Quantum computing in the service of satellite data processing

Piotr Gawron

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences

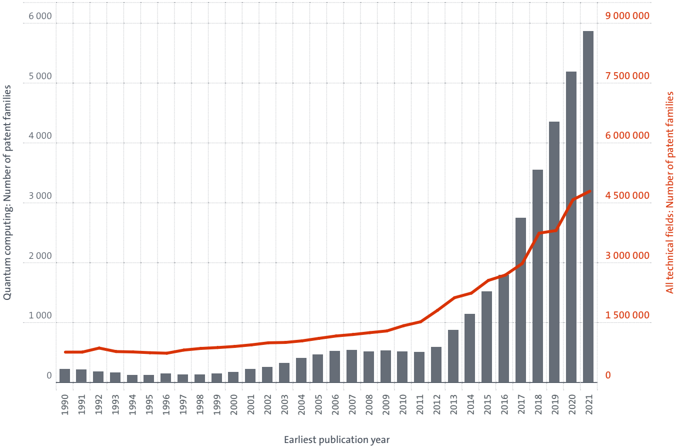
2nd International Workshop on Machine Learning
and Quantum Computing Applications in Medicine and Physics
3–7 June 2024, Warsaw

Motivation

Number of DOCDB patent families per earliest publication year in the field of quantum computing

Figure 2

Number of DOCDB patent families per earliest publication year in the field of quantum computing

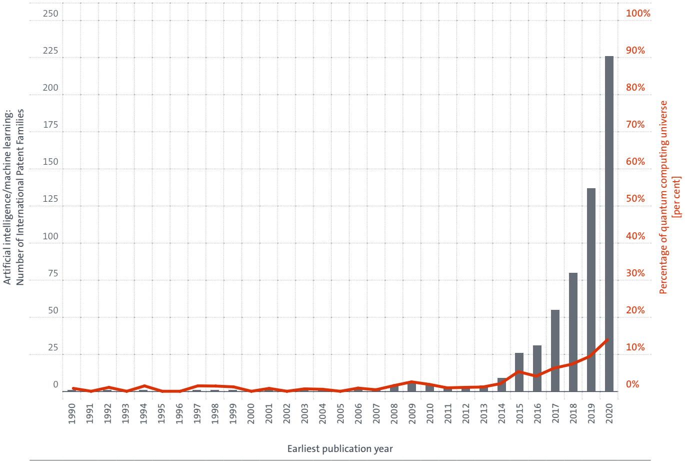


Source: authors' calculations

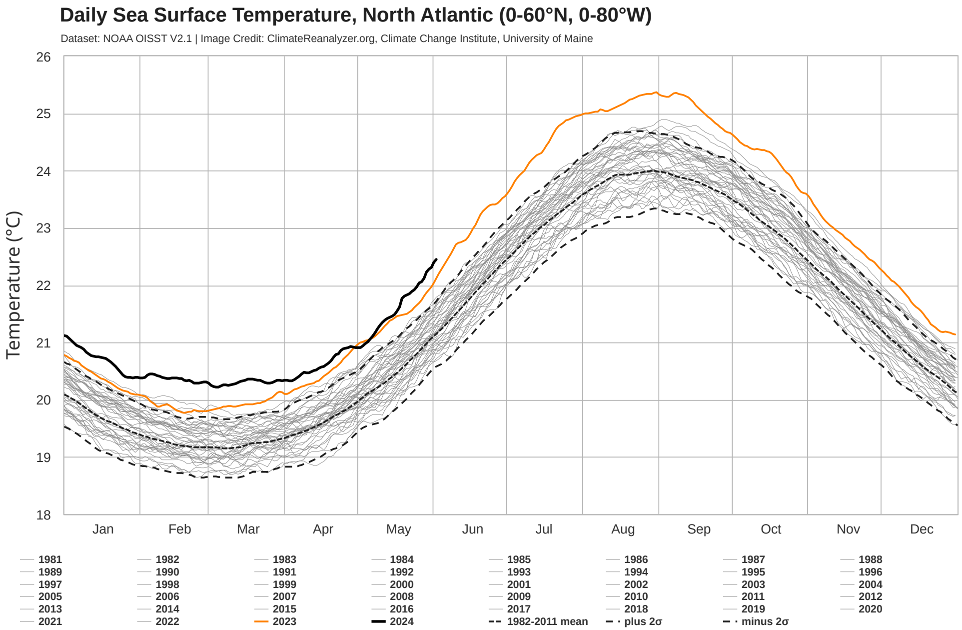
Number of inventions per earliest publication year related to quantum computing and artificial intelligence/machine learning

Figure 16

Number of inventions per earliest publication year related to quantum computing and artificial intelligence/machine learning



Source: authors' calculations


Daily Sea Surface Temperature, North Atlantic (0-60°N, 0-80°W)
Dataset: NOAA OISST V2.1 | Image Credit: ClimateReanalyzer.org, Climate Change Institute, University of Maine
Temperature (°C)
26
25
24
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Aug
Sep
Oct
Nov
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1981
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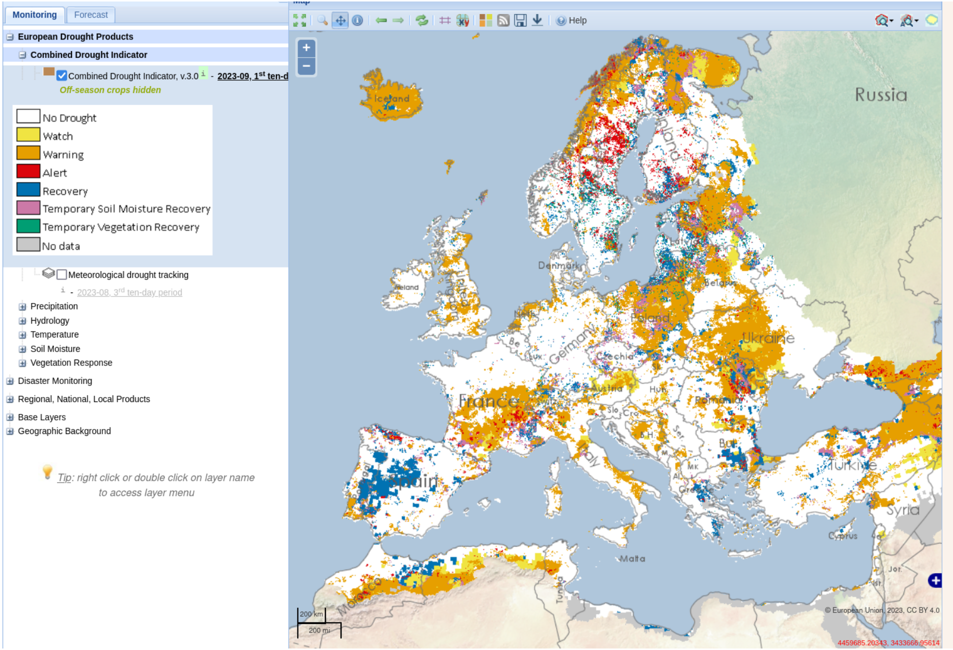
2024
1982-2011 mean
plus 2σ
minus 2σ


Monitoring
Forecast
European Drought Products
Combined Drought Indicator
Combined Drought Indicator, v.3.0 - 2023-09, 1st ten-d
Off-season crops hidden
No Drought
Watch
Warning
Alert
Recovery
Temporary Soil Moisture Recovery
Temporary Vegetation Recovery
No data
Meteorological drought tracking
- 2023-08, 3rd ten-day period
Precipitation
Hydrology
Temperature
Soil Moisture
Vegetation Response
Disaster Monitoring
Regional, National, Local Products
Base Layers
Geographic Background
Tip: right click or double click on layer name to access layer menu
Help
Iceland
Russia
Denmark
Ireland
Belarus
Poland
Ukraine
Czechia
France
Austria
Romania
Spain
Türkiye
Syria
Cyprus
Malta
200 km
200 mi
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4459685.20343, 3433666.95614

Quantum Advantage for Earth Observation

Quantum Advantage for Earth Observation

Report commissioned by ESA

QA4EO

Quantum Advantage for Earth Observation

Soronzonbold Otgonbaatar[1,2], Olli Nurmi[3], Mikael Johansson[4], Jarmo Mäkelä[4], Tadeusz Kocman[5], Piotr Gawron[6,7], Zbigniew Puchała[7], Łukasz Pawela[7], Jakub Mielczarek[8], and Artur Miroszewski[8]

[1]German Aerospace Center (DLR) Oberpfaffenhofen
[2]Ludwig-Maximilians-Universitaet Muenchen
[3]VTT-Technical Research Centre of Finland Ltd.
[4]CSC–IT Center for Science Ltd.
[5]SYDERAL Polska sp. z o.o.
[6]AstroCeNT, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
[7]Etos Centrum Edukacji i Doradztwa Służby Zdrowia sp. z o.o.
[8]Jagiellonian University

ESA Contract No. 4000140122/22/I-DT

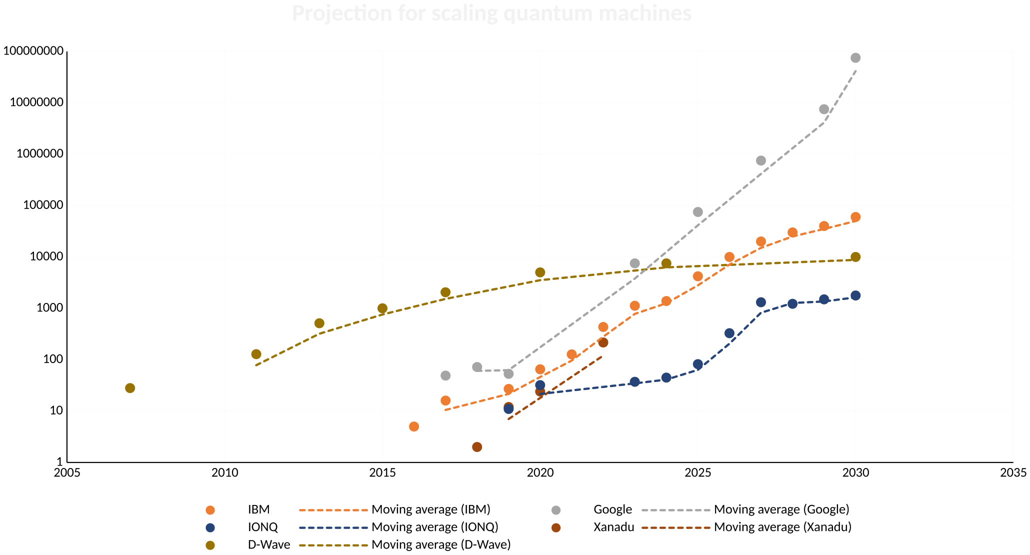
Use-Cases

- Use-Case I: Climate Adaptation Digital Twin HPC+QC Workflow
- Use-Case II: Uncertainty Quantification for Remotely-Sensed Datasets
- Use-Case III: Quantum Algorithms for Earth Observation Image Processing
- Use-Case IV: Feature Selection and Feature Extraction for Satellite Hyperspectal Imagery Data

Methods

- Quantum Variational Algorithms / Eigensolvers
- Quantum Neural Networks
- Quantum Principal Component Analysis
- Quantum Kernel Methods
- Quadratic Unconstrained Binary Optimization-based algorithms

Projection for scaling quantum machines



Quantum machines parameters

Efficiency of variational quantum algorithms depends on multiple factors:

- number of qubits,
- qubits connectivity,
- single-qubit, two-qubit or multi-qubit gate fidelities,
- measurement errors,
- quantum system coherence time,
- execution time of operations reset, gate, and measurement,
- scalability of the quantum computing hardware platform,
- precision of control pulses,
- possibility to perform mid-quantum computing measurement and classical computing,
- classical optimization method,
- ansatze.

Assessing quantum advantage difficulties

Article

Evidence for the utility of quantum computing before fault tolerance

https://doi.org/10.1038/s41586-023-06096-3

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Open access

Check for updates

Youngseok Kim[1,6]✉, Andrew Eddins[2,6]✉, Sajant Anand[3], Ken Xuan Wei[1], Ewout van den Berg[1], Sami Rosenblatt[1], Hasan Nayfeh[1], Yantao Wu[3,4], Michael Zaletel[3,5], Kristan Temme[1] & Abhinav Kandala[1]✉

Quantum computing promises to offer substantial speed-ups over its classical counterpart for certain problems. However, the greatest impediment to realizing its full potential is noise that is inherent to these systems. The widely accepted solution to this challenge is the implementation of fault-tolerant quantum circuits, which is out of reach for current processors. Here we report experiments on a noisy 127-qubit processor and demonstrate the measurement of accurate expectation values for circuit volumes at a scale beyond brute-force classical computation. We argue that this represents evidence for the utility of quantum computing in a pre-fault-tolerant era. These experimental results are enabled by advances in the coherence and calibration of a superconducting processor at this scale and the ability to characterize[1] and controllably manipulate noise across such a large device. We establish the accuracy of the measured expectation values by comparing them with the output of exactly verifiable circuits. In the regime of strong entanglement, the quantum computer provides correct results for which leading classical approximations such as pure-state-based 1D (matrix product states, MPS) and 2D (isometric tensor network states, isoTNS) tensor network methods[2,3] break down. These experiments demonstrate a foundational tool for the realization of near-term quantum applications[4,5].

4 h on a quantum computer

Fast classical simulation of evidence for the utility of quantum computing before fault tolerance

Tomislav Begušić and Garnet Kin-Lic Chan*
Division of Chemistry and Chemical Engineering,
California Institute of Technology, Pasadena, California 91125, USA
(Dated: June 29, 2023)

We show that a classical algorithm based on sparse Pauli dynamics can efficiently simulate quantum circuits studied in a recent experiment on 127 qubits of IBM's Eagle processor [*Nature* **618**, 500 (2023)]. Our classical simulations on a single core of a laptop are orders of magnitude faster than the reported walltime of the quantum simulations, as well as faster than the estimated quantum hardware runtime without classical processing, and are in good agreement with the zero-noise extrapolated experimental results.

Efficient tensor network simulation of IBM's Eagle kicked Ising experiment

Joseph Tindall,[1] Matthew Fishman,[1] E. Miles Stoudenmire,[1] and Dries Sels[1,2]
[1] *Center for Computational Quantum Physics, Flatiron Institute, New York, New York 10010, USA*
[2] *Center for Quantum Phenomena, Department of Physics, New York University, 726 Broadway, New York, NY, 10003, USA*

We report an accurate, memory and time efficient classical simulation of a 127-qubit kicked Ising quantum system on the heavy-hexagon lattice. A simulation of this system on a quantum processor was recently performed using noise mitigation techniques to enhance accuracy (Nature volume 618, p. 500–505 (2023)). Here we show that, by adopting a tensor network approach that reflects the qubit connectivity of the device, we can perform a classical simulation that is significantly more accurate than the results obtained from the quantum device in the verifiable regime and comparable to the quantum simulation results for larger depths. The tensor network approach used will likely have broader applications for simulating the dynamics of quantum systems with tree-like correlations.

7 min on a laptop

Proposed actions

Study the following research ideas

- Idea 1: Hyper-spectral Image segmentation using deep RBMs/QBMs
- Idea 2: Application of probabilistic graphical models for segmentation and post-processing
- Idea 3: Change detection — using hybrid quantum-classical machine learning models
- Idea 4: Application of physics inspired simulated bifurcation, and other hybrid algorithms combined with quantum annealers for EO

Projects

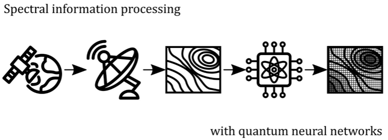
Spectral information processing with quantum neural networks

Piotr Gawron, CAMK PAN

IDEA: I-2021-00015

Spectral information processing with quantum neural networks

Campaign: Quantum Information Processing



3

ALL AUTHORS

P Piotr Gawron

Research Question

Is there a practical reason to use Quantum Computing rather than classical classification techniques for spectral classification task?

Source: ESA

MULTI-SPECTRAL IMAGE CLASSIFICATION WITH QUANTUM NEURAL NETWORK

Piotr Gawron *

AstroCeNT
Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
ul. Rektorska 4, 00-614 Warsaw, Poland
gawron@camk.edu.pl

Stanisław Lewiński

Space Research Center
Polish Academy of Sciences
ul. Bartycka 18A, 00-716 Warsaw, Poland
stlewinski@cbk.waw.pl

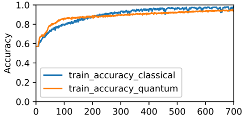
avg \ max	ASC	CA	BTC	CTC	HV	MP	NMS	WB
ASC		91.3	98.8	98.5	95.8	88.3	77.0	99.3
CA	88.9		94.5	96.8	75.0	79.3	79.3	99.8
BTC	97.4	87.5		89.0	92.3	93.3	98.5	99.8
CTC	94.9	91.9	80.7		98.0	93.0	96.3	99.0
HV	92.9	72.0	83.3	94.9		70.3	91.0	100.0
MP	85.7	73.4	77.3	84.8	61.4		85.3	98.8
NMS	71.1	75.4	94.4	89.9	87.9	82.2		97.5
WB	98.9	99.3	99.3	98.9	99.4	98.6	95.7	

Table 1. Average (avg) and maximum (max) over folds of classification accuracies of binary classifiers for pairs of classes, in ptc.

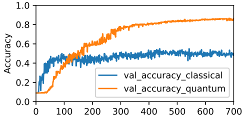
HOW QUANTUM COMPUTING-FRIENDLY MULTISPECTRAL DATA CAN BE?

Manish K. Gupta[1*] *Martin Beseda*[2] *Piotr Gawron*[1†]

[1]AstroCeNT — Particle Astrophysics Science and Technology Centre — International Research Agenda,
Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences,
Rektorska 4, 00-614 Warsaw, Poland
[2]IT4Innovations National Supercomputing Center
VŠB–Technical University of Ostrava
Studentská 6231/1B, 70800 Ostrava–Poruba, Czechia



(a) Classical and quantum training accuracy



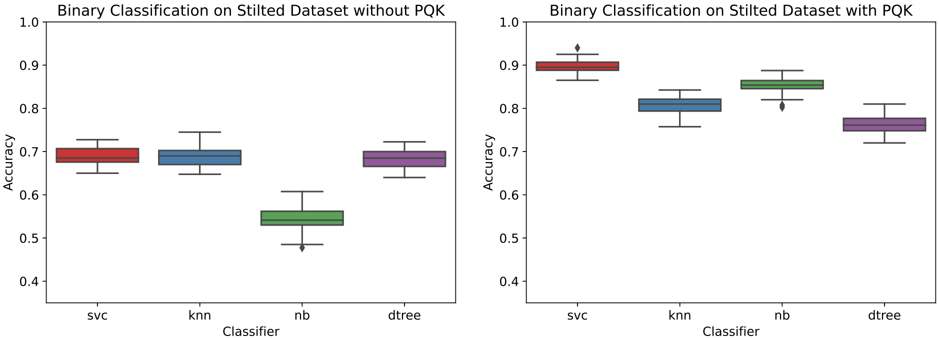
(b) Classical and quantum validation accuracy

Fig. 1. Training and validation accuracy of feedforward neural network with and without access to PKQ features for classes "Broadleaf tree cover — 82", and "Herbaceous vegetation — 102".

- Is there a labelling for a set of data for which quantum kernel method is better than any classical?
- Short answer: Yes. So there is some hope.
- Based on celebrated paper: Huang, H-Y et al. 2021. "Power of Data in Quantum Machine Learning." Nature Communications 12 (1): 2631.

Potential of Quantum Machine Learning for Processing Multispectral Earth Observation Data

With M. Gupta, M. Romaszewski (under review)



Potential of Quantum Machine Learning for Processing Multispectral Earth Observation Data

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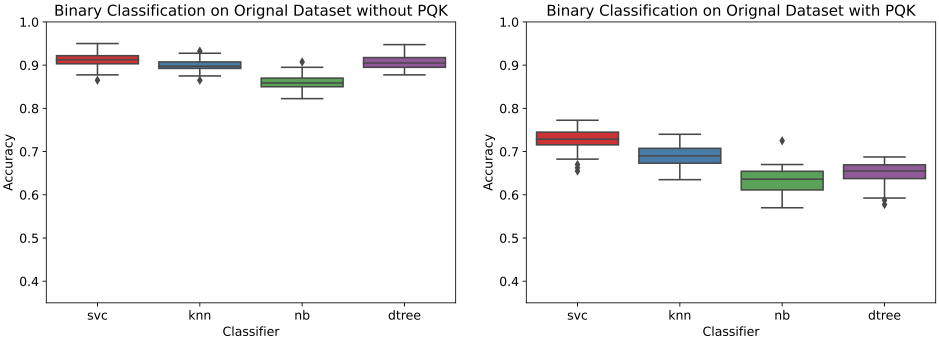

QC4GEO

Studies commissioned by CNES

Quantum machine learning in applications to unsupervised and semi-supervised analysis of satellite images

CENTRE NATIONAL D'ÉTUDES SPATIALES

QUANTUM CONTRASTIVE LEARNING FOR SEMANTIC SEGMENTATION OF REMOTE SENSING IMAGES

Véronique Defonte[1], *Matthijs van Waveren*[1], *Guillaume Pasero*[1],
Mickaël Savinaud[1], *Piotr Gawron*[3*], *Pierre-Marie Brunet*[2], *Orphée Faucoz*[2]

[1] CS GROUP, 6, rue Brindejonc des Moulinais, 31500 Toulouse, France
[2] CNES, 10 avenue Edouard Belin, 31400 Toulouse, France
[3] AstroCeNT, Nicolaus Copernicus Astronomical Center, PAS, Rektorska 4, 00-614 Warsaw, Poland

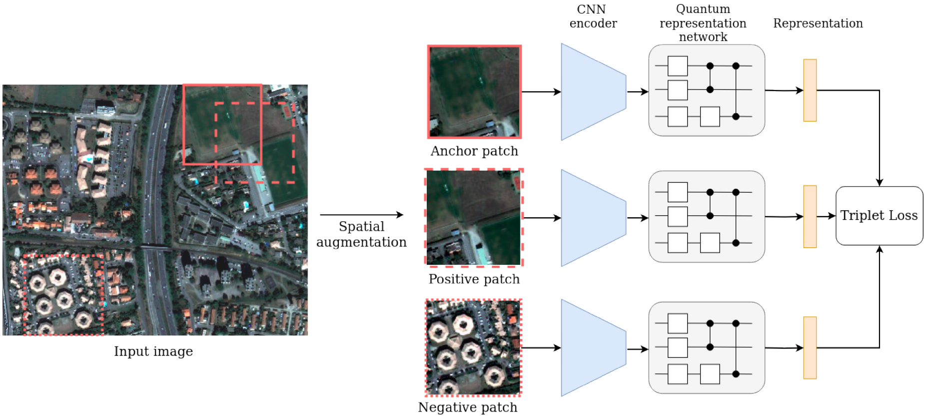

Fig. 1. Illustration of the proposed hybrid contrastive learning framework.

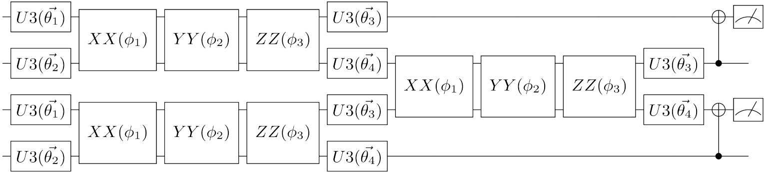

Fig. 2. 4-qubit version of the parameterized quantum circuit. $\{\vec{\theta_1}, \phi_1 ...\}$ represents trainable parameters. We used an 8-qubit version of the circuit in this work

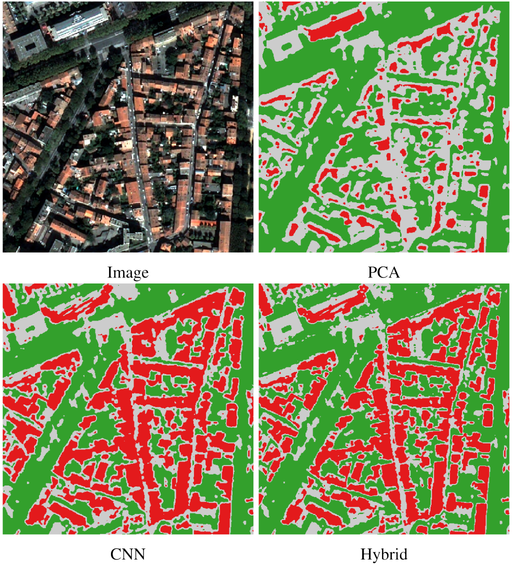

Fig. 3. Semantic segmentation derived from the three methods.

Table 1. Clustering results for each method.

	Method		
F1-score	PCA	CNN	Hybrid
Building	0.38	**0.69**	0.66
Vegetation	**0.81**	0.77	0.76
Bare land	0.25	0.26	**0.30**
Overall	0.57	**0.64**	0.63

CAMK PAN

COMPARISON OF QUANTUM NEURAL NETWORK ALGORITHMS FOR EARTH OBSERVATION DATA CLASSIFICATION

Matthijs van Waveren[1], *Mickaël Savinaud*[1], *Guillaume Pasero*[1],
Veronique Defonte[1], *Pierre-Marie Brunet*[2], *Orphee Faucoz*[2],
Piotr Gawron[3*], *Bartłomiej Gardas*[4], *Zbigniew Puchała*[4], *Łukasz Pawela*[4],

[1] CS GROUP, 6, rue Brindejonc des Moulinais, 31506 Toulouse, France
[2] CNES, 10 avenue Edouard Belin, 31401 Toulouse, France
[3] AstroCeNT, Nicolaus Copernicus Astronomical Center, PAS, Rektorska 4, 00-614 Warsaw, Poland
[4] Institute of Theoretical and Applied Informatics, PAS, Bałtycka 5, 44-100 Gliwice, Poland

Characteristic	Classical algorithm	Single quantum layer QCNN	Full quantum model QCNN	Ortho-gonal quantum neural network
Degree of quantization	None	Low	Medium	Medium
Quantum parameters	Not applicable	Gate angles	Gate angles	Matrix elements
Scaling of feedforward time	$O(N^2)$	$O(N^2)$	-	$O(N)$
Number of parameters	$O(N)$	$O(N)$	$O(\log N)$	-

Table 1. Comparison of quantum neural network algorithms

HYPER-SPECTRAL IMAGE CLASSIFICATION USING ADIABATIC QUANTUM COMPUTATION

Bartłomiej Gardas[1] , *Przemysław Głomb*[1], *Przemysław Sadowski*[1],
Zbigniew Puchała[1], *Konrad Jałowiecki*[1], *Łukasz Pawela*[1], *Orphee Faucoz*[2],
Pierre-Marie Brunet[2], *Piotr Gawron*[1,3]*, *Matthijs van Waveren*[4],
Mickaël Savinaud[4], *Guillaume Pasero*[4], *Veronique Defonte*[4]

[1] Institute of Theoretical and Applied Informatics, PAS, Bałtycka 5, 44-100 Gliwice, Poland
[2] CNES, 10 avenue Edouard Belin, 31401 Toulouse, France
[3] AstroCeNT, Nicolaus Copernicus Astronomical Center, PAS, Rektorska 4, 00-614 Warsaw, Poland
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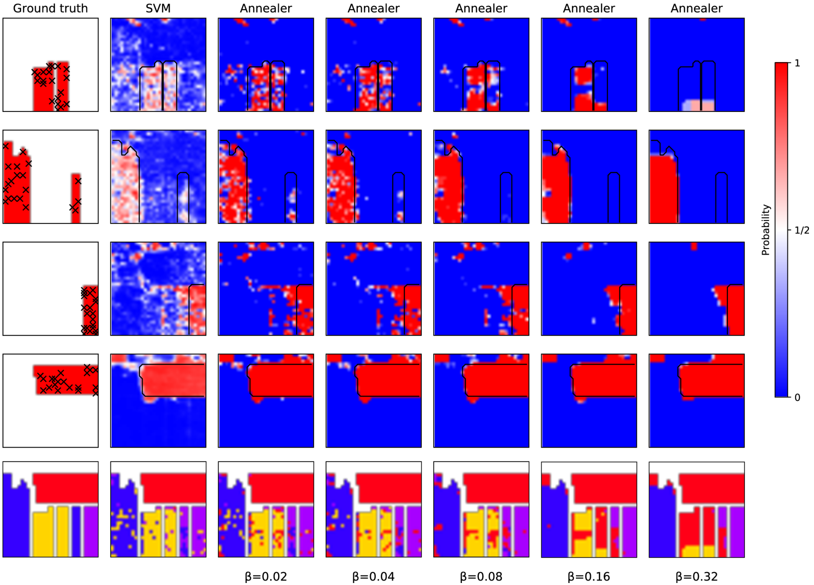

Ground truth
SVM
Annealer
Annealer
Annealer
Annealer
Annealer
Probability
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1/2
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β=0.02
β=0.04
β=0.08
β=0.16
β=0.32

WHAT COULD BE ACHIEVED WITH A MILLION QUBITS QUANTUM ANNEALER IN REMOTE SENSING?

Piotr Gawron[1*], *Przemysław Sadowski*[2], *Przemysław Glomb*[2], *Bartłomiej Gardas*[2],
Matthijs van Waveren[3], *Clément Forray*[3], *Guillaume Pasero*[3], *Mickaël Savinaud*[3],
Pierre-Marie Brunet[4], *Orphée Faucoz*[4], *Zbigniew Puchała*[2], *Łukasz Pawela*[2]

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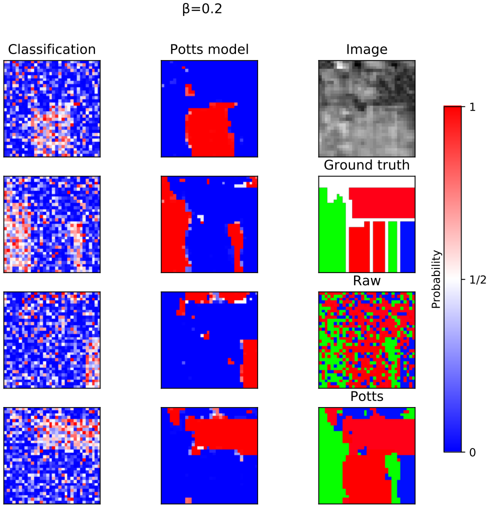
[3] CS GROUP, 6, rue Brindejonc des Moulinais, 31506 Toulouse, France
[4] CNES, 10 avenue Edouard Belin, 31401 Toulouse, France

Markov Random Fields for image segmentation post-processing

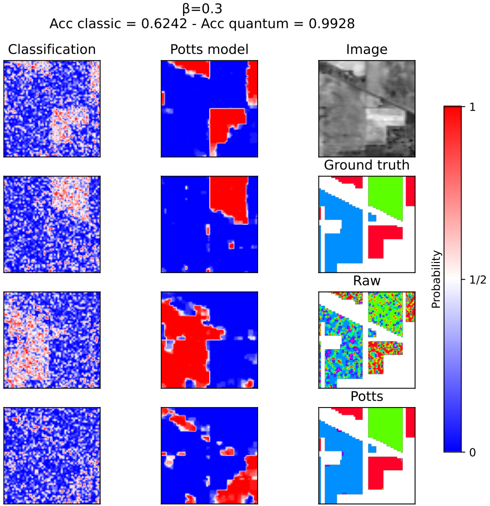
$$E(c) = -\sum_{i\in\mathcal{I}} D(c_i) - \beta \sum_{(i,j)\in\mathcal{I}\times\mathcal{I}} V(c_i, c_j).$$

$$p(c) = \frac{1}{Z}\exp(-E(c)), \text{with } Z = \sum_{c\in\mathcal{C}} \exp(-E(c)),$$

D-Wave Chimera

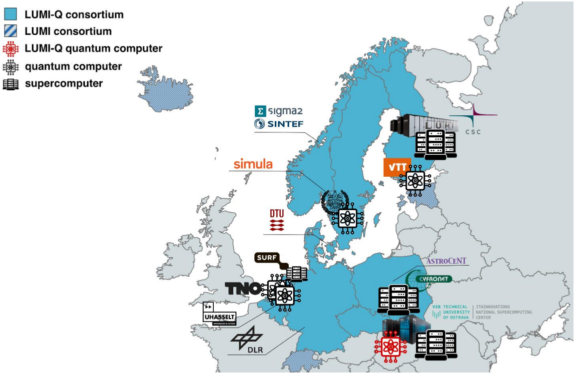


D-Wave Pegasus



EuroQHPC-Integration / LUMI-Q

(To be) funded by EuroHPC JU



Objective of LUMI-Q

Acquisition of a quantum computer and its integration into the HPC environment associated with LUMI.

Objective of EuroQHPC-Integration

Integration of quantum computers and HPC in Europe.
(Applications of QML for EO data processing — as a use-case)

QUantum AnnealiNg for Graphical models in climate Observation

- IITiS, PAN
- Forschungszentrum Jülich
- Durham University/Physics
- CY Cergy Paris University/Geosciences

Objective of the project

Implementation of probabilistic graphical models on quantum annealers

What is needed to progress towards QA4EO?

1. Identification of difficult problems on the EO community side.
2. Explaining what could be achievable with QC.
3. Close and active collaboration between EO and QC communities:
    - theoretical physicists,
    - computer scientists,
    - machine learning / data processing software developers,
    - hardware providers,
    - geoscientists.
4. Funding for basic and low-TRL research.

Passion and hope for future generations

Hope

- We need to give next generations the hope that
  - peaceful,
  - democratic,
  - sustainable,
  - common

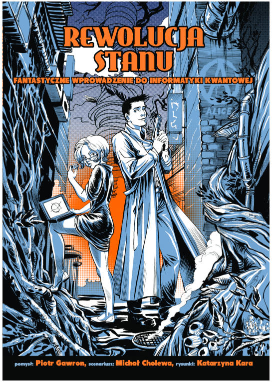
  future exists.

Q4Climate

The union of quantum and climate research

Passion

- We need to ignite the flame of passion for science, space, universe.



CAMK PAN

Thank you for your attention

Piotr Gawron

@ piotr@piotrgawron.eu

http://piotrgawron.eu/

More research is needed. . .

The project is co-financed by the funds of the Polish Ministry of Education and Science under the program entitled International Co-Financed Projects and the European Space Agency.