Calibration Methods to Eliminate Quartz Sensor Drift

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Abstract:

In-situ calibration techniques have been developed to distinguish real seafloor movements from instrument drift. Long-term geodetic measurements may be made with pressure sensors that measure depth changes and triaxial accelerometers that measure tilt relative to Earth's plumb line gravity vector. The initial goal is to measure uplift or subsidence to better than 1 cm/year at depths of 4000 meters and a span of 1 kilometer. The requirement on pressure sensor stability is a few parts-per-million of full-scale per year (ppm/year). If the full-scale range of the triaxial accelerometers is 3 G's, then the requirement on accelerometer drift is also a few ppm/year.

Digiquartz® Pressure Sensors can be recalibrated in-situ by periodically venting from ocean pressures (A) to the ambient pressure (0) within the system housing. Subtracting the drift at 0 from the measured ocean depth readings, A, eliminated sensor drift to a few parts-per-million (ppm) of full scale with a standard deviation less than 1 ppm (< 1 cm/year).

Triaxial Quartz Accelerometers can be recalibrated in-situ relative to Earth's 1 G gravity vector. Over 1045 test cycles using this Accelerometer Calibration Method resulted in an average cycle-to-cycle non-repeatability of 0.10 micro-g. This is equivalent to a tilt of 0.010 cm at a span of 1 kilometer. Longer-term fits to determine drift had a standard deviation less than 0.5 cm.

Background:

Reference 1 analyzes the root causes of Quartz Sensor drift. There are 2 causes of drift that are related to whether the sensors are unloaded or loaded. Tests with the sensors mostly unloaded, 0, show that the resonator frequencies and indicated signal outputs at both zero and full-scale increase with time. One mechanism that can cause increasing frequency outputs is quartz crystal aging or "outgassing" whereby the resonator mass decreases with time. These frequency changes are converted to equivalent error forces through the conformance (linearization) equation. When the sensor is mostly at high loads, A, (e.g. near full-scale), the outputs at zero and full-scale both decrease with time. This is due to attachment or mechanism "creep" deflections that work against the spring rate of the mechanism to generate viscoelastic error forces.

The A-0-A Seafloor Pressure Calibration Method includes a switching valve internal to the sealed housing of the OBS, PIES, or casing line that delivers ocean pressures to the Quartz Pressure Sensors. Periodically, the valve is closed to the seawater pressure, A, and vented to the internal 1 bar absolute pressure, 0. Reference calibration points at 0, as easily measured with a barometer inside the housing, are used to compensate for the drift at ocean depths, A.

The single point reference to eliminate the drift of Quartz Triaxial Accelerometers is a comparison of the measured acceleration vector to Earth's 1 G gravity vector.

A-0-A Seafloor Pressure Calibration Method:

In-situ pressure calibrations require a stable or easily measured reference. Reference 2 describes "A Self-Calibrating Pressure Recorder for Detecting Seafloor Height Change" based on supplying a single pressure point near to the full-scale deployment depth from a piston gauge dead weight tester.

The new in-situ method of seafloor pressure calibration, A-0-A, is based on a metrology technique, 0-A-0, developed by the National Metrology Institute of Japan-(AIST) (Reference 3). The 0-A-0 Metrology Method releases pressure to atmospheric pressure, 0, after each calibration point, A, and the 0 reading is used as an offset correction for the next reading. The A-0-A Seafloor Pressure Calibration Method includes a switching valve internal to the OBS, PIES, or casing line that delivers ocean pressures to the Quartz Pressure Sensors. Periodically, the valve is closed to the seawater pressure, A, and vented to the internal 1 bar absolute pressure, 0. Reference calibration points at 0, as easily measured with a barometer inside the housing, are used to compensate for the drift at ocean depths, A. Figure 1 shows an example of A-0-A testing of 100 MPa (10,000 meters) sensors. Data were provided by Dr. Hiroaki Kajikawa of the National Metrology Institute of Japan--(AIST). Reference 4 applies mathematical models to analyze and fit the drift data.

Full scale pressure was applied at a constant 100 MPa for over 4 months except for 8 brief A-0-A sequences. The 8 points of drift at atmospheric pressure, 0, were linearly connected and subtracted from the measured readings at A. Figure 1 shows the Drift at Full Scale (A = 100 MPa), Drift at 0 (8 points linearly connected), and the Residuals after subtraction.

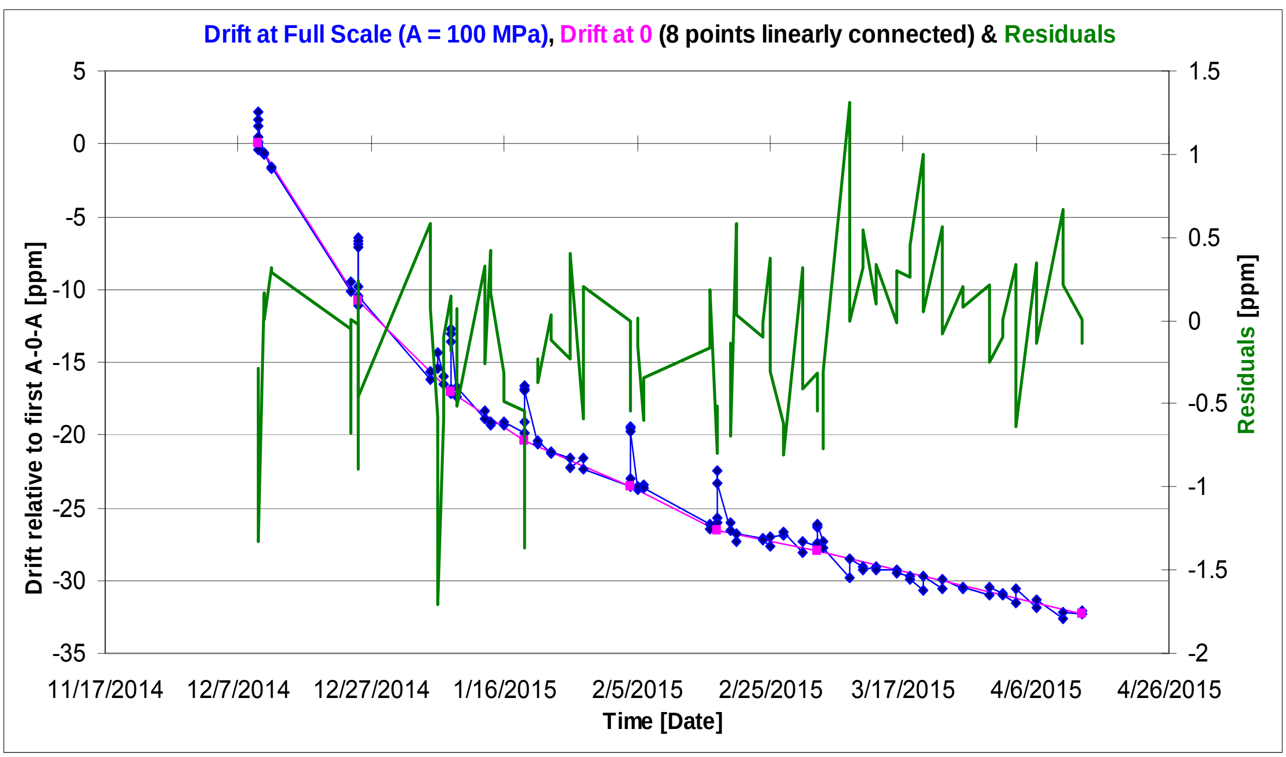
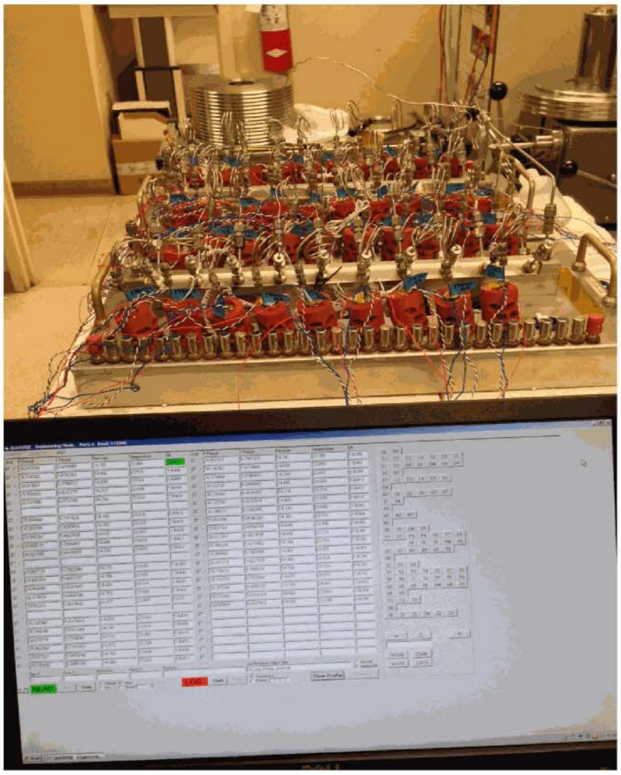
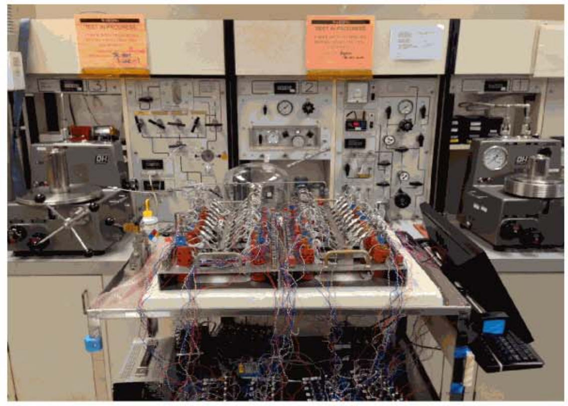


Figure 1

Testing of the A-0-A calibration method was expanded to include 37 standard production pressure sensors with a range of 4400 psi (3000 meters). The experimental setup is pictured in Figure 2.





The A-0-A Calibration Method to Eliminate Drift was tested on a group of (37) 4400 psi (3000 meters) Digiquartz Pressure Sensors.

The 37 sensors were held at 4400 psi, (A) except for brief excursions to ambient atmospheric pressure, (0). A DHI piston gauge standard provided the 4400 psi, (A), inputs and our Nano Baro measured the atmospheric pressure, (0).

Figure 2

A plot of average drift at full scale pressure, (A), atmospheric pressure, (0), and A-0-A Stability (Span) is shown in Figure 3. Over this timeline, the average drifts at full scale minus the drifts at atmospheric pressure are within +/- 5 parts-per-million of full-scale (0.02 psi or 1.4 cm).

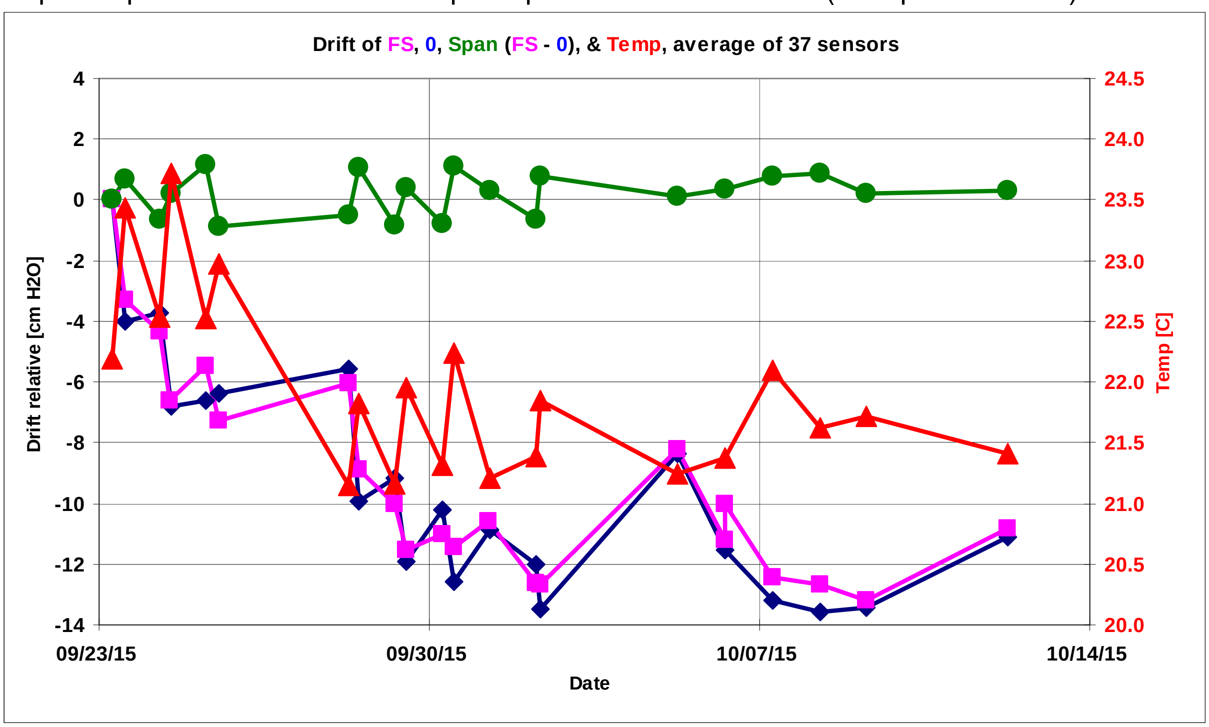


Figure 3

The A-0-A calibration method was applied to 20 sensors (3000 meters range) from Nov. 3, 2015 to Dec. 29, 2015. At the end of the test, 19 sensors were released to atmospheric pressure for several months until another simulated full-scale deployment from April 19, 2016 to August 19, 2016. The results of the two tests are shown in Figures 4 and 5. During the two simulated deployments, the average drifts of span are again within +/- 5ppm of full scale (1.4 cm).

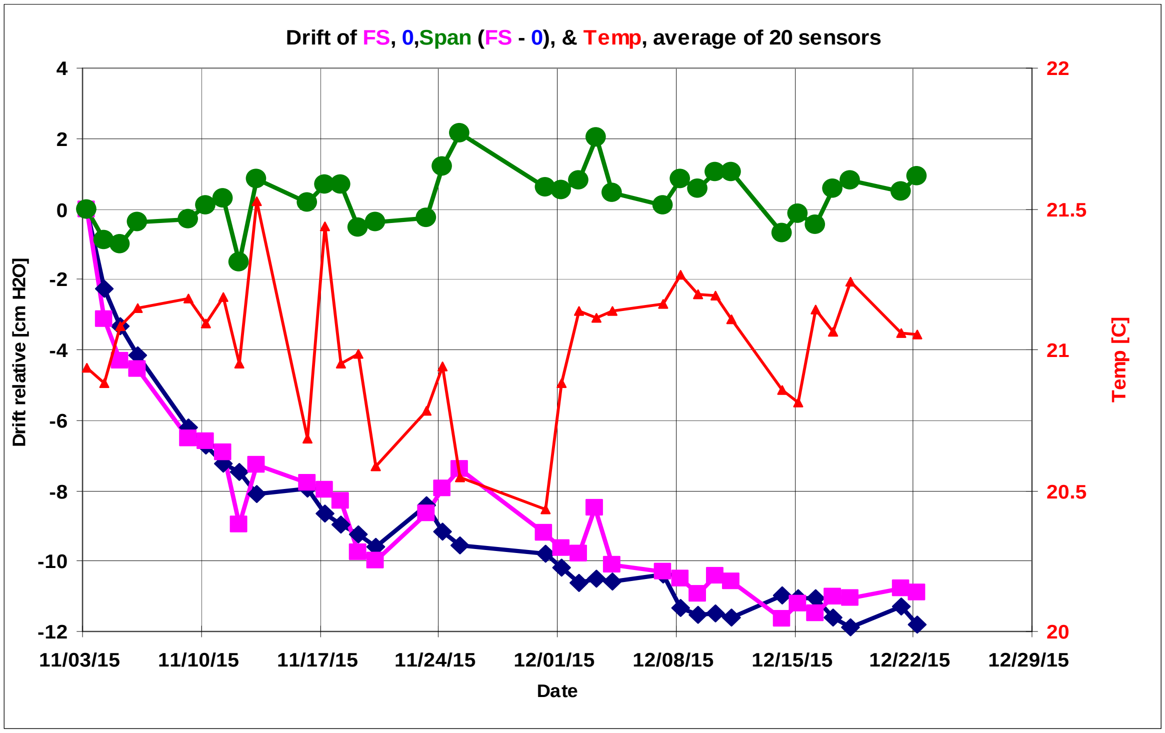


Figure 4

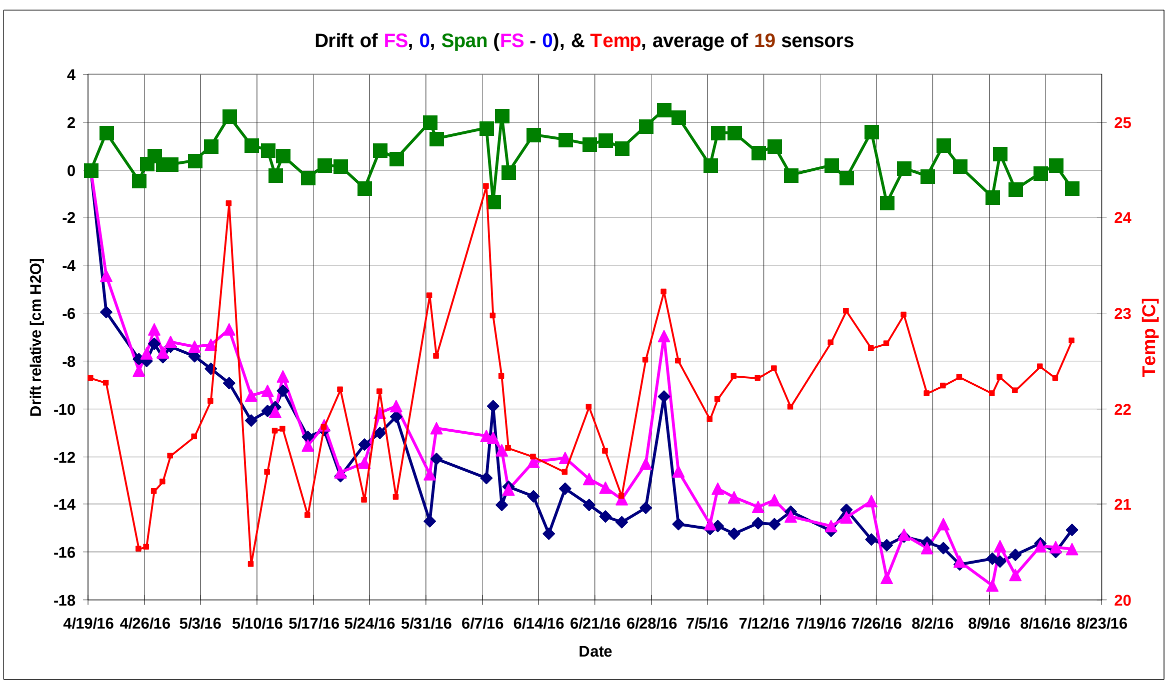


Figure 5

A-0-A Ocean Tests at the Monterey Accelerated Research System (MARS)

Seismic + Oceanic Sensors (SOS) have been developed for disaster warning, geodesy, and climate change measurements (Reference 5). SOS includes the in-situ calibration method, A-0-A, to allow long-term measurements of geodesy and sea level changes. The University of Washington deployed the SOS module at MARS in mid-June of 2017. A major objective of the MARS experiment was to confirm that the A-0-A in-situ calibration method eliminates pressure sensor drift. Three years of drift testing in the laboratory were done using a primary standard piston gauge DWT to measure the span drift at A. The University of Washington SOS deployment at MARS determines the span stability by measuring the difference in pressure readings between two synchronized Absolute Pressure Gauges (APGs).

Periodically, the 2 Absolute Pressure Gauges are switched from seawater pressure, A, to the internal housing barometric pressure, 0, for 5 minutes and then returned to A. The 4th minute averages at 0 are calculated for (P1-Barometric), (P2-Barometric), and (P1-P2). The 0 offsets for P1 and P2 drifted in opposite directions with a relative drift at 0 of about 1 hPa. The drift readings at 0 were then subtracted from the readings at A to determine the span stability.

As shown in Figure 6, drift has been eliminated to a fraction of 1 millimeter (less than 0.1 ppm of full-scale per year). The standard deviation is less than 0.01 hPa (0.1 mm of water).

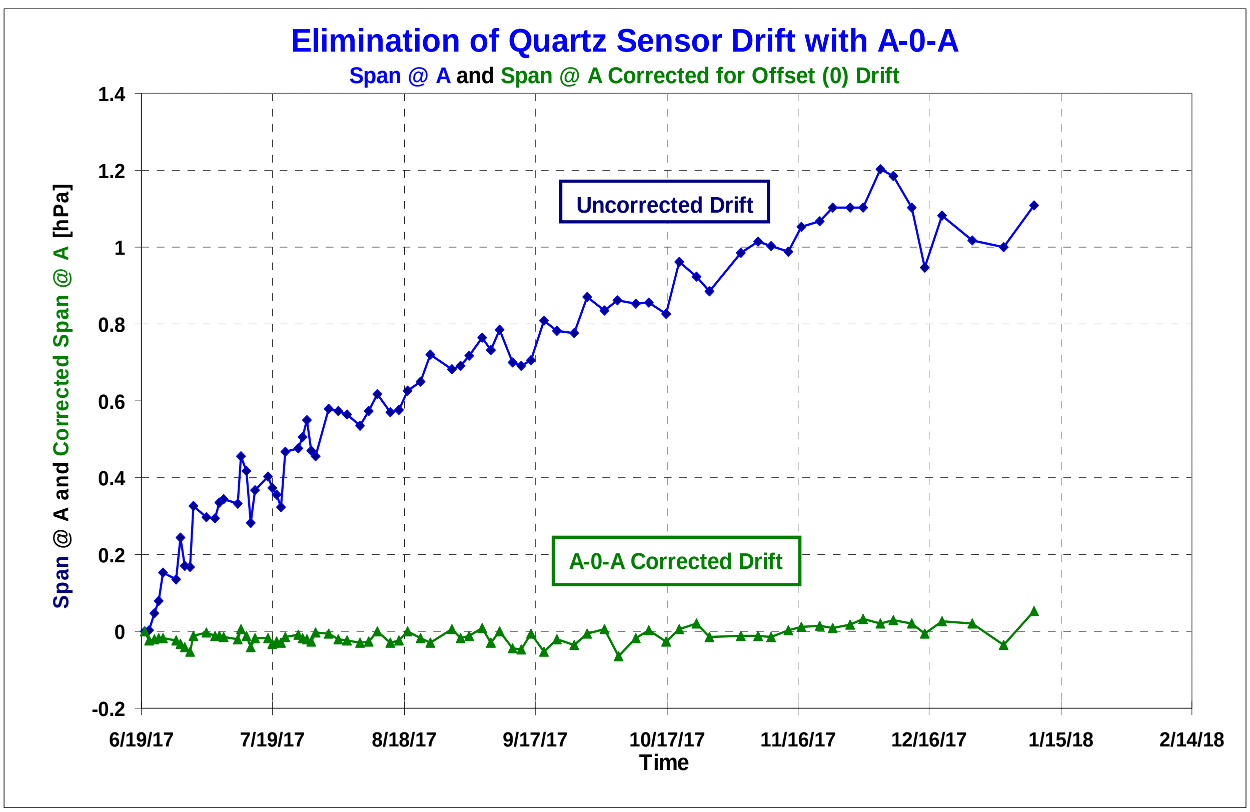


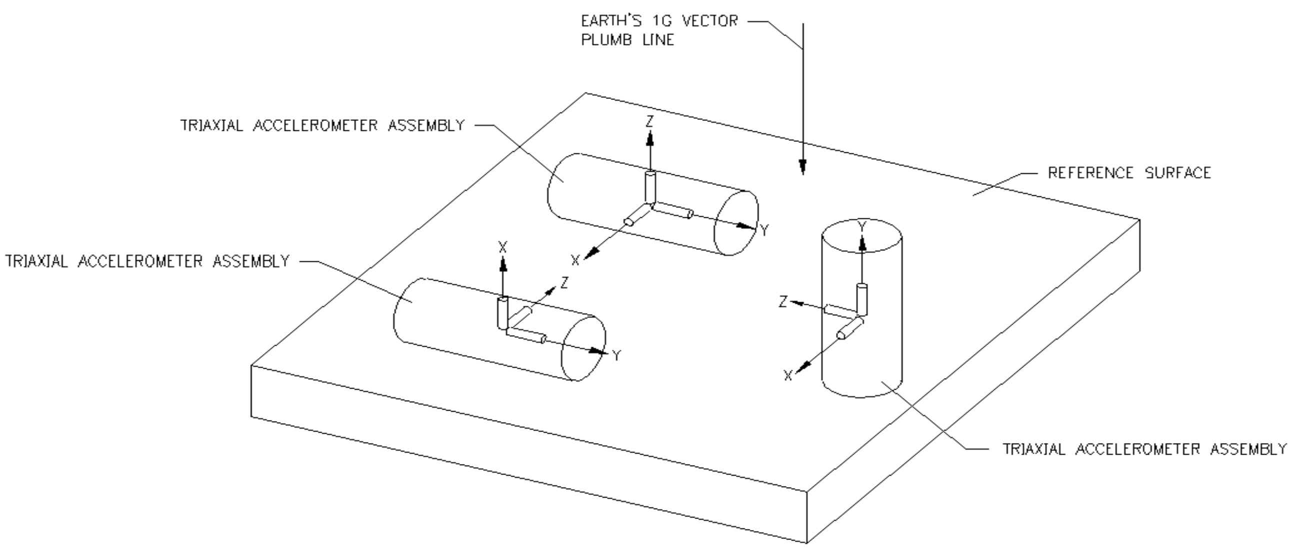
Figure 6

TRIAXIAL ACCELEROMETER ASSEMBLY AND IN-SITU CALIBRATION METHOD FOR IMPROVED GEODETIC AND SEISMIC MEASUREMENTS*

There is a need for a device and in-situ calibration method for improved seismic and geodetic measurements. Traditional strong motion sensors do not have the sensitivity or stability to make good long-term geodetic measurements. Traditional broadband seismometers and tiltmeters operate over a small fraction of Earth's 1G gravity vector and do not have the range to measure strong seismic events and have no absolute reference for long-term measurements.

The goal is to make improved surface, subsurface and submarine measurements of seismic events together with geodetic measurements of earth movements such as tilt, subsidence and uplift. The initial geodesy requirement is to measure earth movements to better than 1 centimeter per year at a span of 1 kilometer. This is equivalent to a tilt of 10 micro-radians or a 10 micro-G's tilt (sine) component of Earth's 1 G static gravity.

In-situ calibrations are performed by rotating a triaxial accelerometer assembly relative to Earth's plumb line and measuring the components of the 1 G static gravity vector on three orthogonal axes. The triaxial acceleration assembly is calibrated with an internal alignment matrix such that measurements of Earth's gravity vector are rotationally invariant with respect to the direction of Earth's plumb line irrespective of the orientation of the triaxial assembly on the reference structure. Drift of the triaxial accelerometer assembly is compensated for by measuring the changes in the values of the invariant static gravity vector for each axis and correcting for the drift with new calibration coefficients.



ROTATION OF TRIAXIAL ACCELEROMETER ASSEMBLY TO ALIGN EACH ORTHOGONAL AXIS, X-Y-Z, WITH EARTH'S 1G PLUMB LINE.

*J. M. Paros, "Triaxial Accelerometer Assembly and In-situ Calibration Method for Improved Geodetic and Seismic Measurements." US Patent 9,645,267, issued May 9, 2016.

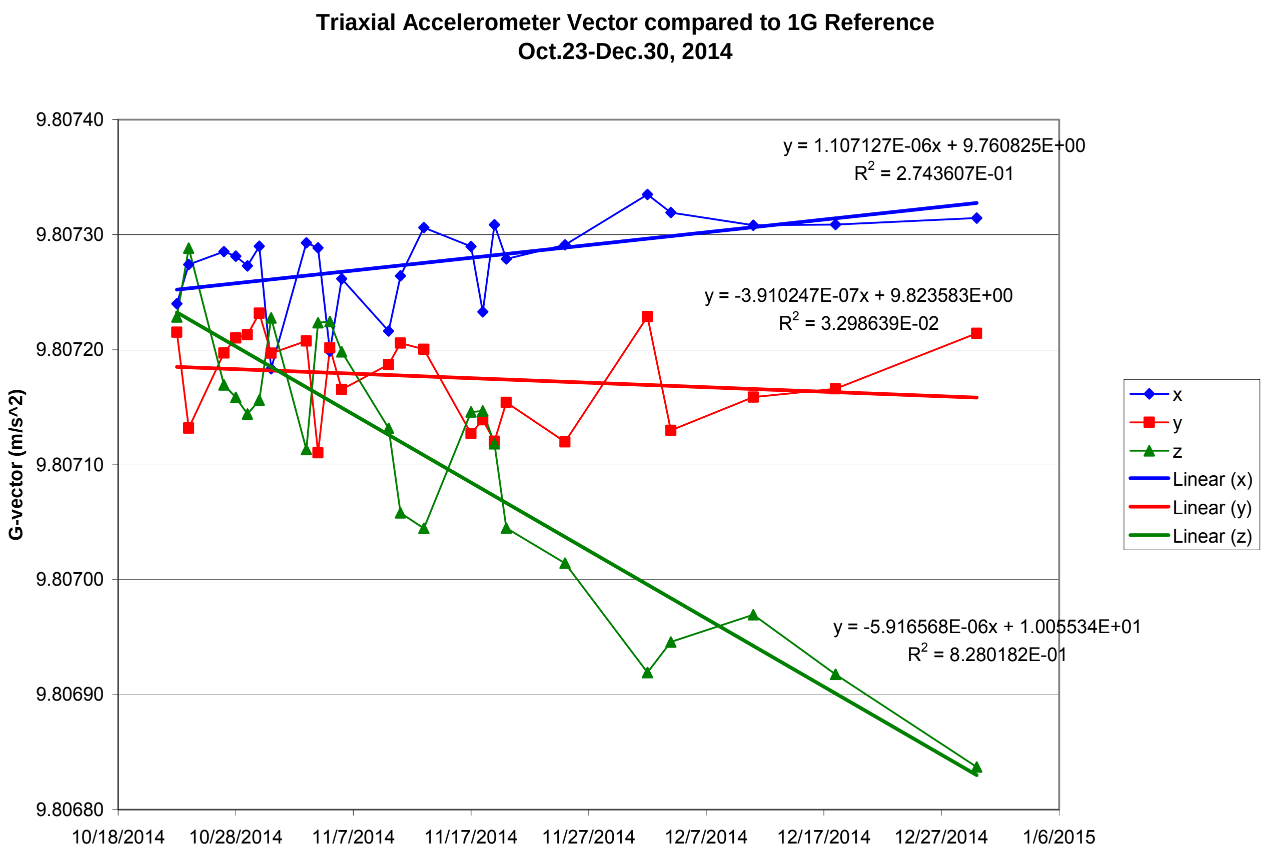
From September 9 to December 30, 2014, tests were performed to determine the repeatability of this recalibration technique. The triaxial assembly consisted of 3 orthogonal nano-resolution quartz crystal accelerometers with a full scale range of 20 m/sec^2 (2 G's). The triaxial acceleration assembly was calibrated with an internal alignment matrix such that measurements of Earth's gravity vector are rotationally invariant with respect to the direction of Earth's plumb line gravity vector. A series of 1045 rotations (Flips) were made to align each axis (X, Y, Z) with Earth's 1G vector plumb line and return. The rotations of each axis do not need to be perfectly aligned with Earth's gravity vector. The drift is apportioned by the changes in output over time when nominally aligned with Earth's gravity vector. For example, if the nominal alignment is within 5 degrees then the drift can be apportioned to 99.6% since the cosine of 5 degrees is 0.996.

Results are shown in the table below:

Average of 337 flips along X axis (µg)	Average of 338 flips along Y axis (µg)	Average of 340 flips along Z axis (µg)	**Average of total 1045 flips (µg)**
0.09 ± 0.04	0.09 ± 0.03	0.13 ± 0.06	**0.10 ± 0.05**

For a total of 1045 Flips, the average non-repeatability = 0.10 µg.
This is equivalent to a tilt non-repeatability of 0.010 cm. on a 1 kilometer baseline.

Linear fits were applied on the data points from October 23 to December 30 to assess the long-term repeatability. The data points and the linear fits are shown in the plot below:



The standard deviation of the data points from the linear fit for each axis is listed in the table below:

Standard deviation (1σ) of the x fit		Standard deviation (1σ) of the y fit		Standard deviation (1σ) of the z fit	
3.25957E-05	m/s^2	3.83282E-05	m/s^2	4.88152E-05	m/s^2
3.323650032	µg's	3.908165203	µg's	4.977485237	µg's

For a period of 2 months, the standard deviation of the G-vector readings from a linear fit was within 5 µg's for each axis. This is equivalent to a tilt of 0.5 cm. on a 1 kilometer baseline.

Conclusion:

Stable, long-term geodetic measurements can be made with in-situ calibration techniques to eliminate drift. Nano-Resolution Quartz Pressure Sensors can be recalibrated by periodic venting to the easily measured ambient pressure of the system housing. Triaxial Quartz Accelerometers can be recalibrated relative to Earth's 1 G gravity vector. The goal is to make long-term measurements of subsidence and uplift to better than 1 centimeter. Laboratory tests of both pressure sensors and accelerometers have shown repeatable measurements equivalent to a fraction of the 1 centimeter goal.

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We would also like to acknowledge the excellent work of Y. Fukao, H. Sugioka, A. Ito, and H. Shiobara in their development of a new Acceleration Ocean Bottom Seismometer (AOBS).

References:

(1) J. M. Paros and T. Kobayashi, "Root Causes of Quartz Sensors Drift", G8101 Paroscientific, Inc., Technical Note

(2) G. Sasagawa and M.A. Zumberge, "A Self-Calibrating Pressure Recorder for Detecting Seafloor Height Change" , IEEE J. Ocean Eng., 38, 447-454, 2013

(3) H. Kajikawa and T. Kobata, "Reproducibility of calibration results by 0-A-0 pressurization procedures for hydraulic pressure transducers", Measurement Science and Technology, 25, (2014).

(4) J. M. Paros and T. Kobayashi, "Mathematical Models of Quartz Sensor Stability", G8095 Paroscientific, Inc., Technical Note.

(5) J. M. Paros and T. Kobayashi, Seismic + Oceanic Sensors (SOS)