environmental agencies more accurately forecast the strength of tropical cyclones. JASON-3 data will also be used for operational applications, including the monitoring of deep-ocean waves; forecasts of surface waves for offshore operators; and forecasts of currents for commercial shipping and ship routing. JASON-3 is operated by the National Oceanic and Atmospheric Administration (NOAA) in partnership with NASA, the French Space Agency Centre National d'Etudes Spatiales (CNES) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

MISSION STATUS

JASON-3 is currently behaving nominally, providing very precise data as expected. KPI are provided by CNES to EUMETSAT (for Copernicus) every 3 months, showing excellent performance.
After several months of formation flying with JASON-2 in order to calibrate its measurements, JASON-3 was left alone on its orbital position, becoming in June 2016 the reference mission for global altimetry.
Its expected lifetime being 2 years, with an extension of 3 years, and the satellite being launched on 17 January 2016, it has today exceeded the first foreseen period, and its mission will have to be officially extended by the end of 2018, requesting an extension to the end of 2021. Knowing the current perfect technical status of the platform and of all its instruments, there is few risk that the extension will be refused. As an example, JASON-2, which was built with the exact same design as JASON-3, celebrated in June its 9th birthday in space, and is still providing very fruitful data.
The last REVEX (REVue d'EXploitation) was held on 2-4 May 2018 in EUMETSAT (Darmstadt), gathering all 4 partners for the annual examination of the system, and ensuring the continuation of the excellent cooperation between them.

Fig. 1: JASON-3 © *CNES/ill/DUCROS David, 2013*
Fig. 2: Map of the geographical distribution of rates of sea level change (Observed by Topex / Poseidon, for the period 1993-2004) © *Legos*

AUTHOR
C. Guinet[1], J.-B. Charrassin[2]
1 CEBC (Chizé Centre for Biological Studies), UMR 7372 CNRS-ULR, Route de Chizé, 79360 Villiers en Bois, France
2 LOCEAN (Oceanographic & Climate Laboratory: experiments and digital approaches), Sorbonne Univ., UPMC Univ, UMR 7159 CNRS, IRD, MNHN, 4 place Jussieu, 75252, Paris, Cedex 5, France

When seals help us monitoring the oceanographic and ecological conditions of the Southern Ocean

Seals are used to collect in-situ measurements of temperature, salinity, fluorescence and light that are performed along seals' tracks during their dives completing surface satellite observations. Information on sea states, wind direction and strength are also sampled. Simultaneously, biological information on nekton and on the concentrations of seals' preys are also collected to investigate how oceanographic conditions influence the distribution of biological fields at a very fine spatial scale.

The use of animal-borne autonomous recording tags is becoming widespread and allows the acquisition of huge quantitative data sets for inferences on movement, ecology and behaviour of animals moving freely in their natural environment. Most oceanic ranging seal species performed long distance foraging trip while diving continuously at great depth such as elephant seals (mean ranging between 400 and 600 metres, but up to 2 000 meters).

As part of the *CNES-TOSCA* programme, multi-channel data loggers mostly developed in collaboration with the Sea Mammal Research Unit (UK) are deployed on these deep diving seals and data are sampled at high-resolution over large temporal and spatial scales, including geographical areas poorly covered by satellite data. Low resolution data can be transmitted through satellite but high resolution data requires recapturing the seals when they come back on land for moulting and breeding to retrieve the loggers.

In addition to providing parameters on animal biological processes, seals provide valuable environmental parameters (e.g., temperature, salinity, light, fluorescence, and dissolved oxygen, etc.) and currently seals data represent 80% of the T/S profiles available south of 60°S and 99% of T/S profiles collected within Antarctic sea ice. The first monthly climatology of chlorophyll profiles was constructed from southern elephant seal data [1]. Recently, acoustic and accelerometer measurements provided by seals used as gliders of opportunity allowed to estimate above-surface meteorological conditions (wind direction and strength as well as waves frequencies and amplitudes) [2, 3].

On the biological side, the local density of biological fields can be assessed by a combination of measurements provided by instrumented seals. Those measurements ranged from fluorescence used as an index of phytoplankton concentrations, bioluminescence assessed from light measurements and active acoustic (*i.e.*, µ-sonar) to estimate the concentration of a broad range of nektonic organisms: zooplankton, jellyfish, squids, fish as well as prey encounter events by seals during their dives [4]. The vast majority of these data are collected for under-sampled high latitude oceans and therefore seals' data are of a particular interest for providing in-situ measurements for a number of CNES sponsored satellite ocean monitoring system such as:

- SENTINEL-3 prolonging surface measurements of sea temperature and chlorophyll in the water column,
- SMOS and CRYOSAT measurements were compared with in-situ salinity profiles provided seals. Those complementary seals' profiles were used to identify areas and the amount of sea ice formation and melting within the Southern Ocean [5, 6].
- CFOSAT measurements were compared with in-situ assessment of wind strength, direction and sea-state provided by seals.

Over the last few years, special attention was paid to better assess oceanic biological fields. As mentioned above, this information was inferred from the combination of several measurements. The most innovative approach was to assess nekton concentration from the detection of bioluminescence events from high resolution light measurements combined with active echo-sounding of the water column with a small size head-mounted micro-sonar developed in collaboration with M. Johnson (SMRU) and the assessment of prey encounter events from head-mounted accelerometers detecting jaw movements.

The simultaneous extraction of data from biological samples and measurements of high resolution oceanographic data provides a unique opportunity to investigate how sub-mesoscale oceanographic processes spatially structure (vertically and horizontally) biological fields. Furthermore, the high resolution density fields obtained from the temperature and salinity measurements (Fig. 1) are currently being used to assess both the meridional transport by currents along fronts as well as the variation in vertical advection intensity related to the sub-mesoscale structures encountered by the seals along their tracks.

To our knowledge, these data are unique and without any equivalent for the Southern Ocean. They are highly relevant to the on-going high resolution altimetry SWOT satellite programme. For instance, these data will allow a better assessment of the vertical advection and therefore of the injection of nutriments within the euphotic layer to sustain primary production in relation to fine scale oceanographic structures. Furthermore, turbulent transport is able to create coherent structures (like reservoirs and transport barriers) that organise the distribution of the transported phytoplankton and nekton. Turbulent transport was found to structure (in space and time) marine ecosystems and biodiversity in the global oceans and explains the foraging success of top marine predators [7] (Fig 2a & b).

High resolution in-situ data sampled by seals provides a unique opportunity to compare the output of those simulations with field observations where such in-situ measurements are lacking. This is particularly the case for the Southern Ocean. Furthermore, these data are crucial to develop new ecological applications inferred from satellite observations of the oceans. In collaboration with CNES and CONAE, these studies will continue for the years to come both on the Kerguelen and the Patagonian sector of the Southern Ocean to better assess the wind stress event on the vertical distribution of phytoplankton.

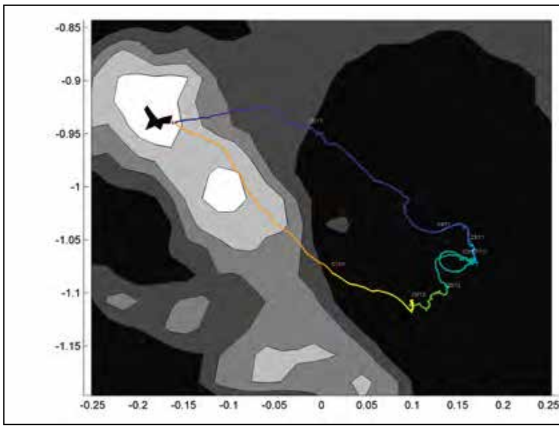

Fig.1a

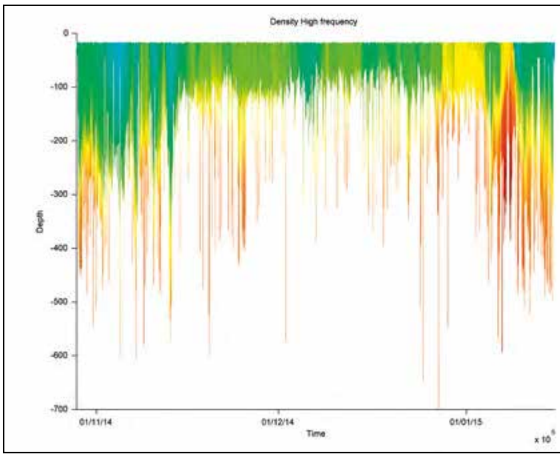

Fig.1b

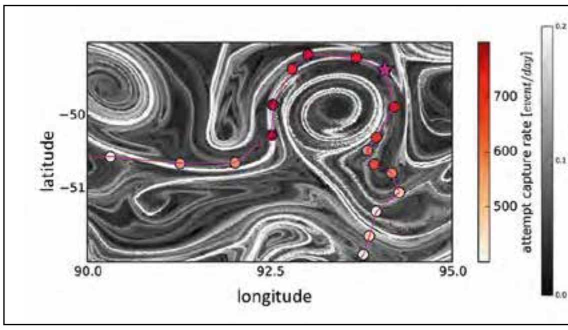

Fig.2

Fig. 1: a) A track of a post-breeding southern elephant seals females colour coded for time from the 10/27/2015 to the 01/12/2016 and b) the corresponding high resolution density profile inferred from in-situ temperature and salinity measurements along the track shown of a southern elephant seal revealing the crossing of density fronts.

Fig. 2: Fronts identified as Finite Size Lyapounov Exponent (gray scale background image) computed the day corresponding to the location marked as a purple star (02/12/2011) correspond to a higher attempt capture rate. Note the higher foraging performances of this seal when foraging on the edges of the cyclonic eddy (From Della Penna, *et al.*, 2015).

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AUTHOR
F. Ardhuin[1], B. Chapron[1], F. Nouguier[1],
LOPS (Laboratory for Ocean Physics and Satellite remote sensing), Univ. Brest, CNRS UMR 6523, Ifremer, IRD, 29200, Brest, France

Monitoring wind, waves and currents: scientific challenges and opportunities for the SKIM mission

Ocean surface velocity combines surface currents (driven by winds, density gradients, tides...) with the wave-induced Stokes drift. They transport heat, salt and everything natural or man-made, including plastics. Wind, waves and currents also control air-sea fluxes. Although satellite altimeters have been around for over 20 years, the along-track sea level anomaly and significant wave height leave most of the multi-scale motions of the oceans uncharted. SKIM [1] is designed to expand these horizons.

SURFACE CURRENTS: THE OBSERVATION GAP

Surface currents are directly observed by in-situ acoustic methods or drifting instruments that report velocities near the surface, typically at depths between 1 to 15 m. Yet, the surface drifter buoy programme only has less than 1500 drifters across the globe (http://www.aoml.noaa.gov/phod/dac/index.php). Alternative and less direct measurement techniques have been developed and are widely used.

High Frequency (5 to 50) MHz Doppler radars (usually called “HF radars”) are now widely used [2]. They measure the phase speed of ocean waves that match the Bragg resonance of the radar, for example a wavelength of 12 m for a 12 MHz radar. These ocean waves are most sensitive to currents in the top 2 metres [3]. However, HF radar coverage is usually limited to less than 300 km from the coast. Elsewhere, less direct proxies are obtained from satellite data using dynamical assumptions of quasi-geostrophic balance.

Hence the deviations of the sea level from the geoid is a “dynamic height” from which a “geostrophic current” can be derived. When combined with an estimate of the mean dynamic topography using gravity measurements and drifters, the sea level anomalies provided by nadir altimeters give precious measurements of the non-stationary currents (rings, meanders of the Gulf Stream, eddies) [4]. This is appropriate for spatial scales typically larger than 200 km wavelength, and time scales of 15 days and more.

This balance is disturbed by many factors, including winds and tides, and a better approximation of the surface current, at least for large time scales, is given by adding a so-called “Ekman current” that is the theoretical response to a constant and uniform wind, to the geostrophic current. The geostrophic breaks down at the equator, making the estimation of tropical currents from altimetry and wind measurements a real challenge. Fig. 1 illustrates the difficulties of a state of the art ocean circulation model to reproduce the variation of currents at time scales of a few days. Especially, the East-West (U) component at the equator is not constrained at all by the assimilated altimetry data.

As a result, many alternative methods have been proposed and demonstrated, in particular the measurement of the range component of the surface current using radar Doppler shifts from a fixed radar antenna [5]. Building on these results, we have proposed a Sea surface Kinematics Multiscale monitoring (SKIM) mission, in order to map the current vector over a wide enough swath (around 300 km) that can provide a global monitoring of surface currents with a revisit time ranging from 6 days at the equator to 12 hours at 83°N.

PRINCIPLE OF THE SKIM MISSION

In currents measuring, a key difficulty of all Doppler radar measurements is that the phase information combines motions of all detected sea surface elements, and instantaneous velocity is dominated by wind-generated waves. Therefore, the mean Doppler velocity contains a wave bias that is a function of radar frequency, incidence angle a sea state. For incidence angles under 20°, the solid theoretical foundation for this wave bias [6] has been verified with platform-based, airborne [6] and satellite data [5]. In general, the wave bias

is proportional to a mean slope velocity that is tightly related to the Stokes drift [6], and the Stokes drift is correlated to the wind speed with a +/- 40% rms variation due to sea state [1, 3]. For these reasons, SKIM proposes to measure the directional wave spectrum down to 20 m wavelength, to make the most accurate estimation of the wave bias.

For these reasons, SKIM is built around a Ka-band Doppler wave spectrometer that includes a nadir radar beam. Wave measurements are well understood at low incidence angles [6], but the current signal increases with incidence angle. We have thus chosen a compromise incidence angle of 12°. From a 700 km orbit this gives a 270 km wide swath. Fig.2 illustrates the sampling (see also https://www.youtube.com/watch?v=x-tgAp_7EmAc).

As a result, the coverage provided by SKIM is sparse (contrary to the visual impression of Fig.2 the footprints do not overlap). Accordingly, SKIM will resolve scales within the 6 km footprint at resolutions of 4 m in range by 50 to 300 m in azimuth, then scales longer than 40 km wavelength by combining the footprints. Therefore, the expected error at that scale is of the order of 5 cm/s [1].

ONGOING WORK

Based on this analysis the SKIM mission was pre-selected for ESA Earth Explorer 9 (EE9), together with the Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM). A detailed study (phase A) started in November 2017, which will lead to a User Consultation Meeting in mid-2019 that will select the EE9 mission (SKIM or FORUM) to be launched in 2025.

The SKIM mission is now being refined around the primary objectives of mapping surface currents, wave spectra and ice drift, and secondary objectives on winds, extreme waves and water levels at the coast and sources of microseisms.

Fig. 1: Snapshot (left) and time series (right, dashed lines) of near-surface current, from the Copernicus Marine Environment and Monitoring Service (CMEMS) 1/12° global ocean model at 2 tropical locations in the Atlantic Ocean. Overlaid solid lines are measured time series at (21°N,23°W) and (0°N, 23°W) are from the PIRATA moorings. © *F. Ardhuin, LOPS.*

Fig. 2: Top-left illustrates the sampling with 8 beams across a 270 km swath. The real diameter of the footprints is 6 km and is here exaggerated for readability. Each colour is a different beam. The underlying map shows current velocity around the Gulf Stream. Top-right shows how the current vector (black) projects onto the different beams (colour), giving series of velocities (bottom) across the current features © *F. Ardhuin, LOPS.*

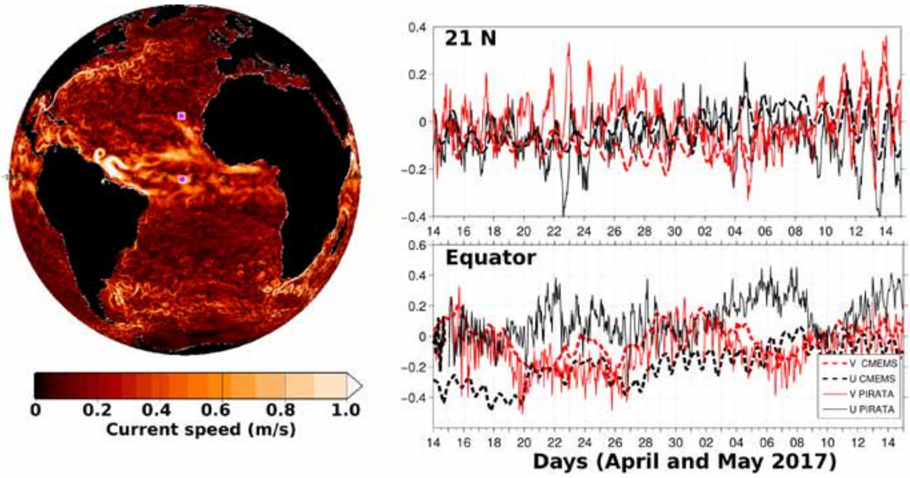

Fig.1

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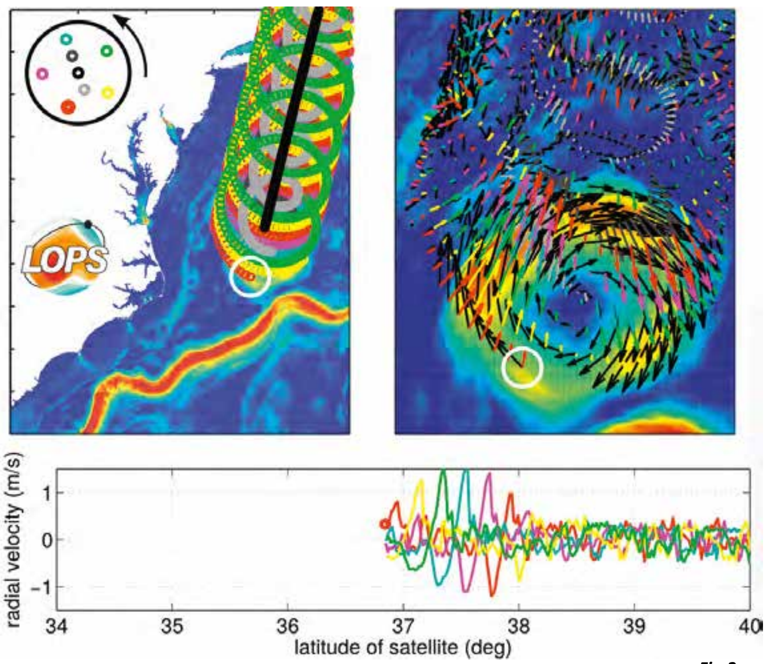

Fig.2

AERIS, data and services hubs for the atmosphere

AERIS is the result of a joint effort, about which a convention has been signed in 2017, between the following organisations: CNES, CNRS, Météo France, IRD, CEA, IGN, Ecole Polytechnique, Université Toulouse III, UPMC, Université de Lille, Région Hauts de France.

Fig.1

The aim of the AERIS project is to provide the scientific community with a high-performance service and tools for collecting, processing and distributing atmospheric data by giving them high visibility, particularly at the international level. AERIS also makes it possible to promote synergy between data (comparisons, model observations, multi-instrument algorithms).

AERIS is now part of a larger entity, the infrastructure of data hub research and Earth System services coordinating the activities of 4 data hubs and thematic services:
- THEIA: continental surfaces
- AERIS: atmosphere
- Form@ter: solid earth
- ODATIS: ocean

AERIS, which has been active for 3 years, now plays a major role in the French and European supply and services, particularly in connection with ESA's Earth Explorer missions, the Copernicus programme and EUMETSAT programmes. The main client of AERIS is the French research community but AERIS can also respond, within the limits of its means, to requests from other actors (including the private sector).

Organisations wishing to propose a project to AERIS go through a year round open invitation to tender (https://en.aeris-data.fr/call-for-project/) which is subjected to arbitration 3 to 4 times a year. Projects are evaluated from a scientific point of view by a Scientific Committee.

Projects mainly fall into the following categories:
- Support for measurement campaigns before, during and after the campaign
- Implementation and / or programming of data processing codes (in-situ data processing, spatial data processing, combination of in-situ data, spatial data and models, etc.)
- Exploitation of data processing codes and data reprocessing
- Archiving, visualisation and provision of datasets (in-situ, spatial, models, fusion products, mirroring of external libraries...)

AERIS provides support in the following projects (non-exhaustive list):
- Space missions: POLDER, PARASOL, MEGHA-TROPIQUES, CALIPSO, GOES, MSG, IASI, GOSAT...
- Ground stations (including ocean sensors): AERONET, ACTRIS, IAOOS, NDACC...
- Databases: Geisa, IUPAC...
- Data collected by airplanes or balloons: SAFIRE, IAGOS, balloon campaigns...
- Multi-sensor campaigns: AMMA, MISTRAL

SCIENTIFIC HIGHLIGHTS

- **L4-TAPEER-BRAIN: finalising the software**

The treatment chain will evaluate the volume of water falling per unit area, with an associated estimated uncertainty. The geographical resolution is 1 deg, and the measurements are recorded daily.

The satellites treated by this chain are:
MT/SAPHIR,
GCOMW1/AMSR-2,
F15/SSMI, F16/SSMIS,
F17/SSMIS, F18/SSMIS,
TRMM/TMI, MFG, MSG,
MTSAT, HIMAWARI,
GOES-E, GOES-W
Data are accessible without restriction.

- **CALIPSO**
  Recovery of all V4.10 data to ICARE (> 70TB) following full reprocessing of the NASA Level 1 product archive (V4.10).
  SODA (Synergized Optical Depth of Aerosols): Development of the 20 km chain.

- **IASI**
  SO_2 products start to be distributed.
  The CO will now be recovered from EUMETSAT and converted back to a common format for IASI A and B.
  CH_4 is distributed to CAMPS for free.

MISSION STATUS

Setting up and opening of the AERIS portal acting as an interface between users and CDS. Queries can be done by accessing a catalog and defining keywords. The portal is accessible at https://en.aeris-data.fr/.

Fig. 1: MERLIN satellite illustration © *CNES/DUCROS David, 2016*

CALIPSO, a minisatellite cracking the secrets of clouds

Orbiting at 705 km above the Earth, the CALIPSO mission (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations) is a pioneering international partnership between NASA and the French Space Agency, CNES.

///

Launched on 28 April 2006, CALIPSO measurements now fulfil a crucial, well-recognised need for high resolution atmospheric profiling, and are proved to be essential in reducing the uncertainties that limit our understanding of the role of aerosols and clouds in the global climate system.

When CALIPSO was first proposed, the lack of accurate knowledge about the 3-dimensional (3D) distribution and properties of aerosols and clouds represented the largest source of uncertainties affecting climate model predictions on the impact of increasing greenhouse gas concentrations.

CALIPSO continues to fulfil crucial measurement needs by providing the high vertical resolution profile measurements and infrared observations of aerosols and clouds that are required in fundamental research to reduce uncertainties in climate predictions. The original CALIPSO mission objectives state that CALIPSO and the A-Train (EOS Aqua at the time) together would provide:

- Observation-based estimates of aerosol direct radiative forcing of climate made from a global measurement suite.
- An improved empirical basis for assessing the aerosol indirect radiative forcing of climate.
- A factor-of-2 improvement in the accuracy of satellite estimates of longwave (LW) radiative fluxes on the Earth's surface and in the atmosphere.
- A new ability to assess cloud-radiation feedback in the climate system.

The CALIPSO mini-satellite—a spacecraft in the 500-kg class—is a joint CNES-NASA mission. CNES is responsible for the satellite and spacecraft bus (designed under contract with Alcatel) and the infrared imager (designed with Sodern), while NASA is leading the mission and supplied the payload (with LIDAR as main instrument) and launch vehicle. Initially scheduled to end in 2011, the mission was extended to the end of 2020.

SCIENTIFIC PAYLOAD

The CALIPSO instrumental suite consists of a 2-wavelength polarisation-sensitive LIDAR, a 3-channel infrared imaging radiometer (IIR) and a single channel wide field-of-view camera.

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS / LABORATORIES
Main instrument: a backscattering LIDAR (532 nm and 1064 nm with polariser), equipped with a 1-metre diameter telescope	provides high-resolution vertical profiles of aerosols and clouds.	Dave Winker, Langley Research Centre (LaRC)
IIR (Infrared Imager Radiometer)	The IIR images provide the context of the LIDAR measurement by night and allow the co-registration with the MODIS multispectral radiometer on board Aqua. IIR measurements, combined with the LIDAR information, enable to retrieve the size of ice particles in semi-transparent clouds.	Jacques Pelon, Latmos/IPSL
WFC (Wide-Field Camera)	The WFC images provide context for the scientific analysis of the vertical profiles measured by the LIDAR.	Dave Winker, Langley Research Centre (LaRC

SCIENTIFIC HIGHLIGHTS

The A-Train is a unique space observatory, by the number of platforms involved, the use of observations and results obtained. Using the CALIOP (Cloud and Aerosol Lidar with Orthogonal POlarisation) backscattering LIDAR measurements, the infrared imaging radiometer IIR (Imaging Infrared Radiometer), designed by France, allowed the characterisation of the optical and micro-

physical properties of semi-transparent ice clouds. The combination of co-located CALIPSO and CloudSat observations led to very important breakthroughs for the characterisation of clouds and the evolution of numerical model parametrisations, particularly using the DARDAR product developed in France and archived at AERIS/ICARE. Thanks to the coupling between these observations of the A-Train, the restitution of the cloud phase of the boundary layer clouds has thus been achieved in boundary layer convective clouds of the southern hemisphere, as presented in Fig. 1. The CALIPSO mission played a key role for cloud phase detection in this approach, with an unmatched vertical resolution.

This observation provided the index of the persistent Southern Ocean cloud bias that is now identified as being due to the lack of supercooled water at the top of the modelled clouds in the cold sector of all weather systems. The representation of these clouds was a major problem in weather and climate prediction models, leading to a large radiative imbalance at mid-latitudes in the southern hemisphere. The modified version of the ECMWF model made it possible to properly represent the occurrence of supercooled water cloud, correcting the bias in the reflected flux.

CALIPSO is also providing aerosol observations. All are thus very intensively used by modellers and many studies have been and are being conducted by the international scientific community to better understand meteorological, physico-chemical (air quality) and climatic processes, and better represent their parameterisations in numerical models. More than 2 000 publications in peered reviewed journals use the observations of CALIPSO, largely in the context of analysis comparisons (directly or using a LIDAR simulator), but also for assimilation purposes. The data set obtained by the mission is now approaching 12 years and the good behaviour of the instruments and platform makes it possible to hope to further increase this set of observations, while the version 4 of the Level 3 data will be available.

MISSION STATUS

The 3-year nominal mission was completed on 28 April 2009, since then, six 2-year mission extensions were decided following the NASA Earth Science Division Senior Reviews / CNES “Revue d’Extension de Mission (REDEM)” in 2009, 2011, 2013, 2015, 2017.

Since science operations began on 7 June 2006, data have been collected almost continuously and all instruments have performed exceptionally well. The primary laser was taken out of service on 16 February 2009 for pressure issue. The backup laser was activated on 12 March 2009, and has since performed superbly. The same issue affected the backup laser, but at this time, observations are continued as data quality is maintained outside the South Atlantic Anomaly region. It should be feasible to restart the primary laser. The spacecraft and platform subsystems continue to operate as expected or even better, with all of their redundancy intact. There are sufficient fuel reserves to allow CALIPSO to maintain its current inclination within the A-Train until at least 2020, after which CALIPSO’s equatorial crossing time will begin to drift outside the MODIS swath. The power system is healthy, and adequate margins remain to support the next 3 or more years of continued operation.

A full catalogue of standard and expedited CALIPSO data products is routinely created, archived, and distributed to scientific researchers worldwide through data centres in the United States and France.
To date, there have been 4 comprehensive releases of the standard data products, with each new release offering substantial improvements in retrieval accuracies and uncertainty characterisation.

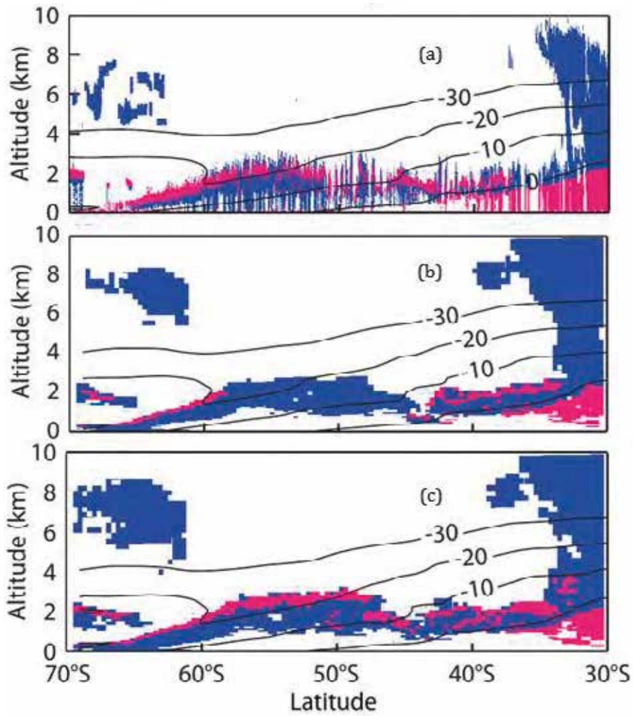

Fig.1

Fig. 1: Vertical section of the cloud phase given by a) observations using the DarDar (Radar-Lidar) product from the combined CALIPSO / CloudSat data (product available on the AERIS database in Lille, France, for more information see http://www.icare.univ-lille1.fr), b) simulations of the ECMWF model prediction model with the standard physical model and c) simulations with an experimental version of the prediction model with a modified parameterisation of the convective cloud phase. Blue is for ice, red is for liquid water and rain.
© from Forbes, R. et al. (2016), Reducing systematic errors in cold-443 air outbreaks, ECMWF Newsletter, 146, 17-22.

AUTHOR

P. Formenti[1], C. Flamant[2], F. Waquet[3], M. Mallet[4], B. D'Anna[5], K. Schepanski[6], S. J. Piketh[7]

1 LISA (Inter-University Laboratory of Atmospheric Systems), UMR CNRS 7583, Université Paris Est-Créteil and Paris Diderot, IPSL, 61 Avenue du général de Gaulle, 94010 Créteil, France

2 LATMOS (Atmospheres, Environments and Spatial Observations Laboratory), UMR CNRS 8190, UPMC/UVSQ, IPSL, 4 Place Jussieu, 75252 France

3 LOA (Laboratory of Atmospheric Optics), UMR CNRS 8518, Université de Lille, 59655 Villeneuve d'Ascq, France

4 CNRM (National Centre for Meteorological Research), UMR CNRS 3589, Météo-France, 42 avenue Gaspard Coriolis, 31057 Toulouse, France

5 LCE (Laboratory of Environmental Chemistry), UMR CNRS 7376, Aix-Marseille Université, 3 place Victor Hugo, 13003 Marseille, France

6 Leibniz-Institut für Troposphärenforschung e.V. (TROPOS), Permoserstraße 15, 04318 Leipzig, Germany

7 Climatology Research Group, North-West University, Potchefstroom, South Africa

AEROCLO-SA, the AErosols, RadiatiOn and CLOuds in Southern Africa

The AEROCLO-SA project investigates the role of aerosols on the climate of Southern Africa, a unique environment characterised by a semi-permanent and extended stratocumulus cloud deck. The project aims to improve our understanding of aerosol-cloud-radiation interactions and the development of innovative aerosols and clouds remote sensing algorithms in preparation for 3MI and IASI-NG on board METOP-SG. It is based on a field campaign conducted in August/ September 2017 over Namibia.

The south-tropical Atlantic off Southern Africa's west coast is highlighted by the latest report of the IPCC |1] as one of the regions of the globe where climate change could be the most obvious. Due to the low temperature of surface waters, the western coast of Southern Africa is characterised by near-permanent marine stratocumulus-type clouds located in the marine boundary layer. Stratiform clouds represent the most efficient cloud regime for reflecting solar radiation to space, thus inducing a significant negative radiative effect at the top of the atmosphere, opposite to that exerted by greenhouse gases. The microphysical and optical properties of these stratocumulus affect the temperature gradients of the surface waters of the Atlantic Ocean and the large-scale energy balance, which determine the position of the intertropical convergence zone, and therefore the monsoons of Western Africa and Asia.

This region is also characterised by high aerosol loads. Southern Africa is the world's largest source of biomass burning aerosols, which develop during the dry season in the southern hemisphere. Desert areas, such as the Etosha Pan desert in Namibia, contribute to the emission of dust. The Benguela upwelling, one of the most productive oceanic upwelling of the world in terms of primary nutrients, contributes to the exchange of materials between the ocean and the atmosphere.

In spite of these facts, the aerosol direct, semi-direct and indirect effects on the regional radiation budget are to date very poorly known, affecting our climate prediction capabilities. The AEROCLO-SA project aims to fill these gaps, by providing, from ground and airborne measurements in the atmospheric column, new solid observations of the regional aerosols, in order to evaluate their representation in climate models.

Because of the possibility of observing complex scenes with absorbing aerosols overlaying clouds, ocean and bright desert surfaces, the project also targeted the advancement of the representation of aerosols and clouds by spaceborne remote sensing. It targeted an observational dataset of absorbing aerosols above ground and clouds to support the development of innovative algorithms for new space missions, including 3MI, heir of POLDER-3, and IASI-NG, heir of IASI, on METOP-SG. This type of product is necessary to acquire a good regional representation of aerosols.

Indeed, climate models suggest that, in this region of the world, the presence of absorbing aerosols from biomass fires transported over the stratocumulus could reduce the radiative flux at the top of the atmosphere, instead of increasing it, thus causing regional warming as greenhouse gases do.

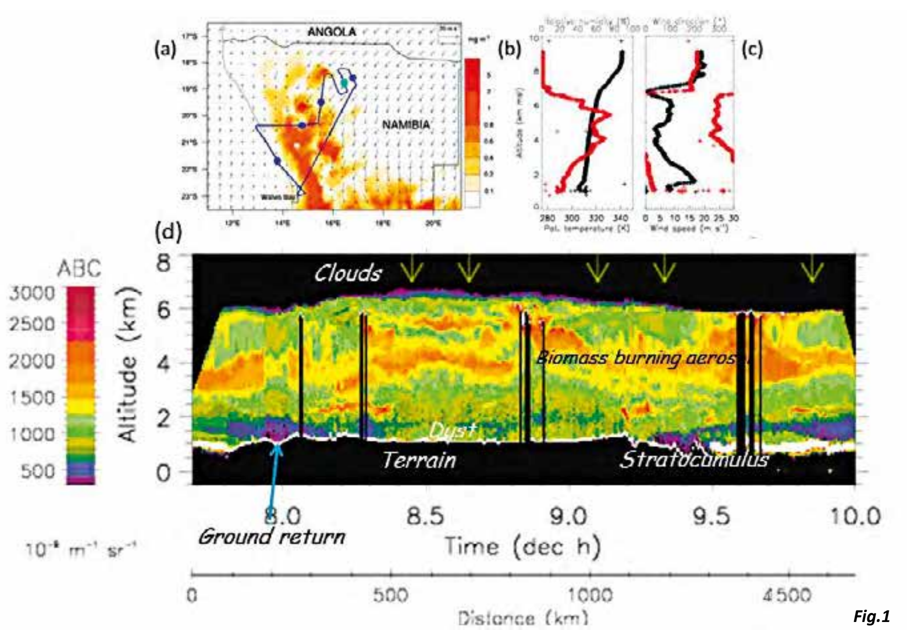

Fig.1

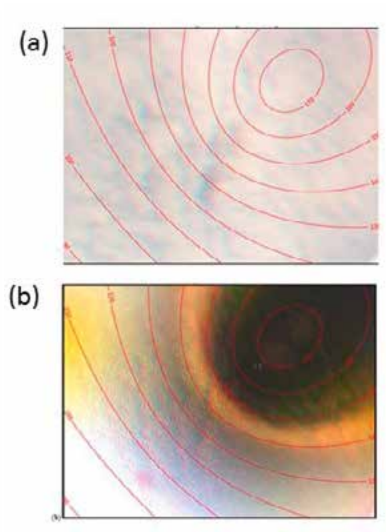

Fig.2

The experimental campaign took place from 22 August to 12 September 2017 on the Namibian Atlantic coast, with the deployment of the Falcon 20 of the Instrumented French Aircraft Service for Environmental Research (Safire) and the mobile station Portable Gas and Aerosol Sampling Units (PEGASUS).

Ten Falcon 20-flights took off from Walvis Bay International Airport for a total of 30 hours of scientific flight. The Falcon 20 was equipped with the LNG lidar operated with the support of the CNRS-INSU technical division, allowing to "profile" the atmosphere at 3 different wavelengths (355, 532 and 1064 nm) to analyse the structure and radiative characteristics of aerosol plumes. It also carried the MICROPOL-UV and OSIRIS instruments measuring total and polarised luminance at several wavelengths from ultraviolet to mid-infrared. OSIRIS is the airborne demonstrator of the future 3MI onboard sensor. AEROCLO-SA was also the first opportunity to adapt the plasma sun photometer aboard the Falcon 20, to measure the extinction by aerosols above and below the stratocumulus clouds.

The PEGASUS ground mobile station was operated on the campus of the SANUMARC Research Centre at the University of Namibia in Henties Bay (22°6'S, 14°30'E). PEGASUS is equipped with isokinetic sampling veins for aerosols and atmospheric gases. It measured the chemical composition of the aerosols, mass and number concentrations, size distribution, optical properties of scattering, extinction and absorption, hygroscopic properties and aerosol cloud activation spectra. The ground-based system was supplemented with a meteorological station and 2 lidars, including the MPL system managed by NASA/GSFC and by a sun photometer part of the AERONET/PHOTONS network.

The airborne campaign benefited from a particularly favourable meteorological situation, favouring the transport of aerosols along the Namibian coast in the Falcon 20 range. A 3-4 km thick layer of aerosol of biomass fires from Angola could be documented in-situ and using remote sensing instruments over different types of highly reflective oceanic (clear skies and stratocumulus) and land (desert, dry lakes) surfaces. The complex folding of the atmosphere between dust, biomass burning aerosols and stratocumulus cloud layers was clearly observed by lidar (Fig. 1). The influence of biomass aerosols on the radiation reflected by stratiform clouds was clearly shown by the spectral total and polarised luminance measurements (Fig. 2), indicating the browning of clouds when biomass burning aerosols are present aloft (Fig. 2b). These observations will serve as a basis for future algorithmic developments.

Fig. 1: (a) Dust emission and 10 m wind field, MESO-NH forecast on 5 September 2017. Black line: Falcon 20 ground track. Blue and turquoise dots: position of dropsondes. (b) Potential temperature (black) and relative humidity (red) from dropsondes. (c) wind speed (black) and wind direction (red). (d) Aerosol backscatter coefficient (LNG lidar). *© C. Flamant, Latmos/IPSL and J.-P. Chaboureau, LA.*

Fig. 2: Colour compositions made from (a) total luminance and (b) polarised luminance of channels 490, 670 and 865 nm observed by the OSIRIS instrument over a cloud scene. The concentric circles represent the isocontours of diffusion angle in steps of 10°. *© F. Waquet and J.-M. Nicolas, LOA.*

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AUTHOR
R. Roca[1], P. Chambon[2],
1 LEGOS (Laboratory for Studies in Geophysics and Spatial Oceanography), CNRS UMR 5566, 14 avenue Edouard Belin, 31400 Toulouse, France
2 CNRM (National Meteorological Research Center), METEO-FRANCE, CNRS UMR 3589, 42,avenue Gaspard Coriolis, 31057 Toulouse Cedex 1, France

Tropical convection revealed: results of the MEGHA-TROPIQUES mission after 6 years in orbit

MEGHA-TROPIQUES (MT) operates on a low inclined orbit that allows for a high revisit capability in lines with the fast fluctuations of tropical atmospheric convection. The precipitation, water vapour and radiation sensitive payloads are used in various scientific explorations. A couple of these are illustrated here. The analysis of the variability of tropical precipitation reveals the specific role of the organised convective systems in the Eastern Pacific. Operational weather forecasts are improved because of the assimilation of SAPHIR data in all sky conditions.

Megha stands for clouds in Sanskrit and *Tropiques* for tropics in French and it clearly convey the core interest of the mission: convective clouds in the tropical climate system. The precipitation, water vapour and radiation sensitive payloads are characterised by high instrumental performances (Roca *et al.*, 2015) [1]. The SAPHIR and SCARAB instruments further show excellent stability since launch in October 2011 enabling the pursuit of the 2 major objectives of the mission: to better understand tropical convection and to improve tropical weather forecasts. Two examples of such investigations are summarised below.

The variability of tropical precipitation is documented using data from the Global Precipitation Measurement constellation and from MT/SAPHIR observations that are merged together through an elaborate algorithm. The associated daily precipitation product has been released in summer 2017. Berthet *et al.* (2017) [2] recently investigated the intra seasonal variability of the Pacific Eastern region using this product. The Figure 1 reveals the striking contrast between the easterly and westerly low-level winds regimes. The northern part of the domain experiences a strong increase in precipitation during the westerly regime contrary to the southern region which shows a significant decrease in precipitation over the Intertropical Convergence Zone. The reasons for these discrepancies are further investigated by a geostationary-based analysis of mesoscale convective systems. In the southern region, only the occurrence of these systems is responsible for the intra seasonal anomalies. There, the normalised cumulated distribution of precipitation to the duration of these systems are identical and characterised by around 80% of the rainfall amount due to the systems lasting up to around 20 h (Fig. 1). On the opposite, the northern region dynamics is characterised by a drastic change in storms morphology with longer lasting systems prevailing during the westerly regime. This modification of the intrinsic properties of these systems has strong implications for the latent heating of the atmosphere by the most organised mesoscale convective systems and the associated feedback on the large-scale circulation of the region.

Despite not being an operational mission, data from SAPHIR instrument on board the MT mission are distributed in real time to numerical weather predictions centres. These data are now being assimilated, in clear sky, by various operational numerical weather prediction centres worldwide (e.g. METEO-FRANCE, Met Office, NOAA) and are globally improving the predictions in the tropics. An emerging scientific question related to assimilation concerns the use of the 183 GHz radiances in scattering regime. Recent developments now allow to study the impact of assimilating these observations under cloudy and precipitating conditions; it is the case at ECMWF for SAPHIR with large observation errors [3] and it is likely to happen in the coming years at METEO-FRANCE. The map on Figure 2 shows an example of the METEO-FRANCE global model ARPEGE errors on winds forecasts at 500hPa for a 24 h range: within the Inter Tropical Convergence Zone, the root mean square errors are of at least 4m/s and up to 7m/s. The whisker plots of Figure 2 show the impact of assimilating SAPHIR observations in total sky: when errors are greater than 4m/s, they are for instance systematically reduced by 1m/s for cases between 6 and 6.5m/s. This opens further possibility for an extended usage of MT/SAPHIR data to improve tropical meteorology forecasts.

The scientific objectives of the mission cover a wider range of questions related to tropical convection than those illustrated above. Beyond tropical meteorology, following SCARAB observations, the role of the organised convection in the energy budget of the planet is currently being studied. Similarly, ongoing researches in hydrometeorology are conducted to analyse flood dynamics in the tropics using error propagation technique in hydrological models. The link between the surface conditions and the precipitation extremes is also being studied.

After a long commissioning phase, the Megha-Tropiques mission now steadily provides data from well performing instruments that do not show any sign of aging after more than 6 years of operation. The scientific exploitation of this important source of water and energy cycle observations is in progress thanks to an active scientific community.

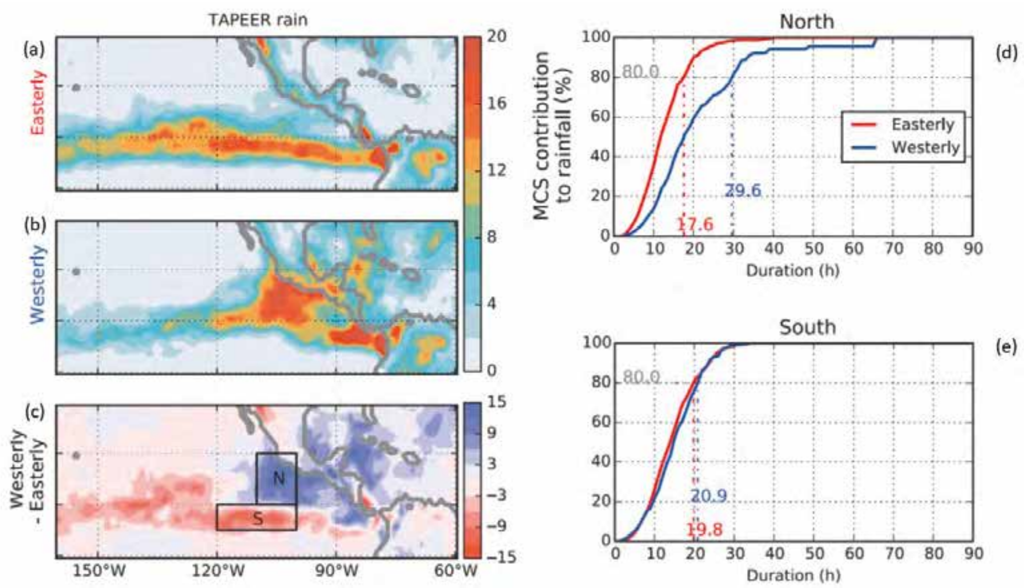

Fig.1

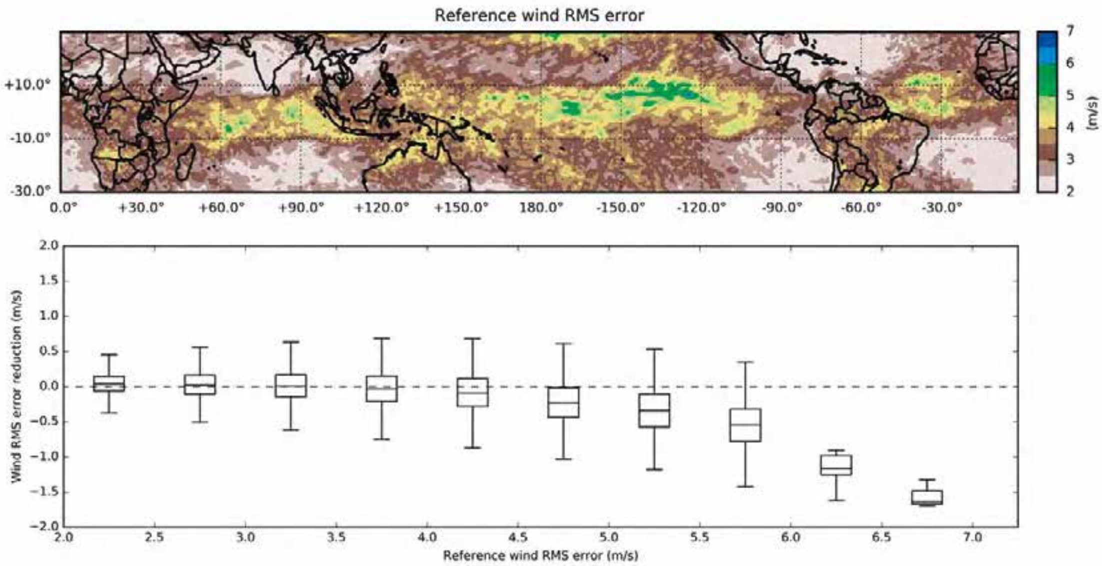

Fig.2

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Fig. 1: (a) Mean precipitation during the Easterly low-level wind regime. (b) same as (a) for the westerly regime. (c) The difference in mean precipitation between the 2 regimes. (d) Normalised cumulated distribution function of precipitation as a function of the duration of the organised convective systems for the northern region presented in (c). The red line corresponds to the easterly regime and the blue line to the westerly. (d) Same as (c) for the southern region. *© From Berthet et al. (2017) [1]*

Fig. 2: (top): Root Mean Square Error of ARPEGE 24h wind forecasts at 500hPa with respect to the ECMWF analysis, over the period 1st January to 28 February 2017. (bottom): Difference of RMSE of ARPEGE 24 h wind forecasts at 500hPa, between an experiment in which SAPHIR data are assimilated within clouds and precipitation in addition to clear-sky assimilation, and a reference experiment, as function of the reference experiment RMSE. A negative difference indicates a reduction of the error *i.e.*, a positive impact. *© From Berthet et al. (2017) [2]*

AUTHOR
O. Dubovik[1], J. Riedi[1], F. Parol[1]
Laboratoire d'Optique Atmosphérique (atmospheric optical laboratory), UMR CNRS 8518, Université Lille, 59655 Villeneuve d'Ascq, France

The PARASOL/POLDER results and outlooks

In the 2005 to 2013 period the POLDER instrument on board the PARASOL micro-satellite measured spectral and polarised characteristics of the reflected atmospheric radiation in up to 16 viewing directions over each observed pixel. By measuring the spectral, angular and polarisation properties of the radiance at the top of the atmosphere, PARASOL/POLDER provides comprehensive data set of observations that is highly suitable for reliable retrieval of atmospheric aerosol and cloud properties from space.

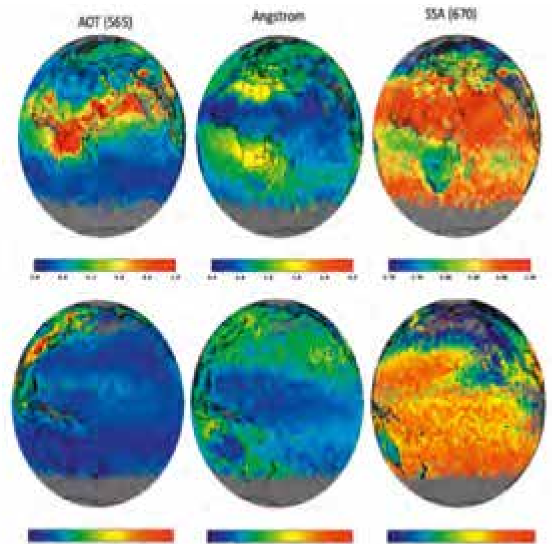

Fig.1

The POLDER observations were used in numerous studies to provide global distribution of aerosol parameters. Initially operational PARASOL algorithms provided properties such as Aerosol Optical Thickness (AOT), its spectral dependence described by Angstrom Exponent (AE) and some information about aerosol layer height [1]. In the recent years there were several attempts to apply the rigorous algorithms that implement statistical optimised fitting of satellite measurements for solution search in continuous space parameters. Such approaches take into account differences in angular, spectral, and polarisation features of atmosphere and surface signals and open new possibilities for accurate extended aerosol and surface properties retrievals. For example, lately, the entire archive of PARASOL data has been processed using algorithm of new generation GRASP (Generalized Retrieval of Aerosol and Surface Properties).

GRASP is an algorithm developed recently designed to achieve complete and accurate characterisation of aerosol and surface properties [2]. It does not use look-up-tables and implements radiative transfer calculations directly during retrieval. It is based on highly elaborated statistically optimised fitting. For example, it uses multi-pixel retrieval when statistically optimised inversion is done simultaneously for a group of satellite pixels. Such concept allows for using additional a priori information about known variability of aerosol of surface properties in time and/or space. GRASP uses a unique set of the assumptions globally, *i.e.* it does not use any location specific information about aerosol or surface type and the retrieval starts from unique initial guess.

GRASP provides complete set of both aerosol and surface properties over both land and ocean. Specifically, the aerosol product includes such parameters as spectral aerosol optical thickness, spectral Single Scattering Albedo (SSA), size distribution, complex index of refraction, sphericity fraction and scale height. For surface reflectance, the algorithm includes surface albedo, vegetation index and detailed spectrally dependent BRDF and BPDF. Fig. 1 illustrates the global distribution of AOT, AE and SSA of aerosol provided by PARASOL/GRASP retrieval. The comprehensive validation of these parameters has been done. The analysis of the validation results shows that GRASP retrievals provide rather solid and complete aerosol characterisation including such properties as absorption and aerosol type even for observations over bright surfaces and for aerosol loading events with very high aerosol loading.

POLDER contribution to cloud properties observation has been diverse thanks to its unique capabilities. First, the polarised observations have offered a unique and unambiguous way to determine thermodynamic phase at cloud top, a method that was further enhanced by synergistic use of simultaneous MODIS observations [3]. High confidence in cloud phase determination proved particularly useful for evaluation of aerosol/cloud interaction in Arctic regions [4]. The high sensitivity of polarisation to the shape of scattering particles proved instrumental in improving our ability to characterise cloud microphysical properties (Fig. 2). For instance, the use of multi-angle polarised measurements for the determination of liquid particle effective size has been a unique contribution of POLDER and, in combination with CALIOP observations, they allowed investigation of Cloud Droplet Number Concentration at global scale [5]. Secondly, the multi-angle observations have been extensively used to characterise cloud bidirectional reflectance and allowed evaluation of cloud models both regarding their macro- and micro-physical assumptions. In particular, the angular variability of cloud optical thickness retrieved from POLDER significantly contributed to a better constraint of ice cloud microphysical models [6]. Another unique contribution of POLDER arose from multi-angle observation of cloud apparent pressure derived from the differential absorption observation in the O2-A-band. Based on those, Ferlay *et al*. (2010) [7] demonstrated the feasibility to obtain information on cloud geometrical thickness from passive measurements. Alone or in combination with other instruments of the A-Train mission, POLDER also contributed to a better detection and characterisation of multi-layered cloud situation [8].

Overall, alone, or in combination with other instruments of the A-Train, the PARASOL/POLDER mission has significantly contributed to improve our understanding of aerosols and cloud properties and also opened new perspectives for remote sensing in very complex situations such as when aerosols occur above cloud layers [9]. The success of the third POLDER mission developed by CNES was undoubtedly key in the development of the Multichannel, Multi-angle, Multi-polarisation Imager (3MI) by ESA and its selection by EUMETSAT to be part of the European Polar System – Second Generation (EPS-SG). At the 2021, 3MI will carry on the POLDER heritage and provide the first multi-angle and polarimetric observations from an operational meteorological system.

Fig. 1: PARASOL/GRASP retrieval of global seasonal mean values of AOT(565nm), Angstrom exponent and SSA(670nm), for Summer 2011 © *LOA*

Fig. 2: Illustration of cloud bow, supernumerary bows and glory as seen in polarised reflectance by POLDER over stratocumulus cloud deck (background image and top left figure). These striking features correspond to the well known rainbow and glory observable in reflectance (bottom left and top right inserts) © *LOA*

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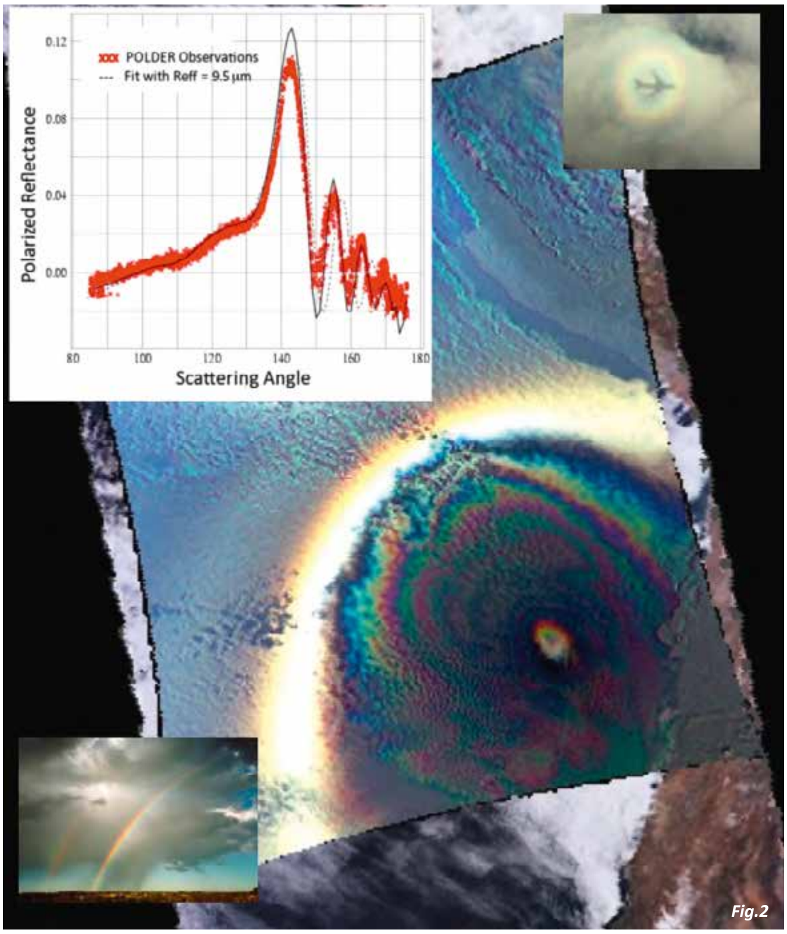


Fig.2

MICROCARB measuring global CO_2 distribution

MICROCARB is designed to map sources and sinks of carbon dioxide (CO_2)—the most important greenhouse gas—on a global scale. The mission is currently in the development phase, with launch of a microsatellite planned for 2021.

How do tropical rainforests and oceans, our planet's main carbon sinks, evolve? How many tonnes of CO_2 are released by the world's cities, vegetation and oceans? As surprising as it may seem, we do not know precisely how much CO_2 is absorbed and released in certain parts of the world, due to a scarcity of ground-based measuring stations. Nor do we know how these amounts vary with the seasons. Yet, this type of information is crucial for understanding the causes and consequences of climate warming, as CO_2 is the most important greenhouse gas produced by human activity.

To fill in these gaps in our knowledge, JAXA launched GOSAT instrument in 2009, NASA launched the OCO-2 satellite in 2014, and China launched 2 dedicated instruments in 2016 and 2017. In 2021, CNES will follow with the launch of MICROCARB. Its dispersive spectrometer instrument will be able to measure the total column concentration of CO_2 with a high degree of precision (of the order of 1 ppm) and with a nominal pixel size of 4.5 km x 9 km.

The instrument will be flown on a microsatellite built around CNES' Myriade spacecraft bus. This mission is developed in cooperation with the UK and involves the French scientific community studying climate change and carbon cycle. It is supported by the French government through the National Investment Plan.

Fig.1

SCIENTIFIC OBJECTIVES

The science objectives of the MICROCARB mission is to monitor and characterise CO_2 surface fluxes, *i.e.*, the exchanges between sources (natural or anthropogenic) and sinks (atmosphere, ocean, land and vegetation).

Annual global fluxes of CO_2 represent a quantity of the order of 200 gigatonnes of carbon. Anthropogenic emissions bring an additional quantity of 10 gigatonnes, with the effect of disrupting the natural balance. This surplus is half absorbed by vegetation, land and oceans, the other half staying in the atmosphere and causing an increase in the atmospheric concentration of greenhouse gases driving to global warming.

MICROCARB aims to get a better assessment of carbon fluxes by:

- Improving our understanding of the mechanisms governing the exchanges between sources and sinks, their seasonal variability, and their evolution in response to climate change,
- Identifying the parameters that control carbon exchanges,
- Validating and improve (through reducing their uncertainty) the models simulating the carbon cycle.

Understanding the carbon cycle is important since it can help us anticipate its evolution according to possible climate change scenarios (the IPCC has already stated that this

evolution will be negative, *i.e.*, uptake will continue to drop as temperature rises).

Fluxes cannot be directly measured from space but can be calculated from precise measurements of atmospheric concentration and powerful inversion model using atmospheric transport. The surface fluxes thus obtained (called Level 4 products) are global fluxes taking into account natural and anthropogenic fluxes.

Values of CO_2 concentrations need to be measured with high precision, of the order of 1 ppm (to be compared with the CO_2 concentration of 400 ppm) to be able to estimate gradients which amounts to a few ppm. Spatial coverage and the repeat cycle of measurements are also important in the process of inversion, which is why space-based observations are so valuable compared to a ground network that is difficult to deploy worldwide.

Concentration values of gases are themselves computed from measurements of the atmospheric spectrum in some wavelengths specific to these gases. CO_2 is a gas with absorption lines in the infrared (at 1.6 and 2.0 μm); solar radiation reflected by Earth then goes through the atmosphere twice before reaching the satellite and carries the signature of these molecules. The concentration is deduced from the depth of these absorptions in the measured spectra.

MICROCARB will then measure the spectral radiance of the solar radiation reflected by Earth, at nadir on land surfaces and at glint on the oceans. These spectral radiance measurements will be converted into column integrated concentrations of CO_2 by applying a mathematical inversion of the spectrum.

SCIENTIFIC PAYLOAD

The instrument on board MICROCARB is an infrared passive spectrometer using an echelle grating (dispersive element) to achieve spectral dispersion. It measures atmospheric spectra in 4 bands:

- Oxygen band (O_2 at 0.8 μm) to retrieve the surface pressure and then normalise the computed CO_2 column concentration,
- Carbon dioxide (CO_2) in 2 bands: a first band around 1.6 μm, a second band around 2 μm,
- AirGlow band (at 1.2 μm) in order to optimise correction of aerosol.

The entrance of the spectrometer is a narrow slit perpendicular to the track of the satellite that scans the ground during the detector integration time.

The instrument will also include a cloud imager to identify clear sky scene, and thanks to the agility of the Myriade platform, it will be able to use several pointing modes: nadir above land, glint above ocean, fixed target for validation purpose. A city mode is also planned with a longer exposition on a specific scene allowing more signal on smaller pixels. This will be tested to get more details on urban area.

MISSION STATUS

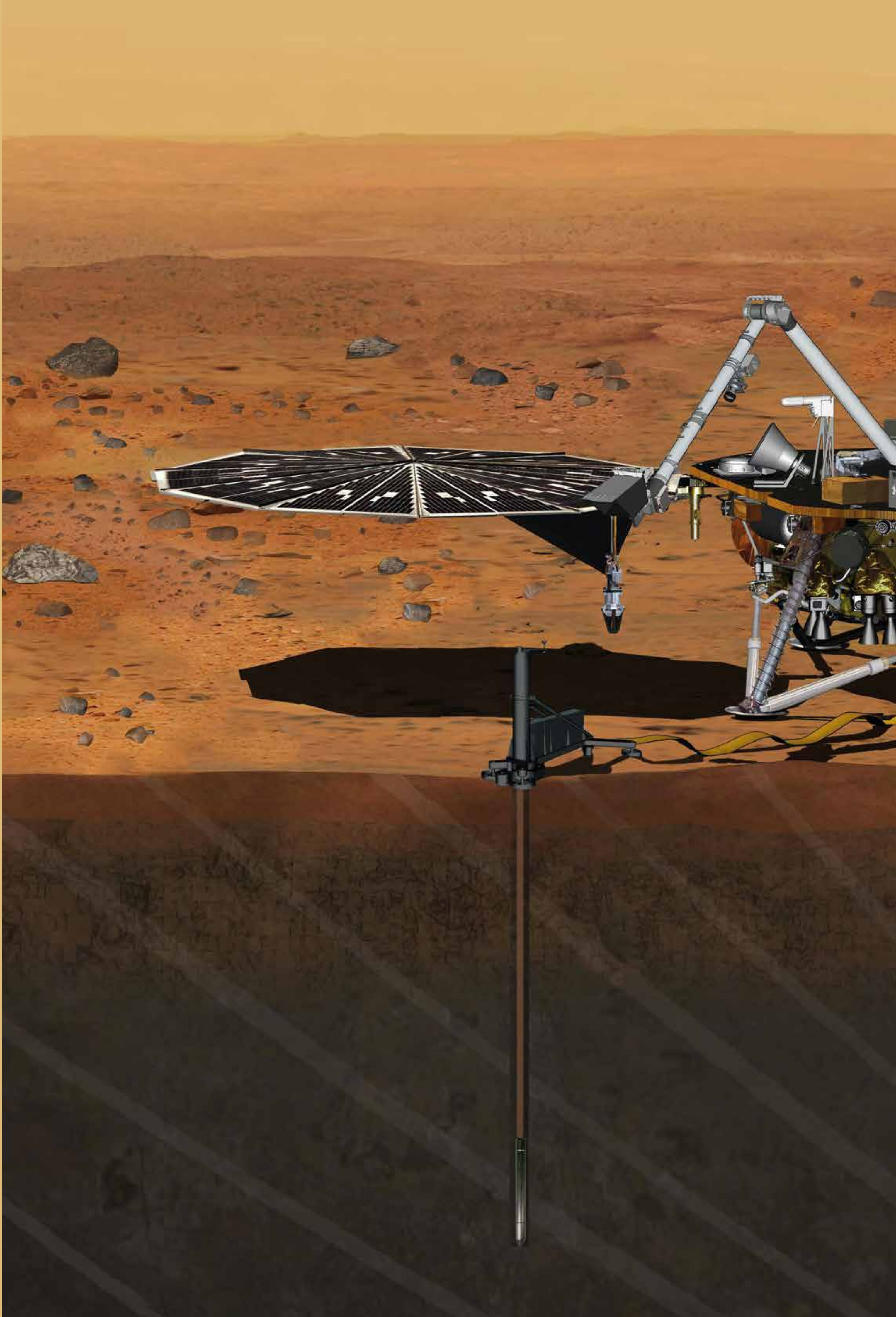
The project is currently in the development phase and should be ready for launch by the end of 2021.

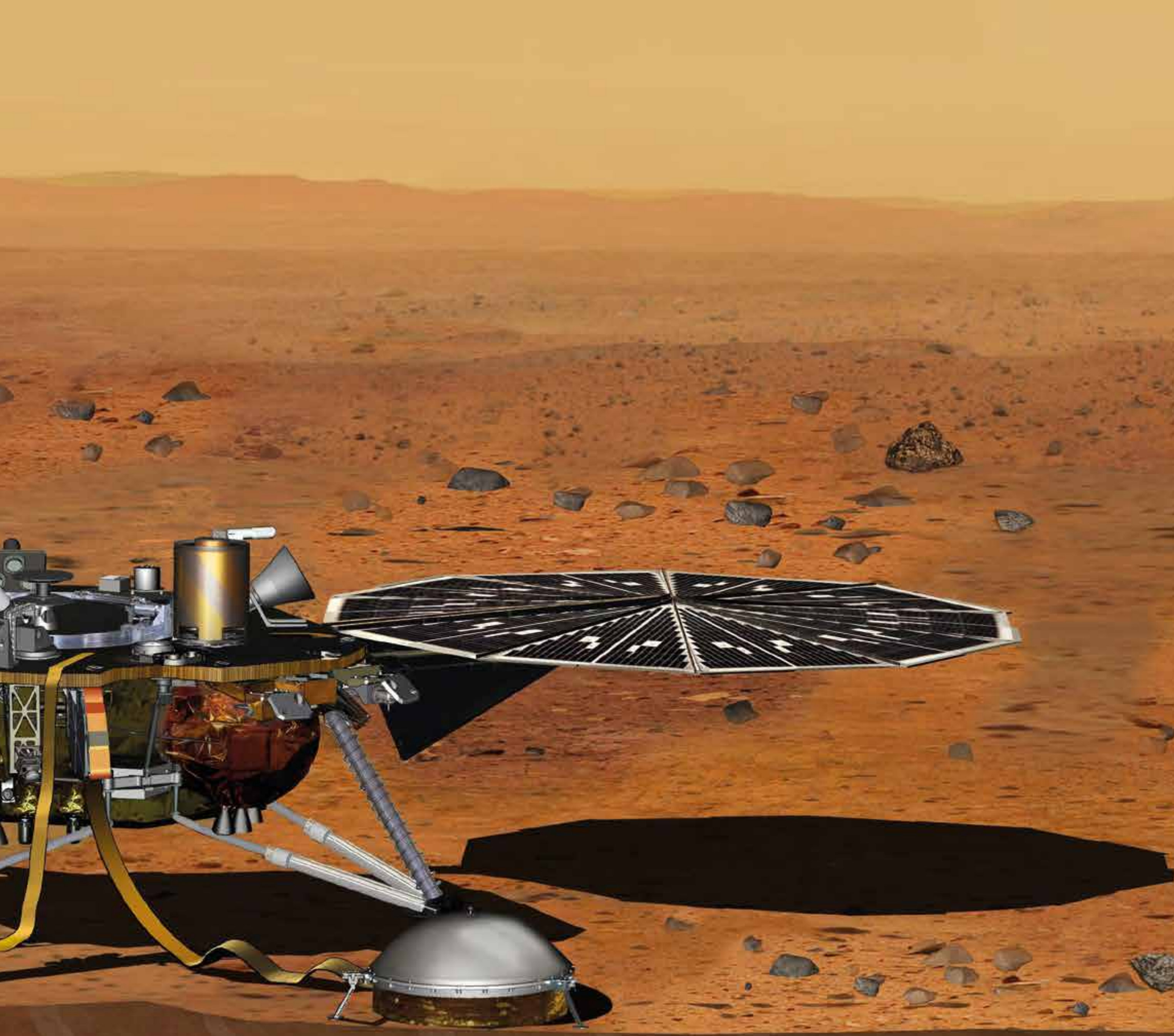
All the sub-system of the instruments is under development and a functional breadboard has been tested. The platform is based on Myriad product and the whole will have a mass of approximately 170 kg.

Hard work is also done in the preparation of ground segment and especially innovative algorithm to achieve the ambitious specification in terms of precision and accuracy.

Fig. 1: View of MICROCARB model exposed at Paris for the Climate Summit in December 2017 © *C. Deniel/CNES*

Fig. 2: View of MICROCARB © *CNES DSO/AVI/MT*





SPACE **SCIENCES** & **EXPLORATION**

Illustration of the InSight mission
© NASA

Fig.1

AUTHOR
J.L. Monin,
Head of the Programme for Space Sciences, Microgravity and Exploration
CNES, 2 place Maurice Quentin, 75039 Paris, France.

Space sciences and exploration

Fig.2

SPACE SCIENCES AND EXPLORATION

Space offers the scientific community many opportunities in both fundamental and applied research. Under the name of "space sciences", we group together all the disciplines of universe sciences (stellar, galactic and extragalactic astrophysics, cosmology, planetary sciences, exobiology and exoplanets, solar physics and magnetospheres), condensed-matter physics and fundamental physics when operating in microgravity. To this group we have to add life sciences whose progress is important for Mars exploration for example.

In November 2016, Thomas Pesquet began the Proxima mission and was the first French astronaut aboard the ISS in 8 years. During his 6-month mission (he returned in early June 2017), he performed many scientific experiments in both life sciences and condensed-matter physics. He notably performed the FLUIDICS experiment which is designed to study the fundamental mechanisms of wave turbulence as well as other experiments on more technological aspects such as the sloshing in space tanks. There are numerous applications for this experiment: oceanic or atmospheric waves, the Alfvén wave in solar wind, the spin wave in solid-state physics... For example, the wave height spectrum is in accordance with the theory of wave turbulence.

Thomas Pesquet also tested the AQUAPAD device, which makes it possible to rapidly determine the level of microbial contamination of drinking

water in the space station while using very little of it, an absolute necessity for long-term flights.

The scientific themes addressed in microgravity sciences can be broken down into research “for space” and “space-based”. For example, the work of FUIDICS on tank sloshing or microgravity combustion studies is carried out “for space”. Work on wave turbulence is “space-based”, as are many basic research studies that use access to sufficient microgravity levels for long periods of time.

Recently, CNES decided to upgrade the DECLIC instrument and manufacture new inserts for new scientific experiments.

In life sciences, the disciplines involved in exploration range from psychology (human and social behaviour in a confined environment) to physiology (effects of microgravity on the cardiovascular system, the immune system, muscles and bones). On this topic, CNES has decided to produce the new version of the CARDIOSPACE instrument that will make it possible to monitor the performance of the cardiovascular system of astronauts, particularly in the context of a partnership with China. These studies are supplemented by experiments and simulation of ground microgravity during bedrest, such as those that ended in 2017 for example. In September 2018, a symposium on microgravity sciences and the adaptation of man to space will be organised in Toulouse.

In October 2016, the ROSETTA probe mission ended in a controlled landing on the comet 67P/Churyumov–Gerasimenko. The images taken by the probe until the last moments showed details at the centimetre level. The last signal was received on 30 September 2016. This was an extremely moving moment for the French scientific community and especially for everyone who took part in this project for the last 30 years. Obviously, the scientific research continues to provide even more information on the Solar System’s origin, on the organic compounds on small bodies, on the origin of water and life on Earth.

Fig.3

In December 2016, the CNES Board of Directors made the decision to start the development phase of the SVOM mission. This Franco-Chinese mission, whose launch is planned for the end of 2021, will observe transient energy phenomena, particularly those associated with gravitational wave emissions. This mission will thus fully participate to the emerging era of multi-messenger astrophysics, with for example the detection in August 2017 by the FERMI and INTEGRAL satellites of a high-energy emission from gamma-ray bursts just seconds after the gravitational burst observed by LIGO and VIRGO on the ground. These observations have been supplemented by a very large number of observations by other telescopes.

The historic announcement of gravitational waves detection in 2016 from Earth has opened a new window to observe the universe, allowing us to *"see" the fusion of black holes and neutron stars, but also the violent phenomena of the beginnings of the universe, and a whole series of events still unsuspected today. This discovery in astrophysics will forever disrupt our vision of the universe. The ESA LISA mission selection in June 2017 was a major decision which puts Europe and its state members at the forefront of this discovery in astrophysics. LISA is the third Large Class Mission of the Cosmic Vision programme and will observe the gravitational waves from space in a frequency domain inaccessible from the ground.*

The path towards the observation of gravitational waves from space had been prepared for a long time and particularly by the ESA LISA PATHFINDER mission launched in December 2015. The measurements obtained in 2016 and 2017 validated the technological feasibility, demonstrating that the original specifications were exceeded by more than an order of magnitude and that the performances obtained are well above the level required for the LISA mission. The French community is deeply involved in the data processing of this mission, in order to be prepared for the future LISA mission. The French scientific community and CNES intends to play a major role in LISA.

On fundamental physics, the publication of the firsts results of MICROSCOPE in December 2017 turned this extraordinary experiment into a global standard in terms of verification of the Equivalence Principle which is based on the theory of general relativity. The measurements obtained on only 120 orbits are already 10 times more precise than those obtained from the ground until now and are sufficient to exclude some alternative theories on gravity. Through its MICROSCOPE mission, CNES is deeply supporting this research on general relativity. There is no doubt that this performance will be largely improved once all the data is processed.

On the Solar system, September 2017 saw the end of the CASSINI mission. With its data acquired for more than a decade, CASSINI revolutionised our vision of the Saturnian system and of its main satellite with the landing on Titan of the European HUYGENS spacecraft that was carrying 2 French PI instruments. The observation of geysers spraying hydrogen through the tiger stripes of Enceladus is also a major discovery. The giant planets of our Solar system, with their ice satellites system whose diversity has proved much richer than initially imagined, remain a primary objective for future planetary missions such as JUICE, which will study the moons of Jupiter as a planetary system model, a science renewed by the discoveries of numerous exoplanets for several years, some of which similar to the Earth.

On exobiology and exoplanet research, the search for potential traces of life under the ice cover on the moons Europe and Ganymede around Jupiter, or Enceladus and Titan around Saturn remains a major objective of future missions towards gas giants. Besides the planetary projects on Mars or on the comet 67P/Churyumov–Gerasimenko searching for the origin of life, the French community is involved in projects for the detection and characterisation of exoplanets. We are also involved in the ground segment of the CHEOPS mission, the first small class mission of ESA's Cosmic Vision programme which is to be launched in 2018. French community is involved in the ESA PLATO mission and we support the development of the AIRS spectrometer, a core piece of the ARIEL mission which has just been selected by ESA. This set of missions studying "new worlds" will take us beyond the era of detection to enter that of the characterisation of exoplanets, with the observation of hundreds of objects and their atmosphere to determine their habitability.

2018 sets out to be a great year for CNES with a lot of achievements towards Mars. TGO, the orbiter of ESA EXOMARS mission, ended its aerobraking phase and the measurements have begun. INSIGHT is to be launched with the SEIS instrument, a seismometer of an incredible sensitivity provided by CNES to determine the Red Planet's internal structure. For many years, France is involved in almost every missions to Mars, MARS EXPRESS, MAVEN, CURIOSITY (MSL), then INSIGHT and MARS 2020. All those missions are dedicated to search for traces of life, for the study of its climate and its evolution, for the study of its surface and its internal structure. Our commitment should continue with a Mars sample-return mission, a major issue that will certainly concentrate many efforts for the ESA's Ministerial Council in 2019.

On the way towards the Mars Sample Return mission, after HAYABUSA, CNES is developing a partnership with Japan on the MMX mission whose purpose is to bring back samples from Phobos in 2028 to improve our understanding of the formation of the Solar system and particularly on the origin of this moon.

On 25th April 2018, the 2nd version of the GAIA catalogue was released which brings unprecedented information on more than 1,7 billion stars of our Galaxy revolutionising the stellar, galactic and exoplanetary astrophysics in a way still impossible to predict today. CNES is heavily involved in the data processing of several ground segment chains.

July 2018 will see the launch of the NASA PARKER SOLAR PROBE, a mission skimming the sun that will pass as close as only a few solar radii from its surface. Several French laboratories are associated with this mission and have provided instruments for the probe. Later on, in October, BEPI-COLOMBO will start its journey to Mercury. This ESA-JAXA mission will also face extreme temperature conditions. The PHEBUS instrument has been provided by a French laboratory, with CNES support. Last but not least, the SOLAR ORBITER mission has been delayed due to satellite problems and should be launched in 2020. This unfortunate delay will give us the opportunity to present this very important solar physics mission during the next COSPAR session.

Recent successes have been achieved with CNES's balloon missions. In September 2017, the second flight of the

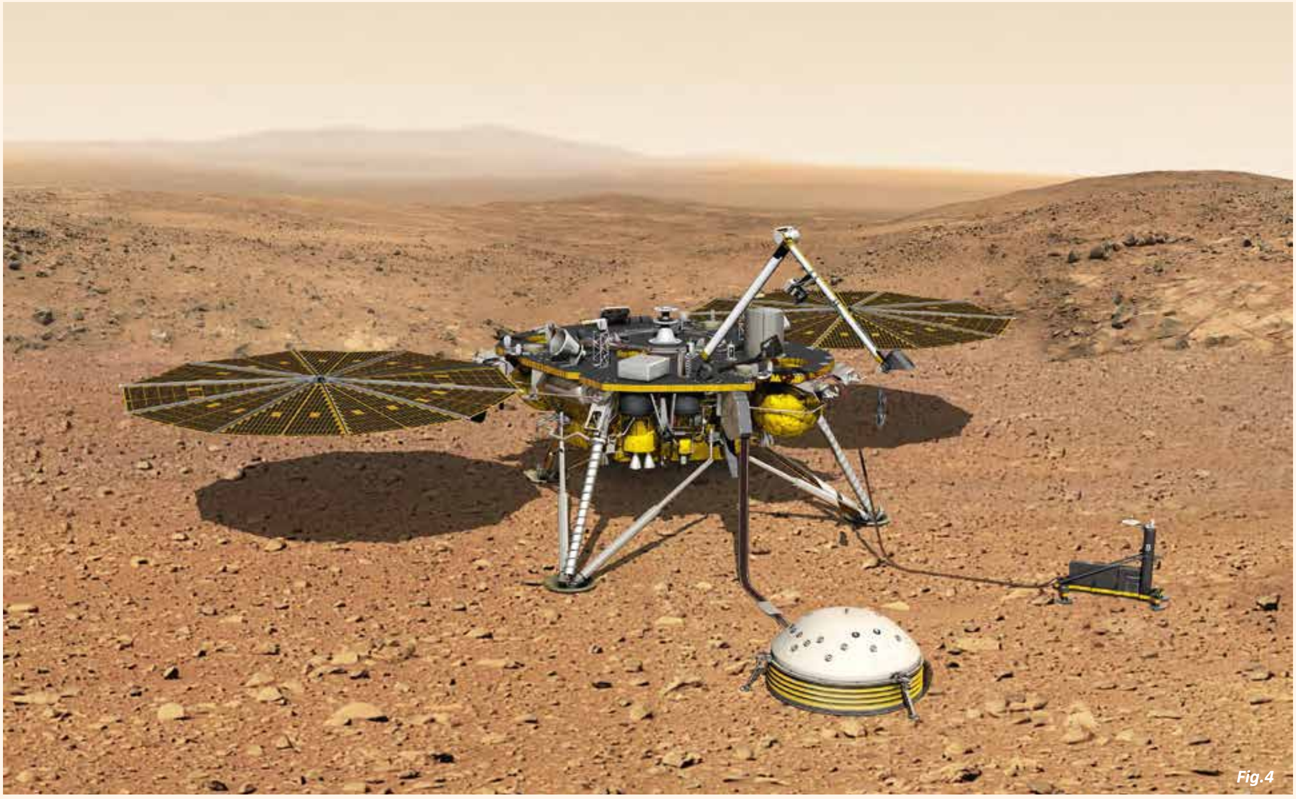


Fig.4

PILOT experiment (Polarized Instrument for Long-wavelength Observations of the Tenuous interstellar matter) made it possible to measure the polarised sub-millimetric emission of interstellar dust from our Galaxy.

To conclude, since the last report to COSPAR, there is no doubt we remain in the golden age of space sciences. The years to come will see the launch of many mission with French scientific community and CNES support. Work progresses on many missions under development, such as the future ESA's L2 mission ATHENA, for which CNES is supporting the French PIship of the X-IFU instrument, and also for EUCLID who will unveil the secrets of dark energy and dark matter. From dark matter to gravitational waves, from the Equivalence Principle to looking for traces of life on Mars or on icy moons in the far reaches of our Solar system, space research is one of the most exciting adventures of our time which uncovers little by little the secrets of the universe.

Fig.5

Fig. 1: Jean-Louis Monin *© CNES/JALBY Pierre, 2016*

Fig. 2: EXOMARS rover *© ESA/ATG medialab*

Fig. 3: Thermal vacuum test of the Microscope satellite *© CNES/GRIMAULT Emmanuel, 2015*

Fig. 4: Artist's view of the InSight lander (INterior exploration using Seismic Investigations, Geodesy and Heat Transport) *© CNES/IPGP/Ill./DUCROS David, 2017*

Fig. 5: Thomas Pesquet's return *© ESA/CORVAJA Stéphane, 201*

The Cocktail bed rest study

Space environment and microgravity cause physiological changes that particularly challenge the cardiovascular, metabolic, muscle, bone, immune and neuro-vestibular functions. This can jeopardise the performance of astronauts, their healthy return to Earth and the success of a mission. With the planned exploration of celestial bodies such as the Moon and Mars, the development of efficient countermeasures is a top priority.

Since the beginning of manned space flights, numerous countermeasures were tested, including drugs, nutrition, and various physical exercise training programmes. However, none were proven to be fully effective so far.

Over the past decade, a growing interest for nutritional countermeasures has emerged. First, to prevent negative protein balance and muscle mass loss. Protein supplementations with or without the use of bicarbonate to buffer changes in blood acidity were tested. Results happened to be highly variable and not conclusive.

Very recent observations from clinical studies and studies conducted either in actual or simulated microgravity pointed towards the use of micronutrients, vitamins and other bioactive compounds from the diet. The widest range of effects was observed for a polyphenol, the resveratrol. In rats, we observed that resveratrol supplementation maintains protein balance, muscle mass, strength and mitochondrial oxidative capacity, bone mineral density and strength. It further protected whole-body insulin sensitivity, lipid trafficking and oxidation, and oxidative stress (Fig. 1).

Based on all the recent findings reported in the literature showing the wide effects of several bioactive compounds from the diet, scientists decided to test a dietary cocktail with anti-oxidant and anti-inflammatory properties as a new countermeasure, for a 60-day bed rest during a workshop on new countermeasures held by ESA in 2014. However, the ESA nutrition expert group strongly suggested performing a preliminary study to assess the efficacy of the cocktail on basic parameters known to be affected by bed rest. It was decided to use a simple outpatient protocol of step reduction to induce physical inactivity in active individuals; physical inactivity being 1 of the major factor inducing adaptation to space environment. In order to boost the metabolic challenge induced by inactivity, the last 10 days of the protocol were coupled with fructose ingestion, which is generally used to induce reversible insulin resistance in biomedical research.

SCIENTIFIC PAYLOAD

The purpose of the Cocktail bed rest study is to test a new nutritional countermeasure that consists of an anti-inflammatory and antioxidant mixture (called XXS-2A-BR2) composed of plant extracts derived from edible plants coupled with vitamin E, dietary omega-3 and selenium to prevent and/or reduce the deleterious effects induced by 60 days of antiorthostatic bed rest. Sixteen scientific protocols (PIs: G. Trudel, JP. Frippiat, J. Fielitz, A. Blaber, I. McDonald, A. Stahn, M. Tagliabue, C. Leguy, D. Thompson, S. Archer, M. Salanova, A. Chopard, M. Heer, S. Blanc, E. Caiani, R. Reynolds) have assessed the modifications in the cardiovascular, metabolism, muscle, bone, neuro sensorial, hematological and immunology systems, and the potential beneficial effects of the countermeasure on these same systems.

SCIENTIFIC HIGHLIGHTS

As for now, the main results of this scientific project have been obtained during the feasibility study. Twenty healthy active (14 000 steps/d measured by accelerometer) young men, randomised in control (n=10) and cocktail supplemented (n=10)

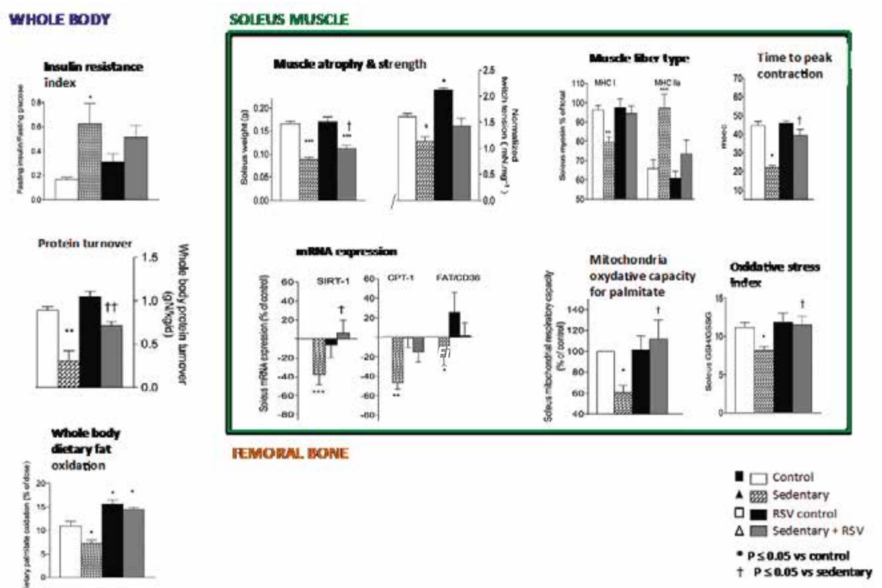


Fig.1

groups, were asked to stop exercise and drastically reduce their daily physical activities (2800 steps/d) for 20 days. The supplemented group received a cocktail composed of polyphenols (530 mg/d), omega 3 (2.1 g/d), selenium (80 µg/d) and vitamin E (168 mg/d). Participants received a fructose supplementation during the last 10 days of the protocol to trigger the development of systemic insulin resistance.

The 20 days of deconditioning induced a reduction of about 20% in both total and type 2-myosin heavy chain cross sectional areas in the control group that was prevented in the supplemented group ($p<0.01$ and $p<0.001$ as compared to control group respectively, Fig. 2a & 2b). While insulin sensitivity was only moderately affected by the intervention in either of the 2 groups (Fig. 2c), plasma concentration of adiponectin, an insulin-sensitiser and anti-inflammatory adipokine, was still higher in the supplemented than in the control group at the end of the intervention ($p<0.05$, Fig. 2d). The supplementation also counteracted the deleterious effects of the intervention in the control group on fasting and OGTT-plasma triglycerides ($p<0.02$ at the end of the intervention, Fig. 2e), on fasting HDL ($p<0.0001$), Fig. 2f) and was associated with a greater lipid oxidation during the OGTT ($p<0.02$, Fig. 2g), greater muscle FATP1 protein content (Fig. 2h) and stable ubiquitous protein content (Fig. 2i). The supplemented group had higher blood anti-oxidant capacities than the control group at the end of the OGTT after 20 days of intervention suggesting improved anti-oxidant reserves ($p<0.01$, Fig. 2j).

Based on these positive results, it was decided by the ESA's bed rest investigators working group and ESA's nutrition group to go on with the cocktail countermeasure and test it during the 60 days bed rest study. Given the small changes observed on the blood anti-oxidant capacity, a slight modification of the cocktail was proposed through a mild increase in the quercitin fraction of the polyphenol's fractions; querticin being known to possess important anti-oxidant properties.

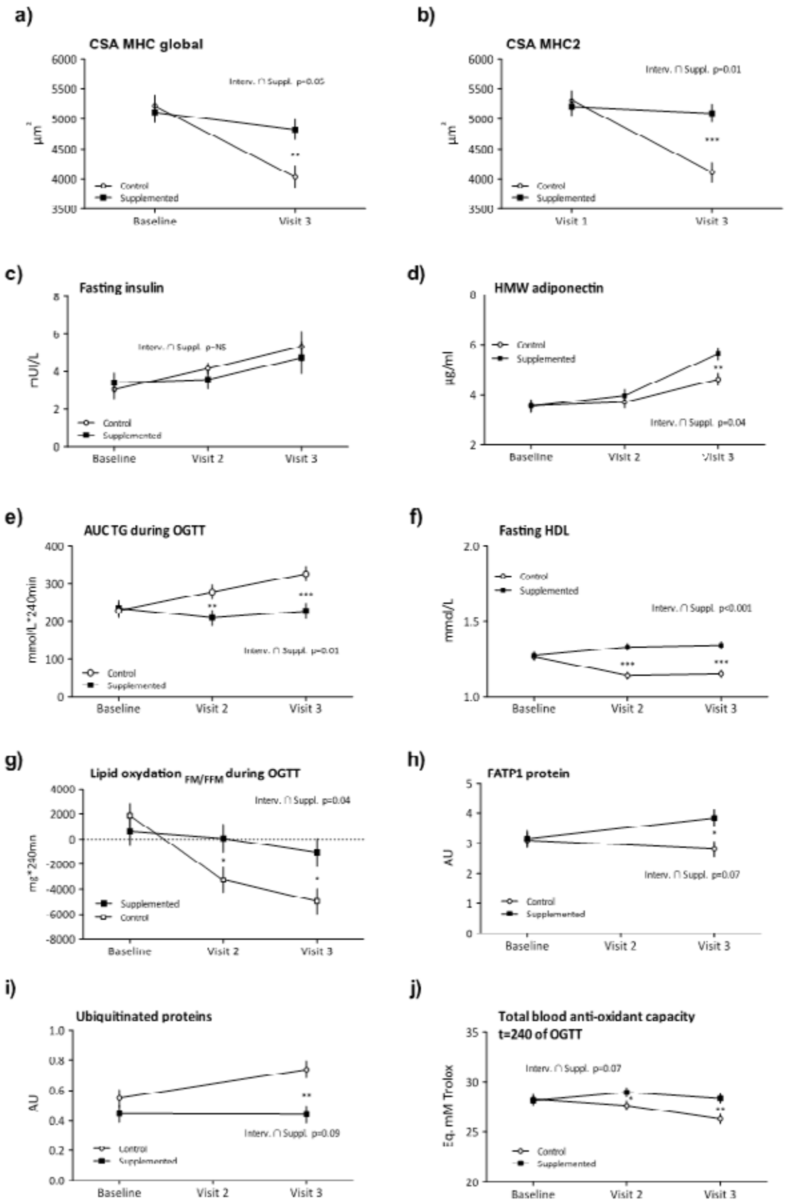


Fig.2

MISSION STATUS

The feasibility study was conducted at the Space Clinic, MEDES at the Hôpital Rangueil in Toulouse, France in September 2016. The team led by S. Blanc (CNRS, Strasbourg, France) was in charge to conduct this first trial. Data and samples have been analysed and a manuscript is in revision at the *Journal of Applied Physiology*. The most conclusive Cocktail bed rest study was conducted during 2 sessions, the first one occurred in January-March 2017 and the second one in September-December 2017. The bed rest study was also performed at the MEDES. Following an extensive and thorough recruitment and screening process, 20 young male adults (10 per session) were selected to take part in the study and provided a signed informed consent. The bed rest study was organised in 3 periods: A 15-day baseline data collection period followed by the 60 days of bed rest and a 15-day recovery period. During the bed rest period, the twenty subjects were randomly assigned to one of the 2 groups, the control group who was in strict bed rest, or in supplemented group who received the cocktail supplementation during the bed rest period. During this study, 16 independent research projects have been conducted on these 20 participants. The study has been successfully completed and all the data and samples have been collected. They are now under analysis in the 16 respective research labs.

Fig. 1: Effect of resveratrol in hind-limb suspended rats © *from Momken I. et al. (2011) Resveratrol prevents the wasting disorders of mechanical unloading by acting as a physical exercise mimetic in the rat, The FASEB Journal, 25, 3646-3660*

Fig. 2: Effects of the cocktail countermeasure to prevent the metabolic alterations induced by 10 days of reduction in daily steps alone (Visit 2) and by 10 more days of reduction in daily steps coupled with fructose supplementation (Visit 3) as compared to baseline. Results are based on analyses using linear mixed models taking into account repeated measures. The interaction between the intervention (inactivity & fructose supplementation) and the supplementation was tested. The post-hoc comparisons between the supplemented and the control groups at the end of the intervention, adjusted on fat-free-mass and on baseline values of the variable of interest, are presented below. © *from JAP (submitted)*

AUTHOR
C. Laurens[1], S. Blanc[1], A. Bergouignan[1]
1 IPHC (Hubert Curien Multi-disciplinary Institute), CNRS UMR7178, 23 rue Becquerel, 67087 Strasbourg, France

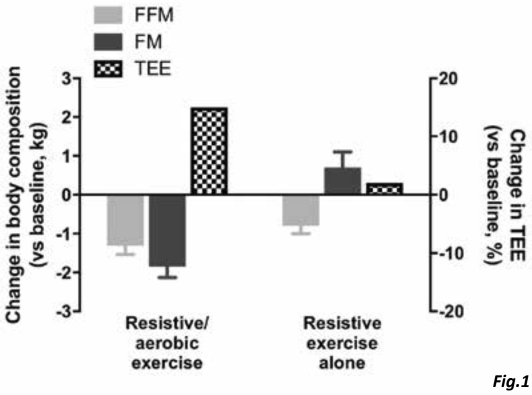
The obligatory exercise countermeasure programme during space flight: is it time for revision?

Astronauts' weight loss is a medical concern since early space flights. The underlying energy deficit is detrimental to health and may jeopardise the missions' success and a healthy return to Earth. Data obtained in both actual and simulated microgravity suggest that the obligatory exercise countermeasures programme may be partly responsible for this chronic weight loss. If validated, this hypothesis will require an in-depth revision of the countermeasures required for planetary exploration.

During short term missions on-board the shuttles and MIR, the systematic in-flight energy deficit [1, 2] is of particular concern. A meta-analysis based on 619 missions estimated an average loss of 2.4% body weight per 100 days spent in space [3], which would represent 15% body mass loss for a mission to Mars. While such energy deficits are tolerable for short-term missions because of body fat stores, a chronic negative Energy Balance (EB), *i.e.* energy intake lower than Total Energy Expenditure (TEE), is an issue [1]. Ground-based data demonstrated that chronic energy deficit exacerbates some of the deleterious physiological adaptations observed during space flights including cardiovascular deconditioning, bone loss, muscle mass and strength losses, impaired EXercise (EX) capacity, and immunity defects. All of this can jeopardise crew health and performance, and the success of the mission. Achieving EB during long term space flights is a research priority for planetary exploration.

Energy requirements during short term missions were reported to be similar to those on the ground [1] if and only if, the cost of EX countermeasure was well accounted for. EX countermeasure is a mandatory programme to prevent the adverse adaptations including the loss of fat-free mass. For longer missions, data are not available and the origin of the negative EB remains unknown. It is likely twofold, *i.e.* too low energy intake and/or too high EE. Calorie intake has been slowly increasing in astronauts on the ISS, but still does not match EE [1]. On the other hand, the EX countermeasure along with the 500 hours of Extra Vehicular Activity (EVA) performed by the astronauts induces very high EE. This high TEE needs to be balanced by greater energy intake, which is not always easy to achieve.

In 2000 P. Stein observed that 15-days Shuttle missions with high physical EX prescriptions were associated with major body mass loss and negative protein balance (index of muscle mass loss), while missions with low EX prescription were associated with stable protein balance and body mass [1]. Pre-flight fitness is another determinant; astronauts who were most trained prior to the mission lost the most, while astronauts relying on walking as EX lost the least [3]. Based on these data, he hypothesised that EX countermeasure was an important driver of weight loss in space. Over the last 10 years, we have collected supportive evidence. Data obtained in simulated microgravity conditions during bed rest studies showed that weight loss was related to the impact of EX on TEE. An EX programme combining resistive and aerobic EX with a high impact on EE induced a loss in both fat mass and fat-free mass [4], while the practice of resistive EX only with a low impact on EE maintained fat mass and prevented the loss of fat-free mass (Fig. 1). During the protocol ENERGY conducted in the ISS since 2011, we further examined the contribution of each component of TEE, *i.e.* Resting Metabolic Rate (RMR), Diet-Induced Thermogenesis (DIT) and Activity Energy Expenditure (AEE), to better understand the in-flight regulation of EB and estimate daily energy requirements. Based on preliminary data, we unexpectedly observed a large variability between individuals who can be divided into 2 groups: those who had an increase in TEE (n=5) and those who had a decrease (n=4) after 3 months on the ISS (unpublished; Fig. 2). These in-flight changes in TEE were not explained by changes in RMR or DIT but by changes in AEE. This is important because astronauts who had an increase in TEE maintained their fat-free mass as



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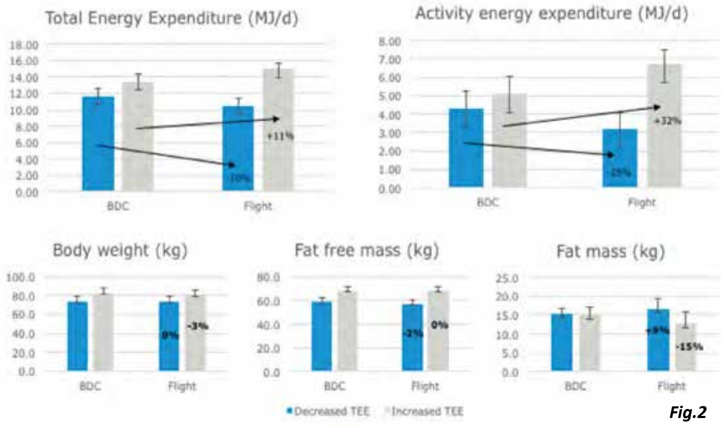

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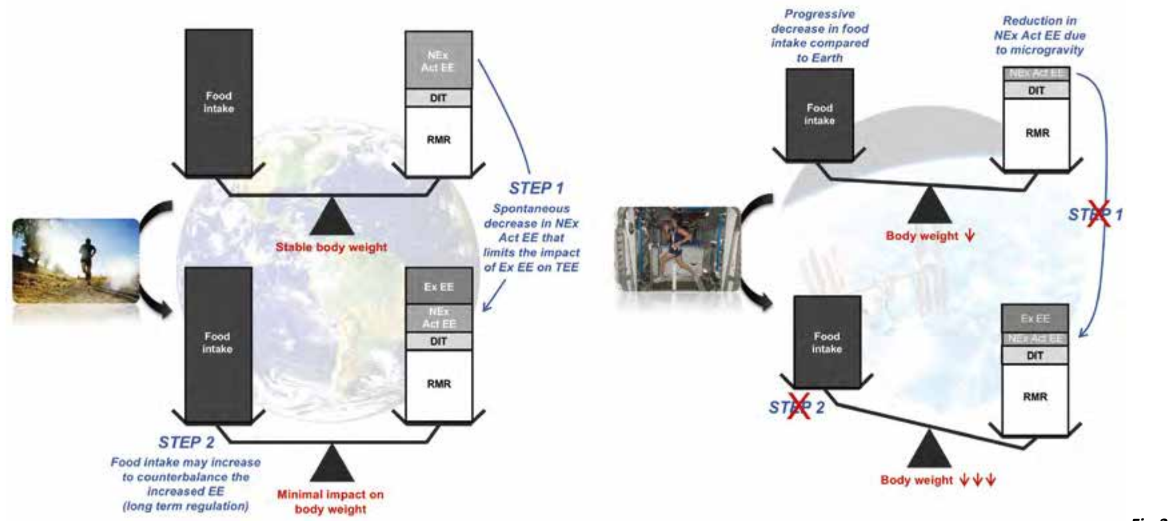

Fig.3

expected but lost fat and body mass. In contrast, astronauts who did not increase their TEE did not lose body mass, gained fat mass, and more importantly had only a minor fat-free mass loss. The changes in fat mass were further correlated with time spent doing EX. These results are in line with P. Stein's hypothesis and are the firsts for long missions. Understanding the underlying mechanisms explaining why astronauts are unable to regulate EB in presence of EX when the performance of EX has a very limited effect on body mass on Earth is key.

AEE is a complex component of TEE. It is composed of energy expended during EX and non-EX activities. On Earth, non-EX AEE represents the energy expended in any body movement during daily life activities (walking, taking the stairs, gardening, etc.). During bed rest studies, we showed that non-EX AEE, and not energy intake, is primarily used to buffer energy deficit induced by high volume of EX and represents a key component of EB control [4]. Because this component is drastically reduced in space due to the very nature of the microgravity conditions, AEE is equivalent to the energy expended during EX and EVA only. Consequently, non-EX AEE cannot be used to restore EB in response to high EX volume prescribed as countermeasure. Weight loss occurs because energy intake does not increase to match EE (Fig. 3).

While not negating the role of EX as countermeasure during space flights, these data challenge the current EX countermeasure programme, especially in the context of planetary exploration. The development of an EX countermeasure programme that has a minimum impact on TEE, while preventing muscle mass loss and the other physiological adaptations is needed. Among possibilities, a large body of data generated on Earth shows that the High Intensity Interval Training (HIIT) fulfils these needs.

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Fig. 1: F Effect of exercise countermeasure programmes combining resistive and aerobic exercise vs. resistive exercise alone on fat mass, fat-free mass and total energy expenditure during bed rest studies.

FM: fat mass; FFM: fat-free mass; TEE: total energy expenditure

Fig. 2: Changes in total energy expenditure and activity energy expenditure after 3 months on the ISS, and impact on body mass, fat-free mass and fat mass.

TEE: total energy expenditure; BDC: baseline data collection.

Fig. 3: General model of energy balance regulation on Earth and in space in response to exercise. EE: energy expenditure; TEE: total EE; NEx Act EE: non-exercise activity EE; Ex EE: exercise EE; DIT: diet-induced thermogenesis; RMR: resting metabolic rate.

Installation and use of the FLUIDICS instrument in the ISS by Thomas Pesquet in May 2017

The study of systems brought away from equilibrium is one of the fields of physics that particularly digs turbulent phenomena. Generally, in those systems, a stream of energy propagates in the form of random waves. But the theoretical approach of wave turbulence shows that these interactions are following very specific laws that are yet to be tested experimentally.

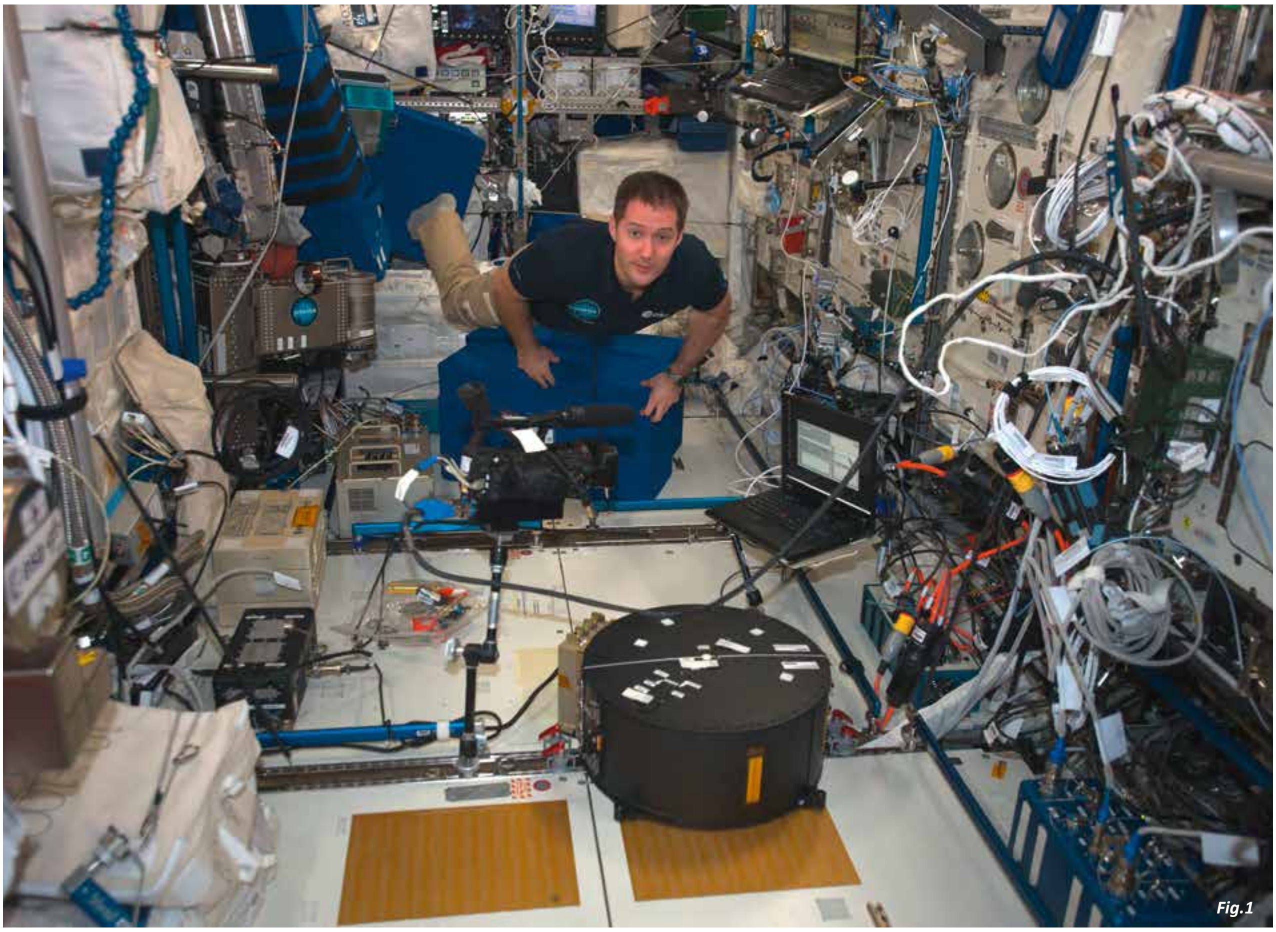


Fig.1

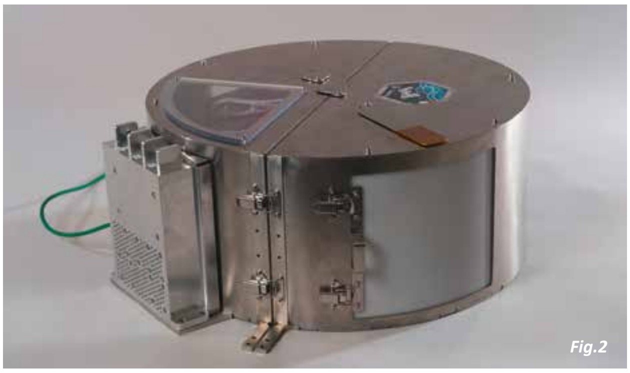
The study of the variations in the amplitude of a liquid inside a container represents the ideal model to study the waves on the surface of the ocean. However, the comparison remains difficult because experiments in containers are inevitably altered by the edges reflecting the waves. Scientists from ENS (École Normale Supérieure) and from Paris Diderot University proposed to bypass this issue by placing a sphere partially filled with liquid in microgravity. The liquid then covers the interior wall of the sphere and organise itself to create waves with various amplitude and length under the effect of imposed vibrations. In this case, these interacting waves display a random dynamic. The measurement of the height of waves, over time, then allows to verify that a relation emerge between the amplitude and the frequency of waves and that this relation is by no means affected by the agitation imposed on the environment.

The FLUIDIDCS instrument has been developed jointly with Airbus Defence and Space in Toulouse to respond to this proposal of experiment. Because with this same instrument, but different spheres, we have also been able to study, inside the International Space Station (ISS), the disturbances in the orientation of satellites caused by the sloshing of liquid-propellant inside their tank.

FLUIDICIS is composed of an oscillating arm holding 2 cameras and 2 liquid level sensors. After having assembled and tested the instrument, Thomas Pesquet successively set up the spheres corresponding to the different experiments.

The results of these technological experiments are useful to adjust the predicative models of the movement of liquid-propellant and will make it possible to better control the positioning of satellites. As for the scientific approach of these experiments, the measurements show a good agreement with the theoretical prediction of surface waves turbulence. Apart from a better understanding of the conditions surrounding the occurrence of the wave turbulence phenomenon, these results will help to better understand the complex evolution of surface waves in oceans, in which similar effects take place. This deeper understanding should lead to an improvement of the parametrisation of the exchanges between the atmosphere and the ocean within the current climates and weather models.

The number of times Thomas Pesquet performed these experiments has been increased within the allocated time and the result is a success. Thus, it has been proposed to ESA to keep the instrument in the ISS to add new experiments to the future European astronauts' programmes. And in turns, new technological and scientific experiments will take place in the ISS, both to test new types of tanks and to test the validity domain of the theory of waves turbulence.



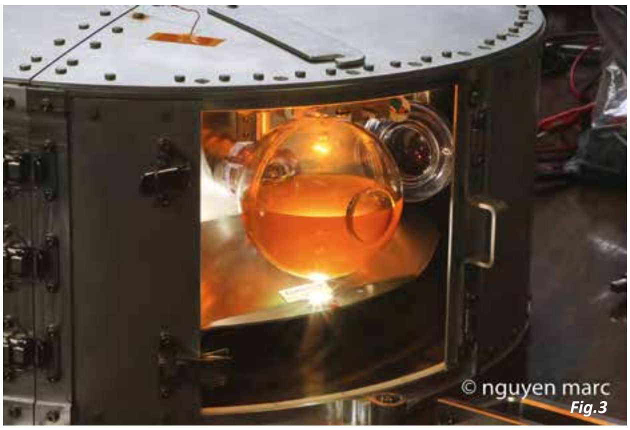


Fig. 1: Fluidics experience aboard the International Space Station *© ESA/NASA/, 2017*

Fig. 2: Preparation of the Fluidics experiment of the Proxima mission at Cadmos © *CNES/GRIMAULT Emmanuel, 2016*

Fig. 3: Preparation of the Fluidics experiment of the Proxima mission at Cadmos © *CNES/NGUYEN Marc, 2016*

AUTHOR
M. Berhanu[1], E. Falcon[1], S. Fauve[2]
1 MSC (Complex Matter and Systems), CNRS UMR 7057, Université Paris Diderot, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
2 LPS (Statistical Physics Laboratory), CNRS UMR 8550, ENS, 24 rue Lhomond, 75231 Paris, France

Wave turbulence in microgravity

We report experiments conducted by the ESA astronauts T. Pesquet and P. Nespoli on the International Space Station in 2017. Using a new device, "FLUIDICS" (Fluid Dynamics in Space), developed by CNES and Airbus Defence and Space, they studied turbulence of capillary waves on the surface of a fluid in a spherical container. Power spectra of wave turbulence have been found to be in good agreement with weak turbulence theory.

Wave turbulence results from the nonlinear interactions among stochastic waves [1]. The first studies have been conducted in the early 1960s motivated by wave forecasting on the ocean. However, it was soon realised that similar techniques could be used to understand nonlinear interactions between waves in many different systems, such as Alfven waves in the solar wind, radar waves in the ionosphere or at much smaller scales, sound waves in solids or liquids. The first analytical studies of wave turbulence have been performed in the early 1970s in order to predict how the distribution of the wave energy depends on their wavenumber. Besides equilibrium spectra (such as the blackbody spectrum for instance), out-of-equilibrium spectra that involve a finite energy flux in Fourier space, *i.e.* a transfer of energy from an injection scale to a dissipation scale, have been found. This out-of-equilibrium behavior is similar to the Kolmogorov cascade in fluid turbulence. Many data from astrophysical or geophysical fluid dynamics obtained using remote sensing have been analysed using the framework of wave turbulence. Several laboratory experiments, performed during the past decade have shown the limits of the theory based on weakly interacting waves. The different requirements for the validity of weak turbulence theory are indeed conflicting. It is assumed that waves propagate in a medium of infinite extension with negligible damping. Experiments of course involve a finite domain. If dissipation is small, resonant modes of the domain are excited dominantly compared to the continuous spectrum predicted by weak turbulence. A too large dissipation requires a strong forcing and is also out of the validity range of weak turbulence. There is probably an optimum dissipation in the limit of a large domain but no criterion is known in that framework. Reflection on boundaries could also affect wave turbulence. We mention below how experiments in reduced gravity can solve some of these problems.

Many laboratory experiments have been performed with surface waves on a horizontal layer of fluid. In this configuration, the dominant restoring force is gravity for large wavelength and capillarity for short wavelength. The transition between the 2 regimes occurs for the capillary length that depend on the surface tension, the fluid density and the acceleration of gravity. For simple fluids on Earth, the capillary length is a few millimetres. Energy transfer mechanisms are different for gravity and capillary waves and this makes the cascade process of the energy more difficult to understand since the mechanisms change when one crosses the capillary length [2]. The first advantage of experiments in reduced gravity is to increase the capillary length above the size of the container and thus to have capillary waves throughout the cascade. A second advantage is related to the geometry of the experiment. At low gravity, the fluid inside a spherical container wets the inner boundary and therefore takes the shape of a spherical fluid layer. Capillary waves propagate on its inner surface without meeting any lateral boundary in contrast to the configurations studied on Earth. Although the infinite medium limit assumed for weak turbulence theory is not achieved, the parasitic effect of lateral boundaries is suppressed.

Capillary waves in reduced gravity have been first studied in parabolic flights [3]. The main limitation is related to the 20 s duration of each parabola that does not allow enough statistics and could be even too short compared to the transient regime. An experimental device called FLUIDICS has been developed by Airbus Defence and Space and CNES and operated by the ESA astronaut T. Pesquet, and then by P. Nespoli, on ISS. This has allowed much longer measurements. This device has been developed to study both capillary wave turbulence and sloshing. Its schematic view is displayed in Fig. 1.

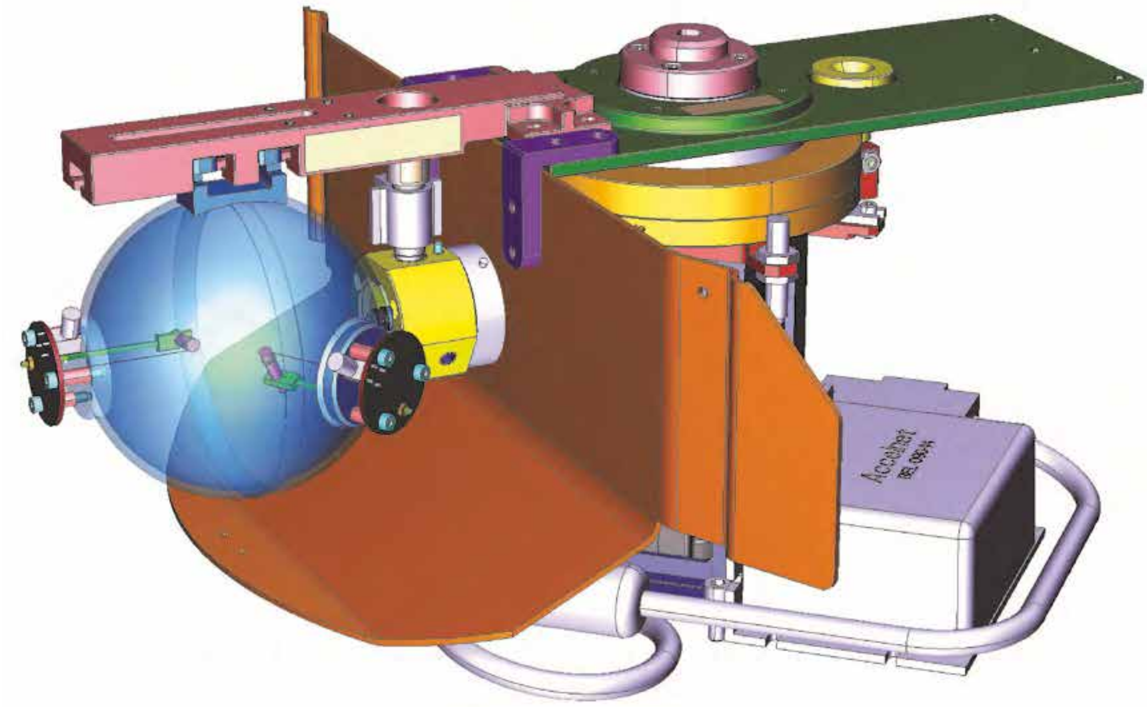


Fig.1

The sphere of inner diameter 100 mm is partly filled with water (30% in volume). The depth of the spherical fluid layer is 5.6 mm. The sphere is driven in an oscillatory rotating motion by a lever and the surface deformation of water is measured by 2 capacitive wires. The power spectrum of the fluctuations of the surface in the turbulent regime is displayed in Fig. 2. Although the excitation is sinusoidal, a continuous spectrum is generated by non-linear interactions that trigger energy transfers between waves of different frequencies. The slope of the spectrum is found to be in good agreement with the prediction of weak turbulence theory.

To conclude, reduced gravity provides better experimental configurations to study capillary wave turbulence than laboratory experiments on Earth. Spatial correlations and probability density functions of the fluctuations of the fluid surface will be studied soon. Using higher frequency forcing will also allow us to test whether scales larger than the one of the forcing are in statistical equilibrium [4]. This work will be pursued by next ESA astronauts. A more technological study has also been performed on ISS with FLUIDICS instrument to benchmark numerical models for a better prediction of slosh dynamics in liquid propellant tanks and their effect on spacecraft trajectories during their manoeuvres [5].

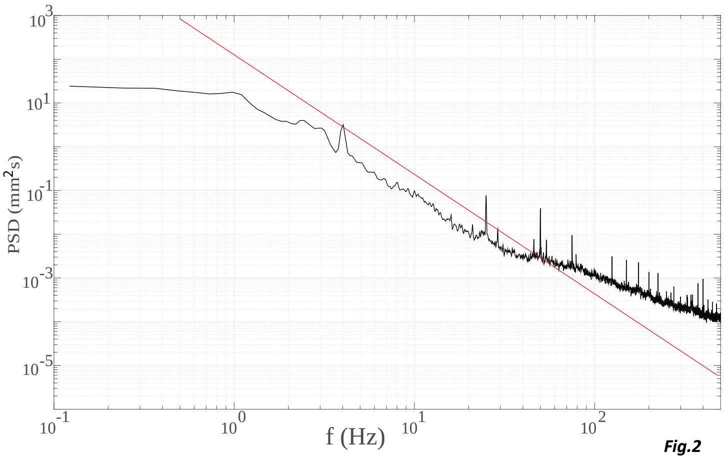


Fig.2

Fig. 1: Schematic view of the experiment: a sphere partly filled with fluid is fixed at the end of a lever that is rotated in order to generate waves on the fluid inner surface. The fluid motions are visualised using two cameras and its height is measured by two capacitive gauges. *© Airbus Defence and Space*

Fig. 2: Power spectrum of the fluid surface fluctuations: the container is driven in an oscillatory rotating motion with amplitude 0.04 rad and frequency 2 Hz. A continuous spectrum is generated by energy transfers between random waves. Straight line: theoretical prediction in the weak turbulence regime. *© LPS, Ecole Normale Supérieure & MSC, Univ. Paris Diderot*

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INSIGHT, geophysical science on the surface of Mars

INSIGHT (INterior exploration using Seismic Investigations, Geodesy and Heat Transport) is a mission from NASA's discovery programme. A lander will deploy geophysical instruments on the surface of Mars to study the planet's deep interior and gain new understanding of how rocky planets form.

INSIGHT aims to study Mars' deep interior structure using a seismometer deployed from a fixed lander to better understand the mechanisms that shaped the rocky planets in our Solar system. Using the SEIS seismometer (Seismic Experiment for Interior Structures), it will measure Mars' tectonic activity to learn more about its structure, for example the size of its core, the thickness of its mantle and crust. Meteorite impacts will also be analysed by measuring seismic waves. The Heat Flow and Physical Properties Package (HP3) will gauge the planet's cooling rate in order to retrace its thermal history. And the RISE instrument (Rotation and Interior Structure Experiment) will acquire precise measurements of the Red Planet's rotation. INSIGHT includes also a suite of environment sensors (APSS-Auxiliary Payload Sensor Suite) including pressure / infrasound sensors, magnetometer and wind sensor.

INSIGHT will land on Mars on 26 November 2018 for a 2-year mission. CNES is overseeing development of the SEIS instrument in partnership with the Paris Institute of Earth Physics (IPGP), SODERN (ArianeGroup), the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), Imperial College London and the Jet Propulsion Laboratory (JPL). INSIGHT is the 12th mission of the Discovery Programme.

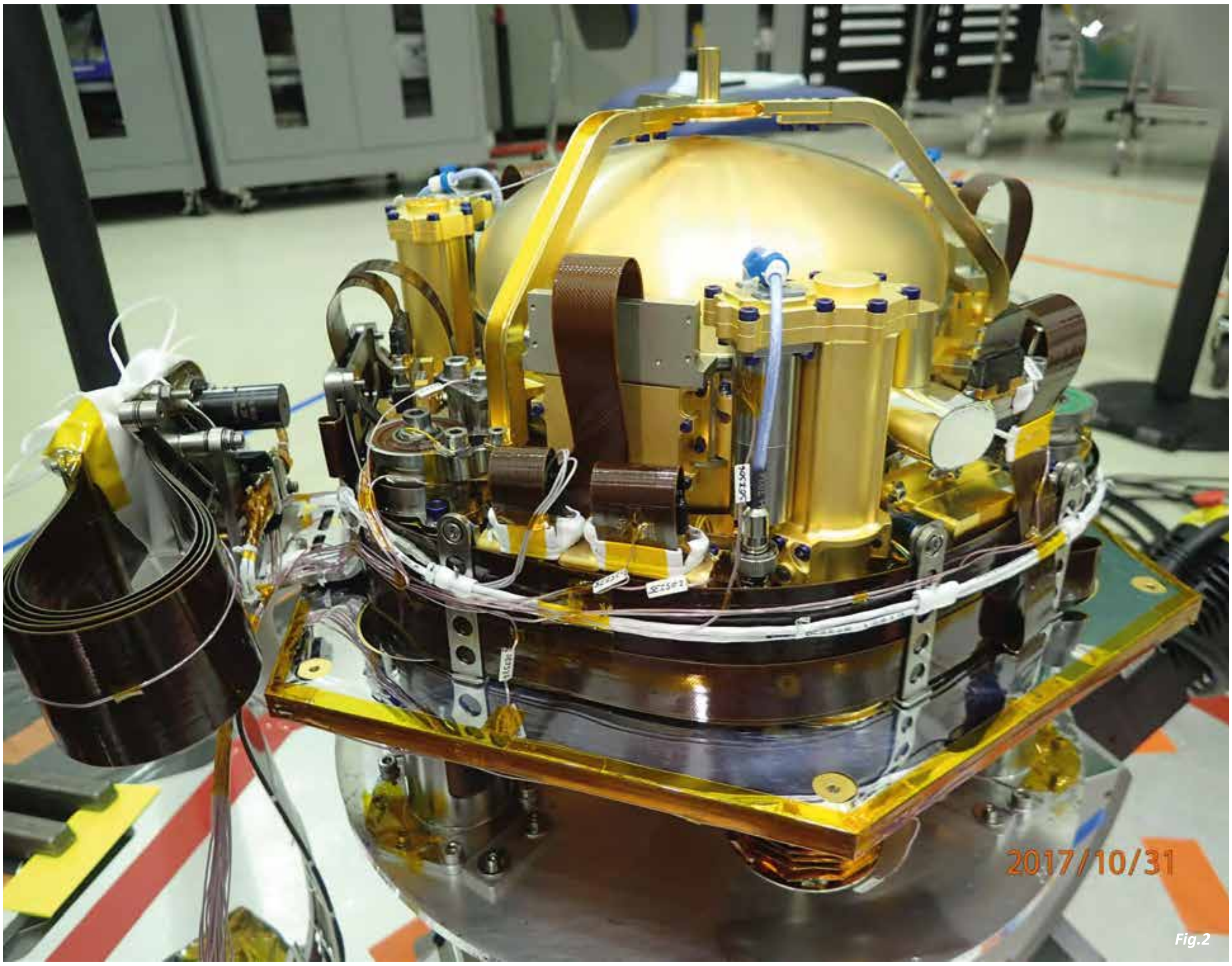
Fig.1

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PI LABORATORY
SEIS (Seismic Experiment for Interior Structures)	Seismometer to measure tectonic activity: Mars quakes, meteorite impacts, Phobos gravity waves.	CNES overall responsibility with IPGP, SODERN, the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), Imperial College London and the Jet Propulsion Laboratory (JPL)
HP3 (Heat Flow and Physical Properties Package)	Instrument to gauge the planet's cooling rate	DLR-Berlin
RISE (Rotation and Interior Structure Experiment)	Instrument to measure the planet's rotation	JPL, Royal Obs. of Belgium (ORB)

SCIENTIFIC OBJECTIVES

INSIGHT's primary objective is to uncover how a rocky body forms and evolves to become a planet by studying the size, thickness, density and overall structure of the Red Planet's core, mantle and crust, as well as the rate at which heat escapes from the planet's interior. Generally, a rocky body begins its formation through a process called accretion. As the body increases in size, its interior heats up and melts. As it subsequently cools and recrystallises, it evolves into what we know today as a terrestrial planet, containing a core, a mantle and a crust. While all the terrestrial planets are by no means uniform, they share similar structures and their bulk compositions are roughly the same due to the fact that they were formed from the same nebulous material. Each of the terrestrial planets reached its current formation and structure through a process known as differentiation, which is poorly



understood. INSIGHT's goal is to solve the mystery of differentiation in planetary formation - and to bridge the gap of understanding what lies between accretion and the final formation of a terrestrial planet's core, mantle, and crust.

The mission's secondary objective is to conduct an in-depth study of tectonic activity and meteorite impacts on Mars, both of which could provide valuable knowledge about such processes on Earth.
To achieve each of these objectives, INSIGHT will conduct 6 investigations on and below the surface of Mars to uncover the evolutionary history that shaped all of the rocky planets in the inner solar system. These investigations will:

- Determine the size, composition, physical state (liquid/solid) of the Martian core
- Determine the thickness and structure of the Martian crust
- Determine the composition and structure of the Martian mantle
- Determine the thermal state of Mars' interior
- Measure the magnitude, rate and geographical distribution of Mars' internal seismic activity
- Measure the rate of meteorite impacts on the surface of Mars

MISSION STATUS

INSIGHT key dates:

- Launch: 5 May 2018 (start of the 30 days' launch window)
- Landing: 26 November 2018 (at 19-20 h UT)
- Surface operations: 720 days / 700 sols
- Instrument deployment: 60 sols (including 20 sols' margin)
- Start of science operations: late January 2019
- Data volume over one Martian year: More than 29 Gb (processed seismic data posted on the Web in 2 weeks; remaining science data less than 3 months, no proprietary period)
- End of nominal Mission: October 2020

Fig. 1: The SEIS FM experiment with the WTS (Wind & Thermal Shield) white dome deployed during a thermal vacuum test at Lockheed Martin in November 2017 © *Lockheed Martin.*

Fig. 2: The SEIS FM experiment during integration and tests at Lockheed Martin last October © *Lockheed Martin.*

MSL/CURIOSITY, a rover exploring Mars

On 6 August 2012, the CURIOSITY rover landed on Mars to determine if the Red Planet could have once harboured life. CNES is closely involved in this mission led by NASA, which has been extended beyond its 22 months' nominal mission.

Was Mars once habitable? That is the main question the Mars Science Laboratory (MSL) mission of NASA's Mars exploration programme is attempting to answer with the CURIOSITY rover operating on the planet's surface. Since its landing in Gale Crater, this 900-kg robotic explorer has conducted a series of analyses aimed at assessing Mars' habitability, estimating its biological potential and characterising its geology.

To accomplish its task, CURIOSITY has a robotic arm equipped with in-situ instruments to survey the soil and rocks, together with a drill and a scoop to pick up samples for further analysis by its SAM (Sample Analysis at Mars) and CHEMIN (CHEmistry & MINeralogy) mini-laboratories. The rover is also equipped with 8 other instruments.

CNES' contribution to the MSL mission is twofold. First, it is overseeing the French instruments SAM and CHEMCAM (CHEMistry CAMera), in which the LATMOS-CNRS and the IRAP-CNRS are involved. Second, CNES is responsible for developing and running the French Instruments Mars Operations Centre (FIMOC) in Toulouse, which operates CHEMCAM and SAM, and exploits the data they gather.

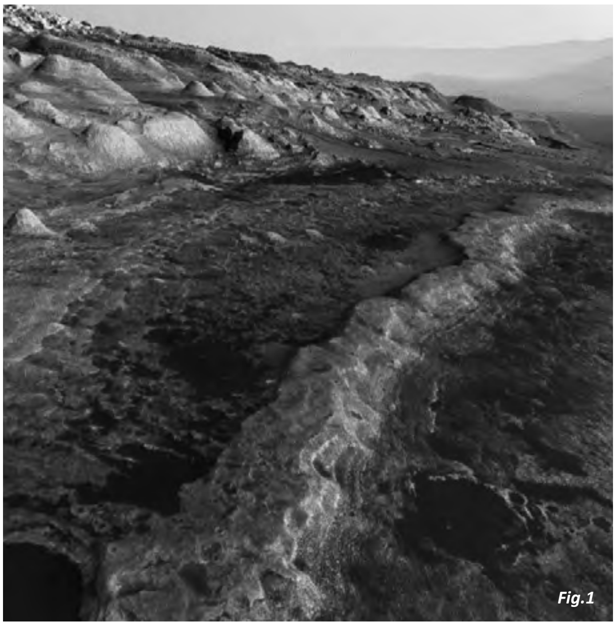


Fig.1

SCIENTIFIC PAYLOAD & FRENCH CONTRIBUTION:

INSTRUMENT	OBJECTIVE	PI LABORATORY
CHEMCAM (CHEMistry CAMera)	It analyses by UV-Vis-NIR optical spectrometry the plasma light emitted by Martian rocks shot with a laser (from a distance of 1 to 9 m). It is composed of the following 2 units: The Mast Unit (mounted on the rover mast) is constituted of a laser, a telescope, and a camera (RMI: Remote Micro Imager). The Body Unit (mounted on the rover's body) is constituted of 3 spectrometers, the power and on-board management electronics. The 2 units are connected by electric cables and optical fibre.	The PI is Roger Wiens from Los Alamos National Laboratory. The Mast Unit suite is supplied by IRAP-CNRS. The Co-PI is Sylvestre Maurice from IRAP. The Body Unit is supplied by Los Alamos National Laboratory (USA). The Optical fibre is supplied by JPL (USA).
SAM (Sample Analysis at Mars)	SAM performs mineralogical and atmospheric analyses; it detects a wide range of organic compounds and performs organic stable isotopes and noble gas analyses. This instrument suite is composed of the following instruments: QMS (Quadrupole Mass Spectrometer), GC (Gas Chromatograph), TLS (Tunable Laser Spectrometer).	Its PI is Paul Mahaffy from GSFC-NASA. QMS is supplied by GSFC-NASA GC is supplied by LATMOS-CNRS. M. Cabane & C. Szopa are the lead Co-I at LATMOS TLS is supplied by the JPL-NASA.

SCIENTIFIC HIGHLIGHTS

CURIOSITY has already determined that conditions on Mars were once conducive to life and discovered an ancient river bed.

Using CHEMCAM experiment, the detection of hydrous manganese and iron oxides with variable phosphorous and magnesium contents in the lacustrine sediments of Murray formation suggests a complex process which may trace a shallow lacustrine environment [1].

A Chemical Alteration Index (CAI) used with CHEMCAM data show that this index increases with altitude on Murray formation suggesting an increase of the alteration by water when approaching the Clay-bearing unit [2].

SAM has analysed 12 samples during the 6 years of the mission. The instrument already has samples in some of its oven that may be analysed when needed. SAM is regularly monitoring the atmosphere and has detected methane at 3 occasions at concentration of 2 to 10 ppbv. Furthermore, a background level of methane is constantly measured at a level around 0.4 ppbv. This low level of methane varies with the season with a maximum of 0.7 ppbv in Northern Summer. No definitive interpretation has been given on this regular variation which does not seems to be explained by the Martian atmospheric cycle of condensation-sublimation of CO_2 in the poles.

MISSION STATUS

CURIOSITY has now driven more than 18 km and is currently on top of the Vera Rubin Ridge. Observations from orbit led to think that this ridge is enriched in iron oxides; its exploration is in progress.
At the moment, CHEMCAM has taken more than 500 000 spectra, which corresponds to almost 15 000 observation points on 1 800 Martian targets during the mission.

Late in 2016, the drilling system started to malfunction. It took more than a year for JPL to set up a new procedure to use the drill safely. A first drill has been performed in January but it was not deep enough to collect samples. It is planned to make other tests using the drill with percussion mode.

A second extended mission of one year up to September 2019 is considered, then a full extension of 3 years will be decided in Spring 2019 for 2020-2022. If this full extension is confirmed, CURIOSITY has the objective to attend the clay-bearing unit follow by the sulphate-bearing unit, driving a total of more than 25 km. The wheels are damaged by the sharp rocks of Mars, but JPL assesses that CURIOSITY will be able to drive the last 7 km without critically damaging one of its wheels.

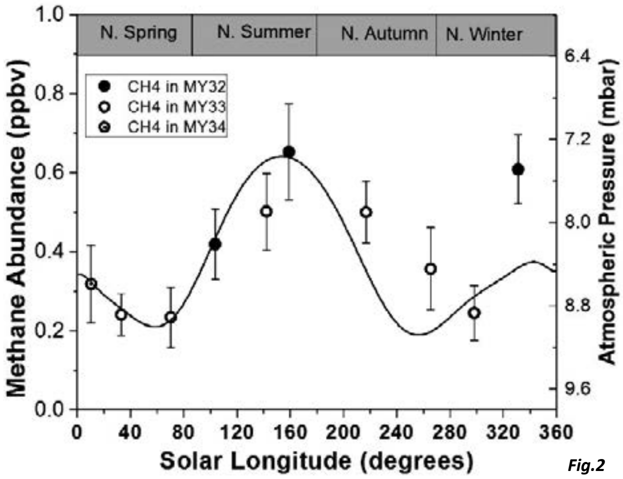


Fig. 1: The Vera Rubin ridge seen by HiRISE. This ridge has been observed from orbit and revealed the presence of hematite mineral, a ferric oxide mineral. Similar hematite has been observed by Opportunity in the form of small spherule. In September 2017, CURIOSITY arrived on top of the ridge. © *NASA/JPL*

Fig. 2: Methane low level variation with seasons (Webster *et al.*, Science, 2018)

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AUTHOR
O. Gasnault[1], S. Maurice[1], R. C. Wiens[2]
1 IRAP (Research Institute in Astrophysics and Planetology), CNRS UMR 5277, Université Paul Sabatier, 9 avenue du Colonel Roche, 31400 Toulouse, France
2 Los Alamos National Laboratory, Los Alamos, NM 87545, USA

MSL/CHEMCAM: 2 000 sols within Gale Crater, Mars

CHEMCAM is the first laser-induced breakdown spectroscopy (LIBS) instrument for planetary science. It is part of the CURIOSITY Mars rover that landed in Gale crater in 2012 that measures bulk chemistry at remote distances in synergy with the 9 other rover instruments. Over the course of 2 000 sols (1 sol = 1 Mars day) more than 1 800 unique targets were analysed, revealing the composition of sediment sources, evolved igneous rocks, vein minerals, hydrated soils, and signatures of minor elements.

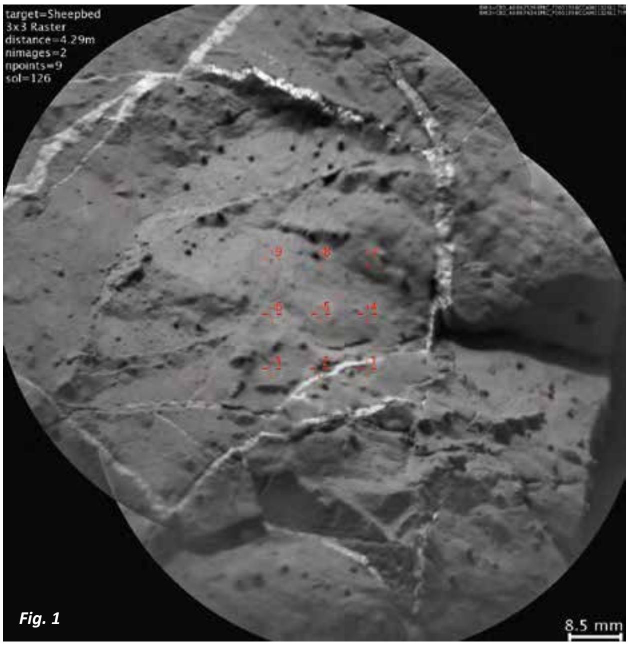


Fig. 1

The MSL mission of the NASA Mars programme is managed by Caltech-JPL. In August 2012 the CURIOSITY rover landed in Gale crater, which is partly filled with sediments. The mission objectives are to explore the sedimentary layers, which are proxies of the successive geological epochs, to evaluate the habitability of that site, and to monitor its current environment. As it progresses, CURIOSITY characterises several sedimentary deposits, some being undetectable from orbit by remote sensing, in an intricate setting resulting from a succession of fluvial, lacustrine, and aeolian episodes (deposits, erosion, weathering) [1]. The past habitability of Mars was established at Yellowknife Bay, a fluvio-lacustrine deposit where the chemical alteration of the clays was limited. A thorough stratigraphy is now being established by the rover from this lowest elevation point explored up to the flanks of the eroded mound at the centre of the crater, Aeolis Mons (or Mount Sharp).

CHEMCAM is a French-US instrument using Laser-Induced Breakdown Spectroscopy (LIBS). It measures the composition of rocks and soils within 2 to 7 m of the rover for major elements (Si, Ti, Al, Fe, Mg, Ca, Na, K), hydrogen, and non-metallic elements when they are sufficiently abundant (F, Cl, P, S), as well as minor or trace elements (Li, Rb, Sr, Ba, Cr, Mn, Ni, and Zn). In addition, CHEMCAM includes a high resolution panchromatic camera, which is used to identify the context of LIBS data (crystals, veins, nodules, grains, cement) and to make high-resolution long distance imaging a few kilometres away (ridges, lineae slopes, preserved alluvial fans, yardangs). CHEMCAM is also used in a solar-induced passive mode either to look for the reflectance of minerals (olivine, hematite) or for temporal studies of atmospheric species (O_2, CO_2). Several geological formations have been studied with CHEMCAM, as well as various outcrops, conglomerates, and soils that attest the fluvial, lacustrine, and aeolian past activities in this region of Mars. CHEMCAM contributed significantly to understanding the geochemical diversity of the landing site (Mg-rich clays, K-rich facies, Ca-rich veins, Mn-rich varnishes, Si-rich alteration halos), reflecting several sources of sediments (in space or time), and the diversity of alteration and diagenesis mechanisms that formed these rocks [2].

In support of the in-situ investigation on Mars, laboratory experiments are conducted at LANL and IRAP (respectively Los Alamos, NM, USA and Toulouse, France) to extend the database of reference spectra, and for specific studies such as the laser interaction with soil grains.

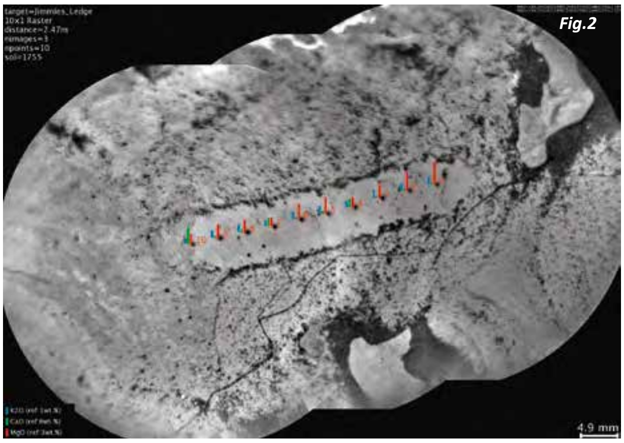
As the rover progresses, the soil composition is regularly characterised with CHEMCAM revealing 2 to 3 components, one with fine-grained hydrated mafic composition and another one with more felsic composition in gravel derived from local rocks [3]. This felsic (Si-, Al-, Na-, K-rich) signature was also seen early in the mission by CHEMCAM in igneous float rocks and conglomerate clasts that were interpreted as samples transported from the crater rim or beyond representing a somewhat evolved crust with alkaline magmatism [4].

CURIOSITY explored the active Bagnold Dunes where the entire rover payload was used to document the subtle compositional differences with the standard soil in the crater, as well as the grain size distribution and the grain motions.

Many precipitate-filled veins are present almost everywhere along the rover traverse. They prove the past occurrence of a subsurface aqueous circulation, which involved water percolation and evaporation, leaving S-rich deposits that were remobilised into the veins that crisscross the sediments (Fig. 1). CHEMCAM showed that those light-toned veins are made of a slightly hydrated calcium sulphate known as bassanite [5]. More generally, the capability of CHEMCAM to investigate the bedrock at submillimetre scales is appropriate to study the small diagenetic figures.

More clays were found in the Murray Buttes region as the rover reached Mount Sharp, and it is known from orbital observations that other clay-rich units will be encountered by the rover with the next few kilometres to come. The paleo-lacustrine mudstone terranes of the Murray Formation are made of relatively Si-, Al-, and alkali-rich sediments suggesting significant weathering in an open system with liquid water [6]. The capability of CHEMCAM to make many measurements is important for studying the chemical diversity of such an area, as shown in Fig. 2 (bars plotted at each observation point show varied chemistry despite a homogeneous-looking surface), and nicely complements the observations made by the other instruments of the payload.

In parallel to CHEMCAM operations on Mars, the next-generation instrument, SuperCam, is being built: in addition to LIBS and imaging, SuperCam will perform Raman and infrared spectroscopy, and will record laser impact sounds; it is one of the payload instruments of the NASA mission Mars2020 that will land at the surface of Mars in 2021.



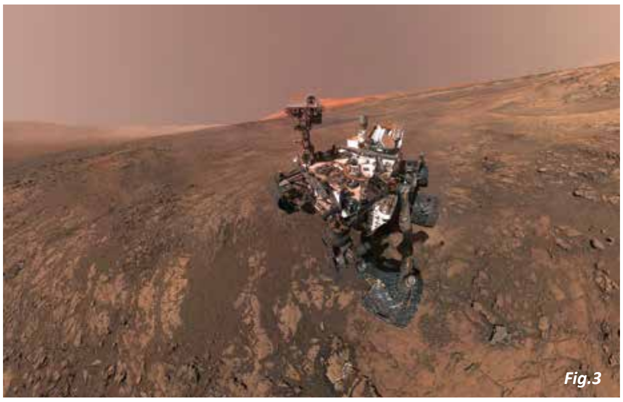


Fig. 1: Sheepbed mudstone crosscut by basanite veins in Yellowknife Bay and sampled by CHEMCAM (points 1 to 9) on mission day 126 © *NASA/JPL-Caltech/CNES/CNRS/LANL/IRAP/IAS/LPGN).*

Fig. 2: Jimmies_Ledge bedrock in the Murray Formation, sampled with 10 CHEMCAM points on mission day 1755. The image shows the dust blown away by the laser impacts on this smooth rock and the compositional variations in Mg, Ca, and K © *NASA/JPL-Caltech/CNES/CNRS/LANL/IRAP/IAS/LPGN).*

Fig. 3: CURIOSITY self-portrait at the Vera Rubin Ridge on mission day 1943. The CHEMCAM telescope is visible at the top of the rover mast (© *NASA/JPL-Caltech/MSSS*). Link to high resolution image: https://photojournal.jpl.nasa.gov/catalog/PIA22207.

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AUTHOR
C. Szopa[1] and the SAM experiment team
1 LATMOS (Atmospheres, Environments, Space Observations Laboratory), CNRS UMR 8090, 11 boulevard d'Alembert, 78280 Guyancourt, France

The chemistry of Gale Crater (Mars) as seen by the SAM instrument on board the CURIOSITY rover

The SAM instrument on board the CURIOSITY rover analyses the chemical composition of the atmosphere, soil and rocks in Gale crater (Mars) for 6 years. For the last Martian years, the instrument continued its harvest of results by improving our understanding of the seasonal variability of the atmospheric composition, contributing to characterise the chemical stratigraphy of Mount Sharp, and by confirming the presence of organic materials at the surface of the planet.

On the way to Gale crater, the CURIOSITY rover analyses the chemical composition of rocks and soil, and surface atmosphere. If several instruments on board the rover provide precious information about the elemental composition of the minerals, SAM is the only experiment which is capable of characterising the content in volatile molecules in the different component of the surface. To this end, it uses a suite of 3 complementary instruments developed by a consortium of NASA and French laboratories. These instruments analyse either directly the atmospheric gases, or volatile species released by the solid samples collected by the robotic arm of the rover. These volatiles are produced by the sampler preparation system of SAM, when the samples are heated up to about 850 °C, or when they are submitted to chemical reactions in contact with a liquid reactant [1]. After almost 6 years operating on Mars, SAM is still in good health and analysed the composition of the hematite rich rocks of the Vera Rubin Ridge where the rover was present in march 2018, and the clays and sulfates rich layers the rover should explore in the years to come.

For the last 2 years, the data collected with SAM allowed to significantly improve our knowledge about the ancient environment of Gale crater and its relevance to a habitable place, and we present here the key results that were obtained.

Regarding the solid samples, a systematic analysis of the major gaseous species released by the 11 different samples delivered by the rover arm to SAM was achieved with the mass spectrometer as a function of the sample temperature [2]. This evolved gas analysis gives information about the mineralogy of rocks and their content in volatile species. This systematic study showed the presence of nitrate in all the samples that were analysed through the detection of NO. This mineral is of high interest as it fixes nitrogen atom in the soil that can be assimilated by living organisms on Earth. In addition to nitrates, the detection of CO_2 released by the samples at different temperatures and especially at temperatures for which O_2 is also released (Fig. 1) strongly suggests the presence of CO_2 adsorbed on the grains, carbonates that decompose at high temperature, and also organic molecules that would be oxidised by O_2. Even if this last conclusion cannot be strictly confirmed, it strengthens the first detection ever of organic molecules indigenous to Mars with SAM a couple of years ago [3], and it suggests that organic molecules could be widespread on Mars despite the harsh conditions of the Mars surface for the organic materials. The presence of both nitrates and organic materials in the Martian soil analysed also strengthens the potential for habitability of Gale crater as these 2 species are known to be used by heterotrophic organisms to build their own material on Earth.

Regarding the atmosphere, SAM was able to finely quantify the amount of noble gases and their isotopic ratio, with a significant improvement for Xe comparatively to those achieved with the Viking probe GCMS instrument. The SAM team compared

the current atmospheric isotopic ratios of Xe and Kr to those measured in the gases trapped in Martian meteorites which are supposed to be representative of the ratios that existed at the period when the meteoritic material was ejected from Mars [4]. From this comparison, it can be seen that the lightest isotopes are present in excess in the current Mars atmosphere (Fig. 2). By considering the different processes that could be involved in the production of this excess of light isotopes, it appears that spallation and neutron capture are among the contributing mechanisms. The evidence of the existence of these processes could help to better constrain the interaction between the mars atmosphere and the solar wind. It could also be a first step in the determination of the age of trapped atmosphere components in Martian meteorites. The measurement of the Mars atmosphere composition to be done with SAM in the future should not bring a significant improvement to these noble gases isotopes study. They will rather focus on the seasonal variation of the major atmospheric gases, and the question of atmospheric methane, at the time when the TGO probe is now fully operational to look for the presence of methane in the atmosphere from the Mars orbit.

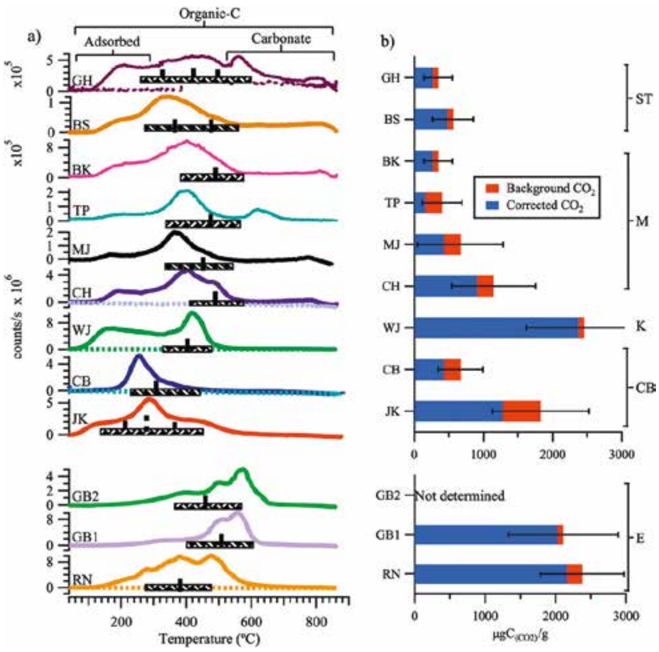

Fig.1

Fig. 1: (a) Evolved CO_2 (m/z 44) (c/s) versus temperature as detected by SAM-EGA. Temperature ranges of possible CO_2 sources are indicated in brackets. Cross-hatched bars indicate temperature range of O_2 evolution (b) Carbon content ($\mu gC_{(CO2)}$/g) derived from evolved CO_2. CO_2 contribution from sample in blue with estimated contribution from background in orange © *Wiley.*

Fig. 2: Martian meteorite, fractionated solar wind, and average SAM Xe data plotted as δ-values referenced to the solar wind (SW) composition, and corrections for hypothetical atmospheric spallation and *n*-capture $^{127}I(n,\gamma\beta-)^{128}Xe$ and $130Ba(n,\gamma\beta-)^{131}Xe$ components © *from Conrad P.G., et al. (2016)*

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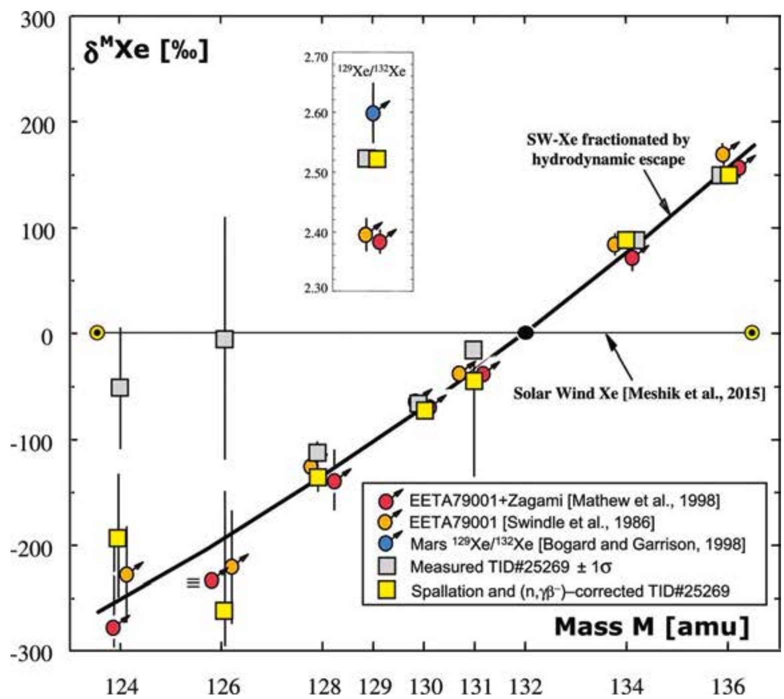

Fig.2

AUTHOR
C. Mazelle[1]
1 IRAP (Research Institute in Astrophysics and Planetology), CNRS UMR 5277, Université Paul Sabatier, 9 avenue du Colonel Roche, 31400 Toulouse, France

Recent MAVEN results from the SWEA instrument at Mars: consequence for the hydrogen exosphere

Foreshock electrons produced at the bow shock of Mars by a mirror reflection of a portion of the incident solar wind show a flux fall off with the distance from the shock. This attenuation, unobserved at the terrestrial foreshock, has been recently explained by the impact of backstreaming electrons on Mars exospheric neutral hydrogen. The important consequence is that foreshock electrons can be used to put constraint on the exospheric hydrogen profile of Mars especially at high altitudes.

A recent study mostly based on the data from the electron spectrometer SWEA on board the NASA spacecraft MAVEN orbiting Mars since the end of 2014 revealed that observations of this instrument obtained in the region upstream from the planetary bow shock could provide a new method to investigate the hydrogen exosphere especially at large distances from the planet [1]. A previous study [2] had already shown that the entire bow shock surface of Mars forms a source for backstreaming electrons, flowing mainly along the magnetic field in the direction opposite to the flow of the incident solar wind in the region called the foreshock, with energies reaching up to ~2 keV. The backstreaming electrons appear as ring-beams in velocity space strongly indicating that the magnetic mirroring of a portion of solar wind electrons taking place at the shock is a plausible mechanism for their production. In addition, the study shows that the electron flux falls off with distance from the shock.

Fig. 1 displays one example of such observation. The upper panel shows the electron fluxes for different energy ranges compared to the magnetic field observations and geometrical parameters when MAVEN is located within the foreshock region after crossing the bow shock. At first glance, electron beams from tens to several hundreds of eV emanating from shock are expected to propagate at a considerable distance beyond MAVEN's orbit before the effects of scattering by magnetic field fluctuations become measurable. There is no evidence in the MAVEN wave data for plasma waves that could efficiently scatter the electron beams. The recent analysis by Mazelle *et al.* [1] provides evidence that the observed foreshock electron flux decrease with distance above some tens of eV is due to collisions with the extended exospheric neutral hydrogen of Mars.

Because of Mars' lack of a global magnetic field, the solar wind can directly interact with the upper atmosphere inducing ion escape via ionization, sputtering and pickup processes. In the later process, which is one of the important mechanisms driving the atmospheric loss of Mars, neutral atoms are ionized and "picked up" by the solar wind embedded magnetic field. Several sources of ionization are possible. In the exosphere, upstream of the bow shock, photoionization and charge exchange are the dominant mechanisms, with ionization through electron impact providing a minor contribution.

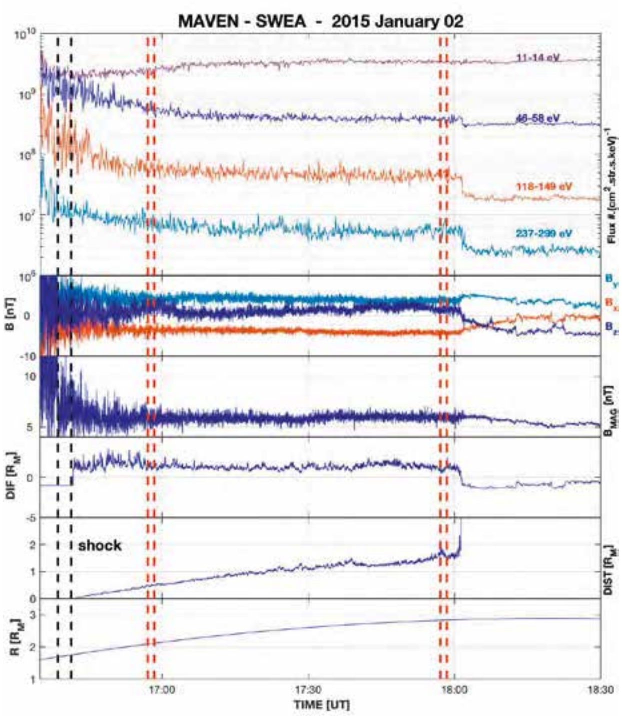

Fig.1

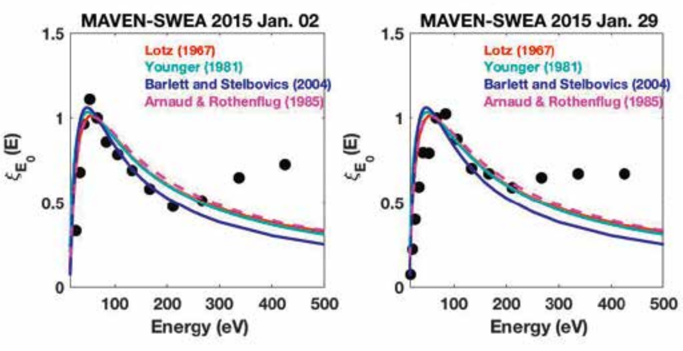

Fig.2

Fig. 1: Top to bottom panels respectively show the electron flux for 4 selected energy ranges, the MSO-IMF components, the magnetic field magnitude, the distance DIST along the ambient IMF of MAVEN to the shock, the foreshock depth DIF and the planetocentric distance R of MAVEN © *Wiley AGU.*

Fig. 2: Open circles indicate $\xi E_0(E)$ ratio versus energy E using E_0 = 52.1 eV (see text for explanation). The continuous lines show the ratio of HI-electron impact cross sections $\sigma(E)/\sigma(E_0)$ from various sources showing the very good agreement for the peak energy © *Wiley AGU.*

In this mechanism, free electrons collide with neutral atoms, and if the energy of the former is higher than the ionization threshold of the latter, an ion can be produced. The collision cross-section indicates the relevance of the impact process and it is expected that the solar wind electron impact neutral ionization remains weak upstream of the bow shock. With a temperature of ~10 eV, most of the solar wind electron flux remains below the level for which the cross section for electron impact ionization for hydrogen peaks (~50 eV). At first glance, the exospheric neutral atoms impact with foreshock electrons may appear quite minor as the foreshock electron density is significantly much smaller comparatively to the solar wind electron density. Nevertheless, the flux of foreshock electrons with an energy above the ionization threshold exceeds that of the solar wind and is significantly enhanced up to a few hundreds of eV in the energy range where electron impact ionization is important.

Quantitative arguments can be developed in support of foreshock electrons impact with exospheric hydrogen. First it is possible to fit the observed decrease of the flux from simple analytical calculations. By considering a mono-energetic beam of electrons with energy E emanating from the shock and colliding with a neutral exospheric atomic hydrogen, the variation of electron flux $F_E(x)$ at a distance x from the shock as the electrons propagating through the exosphere can be governed by the following expression:

$$dFE(x)/dx = -n_H(r(x)) \times \sigma(E) \times F_E(x)$$

where $n_H(r(x))$ is the atomic hydrogen density profile and σ(E) the collision electron cross-section. It is implicitly assumed that the exospheric hydrogen is at rest and the electrons propagate along the magnetic field direction x. Integrating between 2 positions x_1 and x_2 using a bow shock model and assuming an analytical profile for nH as a simple power law with an index very close to an independent determination, it is then straightforward to derive an expression of FE(x) which has been shown to fit well the observations [1]. Pursuing the analysis further and to better adjust a comparison with the observations, the dependence upon the bow shock and hydrogen profile models are then eliminated. For this purpose, for 2 arbitrary energy values E_0 and E and the following ratio is derived at 2 different positions x_1 and x_2:

$$\xi E_0(E) = \ln(FE(x_1)/FE(x_2)) / \ln(FE_0(x1)/FE_0(x2)) = \sigma(E)/\sigma(E_0)$$

Hence, this ratio is solely dependent upon the electron flux levels, and therefore can be directly obtained from observations. The right-hand term can also be determined from ionization cross-section Tables. Fig. 2 shows the result obtained for E_0=52.1 eV, a numerical value corresponding to the maximum electron-hydrogen impact cross-section. However, the results are only weakly sensitive to the choice of E_0. An excellent agreement is obtained close to the maximum enforcing the above interpretation.

These results may have important implications on the pickup ion production rate at distance far from the planet centre. Also, additional pick-up ion production rate due to the electron impact inside the electron foreshock is an important element in our comprehensive understanding of the Martian upstream region variability at small time scales compared to seasonal effects on much larger time scales reported e.g. by Romanelli *et al.* (2016) [3]. Moreover, the experimental flux attenuation fitted profiles could be used as a new tool to constraint the exospheric hydrogen density profiles.

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EXOMARS: two Martian missions for exobiology

Has life ever existed on Mars? ESA planned 2 missions to find it out, one in 2016, and the other in 2020. The later will land a rover – a real laboratory on wheels – on the Red Planet's surface.

Fig.1

This name comes from the contraction of 2 words: "Exo" standing for "exobiology", the science looking for traces of extra-terrestrial life forms, and obviously, "Mars". These missions are directed by ESA in collaboration with the Russian space agency Roscosmos.

CNES is coordinating the contribution to this mission of several French laboratories to the provision of the instruments as well as the scientific processing of the data collected.

EXOMARS must achieve 4 technological objectives:
i) landing a rover equipped with scientific instruments on Mars' surface;
ii) ensuring the rover's progression over several kilometres on Mars' surface;
iii) collecting samples from the Martian underground likely to contain preserved organic matter;
iv) packing those samples so that they can be analysed by various instruments.

Added to these are scientific objectives such as:
i) detecting the presence of gases and measuring the concentration of volatile compounds present in trace amounts in Mars' atmosphere;
ii) searching in samples taken in the Martian underground traces of a present or past Martian life form;
iii) characterising the structure of Mars' underground.

The French teams are in charge of 2 instruments of the European rover. WISDOM is a radar studying the underground in order to characterise the structure and detect the presence of ice. MicrOmega is a spectrometer and imager capable of taking images in the visible and the infrared spectrum, to study the mineralogical composition of the samples collected. Some laboratories also contribute to the development of 3 other instruments (MOMA, RLS and CLUPI) under the responsibility of other country members of ESA. CNES works with ESA to provide software for the visual navigation of the rover in 2020.

EXOMARS 2016

Launched on 19 October 2016 with a Russian rocket Proton, the first mission put into orbit a satellite, the Trace Gas Orbiter (TGO), which will study Mars' atmosphere and evolution and will also be used as a communication relay between the Earth on the various missions operating on the planet's surface. Since April 2018, the TGO begins its science mission to look for gases present in Mars' atmosphere such as hydrocarbons.

In addition to the 4 instruments, it is equipped with 2 radio transmitters and receivers provided by NASA (Electra) which will be used to relay the instructions and data between the Earth and the operating European and US rovers.

Several French laboratories are working closely with their Russian counterparts of the Russian Space Research Institute (IKI, Институт Космических Исследований) for the ACS (Atmospheric Chemistry Suite). LATMOS (France) contributed to the design and production of the instrument and coordinates the involvement of French laboratories in the interpretation of data.

Moreover, ESA selected scientists to contribute to the use of the data collected by the various instruments. Scientists from the Laboratory of Dynamic Meteorology (LMD) will combine the observations of the TGO instruments with atmospheric models and data from other Martian mission. Scientists from the Laboratory of Planetology and Geodynamics (LPG) will use the data from the CASSIS Camera in combination with the data from other instruments and other missions to understand the dynamic phenomena that occur on the planet's surface (accumulation, erosion, transformation). Finally, the Geosciences Laboratory Paris Sud (GEOPS) will use the data from NOMAD and ACS by combining them with the images from CASSIS to determine the connections between the volatile compounds condensed on the surfaces and their behaviour in the atmosphere.

EXOMARS 2020

The second mission, EXOMARS 2020, which will land a Russian platform and a European rover on Mars' surface, will be launched from Baïkonour with a Proton rocket between the 24 July and the 12 August 2020 and will reach its destination in March 2021.

The Surface Platform is provided by IKI and Roscosmos. This platform of 827 kg carries 10 Russian instruments as well as 2 European instruments and will monitor its environment for a Martian year (687 Earth days). There is no direct French contribution to these scientific instruments.

The European rover of 310 kg will be equipped with 9 scientific instruments dedicated to the study of the Martian ground and underground. With a drill able to collect samples down to a depth of 2 metres, this rover will collect samples and analyse them with its instruments. At this depth, organic matter that could have formed billions of years ago is protected from cosmic radiation showering on the planet's surface and oxidising compounds that form on its surface.

The French contributed in 5 out 9 instruments that compose the "PASTEUR" payload.

The WISDOM radar (Water Ice and Subsurface Deposit Observation on Mars) from LATMOS will test the soil at a depth of approximately 5 metres to detect sedimentary layers and identify buried rock boulders or ice. Beyond the science, this will be used to determine the appropriate drilling locations and depths. Data will be coordinated with ADRON (IKI) which seeks the water present a few centimetres below the surface as well as hydrated minerals.

The drill will collect samples at a maximum depth of 2 metres. These core rocks, of approximately 1 cm in diameter and 2 cm length, will be crushed, transported and brought to the analytical instruments. The CLUPI camera (Close-Up Imager), to which contributed the Centre of Molecular Biophysics of Orleans (CBM), equipped with a high magnification lens, will take images of the drilling site, the dust and of the cores after it has been placed in the container.

The surface of the crushed material will first be examined by MicrOmega (Astrophysical Space Institute of Orsay-IAS). This infrared and visible microscope will identify the minerals and detect the potential presence of organic molecules. The most interesting areas will be analysed using the RLS (Raman Laser Spectrometer), with a contribution of the Institute for Research in Astrophysics and Planetology of Toulouse (IRAP). This analysis will complete the mineralogical data and will specify the composition of the organic matter potentially detected. If the sample proves to be scientifically interesting, a small part will be directed to MOMA (Mars Organic Molecule Analyser). This instrument consists of 3 complementary elements. The mass spectrometer will identify ions and organic molecules from the other 2 elements. The LIBS system (Laser-Induced Breakdown Spectroscopy) uses a laser to produce ions that are directed towards the mass spectrometer. An oven system can bring a small aliquot of crushed material at high temperature in the presence or absence of a chemical solvent in order to vapourise the organic matter, then it can direct it towards the gas chromatograph (contribution of the Inter-University Laboratory of Atmosphere Sciences -LISA- of Creteil), then to the mass spectrometer.

The 2 EXOMARS missions attain a critical phase. The TGO mission will indeed begin its scientific mission and provide, with an unmatched sensitivity, a global cartography of the detailed composition of the Martian atmosphere. The mission EXOMARS 2020 enters the delivery phase of the flight instruments as well as their assembly on the different elements of the mission. The schedule is speeding up for both the TGO, with the exploitation of the first data, and for EXOMARS 2020, with the preparation of the calibration and interpretation work that will mobilise the laboratories after the end of the assembly, integration and testing of their instruments on the EXOMARS rover.

Fig. 1: Trace Gas Orbiter aerobraking. With aerobraking, the spacecrafts's solar array experiences tiny amounts of drag owing to the wisps of martian atmosphere at very high altitudes, which slows the spacecraft and lowers its orbit © *ESA/ATG medialab*

BEPI-COLOMBO, two probes exploring Mercury

Mercury is the least well-known of the planets in our solar system. This is largely because its proximity to the Sun is a real challenge for space exploration. To uncover the secrets of this mysterious world about which planetologists still have much to learn, the European BEPI-COLOMBO mission will launch 2 probes in October 2018 - MPO (Mercury Planetary Orbiter) and MMO (Mercury Magnetospheric Orbiter) - for a final insertion into orbit around Mercury late 2025.

BEPI-COLOMBO is the first mission in total collaboration between ESA and JAXA for the interdisciplinary study of Mercury. Mercury, the closest planet to the Sun, is known since Antiquity, but direct observation of Mercury was only performed by the MARINER 10 probe in 1974-75 and by the American probe MESSENGER launched in August 2004 whose mission ended in April 2015 by falling down on Mercury.

MPO will map the entire surface of the planet, will study its inner composition and structure and its immediate environment (atmosphere and ionosphere), while MMO will analyse its magnetic field and magnetosphere. Data gathered will provide new insights into the formation and evolution of 'inner' planets—planets orbiting close to their star—like most of the known exoplanets.

The MPO probe is being developed by the European Space Agency (ESA) and the MMO probe by the Japan Aerospace eXploration Agency (JAXA). CNES is overseeing development of the French contributions to the instruments on BEPI-COLOMBO for all of the research laboratories involved in the mission—8 in all (IAS, IPGP, IRAP, LAM, LATMOS, LESIA, LPC2E and LPP) who are helping to design 6 of the 16 instruments.

SCIENTIFIC PAYLOAD

The allocations of the payload of MPO are a mass limited to 85 kg and a power of 100 W. The MPO orbiter payload is constituted of:

INSTRUMENT	NAME	PI	LABORATORY	FRENCH CONTRIBUTION	CONTRIBUTOR INSTITUTE
Probing of Hermean Exosphere By Ultraviolet Spectroscopy	**PHEBUS**	**E. Quemerais**	**LATMOS (France)**	**Provision of the instrument**	**IKI** **Tohoku University**
Laser Altimeter	BELA	N. Thomas H. Hussmann	Bern Univ. (Suisse) DLR (Germany)	**Rejecter Filter study** **Thermal Model**	**LAM** **IPGP**
Search for Exosphere Refilling and Emitted Neutral Abundances	SERENA : 4 instruments **ELENA,** STROFIO, **PICAM** & MIPA	S. Orsini	INAF-IAPS (Italy)	**ELENA** (Emitted Low-Energy Neutral Atoms) **High Voltage convertor** **PICAM** (Planetary Ion Camera) **ToF detector & imager** **PICAM calibration**	**IRAP** **LATMOS**
Spectrometers and Imagers for MPO BEPI-COLOMBO Integrated Observatory	SIMBIO-SYS 3 imagers STC, HRIC, **VIHI**	G. Cremonese	INAF (Italy)	**Main Electronic Box** **Optics & radiometric Calibration of Simbio-Sys** **VIHI** (Visual and Infrared Hyper-spectral Imager) **detector & electronics**	**IAS** **IAS** **LESIA**

The MMO orbiter payload is constituted of a set of instruments for plasma, field, and particle measurement to study the processes coupling Mercury's surface, magnetosphere, and solar wind. The allocations of this payload are a mass limited to 45 kg and a power of 53 W. The different instrument sub-systems are:

INSTRUMENTS	NAME	PI	LABORATORY	FRENCH CONTRIBUTION	CONTRIBUTOR INSTITUTE
Mercury Plasma Wave Instrument	**PWI** 5 sensors: WPANT, SC, **AM2P,** MEFISTO, **SORBET**	Y. Kasaba	Tohoku University (Japan)	**Provision of SC** (Search Coil magnetometer) **Provision of AM2P** (Active Measurement of Mercury's Plasma) **Provision of SORBET** (Spectroscopie des Ondes Radio et du Bruit Electrostatique Thermique)	**LPP** **LPC2E** **LESIA**
Mercury Plasma Particle Experiment	**MPPE** 5 sensors: **MEA,** **MSA**, SWA, HEP-e HEP-i	Y. Saito	ISAS (Japan)	**Provision of MEA** (Mercury Electron Analyzers) **Provision of « Top Hat » type electrostatic analyser of MSA** (Mass Spectrum Analyzer)	**IRAP** **LPP**

SCIENTIFIC OBJECTIVES

Mercury has a unique structure *i.e.* a very big core (3/4 of the planet's radius). This could be linked to its intrinsic magnetic field. Detailed observations of its interior and surface reveal that the planet formed in the region nearer to the Sun.

BEPI-COLOMBO will provide the first opportunity to compare the planetary magnetic field structure of a telluric planet to the Earth's one.
Indeed, the only telluric planets with an intrinsic magnetic field are the Earth and Mercury. The detailed observation of Mercury's magnetic field and its magnetosphere will lead to the first comparative studies with the Earth.

Thanks to BEPI-COLOMBO mission, Mercury's interior, surface, exosphere, magnetosphere, and environment will be thoroughly studied and a new frontier to solar system science will be open. MPO probe is dedicated to the study of the surface and the interior of Mercury (surface geology, geomorphology, geophysics, volcanism, global tectonics, age of the surface, composition of Mercury's surface) as well as its exosphere.

The MMO probe's instruments will allow to study the magnetic field, the magnetosphere, the inner interplanetary space, the radiations and particles in Mercury's environment and the exosphere. The comparison of the magnetic field and the magnetosphere to those of the Earth will supply a new vision of the magnetosphere's dynamics and physical processes.

Thanks to the MPO instruments coupled with the MMO instruments, coordinated measurements of the planetary magnetic field will be conducted and will therefore solve one of the main limitation of MESSENGER observations, the possibility to disentangle temporal and spatial variabilities in an environment much more dynamic than the Earth magnetosphere, as shown by MESSENGER.

MISSION STATUS

The overall test campaigns of thermal, mechanical, acoustics and vibration testing have been successfully achieved. The shipment to Kourou took place by the end of April.

The launch window for BEPI-COLOMBO by an Ariane 5 opens on 5 October until the end of November 2018 for an arrival at Mercury around December 2025.

Fig. 1: The full BEPI-COLOMBO stack seen in ESA's test centre in May 2017 *© ESA–C. Carreau, CC BY-SA 3.0 IGO*

PARKER SOLAR PROBE, exploring the Sun's corona

The U.S. PARKER SOLAR PROBE mission will begin its journey to the Sun in 2018. It aims at becoming the first spacecraft to venture into our star's outer atmosphere. The first perihelion will reach 35 solar radii in Autumn 2018 and the closest approach, within 9 solar radii from the surface, is scheduled to arrive in 2024.

Once lofted into space by a Delta IV Heavy launcher, PSP will need 7 gravity assists from Venus to reach the Sun's corona. These successive gravitational boosts will make it the fastest spacecraft of all time. It will also be the first to study in-situ the solar wind so close to the Sun with its 4 suites of instruments. The solar wind is the stream of ions and electrons that our star ejects at high speed into interplanetary space. PSP will pass several times within less than 7 million km from the Sun's surface, where it will be exposed to temperatures reaching 1400 °C.

French research laboratories - the LPC2E (environmental and space physics and chemistry laboratory), the LESIA (space and astrophysics instrumentation research laboratory), the IRAP (astrophysics and planetology research institute), the LPP (plasma physics laboratory) - are contributing to PSP's instruments, with support from CNES. The PROMES (PROcesses, Materials and Solar Energy Laboratory), which operates the solar furnace in Odeillo in the French Pyrenees, is also working on the mission, studying the behaviour at high temperatures of the parts of the science instruments that will not be protected by the probe's solar shield.

The PSP mission is being coordinated with the European SOLAR ORBITER mission as part of the joint HELEX programme (HELiophysics EXplorers).

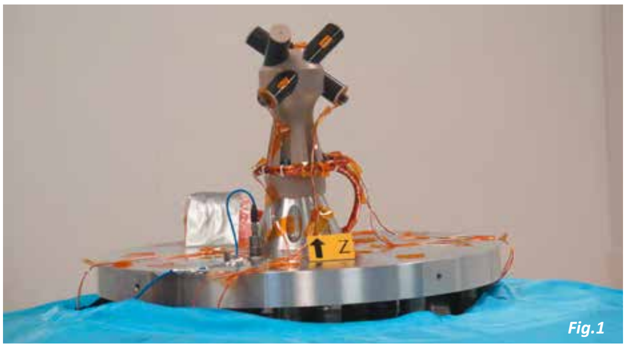

Fig.1

Scientific payload

INSTRUMENT	OBJECTIVE	FRENCH LABORATORY INVOLVED
SWEAP (Solar Wind Electrons Alphas and Protons Investigation)	Counting of the most abundant particles in the solar wind and determining their properties (density, velocity, temperature).	LPP, IRAP
WISPR (Wide-field Imager)	Imaging of the solar corona and inner heliosphere and the transient processes occurring there.	
FIELDS (Fields Experiment)	Measuring the electric and magnetic fields, pointing flux, plasma density, spacecraft potential and radio emissions.	LPC2E, LESIA
ISIS (Integrated Science Investigation of the Sun)	Measuring the most energetic particles in the solar wind.	

France is involved in 2 of the 4 instrument suites of PSP. The IRAP and LPP laboratories provide expertise on the definitions and analyses of the SWEAP observations. The LPP contributes to the electron spectrometer of the SWEAP instrument suit by providing the integrated detection electronics. The LPC2E and LESIA are involved in the FIELDS experiment for their expertise and contributes also to the instrumentation. The LESIA has participated to the design of the radio receiver while the LPC2E has provided the search coil magnetometer (SCM), a sensor measuring the variations of magnetic fields as fast as a micro-second. SCM will be located on the boom of the spacecraft and is the only European sensor on board PSP.

Fig.2

Scientific objectives

The Sun is well noticed in daily life because it shines. However, it also fills the interplanetary space with plasma, a state of matter similar to gas but where particles are electrically charged and that constitutes 99% of the known matter in universe. The corona, the outermost region of the Sun's atmosphere, is where this solar plasma also named solar wind starts its journey. This place exhibits several remarkable features:

- Temperatures there reach 1 million degrees centigrade, more than 100 times hotter than at the Sun's surface which is near 6 000 °C.
- It is the source of the solar wind, this stream of ions and electrons ejected at high speed into interplanetary space, and that reaches each body of the solar system.
- It is a place of violent processes, such as flares and coronal mass ejections, which next propagate in the heliosphere and eventually reach the Earth where they can cause damages on our technologies.

Most of the stars have a corona, and there are good chances that answering questions in the solar case will apply to other stars as well. Since the discovery of the solar corona in the 1940s, scientists have learned a great deal about the solar wind and the Sun itself, but they still don't understand the mechanisms going on inside the corona. The solar surface, the photosphere, is the energy supplier, but how this energy propagates towards and is deposited in the corona remains a mystery. Does it come from waves generated in the photosphere or below, and that then dissipates in the corona? Or, as suggested by Eugene Parker, from nano-flares which are ubiquitous and energetics small reconfigurations of the magnetic field?

Measuring directly the properties of the outer corona will tell us a lot about the processes at play.
Another important question that is related is the acceleration of the solar wind, which occurs mostly within 15 solar radii. Particles are constantly ejected from the Sun at a speed of several hundreds of km/s. During this process, some particles are heated more than others. The properties of the solar wind are also strongly variable, and its evolution during its trip in the interplanetary space is not as predictable. Going as close as possible to the acceleration region will help us understand the reasons and consequences of these observations. Last but not least, the solar wind is a natural laboratory to study turbulence, one of the most fascinating problems in physics.

Finally, because our societies are always more dependent on technologies, they become more and more vulnerable to perturbations coming from space. This has given birth to a relatively new science field, termed space weather, which aims at predicting when strong perturbations from space can affect our activities. Going close to the Sun, where these perturbations have their origin, will help us to understand them better. Because PSP will not image the Sun directly, its science will be complemented by the European SOLAR ORBITER mission that will both measure properties of the solar wind at different distances from PSP, image and analyse the solar atmosphere with magnetograph, telescopes and spectrometers.

Mission status

PSP will be launched from the NASA's Kennedy Space Centre in Florida between 31 July and 19 August 2018. All instruments have been delivered and integrated on the spacecraft. Environmental tests, where spacecraft and instruments experience the harsh conditions of space, including near-vacuum conditions and severe hot and cold temperatures, are performed at the NASA's Goddard Space Flight Centre in Greenbelt. Once ready, the spacecraft will be packed and shipped to Florida for its launch aboard a Delta IV Heavy launch vehicle. All instrument teams are now preparing for the analysis of the first data to come.

Fig. 1:The Search-Coil Magnetometer for PSP/FIELDS prepared for vibration tests © *LPC2E*

Fig. 2: PARKER SOLAR PROBE being tested
© Johns Hopkins Applied Physics Laboratory

GAIA, a satellite mapping the galaxy

Our galaxy, the Milky Way, looks large, peaceful and mature at first glance. But it was probably not the case in the past – and it might not always be so in the future. Astronomers guess that like other galaxies, our cosmic motherland had a tumultuous youth, including intense star formation epoch and accretion of smaller galaxies passing by – which could still occur in the future.

These remarkable events should have left their imprints in the Galaxy, as specific layers in rocks and sediments indicate past events on Earth. Clusters of stars travelling together in unison on a track distinct from those of their neighbours could be former members of an alien galaxy, once absorbed by the Milky Way. Age, chemical composition, temperature, colours of stars are other key insights of the past activity of the Galaxy. And by extrapolation, its future can also be inferred!

The mission that ESA and its Member States decided to carry on by 2000 is to record the position, the velocity and the main physical and chemical parameters of as many stars as possible throughout the Galaxy with a considerable accuracy (about 10 micro-arcseconds, the size of a coin on the Moon as seen from Earth). This mission, GAIA, is about to be accomplished.

The GAIA satellite, a technological jewel, was launched on 19 December 2013, and has since been continuously scanning the whole sky. Light from any source with a G-magnitude up to 20.7 crossing the field of view of its 2 telescopes is recorded by its instruments. About 2 billion stars of the Milky Way and of the Small and the Large Magellanic Clouds are being repeatedly measured, about 80 times on average during the 5-year mission. In addition, tens to hundreds of thousands asteroids, brown dwarfs, exoplanets, and distant quasars will take place in the final catalogues.

Computing highly reliable and accurate parameters for billions of sources from GAIA's Petabytes of raw data – hundreds of billions transit dates and pixel signals – was the second mission's challenge. Any bias – relativistic effects, starlight absorption by foregrounds, telescopes misalignment, detectors' response, etc. – needs correction. Complex software then classifies the sources and derive their parameters. Designed, implemented and operated by the DPAC, a vast consortium of European research institutes and space agencies, they are running on 6 dedicated high power computing centres, including one at CNES premises in Toulouse, France.

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
Astrometer	Positions and proper motions	NA
Blue and Red Photometers	Physical parameters	NA
Radial Velocity Spectrometer	Chemical composition; Radial Velocities	NA

The GAIA satellite, including its scientific payload, was designed and built by Airbus Defence and Space in Toulouse for ESA. It includes 2 one-metre class telescopes feeding the instruments. The spinning satellite sees light from celestial objects crossing consecutively the different instruments 'detectors. The payload is designed and operated in order to reach a record-breaking thermoelastic stability.

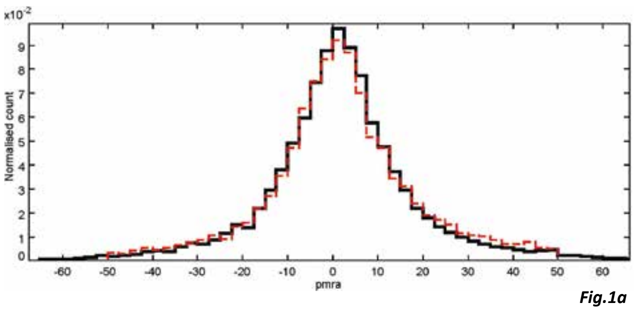

Fig.1a

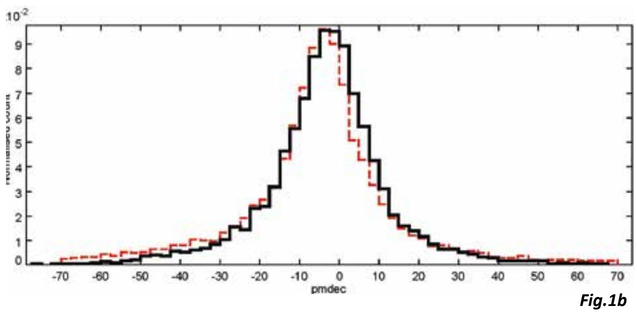

Fig.1b

DPAC involves about 100 scientific institutes and space agencies. Nice and Paris Observatories, as well as CNES, are some of the major DPAC players; UTINAM from Besançon, LAB from Bordeaux, LUPM from Montpellier and Strasbourg Observatory also contribute to DPAC.

SCIENTIFIC HIGHLIGHTS

Highly accurate star positions and parameters were, are and will remain the basement of astronomy. Almost all branches of the discipline, including large scale tests of physical laws, are being fed by GAIA. The first September 2016 GAIA catalogue (so called GDR1), although preliminary, triggered hundreds of scientific publications in a few months.

Detecting Near-Earth Asteroids (NEAs) and assessing reliable levels of associated risks are not only a scientific goal but also a societal challenge. Using GDR1 stars positions as calibrators to improve previous orbit estimates for asteroids, a Nice Observatory's team showed how GAIA, even without the direct asteroids observations only due for the following data releases, could already improve our knowledge of the current NEAs trajectories by one order of magnitude [1].

Possible Sun-stellar encounters were analysed from GDR1. Compared with previous estimates from Hipparcos data, less stars were found on close sun-encounter tracks, but one of them is now expected to pass very close to the Sun in about 1.3 million years from now, and might seriously disrupt the Oort cloud of comets and asteroids [2].

Galactic studies extensively use the so called Besançon model, a reference simulation of the Milky Way. As the considerable accuracy of GDR1 allows to track tiny deviations between the model and the data, both the GDR1 and the RAVE ground-based survey were combined to put the improved model to test. For any of the different criteria and star populations used for the comparison, data and the model remarkably fit (Fig. 1), improving even further the confidence in the model [3].

GAIA also opens the door for original extragalactic studies. Gravitational waves emitted by distant supermassive black holes binary systems should imprint apparent oscillations on star positions as the waves travel through our Galaxy (Fig. 2). Detecting these weak patterns requires a large number of stars repeatedly observed with a high accuracy. A recent study demonstrated how the GAIA final catalogue will be ideal for detecting and characterising such gravitational waves [4].

MISSION STATUS

GAIA has been working as planned since its launch end of 2013. The initial 5-year mission has already been extended for 2 additional years and might be further extended. Science ready data processed by DPAC are planned to be gradually released to the international scientific community. After the 2016 GDR1, the April 2018 GDR2 provides 3D positions, proper motions and mean Green/Red/Blue magnitudes for about 1.3 billion single stars, time-light curves, radial velocities and physical parameters for subsets of them, and dated positions for about 13 000 known asteroids. Further releases, planned in 2020 and beyond will totally fill the still missing parameters and improve the accuracy of the first releases.

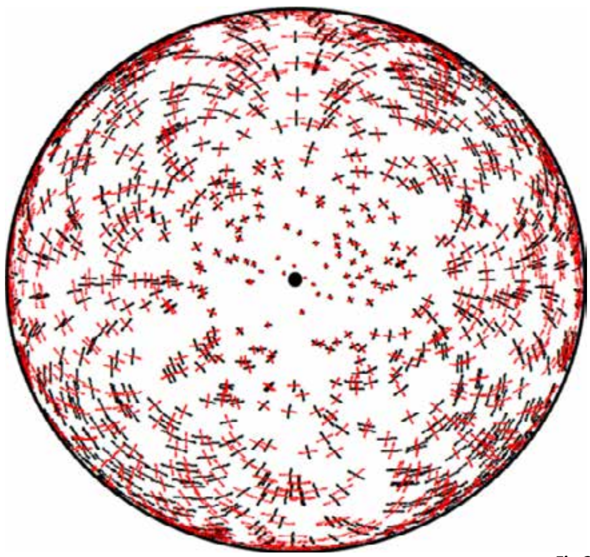

Fig.2

Fig. 1a: Histograms of GDR1 proper motions along the right ascension for stars with metallicity between -0.8 and -0.4 dex, which is dominated by the main galactic thick disk. Data are shown as black lines, and the best-fit model is shown as red lines. (from Robin, A, *et al.*)

Fig. 1b: Histograms of GDR1 proper motions along the declination for stars with metallicity between -0.8 and -0.4 dex, which is dominated by the main galactic thick disk. Data are shown as black lines, and the best-fit model is shown as red lines. (from Robin, A, *et al.*)

Fig. 2: Orthographic projection of the Galactic Northern hemisphere with 10^3 stars (simulation). A gravitational wave (GW) from the North pole (black dot) causes stars to oscillate at the GW frequency. The black (red) lines show movement tracks for a linearly plus (cross) polarised GW. For illustration purpose, the GW has an unphysically large strain amplitude of A = 0.1. (from Moore, C.J., *et al.*)

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AUTHOR
P. Sartoretti[1], D. Katz[1]
1 GEPI (Galaxies, Stars, Physics and Instrumentation), CNRS UMR 8111, Observatoire de Paris, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France

GAIA radial velocity spectrometer: the first data release

ESA's GAIA mission is carrying out an unprecedented census of stars in the Milky Way, aiming to reveal the process of formation and evolution of our Galaxy [1]. The mission was launched on 19 December 2013 and started operations on 25 July 2014. Initially planned for 5 years, GAIA was extended for 1.5 more years in November 2017. The second GAIA Data Release (DR2) [2], issued on 25 April 2018, includes the first catalogue of radial velocities obtained with the on board Radial Velocity Spectrograph (RVS) [3].

GAIA continuously scans the sky with its 2 telescopes, collecting data of any source (mostly stars) detected by the on board system. The data are obtained with 3 instruments: astrometric data are dedicated to the measure of positions, distance and proper motions; photometric data to the determination of stellar physical properties (temperature, mass, radius); and spectroscopic data, obtained with the RVS, to the measure of stellar radial velocities, VR. Combining VR (line-of-sight component of the velocity vector) with the astrometric measurements of proper motion (tangential components of the velocity vector) allows determination of the (3D) star motion.

The first GAIA data release in September 2016, based on 14 months of data, includes the positions on the sky of 1 billion stars, as well as parallax and proper-motion estimates for a subset of 2 million bright stars. GAIA DR2, based on 22 months of data, contains the positions, parallaxes, proper motions and broad-band photometry of over 1.3 billion stars. It also includes the first release of radial velocities obtained from the RVS spectra of a sample of 7.2 million GAIA stars.

The RVS is a slitless spectrometer providing medium resolving power (R ~ 11,500) in the wavelength range [845–872] nm. When GAIA scans the sky, starlight enters the RVS after the astrometric and photometric instruments. Only stars brighter than the magnitude limit Grvs~16 (where Grvs ~ V−1) are candidates to have an RVS observation.

The RVS focal plane is shown in the left panel of Fig. 1 (for the complete GAIA focal plane, see GAIA Collaboration *et al.* [1]), with 12 CCDs laid out in 3 strips and 4 rows. Both GAIA-telescope fields of view are projected simultaneously onto the focal plane. The on board software identifies the pixels containing spectral information, and only the pixels in these windows are read out and telemetered. During each transit (observation), the star crosses all 3 CCDs on the row (on one) row, and 3 spectra are acquired. The spectral-dispersion direction is in the star-motion direction (Fig. 1). The 1296-pixel length of the windows in the spectral direction can lead to overlapping spectra even in modestly crowded sky regions. On average, 40% of the spectra are overlapped.

The exposure time is fixed at 4.42 sec by the scanning requirements. For faint stars, individual spectra have low S/N, and many observations are required to obtain a combined spectrum with sufficient S/N to determine VR. There will be typically 40 RVS observations per star by the end of the nominal mission. In DR2, the typical number was 4–8 per star, and only stars brighter than Grvs ~ 12 had high-enough S/N to be processed by the pipeline and have their VR calculated (fainter stars will await future releases).

The processing of GAIA data is iterative: each data release includes new data, as well as a complete reprocessing of data from the beginning of the mission, with improved calibrations and algorithms. To produce the DR2 radial velocities, 280 million spectra were treated, which represented a major challenge. The processing is managed by a top-level software system called SAGA on a 1100-core and 7.5-TB memory Hadoop cluster system. The processing took 630 000 hours CPU time and needed 290 TB disk space.

The spectroscopic pipeline [4] has 4 main tasks: i) clean and reduce the spectra; ii) calibrate the RVS instrument, including wavelength, stray light, line-spread function, bias non-uniformity, and photometric zero point; iii) extract the radial velocities;

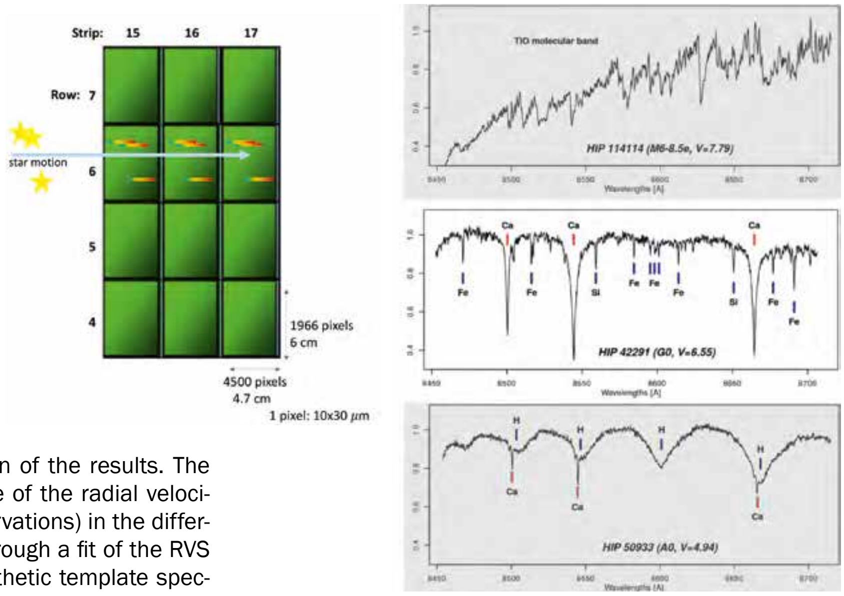

Fig.1

and iv) verify the accuracy and precision of the results. The VR of a star in DR2 is the median value of the radial velocities measured (for successive RVS observations) in the different RVS observations, each obtained through a fit of the RVS spectrum relative to an appropriate synthetic template spectrum. An additional task of the spectroscopic pipeline was to provide first-order estimates of the stellar atmospheric parameters required to select such template spectra. For the hottest (Teff ≥ 7000 K; Fig.1; right panel; bottom) and coolest (Teff ≤ 3500 K; Fig. 1; right panel; top) stars, the accuracy and precision of the stellar parameter estimates are not sufficient to allow (the) selection of appropriate templates. The radial velocities obtained for these stars were not published in DR2. Fig. 1 (right panel, central spectrum) also shows the spectrum of a medium-temperature (a solar-type) star.

DR2 contains the radial velocities of 7.2 million intermediate-temperature stars distributed over the entire celestial sphere. This is the largest existing VR catalogue and the only one covering the full sky. Fig. 2 (upper panel) shows the distribution of GAIA stars with a VR measurement over the celestial sphere, the large majority of which belong to the Milky Way. The corresponding VR distribution is shown in the medium panel of Fig. 2, where we can see the line-of-sight-projected differential rotation of the stars of the Galaxy with respect to the Sun. The bottom panel in Fig. 2 shows the overall precision of the VR measurements as a function of star magnitude. The pre-launch requirement on the end-of mission precision of 1 km/s is indicated as a dotted line; it is met, already in this first release, for the stars brighter than Grvs~ 11.5.

Future releases will contain radial velocities of fainter, cooler and hotter stars than included in DR2, rotational velocities for the brightest stars, and the combined spectra. By the final release, we expect to publish the VR of ~150 million stars, after having processed 35-50 billion spectra.

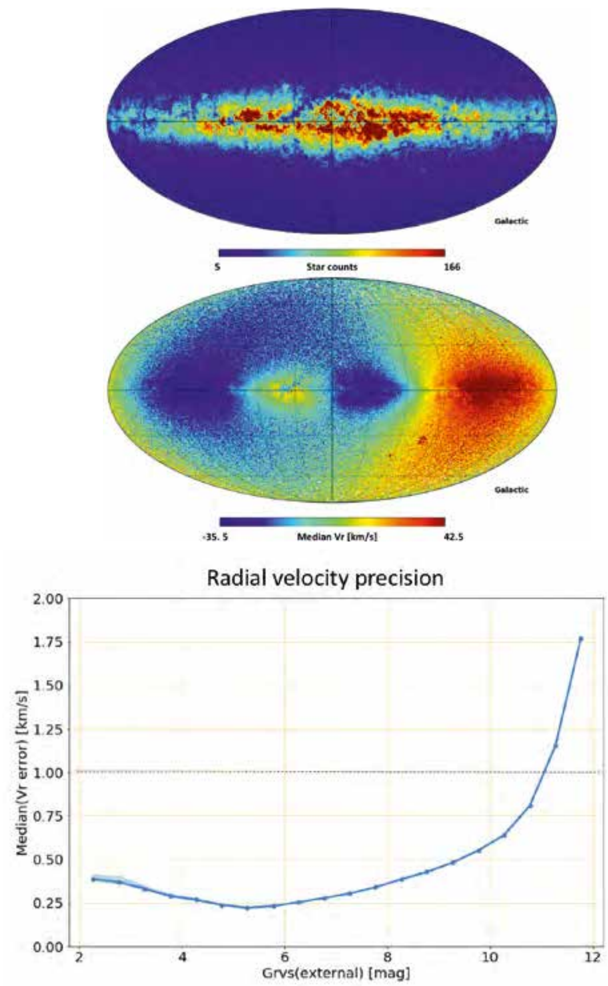

Fig.2

Fig. 1: Left panel: The RVS focal plane. The star images move in the along-scan direction (horizontal arrow). At each transit, 3 spectra are acquired. Star spectra may overlap. Right panel: RVS spectra of 3 stars: a cool (top), an intermediate-temperature (centre) and a hot (bottom) stellar spectra. © *from Katz et al. [5].*

Fig. 2: The DR2 radial velocities. Top: Distribution on the sky of GAIA stars with VR measurements; galactic coordinates projection with pixel size of 0.2 deg^2.Medium: VR distribution; Medium: VR precision; the dotted line is the end-of-mission requirement. © *from Katz et al. [5].*

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LISA PATHFINDER, testing key technologies for the future gravitational wave observatory

On 3 December 2015, the LISA PATHFINDER satellite was launched from Kourou en route to the first Sun-Earth Lagrangian point. Its mission: to test technologies able to directly detect the gravitational waves predicted by Albert Einstein.

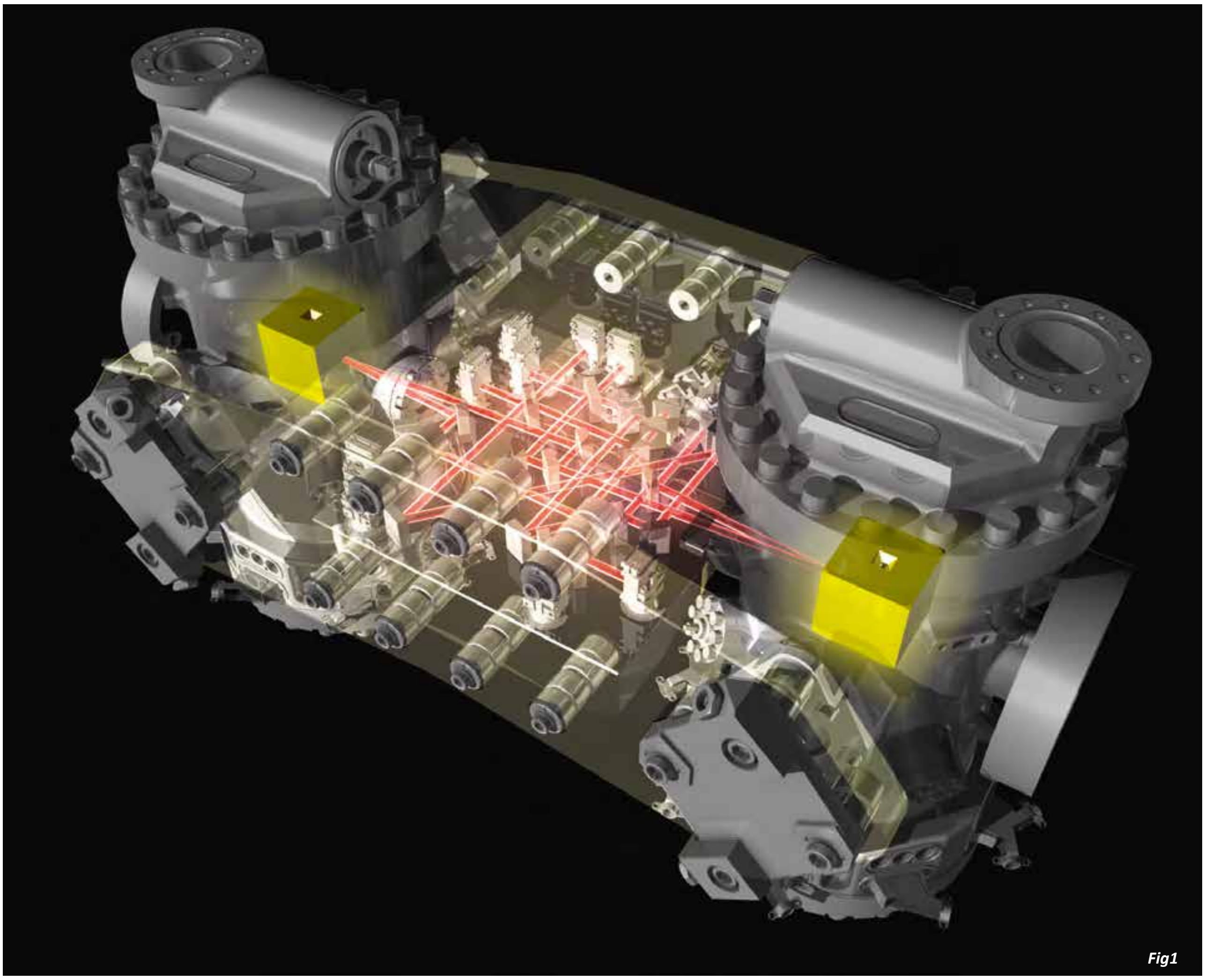

Fig1

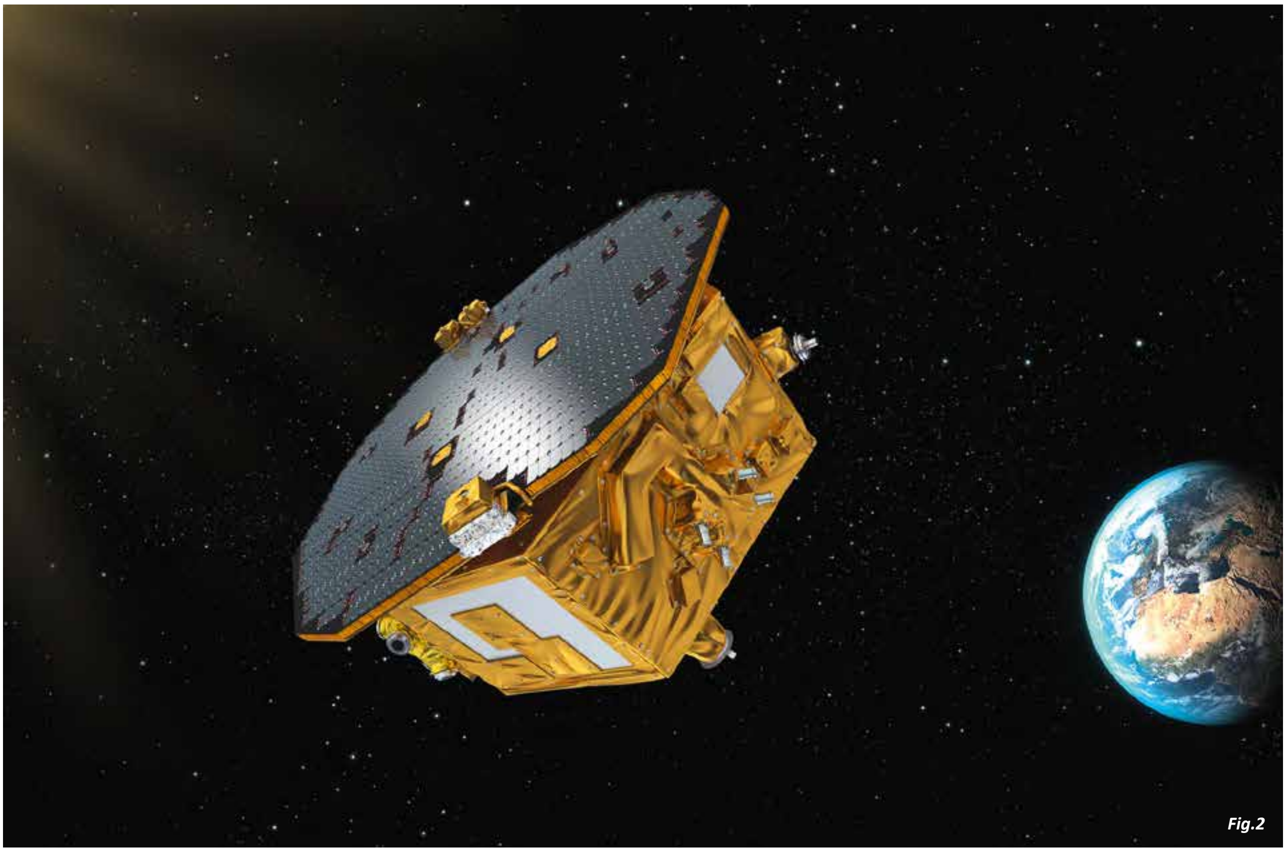

Fig.2

The European Space Agency (ESA) is pursuing an ambitious physics mission about the gravitational Universe (L3 mission) that aims to directly observe gravitational waves—the tiny ripples in the fabric of space-time predicted by Einstein's theory of general relativity—using 3 satellites forming a giant optical interferometer. The presence of these waves will be signaled by minute relative movements between 2 test masses in free fall at the end of each of the interferometer's arms.

LISA PATHFINDER is a scaled-down model of an interferometer arm packed into a single satellite that tests key technologies required to place the 2 test masses in perfect free-fall conditions and measure their relative movement with unprecedented precision. LISA PATHFINDER also draws on the very latest developments to minimise other forces acting on the masses housed inside the LTP instrument (LISA Technology Package) and to measure their movement. With its inertial sensors, laser metrology, drag-free control and ultra-precise micro-propulsion systems, it is a truly ground-breaking mission.

CNES and its partners in the French consortium coordinated by the APC (Astro-Particles and Cosmology) laboratory are involved in this ESA-led mission for which they are supplying a subsystem of the LTP instrument's optical bench. They are also involved in operational science data analysis.

SCIENTIFIC HIGHLIGHTS

Results of the mission, entitled Beyond the required LISA free-fall performance: new LISA PATHFINDER results down to 20 µHz, have been published at the beginning of February 2018 in PRL (Physical Review Letters).

Since the publication of the first results, the noise results have been significantly improved due to the continued decrease in pressure around test masses, through a better correction of non-inertial effects and a better calibration of the electrostatic forces actuation. In addition, the availability of numerous long noise measurement runs has allowed the measurement of noise with statistics down to 20 µHz.

These results recently demonstrate the ability to use an LPF-like geodesic reference system with the required precision to do gravitational-wave science from space at frequencies as low as 20 µHz.

MISSION STATUS

Following a 6-month extension beyond the nominal mission, the LISA PATHFINDER mission ended on 18 July 2017. However, data processing is still under way. Noise results have been recently published (see the above paragraph) while other experimental observations are still under evaluation.

The excellent results achieved are now paving the way to the LISA mission that was selected as the third ESA Large mission, dedicated to the gravitational Universe. The LISA phase A started in April – May 2018, the approuval is expected between 2022 and 2034 to be compatible with launch no later than 2034.

Fig. 1: Artist impression of the LISA Technology Package *©ESA*

Fig. 2: An artist's rendering of LISA PATHFINDER on its way to Earth-Sun L1 *©ESA/C. Carreau*

AUTHOR
A. Petiteau[1], E. Plagnol[1]
1 AstroParticule et Cosmologie (AstroParticle and Cosmology Laboratory), Université Paris Diderot, CNRS UMR 7164, IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10 rue Alice Domont et Léonie Duquet, 75013 Paris, France

New LISA PATHFINDER results: beyond the required LISA free fall performance

The final results of the LISA PATHFINDER mission, the technology demonstrator for the LISA mission, have been published recently [1]. The majority of the limiting noise are understood: optical interferometer precision at high frequencies, Brownian at mid-frequency and actuation, and non-inertial force at low frequencies. The characterisation and correction of glitches enable long measurement. The differential acceleration obtained is $(1.74\pm0.05)\times 10^{-15}$ m. s^{-2}. Hz$^{-1/2}$.

The LISA PATHFINDER mission (LPF) is a technology demonstrator for future space based gravitational waves observatories such as LISA, the large mission L3 of the ESA Cosmic Vision programme that is starting an industrial Phase A. LPF consists of 2 free falling test-masses separated by 37 cm in a single spacecraft (S/C). Each test-mass (TM) is in a housing with electrodes surrounding each of the 6 faces of the TM. The test-masses are Au-Pt cubes of 2 kg and 4 cm separated from electrodes by a gap of 4 mm. The electrodes are used to measure the position of the TMs and also to act on the TMs. The distances between the 2 TMs and between the S/C and one TM are measured with an extreme precision using several interferometers. The S/C is controlled to follow one of the TM (TM1) using a complex system of control loops and cold gas micro-propulsion. The second TM (TM2) is controlled, at low frequencies, on the sensitive axis (the axis joining the 2 test-masses) to stay at a constant distance with respect to TM2. See Fig. 1.

The main measurement is the differential acceleration between the 2 TMs. This measurement is obtained by subtracting the commanded force on TM2 and the weak coupling between the TMs and S/C from the interferometer measurement. The performances are measured between 0.1 and 100 mHz. Since we want to see if the technology is sensitive enough for being used for gravitational wave observatory, the aim is to achieve the lowest possible differential acceleration.

The LPF mission has been launched on the 3 December 2015 from Kourou. In mid-January, it arrived on its final orbit around Lagrange point L1. The nominal operations started on the 1 March and ended the 26 June. The extended operations started in December 2016 and ended in June 2017. The operations consist in a series of experiments either to measure the noise level over the frequency band of interest or to act on the instrument in order to measure the parameters of the system. These experiments last from days to weeks. During the operations the parameters were tuned to optimise the performances.

FIRST RESULTS

The first results have been published in [2] using only the first 45 days of data. The performances obtained were excellent with a differential acceleration 5.5×10^{-15} m.s^{-2}.Hz$^{-1/2}$ (blue curve on Fig. 2).

Interferometer readout performances

At high frequency (> 30 mHz) the measured differential acceleration is not due to TMs motion but is dominated by the performance of the interferometer readout system. The error on measurements of this optical system is about 30×10^{-15} m.Hz$^{-1/2}$ which is 100 times better than the requirement and the on-ground measurements.

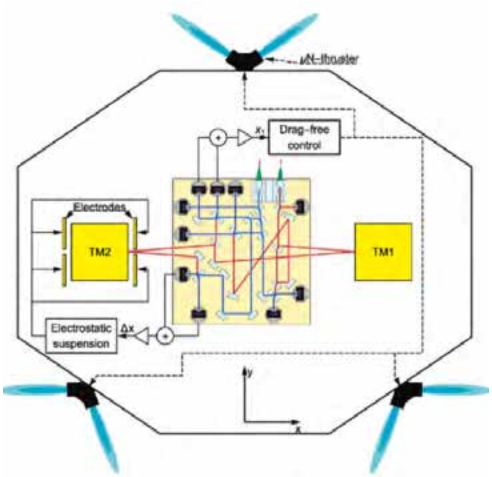

Fig.1

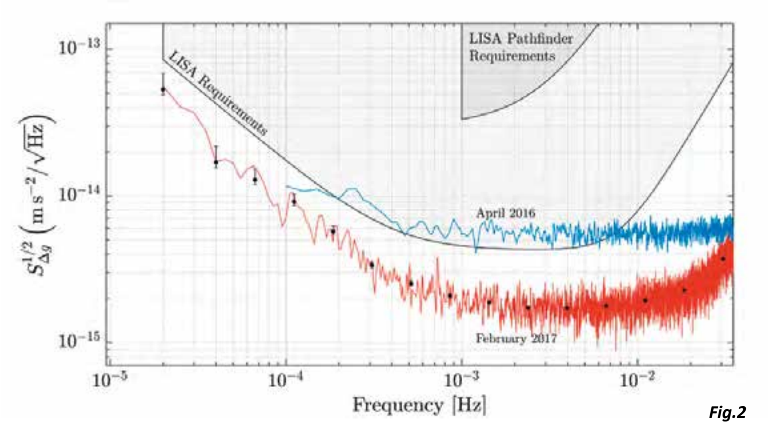

Fig.2

Fig. 1: Simplified representation of LISA PATHFINDER spacecraft showing the Test Masses, the electrodes around them, the optical bench interferometer and the Cold Gas thrusters *© from [2].*

Fig. 2: ASD of differential acceleration of LISA PATHFINDER test masses as a function of the frequency. The red line corresponds to a ~13 day long run taken at a temperature of 11°C in February. The blue corresponds to a run in April 2016 at a temperature of 23°C. See [1] for further information *© from [1].*

Brownian noise

In the mid-frequency band (1 to 30 mHz), the differential acceleration measured is dominated by the Brownian noise, due to the residual molecules in the housing that hits the TMs. The vacuum can surrounding the housing is open to space via a venting duct and the quality of the vacuum consequently improves with time, decreasing the impact of the Brownian noise. A decrease of this noise has also been observed by lowering the temperature.

FINAL RESULTS

During the operation extension, changes have been made both on the hardware and on the data processing in order to optimise the performances. The final result is the red curve on Fig. 2.

Decrease of the Brownian noise

The Brownian noise reduces due to the decrease of pressure in the housing along time and with a reduction of 10° C of the whole temperature of the instrument. The final differential acceleration is $(1.74 \pm 0.05)\times10^{-15}$ m.s^{-2}.Hz$^{-1/2}$, twice the LISA requirements.

Glitches

We observed sporadic quasi-impulse force events or “glitches”. The average rate of glitches is (0.78 ± 2) per day. The physical origin is not yet understood. They are observationally indistinguishable from a quasi-impulsive force acting on one of the 2 TMs, transferring a differential momentum over time spans ranging from seconds to, in rarer cases, hours. Observed glitch amplitudes are as large as pm.s^{-2}, with a typical impulse Δv of the order of 10 pm.s^{-1}.

Low frequency noises

The availability of numerous long noise measurement runs allows to study the low frequency performance. Below 1 mHz, the differential acceleration is observed to follow a 1/f behaviour. After correcting for noninertial effects and optimising the electrostatic force actuation on the second TM, a differential acceleration of $(6 \pm 1)\times10^{-14}$ m.s^{-2}.Hz$^{-1/2}$ has been obtained at 20 μHz.

DISCUSSION

Demonstration for LISA

This performance provides an experimental benchmark demonstrating the ability to achieve the low-frequency science potential of the LISA mission. With similar acceleration noise performance as LPF, LISA will be able to achieve more than the scientific programme described in [3]. For example, it allows the observation of heavy Super-Massive Black Hole Binaries for several periods of 10 days.

Platform stability

One of the important outcomes of LPF is the possibility to estimate the stability of the platform relative to its corresponding geodesic. Using a State Space Model to extract, from the observed S/C movement, the stability on all degrees of freedom, the following values are estimated: At 1 mHz, the stabilities in acceleration are shown to be of the order of 3×10^{-15} m.s^{-2}.H$^{z-1/2}$ for X_{SC} and 5×10^{-15} m.s^{-2}.Hz$^{-1/2}$ for Y_{SC} and Z_{SC} (see Fig. 1). For the angular degrees of freedom, the values are of the order 3×10^{-12} rad.s^{-2}.Hz$^{-1/2}$, for ΘSC and 2×10^{-13} rad.s^{-2}.Hz$^{-1/2}$, for H_{SC} and Φ_{SC}. The corresponding accelerations for LISA stabilities are being estimated.

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MICROSCOPE, a microsatellite challenging the universality of free fall

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

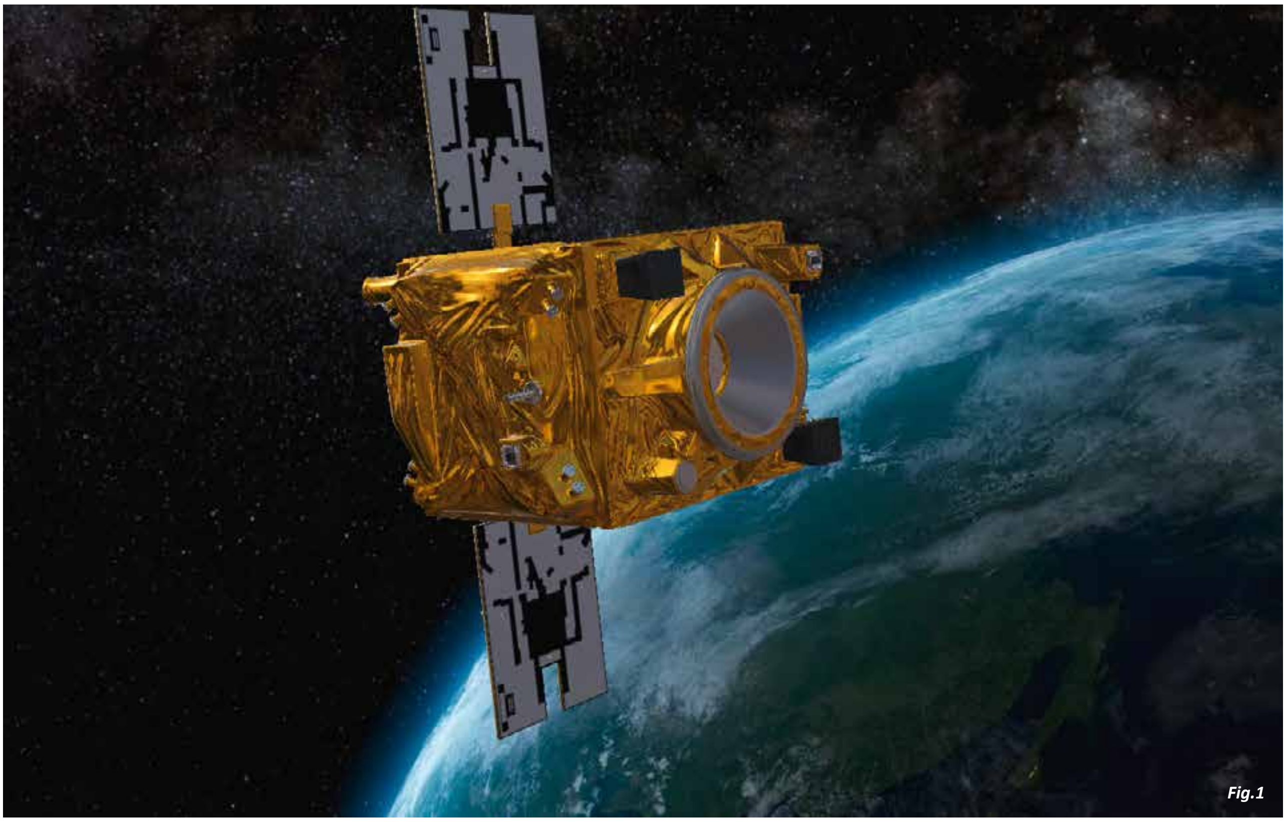

Fig.1

Back in the 17th century, Galileo conceived an experiment, without actually performing it, in which he dropped 2 objects of different composition and mass together from the top of the Tower of Pisa. In his theory, as the 2 objects hit the ground at exactly the same time, he deduced that in a vacuum all bodies fall at the same speed. This is what we call the universality of free fall or equality of gravitational and inertial mass, which Albert Einstein later stated as the Equivalence Principle and made it the basis of his theory of general relativity.

Although it has been verified with a degree of precision of the order of 10^{-13}, this principle is nonetheless being pushed to its limits by new theories seeking to reconcile gravitation with fundamental nuclear and electromagnetic interactions,

which predict that it could be violated at very weak levels. The MICROSCOPE satellite will probe these limits further and test the principle with a precision on the order of 10^{-15}. In space, it is possible to study the relative motion of 2 bodies in an almost perfect and permanent free fall in an orbiting satellite, shielded from perturbations encountered on Earth (notably seismic perturbations), over the course of several months.

The experiment is flown on a 300-kg microsatellite—heavier than a usual 100-150 kg microsatellite—built around CNES' Myriade bus and equipped with cold-gas microthrusters capable of compensating for the tiniest trajectory perturbations that might otherwise skew its results. CNES is providing 90% of funding for this mission, for which it is also prime contractor in charge of satellite bus development, satellite integration and testing up to launch, and construction and operation of the mission control centre.

The development of the MICROSCOPE mission was a cooperation between CNES-ESA-ONERA-DLR-INSU-GEOAZUR-ZARM.

SCIENTIFIC PAYLOAD

The payload is set up at the centre of the satellite with the T-SAGE (Twin Space Accelerometers for Gravitation Experiment) instrument made of 2 independent SAGE differential accelerometers, each possessing a mechanical module and an electronic control unit, plus a joint electronic unit for the interface with the satellite. They are exactly the same, except for the use of different materials for the test masses. In one instrument (SUREF) the 2 test masses have the same composition, and are made from a platinum/rhodium alloy. In the other instrument (SUEP), the test masses have different compositions:platinum/rhodium for the inner test mass and titanium/aluminum/vanadium for the outer test mass.

To achieve the test of the Equivalence Principle, the 2 concentric cylindrical test masses are minutely controlled to maintain them motionless with respect to the satellite inside independent differential electrostatic accelerometers. If the Equivalence Principle is verified, the 2 masses will be subjected to the same control acceleration. If different accelerations have to be applied, the principle will be violated: this event would shake the foundations of physics.

The Principal Investigator is Pierre Touboul (ONERA) and Gilles Métris (OCA – GéoAzur) is Co-PI of the mission.

SCIENTIFIC HIGHLIGHTS

The first scientific results of the MICROSCOPE mission have been published in the Physical Review Letters (PRL) in December 2017. The results, based on about 10 % of the scientific data collected, show no violation of the weak Equivalence Principle and improve the accuracy by an order of magnitude, reaching 2.10^{-14}. This result is given with conservative upper limits for some errors.

MISSION STATUS

As the mission duration is limited by the gas quantity, the scientific mission was achieved in February 2018. Then technological experiments will be conducted until September 2018. Then the satellite will be passivated to avoid any risk of explosion. To be compliant with the law on space operations, MICROSCOPE is equipped with an innovative deorbit system, called IDEAS. This equipment is made of 2 deployable wings of 4,5 metres. At the end of the mission, the wings of IDEAS will be inflated and rigidified to increase the drag surface of the satellite. Thanks to this system, the reentry in the atmosphere will last 25 years instead of 73 years.

In parallel, scientists still have a lot of work to achieve the data processing. The processing of the whole data set will allow improving the statistical errors. Remaining non yet processed data will allow to improve the accuracy of experiment. Specific investigations will be pursued to better understand the systematic errors and possibly correct them.

Hopefully, the final scientific results should be published in 2019.

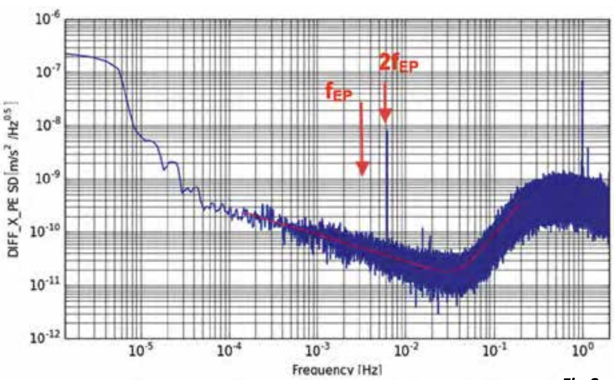

Fig.2

Fig. 1: The MICROSCOPE satellite © *CNES / Virtual-IT 2017*

Fig. 2: Square root of the measured PSD of the differential acceleration along X during the scientific session 218 with SUEP © *OCA / ONERA CMS MICROSCOPE*

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AUTHOR
P. Touboul[1], G. Métris[2], M. Rodrigues[1], Alain J.M. Robert[3]
1 ONERA, chemin de la Hunière, BP 80100, 91123 Palaiseau Cedex, France
2 GEOAZUR, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS UMR 7329, IRD, Géoazur, 250 Avenue Albert Einstein, 06560 Valbonne, France
3 CNES, 18 Avenue Edouard Belin, 31401 Toulouse, France.

The MICROSCOPE mission: first results of a space test of the Equivalence Principle

The MICROSCOPE satellite was launched in April 2016 in a heliosynchronous orbit at 710 km altitude. This space mission is dedicated to test the Weak Equivalence Principle (WEP) with an accuracy of 10^{-15}. At the foundation of General Relativity (GR), it constitutes the major test target for any new theory of gravity. The science payload is based on 2 differential accelerometers that compare the acceleration of 2 pairs of free falling test-masses. In December 2017, the first result of the mission was published in Physical Review Letters [1]: no evidence of a WEP violation with 10^{-14} level of accuracy.

SCIENCE OBJECTIVE OVERVIEW

According to the WEP, all bodies should fall at the same rate in a gravitational field. The MICROSCOPE mission aims to test its validity by measuring the force required to maintain 2 test masses (of titanium and platinum alloys) exactly in the same orbit. A pair of test-masses of the same composition (platinum alloy) is also used to establish the zero of the experiment.

Einstein interpreted this universality of free fall as equivalence between gravity and inertia, and used this principle as the starting point for the theory of General Relativity [2]. GR has an extraordinary capability of prediction in astrophysics, recently well illustrated by the direct detection of the gravitational waves induced by 2 coalescing black holes [3].

However, how should we conceive a unified physics theory that make consistent GR and quantum field theory? In Cosmology, how can we reconcile dark energy and dark matter with the model of the expansion of the universe? Super string or quantum gravity theories could be good candidates to answer these questions. The challenge of these theories is that the WEP has to be violated at a certain level.

MISSION PRINCIPLE

The WEP is often expressed in terms of the Eötvös parameter for 2 materials A and B:
$\delta(A, B) = 2(aA - aB)/(aA + aB)$
aA and aB being the free fall accelerations of the 2 bodies A and B.

In the past decades, the laboratory tests performed on ground laboratories or by means of Lunar Laser Ranging have reached accuracy upper limits on δ of about 10^{-13} [4, 5]. The limitation of these experiments are mainly due to the environment (seismic noise, local gravity field fluctuations, atmospheric turbulences, etc.).

The MICROSCOPE satellite takes advantage of a very quiet environment provided by space. Moreover, the non-gravitational forces or the disturbing torques acting on the satellite are counteracted by on board cold gas thrusters. In order to accurately compare the accelerations of 2 test masses of different compositions "freely falling" in the same orbit around the Earth, the forces required to keep the 2 test masses in relative equilibrium are measured during long periods of time [6, 7].

T-SAGE (Twin Space Accelerometers for Gravitation Experiment) is the scientific payload, provided by ONERA, and is integrated within the CNES' microsatellite MICROSCOPE. It is composed of 2 parallel similar differential accelerometer instruments (called Sensor Unit, SU), each one with 2 concentric hollow cylindrical test-masses, see Fig.1. Both SU are identical except for the outer test-mass. In one instrument (SUREF) the 2 test-masses have the same composition: Platinum/Rhodium alloy (90/10). In the other instrument (SUEP) the test-masses have different compositions: Platinum/Rhodium (90/10) for the

inner test-mass and Titanium/Aluminium/Vanadium (90/6/4) (TA6V) for the outer test-mass. The payload is integrated inside a magnetic shield and a thermal cocoon at the centre of the microsatellite.

Experiencing almost the same Earth gravity field, the 2 concentric test-masses are constrained by electrostatic forces to follow the same orbit. Hence, a WEP violation (δ(A, B) g= 0) would result in a difference −δ(A, B) g in the electrostatic feedback forces, where g is the Earth's gravity field at 710 km altitude (7.9m/s²). The researched signal is modulated at a well-defined frequency, denoted f_{EP}, by the apparent modulation of g seen in the direction of the measurement (cylinder axis) when the satellite orbits in inertial pointing or rotates about the normal axis to the orbit plane (see Fig. 2).

Testing the WEP with an accuracy of 10^{-15} necessitates measuring a differential constraining force per unit of mass (henceforth called acceleration) between test mass pairs with an 1σ accuracy of 7.9×10^{-15}m s^{-2} at f_{EP}. A small disturbance arising from the off-centring between the 2 test masses with respect to the gravity gradient, is well detected at 2 f_{EP}, and can be used for calibration. As the Earth's gravity field is well modelled and the satellite attitude and position are precisely measured, it is possible to estimate the components in the orbital plane Δx and Δz of the off-centring simultaneously to the Eötvös parameter.

THE FIRST RESULTS

Since the end of the commissioning phase, in November 2016, more than 2000 orbits (12×10^6sec) have been collected for the EP test. The first result presented in PRL was performed on only 120 orbits with the SUEP and on 62 orbits with the SUREF. It brings no evidence of violation to 10^{-14} level, one order improvement with respect to previous experiments. The Eötvös parameter δ and the Δx and Δz components of the off-centrings are estimated in the frequency domain with a least-square fit [8, 9]. The SUEP systematic error has been evaluated to be less than 9×10^{-15} and is being better estimated with specific test on board to characterise the temperature sensitivity.

The Eötvös parameter for the SUEP instrument is obtained with 120 orbits (713 518 s):
$\delta(Ti, Pt) = [-1 \pm 9(stat) \pm 9(syst)] \times 10^{-15}$ at 1σ uncertainty on the least-square fit for the statistical error. The test performed with the SUREF instrument over 62 useful orbits (368 650 s) yields: $\delta(Pt, Pt) = [+4 \pm 4(stat)] \times 10^{-15}$ at 1σ. This estimation is fully compatible with a null result (which is expected for this instrument), suggesting no evidence of systematic errors at the order of magnitude of 4×10^{-15}.

CONCLUSION

The WEP test has been currently improved by one order of magnitude with MICROSCOPE. This first results already puts new constrains on some theories ([10], [11]).

Thousands of orbits of scientific measurements should be available by the end of the mission in autumn 2018. The integration over longer periods of the differential accelerometer signal leads already to an important reduction of the stochastic error. Forthcoming sessions dedicated to complete the detailed exploration of systematic errors will allow us to improve the accuracy of the experiment.

ACKNOWLEDGEMENTS

The authors express their gratitude to the different partner entities involved in the mission and in particular CNES, the French space agency in charge of the satellite. This work is based on observations made with the T-SAGE instrument installed on the CNES-ESA-ONERA-CNRS-OCA-DLRZARM MICROSCOPE mission. ONERA authors' work is financially supported by CNES and ONERA funding. Authors from OCA, Observatoire de la Côte d'Azur, have been supported by OCA, CNRS, the French National Centre for Scientific Research, and CNES. ZARM authors' work is supported by the German Space Agency of DLR with funds of the BMWi (FKZ 50 OY 1305) and by the Deutsche Forschungsgemeinschaft DFG (LA 905/12-1).

Fig. 1: Picture of the flight model mechanics that is composed of 2 cylindrical sensor units, each one containing 2 test-masses for the differential acceleration measurement. *© ONERA.*

Fig. 2: Artist view of the satellite in orbit with a schema of the payload and its 4 test-masses. The arrows show the trajectory of the satellite around the Earth and the rotation about the Y axis (normal to the orbital plane): the combination of both motions defines the measurement frequency. *© CNES, Virtual-IT 2017 and ONERA.*

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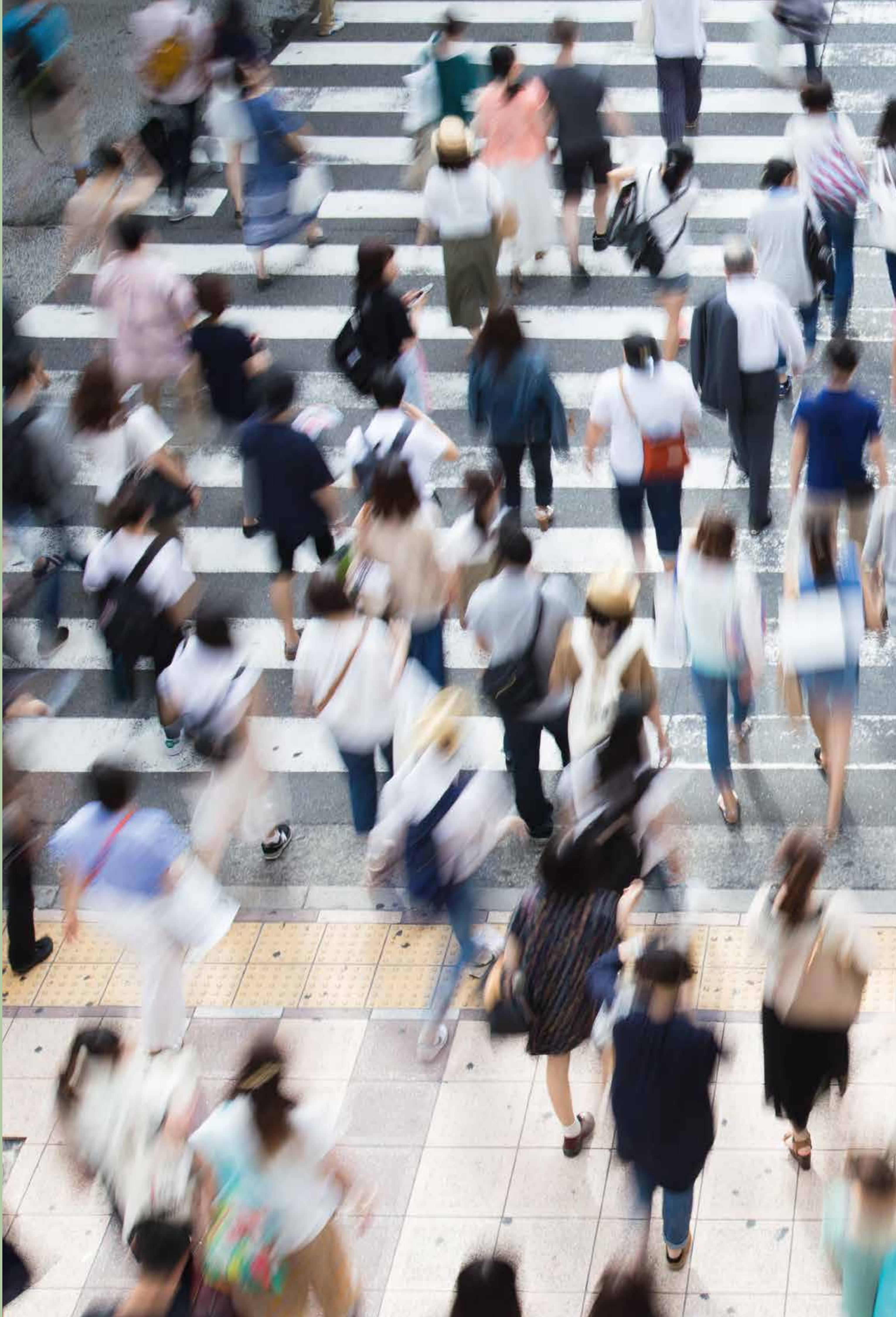

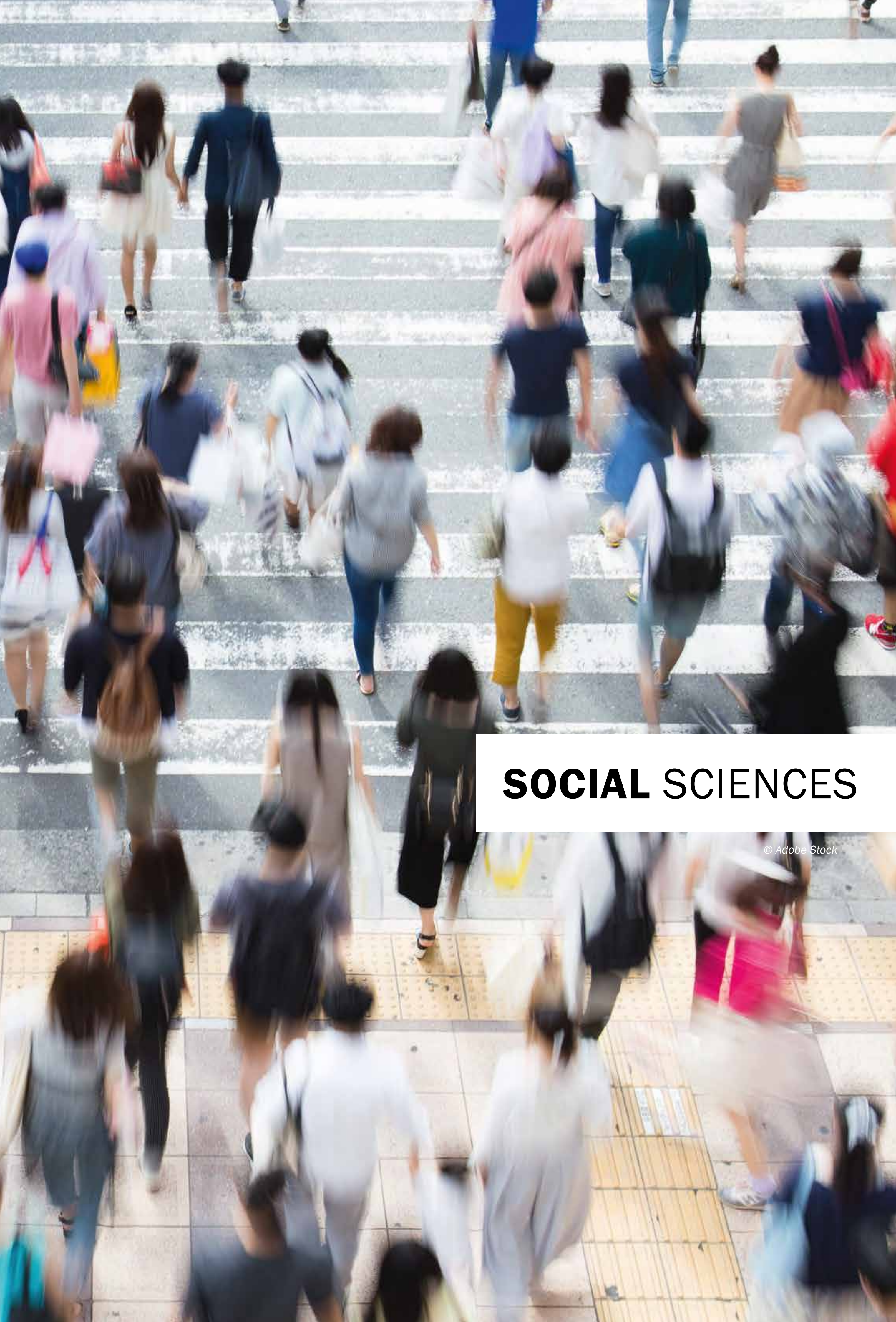

SOCIAL SCIENCES

AUTHOR
Céline Calleya,
Industrial challenges and processes
CNES, 18 avenue Edouard Belin, 31401 Toulouse, France.

Towards an interdisciplinary research in social sciences dedicated to the space sector

Feedback on the partnership with research laboratories in Social Sciences (SS), introduced by a reflection on innovation at CNES, enriched by a better understanding of the contribution of space activities in societal challenges and evolving towards the creation of an incubator for interdisciplinary studies.

ORIGIN

In 2008, a reflection involving partners from social sciences was launched at the request of CNES President, concerning the stakes of innovation. This reflection led to the creation of a unifying research programme conducted in partnership with French laboratories. The aim was to address space activities' contribution to the major contemporary problems of society, focusing on the conditions of this contribution, particularly on the dialogue with public decision-makers, the identification of areas of cooperation and the modalities of co-construction with emerging players. This programme, entitled "Espace Innovation Société" (Space Innovation Society) was in itself a methodological innovation in view of the small proportion of social sciences work on space activities. The questioning expressed was structured around 3 themes: the functioning of the French space agency and the stimulation of its innovativeness; the analysis of the conditions of contribution of space services and applications to the problems of society; the dynamics of interaction and co-construction with an innovative ecosystem.

TANGIBLE RESULTS

Each one of these themes was explored to provide answers to the initial questioning, the researchers below have largely contributed in close collaboration with CNES engineers:

- *Mathias Béjean, researcher at the Research Institute of Management in Paris-Créteil University, investigated possible organisational developments on exploratory studies. This work led to the formalisation of a methodology that enriched the process of conducting these studies.*
- *Sylvain Lenfle, researcher at the Centre of Research in Management at the Polytechnic School. His work shows how identifying all the actors of the ecosystem (citizens, national agencies, politics, scientists) and taking their needs into account very early in the designing process (including the designing of the instrument) increases the value of space data.*
- *Arnaud Saint Martin, researcher in sociology at the Printemps laboratory at Saint Quentin University, takes part in the construction of a sociology of space activities. He began his work with an investigation on the International Charter 'Space and Major Disasters', then he analysed the Copernicus programme to pursue with the study of the transformation of the space sector and of the role distribution between public and private actors.*
- *Flore Guiffault, PhD student in sociology, focuses on the tools creating a risk-based governance in Haiti. The purpose is to oversee the flow of information, from the production of raw data (satellite images, seismic data, etc.) to products that are used for risk management activities, through an ethnographic study.*
- *Francis Château Raynaud leads the GSPR Pragmatic and Reflexive Sociology Group in EHESS School of Advanced Studies in the Social Sciences, his field surveys allow to get as close as possible to the users and thus enhance our understanding of the consequences of the use of data in context.*

Further work will be based on these researchers' results but others took part in the reflection of the programme, such as Isabelle Sourbès-Verger, a researcher at CNRS, the French National Centre for Scientific Research intervening at the A. Koyré Centre.

PROSPECTS

The year 2016 has been dedicated to the outcome of the programme and allowed to highlight 2 main evolutions:

- *Expand the field of action to other disciplines of Social Sciences:*
  This work began with new partners, among which the geographers of the Passage Laboratory in Bordeaux University (studying the citizen movement of participatory mapping), the sociology of politics with the Universities of Paris Nanterre and Picardie Jules Verne (History of the Franco-Russian cooperation regarding the careers of those who lived it) and an economic thesis (macroeconomic indicators of business sectors operating space infrastructures). A dialogue with other initiatives undertook before by CNES will complete this work. These initiatives deal with legal, economic and managerial matters (Sirius chair led by Toulouse Business School and Capitol 1 University in partnership with Thales Alenia Space, Airbus Defence and Space and CNES) as well as ethics.
- *Encourage the emergence of interdisciplinary studies:*
  The experience showed the importance of creating meeting places for researches from very different background, combining soft and hard sciences (Physics, Geology, Biology, Engineering). This space would take the form of an incubator for interdisciplinary studies that would provide the conditions for collaboration. The incubator, which is currently in gestation itself, will be based on the group of researchers from the initial programme. Indeed, the quality and durability of the relation between these researchers and CNES engineers already involved are crucial: they moved beyond the stage of learning the other's language and are now grasping the problematics of each one. Together, they are fuelling a reflection that is materialising through actions in their own field.

Fig. 1: Céline Calleya

Fig. 2: Cove of Saint-Marcel in Saint-Martin, the Caribbean, seen by Pléiades before (February 2017) and after (September 2017) the passage of hurricane Irma. Pléiades *© CNES 2017, distribution Airbus Defence and Space*

AUTHOR
S. Lenfle[1 2]
1 CNAM (National Conservatory of Arts and Crafts), 292, rue Saint-Martin, 75003 Paris
2 CRG (Management Research Centre), Ecole Polytechnique, 828 boulevard des Maréchaux, 91762 Palaiseau Cedex

Floating in space? On the strangeness of exploratory projects

The context in which this research takes place is of particular significance for our argument. Indeed, the space industry constitutes an archetype of the rational approach of project management. Most of the current tools of contemporary project management come from the U.S. aerospace sector, be it military (the Department of Defence) or civilian (National Aeronautics and Space Administration, or NASA, see Lenfle *et al.* (2010) [3]. This gave birth to a model of project management that emphasises the control of project execution through a phased approach; the use of managerial tools to control time, cost, risk, and quality; and the setting up of strong project structures to implement this approach. This method of project management is still dominant in the space industry today.

The strengths and weaknesses of the rational project management approach are well documented in the literature. The great strength of this type of approach is the application of process control techniques developed for production to the designing work. Such processes have been shown to improve control of the convergence toward the predefined goal in terms of cost, quality, and delay. For complex, high-cost space projects there probably is no alternative to the rational project management approach. But problems arise when this approach is blindly applied to all kinds of projects. In particular, Sehti *et al.* (2008) [5] demonstrate the irrelevance of this process in situations where radical innovations are being made. Indeed, this "rational" view of project management does not fit with the logic of radical innovation that is characterised by divergence, discovery and unforeseeable uncertainty Loch *et al.* (2006) [4]. Sehti *et al.* (2008) [5] thus show that stage-gate processes lead to what they call "project inflexibility"—that is, the inability to change the project's goal after initiation. This, they argue, leads ultimately to failure.

At CNES, the problem appeared with the emergence of "strange" projects in the domain of space telecommunications at the end of the 1990s. Our interest in space telecommunication was triggered by a presentation of the head of the navigation and telecommunication projects during a one-day workshop on innovation management. He explained that in the telecommunications sector, CNES was increasingly encountering what he calls "strange projects." In order to illustrate his idea, he presented a slide with Hieronymus Bosch's famous painting *The Garden of Earthly Delights* (see Fig. 1). He used the unexpected and confronting nature of the elements in the painting as a metaphor for his perception of a mismatch between the "strange projects" and the phased approaches that typify project management at CNES. Indeed, the projects he supervised looked nothing like those defined in classical project management frameworks: the goals were not clear at the beginning, the projects worked on new concepts and not necessarily with objects, it was hard to define deadlines and they were frequently changing.

In theoretical terms he was confronted to exploratory projects for which one can neither make the assumption that the goal of the project is clearly defined beforehand, nor that the knowledge base is sufficient [2]. Compared with the dominant model of project management, exploratory projects look strange because there are ambiguous goals and no requirements, the

projects work on new concepts and not necessarily on objects (for example on "flexible payload" for telecommunication satellites), it is hard to define deadlines, and the risks are unknown. In other words, they seem to be "floating." Our purpose in this paper has been to study the management of these "strange" exploratory projects within the context of the space industry. In so doing, we have made 3 contributions:

- First, the case studies provide rich material on how exploratory projects unfold, their management and the problems encountered by the actors. It underlines the need to differentiate management processes according to the nature of the projects, standard or exploratory;
- Second, we demonstrate that exploratory projects are not at all floating. They may appear so, if they are viewed through the rational model. But we show that, on the contrary, these projects are carefully managed, and they actually obey a logic of their own. At a conceptual level, they correspond to the experimental learning process proposed by Loch *et al.* (2006) [4] in which goals and the means to reach them are progressively identified over the course of the project. Design theory helps us clarify the "expansive" logic of these projects, which are exploring both new concepts and new knowledge. We are thus able to characterise how they unfold (double expansion in concept and knowledge), specify their results (EQM, prototypes, new design models, new knowledge), and identify promising criteria (saturation and expandability) for their evaluation.
- Third, we demonstrate that exploratory projects constitute a powerful tool for structuring the potentially very fuzzy processes of exploration for 3 reasons:
  - they are oriented toward goals;
  - they help pace exploration, they provide opportunities for sense making;
  - and they foster coordination between different disciplines that, otherwise, would remain scattered throughout an organisation.

We believe that what is at stake here is important for the evolution of project management research and practice. Indeed, we have to reconsider the concept of the project itself that, for too long, has been equated with the rational model. This perspective has hindered our ability to think about other types of project logic. As a result, project managers of exploratory projects have considered themselves the "dunce" as their supervisors talk of "strange" projects. Given the role of innovation in today's competitive environment, it is all the more important to formalise and circulate a relevant model of exploratory project management.

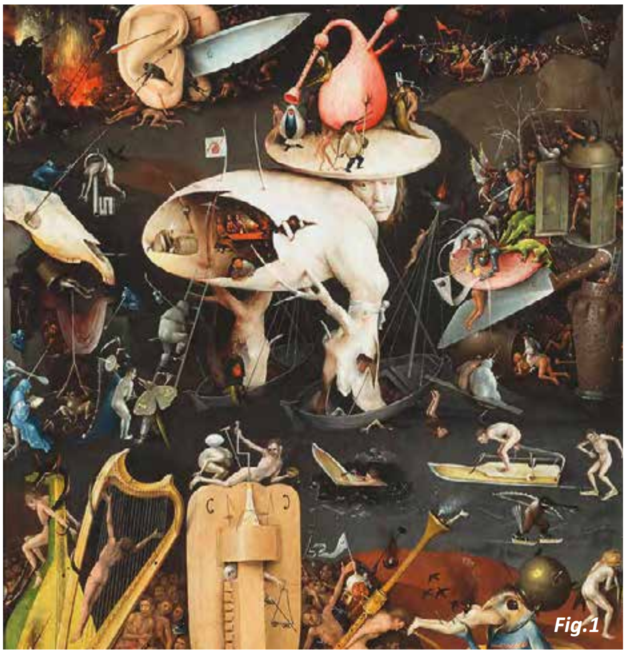

Fig. 1: Bosch's *The Garden of Earthly Delights* (around 1503–1504, Prado Museum).

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AUTHOR
N. Clark[1], F. Guiffault[2]
1 Copenhagen Centre for Disaster Research, Karen Blixens Plads 16, 2300 København S, Denmark
2 GSPR (group of pragmatic and reflexive sociology), 105 Boulevard Raspail, 75006 Paris, France

Geospatial information for disaster management: processes and challenges in Haiti after 2010

While geo-information is a useful tool to manage disasters, it is likely that, in time of crisis, some territories lose their ability to make and use information. Though, a crisis can be an opportunity to access certain devices usually out of reach. In a case study on Haiti after the 2010 earthquake, we explore the consequences of crisis on local data producers. Our results suggest that the earthquake has led to economic, technical and legal challenges for information making and sharing.

Disasters are becoming more and more recurrent because of the global warming but mainly because it is used as a category to govern all kinds of events. Once an event is labelled as a disaster, it allows the mobilisation of different tools to frame a response. Geospatial information is one of these tools. It has been used to characterise a disaster: its nature, its location, its power. It has been used to evaluate its impacts: the number of people, buildings, roads, trees, etc. being affected. And it has been used to organise the action of first aid: to communicate, to get around, to assure safety [1].

Geospatial information however is not available everywhere at the same level. While some territories are information-rich, characterised by a wide production, dissemination and an easy access to information, others are just not [2]. In a case of a disaster, it might as well happen that the information available on a territory is destroyed by the very disaster and/or that the ability of the inhabitants to produce information is reduced. In those cases, the activity of producing geospatial information is carried on by external actors.

In the case of the 2010 earthquake in Haiti, the cartography of the country, including the capital Port-au-Prince, was incomplete and difficult to access from abroad. Besides, a dozen of the top national experts on cartography perished in the destruction of the national center for geospatial information (CNIGS). In response to the great destruction that affected the country, many actors started mapping activities and geospatial information became one of the main response fields. In addition to the usual humanitarian mapping activities, a group of international online volunteers launched the first crisis participative cartography campaign of that magnitude [3, 4].

However, besides the massive mobilisation of many actors to provide geospatial information and several years later, Haiti still lacks some of the basic data needed to build disaster management policies. So why does Haiti still present similarities with information-poor environments? And how did the geospatial information produced in the context of the earthquake's response affect the mid-term and long term national production of geospatial information?

Those issues have been addressed through from 2 interdisciplinary studies – mainly in law, political sciences, sociology and geography – which examine different, albeit interrelated, aspects of geospatial data use for disaster management (DM) in Haiti. Whereas the first study is concerned with ongoing practices and challenges surrounding data use for risk reduction activities, the second focuses on these processes in the context of response and recovery efforts. In this way, the researchers were able to compare and analyse their respective data to get a combined overview of developments around data sharing in all phases of the DM cycle.

Primary data was collected through semi-structured interviews, field (participatory) observations, project meetings and informal discussions with relevant stakeholders within Haiti and abroad. Study one interviewed 46 individuals between the dates of July 2015 to June 2017. Study 2 interviewed

Fig. 1: Cartography of presumed damaged buildings made by SERTIT from satellite imagery © *SERTIT*

Fig. 2: Participative cartography made by Ushahidi volunteers based on information they collected on social networks and by SMS they received © *Ushahidi*

16 individuals between the dates of October 2016 and June 2017. Some interviews were recorded digitally and others were conducted through note taking (by hand or computer) as participants did not feel comfortable being recorded. Secondary data sources included an extensive review of official reports, government texts, media outputs, and prior research on the technical and operational humanitarian-based undertakings by stakeholders at different levels in Haiti prior to and after the 2010 earthquake.

Overall, the article finds that the increasing recognition, use and value of data for disaster management activities since the earthquake is contributing to a number of interrelated economic, technical and legal processes and challenges for data sharing among stakeholders in the country.

Economic findings are primarily centred around the impact which donor funding, project based work and the incursion of “new market” actors is having on data sharing. In this environment data retention has largely become the norm, which has led to the duplication of datasets, quality concerns and informal networks for data sharing at the local level.

These issues feed into technical findings, where the increasing number of actors and projects working with data leads to quality control issues. Here, data producers and users within the country are becoming increasingly hesitant to use and/or release data which has not been internally generated and/or validated. Furthermore, the methods and modes for data exchange have expanded alongside the development of spatial data infrastructure such as web portals. But the expansion also creates some confusion among respondents and hesitance in terms of the relevance and reliability of available data, and where to find it.

Lastly, the legal findings indicate there is an ongoing uncertainty around data licensing, regarding which types of data can be shared and with whom. Importantly, open data is increasingly underlying all of these processes and challenges, albeit not always in the ways in which it was intended for.

As environmental disasters are a growing issue, this study has contributed in understanding the impacts and challenges of an international geospatial cooperation. Some issues deserve further researches such as the CEOS recovery observatory launched after hurricane Matthew stroke Haiti in October 2016.

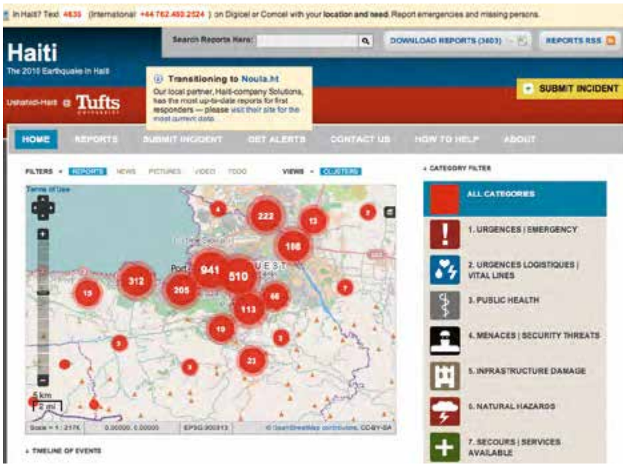

Fig.2

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Centre national d'études spatiales
2 place Maurice Quentin
75039 Paris cedex 01 - France
Tél. : +33 (0)1 44 76 75 00

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