An analysis of passive seismic recording performance

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ABSTRACT

Passive seismic recording has many uses in oil and gas industry. It is used for fracture mapping (often during hydraulic fracturing), casing-failure detection, and passive imaging of stratigraphy. Each of these technologies makes great demands of seismic recording instrumentation. As compared to active seismic acquisition, using vibratory or impulsive sources, passive seismic acquisition requires greater instrumentation sensitivity, noise immunity and bandwidth. When embarking on a passive seismic program, a key factor in determining its success or failure is selection of monitoring equipment. While passive seismic service companies usually take care of equipment selection, it is helpful to understand any issues resulting from the choices made. Some selection criteria are discussed for passive seismic recording systems. Attributes of one passive seismic recording system are discussed in detail as a case study.

INTRODUCTION

Selection of passive seismic monitoring equipment can be daunting. There are a number of parameters to consider. Let us discuss some of these, and their relevance.

At a high level, the monitoring system as a whole should be capable of recording all relevant microseismic activity with fidelity. The system's overall sensitivity must be high enough, not only to capture the amplitude of expected microseisms, but also capture them with enough amplitude so that they can be analyzed and processed in a meaningful fashion. The background noise needs to be of a low enough level that it does not interfere with waveform analysis. The system's maximum amplitude must be great enough to capture the largest expected amplitudes without clipping. Four major parameters combine to define the system: The system sensitivity, the noise floor, the system headroom, and the bandwidth. Other factors are also important, such as distortion, linearity, and cross-axis rejection.

System Sensitivity

We'll define "system sensitivity" as the smallest measurable particle motion that can be recorded. Depending on the sensor type, the motion is measured as either a velocity or acceleration. For passive seismic systems, sensitivity is the combination of sensor sensitivity (different than system sensitivity) and digitizer sensitivity.

Sensor Sensitivity

We most often choose between velocity sensors or accelerometers when planning a passive seismic system. Moving-coil geophones are the most common velocity sensors. Accelerometers are usually one of four designs: MEMS, force balance, crystal and optical. Some newer sensors provide digital outputs, so entire system properties are determined by the sensor. Most sensors, however, generate an output voltage which is proportional to the measured velocity or acceleration. Sensor sensitivity can be increased by placing multiple sensors at one location, and summing he results. We see this

technique most often in geophone-based sensors, where several geophone elements are wired together to increase the aggregate sensitivity.

Table 1. An assortment of sensors and their sensitivities

Sensor	*Sensitivity*
ESG G3070 triaxial geophone	27.5 V/(m/s)
Colibrys Si-Flex accelerometer	30 V/g
Geophone sonde with three GS-14-L3	65 V/(m/s)

Digitizer sensitivity

Digitizers convert the signal, output by the sensor, to a numeric value. Although very successful passive seismic monitoring has been performed using digitizers employing 12 to 22 bits, most modern digitizers use 24-bit converters. Values from 24-bit converters span the range between -2^{23} to $+2^{23}-1$ (one bit for the sign). The smallest measurable non-zero value is thus $1/2^{23}$ of the converter's maximum measured value or full scale range (FSR). Most modern converters specify a FSR of 10V, 5V, 3.3V, or 3V. For example, a 24-bit digitizer with a 3V FSR would have a sensitivity of $3V/(2^{23}$ bits) or 3.576 µV/bit. Most digitizers include an internal or external preamplifier between the sensor and the A/D converter. Gains between 2 and 100 are typical. For the above digitizer adding a gain of 32 increases the digitizer sensitivity to 111 nV/bit. Although the digitizer's sensitivity is a useful measurement to know, it is only one of four factors which define a system's measurement range.
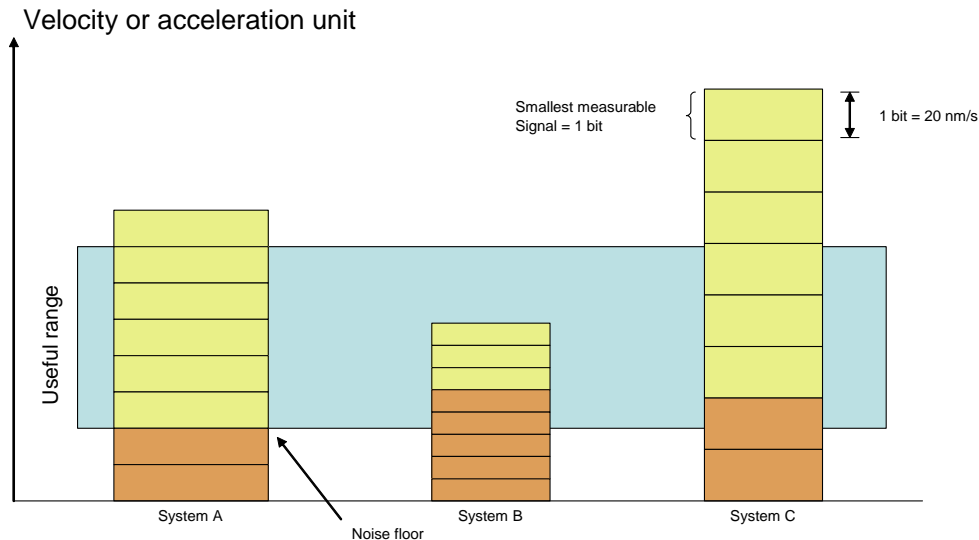

FIG. 1. Comparison of theoretical seismic recording systems. For illustration purposes, we assume each system uses a 3-bit A/D converter (plus a sign). Each block represents one discrete value. Brown blocks are used by background system noise. The number of bits available for useful measuring depends on the full scale range and the noise floor of each system. The best recorder is the one with more discrete measurements within the useful amplitude range (in this case, System A).

Table 2. Digitizer resolution

Instrument	Minimum measurable value
ARAM Aries RAM	18 nV/bit
Geometrics Geode	40 nV/bit
Turtle Mountain digitizer	6.2 nV/bit
Terrascience TMA unit (older model)	18 nV/bit

Noise floor

Of greatest importance for passive seismic monitoring is the system noise floor. Since events distant to the sensor array will attenuate with offset, the ability to distinguish tiny amounts of microseismicity from noise determines both the minimum detectable event-magnitude, and the maximum offset-range. System noise has many contributing factors: The self-generated noise of the sensor, noise generated and picked-up by the cable and the self-noise of the digitizer.

Sensor noise, in the case of geophones, is typically the result of thermal noise. Thermal noise, also known as Johnson noise or Nyquist noise, comes about from thermal agitation of electrons which produce random voltage fluctuations. The noise voltage,

$$E_n = \sqrt{4kTBR} \, , \qquad (1)$$

is proportional to the square root of the resistance. Here, k is Boltzmann's constant, T is the absolute temperature of the coil (°K), B is the bandwidth (Hz) and R is the resistance (Ω). Johnson noise is assumed white, so an effective background-noise figure is easily computed over the bandwidth in question. Thermal noise is also generated within the cable connecting the sensor to the digitizer/preamplifier. The cable resistance is usually much less than the geophone resistance, yet it can contribute to the noise – particularly if the cable is very long.

Noise from the digitizer must be included in computation of the noise floor. The self-noise of digitizers is usually related to the preamplifier stage. Different approaches to preamplifier design (cascaded or monolithic sections) and component selection make a large difference to the digitizer self-noise. Other sources of noise are related to the A/D converter (quantization noise, for example) and power supply. When selecting a digitizer it is useful to view a graph of the digitizer's self-noise spectral density over the pass-band of the instrument. The noise density is usually temperature dependent, so it is important that the test temperature is similar to the temperature of the unit at the installation. Some vendors only quote the dynamic range of the instrument. Unfortunately, this measurement is usually a theoretical value based on the number of bits in the digitizer. If a *measured* dynamic range is provided, one can work back to obtain the expected noise floor for the instrument:

$$E_{adc} = \frac{FSR}{10^{DynamicRange/20}} \cdot \qquad (2)$$

The noise floor in Equation 2 is a statistical value over the entire pass-band. For this reason, it is generally more useful to have a plot of pass-band response when evaluating different digitizer systems.

Other sources of noise

At a producing oilfield, power-line noise (50 Hz or 60 Hz) is usually the main contributor to noise as monitoring systems often coexist with AC equipment drawing high current. There are a number of paths for this noise to enter the acquisition system: Noise can enter through the digitizer power supply, through inductive pick-up in the sensors, signal lines or digitizer. Although resistive leakage in signal lines can be a source of noise, most noise is from EMI or EFI: Interference below 105 Hz is usually magnetically-induced, and is known as EMI (electromagnetic interference). Above 105 Hz, the noise is usually known as RFI (radio frequency interference). In both cases, the noise is undesirable. It is advisable to install any sensitive electronics (the preamplifier and digitizer) in a well-grounded steel box. The ground line should be short, and connected to a single earth point near the borehole. Shielding on the signal cable can reduce some noise, though most thin shielding, such as braided copper or foil, is ineffective against low frequency EMI. Shielding above the borehole is still very helpful in reducing RFI. An even better approach to reducing RFI is minimizing the length of the signal cable above ground. To best eliminate RFI, the digitizing system is best located directly at the top of a borehole.

In spite of best efforts to keep it out, power-line noise appears on passive seismic data with regularity. Paired signal lines and differential inputs on the preamplifier/digitizer help reduce noise by cancelling out any signal common to both signal lines. We call this removal of common-mode noise. In practice this noise-cancelling technique is rarely perfect. The ability to handle common-mode noise is dependent on the *common mode rejection ratio* of the preamplifier and A/D converter. The CMRR is defined as

$$CMMR = 20\log\left(\frac{gain \cdot V_{cm}}{V_{out}}\right), \qquad (3)$$

where V_{CM} is the common-mode voltage and V_{out} is the preamplifier output voltage. Although ideal CMMR values are usually large (in the order of 70-100 dB), common-mode rejection can be reduced through poor thermal design and the use of low-quality parts.

One final concern of passive seismic recording systems is radio frequency interference (RFI). Certain preamplifier designs are susceptible to RFI and rectify these high-frequency signals making them visible as noise in the seismic frequency band. Even certain metal-metal joints can form a diode and induce a rectified noise signal (Cigoy, 1999). Motor control equipment and radio equipment are frequently the cause of this RFI. Proper grounding and careful equipment placement are the best approaches for

minimizing RFI. In some cases RFI is improved by use of a different preamplifier (Figure 2).
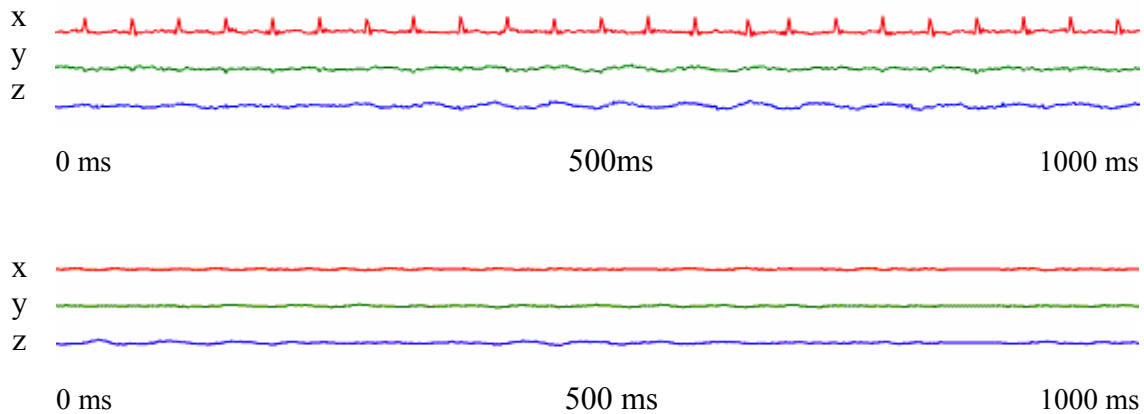

Figure 2. Comparison of two preamplifier outputs in the presence of identical radio frequency interference. The preamplifier design (top) rectifies 2.4 GHz RFI. Each transmitted data packet is visible as a spike on the digitized record. A change of preamplifier circuit (bottom) eliminates the RFI. Both datasets were obtained under identical RFI conditions.

Bandwidth

A passive seismic system's bandwidth is dependent on the type of sensor used, the sample rate, and the frequency response of the electronics. In general, the bandwidth of the system should adequately capture the expected band of the data, but excess bandwidth generally is unhelpful. With greater bandwidth comes more noise. The observed noise amplitude is the integral of the spectral density over the bandwidth, so clearly, reducing unnecessary bandwidth reduces noise.

The bandwidth of different systems varies significantly. We typically consider recorder bandwidth as the maximum window over which frequency response varies by less than 3 dB. One vendor of digitizers advertises the bandwidth as one-quarter of the sample interval. Though this seems small, many competing digitizers do not perform any better. Most digitizers now employ delta-sigma A/D converters which perform anti-aliasing internally. The internal anti-alias filters usually cut high frequencies above 0.8 to 0.95 of the Nyquist frequency. Figure 3 shows the measured frequency response of a Geometrics Geode seismic recorder at two different gain settings when set to a 2 kHz sample rate. The sudden drop of response occurs very near to the Nyquist frequency (1 kHz), though we see a gradual loss of response beginning much earlier. For this recorder, using the 3 dB criterion, we measure a bandwidth of 800 Hz. This bandwidth would be sufficient for monitoring lower-frequency events (e.g. casing failures).
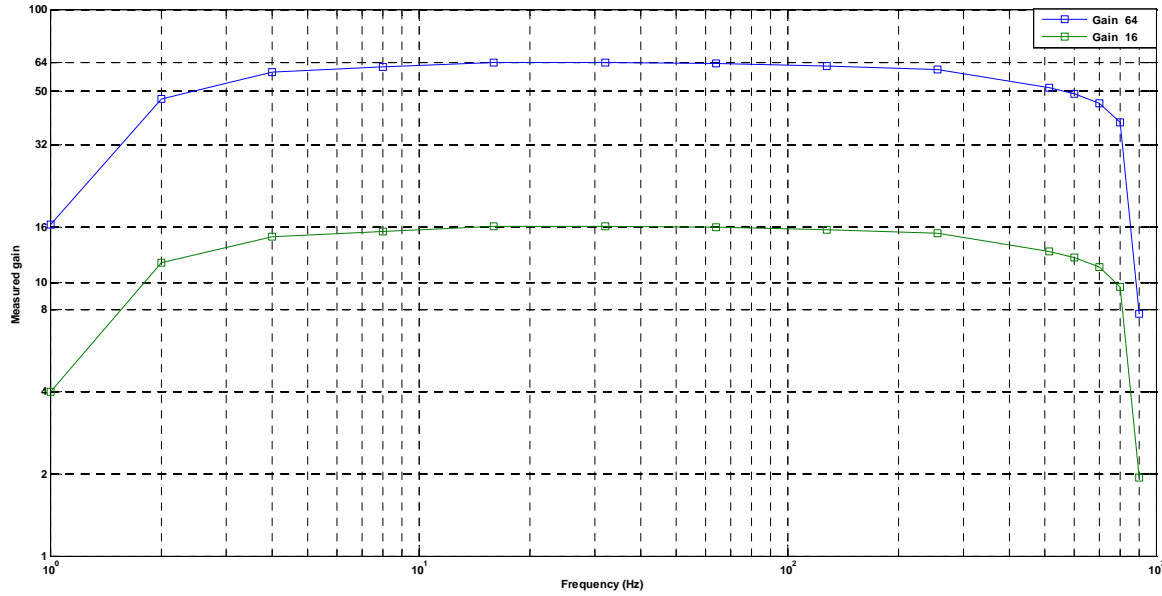
Figure 3. Measured frequency response of a recorder

A CASE STUDY

A passive seismic monitoring system was purchased for a EOR monitoring project at the University of Calgary. It included a set of eight triaxial geophone sondes and a 24-channel digitizer. The sonde sensitivity is 64.96 V/(m/s) and the digitizer's full-scale is 5 V at a full-scale value of 2^{23}-1. Based on this, we can compute the digitizer sensitivity

$$sensitivity_{digitizer} = \frac{FSR}{2^{23}-1} = \frac{5V}{8388607bit} = 0.596\mu V / bit \ . \qquad (4)$$

A gain of 32x is provided by the built-in preamplifier. So, to compute the 1-bit equivalent voltage at the input of the preamplifier

$$sensitivity_{preamp} = \frac{sensitivity_{digitizer}}{gain} = \frac{0.596\mu V}{32} = 16.62 nV \ . \qquad (5)$$

Our ultimate goal is to determine the system sensitivity, that is, what is the particle velocity that corresponds to a single bit of digitizer output. The system sensitivity is therefore

$$sensitivity_{system} = \frac{sensitivity_{preamp}}{sensitivity_{geophone}} = \frac{18.62 nV}{64.96V/(m/s)} = 0.286 nm/s \ . \qquad (6)$$

In the absence of noise, we would be able to resolve the very slightest ground motion with a velocity of only 0.286 nm/s. The maximum measurable velocity, that is, the velocity which makes the A/D converter reach its full scale range (FSR) is

$$FSR_{velocity} = (2^{23} - 1) \cdot sensitivity_{system} = 2.4 mm/s .$$ (7)

Noise floor

The passive seismic recorder was first tested in the lab, with a resistor in place of the dummy geophone. The resistor value, 12 kΩ, was chosen to have the same resistance as the combination of geophone sonde and signal cable. A sample of background noise was collected, and the power spectral density is shown in Figure 4 below. The recorder was next taken to the field, and connected to a true sonde cemented in a borehole. Figure 5 shows the spectrum of the recorder with environmental noise.
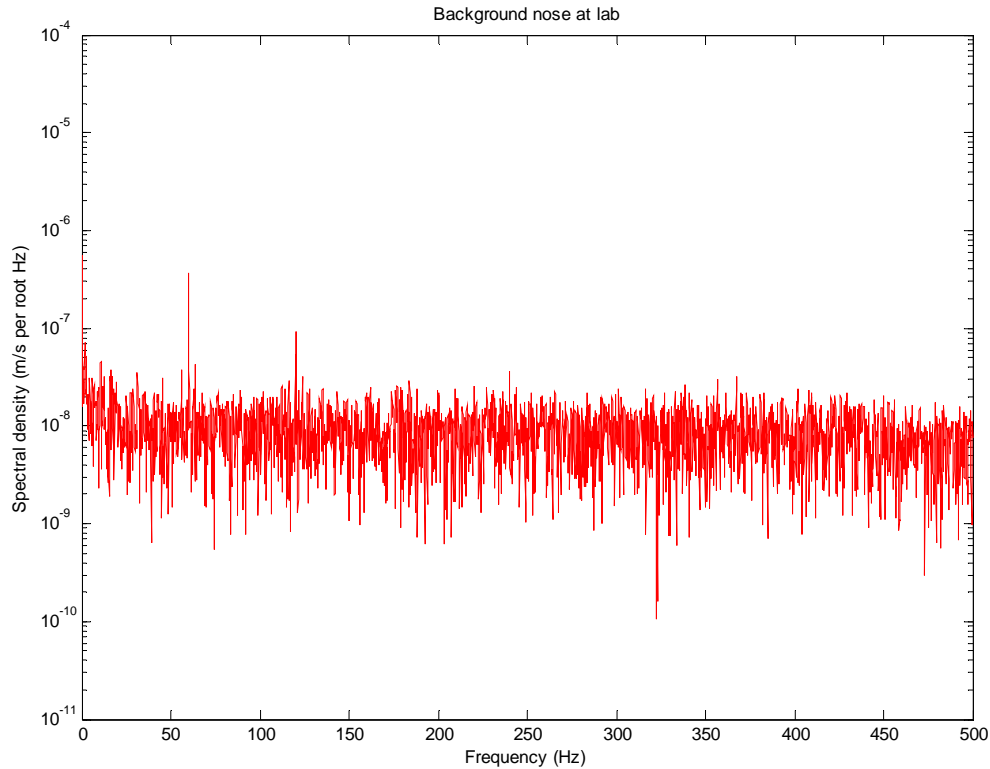

Figure 4. Power spectral density of a noise record collected from the passive seismic digitizer. Here, a 12K resistor stood in place of a geophone sonde. The data were collected in a laboratory. The noise amplitude is reasonably constant at 10^{-8} m/s per root Hz.
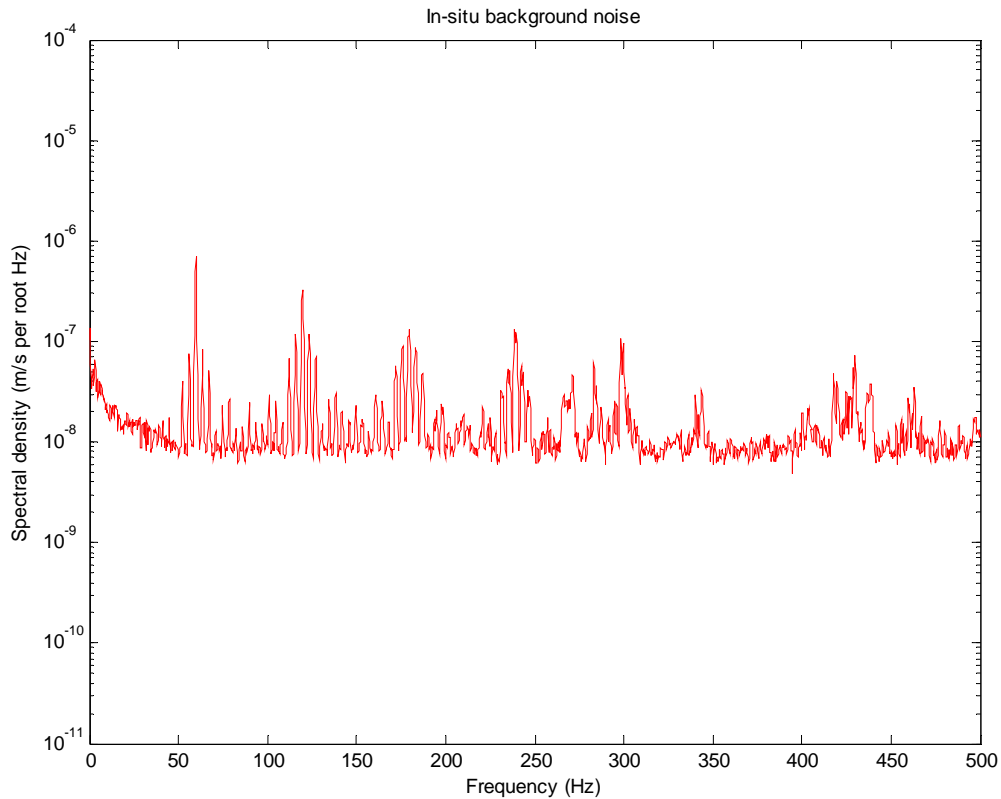
Figure 5. Power spectral density of a noise record collected from the passive seismic digitizer Here, a sonde and 1.5km of cable are connected to the digitizer's input.

If we compare Figure 4 to Figure 5 we see a marked increase in background noise. A large proportion of the noise is related to line power – either direct pick-up of 60 Hz or a harmonic. The particular recorder in question seemed susceptible to RFI at the monitoring site. Use of a high-cut filter helped eliminate a lot of this noise, which was outside the expected seismic signal band.

DISCUSSION

We have reviewed some of the factors to consider when selecting a passive seismic monitoring system. In addition to the parameters motioned, many other factors, unrelated to instrumentation, can affect the usefulness of a passive seismic monitoring system. Of particular importance is the geometry of the sensor array (see Chen, this volume) as it can significantly influence the ability to capture microseismic events. So long as sensors operate in the analog domain, EMI and RFI continue to be an acquisition challenge. Careful planning of the layout and cabling of the passive seismic instrumentation can help reduce these. Quality instrumentation with a conservative bandwidth usually yields the most dependable results. Since hardware and labor costs are often very high, it is worthwhile to verify correct operation of all equipment. Equipment vendors should supply detailed test reports of the sensors and instrumentation, and these reports should be periodically verified.

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