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Solid Earth

Fig.1

The Solid Earth group's interests cover a large domain, including the internal geophysics, geodynamics, geodesy, and the impact of the solid Earth dynamics on external envelopes. The space-time variability of the geodynamic processes makes the Solid Earth system radically more complicated to study. Space and time scales vary on several orders of magnitude: from a second (earthquakes) to millions of years (plate tectonics) and from a centimeter (faults) to tens of thousands of kilometers (plate tectonics). Satellite data complement the airplane and ground-based geophysical measurements to improve the characterization of Earth's system. They also complement in situ data with additional and global observations to monitor Earth's dynamics. A few space missions with a large interest for the French Solid Earth community are presented below.

SWARM – monitoring Earth's magnetic field

The SWARM mission (ESA forth Earth Explorer "Opportunity Mission") was successfully launched in 2013. The three identical-satellite constellation aims to measure Earth's magnetic field. Thanks to the original orbital configuration, the contributions to the geomagnetic field due to different sources can be separated, *i.e.*, contributions from the core dynamo, induced currents in the mantle, lithospheric magnetization, induced currents linked to ocean circulation, ionospheric and magnetospheric currents.

CNES's contribution to this mission consists in providing instruments for measuring the magnetic field intensity (nominal mode), as well as vector components – the Absolute Scalar Magnetometers (ASM). There are two ASMs aboard each satellite (for cold redundancy). The ASMs of SWARM A and B satellites have operated extremely well: the quality of the scalar nominal measurements and the experimental vector measurements has been better than expected. Unfortunately, the redundant ASM on SWARM C was lost at launch (failure of the RF transmitter) and the second ASM stopped working at the end of 2014. Today, the ASMs (and their redundant) on SWARM A and B are the only left. Thanks to the strategic choice of keeping the SWARM C in a low orbit close to A, the impact is

Fig.2

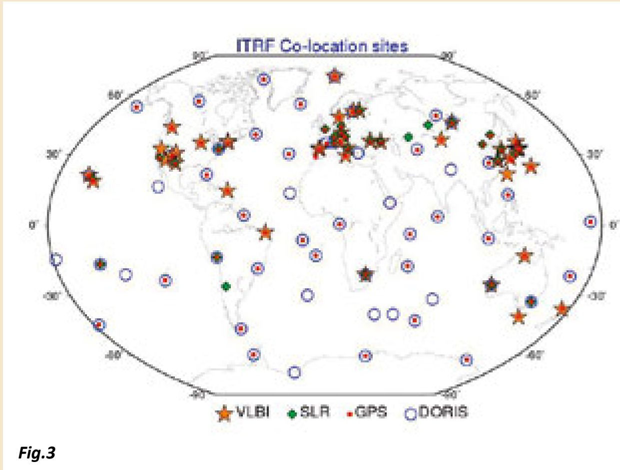

Fig.3

Fig. 1: Swarm is ESA's first Earth observation constellation of satellites. The three identical satellites are launched together on one rocket. Two satellites orbit almost side-by-side at the same altitude – initially at about 460 km, descending to around 300 km over the lifetime of the mission. The third satellite is in a higher orbit, at 530 km, and at a slightly different inclination. The satellites' orbits drift, resulting in the upper satellite crossing the path of the lower two at an angle of 90° in the third year of operations. The different orbits along with the satellites' various instruments optimize magnetic data sampling in space and time, distinguishing between the effects of different sources and strengths of magnetism. The three-satellite Swarm mission aims to unravel one of the most mysterious aspects of our planet: the magnetic field. *© ESA/ill.Pierre Carril, 2013*

Fig. 2: Preparation of the Swarm probe for ultra-high vacuum test in the Toulouse Space Center Laboratory, which participated in the Swarm project. *© CNES/Maligne Frédéric, 2013*

Fig. 3: The distribution of the VLBI, SLR, GPS and DORIS stations which contributed to the 2014 ITRF, based on [3].

Fig. 4: The miniature sensor built by CEA-LETI (bottom of the image) is much smaller than the ASM instrument on board SWARM (the two sensors ensure redundancy aboard), based on [4].

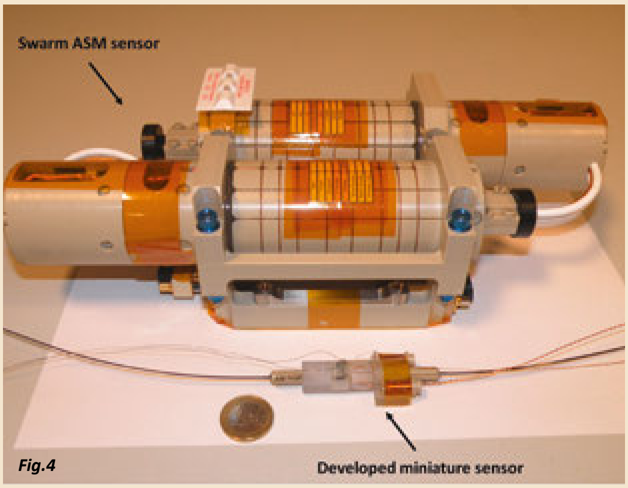

Fig.4

minimized and the mission can continue. As shown in a recent work, thanks to this configuration, the ASM absolute data on board SWARM A can be used to calibrate the VFM (Vector Field Magnetometer) on SWARM C [1].

The three satellites are currently on their orbital positions: SWARM A and C on a low circular orbit and B on a high circular orbit. The French community has already used data from this mission. It is worth mentioning that the working group in charge of developing the IGRF-12 geomagnetic field model (International Geomagnetic Reference Field, 12th generation)(1) was piloted by E. Thébault (LPG Nantes) [2]. As such, all candidate models of the 10 international teams were gathered and analyzed. The results were published in the same special issue of the journal *Earth Planets Space* devoted to the IGRF-12. Other noteworthy scientific results have also been obtained, and a few are presented as follows.

SPOT and PLEIADES – let's scan Earth

On February 22, 1986, Ariane launched the SPOT-1 satellite into orbit. It was followed by the SPOT-5 satellite, from 2002 to 2015. It completed some 70 000 revolutions of the planet, made 25 000 telemetry/telecommand passes and collected nearly 8.2 million 60-km-by-60-km images of Earth's surface over its operational lifetime – it is now stationed in an ellipticital orbit at an altitude of 625 to 809 km. Its successors, SPOT-6 and SPOT-7 (1.5 m resolution, 60 km imaging swath), are commercial satellites (Airbus Defence and Space). Metric resolution imaging and high-frequency scanning of the Earth has therefore become possible.

In 2011 and 2012, CNES launched the PLEIADES 1A and 1B optical satellites (with a 50-cm resolution at nadir). These cutting-edge satellites are capable of providing repeated very-high-resolution imagery anywhere in the world. Beyond the advantage of these new images for traditional photo-interpretation (map-making based directly on an image), the access to extremely high-quality data has boosted the interest of the geoscientific community for techniques which allow optical image disparity calculation using image correlation. Access to PLEIADES data is also possible via the ISIS program (Incentive for the Scientific use of Images from the Spot system)(2). PLEIADES images will allow the scan of transitory deformations (much better than with GPS), but this will require responsiveness and repetition. The potential of PLEIADES images is presented below, through a few noteworthy scientific results.

DORIS – a key positioning system

DORIS is a French civil precise orbit determination and positioning system. It is based on the principle of the Doppler Effect with a transmitting terrestrial beacon network and on board instruments on the satellite payload. Over the last decade, five new satellites have a DORIS system onboard – JASON-2 since 2008, CRYOSAT-2 since 2010, HY-2A since 2011, SARAL/ALTIKA since 2013 and JASON-3 since 2016. The DORIS CNES/GRGS and IGN analysis centers often perform data processing in operational mode for all active equipped satellites, receiving weekly signals from the beacons network. These data and the GPS, VLBI, SLR data (Fig. 3), have been essential to produce the ITRF 2014 (International Terrestrial Reference Frames), released in 2016[3]. In order to ensure ITRF accuracy, the definition of specific parameters (origin, scale and orientation) and their evolution over time must be unambiguously quantified. Any time drift in the physical frame parameters (origin and scale), might have unavoidable consequences on geophysical observations (and their interpretation), which are dependent on ITRF use.

The accurate knowledge of a terrestrial geodetic reference frame is a key factor to many applications in geoscience – average sea level, plate motion, validation of the reference models, etc. An accuracy of about 1 mm in position and 0.1 mm/year in velocity is required to study accurately and continuously phenomena impacting the solid Earth.

GRACE – until GRACE-FO launch

The GRACE mission (Gravity Recovery and Climate Experiment), was launched in March 2002 (lifetime >10 years). It involves twin satellites linked by a K-band ranging system (KBR) which measures the inter-satellite distance with a micrometer precision. They both measure the time-variations in the gravity field at medium and long-wavelength spatial scale and with a ten-day to monthly resolution. Although these data are mostly used to study the water cycle, they are also sensitive to solid Earth dynamics. They offer precious constraints provided that we distinguish climate system and solid Earth contributions to the gravity field's variations.

GRACE variable models produced by the GRGS are described and expressed as spherical harmonic coefficients, geoid height maps or transformed in equivalent water height (EWH) on the GRGS[4] and the BGI's[5] websites. Today, the GRACE satellites are not in a nominal configuration. Their stabilization was achieved but came with a price as some data are missing. GRACE-FO, a second series of similar satellites will be launched in 2017. They will maintain continuity of Earth's gravity field measurements which the scientific community is waiting to exploit.

FORM@TER – a service and data center for solid Earth

The idea of creating a service and data center for the community was initiated in 2012. ForM@Ter[6] was born from a common need to pool the access to data, software resources, and expertise allowing the access to observations of the Earth's surface, shape and kinematics. The project encompasses several scientific themes of the solid Earth.

An unprecedented wealth of data exists today. To optimize their exploitation in support of research and society, centers such as ForM@Ter figure out how to process, store and make data available for as many users as possible. To meet this challenge, one must find new distribution and storage resources such as the implementation of new ways of processing data and of creating approved ready-to-use products. New exchange, reflection and collaborative research platforms must also be created.

ForM@Ter's overall objective is to complement spatial data with added-value products and services available in situ. It seeks a place at the national and European level, and proposes to work jointly with existing and future infrastructures. ForM@Ter's expected products and services are the following:

- A data portal: the current data distribution is mainly divided according to data nature instead of scientific application. Research would benefit from a portal gathering all links (classified according to their scientific challenges) to these data.
- A technology transfer: the scientific community would benefit from a more open distribution of tools and results toward all French laboratories. This may also pave the way for their distribution to decision-makers and the private sector.
- Expertise: the center would aim to provide either expertise or a representation for potential contacts between laboratories.
- A support to international services: France is in charge of several international services; the center should coordinate resources and services, and optimize both cost management and funding research.

The ForM@Ter center forms part of the European sphere, where some infrastructures are already in progress. EPOS (European Plate Observing System)[7] is a European infrastructure project created to observe and understand solid Earth dynamics. It has been included in the ESFRI roadmap (European Strategic Forum on

Research Infrastructures). EPOS ensures data distribution and pioneers the concept of a thematic platform structured around the solid Earth observation data.

Anticipating tomorrow

The French community involved in the Solid Earth Program is also ready for potential future missions. It participates in consortiums to answer invitations to tenders (e.g. ESA's EE9). Here are a few noteworthy proposed missions:

GRASP (E-GRASP) should have the four fundamental geodetic techniques on board – DORIS, GNSS, VLBI, SLR – needed to determine the ITRF. The goal is to achieve a 1 mm positioning accuracy and a 0.1 mm/year velocity (*i.e.*, 1 mm in 10 years) required to meet all types of challenges: the surveillance and the knowledge of Earth's shape and movements, as well as questions on the Earth system – sea level and ice melting surveillance, etc. These are complementary techniques in terms of geographic distribution of the ground network, accuracy, observation time and length, sensitivity to geodetic parameters of interest (station positioning, Earth orientation parameters). Improving our knowledge of these positioning measurements requires an inter-comparison made possible solely by the four techniques on board of this satellite. E-GRASP is a French-leading proposal to the ESA EE9 call, in cooperation with European and U.S. scientists.

NANOMAGSAT aims to build a nanosatellite carrying a magnetometer based on a miniature version of the SWARM ASM ones. The mini-ASM (Fig. 4) would provide both absolute scalar and vector measurements of the Earth's magnetic field (1 Hz), as well as scalar field data at higher frequencies (250 Hz sampling rate). If successful, the ASM would not require instruments such as the VFM (Vector Field Magnetometer). The scientific payload could be a mini-ASM associated with stellar cameras and a Langmuir probe. Payload positioning via the dual band GPS would provide TEC (Total Electronic Content) measurements. NANOMAGSAT is a phase 0 CNES project.

On another topic, the **IONOGLOW** proposition underlines that TEC (Total Electronic Content) and Airglow measurements contribute to characterizing in detail the propagation of seismic and tsunami-caused wavelengths in the ionosphere. The location and time of a tsunami can be predicted by observing these wavelengths from space. In the long run, this pioneering high-resolution (higher than decametric) geostationary optical satellite will improve our knowledge of fast geodynamic processes. This proposition is under a scientific study.

Fig. 5: The Doris antenna on the Jason-2 ocean-observation satellite. *© CNES/ThalesAleniaSpace/OBRENOVITCH Yoann, 2007*

Fig. 6: A new NASA funded study finds that the Greenland and Antarctic ice sheets are losing mass at an accelerating pace, three times faster than that of mountain glaciers and ice caps. *© Eric Rignot. NASA JPL*

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(6) *http://poleterresolide.fr/?l=en*

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Solid Earth

SWARM – Monitoring Earth's magnetic field

The SWARM mission, designed to improve our know-ledge of the Earth's system as a whole, has already shed new light on the processes occurring in Earth's interior and its immediate environment. SWARM takes over from the scientific missions dedicated to the study of Earth's magnetic field, ØRSTED, CHAMP and SAC-C. The advantage of a three-satellite constellation is that it can better isolate, characterize and provide models of the magnetic field sources, thanks to measurements at different altitudes and local times. Here, a few examples are given of the already achieved remarkable results.

IGRF-12 – An international model to describe the geomagnetic field

The IGRF model describes Earth's core field and its large-scale secular variation. It is published every five years and includes a predictive part for the secular variation for the next five-year period. International scientific teams submit candidate models in the form of Gauss coefficients which are then evaluated. The final IGRF model is usually derived from weighted candidate models after a statistical comparison between models [1]. Candidate models can be quite different, as they are built according to different scientific approaches and choices.

The French teams (IPG Paris, ISTerre Grenoble and Nantes LPG) submitted candidate models, both for the main field in 2015 and the secular variation for the interval 2015.0 - 2020.0. It is worth highlighting that the candidate models submitted are based on different approaches.

What singles out the IPG Paris contribution is the data used – experimental absolute magnetometer vector mode data. The model built [2] thus demonstrates the ability of the ASM's experimental vector mode to provide data of an adequate quality to submit a competitive candidate model for IGRF-12.

The Grenoble ISTerre team is heavily involved in the use of a stochastic approach to analyze and forecast the evolution of the magnetic field (in a probabilistic approach, *i.e.*, with a confidence interval). It is therefore possible to reconstruct the evolution of both the magnetic field and fluid flows at the top of the Earth's core, bearing in mind that model errors associated with the unresolved small-scale magnetic field should be accounted for. The implementation of an Ensemble Kalman Filter with augmented state vector (*i.e.*, reversing simultaneously for model errors and flows) resulted in the production of a candidate secular variation model for the interval 2015.0-2020.0 [3].

The LPG Nantes team follows a "Virtual Observatories" (VO) approach based on the Equivalent Source Dipole technique [4]. For each virtual observatory, a dipole mesh is placed below, at a determined depth, and with a certain number of dipoles. Taking into account all SWARM satellite measurements inside the VO volume, the iterative conjugate gradient technique is used to calculate the equivalent magnetization of each dipole. The submitted candidate model results from a comprehensive model obtained using this approach.

The intensity of the magnetic field at the 2015.0 epoch and its temporal evolution over the period 2015 to 2020, calculated from the IGRF-12 model, are presented in Figure 1. One characteristic is the South Atlantic anomaly, a region where the magnetic field has a minimum of intensity.

The South Atlantic Anomaly

The temporal evolution of the South Atlantic Anomaly seen by SWARM and other satellites including RHESSI (Reuwen Energy Solar Spectroscopic Ramaty High Imager) and RXTE (Rossi X-Ray Timing Explorer) is of great significance. The anomaly location varies according to the type of observation, but its drift remains similar. As this anomaly is the main structure of the geomagnetic field near the Earth's surface, its temporal evolution reflects that of the entire field. Some authors claimed to have detected "jerks" in its evolution. Understanding the impact of the South Atlantic Anomaly variable location according to the type of observation will prove useful. It may lead to a better understanding of the proven sensitivity of satellites, which is often correlated to their pass above the South Atlantic or/and above the polar regions, and habitually linked to the high-energy particles generated by cosmic rays.

A highly dynamic core

Data from the SWARM mission, complementing ØRSTED and CHAMP missions measurements, have also been used for re-analyzing the fluid flows at the top of the

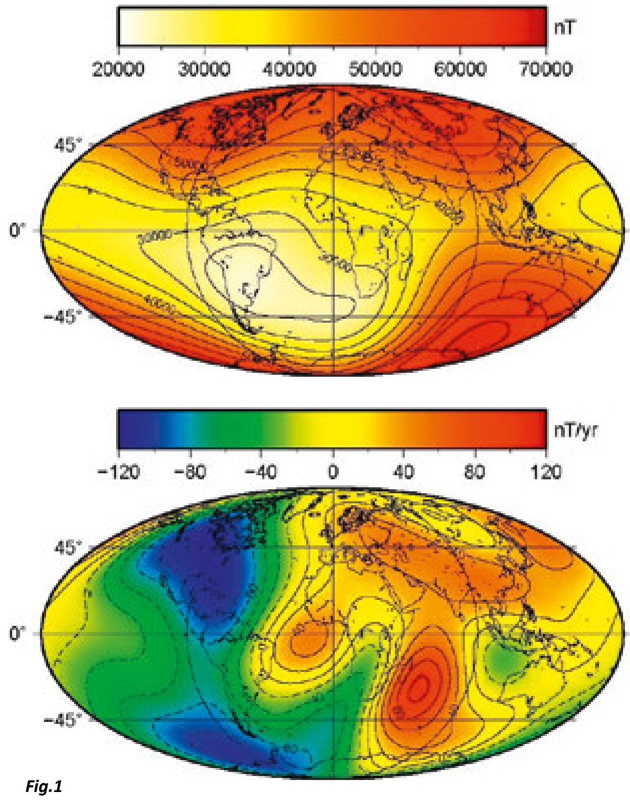

Fig.1

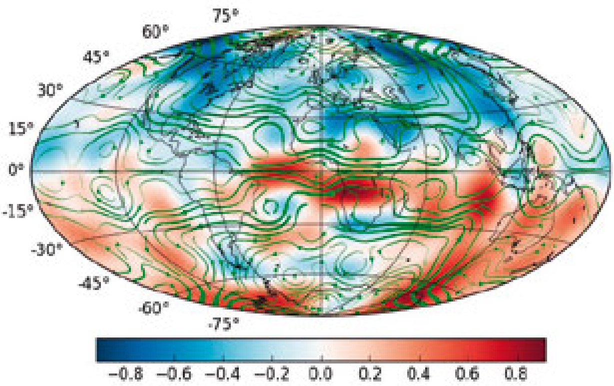

Fig.2

Fig. 1: The map of the Earth magnetic field intensity for the 2010.0 epoch and its secular variation for the period 2015.0 to 2020.0.

Fig. 2: The map of the radial component at the core-mantle interface (in mTesla) and the large-scale core-surface flows.

Fig. 3: The image highlights the new crust (right) and core (center) magnetic field models from Swarm. These preliminary results are based only on the first year of data. *© ESA/DTU Space/ATG medialab*

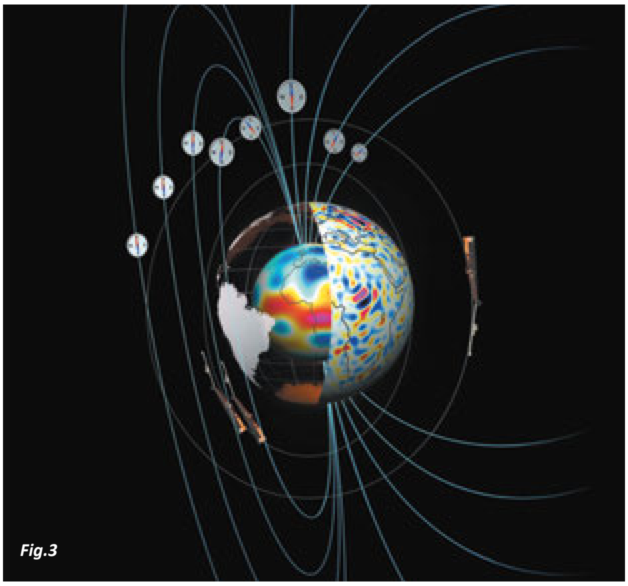

Fig.3

Earth's core during the 1998-2015 period. Prominence is given to the interannual fluctuations and a quasi-geostrophic hypothesis, according to which when the Coriolis term dominates the balance of forces, flows organize in columns aligned with the rotation axis, and they can be described in the equatorial plane. The flows show that interannual fluctuations are especially strong in the equatorial belt [5], where intense fluctuations of the magnetic field time derivative (called "geomagnetic jerks") have been observed. Advances in the description of the core flows and of the magnetic field at the core-mantle boundary suggest that it is possible to interpret the many magnetic jerks observed in the past 15 years thanks to space missions, without resorting to the presence of a stratified layer at the core surface, suggested by seismic constraints and recent estimates of heat flow. This may not be incompatible with such a layer, insofar as the density gradient under the surface can be transparent for large-scale transient flows. This issue still requires further theoretical, numerical and observational investigations.

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Solid Earth

From SPOT to PLEIADES: continously observing the Earth


Fig.1


Fig.2

Several French groups have efficiently developed tools to exploit the data from the PLEIADES satellites in an innovative way – firstly, to calculate VHR (Very High Resolution) local digital terrain models (DTM); secondly, to measure deformation fields. Recent developments on the disparity measurement from optical satellite image correlation are about to radically change our way of measuring deformation events such as earthquakes, volcanic eruptions and large landslides. Some noteworthy results are given below.

The pulse of our planet's glaciers

Ice mass losses, which result from global warming, raise significant scientific and societal issues. The melting of glaciers affects the water supplies of the populations in arid regions (drinking supplies, irrigation, river ecology) and account for one third of the current sea level rise. One of the most appropriate techniques to assess ice mass losses is the difference between two DTMs, calculated every few years. It has been possible for a few years to derive sufficiently accurate DTMs from satellite stereo imagery, including from the two PLEIADES satellites, which is revolutionary for glaciologists. Evaluated from GPS in situ data, the precision of the PLEIADES DTMs is about 1 m and even 30 to 50 cm on the flat glaciers. The effectiveness of accurate DTMs derived from PLEIADES images for studying the cryosphere has been demonstrated in various contexts:

- In the Mont-Blanc: a comparison of a PLEIADES DTM (August 2012) with a DTM derived from SPOT5-HRG images (August 2003) clearly shows the great thinning of the glaciers in these mountains in recent years, especially at low altitude where losses exceed 10 m/yr. The glaciers' lower altitude measured from space is highly consistent with in situ observations. Thanks to PLEIADES and SPOT5, the first mass balance over the whole Mont-Blanc glacier area has been assessed to complete field measurements of a few glaciers. The Mont-Blanc glaciers lose an annual average of one meter in depth [1].
- In the Canadian Arctic: PLEIADES stereo pairs acquired in August 2014 were also used simultaneously with aerial photographs of the 1950s. [2] The PLEIADES data provide the recent topography and control points required for aerial photographs (acquiring ground control points would imply very heavy and costly logistics). The results show that the southernmost ice caps of the Canadian Arctic have lost mass in the recent period (2007-2014, altitude loss of close to 2 m/yr) compared to their evolution in the long term (loss of 0.5 m/yr since the 1950s).

Instantaneous deformations associated with earthquakes

Until recently, deformation measurements were mainly limited to the assessment of sub-vertical deformations thanks to field measurements and satellite radar measurements, such as ENVISAT and SENTINEL-1. Thanks to the development of metric and sub-metric optical sensors (SPOT and PLEIADES), one now gets access to deformation distribution in the horizontal plane with a 2-meter resolution and a 20-centimeter detection threshold.

This methodology has been applied for the first time in 2015 with high resolution images, to measure the deformation associated with a 7.7-magnitude continental quake, which occurred in Pakistan in 2013 [3]. The use of SPOT-5

Fig. 1: Artist's view of the Pleiades satellite. Pleiades is a multi-sensor Earth observation program which succeeds SPOT. It will use smaller, cheaper, more agile satellites. Its first high-resolution optical component (Pleiades HR) is conducted in cooperation with Italy as part of the dual civil/military program Orfeo. *© CNES/Mira Productions/PAROT Rémy, 2012*

Fig. 2: Artist's view of satellite Spot 5, the last of the Spot observation satellites which have been closely monitoring the Earth since 1986. This satellite demonstrates a continuous improvement of the Spot series by providing three-meter resolution images. It is able to take stereo-pair images simultaneously from the same orbit to map relief. The French government decided to initiate the Spot 5 program in October 1994 to ensure the continuity of the civil Earth observation service beyond 2000. Spot 5 was launched during the night of May 3 to 4, 2002, from the Kourou spaceport in French Guiana, by an Ariane 4 launcher. *© CNES/ill./DUCROS David, 2002*

Fig. 3: Map of the horizontal displacement caused by the 7.7-magnitude earthquake (Pakistan, 2013), made from the correlation of Spot-5 images acquired before and after the earthquake (2.5 m resolution and ~ 20 cm detection threshold in displacement). The close-up shows a transfer zone between two fault segments below which is the slip distribution of each segment, showing a perfect slip transfer between the two faults. Based on [3].

Fig. 4: The multi-temporal deformation field of the Achoma landslide (Southern Peru) obtained via the correlation of three PLEIADES images (taken in 2013). The deformation field covers respectively 25 days (left) and 105 days (right). Based on [4].

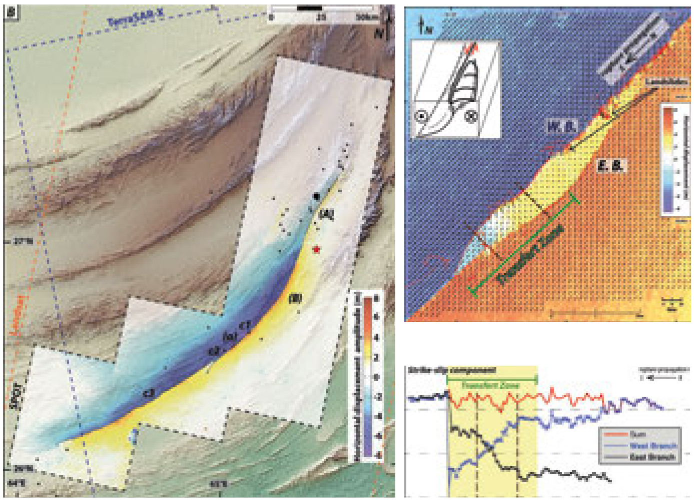

Fig.3

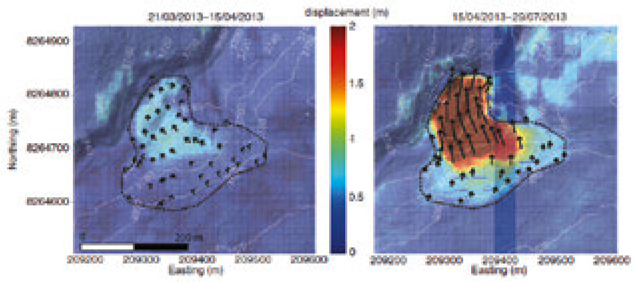

Fig.4

images acquired before and after the earthquake enabled to obtain sub-metric details about the coseismic distribution according to the fault geometry and to quantify the proportion of distributed deformation associated with the main earthquake fault. Although this deformation was often visible on the ground, it had so far remained difficult to assess, for lack of appropriate measurement methods. This measure is yet a major concern for the seismic risk community as it contributes to the definition of the safety area when it comes to building large infrastructures at risk. Moreover, reduced revisit times of the SPOT and PLEIADES constellations and the development of correlation with images from different platforms may enable more systematic monitoring of specific areas, or near-real time calculations of ground deformation and/or displacement maps, which could be used in crisis management in the event of major natural disasters.

Gravitational instabilities

The PLEIADES satellites can provide images of small objects. Thanks to their agility and "on request" acquisition, these satellites are essential to the characterization, mapping and monitoring of gravitational instabilities. These maps enable landslide inventories, especially after intense rainfalls or earthquakes [4]. Figure 4 shows that these inventories are very useful to better understand and quantify the forcing factors which impact gravitational dynamics.

Furthermore, the combined use of high-resolution DTMs and high-resolution deformation fields enables to accurately characterize landslides and to solve their structural complexities. Then comes the inversion of 3D deformation data in order to provide geometry images of the subsurface and volumes involved in slow-moving landslides.

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