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QFT-Based Simulation: Applications in Seismic Attributes and Convolution

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Abstract

Due to the increasing volume and complexity of seismic datasets, seismic processing is confronted with increasing computational demands, which necessitate the implementation of innovative solutions such as quantum computing. This study applies the Quantum Fourier Transform (QFT), implemented via the Qiskit framework, to two geophysical applications: computing instantaneous seismic attributes and performing Multi-Dimensional Convolution (MDC). We present a workflow for preparing seismic data for QFT processing, demonstrating results with accuracy comparable to conventional Fourier Transform (FT)-based methods. Although executed on a quantum simulator, the approach is compatible with quantum hardware, promising significant performance gains through qubit superposition. This work offers a new framework for integrating quantum algorithms into geophysical processing workflows, highlighting their potential to improve efficiency and scalability as quantum technology advances. It is among the first applications of QFT to seismic analysis.

Introduction

In seismic processing, the Fourier Transform (FT) is essential for signal decomposition, attribute extraction, and frequency-domain operations. However, applying the FT to large-scale seismic datasets incurs high computational costs, often requiring advanced computing resources. Despite progress in classical computing, the growing volume of seismic data demands innovative solutions. Quantum computing, a promising paradigm for high-performance computing, offers transformative potential for geophysical applications. Recent studies show quantum circuits achieving inversion results comparable to classical methods on Noisy Intermediate-Scale Quantum (NISQ) devices (Albino et al., 2022) and quantum algorithms using Hadamard gates and tensor encodings reproducing seismic attribute results for fault detection (Alsalmi and Dossary, 2023).

Addressing the computational challenges in seismic processing, the Quantum Fourier Transform (QFT), a cornerstone of quantum computing, offers theoretical exponential efficiency for spectral decomposition via quantum superposition and entanglement (Nielsen and Chuang, 2010). As the quantum analogue of the FT, QFT reduces signal transformation complexity, making it ideal for geophysical applications (Camps et al., 2020). In this study, we apply QFT, implemented via Qiskit 1.4.1 and the Aer simulator 0.16.4 (Javadi-Abhari et al., 2024), to compute seismic attributes and perform Multi-Dimensional Convolution (MDC). We develop a workflow for data preparation, state encoding, QFT processing, and result decoding, tailored to seismic analysis.

Although tested on a quantum simulator without assessing computational speedup, our workflow is compatible with quantum hardware, promising improved efficiency as technology advances (Sakk, 2020). The QFT's efficient circuit design, based on matrix and tensor decompositions, enables its application to multidimensional seismic data (Camps et al., 2020). Numerical results validate the implementation, showing close agreement with FT-based methods, confirming the accuracy and feasibility of the QFT-based pipeline. Despite challenges like quantum noise and high-fidelity gate requirements, emerging solutions such as dynamic circuits enhance scalability (Sakk, 2020). This early demonstration of QFT in seismic processing establishes a scalable framework, paving the way for transformative geophysical workflows as quantum hardware evolves (Nielsen and Chuang, 2010).

Methodology

The QFT performs the discrete FT on quantum state amplitudes using a quantum gate-based model (Camps et al., 2020; Chiaverini et al., 2005). The circuit employs Hadamard gates to create superpositions and controlled phase rotations to encode phase relationships between quantum states and generate interference. For an input of n qubits, the QFT maps a computational basis state $|x\rangle$, where $x \in \{0, 1, \ldots, 2^{n-1}\}$, into a quantum superposition state

$$|x\rangle \rightarrow \frac{1}{\sqrt{2^n}} \sum_{k=0}^{2^n-1} e^{2\pi i x k / 2^n} |k\rangle \,, \tag{1}$$

where $N = 2^n$ is the dimension of the Hilbert space, and $|k\rangle$ represents the computational basis states in this space. The QFT maps a basis state $|x\rangle$ into a superposition of possible states $|k\rangle$, each weighted by a complex exponential factor. These phase factors encode the frequency content of the quantum state, analogous to how classical FT operates on signal amplitudes. To realize this transformation, each qubit undergoes a Hadamard gate followed by a series of controlled-R_k rotation gates, where $R_k = \begin{bmatrix} 1 & 0, 0 & e^{2\pi i/2^k} \end{bmatrix}$. The sequence of operations is reversed in terms of qubit ordering due to the nature of the QFT's output, which stores the least significant bits in the higher qubit indices. In the quantum setting, this entire process leverages quantum parallelism, performing the computation across all basis states simultaneously. While this provides an exponential theoretical advantage in terms of complexity, reducing the operation from $O(N \log N)$, as in the Fast Fourier Transform (FFT), to $O((\log N)^2)$ in QFT circuits, such benefits can only be fully realized on real quantum hardware with sufficient qubit fidelity and low noise.

To implement the QFT, we use the open-source Qiskit framework, which provides tools for designing, simulating, and executing quantum circuits on simulators and quantum hardware. Its modular architecture and gate-level control enable direct translation of quantum models into circuits. In this study, we adopt Qiskit's standard QFT implementation, following the canonical design with Hadamard gates, controlled phase rotations, and qubit reordering. Figure 1 shows the classical-quantum workflow. On the left, it outlines the pipeline from signal input to quantum output decoding. On the right, it displays the QFT circuit adapted from Arsoski (2024). A violet arrow connects both parts, highlighting a processing stage to the quantum operation.

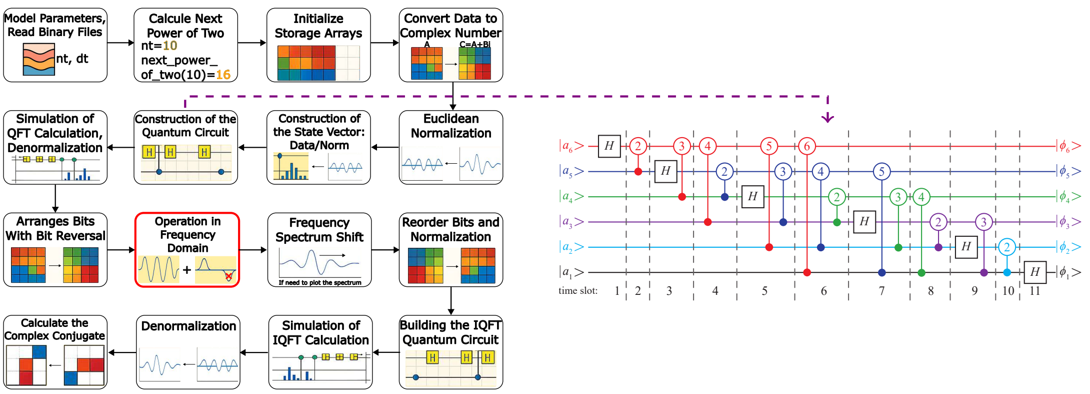

Figure 1: Workflow for QFT-based seismic processing, showing classical-to-quantum stages. The quantum circuit (right) is adapted from Arsoski (2024) for the QFT step.

The QFT circuit uses two registers: ancillary and computational, as in Arsoski (2024). These are denoted by $|a_1\rangle$ to $|a_6\rangle$ for the ancillary qubits and $|\phi_1\rangle$ to $|\phi_6\rangle$ for the computational qubits. Each ancillary qubit is initialized in the $|0\rangle$ state and transformed by a Hadamard gate to create an equal superposition of $|0\rangle$ and $|1\rangle$, enabling parallel execution of computational paths essential for efficient Fourier encoding. Controlled gates are distributed over 11 discrete time slots and are responsible for gradually building the entanglement structure needed for the QFT. This time-resolved encoding scheme allows the implementation of Fourier-like transformations while respecting hardware constraints such as limited qubit connectivity and coherence time. Our implementation uses 11 qubits, matching the seismic trace length (the smallest power of two $\geq$ time samples), instead of the original 12. Notably, the structure and logic of the QFT circuit remain unchanged, ensuring the scalability of the proposed approach.

Figure 1 also outlines the complete data processing workflow, starting with classical preprocessing: reading model parameters, converting real-valued data to complex form, and applying Euclidean normalization. The quantum state is constructed and processed through a simulated QFT circuit. Postprocessing includes bit reversal, spectrum correction, optional frequency shifting for visualization, and inverse QFT (IQFT). Final steps involve denormalization and computing the complex conjugate. This hybrid pipeline enables efficient frequency-domain analysis. The step in the red square denotes the application-specific operation performed in the Fourier domain.

Numerical Examples

To assess QFT for seismic data analysis, we compare its performance with the FFT implementation in NumPy 2.2.3, using mean squared error (MSE) between outputs. The first application computes seismic attributes via QFT (red rectangle in Figure 1). These attributes enhance the interpretation of subsurface structures by highlighting reflection contrasts and amplitude variations. For a seismic trace $s(t)$, the analytic signal is $\tilde{s}(t) = s(t) + j\hat{s}(t)$, with $\hat{s}(t)$ as the Hilbert transform. The envelope is $A(t) = \sqrt{s(t)^2 + \hat{s}(t)^2}$, instantaneous phase $\phi(t) = \arctan[\hat{s}(t)/s(t)]$, and frequency $f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}$. Using the "Riacho São Pedro Jacuípe" dataset, Figure 2 compares envelope, phase, and frequency from FFT and 11-qubit QFT simulation. MSE values are 5.11×10^{-15} (envelope), 1.36×10^{-11} (phase), and 4.08×10^{-7} (frequency). Minor differences appear in areas of high amplitude variation, but overall agreement confirms the accuracy of the quantum approach.

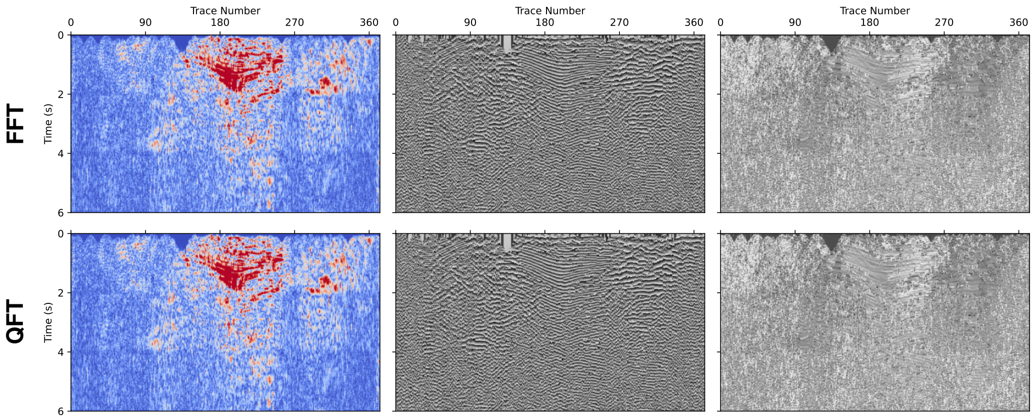

Figure 2: Comparison of seismic attributes computed using FFT and QFT. The columns, from left to right, correspond to the envelope, instantaneous phase, and instantaneous frequency.

The second example employs the Overthrust model and applies MDC in the frequency domain. MDC is the main kernel of many seismic applications, such as Surface-Related Multiple Elimination (SRME) and Marchenko redatuming, among others. In this test, MDC performs an element-wise multiplication between a reflectivity dataset R (with n_{src} sources, n_{rcv} receivers, and nt time samples) and a seismic record generated by a subsurface perturbation. Figure 3 compares FFT and

QFT results, showing strong agreement. The MSE is 5.45×10^{-9}, validating the QFT implementation in Qiskit. These results confirm that quantum algorithms match classical outputs and suggest their potential for seismic processing on future quantum platforms.

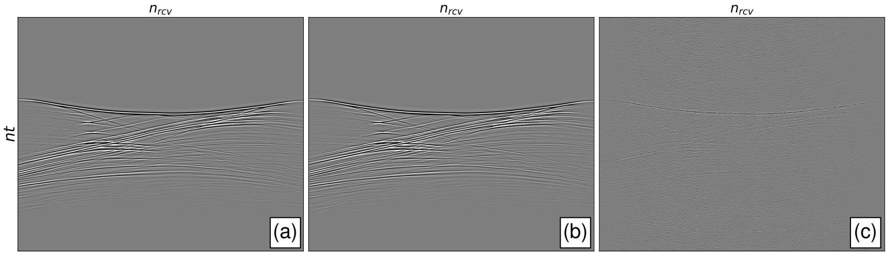

Figure 3: MDC results: (a) FFT output, (b) QFT output, (c) difference (scaled by 10^6).

Conclusions

We presented a QFT-based workflow for seismic processing, with simulated tests focused on computing instantaneous attributes and performing MDC. The results demonstrate that QFT can accurately replicate classical FFT-based outputs, exhibiting errors near machine precision. While our tests were conducted using a quantum simulator, the methodology is fully compatible with quantum hardware. True computational speedups, however, can only be assessed on real quantum devices. Nonetheless, the proposed framework offers a pivotal first step towards incorporating QFT into Fourier-domain seismic algorithms, suggesting a promising avenue for future quantum-accelerated geophysical processing.

Acknowledgments

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