Introduction

Recording seismic in a Transition Zone (TZ) environment is challenging, both because of operational aspects and of data quality issues. The transition zone is often a noisy environment, and the surface and near-surface conditions can vary rapidly along a line. Surface waves are an issue, and the general data quality is more comparable to land than to marine data. Still, we can see that many transition zone surveys are acquired with relatively sparse point receivers, using geometries that are more common to marine than land acquisition. The reason for this is cost, both capital cost for the equipment and operational cost to deploy it. While higher density would be preferred, it is often not economically possible. There have been a few dense surveys, as the Dukhan 3D (Seeni et al., 2011), where the receiver spacing of 7.5 m was kept for the transition zone part of the survey, resulting in a high quality seismic image. This is however an exception. What would it take to make it cost effective to increase density sufficiently to tackle the complexity of the TZ data?

Technical challenges

The first Transition Zone acquisition systems were cable based, usually adaptation of land systems. With difficult access in TZ areas, and reliability issues due to connectors and cable in wet areas, they present significant operational drawbacks. Already in the 90's, nodal systems were developed for TZ to overcome these (Luzietti et al., 1995). A technical challenge for nodes is the synchronization of data. In this case, this was done by radio communication, which was also used to transmit the seismic data. This proved to be a fundamental limitation to the scaling of the channel count.

Later, Ocean Bottom Nodes (OBN) became available, with high accuracy internal clocks. They have been used in TZ surveys (Huang et al., 2023). Their high unit cost makes it however expensive to achieve the receiver density that would be needed.

Using land nodes has also been proposed (Clark et al., 2025). Standard land nodes use GNSS for timing, and can therefore not be placed under water. The solution is to put the node on a float, and have a separate sensor attached via a cable and connector, which is reintroducing reliability and operational issues.

Timing solutions

These different solutions show us that only relying on an external timing source in TZ systems is problematic. The internal clock solution in OBN is attractive, it is however necessary to reduce the cost. Could a good enough internal clock solution be implemented in a small and low-cost node?

OBN have been using several types of clock:

- Chip scale atomic clocks, which are very accurate but very expensive
- OCXO (Oven Controlled Crystal Oscillator), which are not as stable, but cheaper. Their accuracy can be improved by correction algorithms (Bunting et al., 2023)

Land nodes have a GNSS receiver and a low power clock, usually a TCXO (Temperature Compensated Crystal Oscillator). We would need to be able to get adequate timing when GNSS is not available for a few weeks using this clock. As in OBN nodes, we can also develop a correction algorithm for the oscillator to improve its stability.

Land nodes have an advantage over seabed nodes: during land operation, we are characterizing our clocks continuously. Between any two GNSS fixes, we measure the oscillator frequency and also a number of environmental and node parameters. We are collecting a large amount of data that gives an in-depth and up-to-date oscillator characterization.

We can then use Machine Learning to develop behavioural models of the clocks, both nominal for the type of clocks and individual for each component, and update and improve them continuously as we acquire new data. These models can then be used to correct the timing of the data.

Data Example

We have recorded oscillator and auxiliary data from nodes during several deployments while they were recording seismic. They were also getting regular GNSS time stamps. From these data, we have derived a behavioural model for each node, that predicts the clock frequency from auxiliary data.
We have then deployed these nodes again first for two weeks in the lab, and then for four weeks buried in wet soil. We knew the correct timing from the GNSS time stamps. We then calculated the timing error if we only had a correct time at the start and end of the recording and applied a linear interpolation in between. And we the recalculated the timing error, with correct time at start and end and in addition using our behavioural model in between instead of a linear interpolation.

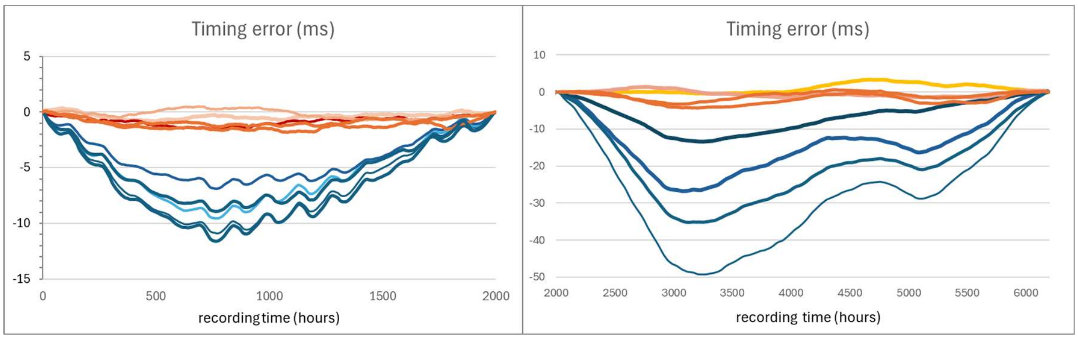

Figure 1 *Timing errors (ms) over 2 weeks in the lab (left) and 4 weeks buried in wet soil; blue with standard linear correction; orange with applied behavioural model correction*

The model-based correction significantly reduces the timing errors. For the two weeks recording, the timing error was below 1.5 ms for over 95% of the data. While this is not yet perfect, it already makes the data useable. This level of error should be compared to other timing errors as statics.
These results encouraged us on the potential of this method, and we are now gathering more data from seismic acquisitions with our nodal systems to improve our model and work towards a commercial implementation.

Conclusion

Improvements in land nodal clock solution and use of machine learning algorithm can enable adequate data timing in conditions with no or poor GNSS reception. By using low-cost and low-weight nodes for Transition Zone surveys, cost-efficient high density acquisition will become possible. The better noise and signal sampling will help solve the data quality issue of Transition Zone seismic.

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