Quantum Fourier Transform as a probabilistic spectral estimator for Earth Observation applications

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Abstract: We characterise the Quantum Fourier Transform as a probabilistic spectral estimator and validate it on 2005 real satellite radar signals. Sub-millimetre velocity accuracy is achieved with 5,000 shots, matching operational Earth Observation products.

The Quantum Fourier Transform (QFT) is a core subroutine of Quantum Phase Estimation and Shor's algorithm. When applied to a quantum state encoding a classical signal, measuring in the computational basis yields outcomes distributed according to the power spectrum of the signal; since each measurement returns a single frequency bin, spectral information must be accumulated over many repetitions (shots), making the QFT an inherently probabilistic spectral estimator. We exploit this property for velocity retrieval in Multi-Temporal SAR Interferometry (MTI), where the dominant frequency of an interferometric phase time series corresponds to the ground deformation rate [1].

We amplitude-encode 2005 real interferometric time series (245 Sentinel-1 C-band acquisitions, Cazzaso test site) into 9-qubit quantum states, zero-padded to 512 samples, and process them through a standard QFT circuit on the Qiskit AerSimulator. Since the QFT positive-phase convention makes it equivalent to the inverse FFT, a bin-index remapping is applied before comparing with classical spectra. Three estimators are then extracted from the measurement histogram (Fig. 1, right column), namely mode with parabolic interpolation, windowed median, and windowed mean, and benchmarked against operational MTI velocities. The median estimator achieves MAE = 0.405 mm/yr, with 90.8% of signals falling within the ±1 mm/yr, consistent with the millimetre-level accuracy of operational InSAR ground-motion services, while outliers remain confined to low-coherence signals whose spectra lack a clear dominant peak. Sub-millimetre accuracy is reached with 5 000–10 000 shots. At fixed circuit depth the estimation precision follows the standard quantum limit; variable-depth approaches such as Statistical Phase Estimation [3] could in principle reach Heisenberg-limited precision. To our knowledge, this constitutes the first validation of a QFT-based algorithm against operational Earth Observation products, addressing a gap identified by the ESA QC4EO roadmap [2].

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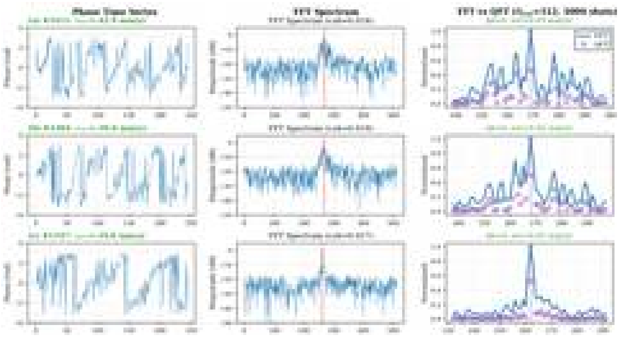

Fig. 1 Three representative persistent scatterer signals from the Cazzaso test site. Left: wrapped phase time series. Centre: FFT spectrum (dB). Right: FFT magnitude (solid) vs QFT histogram (circles, 5000 shots, N_pad = 512).

References

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