Temperature Compensated Clock Drift Correction

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Introduction

The Ocean Bottom Node (OBN) seismic method is unique in the seismic industry in that the recorder is not fed a highly accurate GPS timing measurement while measuring the earth reflections. Instead the method relies on an internal clock which will drift over the dive time of the node. Initially the standard for OBN's was the Chip Scale Atomic Clock (CSAC) which uses a quantum feedback loop to discipline the clock during the dive. More recently contractors have adopted crystal oscillators for practical reasons. This paper will compare the benefits of the two clock types and propose a method to correct for the main deficiency of the crystal oscillator.

Offshore Process

Due to the environment of the OBN it can only synchronize with GPS time immediately prior to deployment and immediately after recovery. While deployed on the seafloor the OBN is reliant on the self-contained clock. Errors in the clock oscillator frequency will distort the digitizer sample interval resulting in a drift between clock time and reference time which must be corrected for. There are two wide-spread acquisition methods to correct for errors in the clock which are used in conjunction and universally used with all node technologies.

- Frequency Disciplining. Prior to deployment the oscillation frequency is tuned to the nominal clock frequency
- The pre and post deployment drift measurements are used to estimate the drift over the dive period of the node, which is subsequently used to correct for the drift during the shot combing process

Theoretical Clock Drift – Estimating the drift model

Regardless of the clock type the oscillator/tick frequency will deviate from the nominal frequency. This deviation is normally termed the clock drift or the clock skew. If we ignore the impact of temperature, the frequency-drift of the clock is described by the equation:

$$\frac{f - f_{nom}}{f_{nom}} = \frac{f_0 - f_{nom}}{f_{nom}} + \frac{d\left(\frac{f - f_{nom}}{f_{nom}}\right)}{dt}.t$$

The left hand side of the equation is the frequency drift of the clock as a ratio of the nominal clock frequency which is also referred to as the relative deviation (Rel. Dev.). The first term on the right side of the equation relates to the frequency error at the start of the experiment. If the clock is perfectly calibrated (i.e. oscillating at nominal frequency) at the start of the experiment this term would be zero. The second term on the right side of the equation relates to the change in frequency error over the course of the experiment, also referred to as aging. While clock aging can be complex it is generally considered acceptable to assume linear frequency aging over the dive periods used in seismic operations.

The time-drift is the integration of this equation with respect to deployment time. If we assume that the clock frequency ages linearly with time, the time drift is represented by the following equation in which A is the linear change in frequency with time.

$$\text{Skew (ms)} = \frac{df_0}{f_{nom}} t + \frac{1}{2} A.t^2 + \text{C}$$

You will note that if the frequency drifts linearly the time skew is parabolic i.e. the timing error associated with aging increases quadratically with deployment time. As such the preferred time skew model is parabolic

Evaluation of Clock Performance

CSAC's are being constantly tuned to the reference frequency but they still suffer from aging, probably d/t a degradation in the vacuum. The CSAC clock manufacturer initially quantified aging at 1e-9 / year. An evaluation of CSAC clocks was performed by Woods Hole institute in a paper from 2016. In this paper they observe that while the initial batch of CSAC clocks generally met this specification, more recent batches did not. This was put down to manufacturing issues and the CSAC manufacturer adjusted the spec to 1e-8/year (one order of magnitude). In the same paper the authors observe that while the CSAC clocks generally meet this new specification the errors are within the order or magnitude of the new specification. Furthermore the authors observe that while some CSAC clocks with initially very high aging will stabilize over time the CSAC frequency-aging is generally linear.

Below the manufacturers aging specs for the CSAC and a representative crystal oscillator are tabulated.

	CSAC			**OCXO**		
	Rel Dev	**Error (s)**	**Aging Coefficient**	**Rel Dev**	**Error (s)**	**Aging Coefficient**
Aging/Day	9.00E-10	7.776E-05	2.083E-14	3.000E-10	2.592E-05	6.944E-15
Aging/year	1.00E-08	0.316	6.338E-16	4.000E-08	1.262	2.535E-15

Based on manufacturer specifications the aging characteristics of CSAC and crystal oscillators are within the same order of magnitude.

Figure 2 *Comparison or Total Drift and Aging for a project acquired using nodes with CSAC's against a project acquired using nodes with crystal oscillators.*

Figure 1 details an empirical evaluation of clock performance of two OBN projects; One using nodes with CSAC's and one using nodes with crystal oscillators. The left hand side details the total drift from the deployment and recovery sync, whereas the right hand side details the distribution of the aging coefficient. For the project using CSAC's the aging coefficient was derived from the clock frequency measurement made pre and post recovery whereas for the project using crystal oscillators the aging coefficient was derived from first break analysis. While the total drift of the crystal oscillator is one order of magnitude higher than the CSAC, the aging characteristics of the two projects are very similar. The reason for this is that the crystal oscillator approach has much less control over the starting frequency. With both clock types the frequency is tuned to match the nominal clock frequency prior to deployment. However crystal oscillators are temperature dependent. See figure 2 detailing an experiment to measure the frequency change as a consequence of temperature. Frequency disciplining performed on the vessel will be imperfect

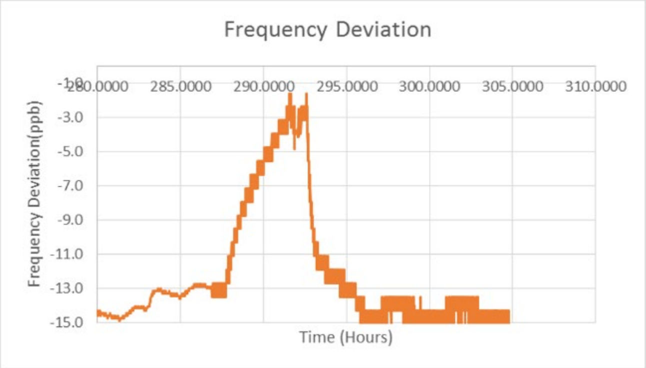

Figure 1 *Results of a laboratory experiment in which the node was deployed in a temperature controlled tank and the clock frequency was continuously recorded. At hour 288 the node was removed from the tank and exposed to room temperature. At hour 290 the node was returned to the tank. There is 10ppb change in the frequency deviation from nominal as a result of this temperature change*

at the temperatures of the seabed. Clock manufacturers wrap the oscillator in an oven to mitigate the impact of temperature effects but this only results in a first order improvement. CSAC's also use crystal oscillators but the frequency is continually disciplined using the quantum feedback loop which is temperature independent and consequently CSAC clocks are not temperature dependent.

Linear and Parabolic Clock Drift models

When using crystal oscillators the general practice is to use linear drift models to correct the seismic data. The linear model is based on skew measurements pre-deployment and post recovery. The impact of temperature on the accuracy of the drift model is not significant because the node spends a very small percentage of the dive time on deck at the higher temperature. This linear drift correction methodology results in an error which is a proportion of the clock aging. The recovery skew measurement is not measuring the linear component of the drift equation but rather the total drift on recovery. If drift correction is applied using this linear model, the max residual drift will occur at the halfway point of the dive and be equal to 25% of the drift d/t aging (Figure 3). Figure 4 details several laboratory experiments conducted at constant temperature in which the drift was continually measured demonstrating the parabolic nature of the clock drift.

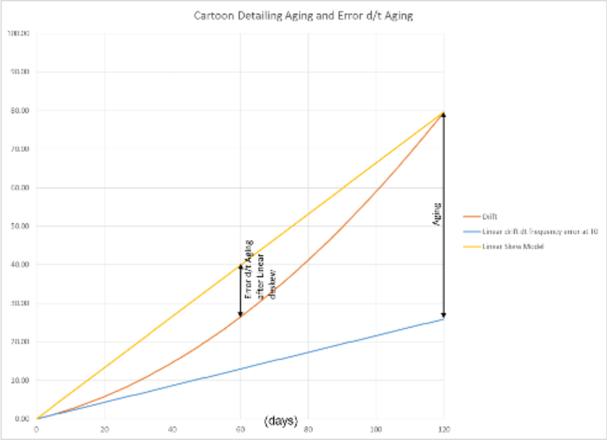

Figure 3 *Cartoon detailing the aging error post linear clock correction*

As previously discussed, a parabolic drift model is a more accurate representation of the true clock drift. It is possible to estimate the parabolic drift model by measuring the frequency error at deployment and recovery. This parabolic drift model method has been used by PXGEO on nodes using CSAC clocks since 2013. Unfortunately, the temperature dependence of the crystal oscillator disqualifies the use of the parabolic drift models for crystal oscillator based clocks. The deployment and recovery frequency measurements are performed at a different temperature than the seabed temperature at which the seismic recordings are made and hence the resulting parabolic model will not represent the clock behaviour.

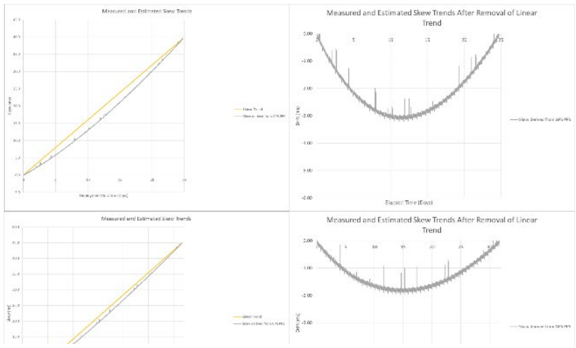

Figure 4 *Evaluation of aging for three OCXO based clocks maintained at a constant temperature detailing the magnitude of the error associated with a linear clock correction. Left details the drift and the linear model and right details the residual drift after linear correction demonstrating the validity of the parabolic model*

Temperature Compensated Parabolic drift corrections

The proposal is to use an additional temperature measurement and a temperature dependent parabolic skew model to accommodate a parabolic skew correction with nodes utilizing crystal oscillators. The obvious benefit of this method is to deliver a seismic dataset with a more accurate timing correction but it also opens up the opportunity to use lower cost oscillators utilizing different crystal cuts, and benefits to the use of nodes in operationally complex areas such as transition zones and surf zones where we can not rely on a constant temperature during operations.

The company conducted a series of laboratory experiments in which the node deployment process was duplicated. i.e the node deployment process was performed at room temperature; the temperature around the node was lowered to 5C over a 30 minute period; the node operated at this lower temperature for 30 to 60 days; the temperature around the node was returned to room temperature over a 30 minute period; the recovery process was performed at room temperature. For these experiments the clock frequency was continuously recorded. Independently the frequency / temperature trend of each clock was measured.

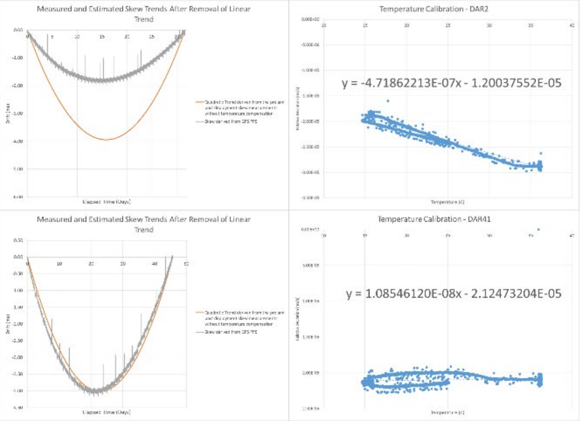

Figure 5 *Two laboratory measurements of the clock frequency over a 30 to 60 day deployment period. Left - post linear correction residual drift and right the clock frequency temperature trend. For the top graphs the frequency temperature trend has a high gradient and it is not possible to estimate the parabolic drift from the deployment and recovery drift measurements. For the bottom graphs the temperature / frequency trend is flat accommodating a successful estimation of the*

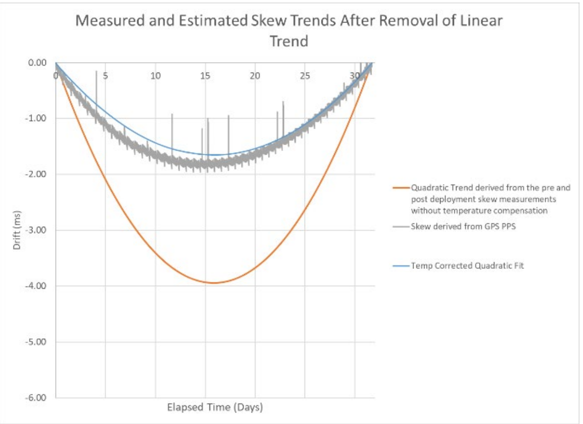

Figure 6 *Comparison of the residual drift and the parabolic model estimated with and without temperature compensation*

Figure 5 details clocks corrected by a parabolic model without considering temperature effects. The parabolic model was derived from deployment and recovery skew measurements performed at a different temperature than the bulk of the experiment. If the temperature / frequency trend is flat the parabolic correction method works well but if the temperature frequency trend has a high gradient the parabolic model will not be representative of the clock behaviour and will result in a higher error than if a linear correction was used.

Figure 6 details another experiment in which the parabolic drift model is estimated from the pre and post deployment skew measurements with and without temperature correction. The temperature compensated drift model is a much better representation of the clock behaviour.

Conclusions

Crystal oscillator based clocks are a very attractive alternative to CSAC's because of the lower cost, lower power consumption and greater reliability. The main benefit of the CSAC clock over crystal oscillator based clocks, for use in OBS projects, is the independence to temperature. Using an additional temperature measurement we have demonstrated that this deficiency of crystal oscillators can be overcome. As well as providing a seismic dataset with a more accurate deterministic clock correction, it will be beneficial for use on seismic projects in which the nodes are exposed to large temperature changes during operations and opens up the possibility of using clocks with lower quality and lower cost crystal cuts.