Root Causes of Quartz Sensor Drift

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

"The standard by which other standards are measured"

Root Causes of Quartz Sensor Drift

Jerome M. Paros and Taro Kobayashi

Abstract:

The root causes of Quartz Sensor drift are analyzed. Models are developed for drift mechanisms that occur when the Quartz Sensors are unloaded ("outgassing") and loaded ("viscoelastic creep").

Background:

Quartz Nano-Resolution Pressure Sensors, Accelerometers, and Tiltmeters are used in disaster warning systems to detect earthquakes, tsunamis, and severe weather. Reference 1 describes in-situ calibration methods that can provide the measurements needed for geodesy and long-term forecasting.

Drift is similar on all of the Quartz Sensors despite completely different mechanisms that apply loads to the quartz crystals. For example, the pressure sensors use bellows, Bourdon tubes, or diaphragms as pressure-to-force converters whereas the accelerometers generate forces due to accelerations acting on inertially suspended masses. The common elements are the crystals and their attachments to the force-producing structures.

Call the drift at zero load "outgassing" and the drift at load (e.g. full-scale) "creep". Both effects diminish exponentially with time but drift in opposite directions. Outgassing (aging) of quartz crystals can produce increasing frequencies with apparently higher force outputs. These frequency changes must be converted to equivalent error forces through the conformance (linearization) equation. Creep is in the direction of lower outputs and is due to attachment or mechanism "creep" deflections that work against the spring rate of the mechanism to generate viscoelastic error forces. The combined drift effects are dependent on the deployment history as illustrated in Figure 1.

The fits to 7 years of typical drift data at 0 were extrapolated and subtracted from 4 months of drift data held mostly at pressure A = 100 MPa. The resulting curves illustrate Drift @ 0 (outgassing), Drift @ A (creep), and Drift @ A combined. Data were provided by Dr. Hiroaki Kajikawa of the National Metrology Institute of Japan--(AIST).

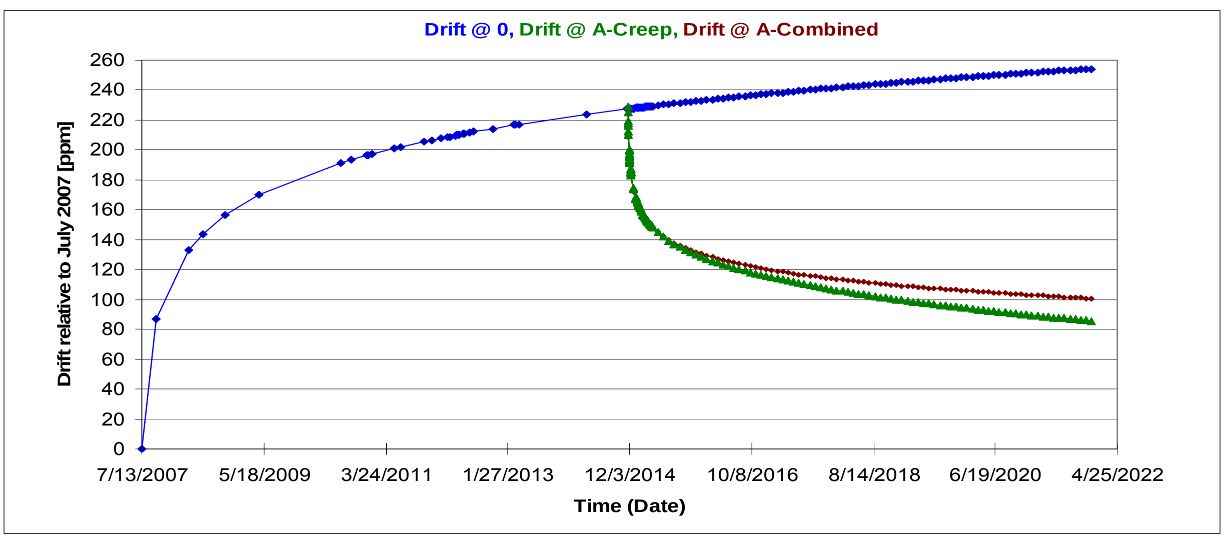


Figure 1

As shown in Figure 2, the combined drift can look quite different depending on the pressure profile.

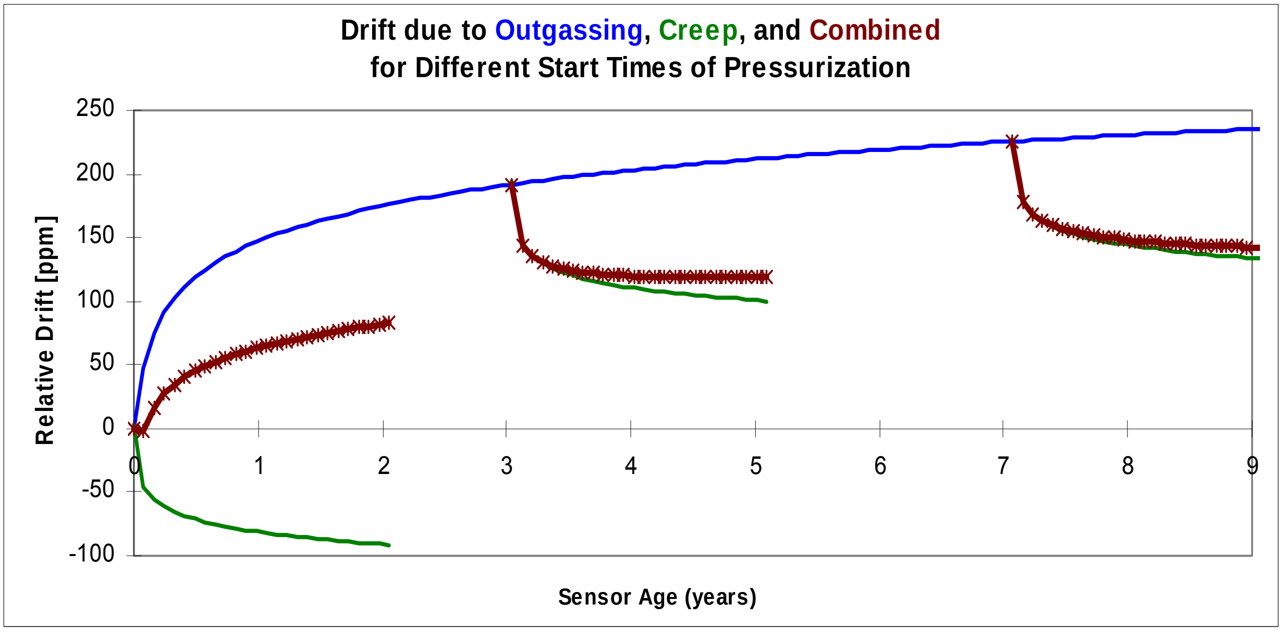


Figure 2

Outgassing:

The Quartz Crystal Resonator Force Sensors have a 10% change in frequency with applied full-scale load. A 1 part-per-million (ppm) drift in frequency represents 10 ppm drift of full-scale output. Figure 3 is a slide from Dr. John Vig's presentation at: http://tf.nist.gov/sim/2010_Seminar/vig3.ppt. The aging curves of standard (unloaded) quartz crystal resonators due to outgassing are in the direction of higher frequencies and look very similar to the pressure sensor drift curves at zero load.

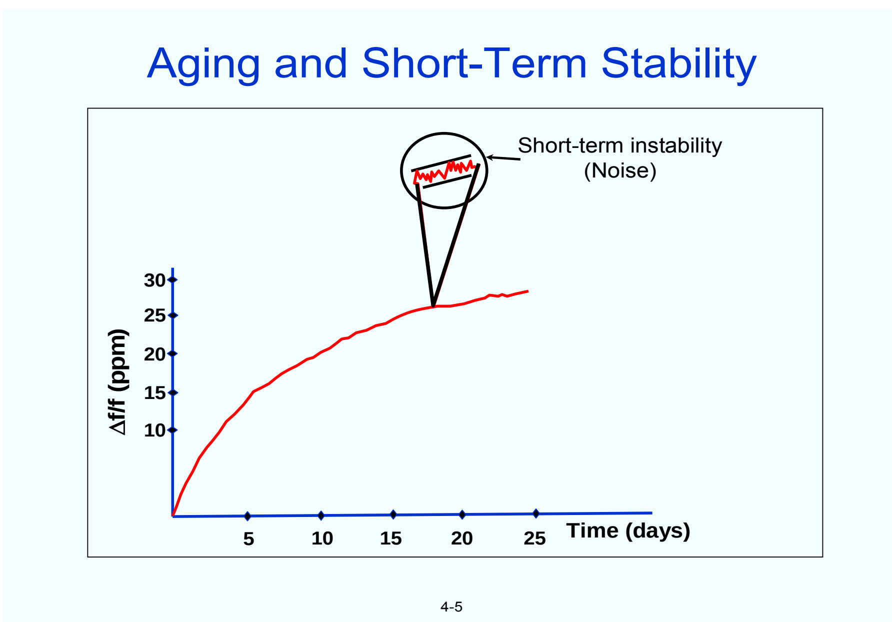


Figure 3

In Reference 2, 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. As shown in Figure 4, the drift curves for the unloaded Quartz Sensors are similar in shape to the aging curve shown above for standard crystals used in counter-timer applications and the mathematical fits are quite good. In the quartz sensors, the frequency changes due to crystal outgassing must be converted to equivalent error forces through the conformance (linearization) equation.

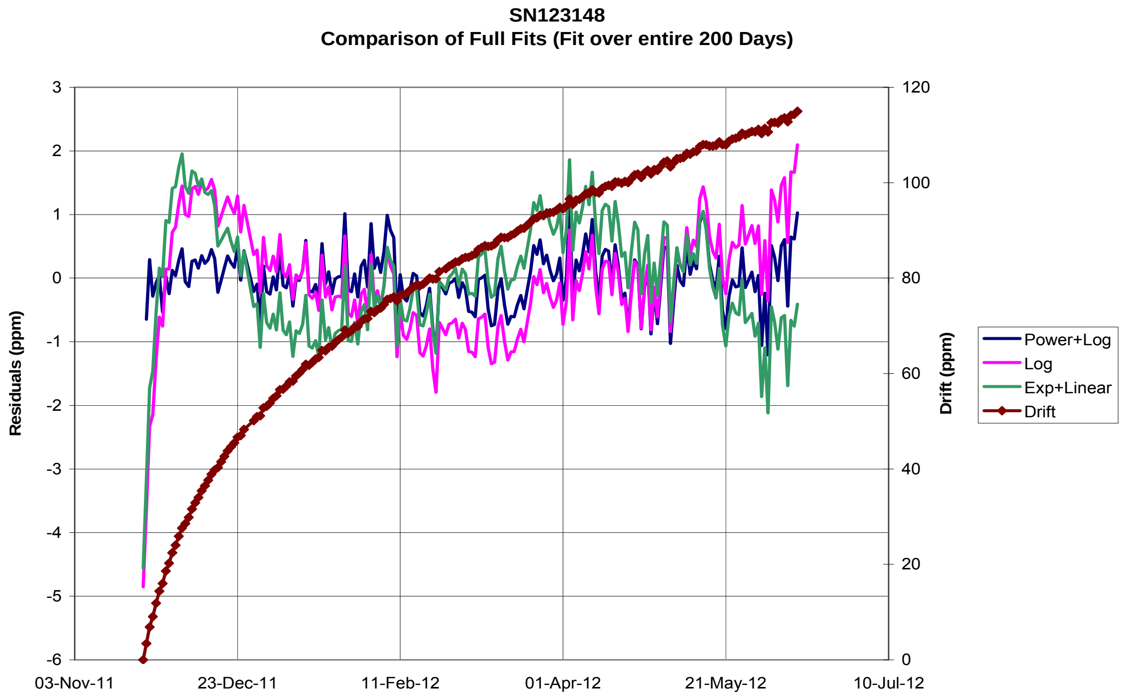


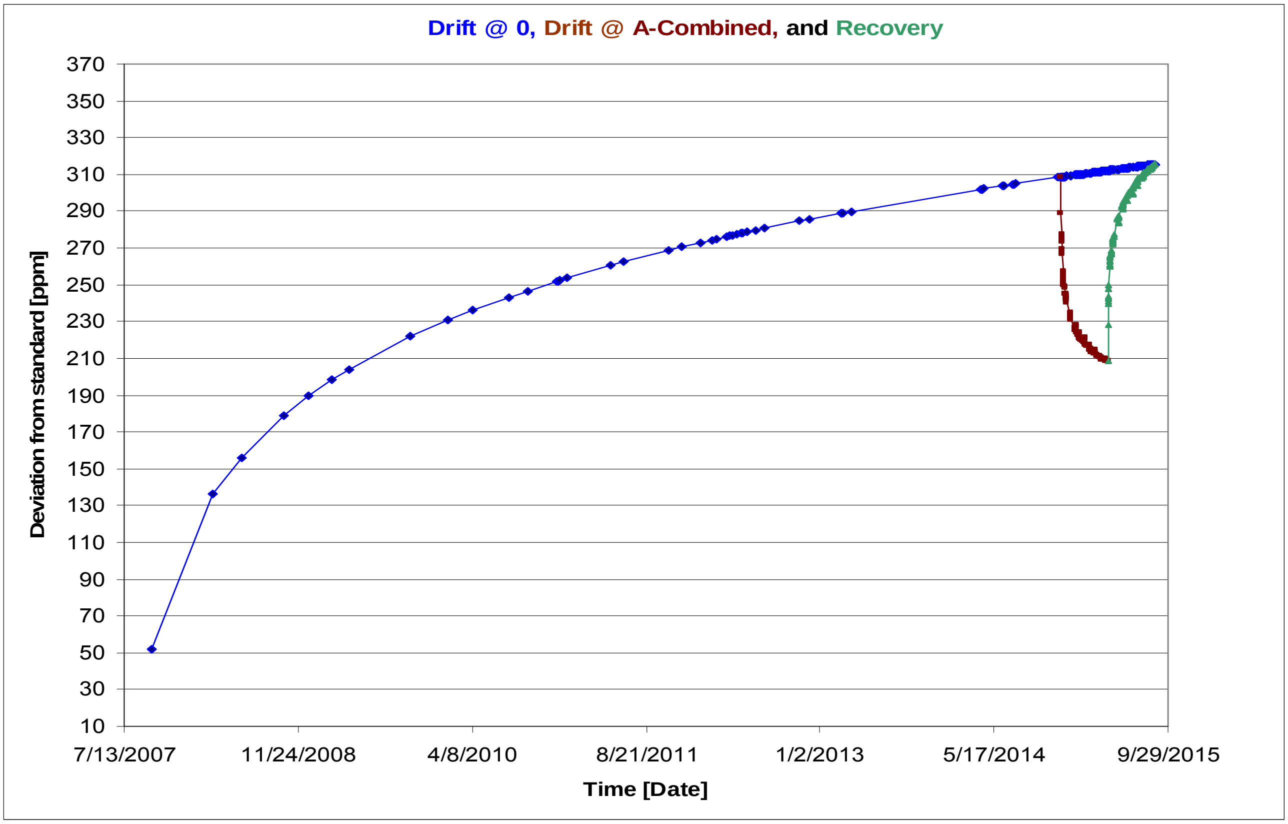
Figure 4

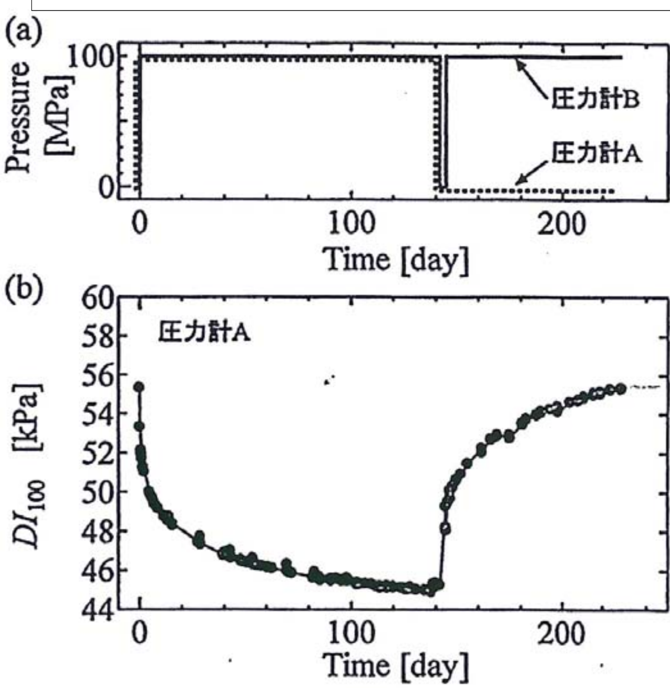
Creep:

Loads applied to the attachment joints produce viscoelastic 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.

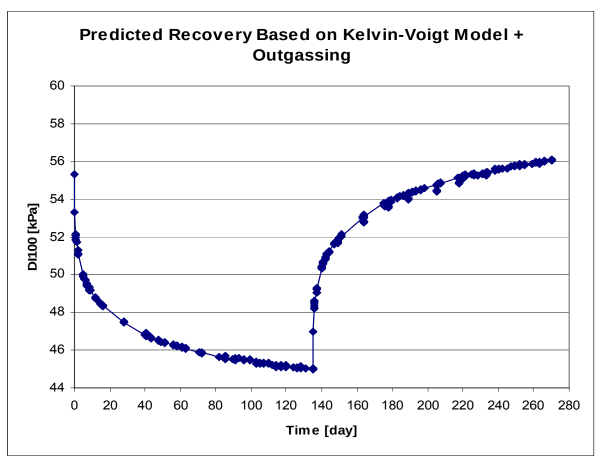
The Kelvin-Voigt viscoelastic model (Appendix I) predicts that drift due to creep is proportional to the reactive spring rate of the mechanism and the applied load. Creep is inversely proportional to the modulus. The time dependence is an exponential function with a time constant equal to the modulus divided by the viscosity. When the load is removed, a viscoelastic "recovery" occurs.

Dr. Hiroaki Kajikawa and his colleagues at the National Metrology Institute of Japan--(AIST) followed seven years of testing with quartz pressure sensors mostly at zero pressure with four months at full-scale pressure at 100 MPa and then returned to zero pressure to monitor the viscoelastic recovery as illustrated below. The fit to the creep model was reversed in sign to model the recovery and the outgassing was added to predict the combined recovery curve. As shown in Figure 5, the predicted recovery compares well to the data plots excerpted from Reference 3.





Actual Creep & Recovery



Predicted Creep & Recovery

Figure 5

Conclusions:

There are two independent root causes for drift--"outgassing" and "creep". Both effects diminish exponentially with time. At zero load, outgassing generates increasing frequencies with apparently higher outputs. When the crystals are loaded, creep is in the opposite direction to outgassing and generates lower outputs. The combined drift effects are dependent on the deployment history.

References:

(1) J.M. Paros and T. Kobayashi, "Calibration Methods to Eliminate Sensor Drift", G8097, Paroscientific, Inc., Technical Note

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

(3) H. Kajikawa and T. Kobata. "Long-term drift of hydraulic pressure transducers constantly subjected to high pressure." Proceedings of the 32nd Sensing Forum, Osaka, Japan, 10-11 September 2015. pp.261-266.

Appendix I Kelvin–Voigt Model of Creep Drift

The Kelvin–Voigt model represents loads applied to a purely viscous damper, D, and purely elastic spring, S, connected in parallel as shown in Figure 1.

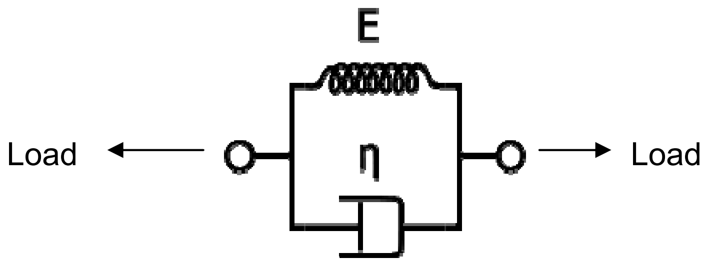


Figure 1 Kelvin–Voigt Model

Since the spring and damper are arranged in parallel, the strains in each component are equal:

Strain = $\varepsilon_{Total} = \varepsilon_D = \varepsilon_S$

The total stress will be the sum of the stress in each component:

Stress = $\sigma_{\mathrm{Total}} = \sigma_D + \sigma_S$

The stress in the spring equals the modulus of elasticity, E, times the strain in the spring. The stress in the damper equals the viscosity, η, times the rate of change of strain in the damper. Thus in a Kelvin–Voigt material, stress σ, strain ε, and their rates of change with respect to time *t* are given by:

$$\sigma(t) = E\varepsilon(t) + \eta \frac{d\varepsilon(t)}{dt}$$

The above equation may be used for both shear stress and/or normal stress load applications.

Response to a Stress Step Function

If a constant stress, σ_0, is suddenly applied to a Kelvin–Voigt material, then the strain approaches the strain of the pure elastic material, $\frac{\sigma_0}{E}$, as a decaying exponential:

Strain $(t) = \frac{\sigma_0}{E}(1 - e^{-\lambda t})$ **,** where t is time and λ is the relaxation rate, $\lambda = \frac{E}{\eta}$

If the stress is suddenly removed at time, t_1, then the deformation is retarded in the return to zero deformation:

Strain $(t > t_1) = \varepsilon(t_1)(1 - e^{-\lambda(t-t_1)})$

Figure 2 shows the deformation versus time when constant stress on the material is applied suddenly at time, t = 0, and suddenly released at the later time, t_1.

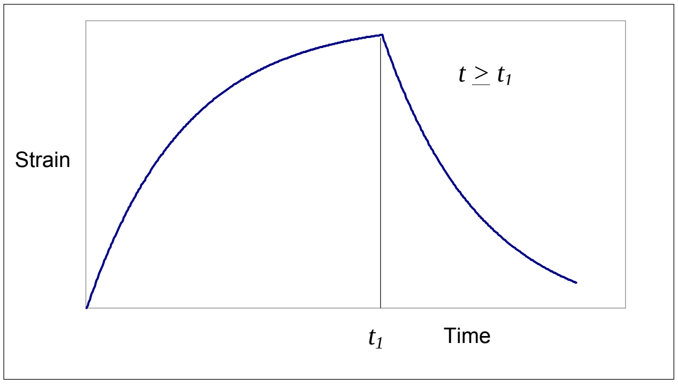


Figure 2: Deformation versus time for sudden application and release of constant stress

The deformation, ΔL, over the length of the attachment, L, is:

$$\Delta L = \left(\frac{L\sigma_0}{E}\right)(1 - e^{-\lambda t})$$

The reactive spring rate of the mechanism, K, acts against the deformation, ΔL, to generate a creep force, ΔF.

$$\Delta F = \left(\frac{KL\sigma_0}{E}\right)(1 - e^{-\lambda t})$$

Drift due to the creep force, ΔF, can be expressed as a fraction of the full-scale force, F_{FS}:

$$\frac{\Delta F}{F_{FS}} = \left(\frac{KL\sigma_0}{F_{FS}E}\right)(1 - e^{-\lambda t})$$

The drift due to creep is proportional to the reactive spring rate of the mechanism and the applied load. Creep is inversely proportional to the modulus. The time dependence is an exponential function with a time constant equal to the modulus divided by the viscosity.

References:

Meyers, Marc A., and Krishan Kumar Chawla. "Creep and Superplasticity." *Mechanical Behavior of Materials*. 2nd ed. Cambridge: Cambridge UP, 2009. 653-688. Print.