A MARTIAN AND LUNAR VERY BROAD BAND SEISMOMETER

S.Tillier[(1)], S. de Raucourt[(1)], P. Lognonné[(1)], T. Nébut[(1)], O.Robert[(1)], T.Gabsi[(1)], B.Lecomte[(1)], O.Pot[(1)], J. Gagnepain-Beyneix[(1)], D.Mimoun[(2)]

[(1)]PRES Paris-Cité, Institut de Physique du Globe de Paris, Planetary and Space Geophysics, Paris – FRANCE, Email: tillier@ipgp.fr
[(2)]DEOS, ISAE, Toulouse – FRANCE

ABSTRACT

The very broad band seismometer (VBB) is a seismic sensor being developed by the Institut de Physique du Globe de Paris (IPGP) in France, under the founding of CNES, the French national space agency.
It is part of a planetary seismometer being developed by an international consortium, which is currently a unit of the core payload for the Martian project GEMS-2 from JPL (Jet Propulsion Laboratory, USA), but also for the SELENE-2 Japanese Lunar project (ISAS–JAXA).
The VBB development relies on a solid technical heritage of a series of aborted Martian projects. But for the Moon's conditions and environment, some design adaptations and performances enhancement have been required, ultimately leading to a new VBB design.

1. SCIENCE OBJECTIVES

The main goal for planetary seismometers is to study the seismic activity of a planet and the meteorite flux at the planet's surface. These seismic events are characterized by their approximate distance and azimuth, and their magnitude. The seismometer allows for the characterization of shallow and deep interior of the planet, and especially the deep subsurface layering structure, the crustal thickness of the landing site, the core size and the mantle structure.
The power of seismology derives from the enormous amount of information encoded in a seismic signal. The vibrations detected by a seismometer reflect the characteristics of the original source, the geometry of the path taken from the source to the receiver (and thus the structure of the planet) and the physical properties of the material through which it has passed.

The magnitude value of a seism is directly linked to the seismic signal frequency: the higher the magnitude, the lower the frequency. Therefore, the sensor bandwidth is linked to the type of signal to measure. Since one of the scientific goals of a planetary seismometer instrument is to measure deep quakes at low frequencies, a Very Broad Band (VBB) sensor is needed.

1.1. Mars

In order to understand how a telluric planet is geologically evolving, a detailed knowledge of its interior structure, of the mineralogy and temperature of its mantle, of the amount of energy released during accretion (and therefore of the size of the main units of the planet: crust, mantle, core), of the heat flux and possibly of the large-scale convective structure is required. We also need to monitor its present geological activity and have a detailed view of its crust and subsurface.
The level of present seismicity gives a measure of the contemporary level of tectonic and perhaps volcanic activity, both in terms of intensity and geographic distribution. Estimates of seismicity depend on thermal calculations or extrapolation of historical faulting. Thus the measurement of seismicity, regardless of the actual number of events detected, provides fundamental information about Mars' dynamics.
Regarding impacts, the unique characteristics of the seismograms they produce, characterized by a relatively low cutoff frequency, allow them to be differentiated from marsquakes. These seismograms can thus provide a direct measure of the current rate of impacts.

Figure 1 gives an example of a prediction of the seismicity map of Mars that has been determined by the Monte Carlo simulation of seismic activity and releases a cumulated moment of $6x10^{17}$ Nm per year. The epicenter location probability is provided by the density of observable surface faults (Knapmeyer, M., J. Oberst, E. Hauber, M. Waehlisch, C. Deuchler, R. Wagner, 2006).

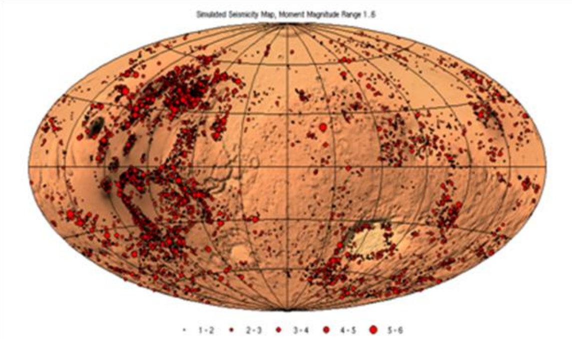

Figure 1 – Seismicity map of Mars

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The working hypothesis is based on the thermo-elastic cooling of the lithosphere, which does not consider any tectonic activity possibly related to volcanoes.

The sensitivity and noise floor of the current seismometers in the expected Martian environment are such that the detection of about 20 quakes with quake magnitude (Ms) from 4 to 5 and 10-20 impacts per Earth's year are expected for a mean model of seismic activity.

1.2. The Moon

While the 381.7 kg of rock and regolith samples returned by the Apollo missions have proven invaluable in advancing our understanding of the Moon, our understanding of the Lunar interior is still rudimentary at best. Some fundamental science questions still remain unanswered: What is the composition and size of the Lunar core? What is the internal structure of the whole Moon? What is the thermal budget of the Moon and how has this impacted its evolution? Did the early Moon have a dynamo and if so, when did it start and when did it stop? These questions do not address only the structure and evolution of the Moon, as the formation of the Moon is probably resulting of a large impact between a Mars-sized planet and the Earth. The size of the Moon's core, the thickness of the crust and the structure of the Lunar mantle are among the few parameters able to constrain this impact and the depth and vigor of the magma ocean that appeared on the young moon, after re-accretion around Earth's orbit. These parameters are therefore crucial to understand how our planet was affected by the impact, from both the energetic and volatile budget point of view, in addition to how a planet like the moon is able to evolve in time.

To answer those questions, the sensitivity and noise floor requirements for a seismometer in the expected Lunar environment have to be about 10 times better than the Apollo Long Period (LP) seismometer in peaked mode.

2. VBB HERITAGE

The Space and Planetary Geophysics (GSP) team from the IPGP (Parisian Earth Sciences Institute) has been working on space seismometers for more than a decade.

2.1. Optimism/Mars96

The first study started in 1993 with a first seismometer named Optimism (See *Figure 2*), which has been on board the Russian Mars96 mission to Mars. Back then, the instrument was a purely vertical seismometer: the sensor's pendulum was in the horizontal position and then could detect vertical ground displacements only. It also included a self leveling mechanism in a very compact design. The mission was launched on September 16th, 1996 on a Proton launcher from Baïkonour, Kazakhstan. Unfortunately the launcher failed during ascent and ended its race into the Pacific Ocean.

Optimism could detect seisms with a ground acceleration resolution up to 10^{-8} $m.s^{-2}$ at the frequency of 1 Hz.

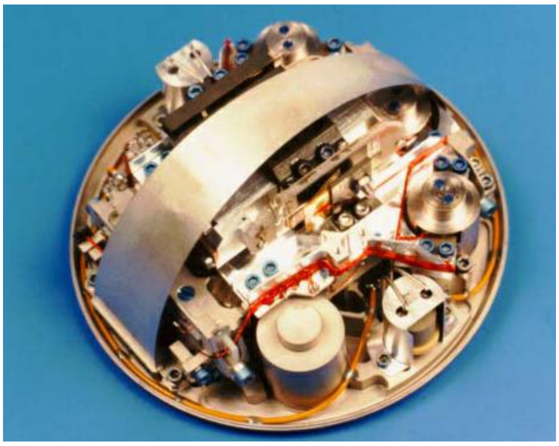

Figure 2 – Optimism version onboard the Mars96 mission

2.2. VBB Mock-up Version #1

In 1996, the seismometer building concept was reconsidered in order to increase the sensor's performances at long periods. A new Very Broad Band (VBB) prototype was designed using the upside down tilted pendulum configuration (see *Figure 3*). This specific position leads to a lower resonant frequency and a higher mechanical gain, thanks to a better use of the mass with the inverted pendulum concept. It leads also to both vertical and horizontal ground movement measurements (which are differentiated using two VBBs face to face). The created prototype resolution could reach 5.10^{-9} $m.s^{-2}$ at the frequency of 1 Hz.

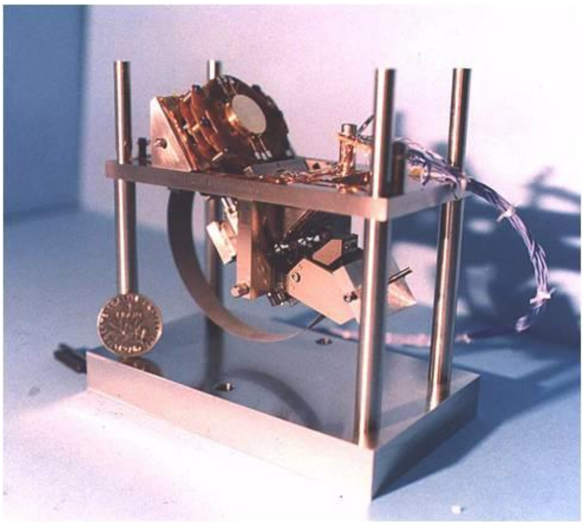

Figure 3 – VBB Mock-up version #1

2.3. VBB Mock-up Version #2

The second version for the Mock-up (see *Figure 4*) was built in 1998. The sensor concept was still similar to version #1 but its resolution was improved: 10^{-9} m.s^{-2} at the frequency of 1 Hz, due to a new capacitive transducer development.

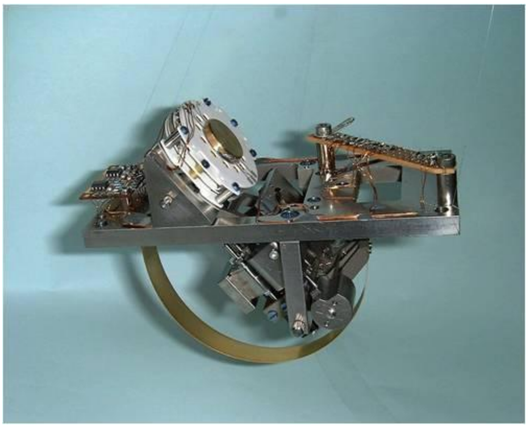

Figure 4 – VBB Mock-up version #2

2.4. NetLander Project

In 2003, the CNES started the NetLander project, which was aiming at deploying a network of seismic stations on Mars. The configuration of the stations' seismometer instrument (SEIS, for Seismic Experiment for Interior Structure) was based on two IPGP VBB axes (derived from the successful Mock-Up prototypes), installed face to face in a vacuum sphere (Figure *6*). This configuration allows for both the vertical and one horizontal measurement in the 0.1 mHz to 10 Hz bandwidth. To complete the 3-axis detection (mainly to be able to get the azimuth of the incoming seismic signal), an additional Broad Band Short Period sensor (10 mHz to 10 Hz) developed by the Imperial College of London (T.Pike) was installed along the second horizontal axis. The complete seismometer sensor resolution was 10^{-10} m.s^{-2} at the frequency of 1 Hz.

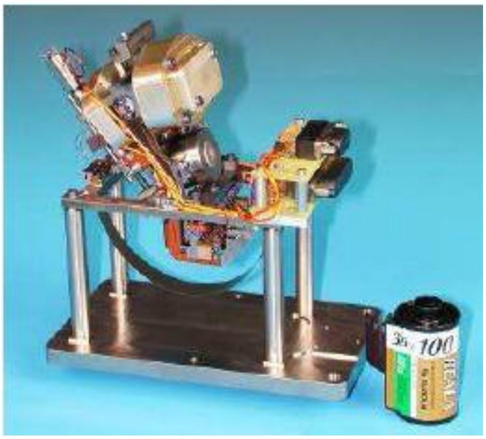

Figure 5 – One of the two Netlander's VBB EMs

Two engineering models (EM) (see *Figure 5* and Figure *6*) and one structural model of the VBB were designed, built and tested for this project, before it was stopped in 2005 due to funding issues. Thanks to NetLander though, the Martian design of the VBB has then reached a very good level of maturity (end of phase B).

Figure 6 – Netlander's EM Sphere with the 2 VBBs

2.5. ExoMars Project

Between 2006 and 2009, for the ESA's ExoMars project, the configuration of the Netlander's SEIS instrument returned, although improvements were made to the VBB sensor design, based on the tests made on the two previously built breadboards. The major modification dealt with the reduction of the sensor's susceptibility to surrounding temperature variations.

Therefore, a mechanical thermal compensating device was developed for the VBB, which principle consists in damping the effects of thermo-mechanical variations coming from the sensor building materials (see Figure *13*).

The development during the ExoMars project allowed the Martian VBB (as well as for associated subsystems of the full SEIS instrument) to reach a technology readiness level (TRL) higher than 5 after a successful ESA ExoMars preliminary design review (PDR) held in 2008. A major step forward was achieved towards the integration of the complete SEIS instrument.

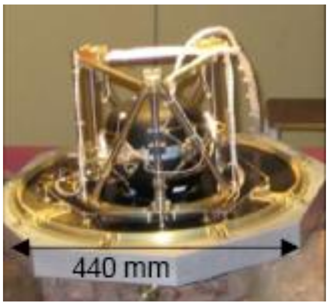

Figure 7 – ExoMars SEISmometer's Integrated Breadboard: The VBBs' Sphere (Black) mounted inside its deployment and leveling system

Figure 8 – ExoMars SEISmometer's Subsystems breadboards:From left to right, lander I/F with launch lock, leveling system, VBB sensor head, VBB sphere integrated in its leveling/deployment system, E-cards of the electronics, E-Box of the electronics

Though, the ExoMars story for the SEIS seismometer and the VBB ended with the large modifications encountered by the mission in 2009.

3. NEW PROJECTS: MARS STILL, AND NOW THE MOON ALSO

3.1. The Marsian Project: GEMS-2 (JPL - NASA)

GEMS-2 is a project proposed by the American JPL (B.Banerdt) for the NASA's DISCOVERY program, which has recently been selected for a phase A study.
It is aiming at deploying a geophysical monitoring station on Mars in the time frame of 2016. The mission makes use of the Phoenix Lander successful heritage by using again the same platform to reach Mars' ground, and deploying a seismometer (the SEIS instrument delivered by CNES/IPGP) and a heat flux and physical property package probe (HP3, delivered by the German DLR) to the soil, thanks to the Phoenix's robotic arm.

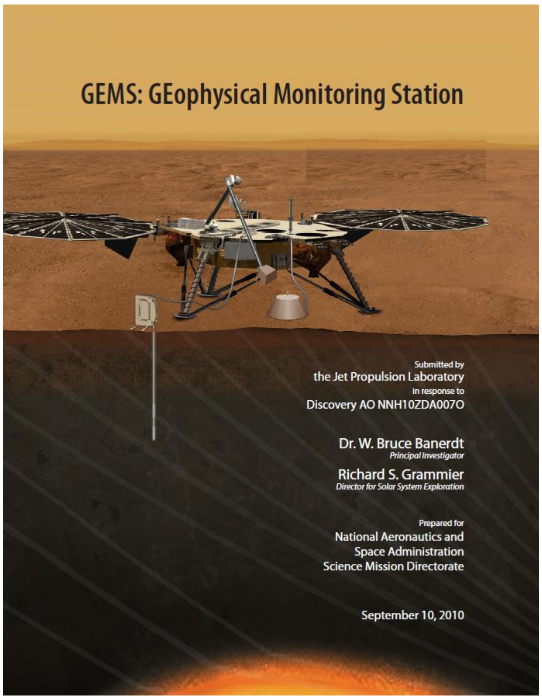

Figure 9 – GEMS-2 proposal front page illustration

The GEMS science goals are simply stated:
1. Understand the formation and evolution of terrestrial planets through investigation of the interior structure and processes of Mars;
2. Determine the present level of tectonic activity and impact flux on Mars.
The GEMS mission is predicated on the ability to retrieve this information from observations at a single location on the surface.
Traditional seismic analysis is based largely on arrival times of body waves acquired by a widely distributed network of stations. But over the past few decades a wide variety of analysis techniques have been developed for extracting information about the properties of the Earth's interior and seismic sources themselves using the data acquired from a single seismometer. The collection of a high-quality broad-band seismic data set for Mars will provide an invaluable resource for the scientific community to apply a wide variety of techniques to learn more about Mars

The long period component of the SEIS instrument for GEMS is based on a full 3-axis VBB configuration.
The VBB resolution requirement is similar to the ExoMars's performances and should be inferior to $1x10^{-9}$ m/s²/sqrt(Hz) @ 0.1 Hz (Figure *10*).

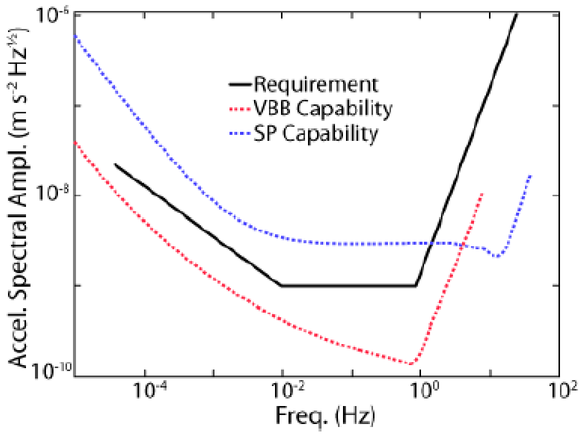

Figure 10 – GEMS-2 Seismometer's noise performance requirement and projections

3.2. The Moon Project: SELENE-2 (ISAS - JAXA)

A Japanese team from ISAS – JAXA is also working on the development of a geophysical mission including a seismometer (S.Tanaka, N.Kobayashi, H.Shiraisi, R.Yamada), but with the Moon as the subject. This project, which started in 2008, is named SELENE-2, and is currently in phase A.
The scientific goal is to determine the internal structure of the whole Moon and more specifically the composition and size of the Lunar core by installing a broadband seismometer on an Apollo landing site, and by direct observation of the initial Moon's crust on sites located by KAGUYA.

The geophysical payload will include the Lunar Broad Band Seismometer (LBBS, a derived version of the SEIS instrument including Japanese short period sensors), a heat flow experiment, a Lunar laser reflector, an EM sounding (mantle and core electrical conductivity), and an inverse VLBI measurement (high precision gravity observation).
The mission is scheduled to be launched by 2018.

Figure 11 – SELENE-2 illustration

As for GEMS, the Moon LBBS is also composed a full configuration of three VBBs, and is expected to have performances about 10 times better than the Apollo Long Period (LP) seismometer in peaked mode.
The VBB resolution has then to be improved by a factor of ten compared to the ExoMars's performances and should be inferior to $2x10^{-11}$m/s²/sqrt(Hz) @ 0.1 Hz, while the instrument is supporting very large temperature variations (several 10s of degrees) compared to those of typical VBB seismometers on Earth.

3.3. Seismometer International Configuration

For both the projects, the complete seismometer instrument (SEIS for GEMS-2, and LBBS for SELENE-2) involve an international consortium. The subsystems configuration is the following (see Figure 12):
• VBB seismic sensors, VBB feedback electronics, Sphere: P. Lognonné, S. DeRaucourt, IPGP, France
• Leveling and Deployment mechanism and electronics: U.Christensen, R.Roll, M.Bierwirth, Max-Planck-Institut für Sonnensystemforschung, Lindau – GERMANY
• Acquisition and Control electronics (AC), Power Convertion electronics (DC/DC) and E-Box system design: D.Giardini, P.Zweifel, D.Mance, Geophysics, ETHZ, Zürich – SWITZERLAND
• Short Period seismic sensors for SELENE-2: N.Kobayashi, H.Shiraisi, R.Yamada, ISAS-JAXA, Tokyo – Japan
• Short Period seismic sensors for GEMS-2: T.Pike, Imperial College, London – United Kingdom

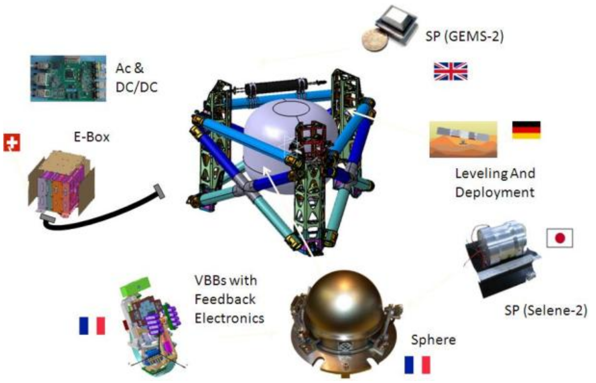

Figure 12 – Seismometer international consortium

• The Sun and thermal shield which protects the sensors platform on the Moon surface for SELENE-2: ISAS – JAXA.
• The Sun, thermal and wind shield which protects the sensors platform on Mars surface for GEMS-2: JPL.

4. A VBB COMPATIBLE WITH MARS AND THE MOON

As the heritage of the VBB is based on purely Martian projects, its design was never considered to be compatible with the Moon.
In order to translate the Martian design of the VBB to the Moon's conditions and environment, it was to be adapted. The two main points impacting the VBB are the different gravity between the two planets and the performance requirement which is higher for Moon science.
In order to reach the scientific goals and raising the performances, two technical axis have been considered: on one hand taking advantage of the maturity of Netlander's and Exomars' developments and studies by achieving the work engaged, and on the other hand testing new enhancements and developments.
Then the design of the VBB has been reworked. The aim has been to integrate the recently tested enhancements and devices to the proven existing design, while having a VBB compatible with both Martian and Lunar missions.

4.1. Reducing The Thermal Sensitivity

During the previous developments, an analytic theoretical noise study of every VBB's subsystems has been realized and corroborated with field experimental measurements.
It appeared that a trade-off between resolution and VBB thermal sensibility was possible. Then, during the ExoMars time, a passive thermal compensating mechanical device has been designed and tested at IPGP (see *Figure 13*), reducing VBB's thermal sensitivity by a significant factor (reducing the Mock-Up sensitivity from 8µm/°C at DCS level, to less than 1µm/°C). It is possible then to improve the resolution consequently if thermal sensitivity is reduced.

The thermal compensating device is a passive self actuating mechanism designed to automatically adjust the center of gravity of the pendulum with respect to ambient temperature variations. Indeed, when the environmental temperature evolves, the built-in materials expand or retracts, which implies a variation in the center of gravity position. This variation affects the balance position of the sensor, which produce unwanted signal in the measurement. So this is the reason why a passive, self-contained mechanism was required, in order to make the balance position of the VBB's pendulum independent of temperature variation.
The device has been designed to take up with a variation of 80 °C/day (at VBB level), and a VBB sensitivity of 10µm/°C.
Breadboards have been built and tested on the VBB Mock-Up, and the mechanism is now integrated to the last VBB design (see *Figure 19*).

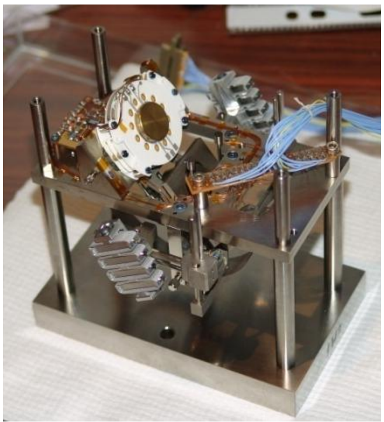

Figure 13 – Thermal compensation device tested on VBB Mock-Up #2

4.2. Improving The Displacement Capacitive Sensor

Efforts have also been made on both the pendulum's mechanical design and the Displacement Capacitive Sensor (DCS).
The DCS geometry and electronic has been improved. By modifying the electrodes' shape and construction, in order to enhance and ease the integration procedure, and then optimizing the gap between the electrodes (100µm), the signal to noise ratio has been improved. A DCS prototype integrating the new electrodes was built and integrated on the two NetLander's EM (see *Figure 14*).
This prototype also includes a selectable electronic either onboard (on the pendulum) or external (beside the pendulum). The aim is to enlighten the role of DCS' power dissipation on the long-term global VBB noise, which is suspected to have a significant impact on the currently recorded performances.

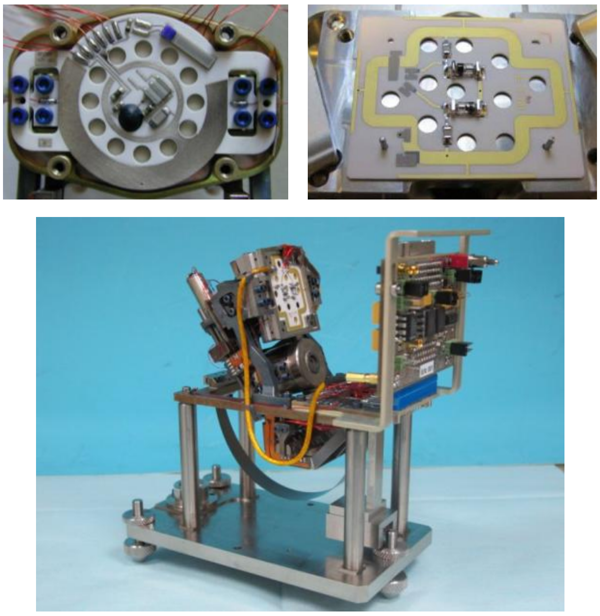

Figure 14 – The old (Top left) and new (Top right) DCS' ceramic electrodes, and one of the two enhanced VBBs' EM integrating the new DCS (bottom)

4.3. Optimizing The Mechanical Gain

Regarding the inverted pendulum principle, theoretical analysis and tests on VBB Mock-Up demonstrate that by optimizing the design, the mechanical gain of the sensor (which definition is the ratio between the pendulum's displacement at DCS level along the Xc direction on *Figure 15* and the corresponding ground acceleration along the same direction) can be improved by a factor of 3 to 5.
Indeed, the inverted pendulum counterbalanced configuration is a balance between positive spring stiffness and negative stiffness due to the instable pendulum involved.
This equilibrium can be tuned. Considering a given spring, the global stiffness of the system can then be set by adjusting the inclination of the pendulum's center of gravity (COG) with respect to the center of rotation (at the pivot) and the vertical direction (see angle "α" on *Figure 15*).

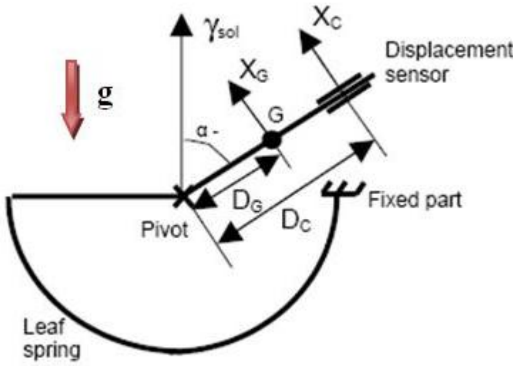

Figure 15 – Inverted Pendulum Principle Schematic

So for a given spring, the pendulum's mechanical gain (and the associated natural frequency) with respect to the inclination of the COG follows the curve depicted on *Figure 16* (and *Figure 17*). The gain rises (and the frequency decreases) when the angle decreases, untill a critical angle where gets instable (arround 33° on *Figure 16* and *Figure 17*).

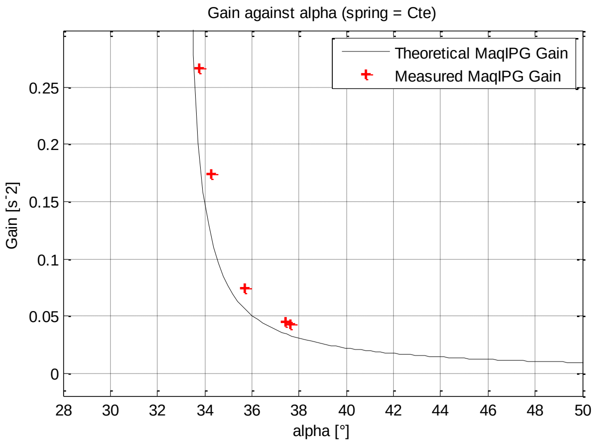

Figure 16 –Theoretical and measured variation of the mechanical gain versus inclination of COG

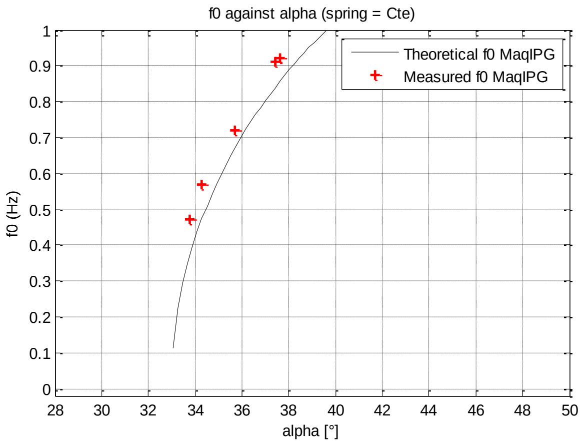

Figure 17 – Theoretical and measured variation of the pendulum's natural oscillating frequency versus inclination of COG

Though it seems very interesting to increase the mechanical gain just by tilting the pendulum, there is a risk and a limit while going closer to the instable point. Indeed, there is latitude in the pendulum's natural frequency once built with respect to the theory, depending on the actual stiffness of the real pivot and the real leaf spring. The latitude is small, but enough though to bring a newly built VBB to instability if not enough margin from the critical point was considered during the design phase.

Then for the new projects, the VBB's pendulum working point has been reconsidered in order to reach a higher gain. Indeed, considering the experience obtained through the past projects regarding the springs and pivot constructions, the safety margin could be reduced. So the new pendulums are now to have a mechanical gain as high as 0.25 $m/m.s^{-2}$ and a natural frequency down to 0.2 Hz (from a former mechanical gain of 0.05 $m/m.s^{-2}$ and a natural frequency of 0.5 Hz on NetLander's and ExoMars' Designs).

4.4. Adapting The VBB's Balance To The Planet

As the VBB uses a pendulum under balance between a spring and a weight, it is highly dependent on gravity, as shown on *Figure 15*.
In order to adjust the mass and the position of the COG of the pendulum to the spring's torque and local gravity, counter masses are used, as see in *Figure 18*.

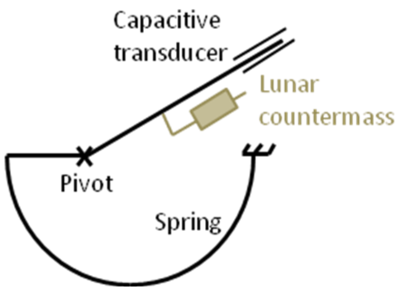

Figure 18 – Counter mass Principle Schematic

The pendulum mass is preliminary configured to work on Mars.
But due to the relatively low gravity on the moon, quite a heavy mass (of the order of 60gramms) has to be added to the pendulum to ensure its balance. Previous versions of the VBB were not compatible with such a charge, and its structures had then to be resized in order to support it during launch and landing's shocks and vibrations.

4.5. The Resulting New Martian/Lunar VBB Design

The reworked design of the VBB *Figure 19* integrates the recently tested enhancements and devices presented above to the proven existing NetLander/Exomars design, while having a VBB compatible with both Martian and Lunar missions.

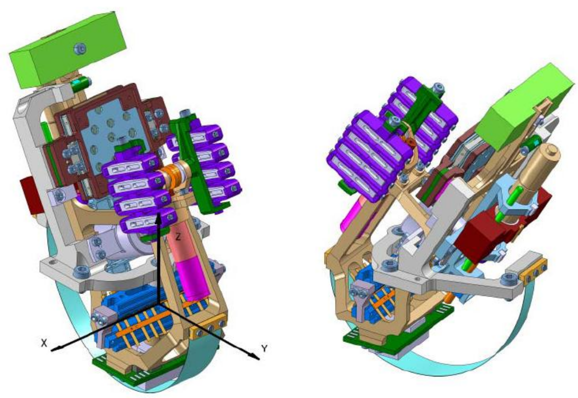

Figure 19 – Selene-2 / GEMS-2 VBB preliminary design, including the Moon counter weight at the top of the pendulum (green part)

This latest development of the IPGP's VBB have been through a preliminary design review process at the beginning of 2011, with an independent review board composed by French experts, and also involving the CNES.
According to the recommendations of the review board, a breadboard of the design is to be built in the coming year. In the prospect of the GEMS-2 project, which in case of final selection decision in 2012 would have a tight schedule, this breadboard will be used to refresh and prepare the building procedures of the VBBs, but also to provide the IPGP with an additional breadboard to further test and qualify the VBB.

5. CONCLUSION

To meet the requirements for the new geophysical missions to Mars and the Moon, the Very Broad Band seismometer developed by IPGP has known several recent evolutions.
Those evolutions build upon the solid heritage obtained through the previous developments achieved since 1993, with the Optimism Martian seismometer, NetLander and ExoMars Martian projects, with which the maturity of the IPGP's VBB has reached an end of phase B readiness level (ESA TRL higher than 5).
Enhancements have been tested and approved with breadboards in order to improve further the noise performances, and have now been integrated to the new design.
The IPGP's VBB design has also now evolved toward a version compatible with both Martian and Lunar projects, with only minor adaptations between the two configurations, which is allowing saving costs as well as qualification and building time.
An engineering model breadboard of this last VBB design is to be built by 2012, and tests are also continuing on the existing breadboards in order to have the readiness level progressing, with full SEISmometer instrument integration and environmental tests under preparation and scheduled by the end of 2011, aiming at reaching a TRL level of 6 by then. This is necessary to meet the GEMS-2 schedule which is planned for a launch in 2016, and also for SELENE-2, which may follow on tightly.