

Fiber-Optic Gyroscope for 6-component planetary seismology

F. Guattari^a, E. de Toldi^a, R.F. Garcia^b, D. Mimoun^b and the PIONEERS Team

^aiXblue, 34 rue de la Croix de Fer, F78100, Saint-Germain-en-Laye, France

^bISAE-SUPAERO, Université de Toulouse, 10 Avenue Edouard Belin, F31400 Toulouse France

ABSTRACT

Planetary seismology is a key technique for imaging the internal structure of planetary objects. It targets some of the most fundamental science objectives, from the formation of planetary systems to the characterization of habitable worlds. However, standard methods suffer from various limitations inherent to planetary missions, first one being that a single station is much easier to settle than an array.

Taking benefit of the latest developments in so-called “rotational seismology”, it appears that a single instrument able to monitor both translations and rotations of planetary surfaces would be a game changer in planetary seismology. Indeed, in addition to perform both seismology and global rotational monitoring of the planetary object, the measurement of 6 Degrees of Freedom (DoF) brings a significantly increased scientific return compared to classical 3-DoF sensors.

Hence, to enter a new realm of planetary exploration with an innovative ground motion instrumentation concept relying on high precision sensors based on optical interferometry, a project named PIONEERS has been submitted (April 2018) and accepted (July 2018) by European Commission through its H2020 program.

Under the leadership of ISAE-SUPAERO, gathering IPGP, ETH-Z, Royal Observatory of Belgium, LMU and iXblue, the PIONEERS team aims to develop two innovative 6-Dof instruments for measuring ground deformation on planetary objects.

The first instrument is a prototype of very low noise 6-Dof sensor dedicated to the imaging of the internal structure of terrestrial planets. The second one is a high TRL CubeSat version of the same instrument concept for exploration of small bodies.

Keywords: planetology, gyroscope, rotation, seismology, PIONEERS, FOG

1. INTRODUCTION

This ICSO paper has been submitted between submission and approval of PIONEERS project. It means that the definition of this H2020 proposal was at the origin of this paper, and since its approval, ascertaining the relevance of its objectives, the scope and possibilities of corresponding work have been upgraded. It explains first some changes compared to initial abstract, and second that all participants to PIONEERS project are not official co-authors of this paper while they will be an integral part of work to be done. We acknowledge the contribution of the key personnel of the PIONEERS team here under, as follows:

Institut de Physique du Globe de Paris	IPGP	France	Philippe Lognonné Sébastien de Raucourt
ETH Zurich	ETHZ	Switzerland	Domenico Giardini Cedric Schmelzbach Simon Stähler Luigi Ferrailoli
Royal Observatory of Belgium	ROB	Belgium	Ozgur Karatekin Birgit Ritter
Ludwig-Maximilians-University	LMU	Germany	Heiner Igel Joachim Wassermann Felix Bernauer
iXblue	IXBLUE	France	Saloomeh Shariati Jean-Jacques Bonnefois

1.1 PIONEERS Project executive summary

PIONEERS will allow Europe to enter a new realm of planetary exploration with an innovative ground motion instrumentation concept relying on high precision sensors based on optical interferometry.

Willing to keep the European leadership in planetary seismology and high precision measurements of ground deformations, we will develop two innovative 6 degrees of freedom (6-Dof, with 3 translations and 3 rotations) instruments for measuring ground deformation on planetary objects. The first instrument is a prototype of very low noise 6-Dof sensor dedicated to internal structure imaging of terrestrial planets. The second one is a high TRL CubeSat version of the same instrument concept for exploration of small bodies.

For single to sparse networks, 6-Dof measurements provide substantially more science return compared to classic 3-Dof measurements. Only currently emerging for terrestrial applications, 6-Dof measurements target fundamental science objectives from the formation of planetary systems to the characterization of habitable worlds, and will support planetary defense and asteroid resources applications.

Instruments will be designed based on scientific requirements, and re-using planetary seismology expertise and space qualified, high performance optical technologies provided by the PIONEERS partners. The science case of 6-Dof planetary exploration will be demonstrated through simulations, application of innovative data analysis methods, and testing in Earth analogue and laboratory environments.

An improvement of instrument noise of two orders of magnitude is expected for the planetary prototype by using optical sensing technologies. Cost optimization, ITAR free strategy and adaptation to CubeSat standards will drive other technological developments that will open new markets for high precision scientific instrumentation.

Instruments developed by our consortium members are demonstrating their leadership this year (SEIS on board INSIGHT, blueSeis commercial rotational seismometer release, ROMY laser interferometer). It is the right time to keep European leadership by innovating both on instrument concept and technology.

1.2 Scientific aims

The discovery of many extra-solar planets by recent astronomical observations is constantly raising the question of habitability of these new worlds. The crucial role of planetary internal structure and dynamics on the long-term evolution of planetary atmospheres is now clearly established ([13] Gillman, 2013). However, despite decades of orbital observations of solar system planetary objects, their internal structure is poorly known. Solar system planetary scientists cannot even explain why Venus and Mars, which are close to solar system “habitable zone”, evolved so differently from the Earth. Consequently, they cannot extrapolate their results to constrain exo-planet habitability.

The situation is similar for small bodies, which are remnants of solar system formation mechanism. Whereas the knowledge of the internal structure of asteroids would help to understand the accretion of planets and their volatile budget, many different internal structure models are still competing: rubber pile, fine grained, monolithic (Asphaug et al., 2002). For the Earth-crossing small bodies, most of the mitigation strategies depend on the internal structure of the asteroids ([3] Belton, 2004).

In addition, the search of life habitats in the icy worlds of our solar system requires to image the internal structure of these objects. Mapping of liquid water distribution and thermal and pressure conditions inside these bodies are keys to understand where life may have appeared ([43] Vance et al., 2018).

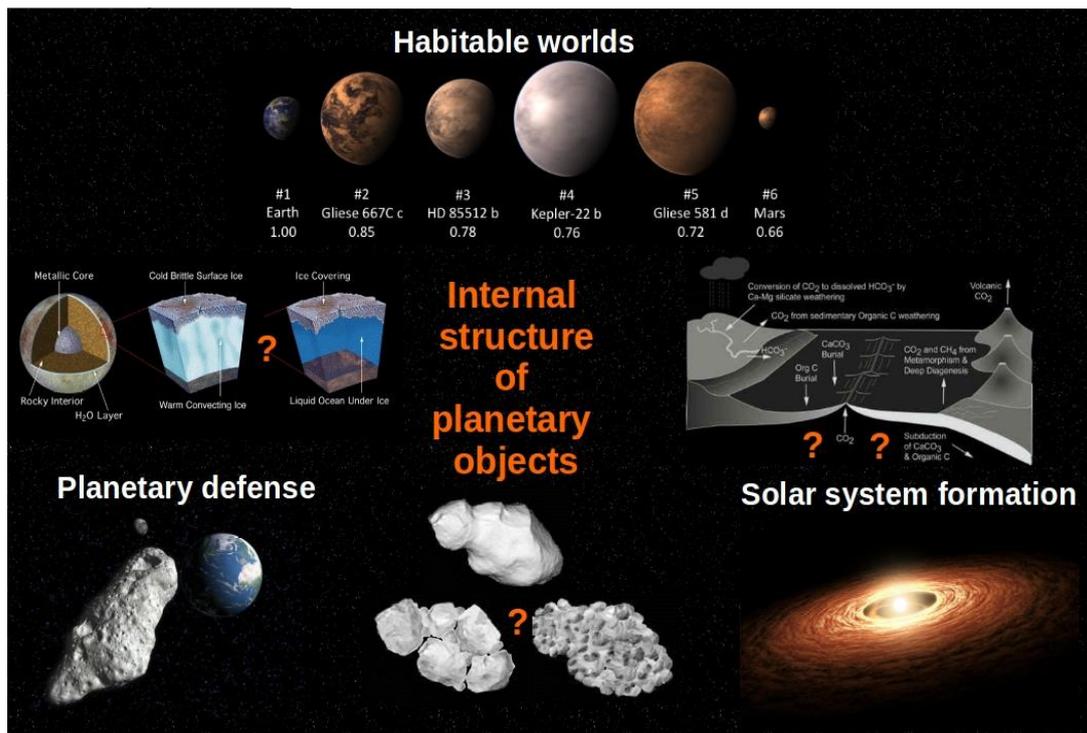


Figure 1 : The knowledge of the internal structure of planetary objects is the key to solve various science questions, from the habitability of planets to the formation of solar-like systems, but it is also crucial for asteroid threat mitigation.

- On top, comparison of various Earth-like exo-planet models to Earth and Mars.
- In the middle, on the left, various models of internal structure presenting or not a liquid water ocean and CO₂ trapping by plate tectonic. As on Earth, they are key parameters for habitability.
- In the bottom, from left to right, artist view of near-Earth object threat, various internal structure models of asteroids and artist view of solar system formation mechanism.

As a consequence of these outstanding scientific questions (**Figure 1**), investigations of the internal structure of planetary objects has become a high priority for space agencies. A first step in this direction has been performed by NASA through the InSight mission to Mars. The main goal of this mission is to understand the formation and evolution of terrestrial planets through investigation of the interior structure and processes of Mars.

The main scientific instrument of this mission (SEIS) is a highly sensitive seismometer led by a European consortium, with US contributions. This recognized European leadership in planetary seismology must therefore be kept to allow European laboratories and industries to participate in future planetary internal structure exploration missions, from ESA in the framework of the Moon Village efforts, but also from NASA (e.g. NF Lunar Geophysical Network), JAXA (e.g. SELENE-R) and CSA (e.g. post Chang's missions). As pointed above, these planetary targets are of a high scientific interest, from telluric planets through icy worlds and small bodies. Consequently, the potential market for instruments sounding the planetary internal structure is huge. However, in order to keep and reinforce the European leadership in this field, innovative solutions must be developed and validated.

The members of PIONEERS already developed, tested and validated the first broadband planetary seismometer for 40 years (SEIS instrument on board INSIGHT NASA mission) but also the first ever portable broadband rotational seismometer for Earth applications (see **Figure 2**). While SEIS instrument will send back its first data from Mars by the end of this year ([23] Lognonné & Pike, 2015, [28] Mimoun et al., 2017), blueSeis instrument (from iXblue) will continue to demonstrate the interest of 6-Dof seismology for Earth applications ([5] Bernauer, 2009, [4] Bernauer, 2018; [39] Schmelzbach, 2018).

The timing is therefore perfect to keep the European leadership in planetary seismology by developing the next generation of planetary seismometers that will go far beyond existing instruments, and allow a breakthrough in planetary

sciences by opening a new science field based on a 6 Degrees of Freedom (DoF) instrument concept, substantially increasing the science return compared to classic instrumentation concepts. The main innovations that will be developed through this project are to combine rotation and translation measurements, and to improve the performance of planetary seismometers by 2 orders of magnitude. This will be enabled by the use of optical technology in which Europe has a leadership position.



Figure 2 : **State-of-the-art seismological instruments developed by consortium members.**

From left to right, SEIS VBB sensors and sphere (IPGP), SEIS electronics box (ETHZ) and first commercial instrument for seismological rotations (blueSeis, iXblue)

The scientific need to image internal structure of planetary objects depends strongly on the object's size and surface environment conditions. The geophysical signals targeted by the instruments developed in this project are described in *Figure 3*. However, two types of missions/experiments are usually envisioned for such investigations.

First, long duration passive seismology relies on weak natural seismic sources. For such a mission profile, typical instruments should have a high sensitivity, a large bandwidth, a very low noise, a low power consumption and additional sensors to correct for environment disturbances on the sensor. This is the science case of SEIS instrument on-board INSIGHT Mars mission. This sensor is monitoring only translations of the ground whereas the Mars environment is expected to induce significant rotational noise projected into translation measurements. The noise level of SEIS is currently close to the lower limit of what can be obtained. To go further, an improved science return requires including rotation sensors: to correct for atmospheric perturbations on planets with atmosphere, to improve the imaging capability of a single instrument deployment ([39] Schmelzbach, 2018) and to open the way to a continuous monitoring of planetary rotation.

A second type of seismic experiments on planetary surfaces relies on short duration active source seismology. For such experiments, a seismic source is artificially produced in such a way that seismic signals have a high amplitude and a broad frequency content, but sounding depths are limited. For such a case, typical instruments should be compact (to save mass for the source creation), require a low power (to be able to run on battery capacity) and should provide the capability to extract as much information as possible from the recorded data. This was the science case of Apollo active seismic experiment including a small seismic array and explosive sources deployed by astronauts. This experiment allowed the imaging of the first kilometers of the Lunar Moon subsurface ([44] Watkins and Kovach, 1972). To go further, an improved science return requires to record rotations, in addition to translations, in order to obtain a science return similar to the one of a seismic array while avoiding its complicated deployments ([40] Sollberger et al., 2016). The reason is that single point 6-Dof measurements are capable of returning information equivalent to small seismic arrays. In addition, the continuous monitoring of planetary object rotation is particularly relevant for small bodies having rotations presenting fast rates and complex features ([35] Pravec et al., 2002). It would also allow to infer the internal structure through moments of inertia, global rotation dynamics or response to tides.

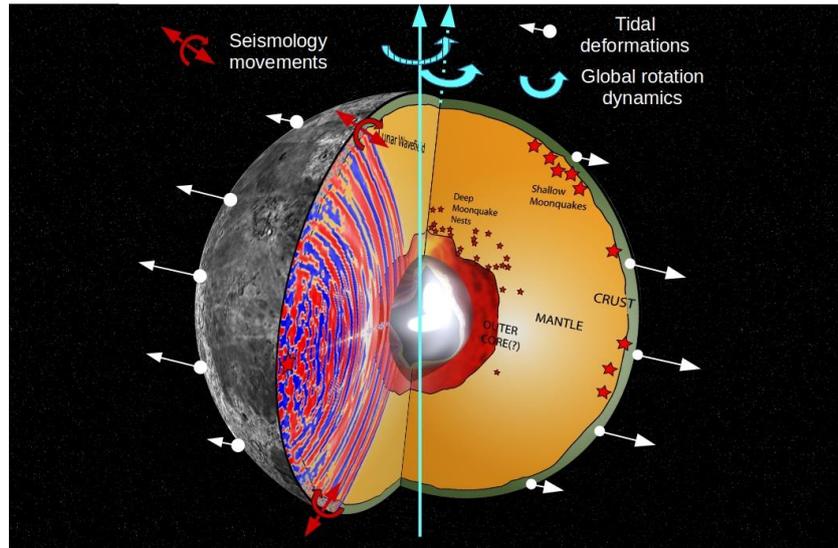


Figure 3 : Deformation/rotation signals potentially recorded by a 6-Dof instrument deployed on the surface of a planetary object. The amplitude, phase, arrival times and polarization of these signals strongly depend on the internal elastic properties of the object, thus allowing an inverse imaging of its internal structure. Illustrated here for the Moon, and adapted from an image produced by Michael Thorne showing the seismic wave field emitted by a shallow moon quake, the internal structure of the Moon and Moonquakes locations.

The development of such innovative scientific instruments for planetary sciences is performed by a consortium involving research laboratories and medium size company because it requires long term investments from space agencies to fund prototyping and R&D activities in the laboratories, and because the market is limited by the number of planetary missions selected.

An important part of the innovation brought by this project is to take benefit of the very last improvements in seismology. The first of them is the 6 Degrees of Freedom (DoF) seismology which demonstrates the significant increased science return of a single station recording the 3-Dof rotations in addition to the usual 3 components of translation ([17] Igel et al., 2015, [41] Sollberger et al., 2017). The second one is the use of state-of-the-art optical instrumentation for both rotation and translation sensors to reach outstanding performances thanks to European leadership in this domain ([4] Bernauer et al, 2018).

1.3 Outcomes of the PIONEERS project

The project will provide various outcomes necessary for the selection of an instrument as payload of a planetary mission:

- Science requirements, including environment noise analysis, for the translation and rotation measurements of various physical processes in different planetary deployment conditions
- Planetary Seismology breadboard: A (TRL 4/5) of high performance 6-Dof instrument for planetary seismology
 - A prototype (TRL 4/5) of high precision accelerometer sensor based on optical interferometry for very high-resolution translation measurements in the seismic frequency range
 - A prototype (TRL 4/5) of very low noise fiber-optic rotational sensor, based on fiber-optic gyroscope (FOG) technology
- Small bodies geophysics PFM: A (TRL 6/7) 6-Dof compact instrument at CubeSat format for small bodies geophysics

- A compact TRL (6/7) fiber optic rotational sensor
- MEMS accelerometers
- High performance electronic board for FOG rotation measurements, shared by the two instruments in different versions (EM and PFM), to demonstrate performance scalability with the size of FOG sensing fiber-coils
- Data analysis methods specifically designed for a combined 6-Dof rotation/translation sensor
- High performance instrument testing facility and Earth analogue field testing

The hardware developments are summarized in *Figure 4*. The same electronic board will be used by the two instruments for both fiber optic rotational sensors.

These achievements will allow our consortium to compete for future space mission opportunities at international level.

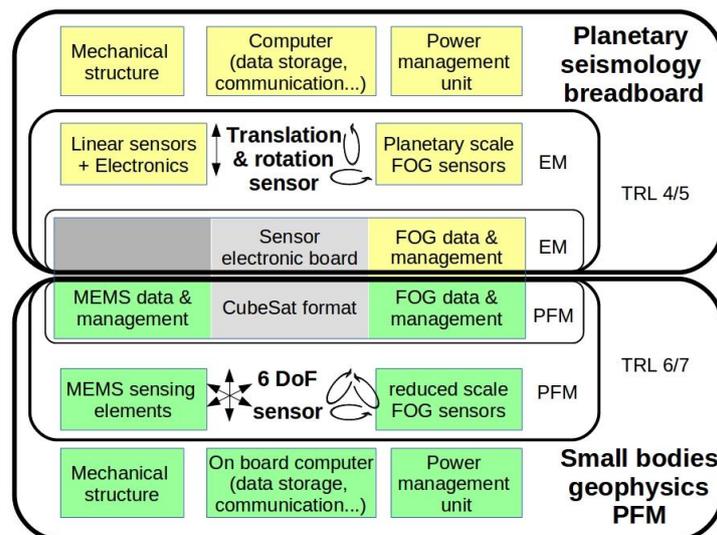


Figure 4 : Main outcomes of the project

Sub-system descriptions of electronic board, sensor and instrument models developed during the project. Two different models (EM and PFM) of the same electronic board will be associated to different sensing elements to form two different instruments. Green = TRL 6/7 (PFM), Yellow = TRL4/5 (EM) expected at the end of the project.

It was important to give an exhaustive overview of what is the PIONEERS project as an introduction because it allows to understand specific development on Fiber-Optic Gyroscope that will be described in more details in next chapters.

2. FIBER-OPTIC GYROSCOPE PLANETOLOGY BENEFITS

2.1 6 Degree of Freedom as a key for innovative planetary measurements

2.1.1 From plurality of sensors to a single one

Imaging the deep internal structure of planetary objects relies mainly on standard seismology method. This method suffers from various limitations inherent to planetary missions. The main one is that instrument deployments on the surface of planets are usually limited to a single unit. That's why a single instrument will be developed to monitor both translations and rotations of planetary surfaces that would allow one to perform both seismology and global rotational monitoring of the planetary object. For seismology, the recent development of commercial rotation sensors has demonstrated that adding rotation sensors to the usual translation seismometers allows one to access additional wavefield characteristics and sub-surface seismic properties ([17] Igel, 2015, [41] Sollberger, 2017, [4] Bernauer 2018).

Such a 6-Dof sensor would be very innovative because combined 6-Dof measurements by the same instrument are not even available on Earth.

2.1.2 A direct access to the planetary object rotation parameters

There are various ways to measure the global rotation of planets : from the orbit of planetary spacecrafts sounding variations of planet gravity field ([1] Banerdt et al., 2014; [6] Dehant and Van Hoolst, 2014) length-of-day of Mars has been determined from orbiter at the 10% level, see [20] Konopliv et al., 2016, for the exact values), from analysis of pictures taken by imaging instruments on board of planetary spacecrafts, and from Doppler effects on radio link between the Earth and transceivers deployed on the planetary surfaces (also at the 10% level, [21] Kuchynka et al., 2014, except for the precession). These methods are combined to retrieve global rotational dynamics (length of day, nutations, precessions) of planetary objects but often suffer from discontinuous observations and biases due to observation sampling specific to each method.

The rotation sensor targeted in this project being based on the Sagnac effect, it is directly sensing the rotation of the planetary object without requiring orbit or attitude reconstructions.

2.1.3 6-Dof seismology latest developments

LMU (= Ludwig Maximilian University of Munich) seismology department has been focusing on development of 6-Dof instrumentation concepts for Earth ground motion observations for over 15 years. It includes the development and further adaptation of large ring lasers for seismological purposes leading to the first >4 DoF processing schemes and a seismic event data base of thousands of earthquakes. In terms of observational infrastructure regarding high-resolution rotation measurements, it is fair to say the LMU is currently the world leader. The new ROMY ring laser provides multicomponent rotation observations at extremely high resolution, senses the ocean generated noise (and probably soon free oscillations) and can thus provide a reference for other portable sensors to be developed in this project (Hand, E., The lord of the rings, News feature, Science, 20. April, 2017).

Classically, seismometers record ground displacement along three orthogonal axes. However, the deformation of the ground due to seismic waves also includes rotational motion ([39] Schmelzbach et al. 2018). If both translational and rotational motions are recorded (ideally 3-Dof of translation and 3-Dof of rotation amounting to 6-Dof), a more complete representation of the ground deformation is possible. It allows, for example, an improved wavefield characterisation, wavefield separation ([41] Sollberger et al., 2018; [42] Van Renterghem et al., 2018), and improved study of the sources and subsurface structure. The inverse theory for structure and source was extended to include rotational ground motions and could show theoretically that single 6-Dof stations allow the recovery of subsurface structure below the receiver ([5] Bernauer et al., 2009). They also showed that additional rotational observations improve the resolution of earthquakes source properties ([17] Igel et al., 2015). Furthermore, rotational motion at the Earth's surface is directly related to the spatial gradient of the wavefield, a quantity that would otherwise only be measurable with (large) arrays of seismic stations. In addition, as rotational noise contaminates translational measurements, rotational-motion measurements can significantly improve the data quality of poorly coupled stations such as often encountered with ocean-bottom sensors ([22] Lindner et al. 2017), but also applicable to planetary cases.

The figure below summarises applications where 6DoF computation creates special and innovative insight.

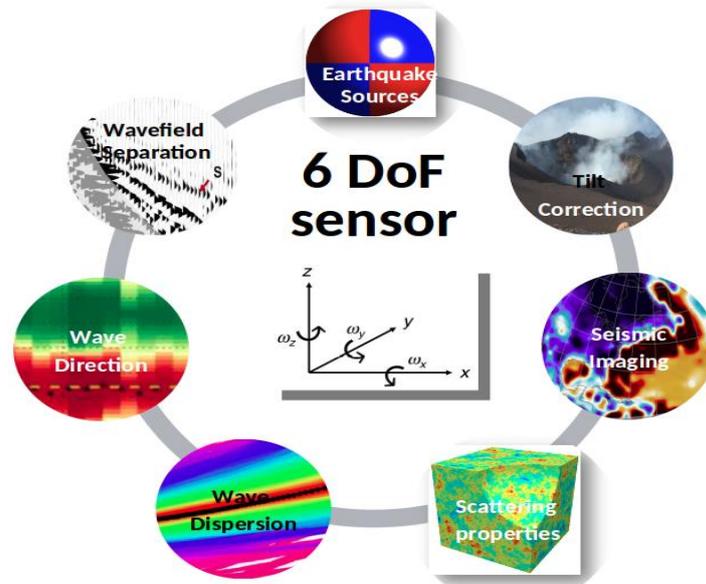


Figure 5: Illustration of application domains of 6-Dof (3 translations + 3 rotations) ground motion observations:

- Remove the ambiguity of tilt vs. translation, highly relevant for environmental signals.
- Allow recovery of local velocity information through dispersion observations (tomography)
- Allow separation of seismic phases (e.g., P and S waves), and direct observation of their partitioning (scattering properties)
- Improve the recovery of seismic source properties and gives better access to propagation directions (source location)
- Provide a point measurement equivalent to a small classic array of 3-Dof seismometers (see references).

2.1.4 State of the art of rotation measurement performance compared to expected signal

The development of a planetary rotational sensor is opening the way to a new type of planetary data. First the rotations felt by the sensor will include the rotation of the planet itself thus paving the way to the continuous monitoring of its global dynamics which is another way to constrain its internal structure. This direction could be followed because the fiber-optic gyroscopes developed in this project present a very low bias (much below the usual rotation rate of planetary objects) and an improved noise level at low frequencies. If the measurements of the rotations can by itself constrain the seismic wave field, the main improvement brought relies in the simultaneous measurements of the 6-Dof (translation and rotation). Such combination is only possible since very recently on Earth, it has demonstrated that it gives a direct access to the mechanical properties of the sub-surface below the instrument. It also allows one to easily separate different seismic wave types arriving at the same time after a seismic event, thus improving greatly the imaging and event location capabilities of a single sensor. This point is critical for planetary exploration because the planetary missions usually offer the capability to deploy a single instrument. Finally, for planets with atmosphere a large part of the seismic noise is induced by pressure variations generating ground rotations that can be corrected by using rotation measurements.

2.2 FOG solution definition to build an efficient 6DoF planetary instrument

Following what was described above, the innovation of this project lays on designing beyond state-of-the-art solutions for planetary seismology instrumentation fulfilling the most stringent scientific requirements. Here, we detail more on how the optical technology enable us to go beyond the state-of-the-art on rotational seismology sensors.

No rotational sensor is currently available for planetary seismology, but a commercial version of this type of instrument was made available by iXblue for Earth sciences just one year ago, initiated by a collaboration with the ROMY project (ERC funded). The performances of the only available sensor on the market (blueSeis) present a noise level of $2E-8$ rad/s/sqrt(Hz) in the 0.01-50 Hz frequency range. However, its mass (20 kg) and power consumption (15 W) are far

away from planetary standards, but it is a good starting point for the project to build a FOG solution adequate to planetology needs. Next chapters will enter in details on how and why FOG could do it efficiently.

2.2.1 SWAP parameter (Size, Weight and Power)

An important limitation in planetology is related to the overall budgets of mass, volume and power. Through its scalability FOG technology is able to adapt to various kind of mission, but spatial electronic boards currently used in satellite navigation are not compliant with requirements of planetology. That's why we will define a specific task on the FOG electronics to reduce its size and power down to planetary instrument standards.

2.2.2 Vibration hardened

Another technological issue from planetary missions is the ability of such precise sensors to resist to the strong vibrations levels experienced at lift-off and landing. FOG technology have already demonstrated to be able to resist to high vibration levels during previous space missions, thus excluding this major failure risk.

2.2.3 Absolute measurement

A major asset of FOG is its ability to perform absolute measurement of rotation rate. The benefit of this particular feature is shown mostly in planetary broadband seismology: while studying in detail the design of the SEIS InSight seismometer, the variations of the instrument tilt while installed on the Mars ground ([28] Mimoun et al., 2017, [29][30]Murdoch et al., 2017) was quite high. This tilt was generated by various external sources, as the wind or the atmospheric pressure variations. On InSight this has been solved by adding wind and pressure measurements, as well as developing processing methods to take into account these contributions. The absolute rotation provided by the fiber optic rotational sensor will help to mitigate this error, without having to deploy additional instruments which make the system far more complex and expensive.

2.2.4 Not an inertial sensor

Another key point of FOG technology is that the measurement of the rotation is made through Sagnac relativistic effect involving photons, which are massless particles. Practically, it allows FOG rotational seismometer to be an instrument without any moving part, and intrinsically not sensitive to inertia, which makes its sensitivity to linear motion almost null (only limited by conversion of translation into rotation through mechanical flexion, which is easy to avoid at seismic frequencies).

2.2.5 Scalability

Scale factor of a FOG, and thus its sensitivity, is directly linked to the enclosed area of the coil. Enclosed area is the product of number of loops and the area of one loop. So, given the fact that there is finite optimum fiber length for a given fiber attenuation, the only way to increase the sensitivity (through scale factor improvement) is to increase the diameter of the coil.

Standard navigation products using FOG or RLG (=Ring Laser Gyroscope) have typical diameters from 50mm up to 200mm. Pushing the boundaries of performance, the size increases up to 12meters for last tetrahedral Giant-RLG of ROMY project led by LMU. Following this path, iXblue is conducting an internal project named Giant-FOG to investigate the limit of FOG performance using a transportable instrument. Figure 7 presents the road-map of this project, showing already done and to-be-done mockups, compared to other attempts to reach very high performance in rotation measurements.

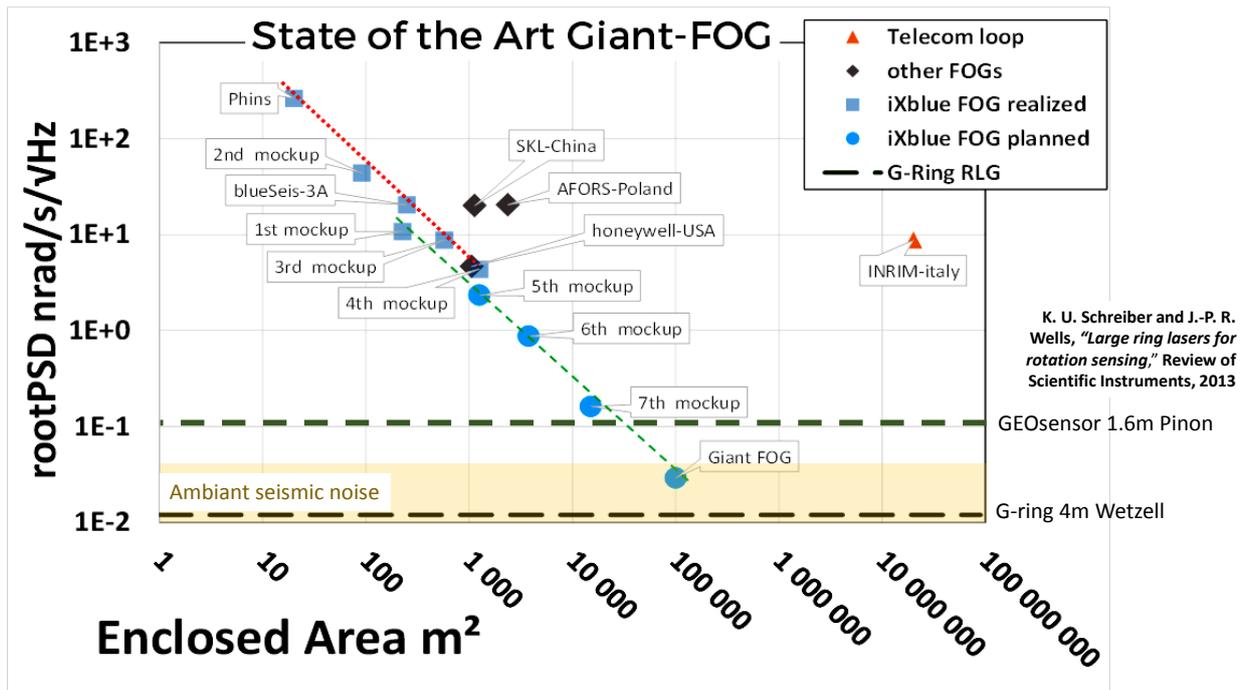


Figure 7: Giant-FOG road-map showing the natural decrease of self-noise with the increase of enclosed Area. iXblue is already paving the road to reach 0.1 nrad/s/√Hz with its 7th mockup, which will be the most sensitive transportable rotational sensor ever.

The 7th mockup will be the last mockup before Giant-FOG, and consequently it will exhibit the better performance achieved with a transportable instrument. So, it will be the model to design the PIONEERS planetary seismology model with a targeted performance of 10-10 rad/s/√Hz for a metric scale coil.

2.2.6 Comparison with other space-proven rotational technologies

The table below allows to understand how this sensor will compare to existing technology available to measure rotation in outer space. Indeed, there are 3 COTS spatial technologies available today, RLG suffering from vibration needed to avoid blind zone which makes it useless for seismology and degrade its self-noise, HRG (=Hemispheric Resonator Gyroscope) with interesting potential in terms of noise, but strongly limited by its power consumption, and its poor scalability, and FOG offering the lowest power consumption for the lowest self-noise, with an unbeatable scalability to reach higher performances.

	Honeywell	Northrop	iXblue/Airbus		PIONEERS project	
	<i>MIMU</i>	<i>SIRU</i>	<i>ASTRIX 120</i>	<i>ASTRIX 200</i>	<i>EM planetary</i>	<i>PFM cubeSat</i>
Gyro technology	RLG	HRG	FOG	FOG	FOG	FOG
Architecture	2x3 axes	4 gyros axis cross strapped with 2 electronic	4 independent gyro channels	4 independent gyro channels	3 independent gyro channels	3 independent gyro channels
Geometrical configuration	3 perpendicular axes	Tetrahedron	Tetrahedron	Tetrahedron	3 parrallel axes	3 perpendicular axes
Sensor diameter	~150mm	~50mm	~120mm	~200mm	45mm 200mm >1000mm	~45mm
Mass	9.4 Kg	7 Kg	6 Kg	10 Kg	TBD	< 2 Kg
Power consumption	32 W	45 W	18 W	18 W	<10 W	< 10 W
Solid state	No = vibrations to avoid blind zone)	Yes	Yes	Yes	Yes	Yes
root DSP in nrad/s/√Hz	720	30	330	20	<20 ~0.1	<1000

Figure 8: State-of-the-art of rotational sensors. FOG technology presents the lowest power consumption for the better self-noise, with a scalability allowing very high performances meeting planetary seismology needs.

3. EXPECTED IMPACT

3.1 Scientific return

Our project will define instrument requirements for various planetary deployments and science cases. However, instrument development will be performed for two main application cases: terrestrial planets seismology (Moon being the reference object) and small bodies geophysics (asteroids with size < 30 km being the reference objects).

The science objectives of the planetary seismology breadboard EM are related to the investigation of the deep structure of the planetary object, from monitoring of small quakes and background noise, to fundamental physics analysis through very low noise broadband linear seismological sensors. Other objectives are related to shallow surface investigations and to environment monitoring through rotations measurements by fiber optics rotational sensors. The instrument will be defined and implemented up to TRL 4/5. More details are given further in the document.

The science objectives of the small bodies' geophysics PFM will be entirely related to the internal structure imaging through active seismic experiments, analysis of global rotation dynamics and instrument/object mechanical interactions (e.g., rebounds) allowed by rotation and translation measurements. The instrument will be designed and implemented up to TRL 6/7.

The instrument development will target all the technological challenges of planetary instruments. The improvement of instrument noise level by two orders of magnitude is expected by using innovative sensing methods based on optical interferometry sensors. The cost improvement is expected by re-using already space qualified technologies and through an industrial partner (iXblue) already developing state-of-the-art space and Earth instruments from component to commercial models. A specific ITAR free strategy will be implemented to allow our consortium to propose the instruments at international level for collaborations between EU space agencies and all space/planetary access providers.

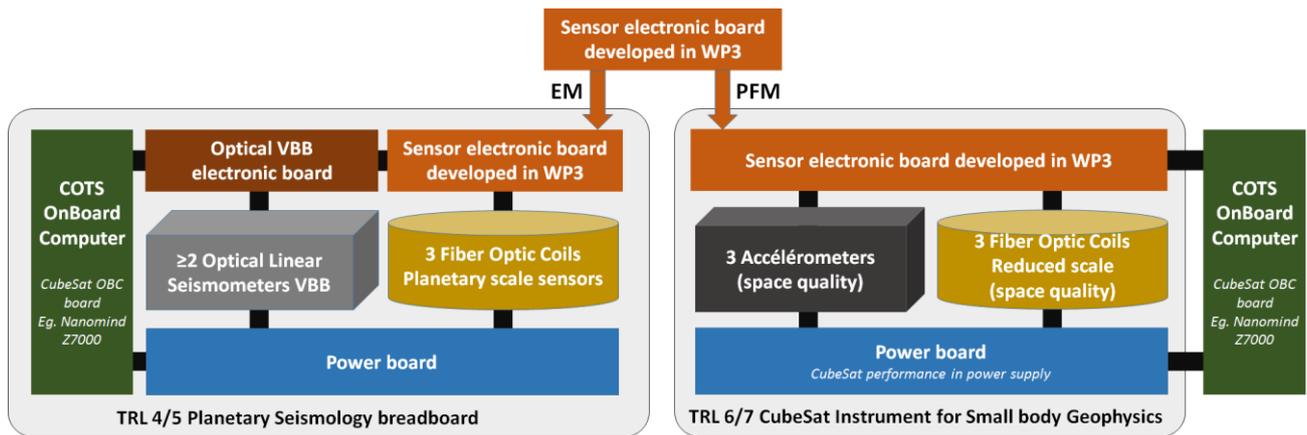


Figure 9 : Outlines of the planetary seismology breadboard (EM, TRL4/5) on the left, and the small bodies geophysics (PFM, TRL 6/7) on the right, sharing the same sensor board at different development stages

The scientific achievements expected from the deployments of the instruments designed in this project are depending on the planetary target.

For terrestrial planets, the improvement of noise level of translation measurements will allow to measure planetary deformations by tides, normal modes of vibrations and seismic surface waves. These low frequency signals can be inverted to retrieve the whole planetary structure and circumvent the single instrument limitation ([24] Lognonné, 2005; [38] Rivoldini et al., 2011; [33] Panning et al., 2015). At high frequency, the improvement will allow to measure the background seismic noise and to estimate micro-meteorite flux ([26] Lognonne et al., 2009) or atmosphere/solid interactions ([25] Lognonné et al., 2016) depending on the planetary target. The improvement of noise and bias of rotation measurements will allow to measure the global rotation dynamics of the planet which is particularly efficient at inferring internal density structure stratification ([7] Dehant and Mathews, 2015) and fluid layers (liquid core, ocean under ice shell ([8] Dehant et al., 2017). This case may apply to Mars and icy moons. Another signal target will be the rotations induced by seismic waves, with imaging capabilities complementary to seismometers ([17] Igel et al., 2015). Finally the combination of translation and rotation measurements will allow to correct for atmospheric effects that generate large tilt noise on horizontal linear sensors ([31] Murdoch et al., 2017, [22] Linder et al., 2016), allowing to detect low amplitude signals.

For small bodies, their internal structure is known only through their average density, and no previous seismic experiment was attempted on such objects. The precise measurement of their rotation dynamics will allow to infer the moments of inertia of these objects, as a first estimate of internal mass distribution, and to validate models of orbit/rotation interactions (YORP and Yarkovsky effects) which are critical for predicting orbits of NEO. The MEMS accelerometers will allow the measurement of high frequency seismic waves generated by artificial impacts ([11] Garcia et al., 2015, [31] Murdoch et al., 2017). The analysis of these signals can be inverted to infer ground mechanical properties below the station and level of heterogeneity inside the object ([37] Richardson, 2005). Finally, the combination of translation and rotation measurements can also be used to precise estimate trajectory of lander and rebounds in order to infer local gravity variations and mechanical properties of the ground ([30] Murdoch et al., 2017).

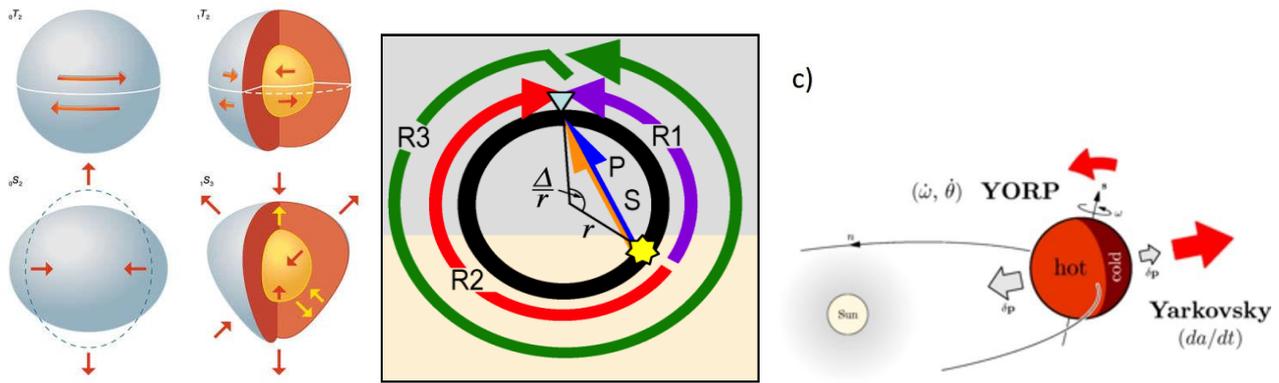


Figure 10 : From left to right;

- illustration of planetary deformations under toroidal and spheroidal normal modes of vibration
- principle of single station location of quakes by using seismic surface waves 'Rx' and 'P/S' body waves
- illustration of YORP and Yarkovsky effects which are critical to determine NEO orbits

The technical developments will directly impact the emerging field of 6-Dof Earth seismology. These new sensors are currently demonstrating that they can bring a lot to the society thanks to a better understanding of various aspects of natural hazard like volcanoes and earthquakes or even tsunamis ([17] Igel et al., 2015, [36] Reinwald et al., 2016). Some of the aspects of the development (e.g. processing methods or rugged instrumentation concepts) that will be performed should have direct applications for these more terrestrial applications, especially as field tests to better understand our performance level will be carried out.

No one has ever developed or designed a 6-Dof ground motion sensor for space. It is even on Earth an entirely new concept.

In addition to these deliveries, the project will allow to form young professionals (engineers and doctors) to these innovative technology developments in order to support the development of the related European industry. The need of young people is due to the long development times of planetary missions.

Finally, this project will open new markets to iXblue company industrial partners and various European sub-contractors in space (and Earth) instrumentation.

3.2 Market evolution

3.2.1 Space exploration

Several Space agencies are considering to possibly select and then launch missions with science goals requesting 3-Dof or 6-Dof planetary seismometers. On the Moon, the first one is NASA, which has listed the Lunar Geophysical Network mission as one of the candidate for the next AO of the New Frontier Program. LGN will compete for NF5, with an AO targeted in 2021-22 and for a 1 billion USD budget, including launch. LGN is the continuation of previous proposals or project, including the Lunette Discovery mission proposal which integrated several PIONEERS partners together with JPL and Notre Dame University as well as the International Lunar Network (ILN). The second opportunity is the Chinese post-Chang'e Lunar program, which is expected to send after Chang'e 6 three additional landing missions to the Moon in the 2020-2030 period and possibly to put the first base of an International Moon Base or Village, possibly in collaboration with ESA. Note that the Chinese Space Agency contacted several PIONEERS team members for a possible delivery of a Lunar VBB in the frame of the Chang'e 4 mission. This flight opportunity was however declined due to funding and programmatic conflict with NASA InSight mission. Both the NASA and CSA opportunities might be targeted toward passive seismology with science goals related to the lunar core and deep interior. The third lunar opportunity might be the SLIM polar lander of JAXA targeted toward resources detection near the pole, and for which active seismic investigation might be considered ([18] Kawamura et al., 2017), enabling the use of 6-Dof PIONEERS hardware.

Regarding small bodies and asteroids, several PIONEERS team members contributed to the BASIX Discovery proposal led by Boulder University aiming to perform active seismology on asteroid Didymos, or performed the concept study

AGEX also targeting Dydimos but in the frame of the ESA AIM project ([16] Hamilton et al., 2016). New opportunities exist in proposed ESA mission study Hera ([27] Michel et al 2017), and in M5 missions (in selection process) if the mission includes a cubesat and/or lander. Additional opportunities will appear in the frame of the future Discovery Missions AOs and/or international collaboration (China and Japan planning mission to small bodies). The 6-Dof instrument will be very well suited to the context of low gravity seismic measurements as well as active seismic experiments.

3.2.2 Earth seismology

The world renewal market of standard translational seismometers is >100M€, mainly shared by 4 companies: Nanometrics (Canada), Guralp (Great Britain), Kinematics (USA), and Trimble (USA). It is a mature market, where innovations are mainly linked to “ease of use” rather than to performances. It is due to the fact that thanks to decades of continuous improvements, these sensors already beat the low-noise model on Earth.

FOG technology is used today for satellite navigation, underwater navigation and positioning (nuclear submarine, remotely operated vehicle = underwater robots), mobile mapping, surface navigation, and quite recently in geoscience thanks to blueSeis product line from iXblue. It has already been pointed out in the document that the future of seismology instrumentation is really to be able to offer the best level of performance in a single instrument offering 6-Dof. That is why iXblue being at the borderline of geosciences instrumentation and optical expertise is willing to move forward with optical translation measurement at the highest grade.

iXblue has already made a first step by offering to seismologist the first low-noise broadband rotational seismometer blueSeis-3A. One can think that in next decades there will be the same number of rotation sensors as the one of standard translation, and probably in a single instrument, as in navigation application where it is pure obviousness to have 6-Dof in a single box.

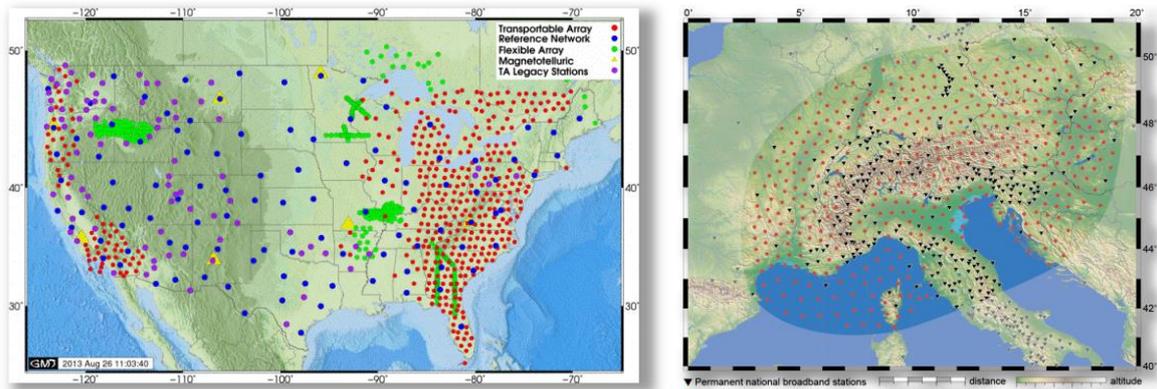


Figure 11 : From left to right, US and Alp Array of standard seismometer. Blue dots are permanent 3-Dof stations, and red dots are temporary 3-Dof stations. Each station total cost (labor+setup+equipment) is ~30k€. These networks may be enhanced by a smaller number of 6C nodes surrounded by 3C stations.

3.3 Environmental and social impacts

The imaging of Near Earth Objects internal structure is a key to ensure planetary defence against this threat. Our instrument may allow to reveal the internal structure of asteroids with enough precision to ensure that mitigation methods can be properly simulated, as well as to understand the interaction of objects landing at the surface of asteroids.

Our knowledge of the internal structure of asteroids is, so far, indirect – relying entirely on inferences from remote sensing observations of the surface, and theoretical modelling. What are the properties of the regolith and deep interior? And what are the physical processes that shape their internal structures? In the former case, what is the size distribution of constituent blocks, and the spatial distribution of voids?

Physical and dynamical properties of an asteroid such as the mass, rotation state and surface strength are necessary improve our ability to understand and model the mechanisms driving NEO deflection and other risk mitigation techniques.

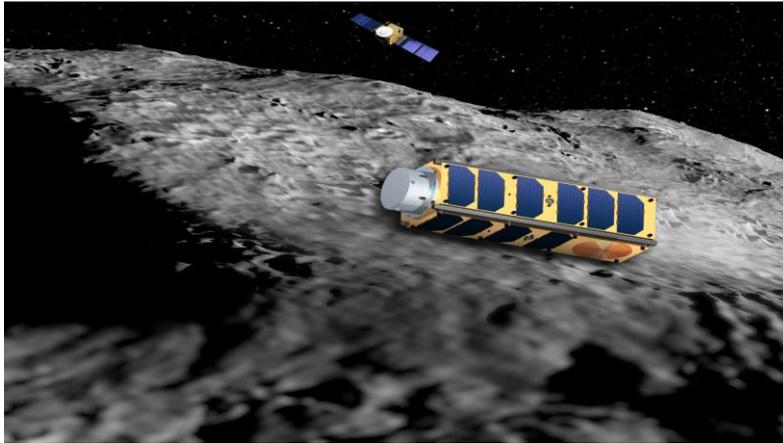


Figure 12: Artist view of a CubeSat implementing the PFM payload landed on an asteroid.

The uniqueness of the proposed concept is that it may be the first of its kind to utilize the Interplanetary CubeSats for in-situ measurements from the surface of a small solar system body

In addition, the capability of our instruments to determine the sub-surface mechanical properties is of great interest for planetary resources exploitation of asteroids and human settlement on the Moon surface. The rebound of the Rosetta spacecraft on the target comet illustrates perfectly the difficulty of mechanical interaction with the surface of a low gravity asteroid.

The overall number of positions that could be created and/or maintained in case of the selection of the instrument for a mission could be up to 100, across all the structures concerned by the development of the instrument.

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