A VERY BROAD BAND 3 AXIS SEISMOMETER TO STUDY INTERNAL STRUCTURE OF MARS

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ABSTRACT

Very Broad Band seismometers are the best instruments for studying internal structure of telluric planets [1]. Development of such instrument dedicated to Mars observation take up a real instrumental challenge. In fact they must be able to :

- detect ground displacement of a few 10 pm in a bandwidth from DC to 20 Hz in the 3 directions,
- have a very low sensitivity to temperature, pressure, gravity…
- be installed automatically on any ground,
- have a low mass (< 2 kg with the installing devices) a low volume and low power consumption (< 1 W),
- resist to landing shock, usually close to 200 g.

Such instrument [2] have been developed by IPGP and INSU, with the industrial collaboration of SODERN, under an R&D contract from CNES. It will be part of each lander of the Netlander mission, which plan to deploy 4 small stations on Martian ground in 2006, to perform a geophysical study of this planet.

1. INTRODUCTION

A seismometer is an instrument which measures the local acceleration variation of the ground where it is installed. Such data contain signals related to the seismic and tidal activity of the planet. Analysis of these data has permitted, this century, a better understanding of the mechanisms involved in the seismic events. At the beginning of the 80's, progresses in seismic instrumentation have permitted the realization of a new kind of seismometer : the Very Broad Band instruments. These sensors like the STS-1 and STS-2, by Streckeisen [3], and the CMG-3, by Guralp [4], are mainly characterized by a high sensitivity (better than 10^{-9} $m.s^{-2}.\sqrt{Hz}$) and two different outputs :

- a velocity one, dedicated to the record of seismic signal issued typically from earthquakes (bandwidth : 360 s or 120 s up to 20 Hz),
- a position or tidal one, dedicated to the record of tidal signals, liquid and solid (bandwidth : DC to 360 s or 120 s).

These seismometers, oftenly used in Very Broad Band seismic network like IRIS for the USA or GEOSCOPE for France, still remain as references in seismic instrumentation. High quality of data provided by such sensors has permitted to establish the first 3D models of our planet, giving us the details of its internal structure.
It is so theoretically possible to use these types of sensors to perform the same analysis for a telluric planet of our solar system.

Mars is the best candidate for such analysis due to the many similitudes existing between this planet and the Earth, and in consequence due to the many missions programmed toward this destination. Our knowledge about this planet will permit a better understanding of origin and future of the solar system telluric planets.
The problem of using VBB terrestrial sensors is :

- they are too heavy (between 25 and 60 kg),
- they are too much power consuming (between 5 and 10 W),
- they are very sensitive to pressure and temperature,
- they are not very robust,
- they need a human presence to be installed…

In that respect, they have no capability to be used in spatial application. Moreover, Martian seismic activity is expected to be 2 or 3 order of magnitude lower than the Earth one, so their sensitivity for such measurement is problematic.

The challenge we are facing is then : doing better with low mass and volume.

2. DESCRIPTION OF THE SENSOR :

A seismometer is usually composed of two subassemblies : a mechanical one and the electronics.

2.1 : The mechanical subassembly :

The mechanical part consists in fact in a pendulum realized using a spring supporting a mobile mass (Fig. 1). Its function is to convert the acceleration applied on it, into a displacement of its mass.

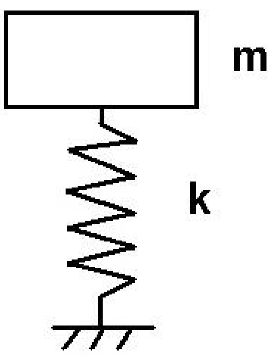


Figure 1 : ***Principe of a vertical seismometer.***

Mathematics equation describing the behavior of such pendulum shows that, in the useful bandwidth : for frequency lower than the resonant frequency, the sensitivity (Eq. 1) is proportional to the mass (*m*) of the mobile part and to the inverse of the spring stiffness (*k*).

$$S_{f<f0} = \frac{m}{k} \qquad \text{Eq. 1}$$

For terrestrial instruments the best way to reach a high mechanical sensitivity (about 10^{-2} s^2) is to use a relatively heavy mass, which imply to use spring with an important size. In fact, springs used are subjected to high deformation loading, which requires important volume. That explains the consequent volume and mass necessary for these sensors.

The concept used in our sensor can be called ‘inverted tilted pendulum’ (Fig. 2).

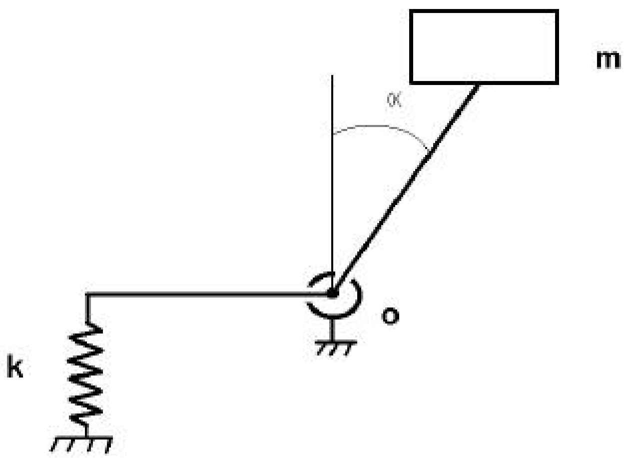


Figure 2 : ***Principe of our ‘inverted tilted pendulum’.***

Such disposition permits a higher sensitivity than usual systems for the same mass and volume. The sensitivity of such device becomes, after simplification, for frequencies lower than the resonant frequency :

$$S_{f<f0} = \frac{I}{k_\theta - M^t \cdot tg(\alpha)} \qquad \text{Eq. 2}$$

In our inverted tilted concept, described now in a cylindrical reference, (*I*) is the moment of inertia, (k_θ) is the rotational stiffness of the spring, (M^t) is the moment of equilibrium and (α) is the tilt of the pendulum. Behavior of this pendulum is very interesting, because we can show than, theoretically, it is possible to have an infinite sensitivity ! In fact the limitation comes from the aptitude to adjust the equilibrium of the pendulum when its frequency is getting close to zero.

On our instrument, the spring used is a leaf spring (thickness close to 0.1 mm) permitting to reach a low stiffness in a low volume.

The rotation of the pendulum is allowed in point O by a leaf-cross pivot. This device is constituted of alloy leafs cross-arranged between 2 rigid parts. Optimization of this system permit to use it as a pivot : fixing one of its rigid part, the other one can describe motion located on a circle arc, for small angles. Leaf elasticity is used : such system permits rotation with very low damping.

On the first mock-up realized, the obtained sensitivity is close to 10^{-3} s^2 with a free frequency close to 1.5 Hz.

Damping in this type of pendulum must be considered as an important point. Friction forces acting directly on the pendulum generate damping. Unfortunately these forces produce heat which induces Brownian noise in the structure around its equilibrium position.

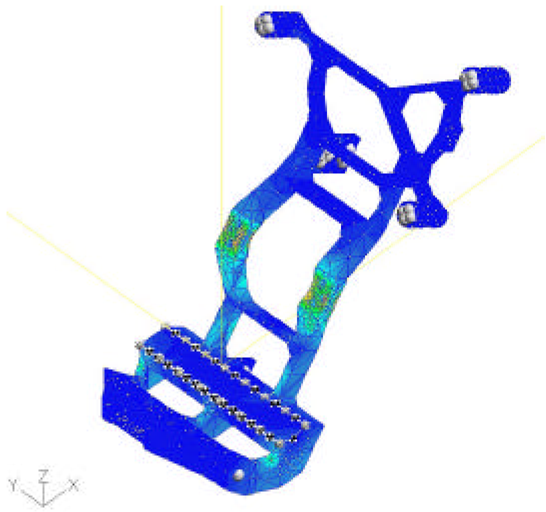
For a vertical seismometer we can show [5] that this noise is, expressed in spectral density of acceleration ($m.s^{-2}.Hz^{-1/2}$), related to the mobile mass (*m*), the free period (*T*) and the quality factor (*Q*) :

$$\Gamma = \sqrt{\frac{10^{-19}}{m \cdot Q \cdot T}} \qquad \text{Eq. 3}$$

This white noise (spectral density constant in the frequency bandwidth) provides the measurement limitation for the instrument. Our scientific objective for Mars is to reach a resolution better than 10^{-10} $m.s^{-2}.Hz^{-1/2}$, which means a (*m.Q.T)* product greater than 10.
For a terrestrial instrument this is generally obtained with a free period close to few seconds, a quality factor lower than 50, and a relatively high mass, between 1 kg and 500 kg.

For our spatial instrument, the constraints are different : with a mass lower than 100 g, we can not reach easily high free periods and, the effort must be mainly done on the quality factor. The technology used for the structure is quite monolithic; technology of assembling is specific to assume low dynamic loss. The spring has been designed to reach a high (*Q)*, looking to the loads applied and to specific heat treatments.
The specific (*Q)* of the pendulum, reached for vacuum close to 10^{-3} mbar is higher than 1000. As the main structure has been designed to offer a minimum of viscous damping in the air, it is still possible to reach (*Q)* value higher than 100 for a vacuum near to 10^{-1} mbar, not so difficult to obtain and maintain.

Thermal properties of the pendulum are an important problem too, when you want to measure displacements close to a few tenth of picometers. Thermal drifts of the structure and thermal variation of mechanical properties produce variation on the equilibrium of the pendulum. Efforts have been made in the materials choice (titanium), in the main strucutre geometry (optimized using finite element software) and in the spring behavior. The thermo-mechanical properties of the spring have been adjusted by heat treatments to compensate the thermal drifts of the mobile aggregate. Such concept permits to reach a thermal sensitivity lower than 0.1 µm/K.



<u>Figure 3 :</u> Main titanium part of the structure optimized to reach high mechanical properties, low viscous damping in the air and low thermal drifts. Dimensions : 7 cm x 3 cm, mass : 12 g.

An equilibrium mechanism has been designed to balance the instrument. Sensors sensitivity used for the displacement measurement of the mobile mass requires to adjust the equilibrium of the pendulum with an accuracy of about 2 µm. This requirement is not so trivial taking into account the fact that our instrument must be able to operate in many areas of Mars, at various altitudes (meaning various gravity's). This function is realized using a micro-motor with a high ratio gear box coupled to a high precision screw on which is mounted a small mass screw nut with take up clearance. The reached positioning accuracy is around 1 µm.

2.2 : The electronics :

The displacement measurement will be done by two independent transducers :

- an Oscillating Cavity Sensor (OCS), producing a digital tidal output (f < 10^{-3} Hz), with a dynamic range of 32 bits;
- a Differential Capacity Sensor (DCS), providing an analogue long period seismic output (10^{-3}–10 Hz), with a dynamic range of 140 dB (with a spectral noise close to 1 pm/$Hz^{1/2}$ at 1 Hz).

Feedback, necessary for a such high (*Q)* and sensitive instrument, is performed with both sensors, in order to reduce the mechanical re-centring and to provide the ideally continuous record necessary for tidal analysis. The OCS contributes to the digital part, to prevent long period drifts, and the DCS contributes to the analogue part, permitting an adjustment of the gain, of the instrument stability and of the resonance peak.

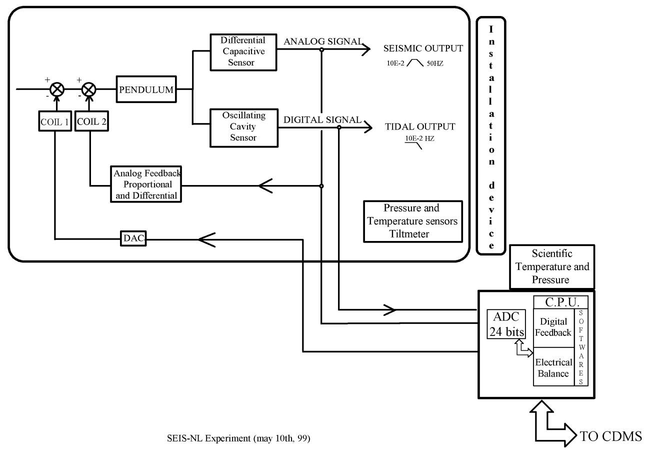


Figure 4 : ***Instrument electrical block diagram.***

Pressure and temperature will be recorded with high resolution (µb and µK) in order to remove their influence on the seismic signal.

2.3 : Mock-up realized :

Three sensors, respecting the concept presented just above, were realized in 1997 with SODERN participation, to obtain a complete three-axis sensor.

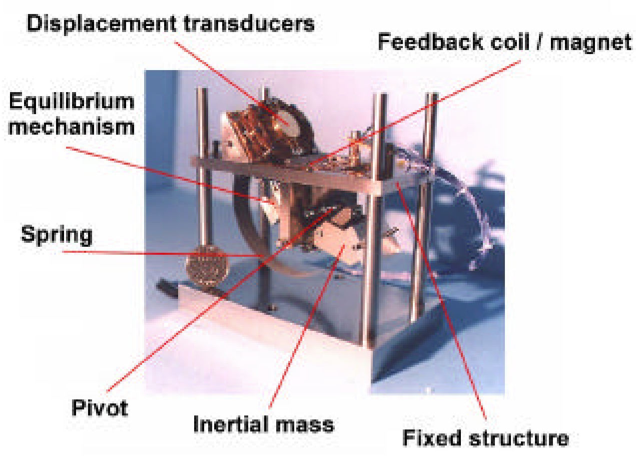


Figure 5 : ***Mock-up of one axis sensor realized in 1997.***

3. FIRST RESULTS :

Tests have been made using the mock-up realized. We have used an STS-2 as a reference terrestrial seismometer.
Results are very encouraging, because this first mock-up shows performances close to the STS-2, with a (*m.Q.T)* product close to 15 (STS-2 value is around 10).

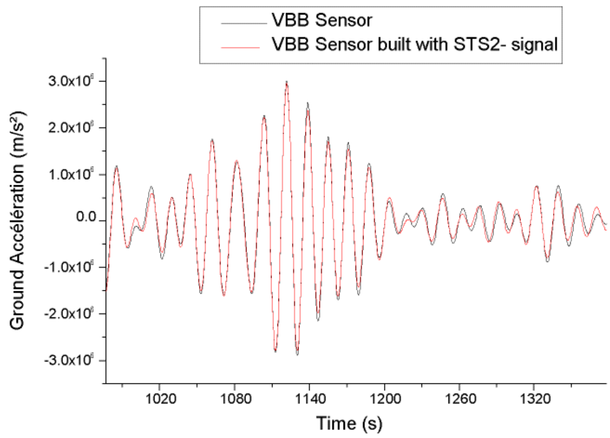


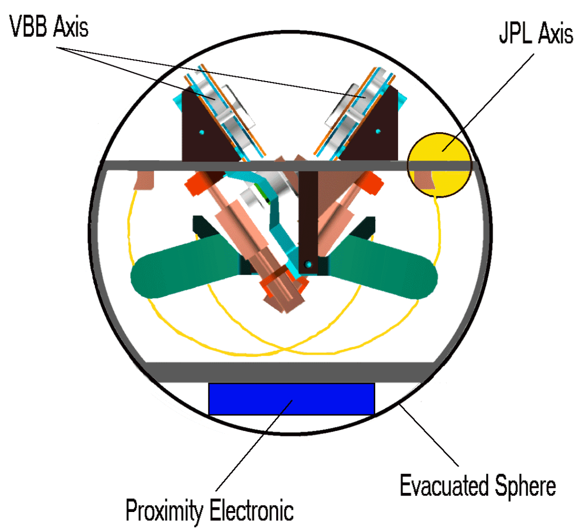
Figure 6 : ***Quake occurred in Afghanistan, recorded by an STS-2 and by the VBB mock-up, on May 30, 1998. The signal was recorded in a seismic vault, in Saint-Maur, France. The quake has a magnitude of 6.9. The STS-2 outputs were used to compute the oblique output compared to the mock-up signal. Note however that the breadboard was operating without***

feedback and a slightly different place than the STS-2, which may explain the small differences between the two signals.

The actual performances make our instrument a terrestrial good one. Martian objective implies a minimum of one order of magnitude improvement. For the future we plan to reach such performances looking at a modified design, in which the pivot and the spring will be differently loaded to have a better sensitivity.

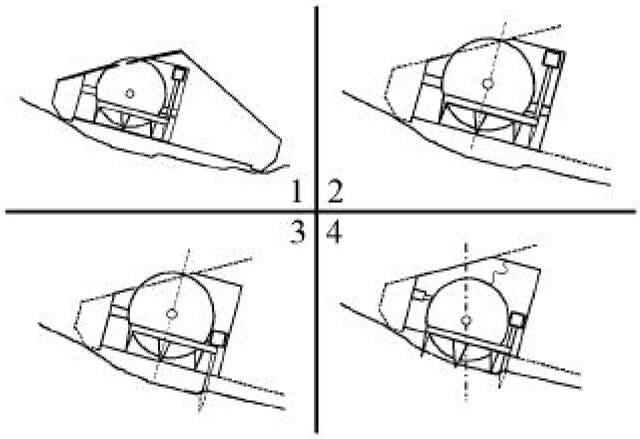
4. NETLANDER INTEGRATION :

The instrument, which will be integrated on the Netlander, will be composed of two-tilted axis providing, after recombination, data of one horizontal axis and one vertical axis. The limitation to two axis is related to the size of the lander. However the use of a micro-seismometer provided by JPL for the second "missing" horizontal component allows the measurement of all three axis signals.
All these sensors plus the proximity electronic take place in an evacuated sphere of 13cm diameter (Fig. 7).



<u>Figure 7</u> : Side view of the evacuated sphere with the 2 VBB axis and the JPL micro-seismometer. Sphere diameter : 13 cm.

This sphere can be levelled and is supported by 3 small passive feet in parallel with a larger active one.
This aggregate will be locked on the lander by 4 equatorial finger devices. All mechanisms will be designed to support a landing shock of 200 g - 20 ms.



<u>Figure 8</u> : Installation scenario of the seismometer. Objective is to uncouple the instrument from the lander and to assume a correct coupling with the ground.

The seismometer deployment (Fig. 8) will start with the descent of the main foot. This device is a penetrating spike with an electro-mechanical hammer, with a design originating from the ROSETTA- MUPUS spike. This spike will anchor the sensor to the ground using the lander as a reaction mass. In order to minimise the power, this stage will be done over a few hours. If the ground is not encountered (e.g., if a hole is under the lander) or in case of problem, the seismometer will stay coupled to the lander.
After the successful penetration of the foot, the seismometer will be unlocked and will fall along the main foot until the three small feet contact the ground. The sphere containing the sensor will then be levelled automatically (with an accuracy of a few fraction of degree), and locked.
The system used for the seismometer deployment, even if not comparable with a full robotic or human installation, is therefore expected to provide a good installation. The influence of the lander on the seismometer will be minimised due to the enhanced de-coupling and coupling with ground at high frequency (f > 10 Hz). Finally, the lander will act as a thermal and wind shield for the instrument. This system will be designed to work for lander tilted up to about 30°.

The mass of the sensor head is about 700 g. Total mass of the experiment, including locking, leveling, deployment devices and electronics is about 1.9 kg.

Total power consumption is about 500 mW.

The first subassembly, the sensor, levelling system, installation system, locking mechanism and environmental sensors, as well as the overall instrument integration will be under the responsibility of the Institut de Physique du Globe de Paris, France (PI: P. Lognonné). The second part of the sensor will be the proximity electronics, a double-face electronic card for the CDMS I/F , A/D and feedback electronics, and the mass memory for the data logger. This part of the experiment is under the responsibility of Switzerland, Institüt of Geophysics (co-PI: D. Giardini). The last part of the seismometer package will be the micro-seismometers, either in the VBB sphere or on the spike. This part will be under the responsibility of the Jet Propulsion Laboratory, USA (co-PI, B. Banerdt).

5. CONCLUSION :

The NetLander mission is expected to provide the first network on Mars. The preliminary expected performances of the seismometer planned in the payload will allow [6] to monitor the Martian seismic activity, especially in the Tharsis area. Attempt to monitor the continuous excitation of normal as well as the gravity tides of the Sun and Phobos will also be performed.

The NetLander mission, presently in phase A, is expected to start phase B in 2000, for a delivery of the instrument in late 2003-early 2004. After a launch in mid 2005, the seismic network will operate from early 2006 to early 2008, during therefore one Martian year.
With these new seismic data, much of the unknown internal structure of Mars will be discovered, a second telluric planet might therefore be characterized.

6. REFERENCES :

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