What Receivers will we use for Low Frequencies?

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Summary

With the increased industry interest in low frequencies down to less than 1 or 2 Hertz, there has been a significant effort in developing techniques that can source these low frequencies. Low-dwell, non-linear sweeps and pseudorandom sweeps have been developed by a number of companies to increase vibrator output at low frequencies. Equipment manufacturers have made improvements to vibrators to increase reaction mass and upgrade base-plates. But what about the recording units and the receivers that make up the remainder of the acquisition system? Do we need something special here? We discuss some of the special requirements for low frequency recording and review different receivers, their applicability and limitations.

Introduction

For many years now we have perhaps been more focused in extending the recording bandwidth to the upper frequencies in the pursuit of higher resolution. The most common geophones used today have a natural frequency of 10Hz providing a flat response proportional to ground velocity above this frequency and a response falling at 12 dB/octave, below. Over time improvements have been made in such geophones to tighten parameters and reduce distortion yielding the range of high specification geophones that most recording crews use today. Improvements in digital filtering in our recording systems have allowed for steeper-sloped anti-alias filters pushing the -3dB point toward 80% Nyquist. As most data is now recorded at 2ms with anti-alias starting above 200Hz, this has led to geophones with higher spurious frequencies pushed up into the rejection band near Nyquist. All this technology improvement has gone into what manufacturers term the "industry standard", a 10Hz geophone.

Extending bandwidth on the high end is not the only way to improve resolution. Adding an octave or two on the low end serves us as well. Clearly, if we wish to record signal with good signal to noise ratio down to 3Hz or 2Hz or even down to 1Hz, we need to consider the receivers and recording systems we will use. Thankfully the latter is not really an issue with modern acquisition system front ends. These systems mostly have DC response, that is, they can record a constant level, so have nothing "built-in" that limits their low frequency response. Our high specification 10Hz geophones however will show a falling response at low frequencies. A 10Hz geophone with 70% damping is already -3dB at 10Hz and will be an additional -24dB at 2.5Hz and -36dB at 1.25Hz. There are low frequency geophones available, which we will discuss later, but these are not high specification geophones. So will we be forced to relax our demands on high performance to enable us to look at low frequencies?

Another sensor type that is available these days is the MEMS sensor. These digital sensors also have a DC response and so are favorable for low frequency recording. However, experience has shown that their application has to be considered carefully. In conditions with extremely low ambient noise the internal noise of the sensors may become the dominant noise source, more on this later.

The electronics in the recording system also produce noise, thermal or Johnson noise. This noise is a function of temperature but is also frequency dependent. Typically electronics will exhibit an effect roughly proportional to 1/frequency that means that the random electronic noise will increase as frequency reduces. A similar 1/f effect is seen in MEMS sensors.

Low frequency challenges

While acquiring vibrator data using conventional geophone receivers, we typically experience an overall 30-dB/octave obstacle that must be overcome to recover useful low frequency energy. A combination of vibrator pump flow and reaction mass stroke can impose more than a 12-dB/octave constraint in and of itself (Sallas 2010); see Figure 1. The differentiation effect of the surface vibroseis source when going from ground force to far-field particle velocity adds a 6-dB/octave loss (Baeten, Fokkema and Ziolkowski 1988). Moreover, when 10 Hz geophones are used, another 12-dB/octave penalty is imposed below 10 Hz; see Figure 2. All these effects combine to produce a 30-dB/octave low frequency decay of the received signal. In dynamite surveying we should be better off, we do not have the 6-db/octave loss from ground force to far-field particle velocity; nor do we see the low frequency vibrator limitations. However we will still see the 12-dB/octave roll off from the geophone response. It should also be remembered that explosives do not provide a flat spectrum down to very low frequencies and the response may be quite variable depending upon ground conditions, charge size, hole depth, etc.

New source techniques have recently emerged that take into account the vibrator constraints and provide coherent energy to quite low frequencies. These techniques can help to reduce or eliminate the vibrator pump flow and mass stroke constraints.

There is nothing that we can do about the ground force to far field particle velocity attenuation, or to the natural energy radiation attenuation. To our advantage is that low frequencies tend to be less attenuated in travelling through the ground.

The -12-dB roll-off inherent in geophone design can be corrected for by inverse filtering; see Figures 3 & 4. This process flattens the geophone response below the natural frequency. It works well so long as there is adequate signal-to-(system) noise ratio; see Figure. 3. It should be noted that the self-noise of an analogue geophone is extremely low since this is caused by the thermal or Brownian motion of the air molecules surrounding the moving mass. Because the geophone low frequency roll-off is a mechanical effect it will reduce the signal and the ambient noise to the same degree, preserving signal-to-(ambient)noise ratio. However under some conditions, typically low signal strength, the amplitude of the signal from the geophone may fall below the noise floor or the recording system, then the signal to total noise ratio becomes compromised: see Figure 4. A significant benefit of analogue geophones in such cases with very low levels of signal is that their output may be summed in arrays to improve the signal-to-noise (both ambient and system) ratio. Typically, with reasonable signal strength, we can flatten the geophone response to about 2 octaves below the natural frequency, so for a 10Hz geophone we can get down to about 2.5Hz. Some companies have built sensors that use higher frequency geophones with electronic, non-linear amplification to make their output flat to lower frequencies. This is utilizing inverse filtering in the sensor unit. Modern, 24-bit recording systems typically have DC coupled inputs. That is to say that they do not have input transformers or DC blocking filters that impose a low cut response. This means that they have an inherently flat response that helps in recording low frequencies. One exception is when connecting a high impedance sensor such as a (streamer) hydrophone. The combination of the capacitance of the hydrophone (or streamer group) with the input impedance of the 24-bit digitizer form an RC circuit that imposes a low cut filter (-6-dB) and so limits the very low frequencies. Typically this low cut is set at about 3Hz. In land systems this is not an issue because the geophones, or strings of geophones, we use do not have high enough impedance.

Other influencing factors come from the recording system. By its electronic nature there will be some 1/f noise effect in the input circuitry. This effect raises the noise floor at low frequencies proportional to 1/frequency, so the lower frequency we record the higher the random noise contribution from the electronics themselves. This noise is thermal or Johnson noise in the electronics. It is random in nature and so will attenuate through summing. The electronics can also show DC offset. This offset is frequently introduced in the A/D converter and biases the data positive or negative. The offset can be removed by computing an average value over a record and then subtracting that value from all samples. Modern systems do this as part of the acquisition process. If very long recordings are made this offset can change over time causing a drift effect that may look like a very low frequency, usually of period much greater than 1s. The low frequency drift can be removed by low-cut filtering.

By using geophones with lower natural frequencies we can maintain sensitivity to lower frequencies and then inverse filter to very low frequencies. The drawback with this solution is that low frequency geophones are not built with the same high specifications as the 10Hz high performance phones. This means we compromise on distortion, close tolerances, etc. Additionally lower frequency geophones tend to be larger, heavier, more expensive and less robust, the latter being the main issue for seismic field use. A physical consequence of lowering natural frequency is a lower tilt tolerance. As a consequence, low natural frequency geophones must be planted closer to vertical in order to meet specifications, or even to operate, resulting in another field limitation.

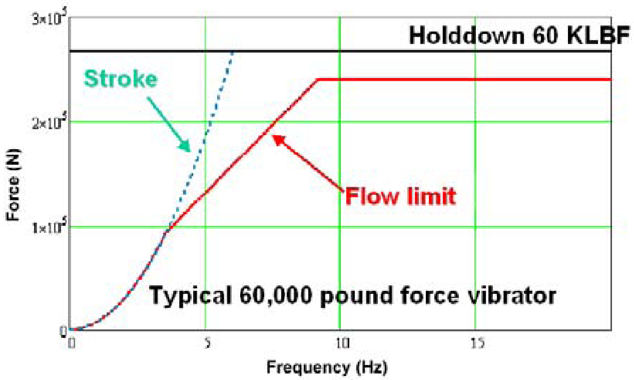
MEMS (Micro-Machined-Electromechanical-Systems) digital sensors are accelerometers and so have a lesser (-6-dB per octave, re. particle velocity) roll-off to low frequencies; see Figure 2, dotted green line. Additionally, they have a response to DC, this should make them good candidates for low frequency recording. However, the noise floor of these sensors, which is higher than that of a geophone/analog input 24bit system, may be a limitation for recording low amplitude low frequency signals. If the signal is strong these accelerometers would indeed be good candidates.

Other sensor types have emerged which show amplitude responses that are combinations of a geophone response and an accelerometer response. Some of these devices are analog but showed very low sensitivity, others are electronically controlled and so noise floor should be considered. They may offer some low frequency advantage with a less sharp roll-off compared to a geophone.

Earth unrest should also be considered. In the normal seismic band, earth tide and other low frequency motions are well below the surface ambient noise and so do not trouble us. As we go to lower frequencies these earth noises become stronger, again following a 1/frequency relation (Peterson model) and may need to be considered.

Conclusions

Given today's seismic technologies, there does not appear to be a universal solution to the challenges of low-frequency data acquisition. There are many variables to consider in choosing the most appropriate equipment. In high signal-to-noise environments and where we can anticipate good low frequency energy the MEMS digital sensors probably offer the cleanest approach. In low signal strength environments we may be better served using geophones in some form of array. The purpose of this paper is to bring these issues to the surface, make people aware of the considerations and encourage solutions to be developed.



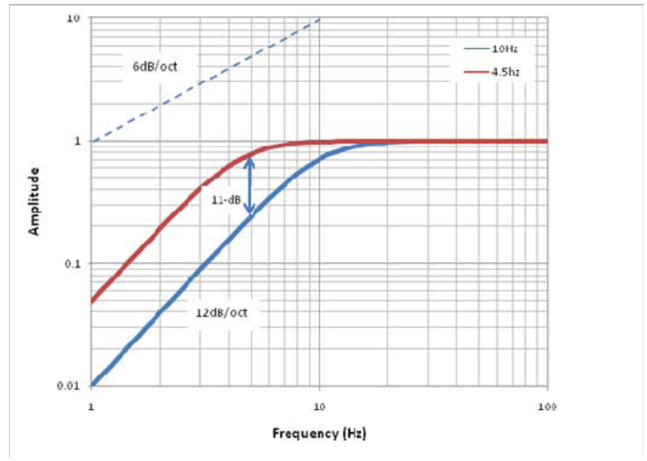
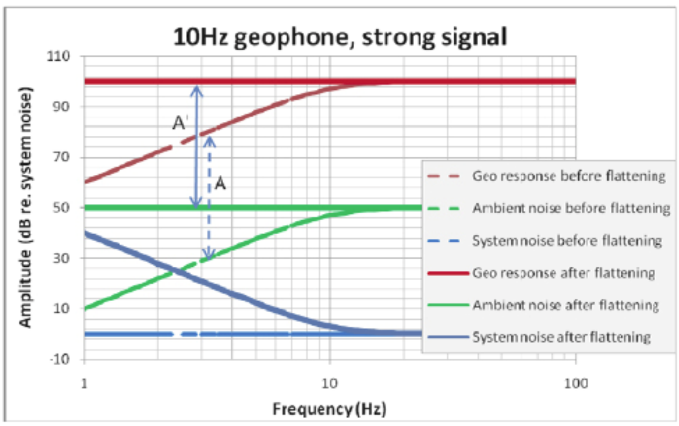


Figure 1. Low frequency vibrator system constraints.

Figure 2. Geophone response for natural frequency of 10Hz (blue) and 4.5Hz (red). A flat acceleration response converted to velocity (dotted green) for comparison of slopes.



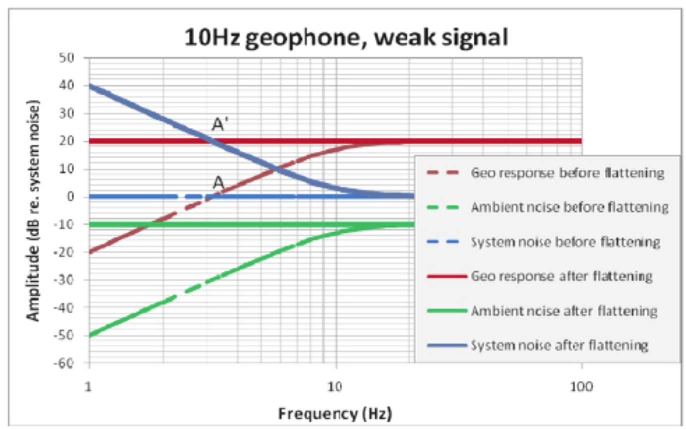


Figure 3. Inverse filtered geophone response (solid red) and the effect on system noise (solid blue) and ambient noise (solid green). Dynamic range A before filtering equals A', after filtering, as long as the signal is strong.

Figure 4. Similar to figure. 3 but now with weak signal. The geophone response falls below system noise at A and cannot be recovered by inverse filtering A'.

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