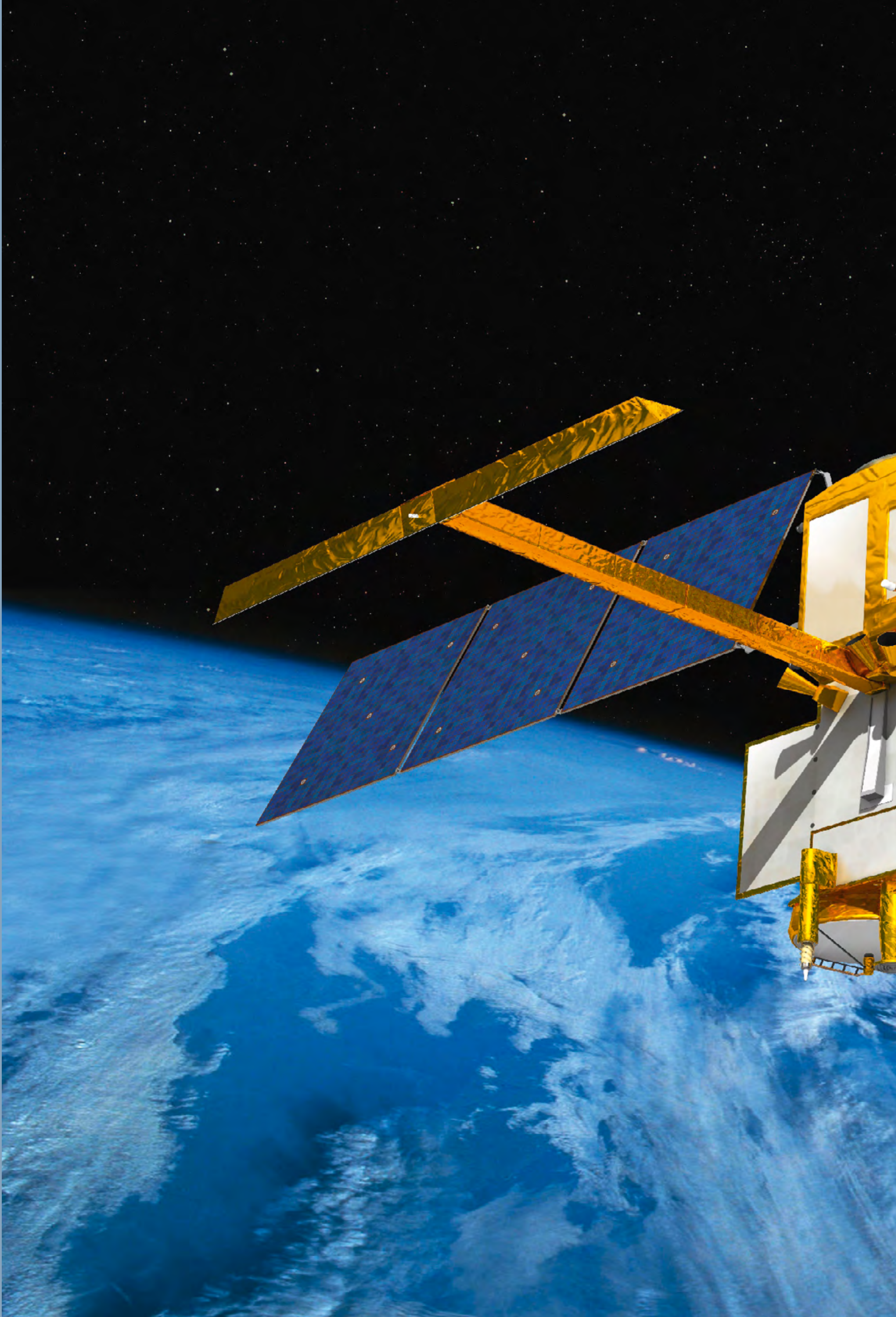

EARTH SYSTEM

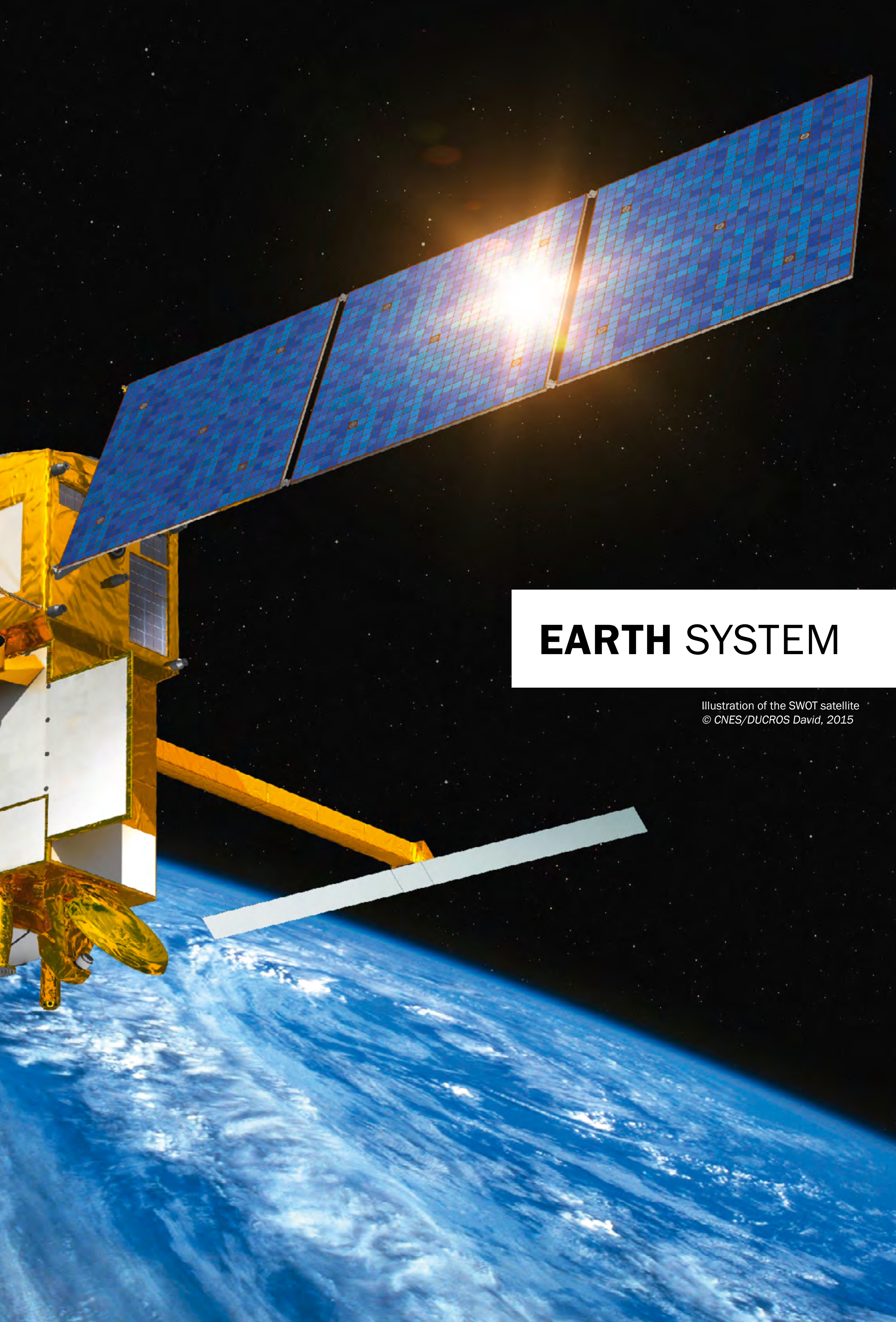

Illustration of the SWOT satellite
© CNES/DUCROS David, 2015

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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.

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.).

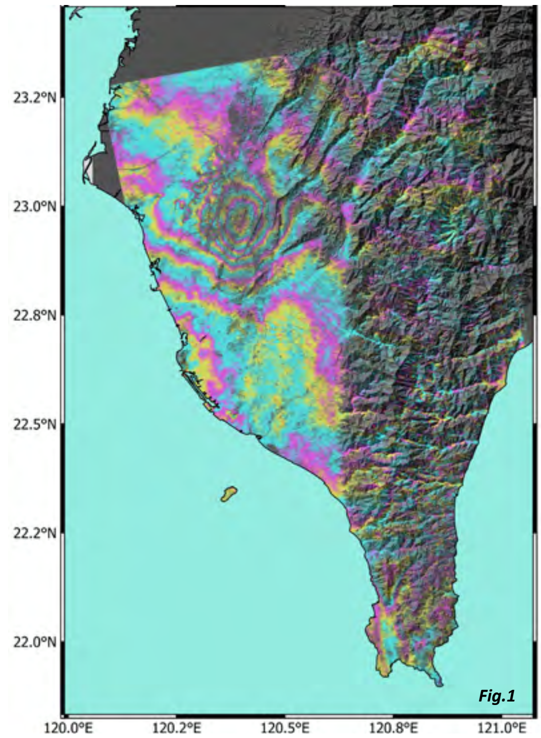
SCIENTIFIC PAYLOAD

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

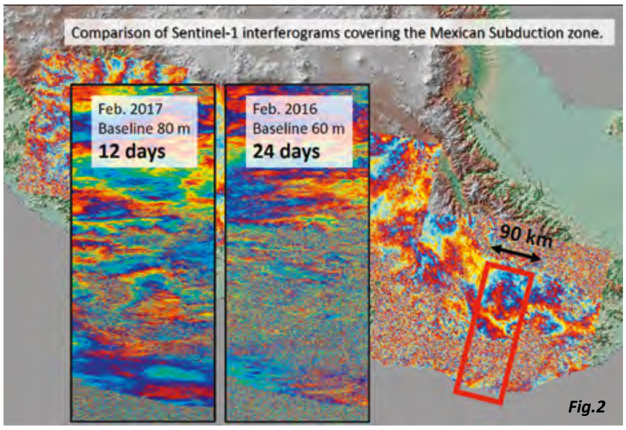
SCIENTIFIC HIGHLIGHTS

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.



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).



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/

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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.

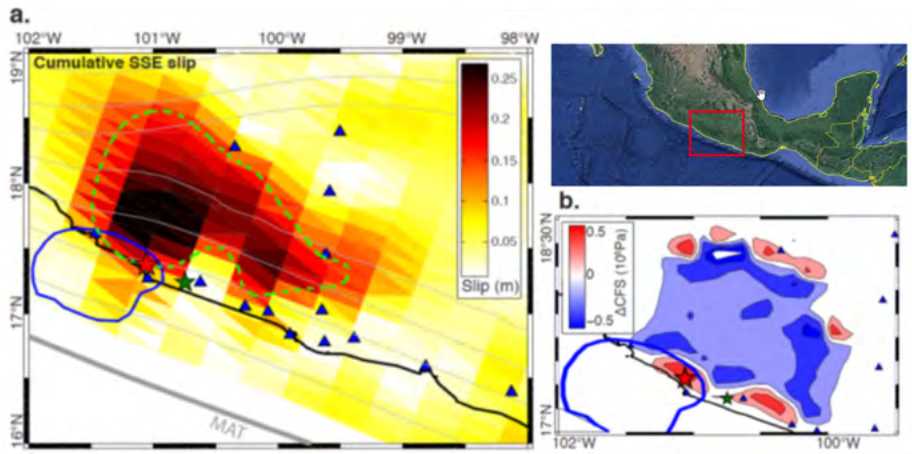

Fig.1

Fig. 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).

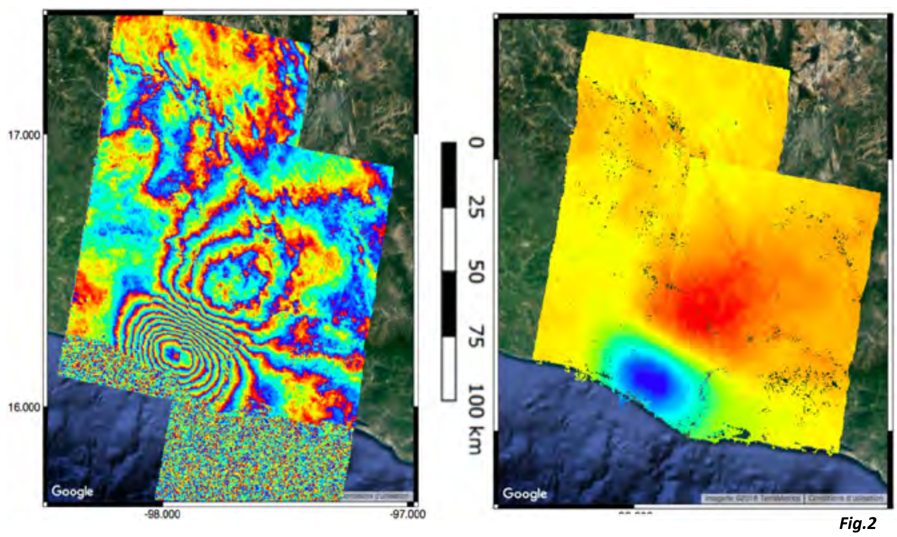

Fig.2

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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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.

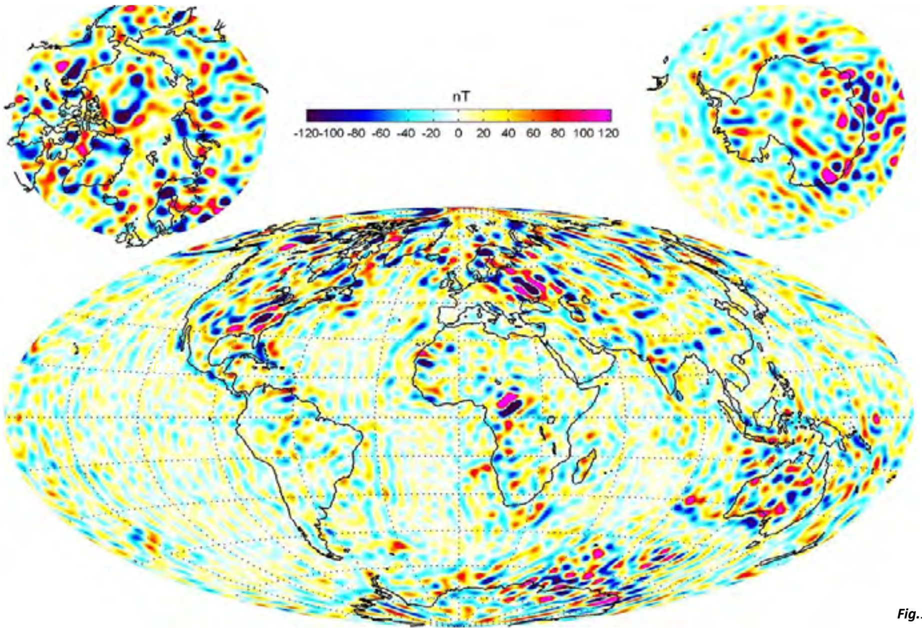

Fig.1

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].

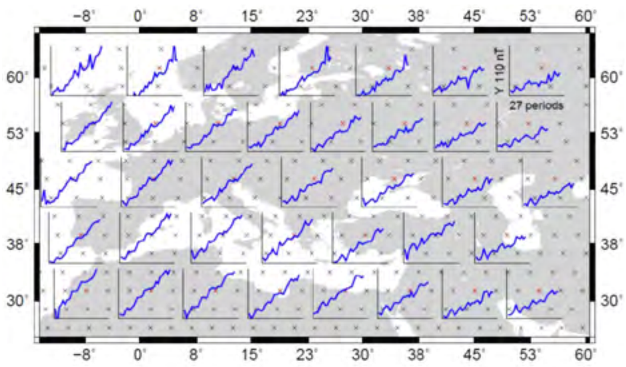

Fig.2

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.

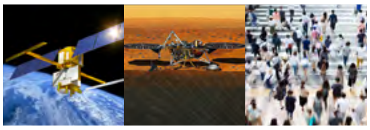
The 2.5 years VENμS' science mission will be followed by a one-year technology mission during which its altitude will be lowered to 410 km to gauge the performance of a Hall-effect plasma thruster developed by the Israeli Space Agency (ISA) to counter orbital decay caused by atmospheric drag.

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.

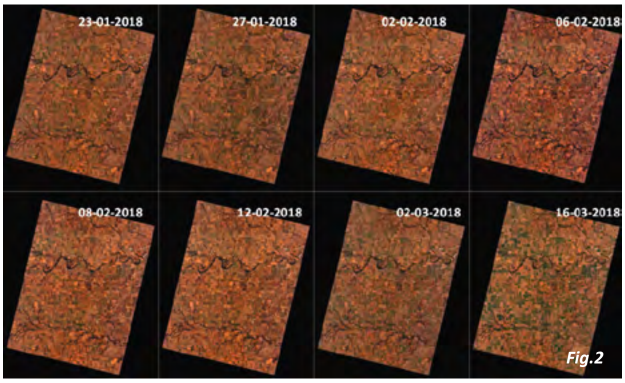


Fig. 1: Artist view of the VENμS satellite © *IDÉ/SARIAN Robin, 2015*

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.

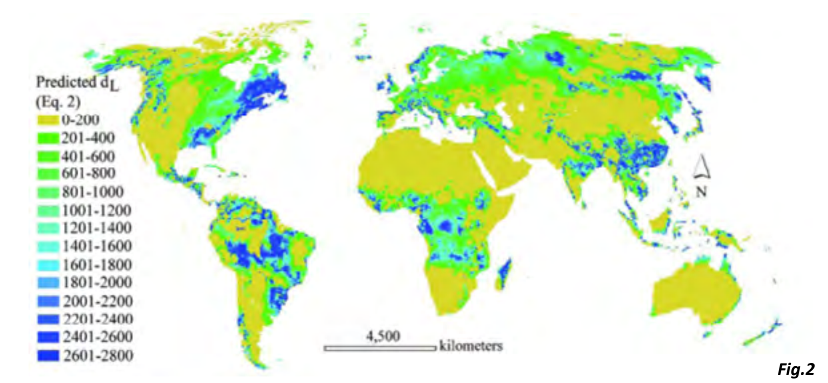

Fig.2

Fig. 1: Ilustration 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.

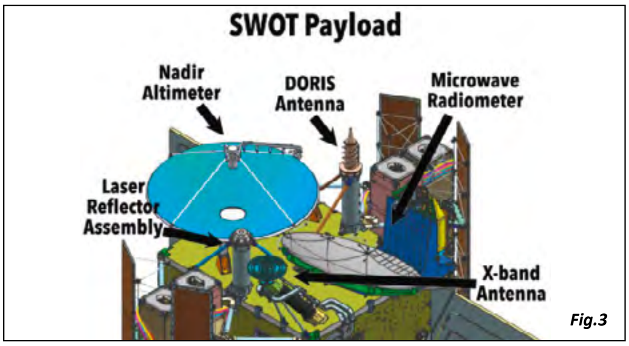

Fig.3

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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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.

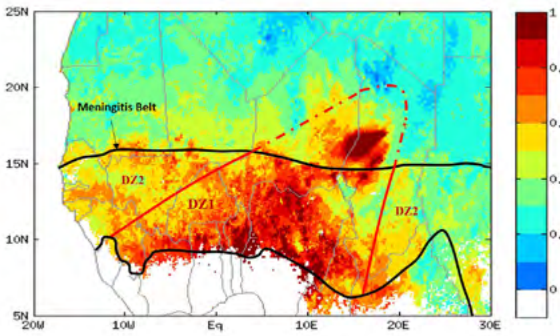

Fig.1

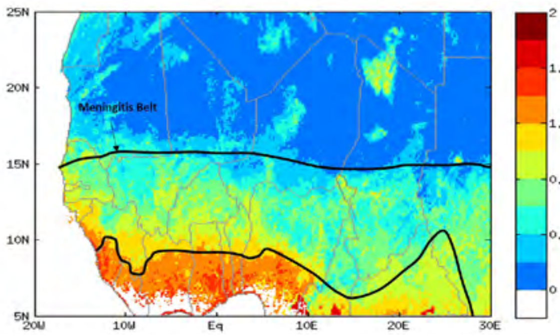

Fig.2

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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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.

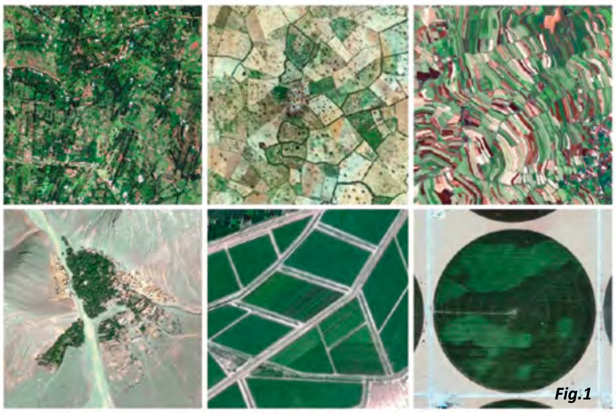

Fig.1

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.

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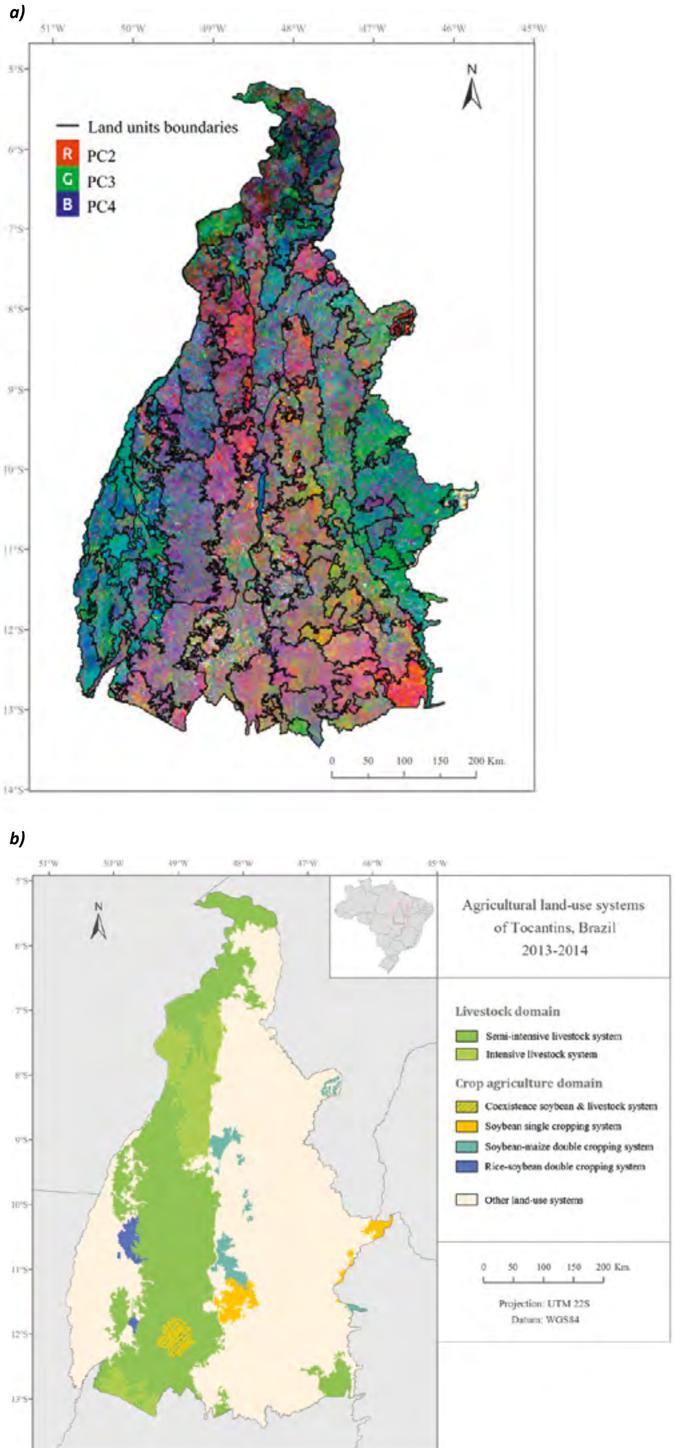

Fig.2

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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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].*

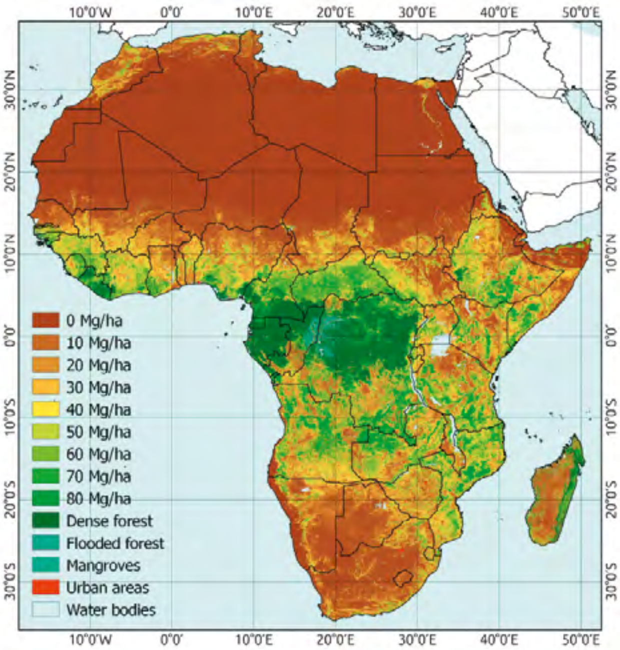

Fig.1

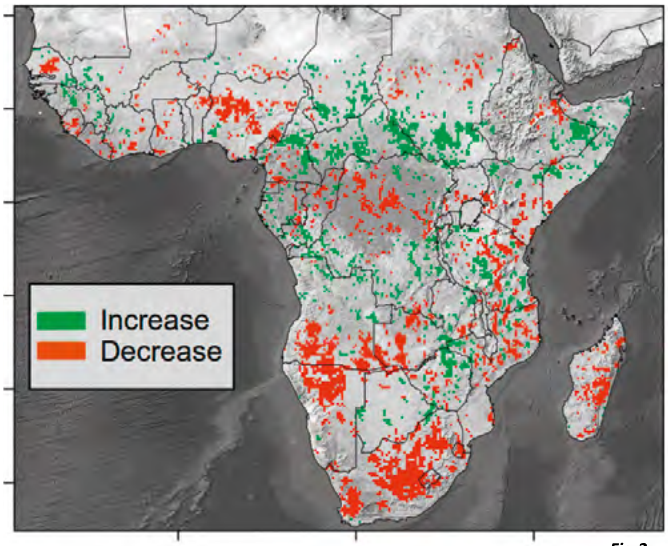

Fig.2

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.

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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

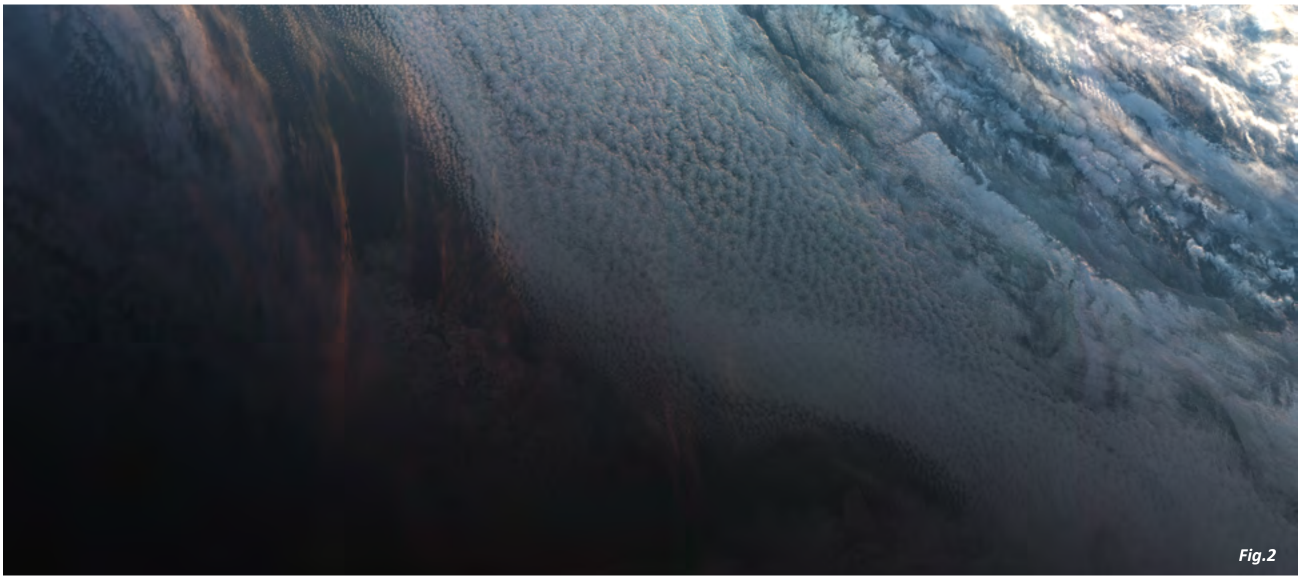

Fig.2

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 1 250 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.

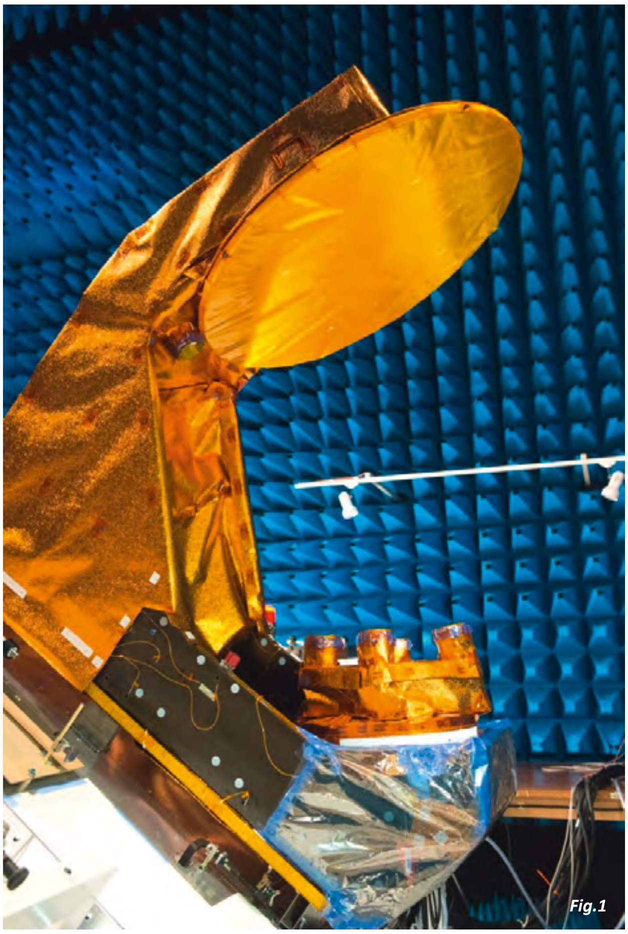

Fig.1

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.

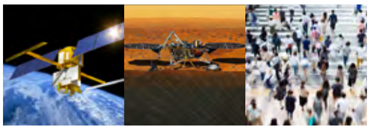

Fig.2

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, 1336 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 1336-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.

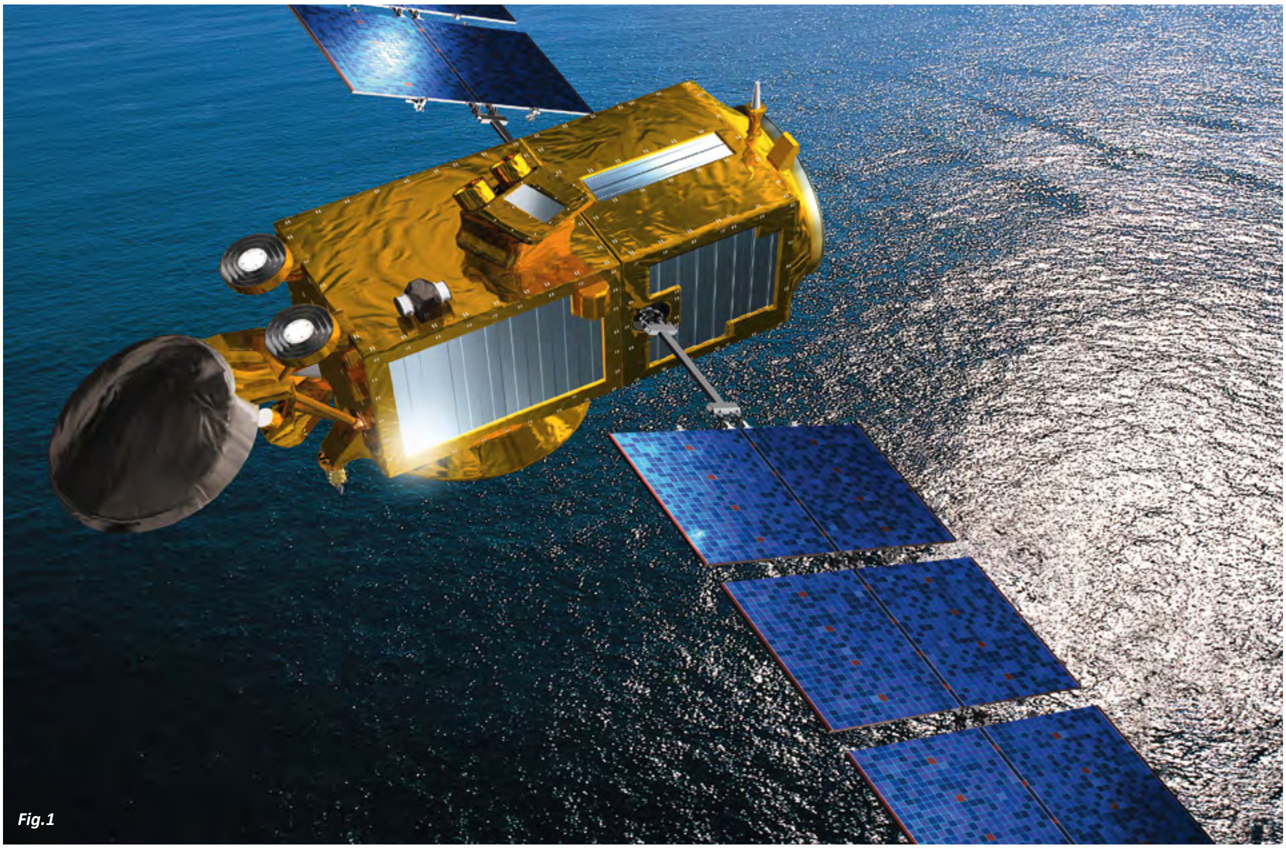

Fig.1

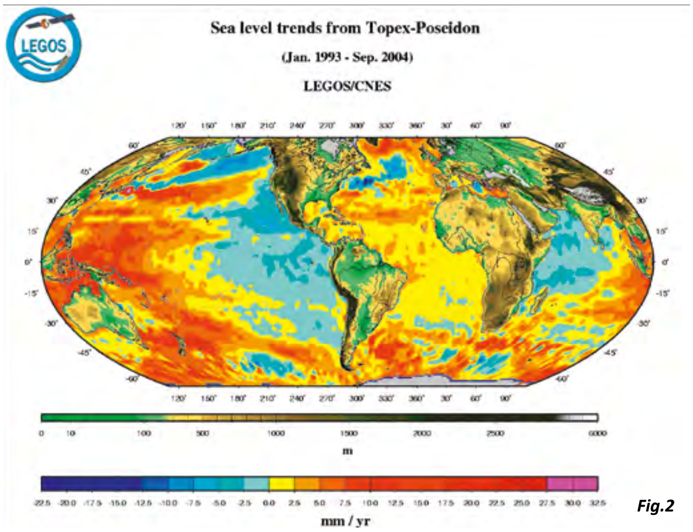

Fig.2

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*

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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.

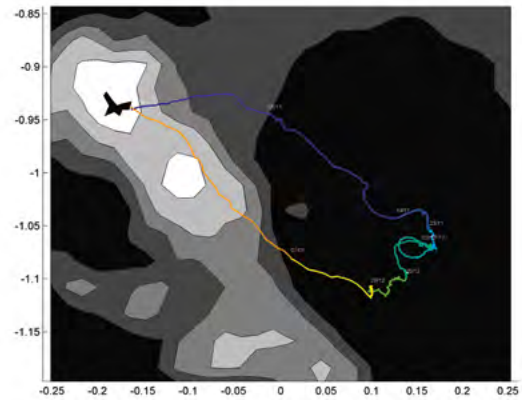

Fig.1a

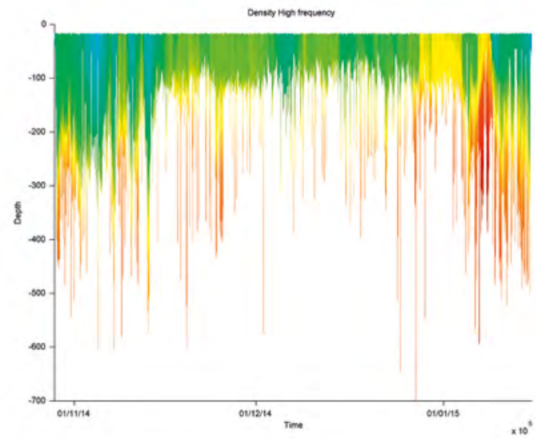

Fig.1b

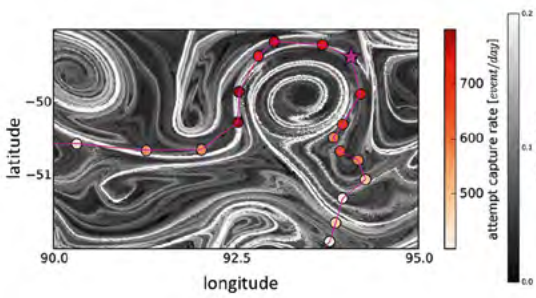

Fig.2

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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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.

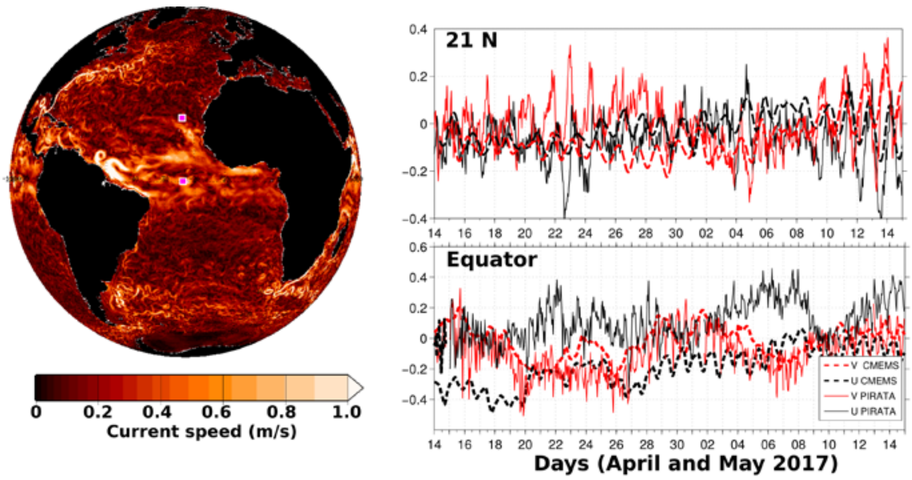

Fig.1

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.*

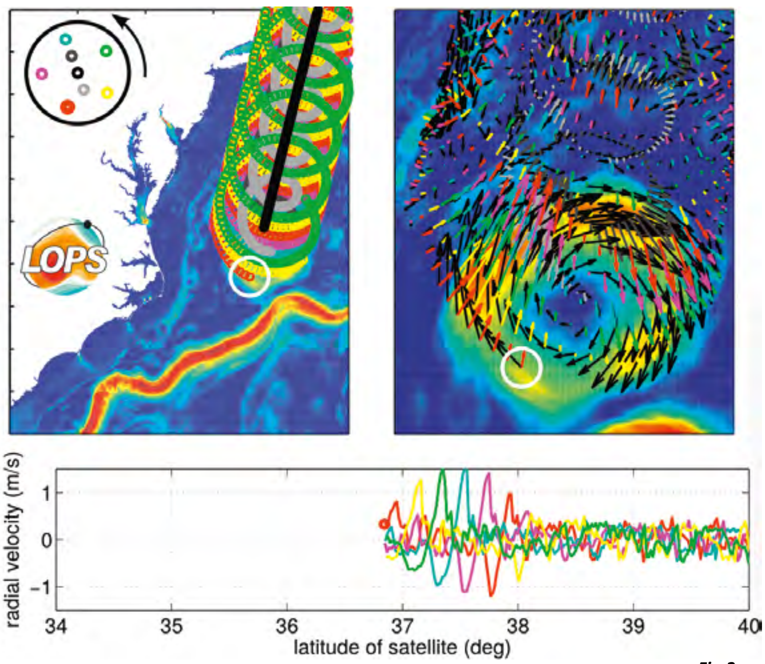

Fig.2

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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**
  SO2 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.
  CH4 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.

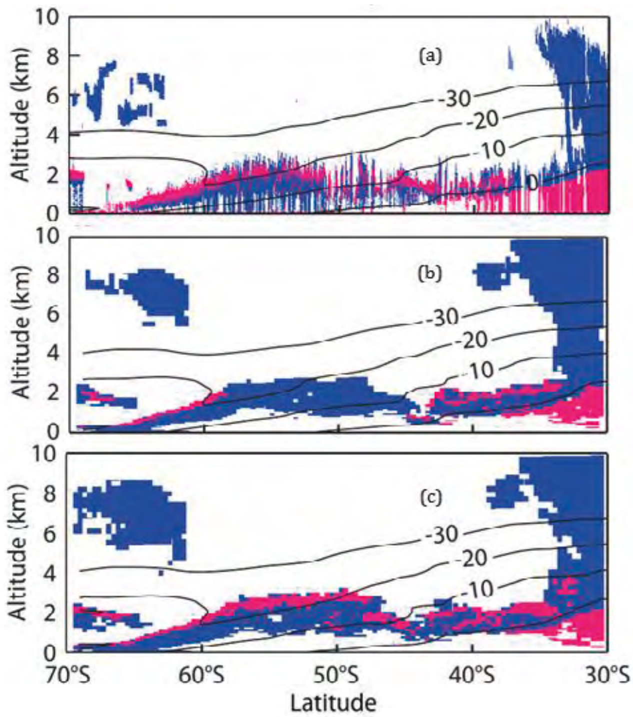

Fig.1

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.

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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.

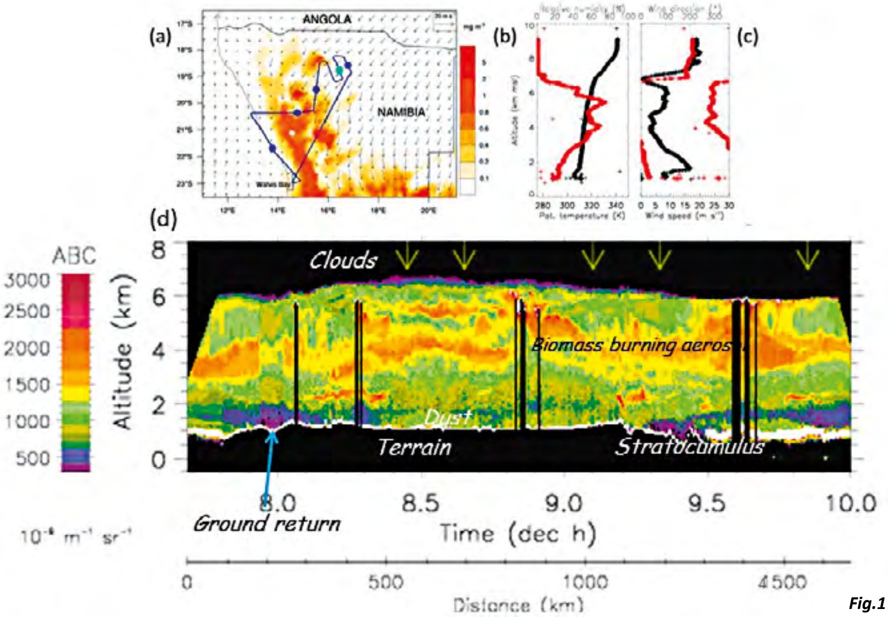
The south-tropical Atlantic off Southern Africa's west coast is highlighted by the latest report of the IPCC |1] as one of the regions of the globe where climate change could be the most obvious. Due to the low temperature of surface waters, the western coast of Southern Africa is characterised by near-permanent 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.



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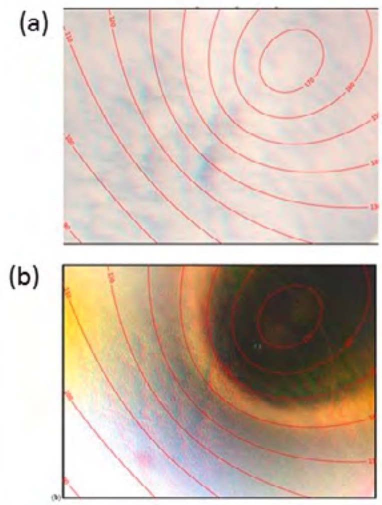

Fig.2

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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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.

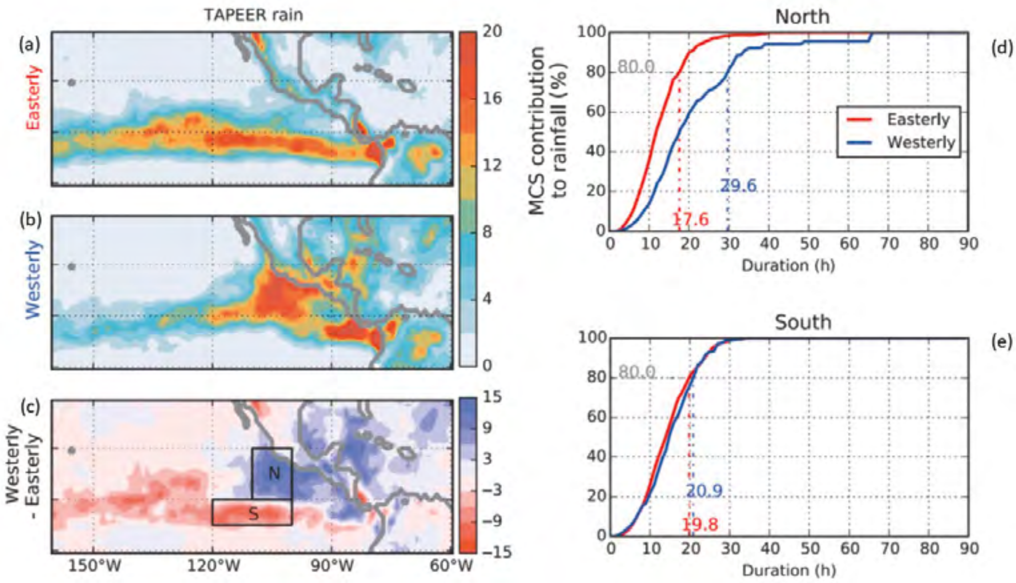

Fig.1

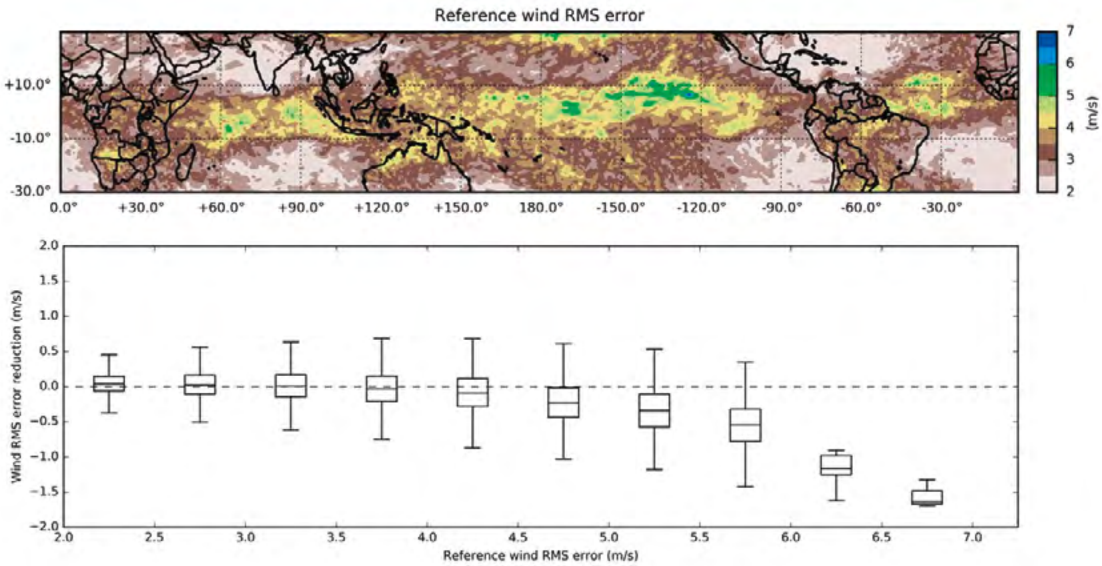

Fig.2

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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]*

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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.

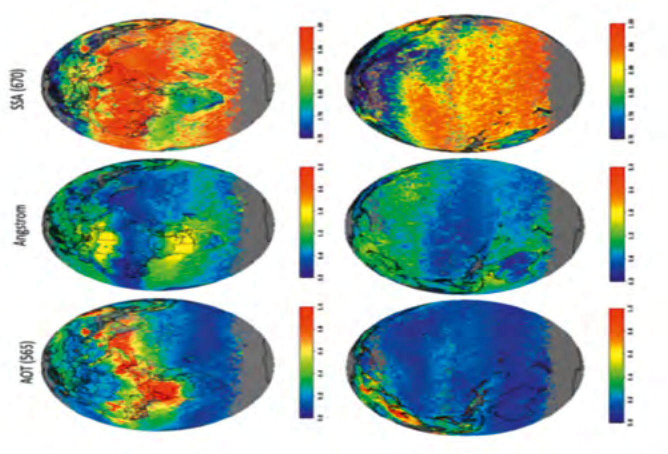

Fig.1

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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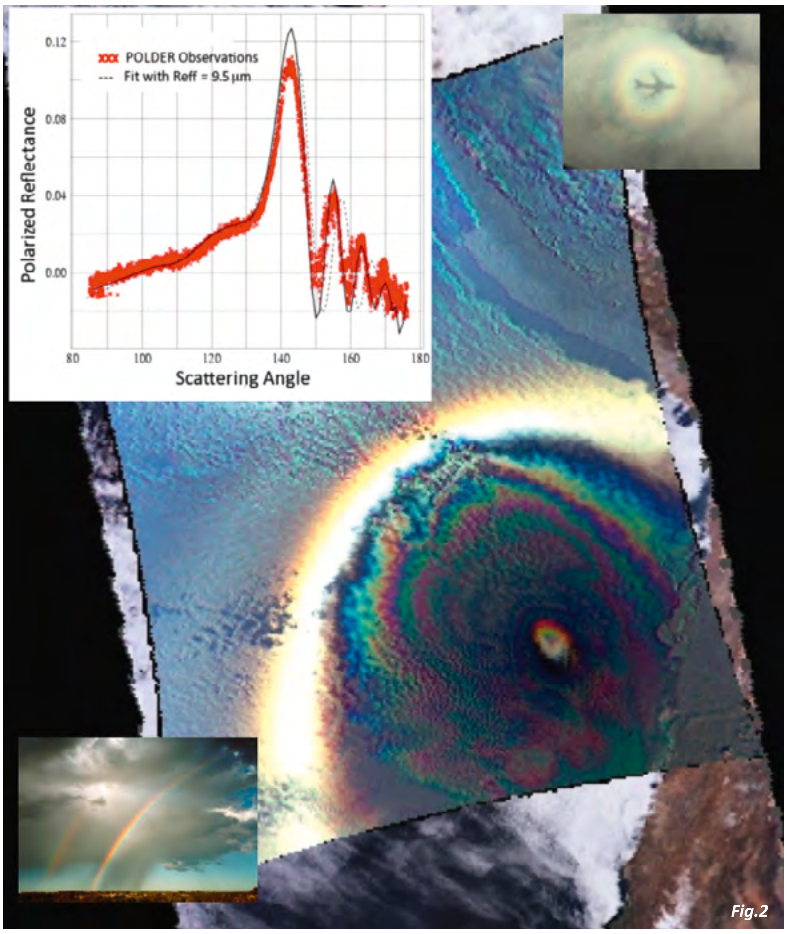

MICROCARB measuring global CO_2 distribution

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.

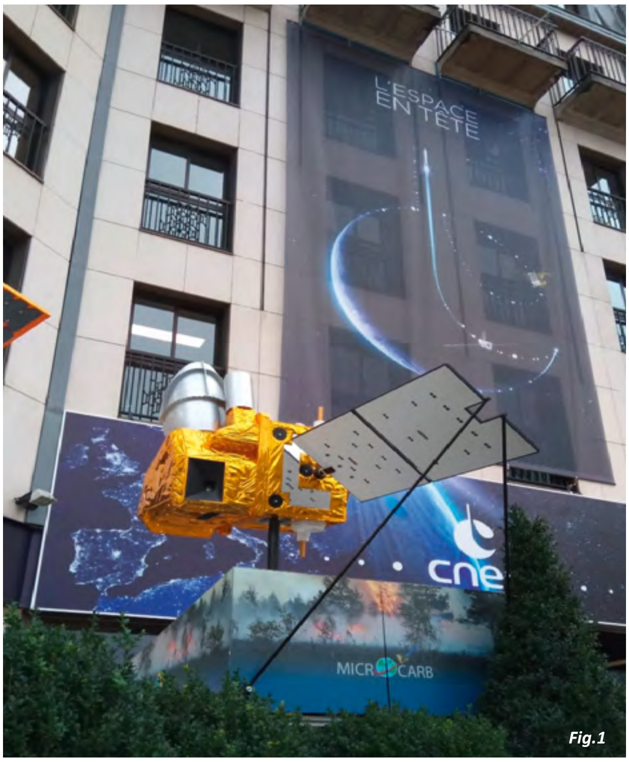

Fig.1

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.

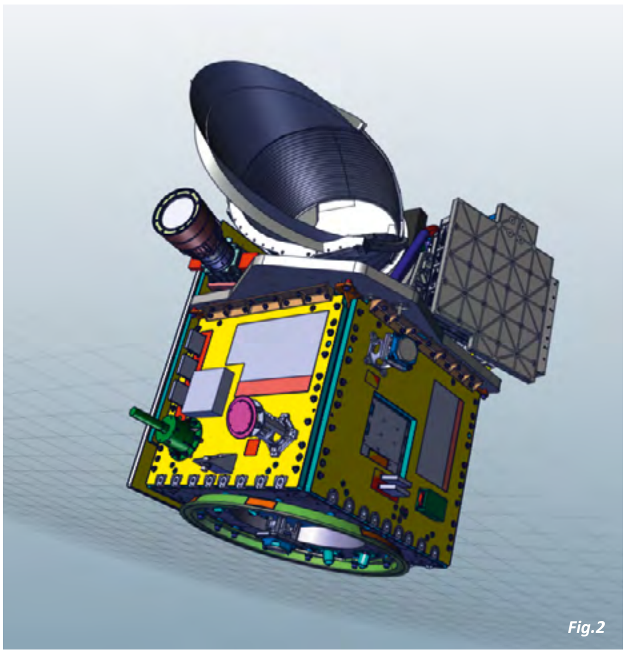

Fig.2

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*