Measuring Gravitational Forces Using Quartz Tiltmeters

Paroscientific, Inc.
4500 148th Ave. N.E.
Redmond, WA 98052, USA
Tel: (425) 883-8700 Fax: (425) 867-5407
www.paroscientific.com
support@paroscientific.com

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Krishna Venkateswara, Quartz Seismic Sensors, Inc. 2/5/2024

Gravitational force is amongst the weakest of the four fundamental forces and is the most difficult to measure precisely. Gravitational force measurements typically require highly specialized apparatus such as torsion balances, superconducting accelerometers, and atom interferometers (References 1-3).

Quartz Tiltmeters have been developed with parts-per-billion resolution. Figure 1 shows the measured noise floor plot of two Model QT-2 Tiltmeters (Full scale range = 0.2 radians). Measuring the difference between the two tiltmeters allows us to subtract the common background noise that is three orders of magnitude higher than the noise floor.

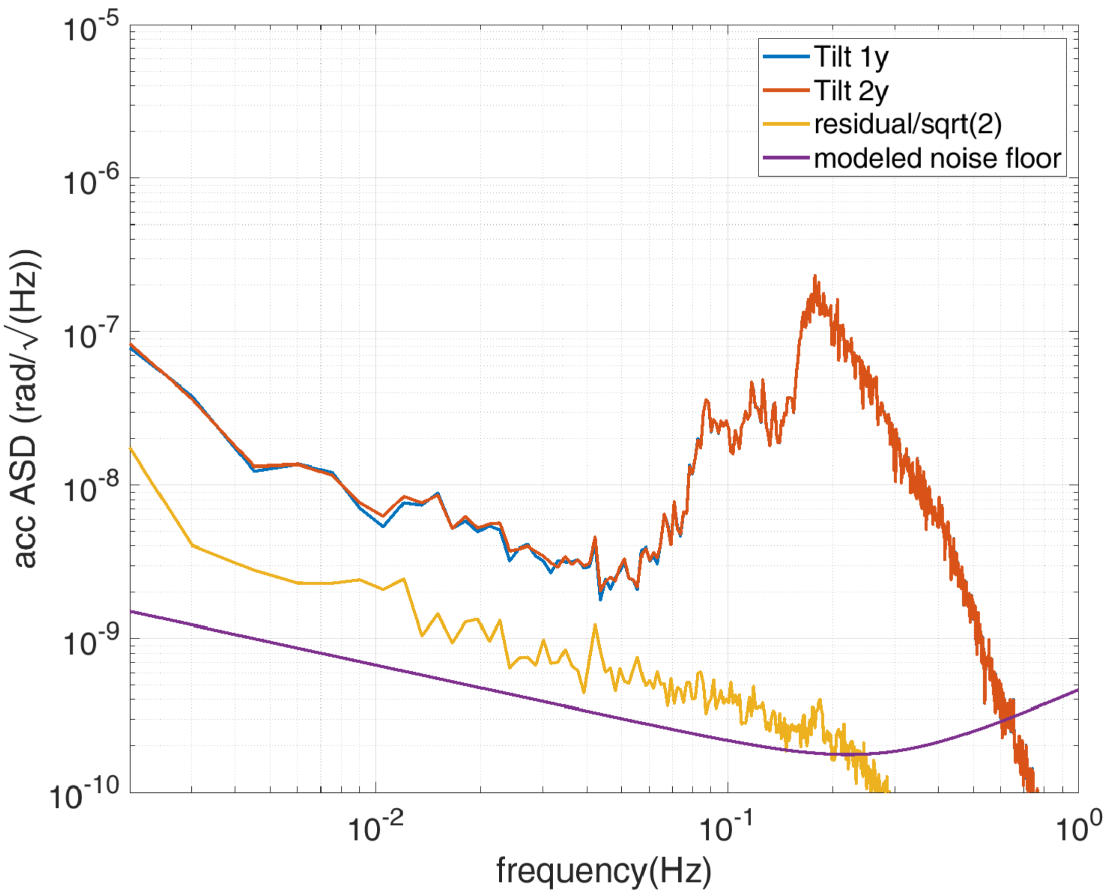
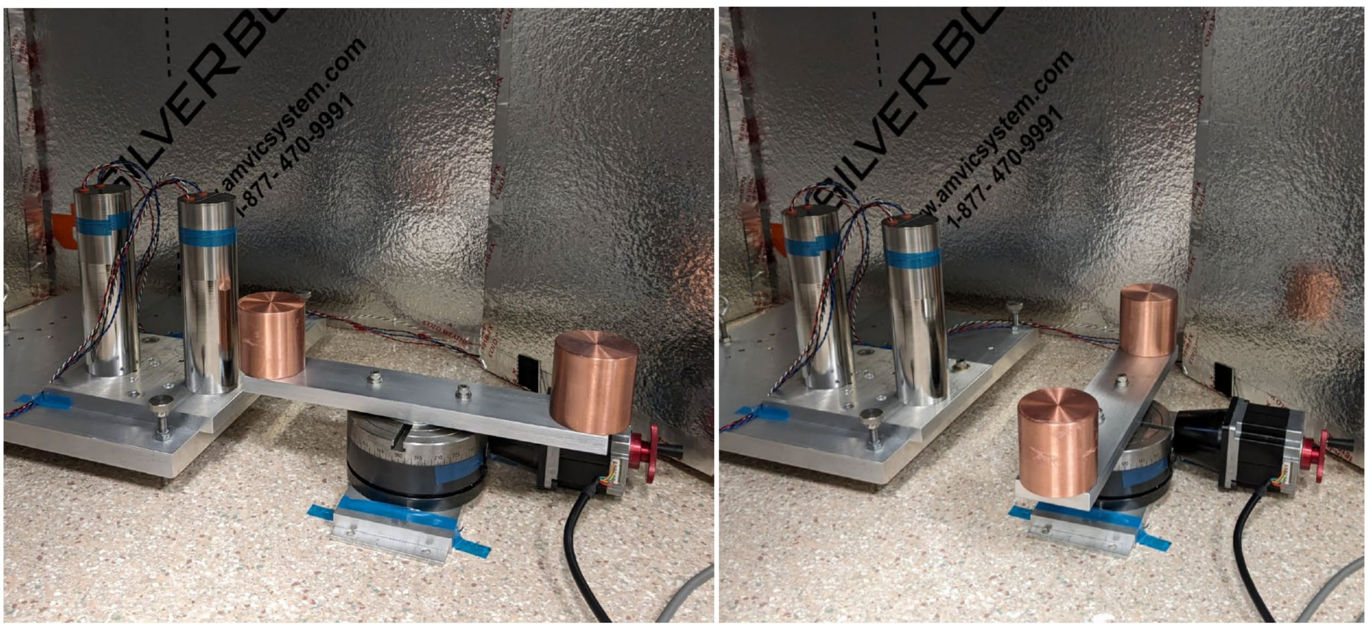


Figure 1: Noise floor of QT-2 Tiltmeters.

In the experiment described below, we demonstrate the high sensitivity of Quartz Tiltmeters by measuring the gravitational forces from a pair of copper masses mounted on a rotary table. The use of a pair of tiltmeters allows us to subtract the common background acceleration noise from the microseisms and any tilt produced due to residual mass imbalance in the rotor. The setup is shown in Figure 2. The y-channels of the tiltmeters were aligned with the line joining the tiltmeters.
When the mass is closest (Fig. 2A), the separation between the center of the copper mass and the center of the test mass is about 5.6 centimeters. The copper masses weighed about 0.9 kg and the aluminum parts were about 0.1 kg. Therefore, the expected gravitational acceleration from the copper and aluminum mass is $\frac{GM}{R^2} = 2.2 \times 10^{-8}$ m/s^2 or about 2.2 nano-g. When the mass is further away (Fig. 2B), the force falls off quickly due to the inverse square law. Likewise, the force/acceleration on the second tiltmeter due to the copper mass is also reduced by an order of magnitude due to the extra distance to it.



A B

Figure 2: Measurement setup.

Figure 3 shows a bandpass filtered (30-100 mHz) difference between the y-axis tilt signals converted to acceleration (units of m/s^2). The motor was turned ON at ~300 s and run for about 500 s. The rotor did one complete rotation every ~48 seconds (F=21 mHz). Since there are two masses on the rotor, the gravitational signal is exerted at twice the rotation frequency (2F) and at higher harmonics due to the non-linearity of the interaction. The first and last ~300 seconds show the background noise, which is a bit elevated compared to the sensor noise floor due to the lack of sufficient thermal shielding. The red line shows a simulated signal with simulated noise.

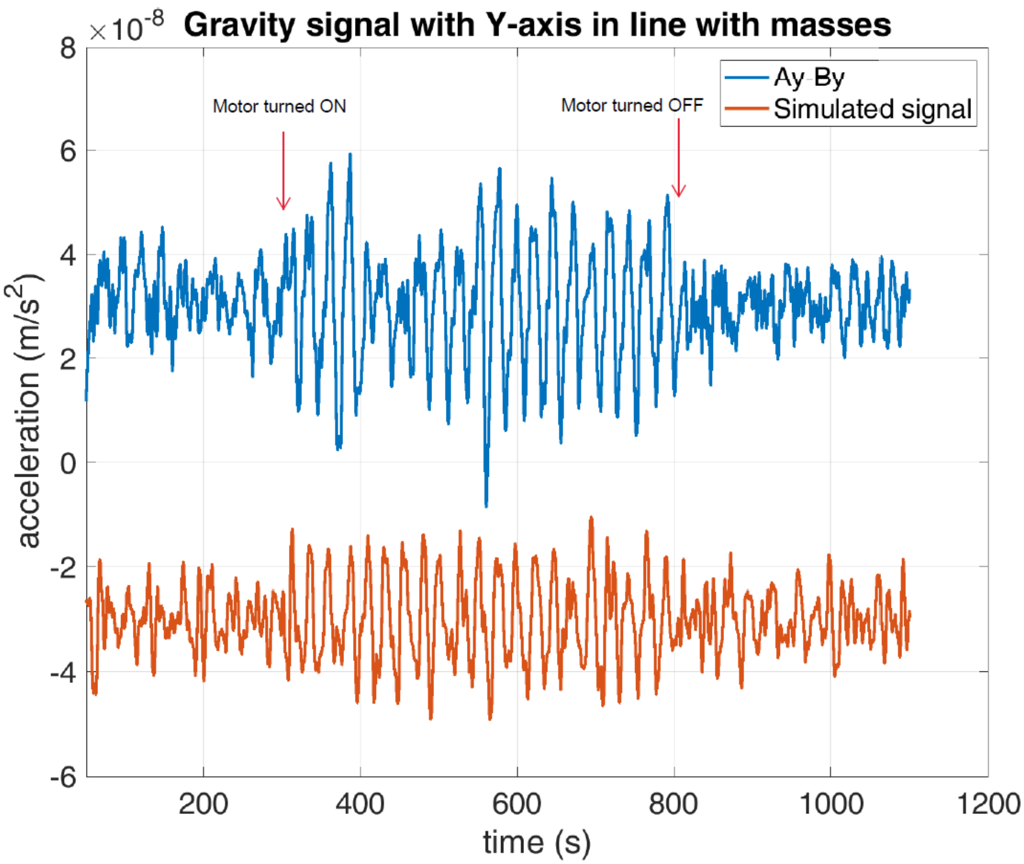


Figure 3: Difference between the two y-axis tilt signals (blue) and a simulated signal (red).

Figure 4 shows the Amplitude Spectral Density (ASD) of the time series signals between 300 and 800 seconds. The blue and red lines are the tilt signals, which show a large secondary microseismic peak and a steep drop-off at frequencies below 100 mHz. The difference between the two y-axis signals is shown in yellow, which is a little elevated from the theoretical noise floor due to the reasons explained earlier. The first tiltmeter (blue) shows a larger 2F signal as expected. Also, note that the 4F peak is visible (as expected) but not the 1F peak – which suggests that the rotor is well balanced and not producing any tilt signals. Given the limitations of measurement of distances and alignment, and the measurement resolution, the resolved signal is consistent with the expected gravitational signal.

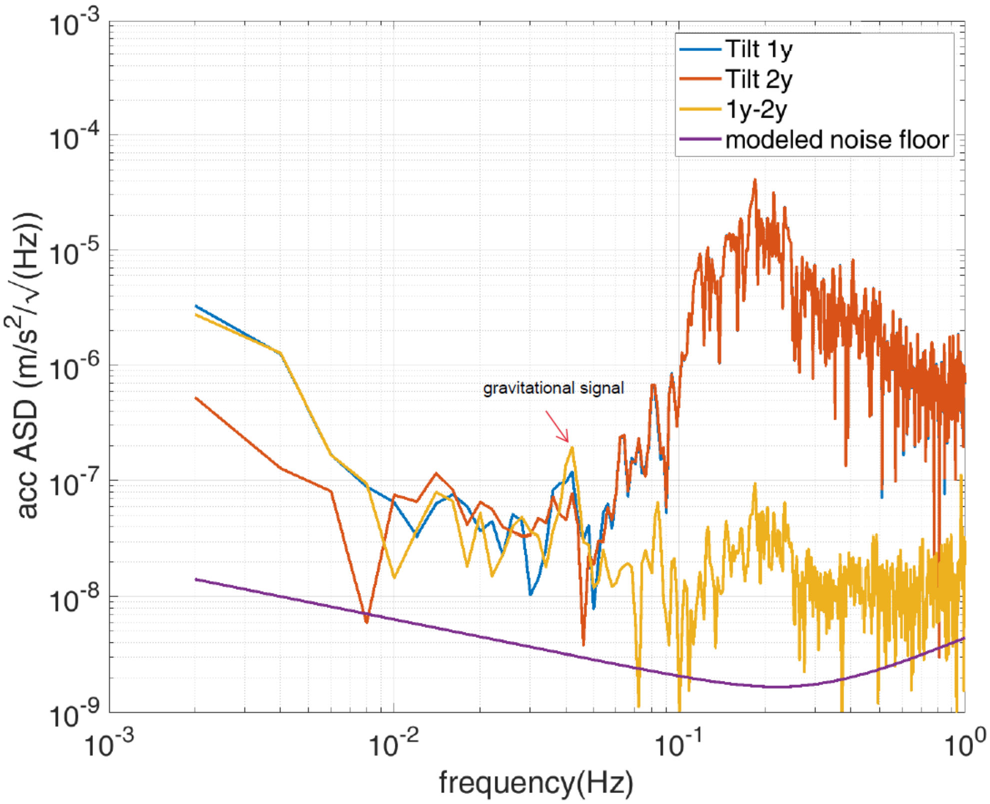


Figure 4: ASD of the y-axis tilt signals and difference during rotation of the masses.

Figure 5 shows the ASD of a very similar data set recorded with the Y-axis of both tiltmeters rotated by 90 degrees. As expected, no gravitational signal is visible in either channels or the residual.

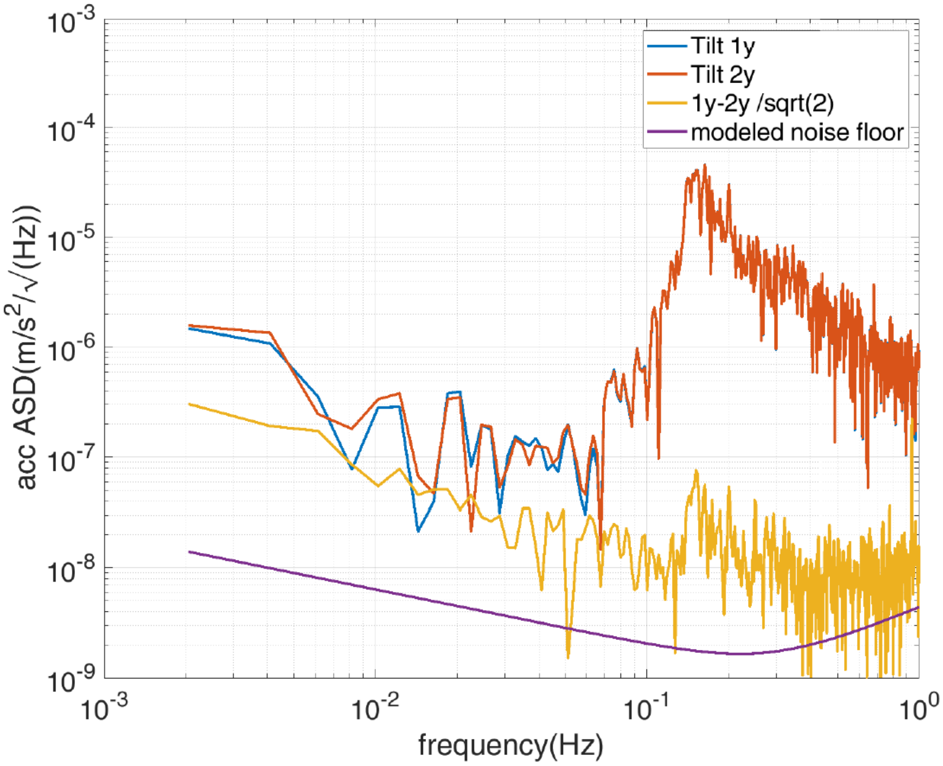


Figure 5: ASD of the signals with y-axis rotated by 90 degrees and rotor ON

Summary: The QT-2 tiltmeters can resolve the gravitational force from a small nearby mass.

References:

1. Gundlach, Jens H. and Merkowitz, Stephen M., "Measurement of Newton's Constant Using a Torsion Balance with Angular Acceleration Feedback", Phys. Rev. Lett., **85**, 2869—2872 (2000), doi: 10.1103/PhysRevLett.85.2869

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