QUANTUM COMPUTING FOR EARTH OBSERVATION

M2GARSS 2024 - Tutorial

April 15, 2024 Amer Delilbasic, Gabriele Cavallaro

JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE

UNIVERSITY OF ICELAND

esa

IEEE GRSS ESI Earth Science Informatics Technical Committee

Driving questions for the tutorial

- **What is quantum computing?**
- **Why the quantum computing hype?**
- **How can Earth observation benefit from quantum computing?**
- **Which algorithms and resources are relevant for me?**

Tutorial structure

Part 1: Introduction

Quantum computing

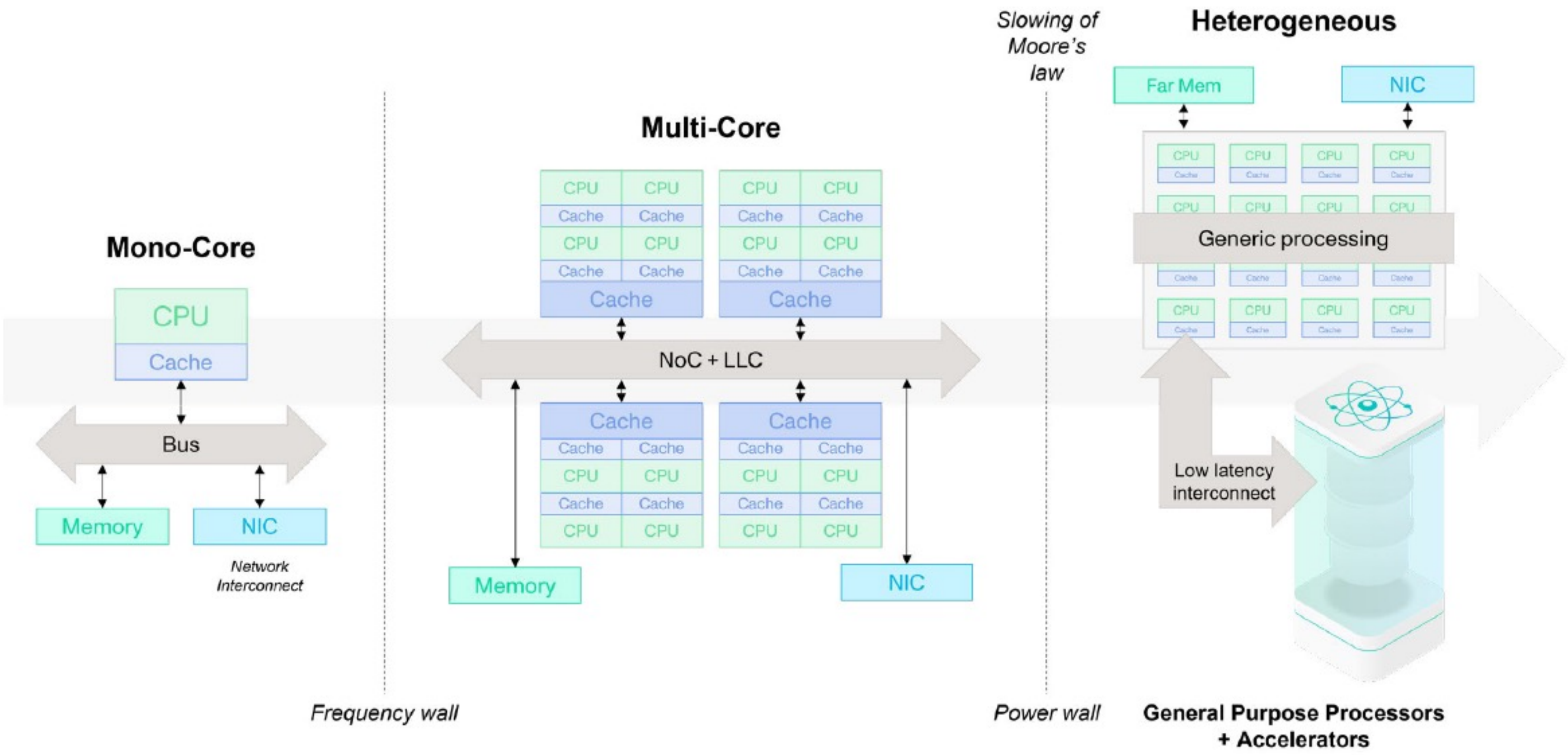
Quantum optimization

Quantum machine learning

Part 2: Examples

Acquisition planning for EO satellites

Evolution of computing architectures



IQM – LRZ, "Bringing quantum acceleration to Supercomputers", whitepaper, May 2022

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Principles of quantum mechanics

Quantum computing *is defined according to the postulates and laws of* ***quantum mechanics.***

Underlying concepts:

Superposition	Measurement	Entanglement
Quantum systems can be described as a superposition of quantum states	Measuring the state of a quantum system affects the state of the system in a random way	In an entangled system, the states of the system particles are related to each other

Qubit as information unit

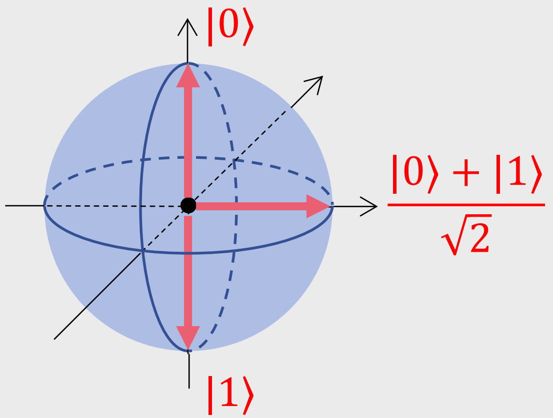
Classical bit

It can be either 0 or 1

0	1	0	0	1	0	0	0
0	1	0	0	1	0	0	1

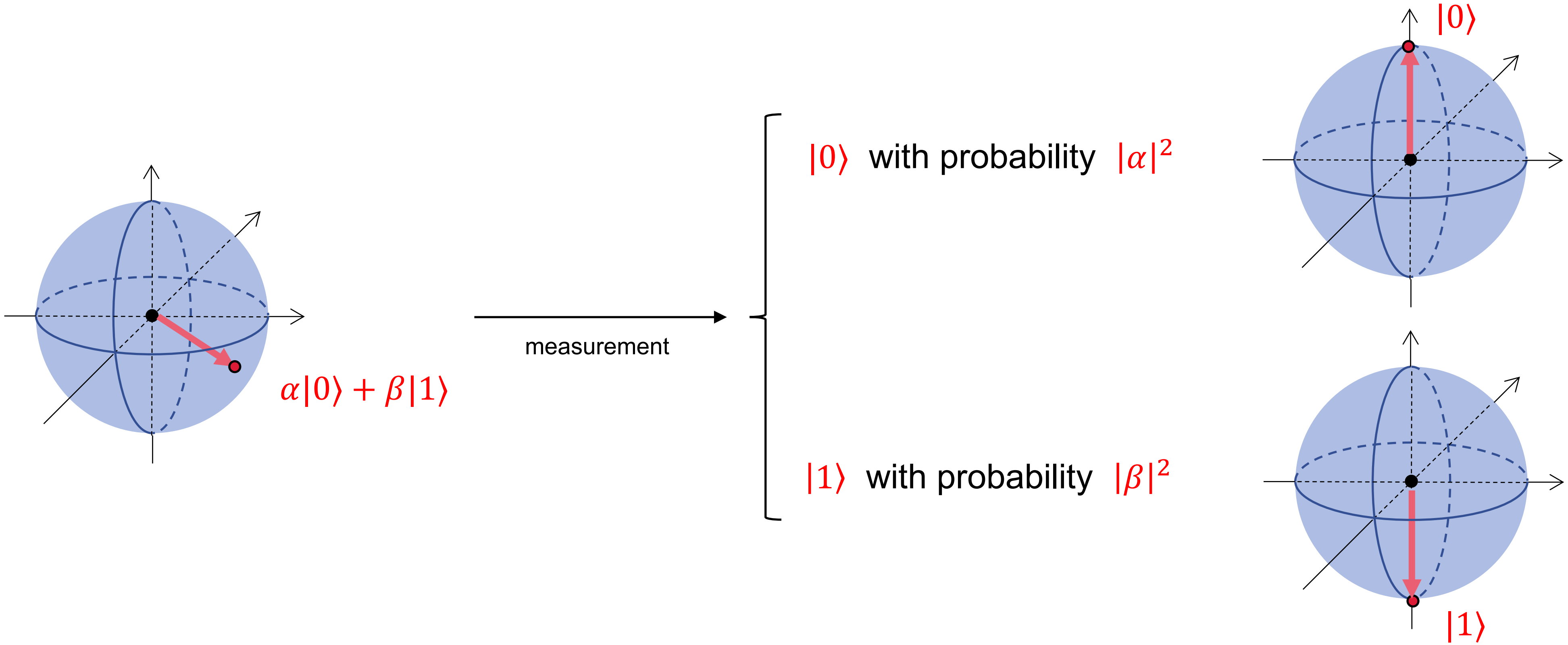
Quantum bit (qubit)

It can be $|0\rangle$, $|1\rangle$ or both at the same time!



Bloch sphere representation

Measurement and qubit collapse



Measuring a qubit leads to a **random result** and affects the qubit irreversibly.

The original state is lost, and no copies can be made (**no-cloning theorem**).

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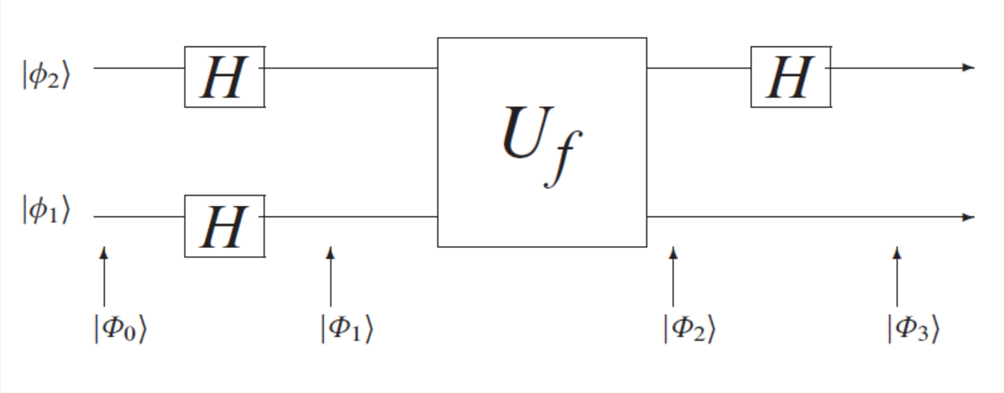
Quantum computational models

Quantum circuit model

Model where **quantum gates** and **measurements** are applied to qubits

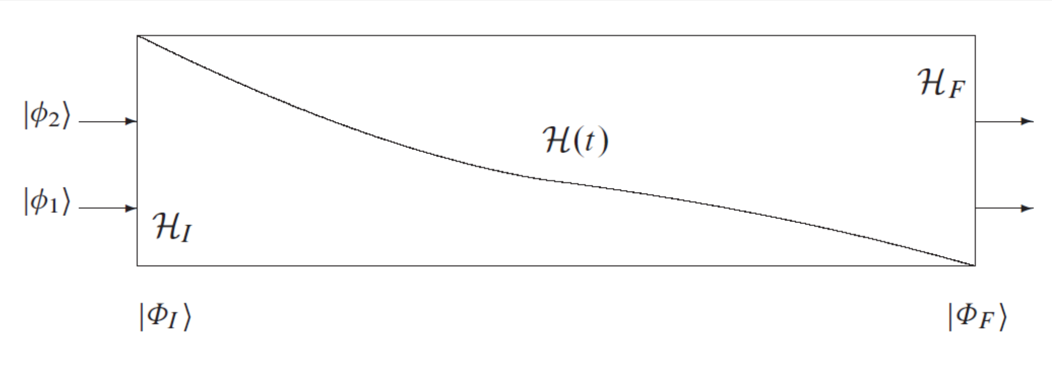


Catherine C. McGeoch, Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice , Morgan & Claypool, 2014.

Adiabatic quantum computation

Model where the time evolution of a quantum system under **adiabatic** conditions is described by the Hamiltonian $\mathcal{H}(t)$ and ruled by the Schrödinger's equation

$$i\hbar\frac{d}{dt}|\Phi(t)\rangle = \mathcal{H}(t)|\Phi(t)\rangle$$



Catherine C. McGeoch, Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice , Morgan & Claypool, 2014.

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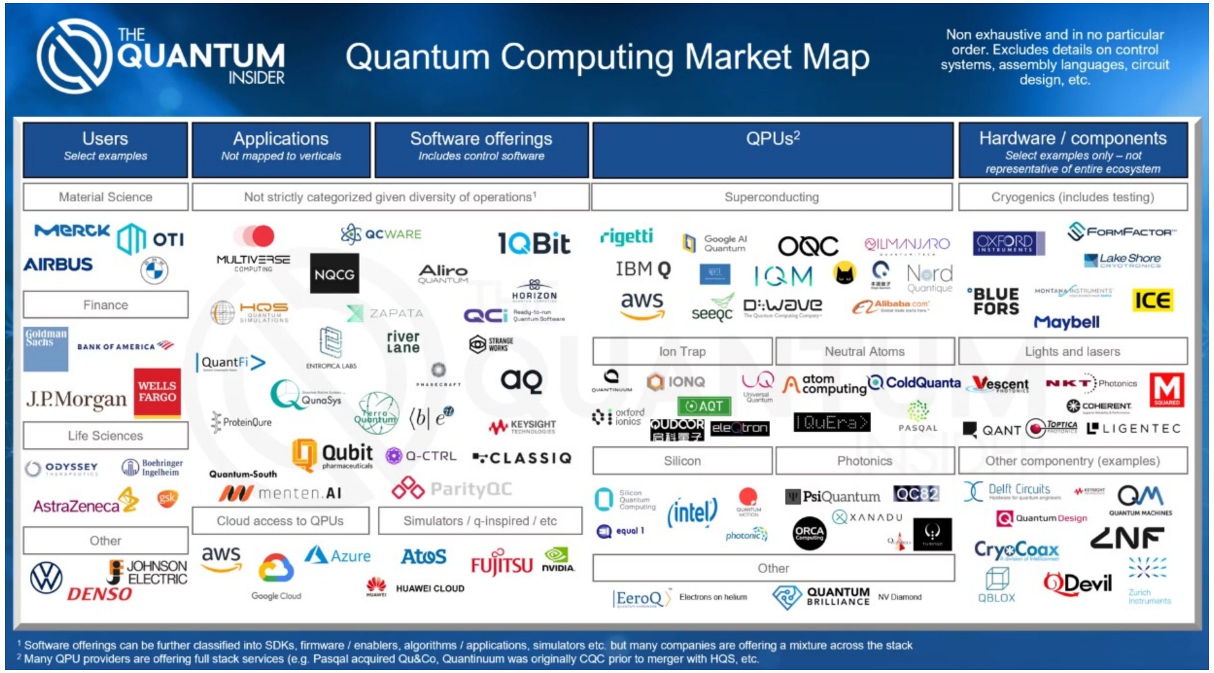
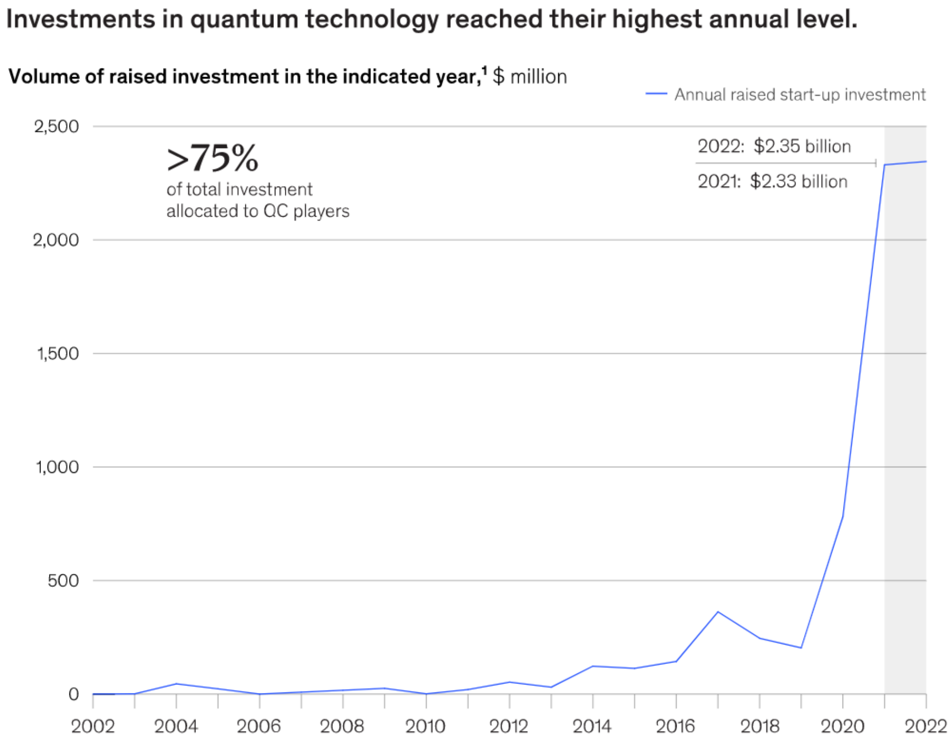
The quantum computing landscape



https://thequantuminsider.com/2022/05/09/quantum-computing-market-map-and-data-2022/



https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-technology-sees-record-investments-progress-on-talent-gap

Quantum computing can provide a substantial computational advantage

Grover's search algorithm

Iterative algorithm that searches for an item in an unstructured database of N objects

Time complexity: $O(\sqrt{N})$ instead of $O(N)$

Multiple applications and **building block of many quantum algorithms**

Shor's factoring algorithm

Finds the prime factors of an integer N

Time complexity: polylogarithmic instead of sub-exponential

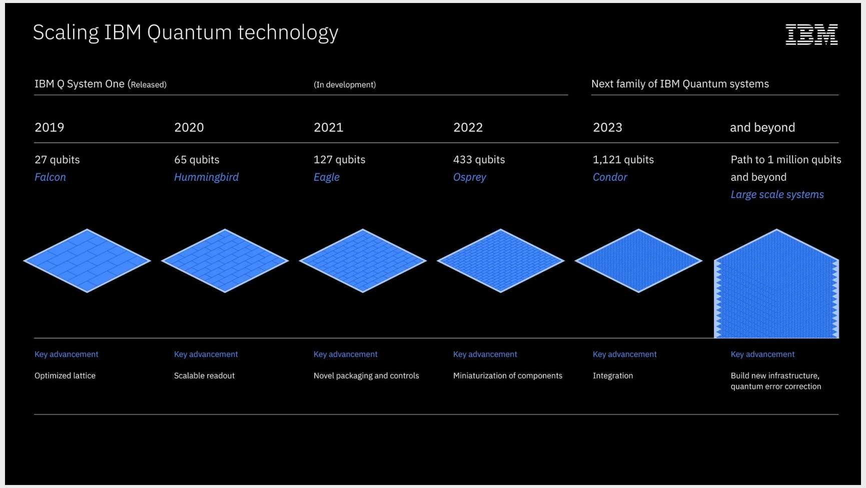
Applications in **cryptography**

Quantum computers present practical limitations

- Quantum information theory neglects physical implementation
- Current state: **Noisy Intermediate-Scale Quantum (NISQ)** devices
- Insufficient scale for a practical quantum advantage

Number of qubits

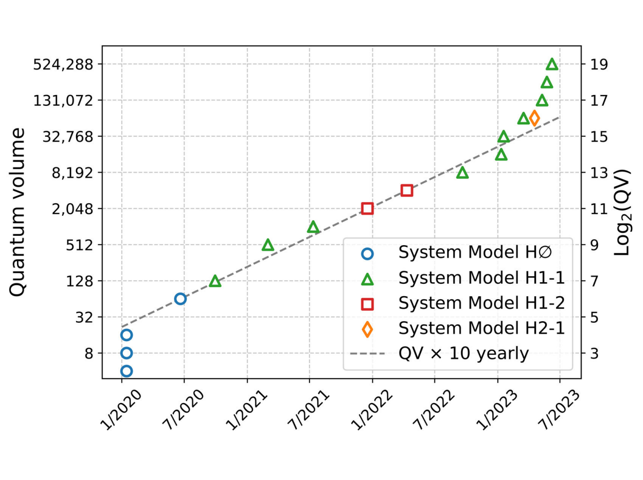
Dimension of quantum data that can be processed in a single QPU



https://www.ibm.com/quantum/blog/ibm-quantum-roadmap

Quantum volume

Dimension of the circuit that can be implemented with low error



https://www.quantinuum.com/news/quantinuum-h-series-quantum-computer-accelerates-through-3-more-performance-records-for-quantum-volume-217-218-and-219

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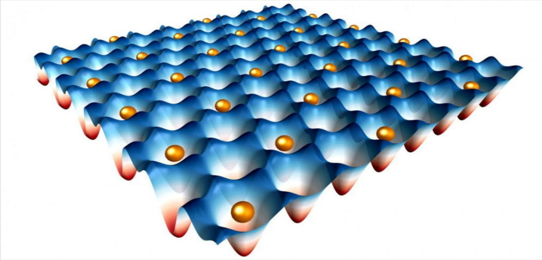
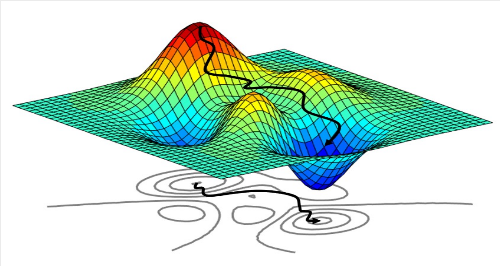
Main applications of quantum computing

Quantum simulation



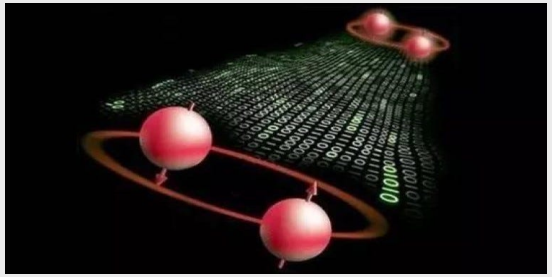
https://quantum.cornell.edu/files/2021/11/quantum_simulation-1024x576.jpg

Quantum optimization



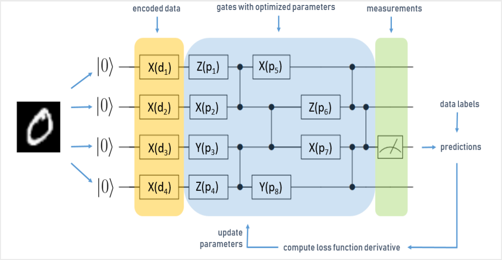
https://towardsdatascience.com/an-introduction-to-surrogate-optimization-intuition-illustration-case-study-and-the-code-5d9364aed51b

Quantum cryptography



https://miro.medium.com/v2/resize:fit:760/0*ccRjnUb2QLCYTK5a.jpg

Quantum machine learning



https://blog.tensorflow.org/2020/08/layerwise-learning-for-quantum-neural-networks.html

Which are the most relevant for Earth observation?

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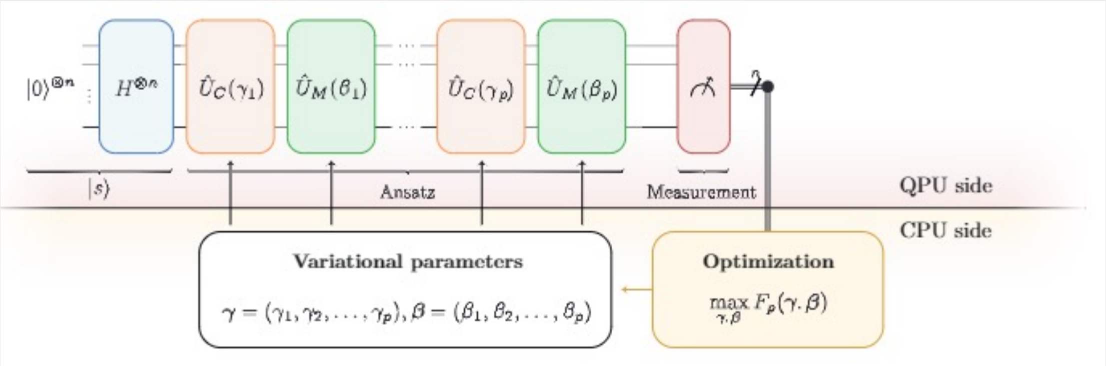
Examples of quantum optimization algorithms

Quantum Approximate Optimization Algorithm (QAOA)

Model: quantum circuits

Purpose: combinatorial optimization

Design: n qubits for 2^n possible solutions, accuracy increases with repetitions



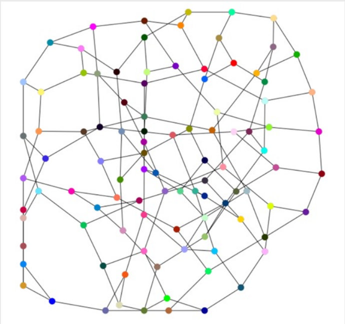
Blekos, Kostas, et al. "A review on quantum approximate optimization algorithm and its variants." Physics Reports 1068 (2024): 1-66

Quantum annealing

Model: adiabatic quantum computation

Purpose: combinatorial optimization (QUBO)

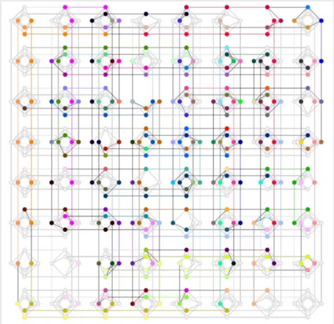
Design: n qubits for 2^n possible solutions, a coupler for each non-zero coefficient



QUBO problem

minimize $f(a) = \sum_{i \leq j} a_i Q_{i,j} a_j$

embedding



Hardware graph

Catherine C. McGeoch, Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice , Morgan & Claypool, 2014.

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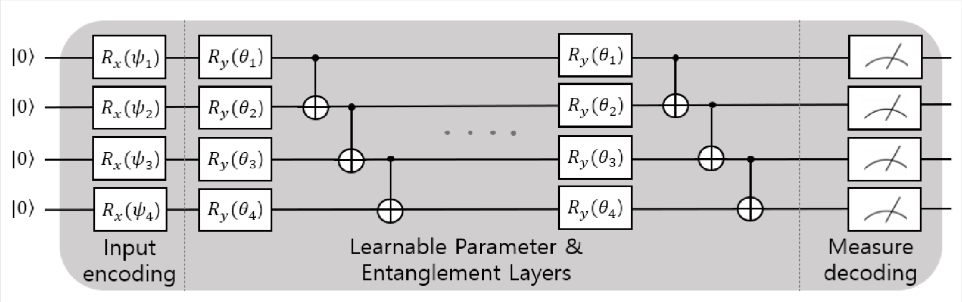
Examples of quantum machine learning algorithms

Quantum neural networks

Model: quantum circuits

Purpose: learn the circuit parameters that generate the desired output, starting from a training set

Design: multiple architectures, usually n qubits for n-dimensional data, subject to trainability requirements



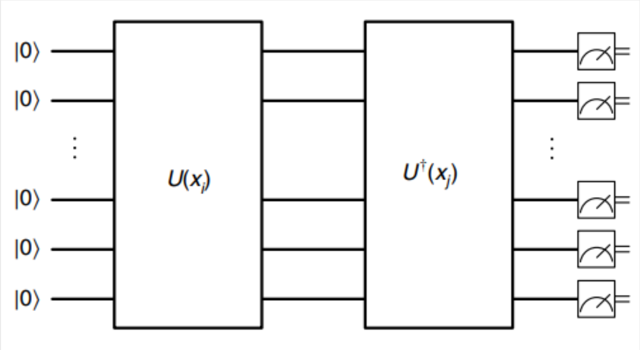
Kwak, Yunseok, et al. "Quantum neural networks: Concepts, applications, and challenges." 2021 Twelfth International Conference on Ubiquitous and Future Networks (ICUFN). IEEE, 2021.

Quantum kernels

Model: quantum circuits

Purpose: encoding data to a high-dimensional feature space and calculating the kernel matrix

Design: n qubits for n-dimensional data, a run for every pair of training examples, circuit choice depending on data structure (can be trained), subject to trainability requirements



Liu, Yunchao & Arunachalam, Srinivasan, Temme, Kristan. “A rigorous and robust quantum speed-up in supervised machine learning”, Nature Physics, 17, 1-5, 2019.

Earth observation requires increasing computing capabilities

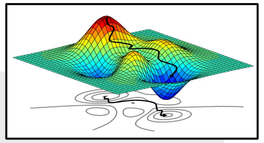
https://www.hzdr.de/db/Cms?pOid=45916&pNid=3635

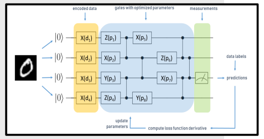
Where does quantum computing fit?

Photo by Donald Giannatti on Unsplash

QC4EO Study technical reports: https://eo4society.esa.int/projects/qc4eo-study/

Contributions to quantum computing for Earth observation





Mission analysis

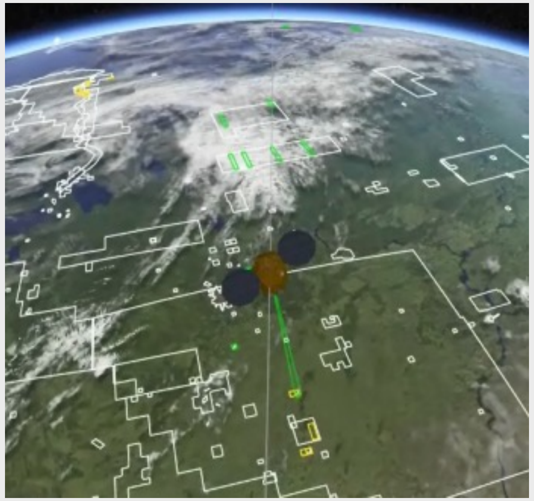
Data acquisition

Raw data processing

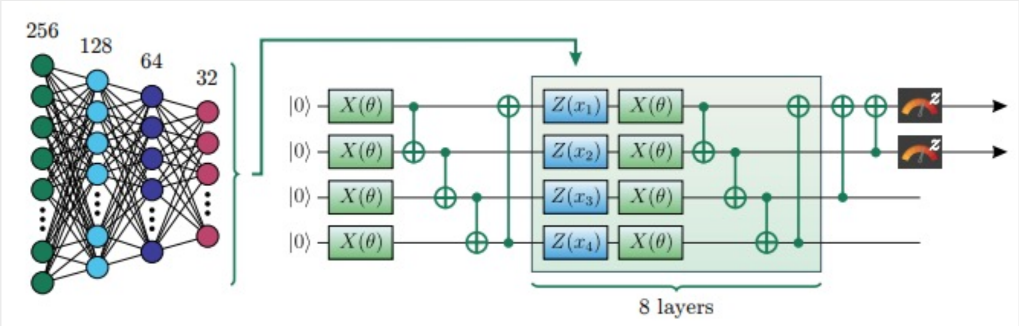
Data analysis

Acquisition planning for EO satellites

Operational planning of satellite acquisition processes



Stollenwerk, Tobias, et al. "Image Acquisition Planning for Earth Observation Satellites with a Quantum Annealer." arXiv preprint arXiv:2006.09724 (2020).



Rainjonneau, Serge, et al. "Quantum Algorithms applied to Satellite Mission Planning for Earth Observation" submitted to IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING (2023) and arXiv preprint arXiv:2302.07181v1 (2023).

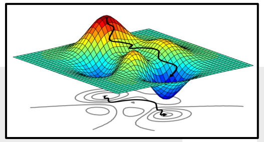
Contributions to quantum computing for Earth observation

Mission analysis

Data acquisition

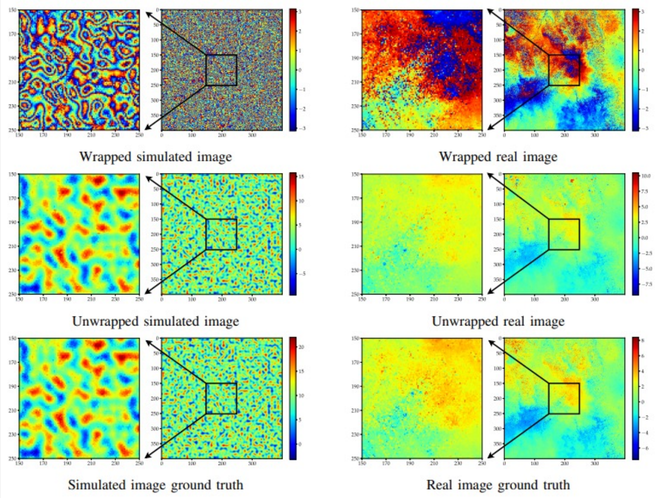
Raw data processing

Data analysis

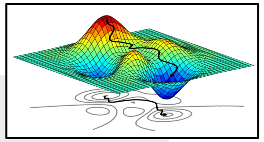


InSAR phase unwrapping

Generation of 3D topography maps from modulo 2π phase maps

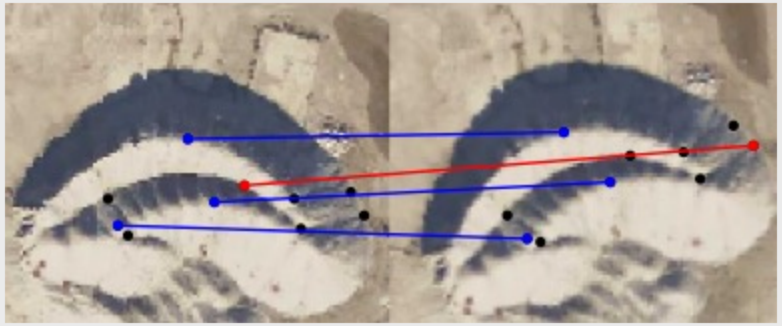


Kelany, K. A. H., Dimopoulos, N., Adolphs, C. P. J., Barabadi, B., & Baniasadi, A. (n.d.). *Quantum Annealing Approaches to the Phase-Unwrapping Problem in Synthetic-Aperture Radar Imaging.*



Bundle adjustment

Keypoint extraction and feature matching for data fusion of images taken from different points of view



Nico Piatkowski, Thore Gerlach, Romain Hugues, Rafet Sifa, Christian Bauckhage, Frederic Barbaresco, “Towards Bundle Adjustment for Satellite Imaging via Quantum Machine Learning”, arXiv:2204.11133 (2022).

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Contributions to quantum computing for Earth observation

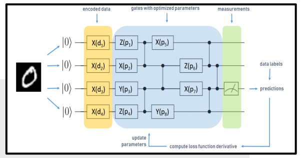
Mission analysis

Data acquisition

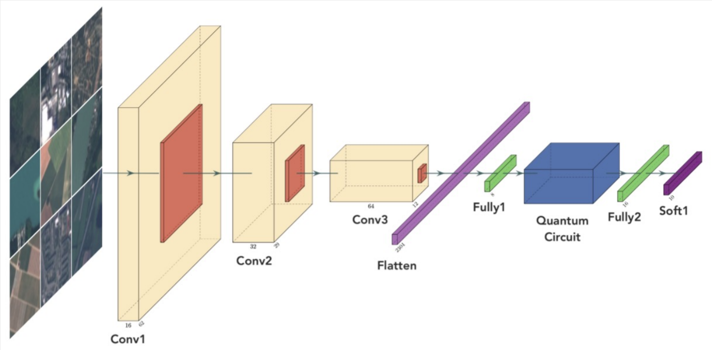
Raw data processing

Data analysis

Event detection

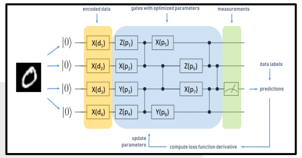


Supervised training of hybrid quantum convolutional neural networks on multispectral image datasets

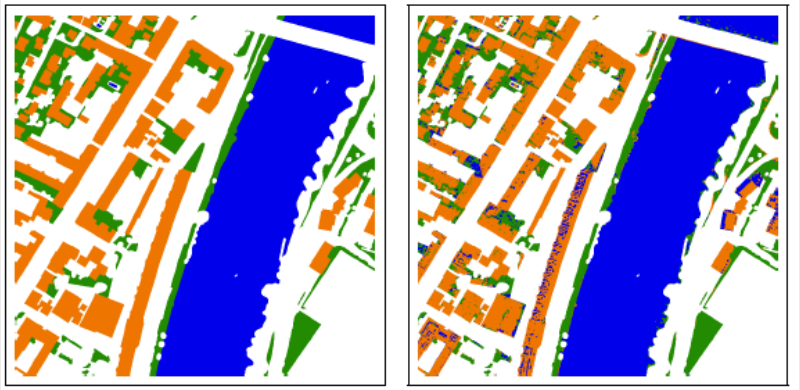


A. Sebastianelli, D. A. Zaidenberg, D. Spiller, B. L. Saux, and S. L. Ullo, "On Circuit-Based Hybrid Quantum Neural Networks for Remote Sensing Imagery Classification," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 15, pp. 565–580, 2022.

Semantic segmentation



Supervised pixel-based or region-based kernel methods (quantum kernels, quantum SVM)



(a) Ground truth (b) OVO

Practical examples

Acquisition planning for EO satellites

Use case for **quantum optimization** algorithms (QAOA, QA)

Semantic segmentation of satellite images

Use case for **quantum machine learning** algorithms

→ **Session “Quantum Approaches in Remote Sensing”**

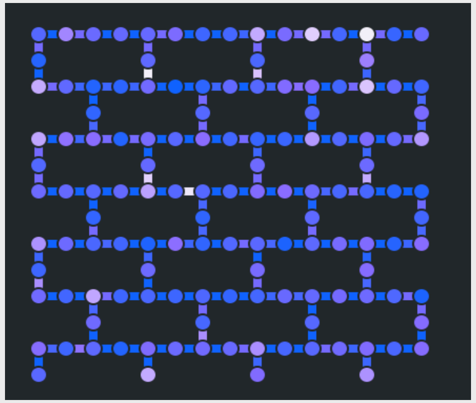
Tools for testing quantum algorithms

Qiskit

Creating and running **quantum circuits** on multiple backends

Example: IBM Torino: 133 qubits

Free access to QPUs (queue time may vary)



https://quantum.ibm.com/

Qubit structure of IBM Torino

D-Wave Ocean

Creating and solving **QUBO optimization problems** on multiple backends

Example: D-Wave Advantage quantum annealer: 5000+ qubits

1-min free computing time

https://www.fz-juelich.de/en/ias/jsc/systems/quantum-computing/juniq-facility

JUPSI, a D-Wave Advantage quantum annealer hosted at FZJ

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Acquisition planning for EO satellites

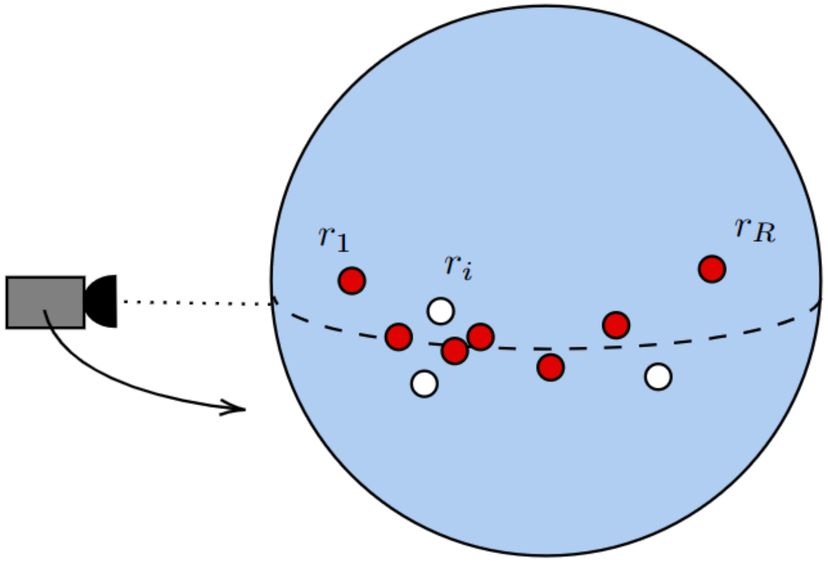
mqt-problemsolver: great library for testing QAOA for acquisition planning

Quetschlich, N., Koch, V., Burgholzer, L., & Wille, R. (2023). A Hybrid Classical Quantum Computing Approach to the Satellite Mission Planning Problem. https://arxiv.org/abs/2308.00029v1

```python
def init_random_acquisition_requests(n: int) -> list[LocationRequest]:
    """Returns list of n random acquisition requests"""
    np.random.seed(10)
    acquisition_requests = []
    for _ in range(n):
        acquisition_requests.append(
            LocationRequest(position=create_acquisition_position(), imaging_attempt_score=np.random.randint(1, 3))
        )

    return sort_acquisition_requests(acquisition_requests)
```

```python
def solve_using_qaoa(qubo: QuadraticProgram, noisy_flag: bool = False) -> Any:
    if noisy_flag:
        qaoa = QAOA(
            QAOA_params={"reps": 3, "optimizer": COBYLA(maxiter=100), "sampler": BackendSampler(FakeMontreal())}
        )
    else:
        qaoa = QAOA(
            QAOA_params={
                "reps": 3,
                "optimizer": COBYLA(maxiter=100),
                "sampler": Sampler(),
            }
        )
    qc_qaoa, res_qaoa = qaoa.get_solution(qubo)
    return res_qaoa
```



Example problem instance

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Acquisition planning for EO satellites

Solving QUBO with quantum annealing:

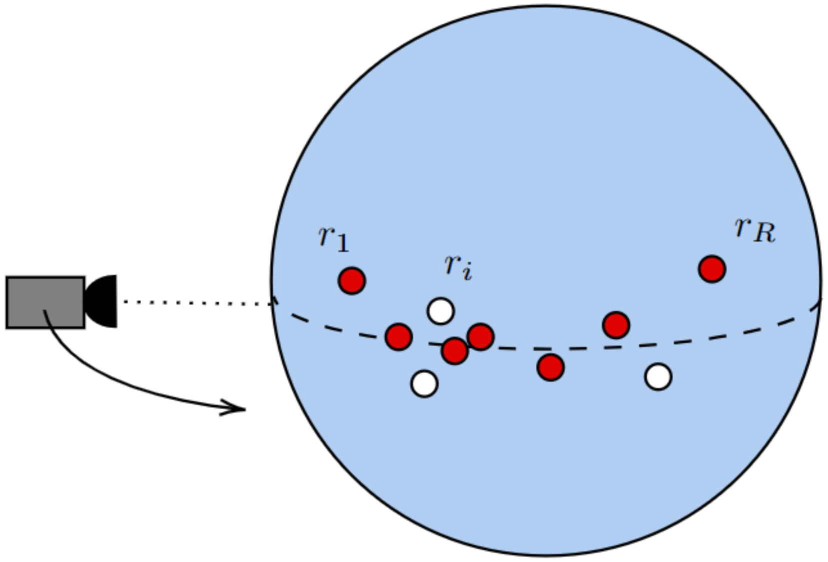
```python
def solve_using_qa(qubo, qa_setup: dict[str, Any]):
    # Create a client instance
    client = Client.from_config()

    # Get the list of available solvers
    solvers = client.get_solvers()

    # Print the name of the used solvers
    print("Using solver", solvers[0].id)

    # Create a sampler
    sampler = DWaveSampler(solver=solvers[0].id)

    # Solve the QUBO using the D-Wave sampler
    sampleset = sampler.sample_qubo(qubo, num_reads=qa_setup("num_reads"), label='Acquisition Planning')
    return sampleset
```



Example problem instance

Conclusions

- Multiple tools are available and multiple applications are possible
- Testing today: insights on the behavior of quantum algorithms > actual advantage
- Fast development of quantum hardware can change the game

Session “Quantum Approaches in Remote Sensing” (tomorrow, 9.30-10.30, in this room)

- **Quantum neural network for semantic segmentation of radar sounder data:** 9.45-10.00
- **Quantum annealing for semantic segmentation of optical images:** 10.15-10.30

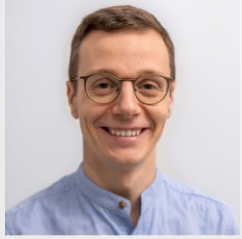
Thanks to GRSS

Join us!

CHAIRS

Manil Maskey

Peter Baumann



Gabriele Cavallaro

Earth Science Informatics (ESI) Technical Committee

Advance application of informatics to geoscience and remote sensing

https://www.grss-ieee.org/technical-committees/earth-science-informatics/

LEADS

Dora Blanco Heras

Iksha Gurung

Rocco Sedona

Sudan Jha

High-performance and Disruptive Computing in Remote Sensing (HDCRS) Working Group

Connect and support the community of interdisciplinary researchers in remote sensing who are specialized in emerging computing paradigms

https://www.grss-ieee.org/community/groups-initiatives/high-performance-and-disruptive-computing-in-remote-sensing-hdcrs/

G. Cavallaro, D. B. Heras, Z. Wu, M.Maskey, S. Lopez, P. Gawron, M. Coca and M. Datcu, "High-Performance andDisruptive Computing in Remote Sensing: HDCRS-A New Working Group of the GRSS Earth Science Informatics Technical Committee," in IEEE Geoscience and Remote Sensing Magazine (GRSM), vol. 10, no. 2, 2022, https://doi.org/10.1109/MGRS.2022.3145478

Upcoming event: School on High Performance and Disruptive Computing in Remote Sensing
4-7 June 2024, Santiago de Compostela, Spain (https://www.hdc-rs.com/)

Questions?

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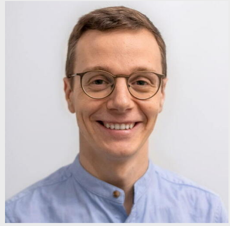

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