11.3 Observations of planetary surface deformations

A. Context and state of the art

The lithosphere, superficial and rigid envelop of terrestrial planets, can be affected by deformations. Those deformations, elastic, brittle or ductile, respond to large movements affecting the planetary surfaces at different time scales. Beside the presence of liquid water, a fundamental difference between the Earth and the other telluric planets is that for the first, the lithosphere is divided into mobile plates continuously recycled in the mantle, and that the seconds never developed plate tectonics: a single spherical and rigid shell shapes the Moon, Mars, Venus and Mercury, preserving their geological history on their surface. Besides, among the large variety of surface features shown by the icy moons, from *Voyager 2* to *Cassini,* spacecrafts have revealed a stunning Encelade surface with deformation structures shaped by very active ice plates tectonics. The lithosphere thickness, temperature and pressure of the terrestrial planets (see C4PO project 9.2 "Terrestrial planets") and icy moons are also obviously different. In this project, the members of the team propose to focus mostly on the observations of terrestrial planetary deformations, starting from their experience on data collected from a large and increasing amount of satellites orbiting around the Earth.

Observations of the large-scale deformations of the Earth's surface are indeed intensively conducted remotely using satellite imagery and space geodesy. Long-term deformations (mountains building, lithospheric deformations in subduction zones, etc.) and shorter time scale deformations due to earthquakes or external loadings (atmosphere, glaciers, etc.) are the most striking signatures of the geodynamics of the Earth and other terrestrial planets. As a matter of fact, geological processes as mountain building, faulting and rifting (as Valles Marineris on Mars) were observed in optical images from satellites orbiting around Mars and testified of stresses induced by the internal dynamics of the planet. Further understanding of the surface deformation processes relies on obtaining precise satellite geodetic observations.

The members of the team are recognized experts on the processing and analysis of GNSS (Global Navigation Satellite Systems, such as GPS, GLONASS and Galileo) and InSAR (Interferometric Synthetic Aperture Radar) data, and/or expert in geomechanical modeling. Space geodetic tools are of particular interest and efficient to measure surface deformations that are a good proxy of the internal stresses of the planet lithosphere. Thus, observing deformations allows to indirectly access to the related geodynamic processes. Understanding the dynamics of surface deformation processes on Earth will allow defining the future space missions dedicated to the observation of short-term geological processes on Earth and other terrestrial planets.

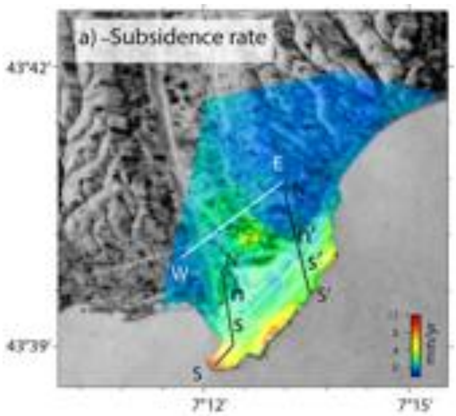
B. Current activity

Observing the planetary surface deformations: use of space geodesy to detect very small deformations

InSAR technique that uses radar (SAR) images is one of the most powerful space geodetic techniques to observe Earth's ground displacements. It can be used to monitor surface deformations due to various processes (e.g. seismic cycle, volcanology, subsidence, ice flow). It provides significant, robust and precise 1-D estimates (along line-of-sight), potentially 3D estimates of the deformation with an unprecedented high spatial density. Most recently, optical image correlation techniques have been developed in the Earth observation community. It has demonstrated to be a potentially great asset for planetary applications by following the sand dunes migrations on Mars from successive optical images acquired by the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (Bridges et al., 2012). On the other side GNSS positioning technique provides direct and precise 3D measurements of the Earth's motions and deformations with time scales ranging from seconds to a decade. GNSS systems are increasing with new global or regional systems (e.g. European Galileo should be 50 to 70% operational end of 2016) that complete the current American GPS, Russian GLONASS and Chinese Beidou systems. However, this technique lack of spatial resolution (continuous but punctual measurements) and is difficult to achieve in the near future on other planets than Earth. We thus propose to focus on the development of the InSAR and optical correlation methodologies and processing to observe planetary surface deformations and to complete these data with GNSS data, for the Earth case, when the added value is high.

SAR images are acquired by illuminating the ground with electromagnetic waves in the microwave range and by collecting the reflected signal. SAR Interferograms are generated by differentiating the phase of two SAR images acquired at different times. Optical image correlation involves sub-pixel correlation between two co-registered optical satellite images and is achieved through free software packages such as COSI-Corr (Co-registration of Optically Sensed Images and correlation – Leprince et al., 2007) and IGN's MicMac. In active tectonics, this technique has been developed recently (Michel & Avouac 2002) to address the phase decorrelation which occur close to fault ruptures with InSAR measurements. It is also a technique currently used to observe glacier displacements and landslide.

As an illustration of our recent progress in InSAR processing, we have conducted the measurement of the subsidence of the Var delta (South of France). The Var river is the main stream of the French Riviera. At its estuary level, the international airport of Nice Côte d'Azur has been built on reclaimed land from the sea. This infrastructure is permanent concern since part of airport extension collapsed in the sea in 1979. By carefully processing SAR images from *Envisat* satellite over this area, we



managed to measure the subsidence of the whole delta at a rate ranging from less than 1 mm/yr upstream to more than 10 mm/yr on the airport platform (Cavalié et al., 2015).

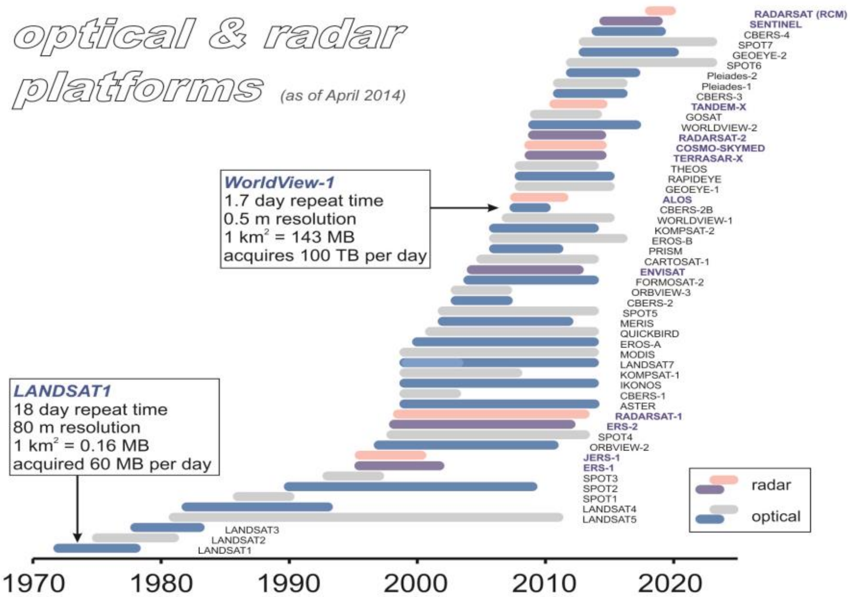
C. Future steps

Loadings

Understanding how the planet deforms following variations of masses at the surface and how masses are redistributed incite us to investigate the Earth's rheology. The observed surface deformation indeed depends mostly on mantle rheology and viscosity. Several studies used the icecap thaw after the last ice age as superficial load variations. Members of the team investigate the glacial isostatic adjustment subsequent to Pleistocene and little ice age deglaciations as well as the current mass changes of glaciers and ice sheets. They develop models to describe these mass redistributions in order to explain observations of ground motion and gravity variations. The post glacial rebound analysis are concurring toward a high viscosity in the mantle and long relaxation time (> 5000 years) for areas located on cold cratons (Canadian or Scandinavian) (Breuer et al. 1995 ; Memin et al., 2013). The specific rheologies of cratons (old, stable and thick part of the continental lithosphere) are also our best analogs for the contemporary lithospheres of other terrestrial planets, resulting from a stagnant lid convection regime. We will first confront our models to the lithospheric loading by the Martian CO_2 ice cap in order to invert for the mantle viscosity and compare the results to the litterature (e.g. Johnson et al., 2000). In a second step, we will investigate the effects of atmospheric pressure loadings on the Venusian lithosphere using atmospheric general circulation models (GCM).

Earth observation data, methodological developments

A compilation of public and commercially available optical and InSAR satellites shows the increasing amount of data. The repeat times, data quantity and resolution are increasing exponentially, with no real provision for how to deal with such data quantities. These datasets offer huge potential for the scientific community.



At the current centimetric level of precision on orbit determinations, the strongest limitation on precision on the positions and dynamic displacements measurements using space geodetic techniques as GPS and InSAR is due to the atmosphere. Indeed the atmospheric disturbances affect the radar signal while traveling from the satellite to the ground and back. Thus we propose to focus on improving the modelling of the propagation of radio waves through the Earth's atmosphere (the ionosphere and the troposphere). Several techniques have been developed now to overcome this limitation and when atmospheric corrections are properly applied, InSAR is able to measure deformation rates with a sub-millimetric precision. In the perspective of future planetary SAR missions such as the preselected NASA Discovery Mission VERITAS, we propose to compute tropospheric phase delays under the form of troposphere correction maps in order to estimate the impact of the troposphere of Venus, a planet surrounded by a dense and windy atmosphere. This topic will be addressed in close relation with the C4PO projects 9.2 "Terrestrial planets" and 9.4 "Orbital and rotational dynamics as constraints on planetary bodies".

We also envision further data processing methods that will make use of natural permanent scatterers relying on studying pixels that remain coherent over a sequence of interferograms. On Earth, the technique would be useful in areas where coherence is lost due to the growth of vegetation. We propose to test scenarios where passive reflectors would be installed on the surface of other terrestrial planets in order to better correct from the atmosphere contributions.

Finally we will prepare science cases by conducting geomechanical modeling of the lithosphere response to loadings and to seismic/aseismic rupture processes. This will be also useful to assess if the internal stress can be released seismically or aseismically in an icy satellite like Enceladus or a hot planet like Venus.

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D. International collaborations

- University of Tasmania and Australian National University (GNSS data processing and analysis)
- Jet Propulsion Laboratory (Passive reflectors for InSAR monitoring of planetary tectonic activity)

E. List of people involved in the project

Lucie Rolland (40% ETP), Olivier Cavalié (50%), Riad Hassani (10%), Anthony Mémin (50% TBC) and Mathilde Vergnolle (10%) with PhD student Mathilde Marchandon.

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F. Most significant publications of the team

Cavalié, O., M.-P. Doin, C. Lasserre, and P. Briole (2007), Ground motion measurement in the Lake Mead area, Nevada, by differential synthetic aperture radar interferometry time series analysis: Probing the lithosphere rheological structure, *J. Geophys. Res.*, **112**, B03403 (2007).

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I. Short CV of participants

L. Rolland (CNAP Associate Professor, Géoazur) specializes in natural hazards monitoring using space geodesy (e.g. GNSS precise positioning and ionospheric sounding). She is scientific collaborator of the NASA *Insight* mission to Mars, co-PI of the ISSI team *Understanding Solid Earth/Ocean-Ionosphere coupling* and chair of the IAG study group on ionosphere/atmosphere coupling. She has published 17 referred publications.

O. Cavalié (UNS Associate Professor, Géoazur) is an InSAR specialist aiming at measuring subcentimetric deformation over large areas. He is an active member of the national InSAR working group organized within the Form@ter national CNES-INSU data pole. During the last past years, he has focused on three main thematics : 1) methodology to improve InSAR accuracy, 2) the seismic cycle, and 3) surface mass movement.

R. Hassani (UNS Professor, Géoazur) is a specialist in geodynamic modeling and develops numerical thermo-mechanical models based on finite-element modeling. He has particularly worked on the Coulomb coefficient of friction in elasticity problem and has developed a physics-based model that allows modeling the earthquake cycle and postseismic deformation. Head of the Earth Science department at the University of Nice.

A. Mémin (UNS Associate Professor, Géoazur) is expert in using space-based geodetic observations to understand the spatio-temporal Earth's response to geophysical processes. Co-chair of the IAG-IERS joint working group on modelling environmental loading effects for Reference Frame realizations, 8 referred publications.

M. Vergnolle (CNRS Researcher, Géoazur) specializes in seismic cycle, in particular transient processes, and Earth lithosphere rheology. She is an expert in GPS geodesy and numerical modeling. PI of the E-POST Young Researcher ANR project (2015-2019). She is in charge of the Geodesy Observatory for Tectonics at Géoazur and a former coordinator for the space geodesy expertise of the French post-seismic intervention cell (2009-2016). She has published 22 referred publications.