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. Simply 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:

There are at least 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 outputs is quartz crystal aging or "outgassing" whereby the resonator mass decreases with time. 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 can be due to attachment joint or mechanism "creep". Both causes of drift, (outgassing and creep), only produce offsets with no span changes. Thus, with a single reference point, the offset drift can be subtracted from all the other measurement points to eliminate drift. 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 Earth's 1 G gravity vector.

Pressure Calibration Methods:

In-situ pressure calibrations require a stable or easily measured reference. Scripps has developed "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 [1]. Thousands of Digiquartz® Pressure Sensors have been stability tested at atmospheric pressure, 0, in our laboratory. It is possible to make accurate laboratory measurements of sensor drift at atmospheric pressure to 1 part-per-million of full-scale by comparing the outputs to our barometers.

Making accurate laboratory measurements of drift under high pressure, A, has only recently been done to 1 ppm precision at the National Metrology Laboratory of Japan-(AIST).

A-0-A Seafloor Pressure Calibration Method

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) [2]. 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. The reference calibration points at 0 are linearly connected and then simply subtracted from the ocean pressure readings. This method works regardless of the causes of offset drift or pressure profile. 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).

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 simply 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.

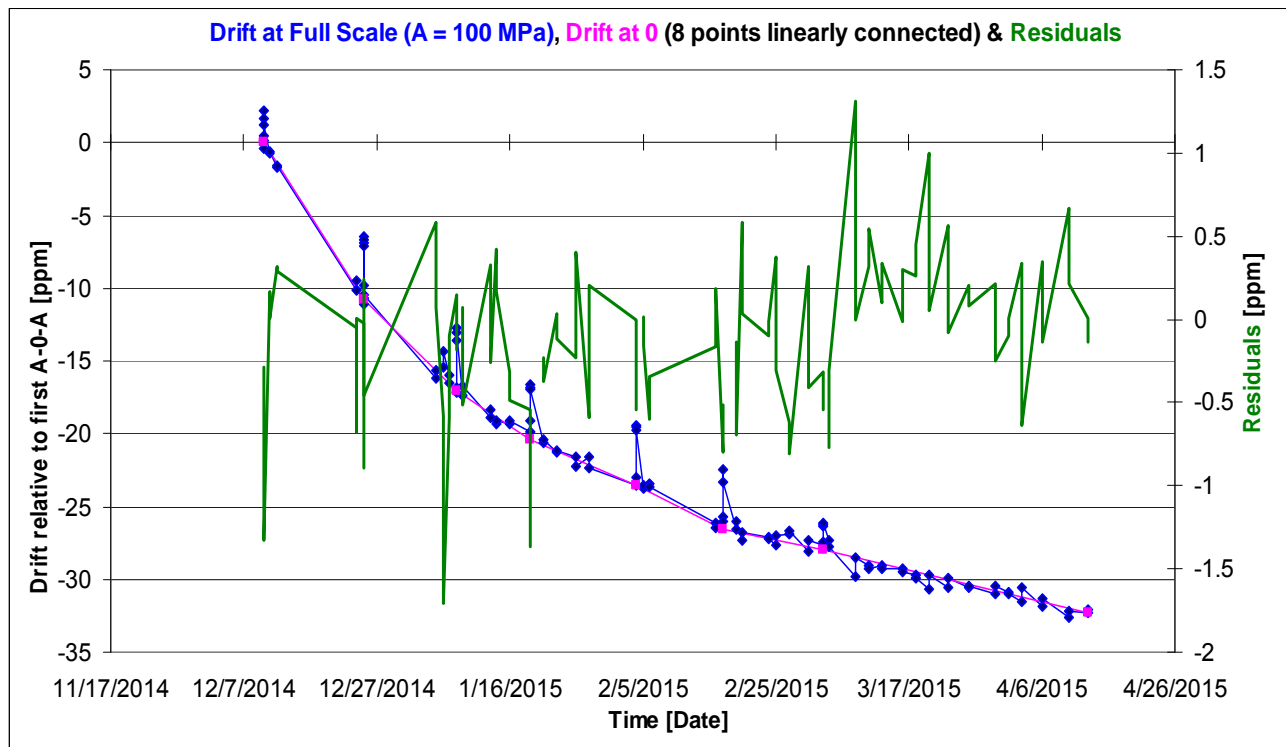**Full scale drift has been eliminated within a standard deviation of 0.5 ppm.**

Figure 1

Root Causes of Drift:

The A-0-A method eliminates drift regardless of the root causes. There are at least 2 causes of drift that are related to whether the sensor is mostly at zero pressure, 0, or mostly at high pressure, A. Tests with the sensor mostly at 0 show that the frequency (and pressure) outputs at zero and full-scale both **increase** with time. When the sensor is mostly at high pressure (e.g. full-scale pressure), the outputs at zero and full-scale both **decrease** with time. Testing for drift under pressure, A, **combines** the drift effects of outgassing and creep. We want to distinguish the outgassing effect from the creep effect. Reference 3 has analyzed the drift at 0 using different mathematical models. The fits to 7 years of typical drift data at 0 were extrapolated and subtracted from the 4 months of drift data held mostly at pressure A = 100 MPa. The resulting drift curves are extrapolated and illustrated in Figure 2 for Drift @ 0 (outgassing), Drift @ A (creep), and Drift @ A combined.
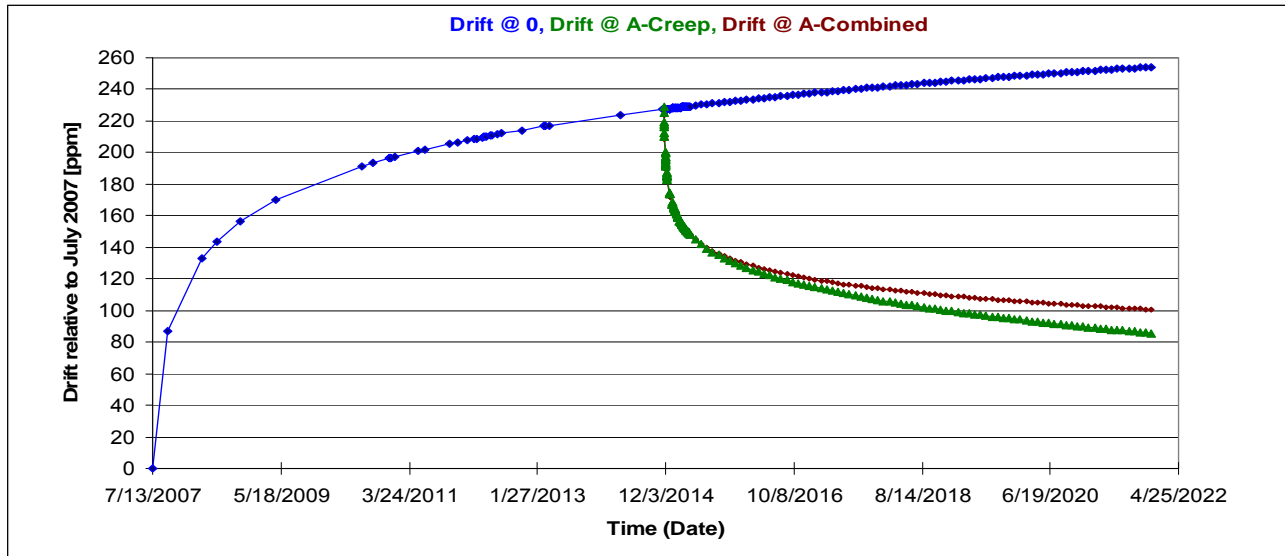

Figure 2

As shown in Figure 3, the combined drift can look quite different depending on the pressure profile.
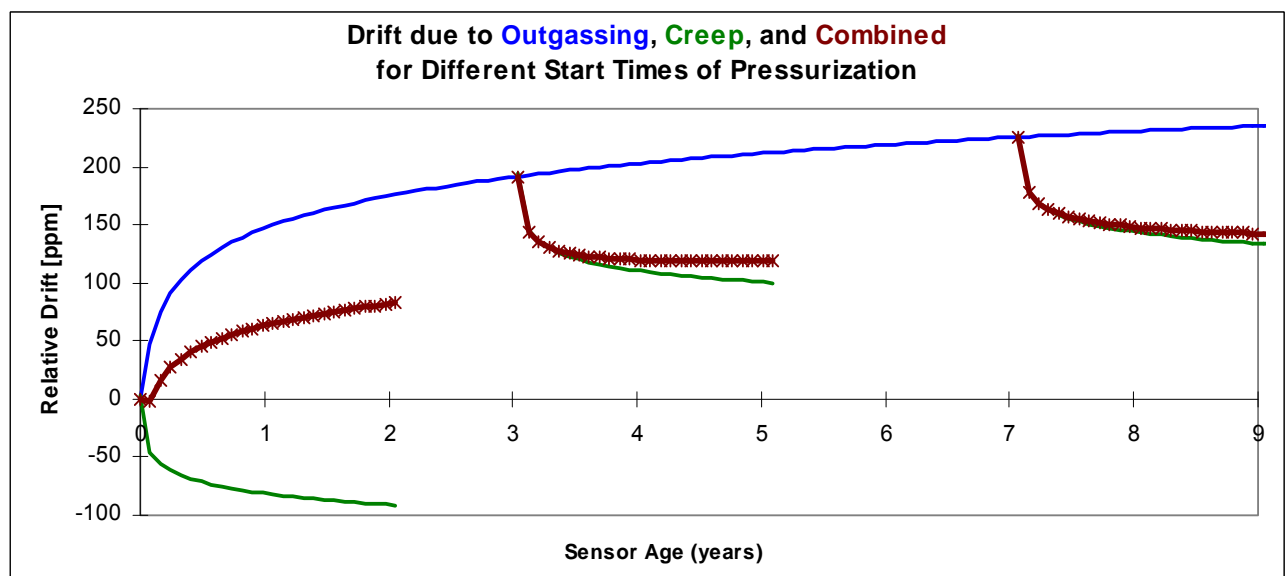

Figure 3

In Reference 3, Quartz Sensor stability was mathematically modeled using data from Paroscientific pressure sensors and Quartz Seismic Sensors accelerometers. Qualitatively, we looked for models that related to physical reality and quantitatively we looked for the best fits with the fewest free parameters and the best predictive behavior. Stability data were fit with various models and the residuals between the data and each fit were compared. Fits were derived from early data points and extrapolated to see which fits could best predict future behavior. The absolute drift was modeled down by almost two orders of magnitude.

Three different mathematical models were used to characterize drift:
"Power + Log", "Log" and "Exponential + Linear".

Power + Log = $A*t^B + C*\ln(t) + D$
Log = $A*\ln(t-t_0) + D$
Exp + Linear = $A*\exp(-t/B) + C*(t/365) + D$

One mechanism that can cause increasing outputs is quartz crystal aging or "outgassing" whereby the resonator mass decreases with time. Decreasing outputs can be due to attachment joint or mechanism "creep". Separating out and modeling the outgassing and creep effects can yield insights into the root causes of drift.

Outgassing:

Reference 3 modeled the drift at 0 due to outgassing using the above three models. A comparison of the three fits is shown in Figure 4. The Power + Log fit modeled the drift down by two orders of magnitude to one part-per-million of full scale.
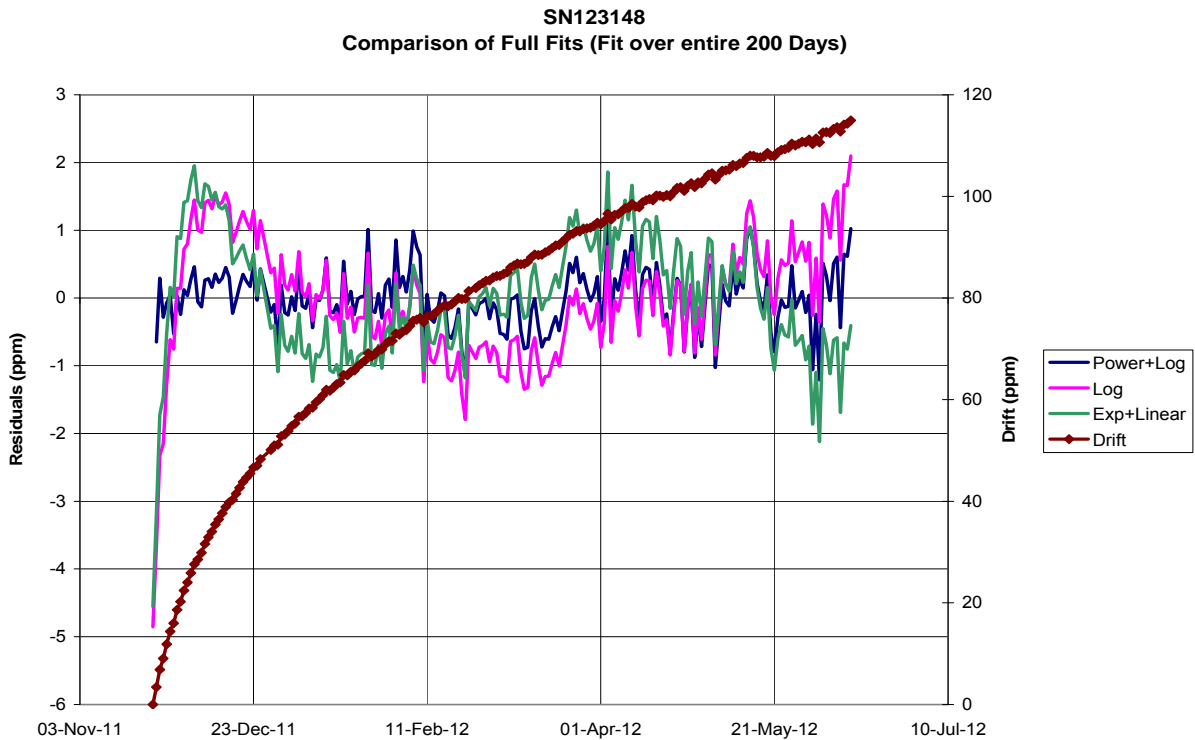

SN123148
Comparison of Full Fits (Fit over entire 200 Days)

Figure 4

Figure 5 compares the residuals of the "Power + Log" fit for different baselines of 17, 30, 60, and 90 days extrapolated to the full 200 days data set. The fits improve with longer baselines but are quite good even when extrapolated from a short baseline when drift due to outgassing is at its highest level.
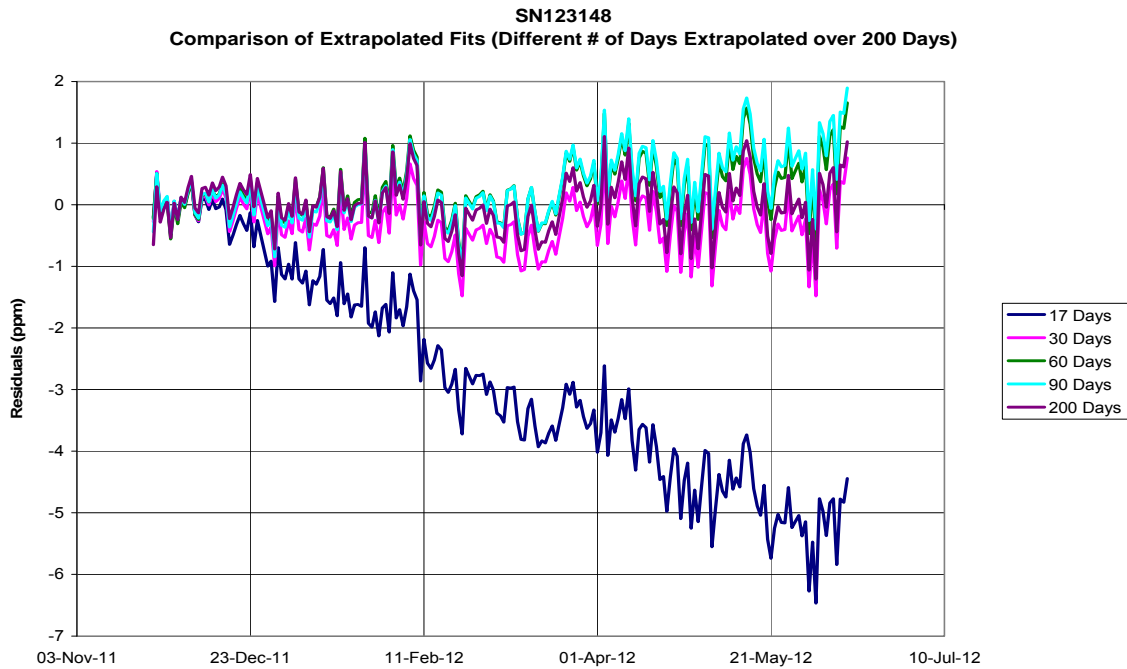
SN123148
Comparison of Extrapolated Fits (Different # of Days Extrapolated over 200 Days)

Figure 5

Our Quartz Crystal Resonator Force Sensors have a 10% change in frequency with applied full-scale load, so a 1 ppm drift in frequency represents a 10 ppm drift of full-scale output. A great presentation on quartz crystals is at: http://tf.nist.gov/sim/2010_Seminar/vig3.ppt . As shown below in a slide from Dr. John Vig's presentation, the pressure sensor drift curves due to outgassing look very similar to the aging curves of standard (unloaded) quartz crystal resonators.

Aging and Short-Term Stability
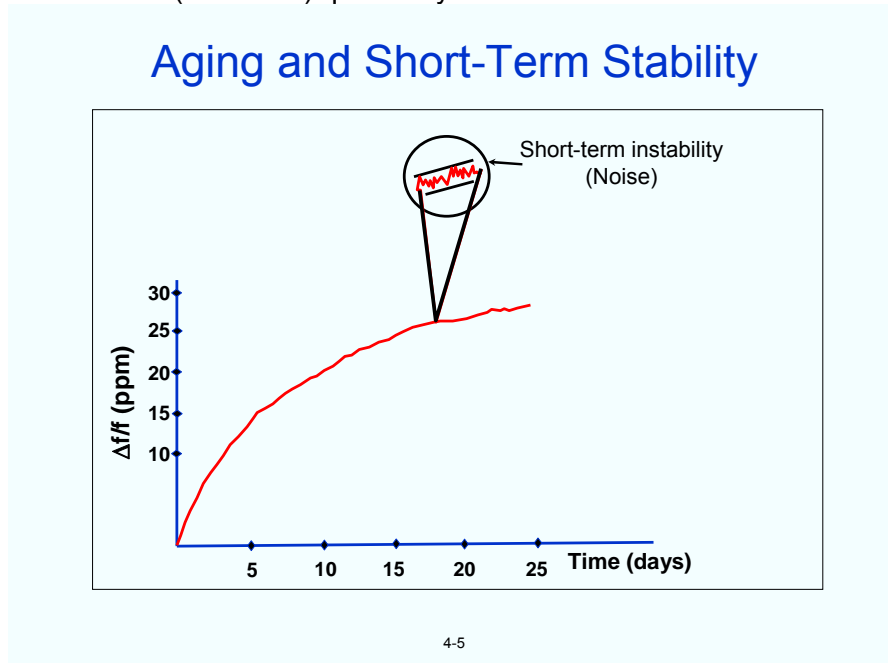
Creep:

The curves for sensor drift due to creep are similar for both pressure sensors and accelerometers. The load-generating mechanisms for these sensors are completely different. The pressure sensors convert pressures to forces on the quartz resonators using Bourdon tubes or bellows. The seismic instruments generate forces by accelerations acting on suspended inertial masses. However, the attachments of the quartz resonators to the force-producing structures are similar so drifts due to creep are likely related to the attachment joints. Loads applied to the attachment joints may produce visco-elastic creep (deflections) that act against the spring rates of the mechanisms to generate error forces. The quartz resonator cannot distinguish the error forces due to creep from the sensed input forces. There is some evidence that mechanisms with lower reactive spring rates exhibit less drift due to creep. Drift due to creep may also be proportional to the applied load.

In order to separate out and model the creep effect alone, the drift at 0 was subtracted from the combined drift at A as illustrated in Figure 2. Pressure sensor creep was then modeled with the same three fits that were used to model outgassing. The Power + Log and Log fits were almost identical and this suggests that the natural log is the dominant function in characterizing creep. The residuals for the Log Fit in Figure 6 have a standard deviation of 0.5 ppm.
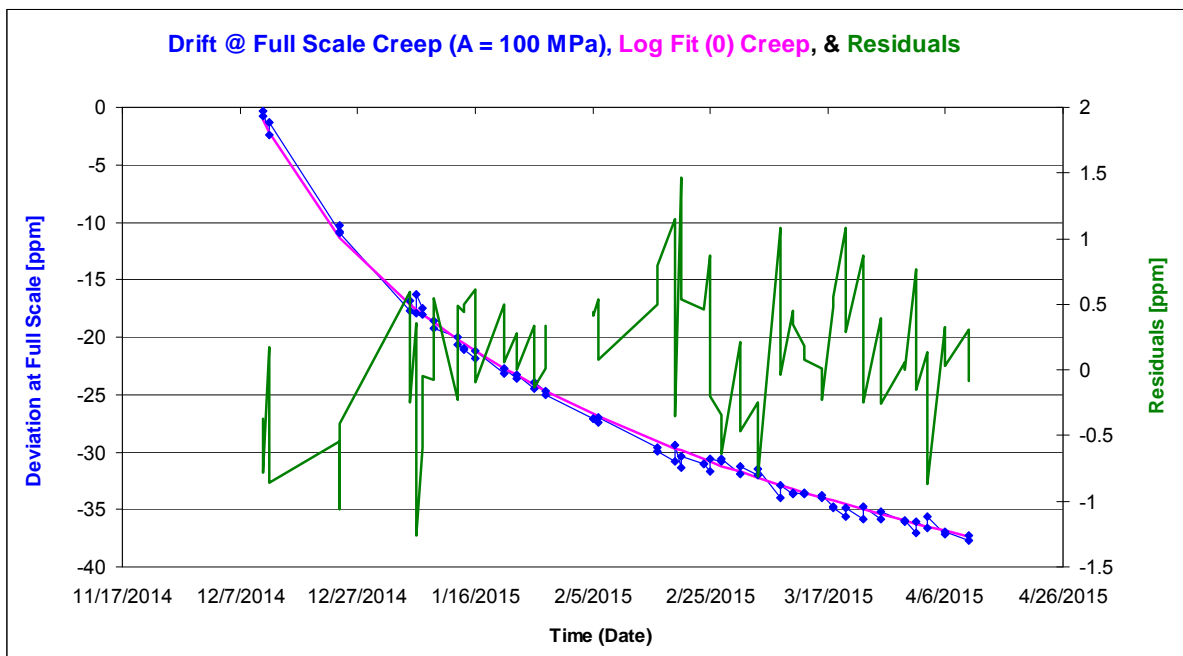

Figure 6

Conclusion:

Both of the presumed causes of drift can be modeled with high precision. The A-0-A seafloor calibration should work regardless of the root causes of drift and the way that they combine.

The A-0-A in-situ seafloor calibration can eliminate quartz pressure sensor drift to a few parts-per million of full-scale with a standard deviation less than one ppm.

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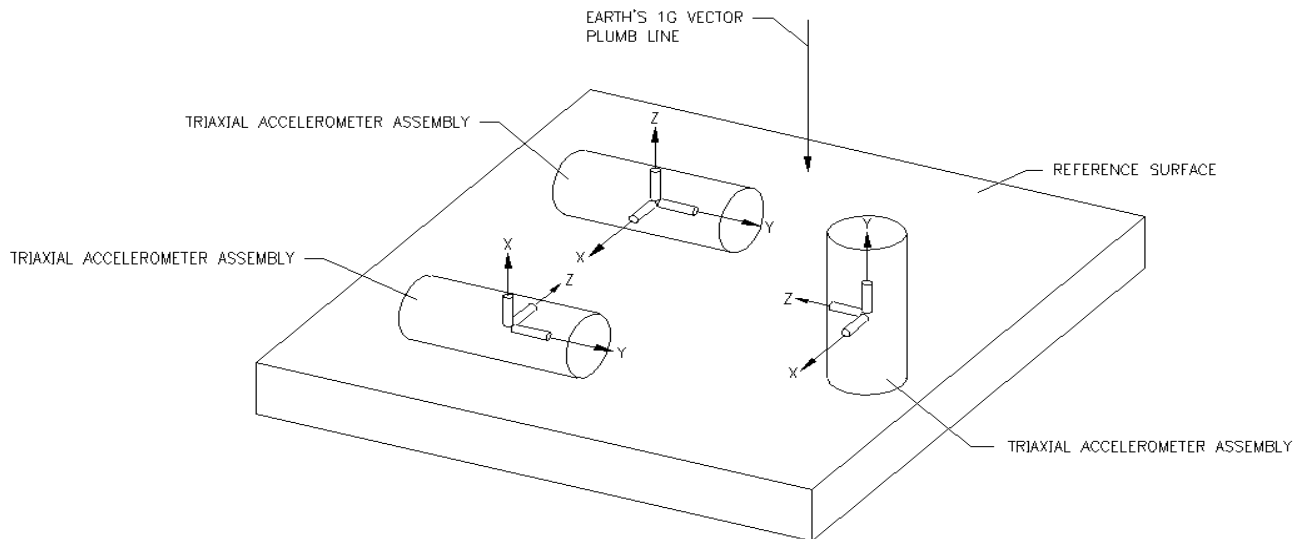
ROTATION OF TRIAXIAL ACCELEROMETER ASSEMBLY
TO ALIGN EACH ORTHOGONAL AXIS, X-Y-Z, WITH
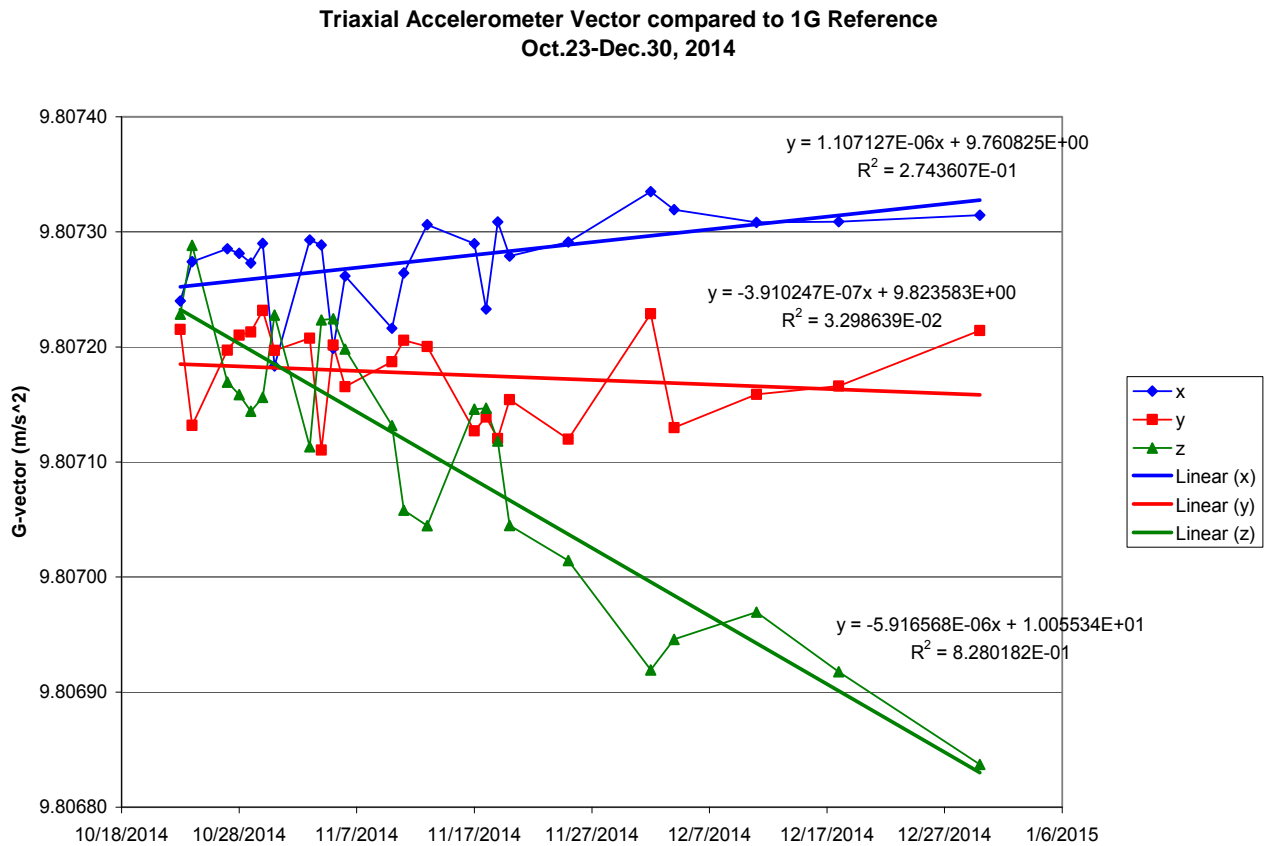EARTH'S 1G PLUMB LINE.

* Patent Pending

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:

Triaxial Accelerometer Vector compared to 1G Reference
Oct.23-Dec.30, 2014

$y = 1.107127E{-}06x + 9.760825E{+}00$
$R^2 = 2.743607E{-}01$

$y = -3.910247E{-}07x + 9.823583E{+}00$
$R^2 = 3.298639E{-}02$

$y = -5.916568E{-}06x + 1.005534E{+}01$
$R^2 = 8.280182E{-}01$

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.

Acknowledgements:

References:

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

(2) 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).

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