Introduction
The promise of a digital MEMS accelerometer to deliver a more faithful reproduction of the ground’s movement has led several authors (e.g., Gannon et al., 1999; Mougenot, 2004; Gibson and Burnett, 2005) to compare the merits of the digital accelerometer and the analog coil geophone. Considerable effort is underway to find out whether the potential of digital accelerometer acquisition is being realized. Field comparisons (Ronen et al., 2005; Lawton et al., 2006; Stewart et al., 2006; Hons et al., 2007) generally show no geophysical advantage either way if one takes aside the debate as to single-point versus arrays of receivers, appropriate spatial sampling for signal and noise, sensor coupling, or acquisition system versus acquisition system. To obtain further insight, comprehensive investigations have been conducted at the University of Calgary. The goal has been to develop a methodology and experimental facility for objective, in-depth assessment of seismic grade motion sensors.

The performance of several geophone elements (Oyo GS series and ION-Sensor SM series) and MEMS accelerometers (from Applied-MEMS and Kistler) in both vertical and horizontal configurations has been compared. Mechanical testing of sensors from very weak to strong excitations within the seismic frequency band is a trying subject. The focus is on ascertaining as precisely as possible to what extent recorded deviations from the modeled sensor response are due to non-linearities in the sensor, and to what extent they are due to imperfections in the testing equipment. As such, refinement of the testing equipment and procedures is ongoing. Nevertheless, important conclusions are apparent when analyzing the response of the tested seismic sensors.

Laboratory Equipment
There are two common methods of quantifying the response of a sensor. Geophones are generally tested electronically (e.g., Hagedoorn et al., 1988). Alternatively, sensors can be mounted on an accurate actuator or table and subjected to precisely controlled harmonic or other waveforms to find the response. The second method can be used to test multiple sensors at the same time with the same motion, and is the method used in this research. A schematic of the experimental setup is shown in Figure 1. Key components in the laboratory are:
- vibration isolation equipment such as a minusK 100BM-4 anti-vibration table,
- linear exciters such as an Aerotech AB2000 air bearing stage (ALE),
- independent sensors such as a Wilcoxon P731A low noise accelerometer and Polytec fiber-optic laser interferometer,
- National Instruments data acquisition hardware (DAQ).

The Aerotech and other precision actuators are equipped with internal displacement sensors featuring sub-nanometer resolution. Despite robust actuator design and high accuracy, these internal sensors measure displacements in the exciters with respect to their own inertial reference frame. The monitoring of small vibrations of an exciter’s reference frame employs a differential laser interferometer installed on a reference frame whose motion with reference to the inertial coordinates of the earth is very small and precisely monitored. An improvement in the experimental apparatus will be the development of a multi-sensor “inertial cage” capable of measuring the true 6-degree of freedom motion of components of the apparatus with reference to the inertial coordinates of the earth, so that “true” motions of the tested sensors can be compared with their responses. The objective is to remove ambiguities in the results down to a distortion of 0.005%. Figure 2 illustrates a layout of the laboratory showing most of the equipment. Figure 3 shows a close-up of several sensors mounted on the ALE.

Experimental Results
Most commonly the waveforms input to the actuators are sinusoids, one frequency at a time, and the output magnitude and phase are recorded. Other waveforms can also be used, which effectively input a continuous range of frequencies into the sensor all at once (e.g. Gaussian noise). Results for sinusoidal waveforms (also called a “harmonic scan”) will be considered here. Frequencies investigated are 0.4 Hz up to 200 Hz, with varying amplitudes of excitation, in this case vibration table stage velocity.
Figures 4 and 5 show results for medium excitation amplitudes (0.5 – 5 mm/s) for a 15 Hz geophone damped at 68% and a MEMS accelerometer respectively. The geophone almost exactly matched the analytically modeled response for all frequencies between 2 Hz and 200 Hz. The accelerometer plots illustrate the flat magnitude and phase responses as expected, however, they indicate that one must take proper precautions against ambient disturbances.

Examination of results for ultra-weak excitation (<10 $\mu$m/s) (Figures 6 and 7) illustrates that the sensors perform similarly down to ~10 Hz. Below 10 Hz, both sensors show large deviations from the model response. Errors as large as these in either amplitude or phase would degrade the ability of these small amplitudes to be used in real data, likely interpreted as noise. In this experiment, the amplitude of excitation at 10 Hz was ~0.7 $\mu$m/s, equivalent to an acceleration of $\sim 4.5 \times 10^{-6}$ g. The 15 Hz geophone detects this amplitude at about 5 dB down, or $\sim 2.5 \times 10^{-6}$ g. There is considerable scatter in the accelerometer response at these excitation amplitudes; however, the data illustrates the flat amplitude and phase response expected from the accelerometer. Sources of error in a test introducing small excitation amplitudes become magnified; due to noise in the test environment, nonlinearity in the exciter and noise within the sensors and data acquisition channels themselves. It is nonetheless impressive that both sensors operate very near to their theoretical models at vibration amplitudes down to and below 10 $\mu$g in this particular experiment. Tests are now being conducted down to levels of 1 $\mu$g.

**Conclusions**

A seismic sensor test facility with the ability to mechanically test both geophones and accelerometers has been set up at the University of Calgary. Improvements in the apparatus are on-going; so as to remove ambiguities in the test results due to introduced motion distortions. Tests performed on several sensors illustrate the excellent performance of both geophones and accelerometers down to very weak excitations.

**References**


Passive anti-vibration table

Active anti-vibration platform

Precision actuators (vertical or horizontal)

Tested geophones, MEMS accelerometers

Differential laser sensor (acceleration / velocity / displacement)

24-bit resolution, Low noise, Signal acquisition, Archiving, Process and Control System

Figure 1: Schematic of the experimental setup consisting of an anti-vibration platform, actuators, sensors, and recording equipment.

Figure 2: A layout of the laboratory with the experimental setup for evaluation of accelerometers and geophones.

Figure 3: Close-up of sensors and fixture mounted on the Aerotech air bearing stage.
Figure 4: Geophone response to medium excitation (0.5 to 5 mm/s).

Figure 5: Accelerometer response to medium excitation (0.5 to 5 mm/s).

Figure 6: Geophone response to ultra-weak excitation (<10 μm/s).

Figure 7: Accelerometer response to ultra-weak excitation (<10 μm/s).