# Noise Floor of Quartz Crystal Sensors

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“The standard by which other standards are measured”

# Noise Floor of Quartz Crystal Sensors

## Abstract:

The noise floors of Quartz Crystal Resonator Barometers, Depth Sensors, Accelerometers, and Tiltmeters are described.

## Background:

A low instrument noise floor is very important for making good geophysical measurements (See http://paroscientific.com/pdf/P10_Quartz_Sensors_Solutions_Slides.pdf). Barometers, Depth Sensors, Accelerometers, and Tiltmeters using resonant quartz crystal sensing elements have a sensor resolution of a few parts-per-billion of full scale. Reference 1 describes counting and filtering methods that result in high resolution over an expanded frequency spectrum. The Appendix describes how the noise floor and resolution are calculated and the settings available with the Digiquartz® Nano-resolution Electronics.

All of the different sensors use equivalent quartz crystal resonators, oscillators and nano-resolution processing electronics and thus have similar noise floors that are related to the full-scale (FS) range of the sensors. The noise floor has been measured by completely isolating the quartz resonator from external inputs. Another way of making noise floor measurements is to determine the uncorrelated noise between two sensors.

## Noise Floor of Isolated Quartz Crystal Resonator:

Figure 1 shows the noise floor with fractional full-scale scaling and PSD units of (Fractional FS)$^2$/Hz. Figure 2 shows the noise floor in (Pa)$^2$/Hz for a barometer and a depth sensor of 3000 meters range. Figure 3 shows the noise floor in (m$^2$/s$^2$)$^2$/Hz for a ± 20 m/s$^2$ accelerometer and a ±10 degrees tiltmeter.

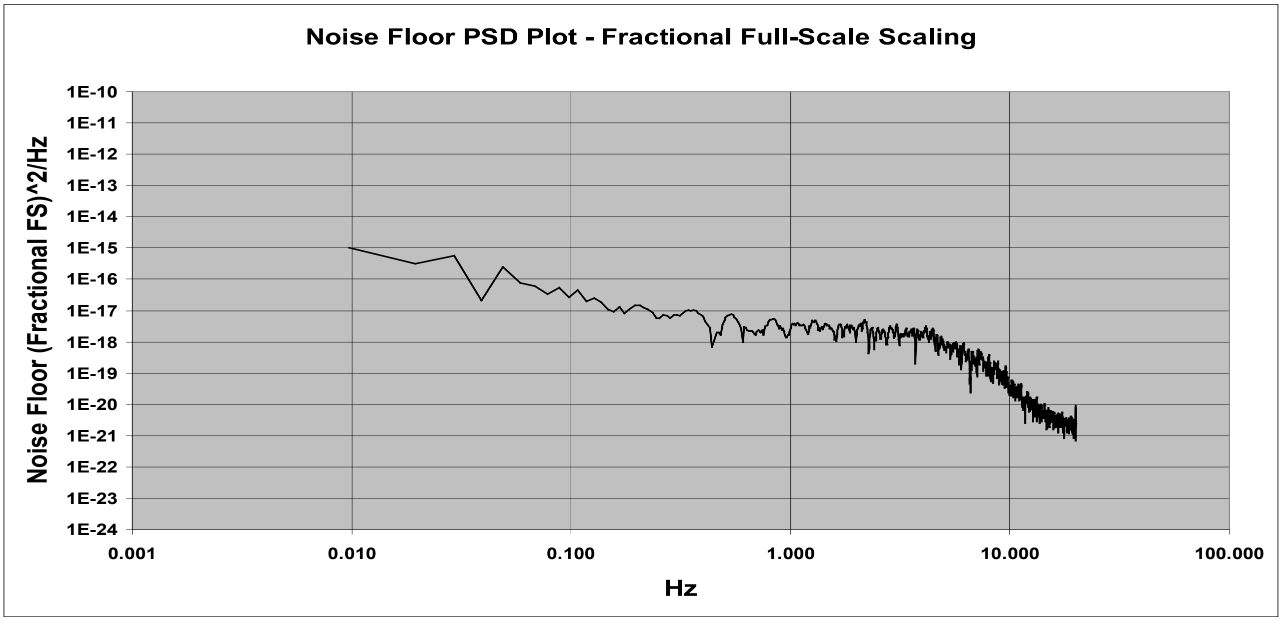


Figure 1

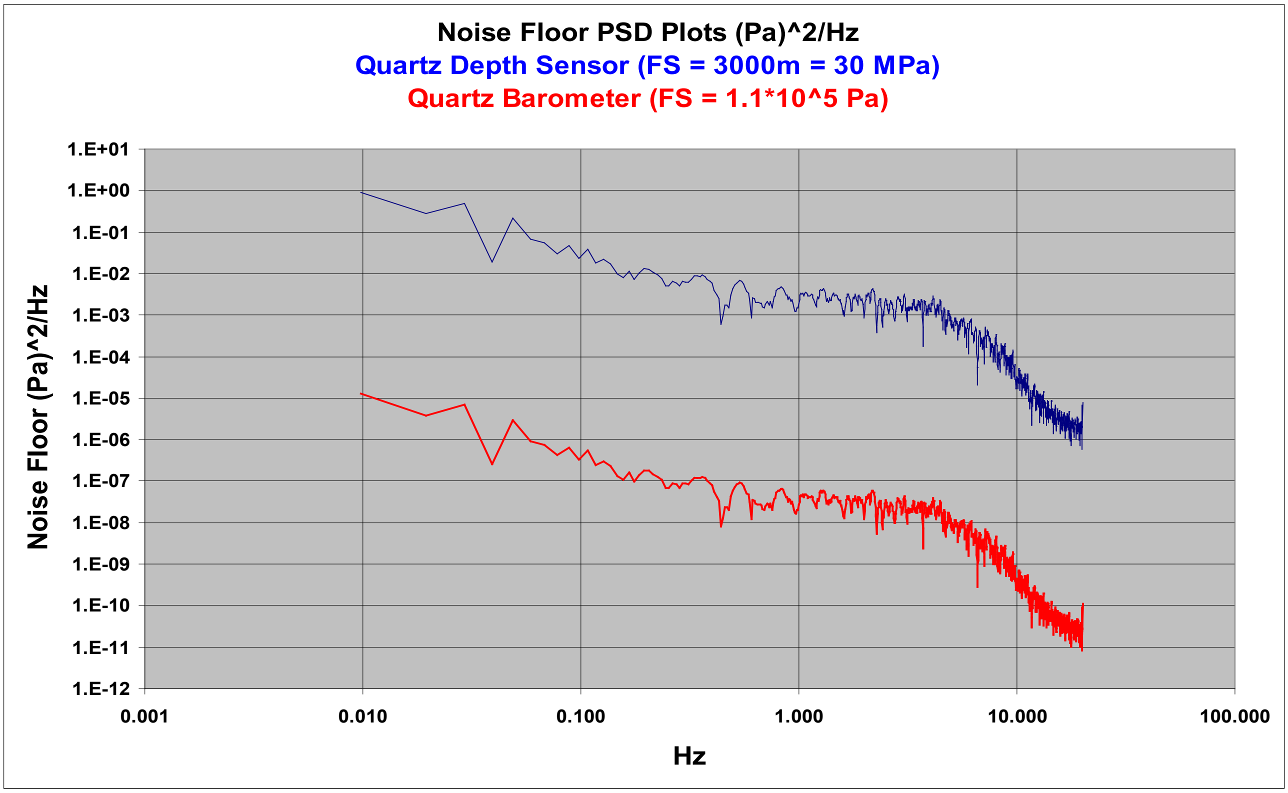


Figure 2

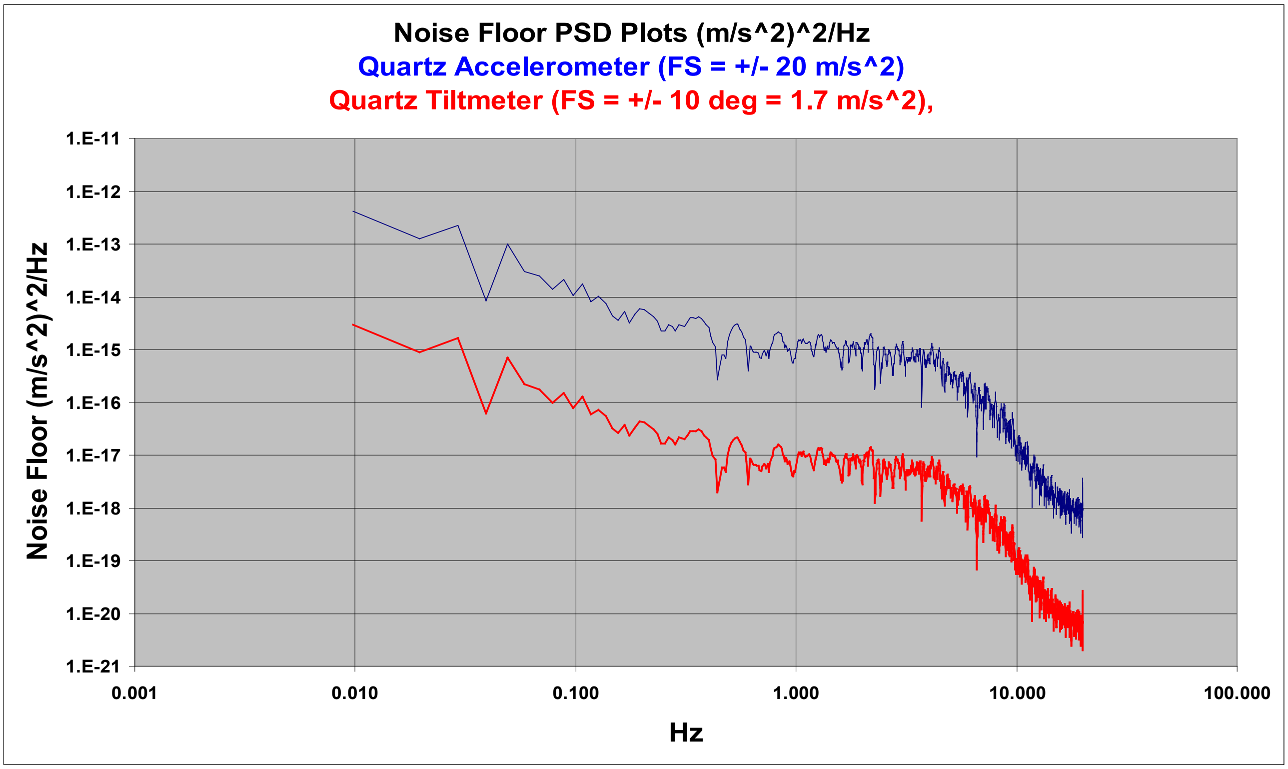


Figure 3

Figure 4 are PSD plots of ambient acceleration signals measured with a quartz accelerometer with a range of ±20 $m/s^2$ and various ranges of Force-Balance Accelerometers. The microseismic peak is clearly measured by the quartz accelerometer but not by the other accelerometers. The noise floor of the quartz accelerometer is shown as the solid red line and is generally 20 dB lower than the other sensors over the frequency range of interest.

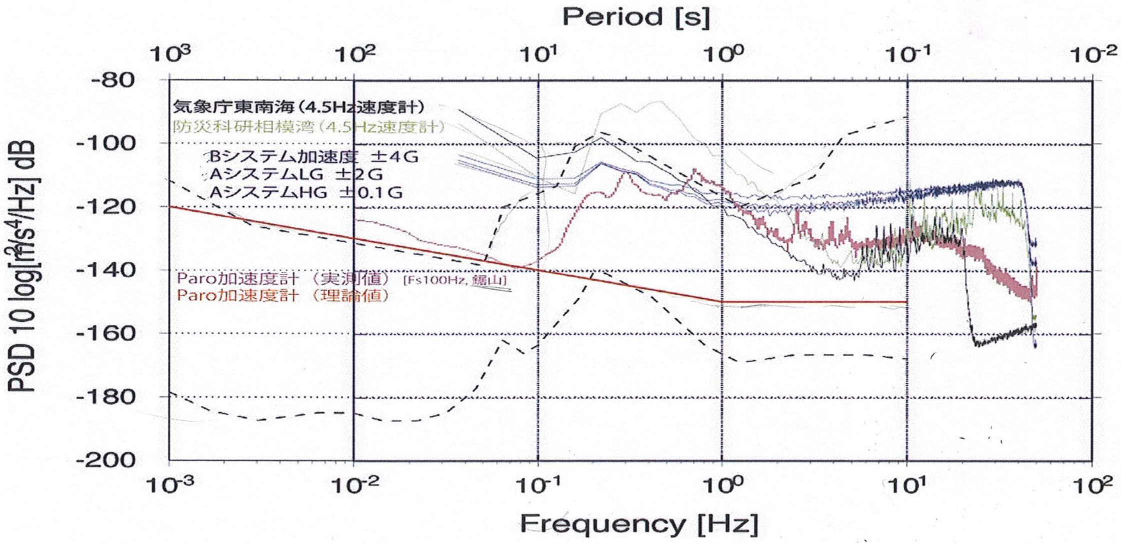


Figure 4 (Courtesy of Dr. Kanazawa)

Figure 5 shows spectra of ambient noise measured with the quartz accelerometer using an IIR filter with a 200 MHz counting frequency (Reference 1). Spectral lines above 1 Hz are associated with noise from nearby vibrating machinery.

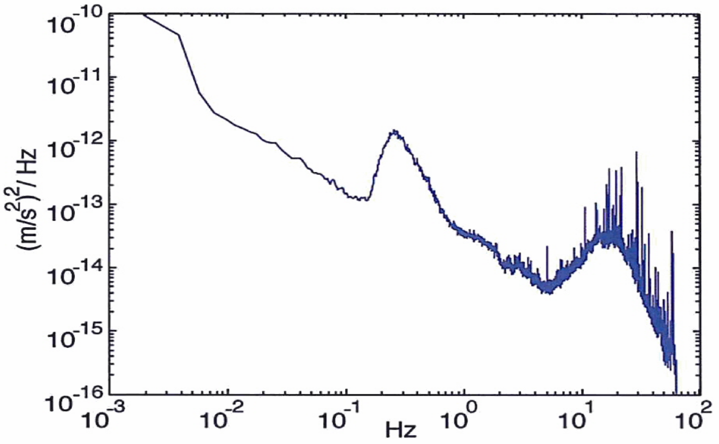


Figure 5 (Courtesy of Dr. Spahr Webb)

## Uncorrelated Noise Floor Measurements:

The sensor noise floor can also be determined by measuring the uncorrelated noise between sensors. Figure 6 shows the average and difference ambient spectra between two quartz accelerometers with ranges of ±20 m/s$^2$.

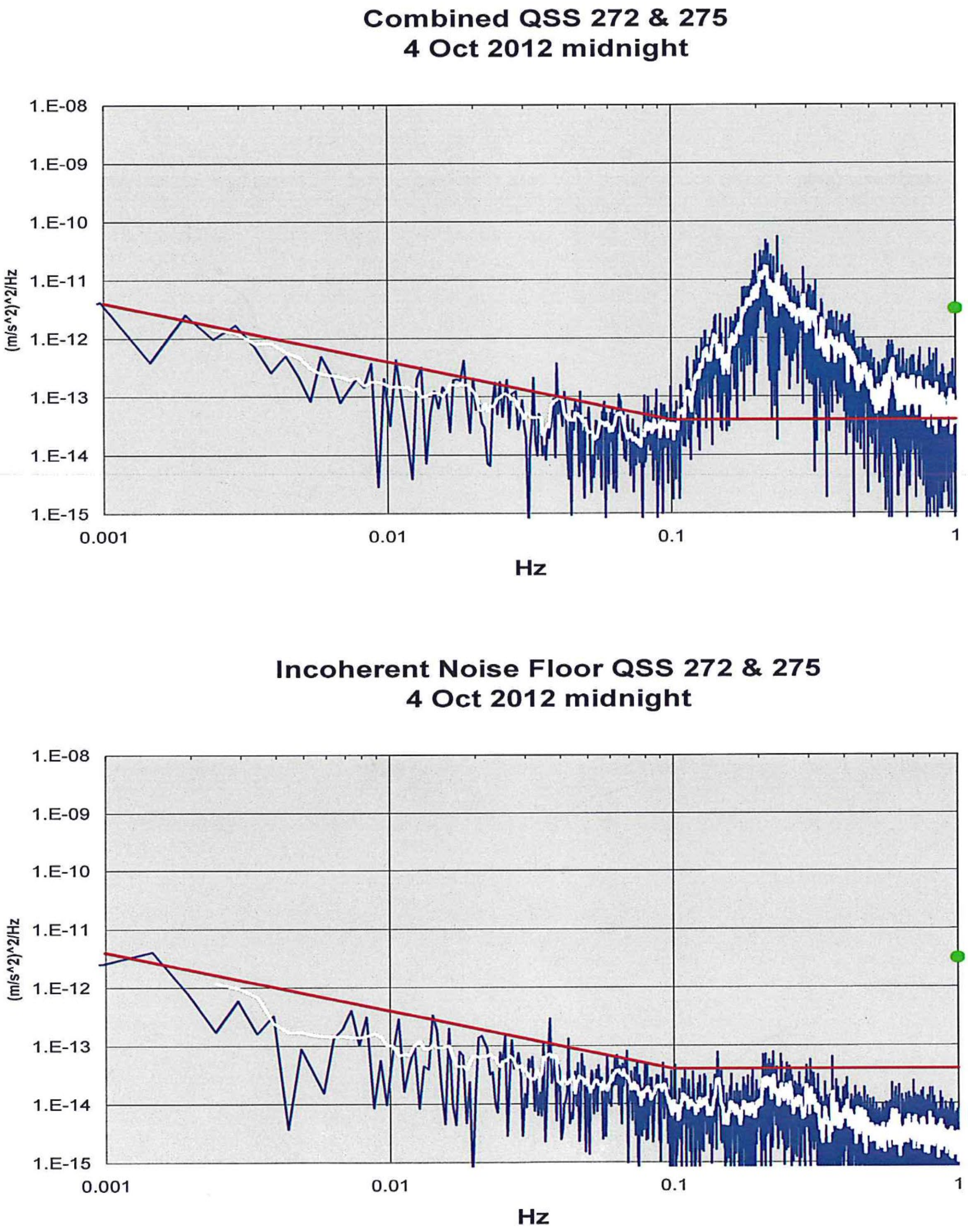


Figure 6

## Advantages of High-Resolution Absolute Sensors:

As discussed in Reference 1, there are significant advantages to using high-resolution absolute sensors over differential sensors. Differential pressure gauges can only measure fluctuating pressures over a limited range and clip (saturate) with large pressure signals generated by local earthquakes. Quartz absolute pressure gauges operate over a broad spectrum enabling observations of depth, oceanographic currents, tides, infragravity waves, microseisms, Rayleigh waves, and body waves from earthquakes. Similarly, traditional broadband seismometers and tiltmeters operate over a small fraction of 1G and do not have the range to measure strong seismic events. Traditional strong motion sensors do not have the sensitivity or stability to make long-term geodetic measurements. In-situ calibration methods have been developed for quartz absolute pressure sensors and quartz triaxial accelerometers to distinguish earth movements from instrument drift (http://paroscientific.com/pdf/G8097_Calibration_Methods_to_Eliminate_Sensor_Drift.pdf).

Figure 7 shows side-by-side comparisons of quartz triaxial accelerometers to broadband seismometers and tiltmeters deployed near the epicenter of the Tohoku earthquake. Clear measures of co-seismic signals and post seismic tilts were possible only with the quartz accelerometers because the seismometers and tiltmeters saturated not only for this 2013/10/25 event, but for almost all the seismic events.

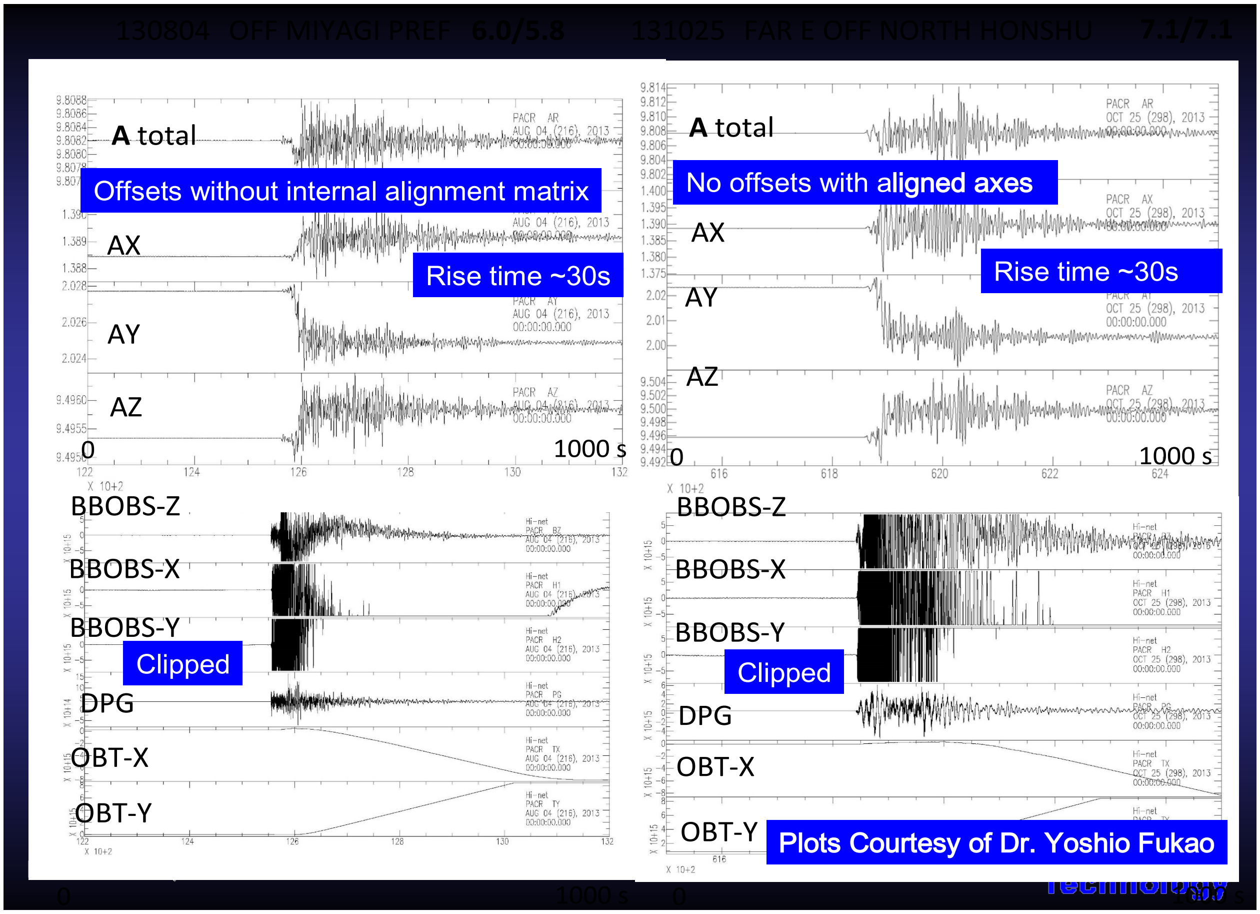
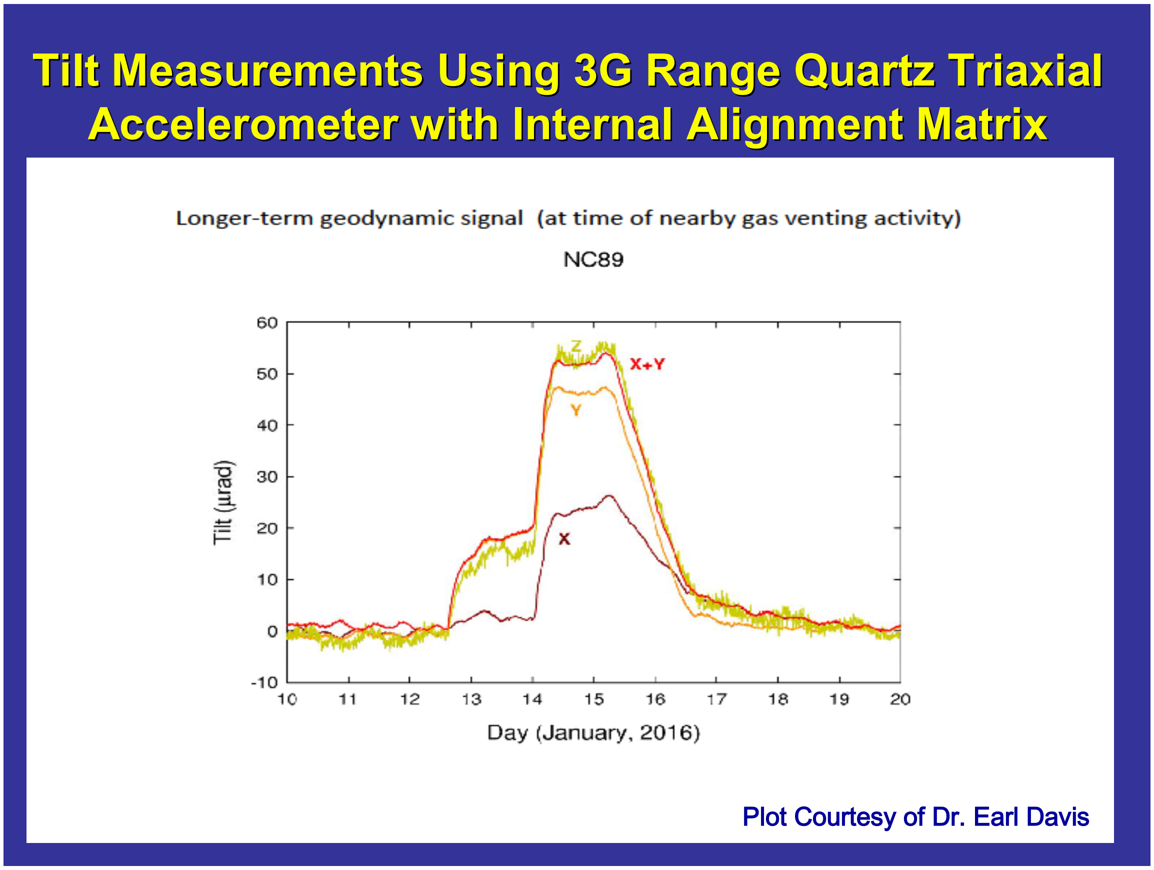


Figure 7

See “Sensing of upslope passages of frontal bores across the trench slope break of the Japan Trench” http://onlinelibrary.wiley.com/doi/10.1002/2015JC011432/full .

Comparative measurements between quartz triaxial accelerometers and depth sensors versus broadband seismometers have been made by Earl Davis and his colleagues at NEPTUNE-Canada. See (http://paroscientific.com/pdf/110%20Neptune-Triax%20&%20Pressure%20Update2016.pdf). Figure 8 shows micro-radian tilt measurements made with a ±30 m/s$^2$ (±3 G) full-scale Triaxial Accelerometer.



**Tilt Measurements Using 3G Range Quartz Triaxial Accelerometer with Internal Alignment Matrix**

Longer-term geodynamic signal (at time of nearby gas venting activity)

NC89

Plot Courtesy of Dr. Earl Davis

Figure 8

**Conclusion:**

The low noise floor associated with quartz resonator sensors allows high-resolution measurements of pressure, acceleration, and tilt over a frequency spectrum of interest to the geophysical community.

**References:**

Spahr C. Webb and Scott L Nooner, High-Resolution Seafloor Absolute Pressure Gauge Measurements Using a Better Counting Method, *Journal of Atmospheric and Oceanic Technology*, September 2016, http://journals.ametsoc.org/doi/10.1175/JTECH-D-15-0114.1

## Appendix

## On Noise floor, Resolution, and IA setting

The power spectral density (PSD) of the frequency output of an isolated quartz resonator is representative of the noise floor of our sensors. The PSD is calculated using the Welch periodogram method [1] based on the discrete Fourier transform of the signal.

Physically, the noise floor can be thought of as the ability to resolve a periodic signal relative to noise. The noise floor is a function of the frequency of interest. Since noise is randomly distributed, averaging a periodic signal for longer duration reduces the noise in the measurement or improves the resolution.

Resolution of the sensor is the noise (standard deviation) in the measurement of a signal at a specific frequency, f, over a specified measurement period or bandwidth. It is the square root of noise floor (PSD) multiplied by the bandwidth, or divided by the duration or period of integration, as follows:

$$Resolution(f) = \sqrt{PSD(f) * Bandwidth}$$

$$Resolution(f) = \sqrt{PSD(f) * \frac{1}{Duration}}$$

As an example, consider a 1-Hz sinusoid signal applied to the resonator. The noise floor of the crystal at 1 Hz with IA setting from 7 to 10 is roughly $3\times 10^{-18}$ in units of (fraction of full-scale)$^2$/Hz. The resolution at 1 Hz in 1-second is therefore = $\sqrt{3 \times 10^{-18} \times 1} = 1.7 \times 10^{-9}$. If the signal is captured for 10-seconds, then the resolution is = $1.7 \times 10^{-9} * \frac{1}{\sqrt{10}} = 6.32 \times 10^{-10}$.

If the signal amplitude is $1\times 10^{-8}$ or 10 ppb of full-scale, then the signal to noise ratio (SNR) in 1 second is 5 and in 10 seconds, it would be about 15.8.

The table in the Digiquartz® manual calculates the resolution at the corner frequency of the IIR filter and the duration of measurement is assumed to be the inverse of the frequency.

The fundamental noise floor increases as 1/f at low frequencies. As a consequence, for the same measurement duration, the noise in a measurement is independent of which frequency it is measured at below ~1 Hz. At frequencies above 1 Hz, the noise floor increases as $f^2$. Consequently, the resolution is diminished at high frequencies for the same measurement duration.

In practice, there are extra sources of noise at low frequencies such as temperature, temperature gradients, aging, etc. which can add to the fundamental noise of the crystal. Thus, it is best to keep the measurement duration relatively short but long enough to exclude short transients.

### IA setting and IIR Corner frequency

The low-pass IIR filter is a digital anti-aliasing filter that prevents bleeding of high frequency noise in to lower frequencies. The sampling frequency and the filter's corner frequency should be chosen depending on the frequency region of interest. Ideally, the corner frequency should be chosen to be well above the highest frequency of interest and the Nyquist frequency (which is half the sampling frequency) should be well above the corner frequency of the filter.

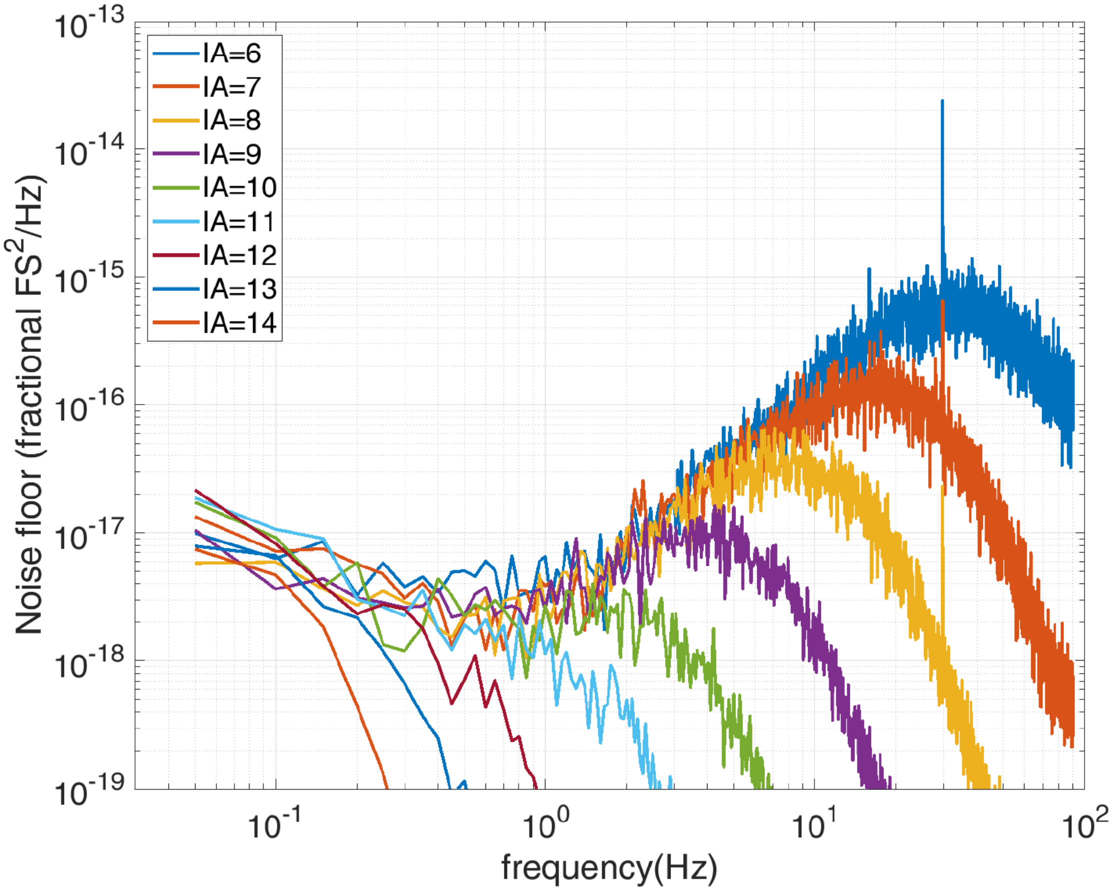


Figure 1

Figure 1 shows the noise floor of an isolated quartz resonator as measured by our Nano-resolution Electronics (intelligent sensors with firmware version Q2.00 or later). The plot shows the measured PSD for different IA settings and a sampling frequency of 180 Hz, which is the maximum allowable rate. At IA = 6 (or higher), aliasing is reduced below the intrinsic noise floor. For higher IA settings, the sampling frequency could be lowered by at least a factor of 2 per IA value, without compromising the noise floor.

Figure 2 shows the noise floor of the same resonator measured by a second set of Nano-resolution Electronics (Intelligent Sensors with firmware version R5.24 or M3.10 (MET4) or later). Note that the IA settings here correspond to different corner frequencies compared to those in the Q2.00 firmware version.

The above example was with an isolated quartz resonator. Real applications might have a different background spectra which might require adjusting the IA setting and sampling frequency accordingly. We recommend adjusting these parameters until sufficient anti-aliasing is achieved and the data rate is considered acceptable.

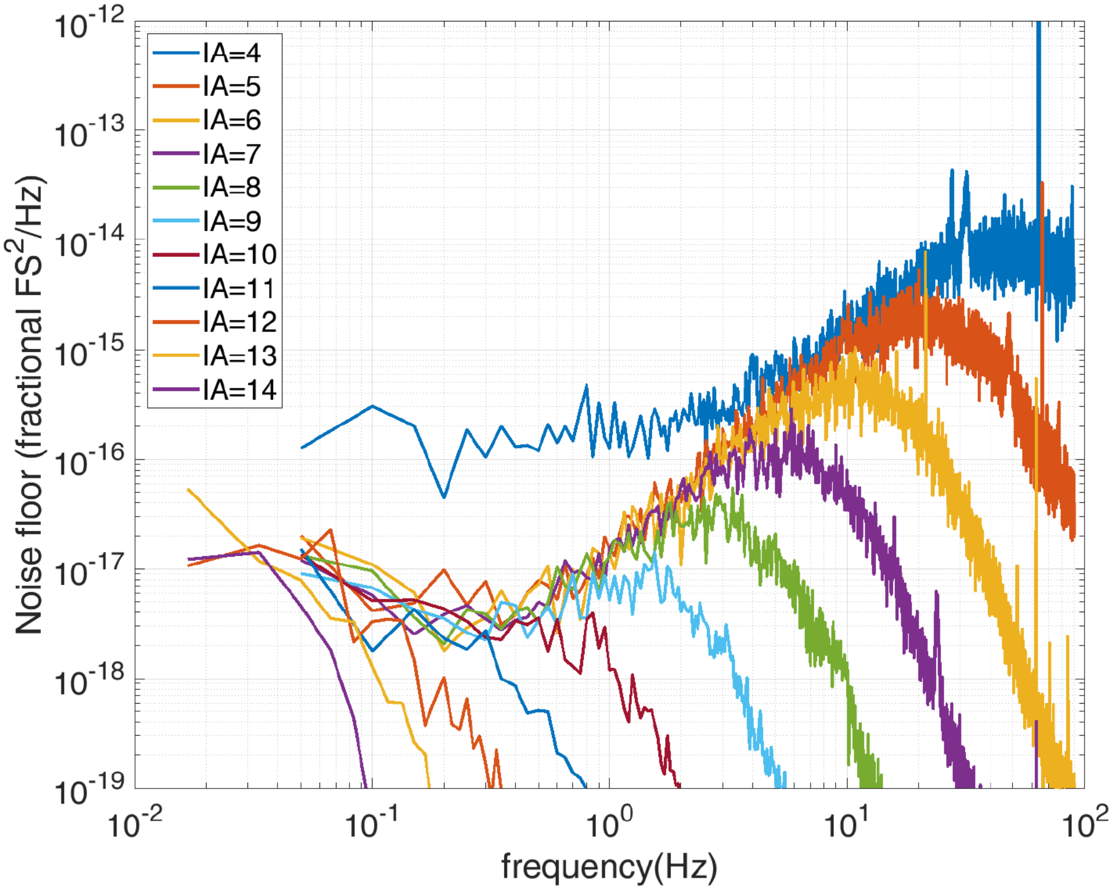


Figure 2

Appendix References:

1. P. D. Welch, ``The use of fast Fourier transforms for the estimation of power spectra: A method based on time averaging over short modified periodograms,'' IEEE Transactions on Audio and Electroacoustics, vol. 15, pp. 70-73, 1967.