Timing robustness and predictability of dual-clock architecture for long-duration Ocean Bottom Node acquisition

Introduction

Ocean Bottom Nodes (OBNs) play a central role in modern seismic exploration and monitoring, enabling high-resolution imaging and long-offset acquisition in increasingly challenging environments. As operational requirements evolve toward deeper waters, more remote locations, and extended recording durations, node autonomy has become a key design driver.

In autonomous OBN deployments, continuous GPS synchronization is not available, and timing accuracy relies entirely on the internal clock. Traditionally, clock performance has been assessed primarily through metrics such as absolute frequency stability and total accumulated drift (Beng Seong, et al.,2024). Modern seismic processing workflows increasingly rely on post-acquisition drift estimation and correction, often using data-driven inversion methods (Olofsson, et al.,2010). In this context, the robustness, predictability, repeatability, and determinism of clock behavior become essential properties.

While chip-scale atomic clocks (CSACs) offer excellent intrinsic stability (Rentsch, et al.,2023), their high power consumption and cost may be disproportionate to the requirements of many OBN applications. Conversely, crystal-based solutions such as oven-controlled crystal oscillators (OCXOs) can deliver highly predictable drift behavior, enabling accurate correction, but at the expense of significant power consumption due to oven stabilization.

To address the challenge of increasing mission durations under strict energy constraints, a dual-clock architecture has been developed. By combining a low-power temperature-compensated crystal oscillator (TCXO) with a highly stable reference clock that is only intermittently powered, power consumption drastically reduces. However, intermittent timing strategies may be perceived as introducing additional risks that must be explicitly addressed.

This study focuses on the robustness and predictability of a dual-clock timing architecture for OBN acquisition, in addition to its nominal stability.

Timing robustness requirements for long-duration OBN surveys

For long-duration autonomous seismic surveys, the key requirement is not merely minimizing clock drift, but ensuring that drift behavior remains smooth, deterministic, and predictable over time. Data-driven drift estimation techniques assume that clock behavior can be represented by low-order parametric models, typically linear or polynomial.

Any unpredictable behavior can significantly degrade the conditioning of drift inversion and ultimately impact seismic data quality. From this perspective, timing robustness encompasses several critical aspects: absence of switching-related artifacts, stability under thermal variations and compatibility with simple drift correction models.

Dual-clock architectures inherently rely on the coordinated operation of two oscillators with distinct characteristics and power states. While this approach provides clear energy-efficiency benefits, it requires particular attention to timing continuity and long-term behavior, especially during synchronization and power-state transitions.

Dual-clock architecture and expected behavior

The proposed dual-clock architecture relies on a low-power TCXO that serves as the primary timing source during acquisition, periodically corrected using a high-stability reference clock. The reference clock remains powered off for most of the mission duration, significantly reducing overall power consumption.

To achieve high predictability and stability of the clock specific attention has been led to an accurate characterization of both oscillators particularly regarding their behavior at power-up and over transient temperatures.

In this architecture (Fig. 1), the timing function does not rely on switching between oscillators. The TCXO remains the master clock at all times, ensuring continuous timebase generation, while the reference clock is used intermittently solely to measure the TCXO frequency. Any correction is applied smoothly at the processor level, preserving timing continuity and avoiding discontinuities or transient effects in the timebase.

In addition, the continuous accumulation of in-operation measurements enables characterization of the TCXO behavior over time, allowing its evolution to be learned and anticipated, thereby further improving timing predictability during long-duration deployments.

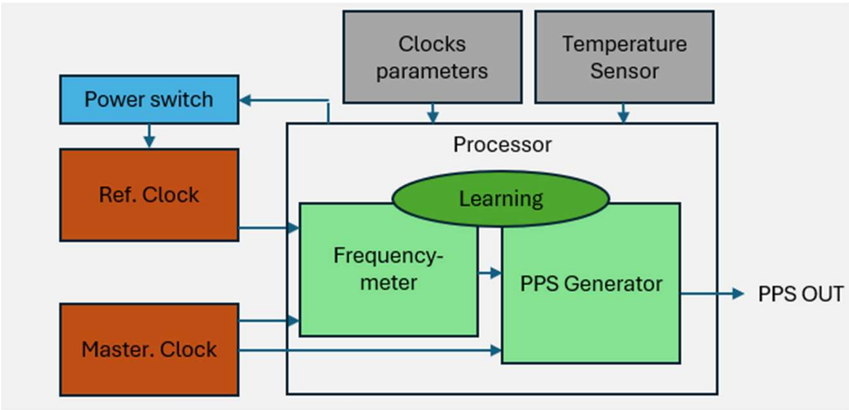

Figure 1 *Dual-clock principle*

Experimental protocol

A series of controlled laboratory experiments was conducted on several Ocean Bottom Nodes equipped with the dual-clock timing system. The experimental protocol was designed to emulate key aspects of a realistic deployment while stressing the timing system with temperature variation. For characterization purposes, for all nodes, the clock frequency and clock drift was continuously recorded as well as temperature trend of each clock.

Results and discussion

First test aim was to characterize the inherent stability and predictability of 10 nodes' s clock. These nodes were initially operated at a stable temperature of 25 °C for one day, simulating pre-deployment conditions. The ambient temperature was then reduced to 5 °C over a 30-minute transition period, representative of deployment into cold marine environments. The nodes subsequently operated continuously at this lower temperature for more than 60 days.

The experimental results demonstrate a high degree of consistency across all tested units. Raw drift measurements show that accumulated clock drift remains below 10 ms over the full 60-day test period for all nodes (Fig. 2a), a level comparable to best-in-class OCXO-based solutions, despite significantly lower power consumption.

More importantly, the drift evolution is smooth and highly repeatable across units, with no evidence of abrupt changes, switching-induced artifacts, or anomalous behavior during long-term operation. This repeatability is a critical indicator of robustness and predictability.

After applying a second-order polynomial fit to the raw drift data, following standard data-driven drift correction methodologies, residual timing errors remain better than 50 µs over the entire test duration for all units (Fig. 2b). The low residuals confirm that the clock behavior is well captured by simple parametric models and is therefore fully compatible with existing seismic processing workflows.

For a representative seismic travel time of 1 second, this 50µs residual error corresponds to a relative timing uncertainty of approximately 50ppm. This has to be compared to uncertainties in water velocity estimation, commonly on the order of 0.1% to 1%.

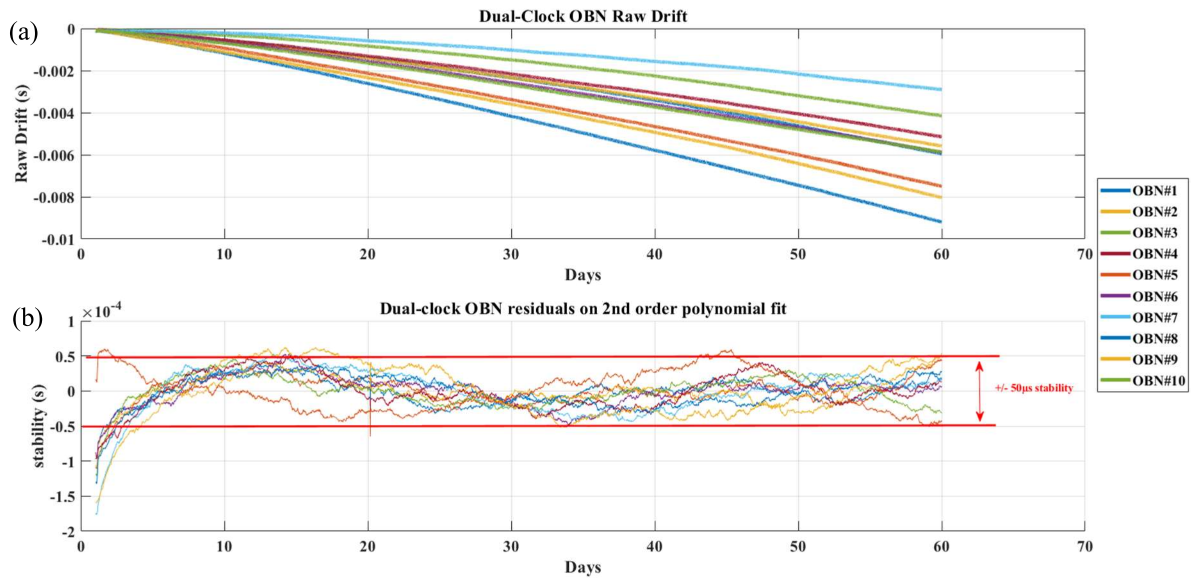

Figure 2 *(a) Dual-clock OBN raw drift over the 10 products (b) dual-clock residuals after 2nd order polynomial fit on frequency drift.*

A second test reproduce long term deployment with a more classical approach. In that case, a deployment close to 140 days has been realized. Raw drift measurements show that accumulated clock drift remains below 25ms over that period for all nodes, still comparable to best OCXO-based solution (Fig. 3a).

For this test, time drift has been corrected based only on the initial and final drift of the deployment as it is performed during seismic operation. We are no more looking at the inherent stability of the dual-clocks covered by the first test. Results are presented on figure 3b for several deployment’s duration. After correction, clock drift error remains below 1ms after 100 days.

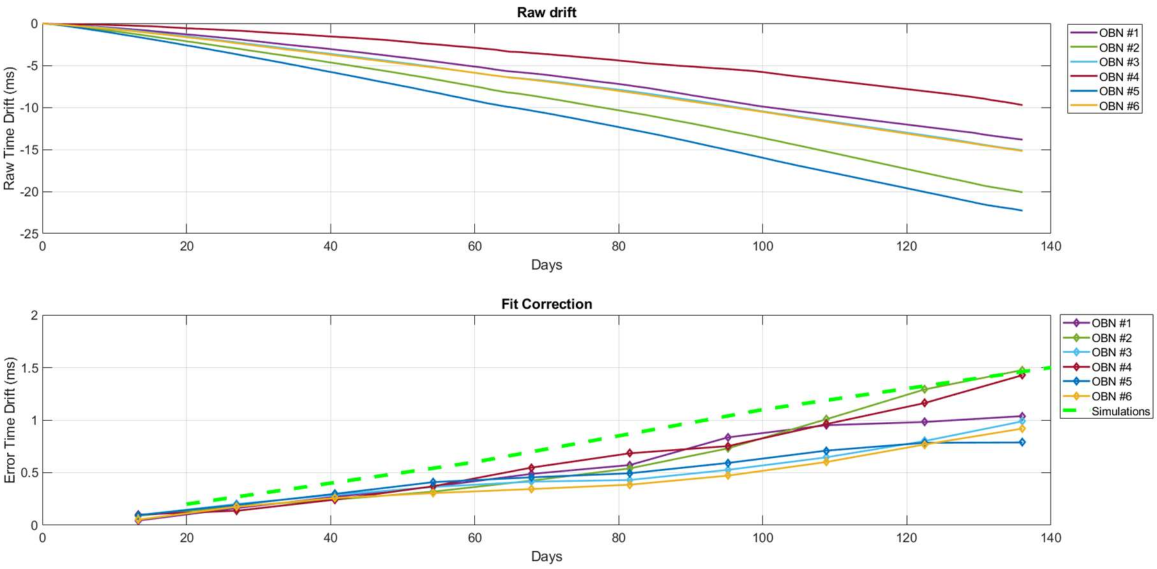

Figure 3 *(a) Dual-clock OBN raw drift over the 6 products (b) dual-clock residuals after 2*nd *order polynomial fit on frequency drift.*

Conclusion

This study demonstrates that a dual-clock timing architecture can deliver not only significant power savings, but also the level of robustness, predictability, and repeatability required for long-duration Ocean Bottom Node seismic acquisition.

Through extended laboratory testing on multiple units under controlled thermal conditions, the dual-clock system was shown to exhibit smooth, deterministic drift behavior, absence of switching-related instabilities, and excellent compatibility with data-driven drift correction techniques.

These results confirm that this timing architecture meet seismic-grade timing requirements. The proposed dual-clock solution therefore represents a reliable and energy-efficient alternative to conventional always-on timing technologies, enabling extended mission durations and new deployment scenarios for OBN surveys.

References

Rentsch, S., Thompson, J., Adams, R., Moore, D. and Raborn, R., 2023, 100 Ocean Bottom Nodes with their CSAC clock drift analysed for 91 days: three controlled experiments: *74th EAGE Conference & Exhibition*

Olofsson, B. and Woje, G., 2010, Ensuring correct clock timing in ocean bottom node acquisition: *SEG, Denver, Annual Meeting*

Beng Seong, O., Zhaojun, L., and Carsten, U., 2024, Stabilizing two-term clock-drift inversion in ocean-bottom node processing: *SEG Technical Program Expanded Abstracts* : 2043-2047.