Uncertainty Quantification for Remotely-Sensed Data-sets

Earth observation satellites sense spectral signals reflected on objects on Earth's surface, storing Terabytes of data per day in data storage devices at the European Space Agency (ESA). The EnMAP satellite collects hyperspectral imaging data to provide vital information for scientific inquiries, societal grand challenges, and key stakeholders and decision-makers. However, deep neural networks (DNNs) require large labeled data-sets for data-driven tasks, while hyperspectral images (HSIs) for hazard and risk assessment have limited label information, making it challenging to obtain sufficient benchmark HSIs for training. Bayesian neural networks (BNNs) can be trained on limited-label data-sets since they provide uncertain information in their predictions and weights. Classical Variational Inference (VI) techniques are used to generate samples from the posterior of BNNs. Quantum algorithms will have an enormous impact on processing BNNs on limited benchmark labeled-HSI data-sets for making high-stakes decisions when we have access to reasonable noisy intermediate-scale and fault-tolerant quantum computers (QCs) integrated with supercomputers, high-performance computing (HPC). Hence, this study explored quantum algorithms for improving conventional VI techniques in processing limited-label HSIs: Quantum Variational Inference (QVI) for limited-label HSIs. The analysis and projection of quantum machines for QVI on limited-label HSIs:

- **Present Day:** Superconducting-based quantum machines in the current market comprise around 100 error-prone qubits and depth-5 faulty quantum gates, while quantum learning models require more than depth-5 quantum gates. Hence, quantum variational inference models can only be implemented as a proof-of-the-concept when the elements in HSIs have no more than 5-10 percent overlap.
- **3-5 years:** Quantum machines begin to have 100 error-prone input qubits and depth-100 faulty quantum gates. Quantum variational inference models can be executed on those quantum machines, while the elements in HSIs could overlap up to 10-30 percent.
- **15 years:** By this time, quantum machines will have around thousands of error-corrected input qubits and more than depth-100 quantum gates. Quantum variational inference models can then be implemented for operational-sized HSIs having more than 30 percent overlap in their elements on fault-tolerant quantum machines.

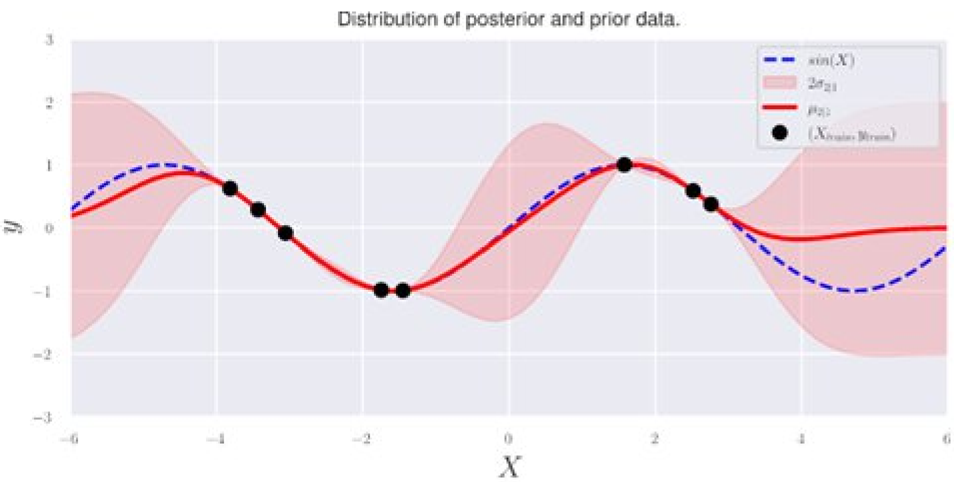

Figure I: Uncertainty quantification for a synthetic data-set. The quantum approach for uncertainty quantification may help reduce the model's uncertainty given a few data points.

In conclusion, it is vital to assess the models' uncertainty in order to obtain trustworthy solutions for climate challenges. Quantum models may reduce model's uncertainty for climate-related decisions. The lower the model uncertainty, the lower the decision-making costs. We are hopeful that we will be able to use a quantum computer that has over 100 high-quality qubits and an error rate of 10^{-13}. However, if our luck is not so good, we may only have access to a quantum computer with around 300 low-quality qubits and an error rate of 10^{-7}. To achieve a useful quantum advantage, we must first investigate quantum models for uncertainty quantification more in-depth and the required quantum resources in the next 1-3 years (see *Table I*). After that, we should focus on the demonstration of practical quantum advantage over traditional classical algorithms.

Table I: We presented the main quantum parameters of a superconducting quantum machine for our identified use-case [theoretical speculation, subject to change]. Here, theoretical speculation refers to gate error rate and gate fidelities, whereas the number of physical qubits are promised the quantum roadmap provided by industry.

	Present Day	3-5 years	5-15 years
Number of physical qubits	100	100-300	1,000
Circuit depth	5	100-300	1,000
Error rate/threshold error rate (p/p_th)	0.0149	0.0051	0.1823
Logical error rate	10^{-7}	10^{-13}	10^{-20}
1Q Fidelity	99.99%	99.99%	>99.99%
2Q Fidelity	99.97%	99.98%	>99.99%