Long term seismic noise acquisition and analysis in the Homestake mine with tunable monolithic sensors

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Long term seismic noise acquisition and analysis in the Homestake mine with tunable monolithic sensors

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Abstract. In this paper we present and discuss the scientific data taken by two mechanical monolithic horizontal sensor prototypes located at the 2000 ft deep level in the Homestake mine (South Dakota, USA). The main goal of this experiment was to provide a preliminary characterization of the Homestake site in the frequency band $10^{-4} \div 30\,Hz$, necessary to evaluate the feasibility of underground gravitational-wave interferometers sensitive at $1\,Hz$ and below, and to test the sensor prototypes in the band $(10^{-6} \div 30\,Hz)$. The first results show the good performances of the sensors, being they able both to detect the Peterson Low Noise Spectrum and, in the very low frequency region, the peaks due to Earth tides, although configured with a limited sensitivity (resonance frequency of $\approx 300\,mHz$ and optical lever readout).

1. Introduction

The Homestake mine is the largest known iron-formation-hosted gold-ore body, marked by a rather complicated stratification and history of folding events and metamorphosis of igneous and sedimentary rocks. It lies far from the oceans in the Lead-Deadwood Dome of the Black Hills (South Dakota, USA) and has the deepest reaching tunnels in North America (8000 ft) which provides an optimal stage for monitoring the seismic noise with a three dimensional network of seismometers, but also a very good testbed for seismic sensor prototypes.

Recently, the Homestake mine was chosen to host the Deep Underground Science and Engineering Laboratory (DUSEL). For this task, in August 2008 a first series of seismic measurements was performed at different underground levels in the Homestake mine, the 300 ft, the 800 ft and 2000 ft levels, intended as a starting point for a more exhaustive survey [1].

In December 2008, the group of Applied Physics of the University of Salerno installed at Homestake two tunable monolithic seismometers in thermally insulating enclosures onto concrete slabs connected to the bedrock and behind a sound-proofing wall at the 2000 ft level.

In this paper the monolithic seismometers, their installation at 2000 ft and the DAQ system architecture are described. Then, the first scientific data acquired are presented and discussed.

2. The Monolithic Sensor

The structure of the tunable mechanical horizontal monolithic sensor is based on the Folded Pendulum (hereafter FP), called also *Watt-linkage*, a classical suspension system developed in 1962 [2], recently rediscovered for application in gravitational wave research as ultra-low frequency pendulum resonators for vibration isolation in interferometric detectors of gravitational waves [3].

Based on the FP basic scheme, single-axis monolithic accelerometers have been developed as sensors in the control system for advanced seismic attenuators [4]. The progress in precision micro-machining, that has allowed the construction of tunable sensors of small size with extremely soft flexures at the pendulum's hinges, and the innovative application of laser optics readout techniques have largely improved the their sensitivity in the low frequency band and increased their immunity to environmental noises [5, 6]. Special tuning procedures have been also developed to decrease the sensor natural frequency (to values as low as $\approx 70\, mHz$) and dimensions, allowing its use both as seismometer and accelerometer for seafloors or boreholes [5].

On the basis of these scientific results, a low-noise high-resolution horizontal monolithic FP sensor was developed at the University of Salerno for geophysical applications aimed to explore the low frequency band of the seismic spectrum, both as a stand-alone sensor or as part of large and geographically distributed seismic networks.

The theoretical FP transfer function, describing the FP dynamics as seismometer and/or accelerometer, can be easily obtained using the simplified Lagrangian model developed by J.Liu et al. [3]. This model, based on the mechanical scheme shown in Figure 1, describes only the FP basic dynamics, but it is anyway very useful to understand the FP main characteristics and expected performances.

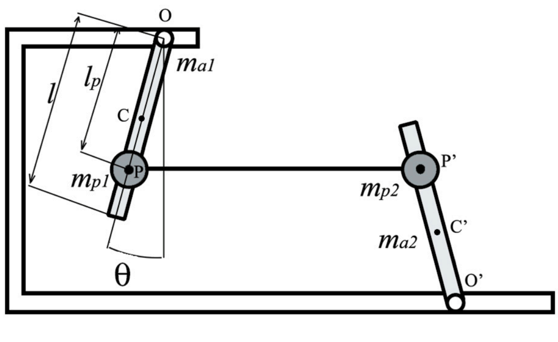

Figure 1. Folded Pendulum mechanical scheme.

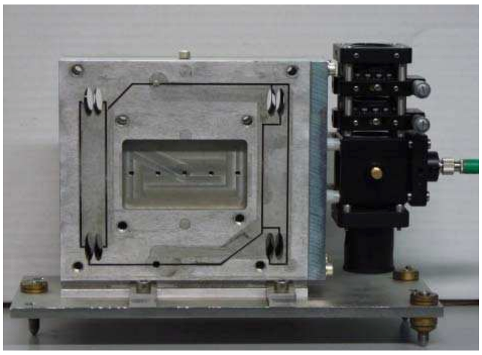

Figure 2. Mechanical monolithic horizontal seismometer prototype (mod. 08F_100_AL1).

In particular, defining the coordinate of the pendulum frame (fixed to the ground) as x_g and the coordinate of the FP central mass as x_c (Figure 1), then the FP transfer function is

$$\frac{x_c(\omega)}{x_g(\omega)} = \frac{\omega_o^2 - A_c\omega^2}{\omega_o^2 - \omega^2} = 1 + \frac{(1 - A_c)\omega^2}{\omega_o^2 - \omega^2} \tag{1}$$

where A_c is the parameter related to the center of percussion effects [3] and

$$\omega_o = \sqrt{\frac{(m_{a1} - m_{a2})\frac{gl}{2l_p^2} + (m_{p1} - m_{p2})\frac{g}{l_p} + \frac{k_\theta}{l_p^2}}{(m_{a1} + m_{a2})\frac{l^2}{3l_p^2} + (m_{p1} + m_{p2})}} \tag{2}$$

is the FP angular resonance frequency. The mass displacement transfer function with respect to the ground displacement can be obtained as

$$\frac{x_c(s) - x_g(s)}{x_g(s)} = \frac{(A_c - 1)s^2}{s^2 + \frac{\omega_o}{Q(\omega_o)}s + \omega_o^2} \tag{3}$$

where $Q(\omega_o)$ is the global quality factor, that includes the dissipative effects.

The configuration of the monolithic FP as seismometer is straightforward: the readout output signal $(x_p(\omega) - x_s(\omega))$ is acquired, calibrated and processed according to Equation 3.

The sensor prototype (mod. 08F_100_AL1) is made of Aluminum, shaped with precision machining and electric discharge machining (EDM) from a $134 \times 134 \times 40\,mm$ block of metal (Alloy 7075-T6) (Figure 2). The four flex joints have an elliptical profile with $100\,\mu m$ minimum thickness and ellipticity ratio of $\epsilon = 16/5$. This shape ensures robustness and long-term durability to the mechanics [5, 6]. The pendula arms ($71.5\,mm$ length and spaced by $102\,mm$) minimize mass and moment of inertia, without reducing rigidity and symmetry. The values of the masses of the pendulum arm, of the inverted pendulum arm and of the central mass are $m_p \approx 40\,g$, $m_{ip} \approx 50\,g$ and $m_c \approx 600\,g$, respectively. The FP frequency tunability was obtained as described in [5], machining a large recess in the central mass to hosting suitable shaped and positioned tuning masses. The gaps between central mass-arms and arms-frame are $1\,mm$ large to increase the FP mechanical dynamics and the quality factor for applications in air.

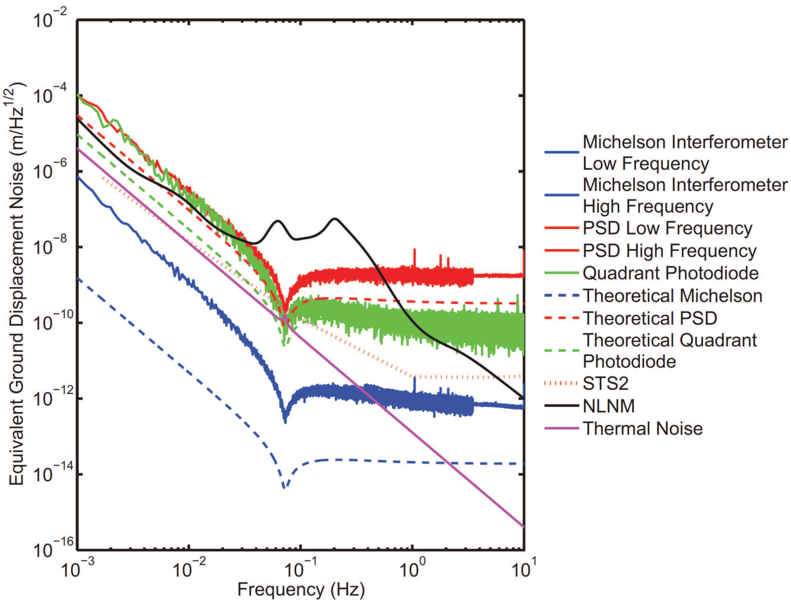

Figure 3. Theoretical and experimental sensitivity curves of the monolithic FP seismometer.

We measured the three sensitivity curves corresponding to optical levers (with PSD and quadrant photodiodes) and interferometer readouts. In Figure 3 the best theoretical and experimental sensitivities curves at $T = 300\,K$ and $f_o = 70\,mHz$ in air and without thermal stabilization are shown.

To compare the sensitivity of the FP seismometer with other geophysical instruments, we reported in Figure 3 also the sensitivity of the STS-2 by Streckeisen, that represents the state-of-art of the low frequency seismic sensors [7]. Figure 3 shows that the monolithic FP sensor has already a sensitivity comparable or better (with interferometric readout) than the STS-2 in the band $10^{-3} \div 10\,Hz$. We reported also the Peterson New Low Noise Model (NLNM) [8], that is the Minimum Earth Noise evaluated from a collection of seismic data from 75 sites located around the world, that describes the minimum level of earth noise: noise levels below this are never - or extremely rarely - observed.

3. The $2000\,ft$ Seismic Station at Homestake

The $2000\,ft$ station was built in August 2008 on the concrete platform of an old charging station located on the bedrock, having carefully checked that any audible source of dropping water were eliminated as good as possible. It was obtained sectioning a tunnel and sealing it from two sides with double layered walls. Many instruments were located in the station inside a specially designed insulated box. A separate hut at some distance to the instrument area hosts the data acquisition PCs and the DC power supply [1].

The environmental conditions at the $2000\,ft$ level are stable around $20^o\,C$ with an rms of about $0.2^o\,C$. Sensors are installed close to the seismometers to monitor the most important environmental quantities: temperature, pressure, humidity, sound and magnetic field. Humidity monitoring is relevant because the humidity levels may reach 100% and condensation of water on the electronics could start soon, although the insulation boxes are good enough to bring humidity down to $80\% - 90\%$ also in presence of 100% humidity. Pressure and sound monitoring is important because these quantities may show significant correlation with seismic data since both could generate rock vibrations or may even directly act on seismometers despite all efforts to isolate the instruments.

The data-acquisition system includes the configuration of the local network and remote access to PCs. The acquisition system is based on the PCI 6289 card from National Instruments^{TM}. It contains a 18 bit ADC and an internal amplifier with a maximum amplification of 100. The input range is limited to $\pm 10\,V$. The Data Acquisition is managed by Labview^{TM}programs which also generate analog-output signals to initiate mass-centering procedures of seismometers, if necessary. The data are first stored in ASCII files as $128\,s$ records sampled at $100\,Hz$. Then the data is made available to the outside world by an ftp server while the timing signals are provided to the acquisition system through optical fibers.

The sequence of installation of the monolithic sensor within the insulated box of the $2000\,ft$ station is shown Figure 4.

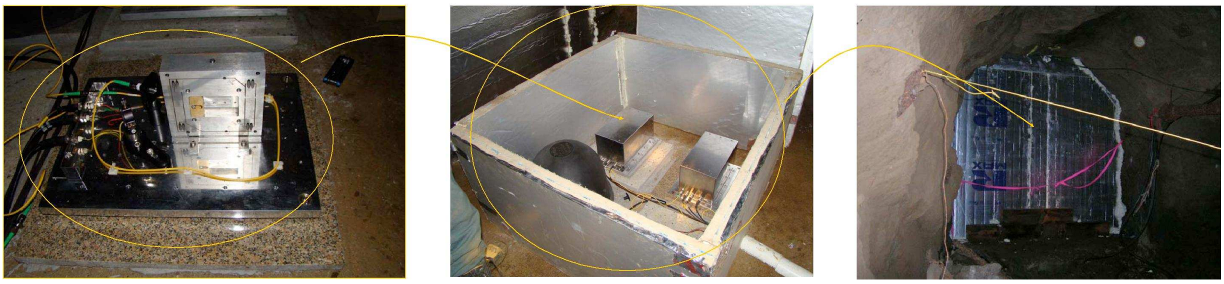

Figure 4. Installation of the monolithic sensor within the insulated box of the $2000\,ft$ station.

4. Experimental Results

In this section we present some of the preliminary results of the first month of data acquisition of FP monolithic sensor prototypes. In particular, the power spectral density of ground displacement at $2000\,ft$ underground level (compared with the theoretical expected FP noise, the simulated horizontal semidiurnal Earth tides [9] and the Peterson's New Low Noise Model) is shown in Figure 5. What is relevant to note is its large measurement band ($10^{-5} \div 30\,Hz$)

and the good sensitivity, although the latter is largely limited by our technical choice of using an optical lever readout, surely more robust than an interferometric one but less sensitive, and a safe resonance frequency ($300\, mHz$) for this first long unattended test in the Homestake mine. Tuning the FP sensor at a lower resonance frequency would simply translate the sensitivity curve towards the low frequency region, enlarging the low frequency band. Nevertheless, even with this not optimal configuration, the instruments is able to detect part of the Peterson Low Noise Spectrum and, in the very low frequency region, the peaks due to Earth tides (Figure 5).

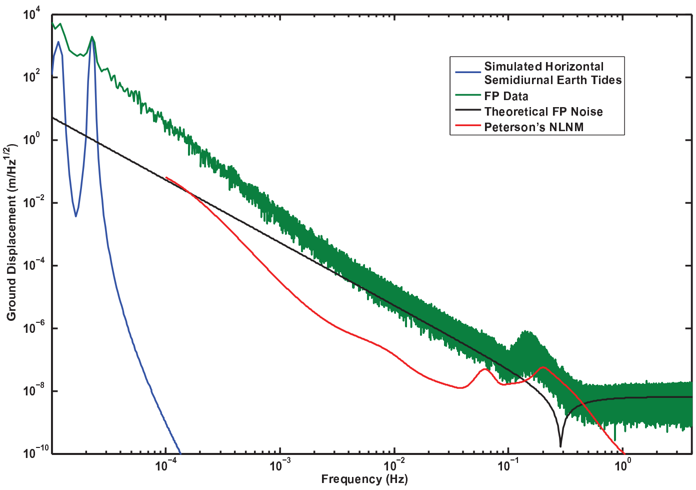

Figure 5. Power Spectral Density of ground displacement at 2000 ft underground level (compared with theoretical FP noise, simulated horizontal semidiurnal Earth tides and Peterson's New Low Noise Model).

The apparent limitation in the low frequency band is simply due to the fact that the power spectral density has been evaluated only for one month of data. Longer runs will allow the exploration of lower frequency regions. In fact, the FP monolithic sensor is an open loop sensor, so that there are no limitations coming from the feed-back control, as it happens in the majority of the commercial instruments used for seismic noise acquisition. The limitations are mainly due to the electronic noise of the readout system, to the thermal noise of the mechanical joints and to the effects of the air for sensors not operating in vacuum.

For completeness, the spectrogram $500\, h$ of data of ground displacement as recorded by our seismometer is shown in Figure 6. This figure shows the very resonance frequency of the instrument and its ability of measuring teleseimic earthquakes. Of course, longer data acquisitions are necessary for a more accurate analysis of the performances, although these preliminary results are already very promising.

5. Conclusions and future developments

Two FP monolithic sensors are installed into the $2000\, ft$ station in the Homestake mine since December 2008, equipped with a National Instruments^{TM}(32 channels - 18 bit ADC) data acquisition system, a network access through optical fibre cables and an environmental monitoring system.

The FP sensor sensitivity is close to the theoretical one in the band ($10^{-5} \div 30\, Hz$) for the resonance frequency of about $300\, mHz$ and for the optical lever readout configuration. Better sensitivities could be obtained reducing the resonance frequency of the instrument and using more sensitive optical readouts, but it was preferred to priviledge the instrument robustness

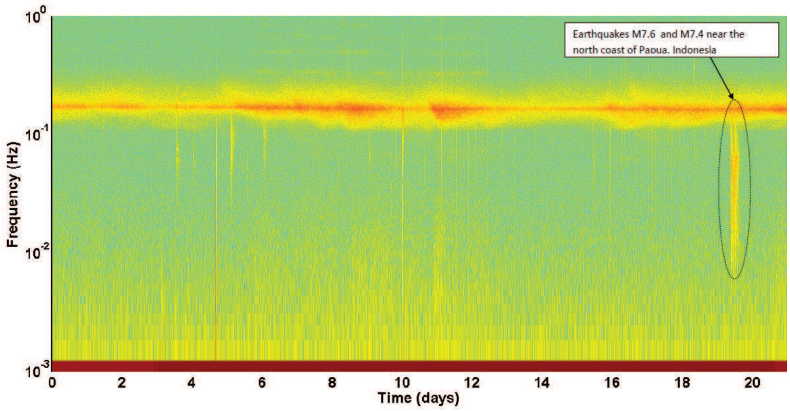

Figure 6. Spectrogram of ground displacement data of 500 h as recorded by our seismometer. Two teleseismic earthquakes near north coast of Papua, Indonesia, are shown (January, 03, 2009, 19:43:50 UTC time and Saturday, January 03, 2009, 22:33:40 UTC time).

for this first unattended measurement in the Homestake mine. Nevertheless, even with this not optimal configuration, the instruments is able to detect part of the Peterson Low Noise Spectrum and, in the very low frequency region, the peaks due to Earth tides.

These data, together with all the auxiliary technical information obtained with this test, will be used to organize a new experiment for the low frequency seismic characterization of the Homestake site with an improved version and configuration of these sensors to be positioned at different levels and orientations.

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