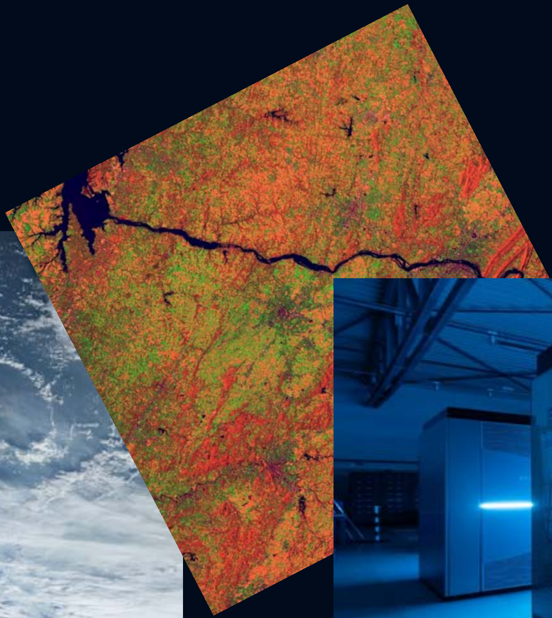

QUANTUM COMPUTING FOR EARTH OBSERVATION: SEARCHING FOR QUANTUM ADVANTAGE

Workshop “Classical HPC & QC: the way to foster the integration” (HiPEAC) | 26 January 2026 | Kraków, Poland

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ASSOCIATE PROFESSOR, FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING (UNIVERSITY OF ICELAND)

UNIVERSITY OF ICELAND | JÜLICH Forschungszentrum | JÜLICH SUPERCOMPUTING CENTRE | esa | rannís

APPLICATIONS WITH POTENTIAL QUANTUM ADVANTAGE

- **Simulations of quantum physical systems**, solid state physics and quantum chemistry
- **Engineering problems**, solution of complex partial differential equations with vast areas of application in the design of various systems in aerospace, engines and fluid mechanics
- **Cryptanalysis**, methods for breaking public encryption or signature keys used on the Internet
- **Decision and optimization problems**, found in a wide range of fields
- **Machine learning,** for both training and model inference

Practical realization of quantum computing solutions in all these areas is still hypothetical.
It depends on numerous scientific and technological factors and uncertainties.

National Academy of Technologies of France, State of the art in fault-tolerant quantum computing – Questions and issues, https://www.academie-technologies.fr/en/publications/state-of-the-art-in-fault-tolerant-quantum-computing-questions-and-issues/

OBJECTIVES

- **Earth Observation (EO):** exponential satellite data growth and constellation-management complexity drive the need for scalable computational paradigms
- **Hybrid quantum–classical workflows:** concrete EO and space applications
- **Reality of "Quantum Advantage":** realistic performance assessment and identification of promising trends
- **International research landscape:** global initiatives, funded studies, and pathways toward practical and commercial impact

OUTLINE

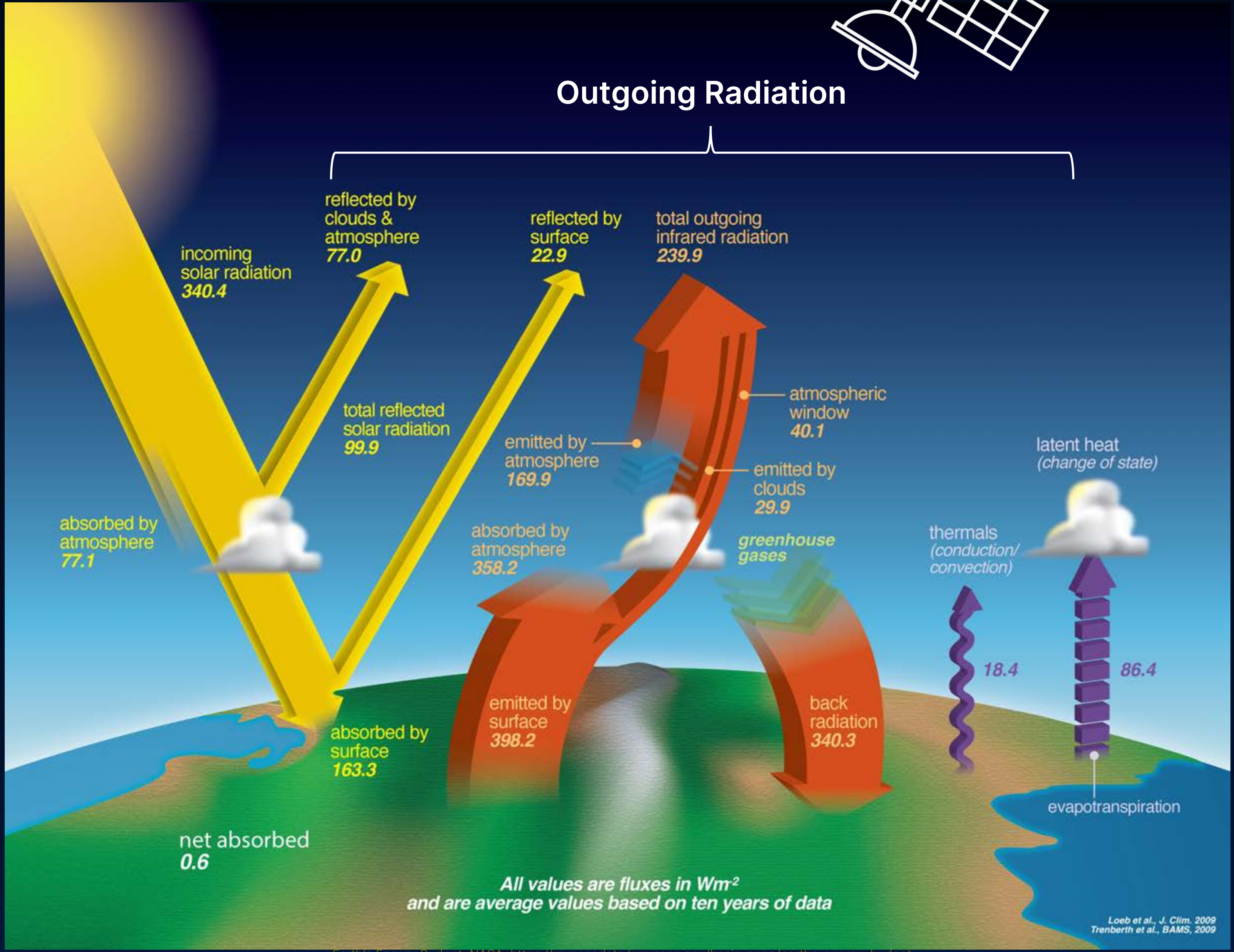
1. Earth Observation (EO) with Satellite Remote Sensing
2. Hybrid Quantum-Classical Algorithms for EO Applications
3. International Activities and Outlook

1

EARTH OBSERVATION WITH SATELLITE REMOTE SENSING

EARTH OBSERVATION WITH SATELLITE REMOTE SENSING

Sensing and recording emitted or reflected energy



Earth's Energy Budget, NASA, https://mynasadata.larc.nasa.gov/basic-page/earths-energy-budget

SATELLITES PROVIDE ESSENTIAL DATA FOR UNDERSTANDING AND MANAGING OUR PLANET

- Constant operation and broad coverage

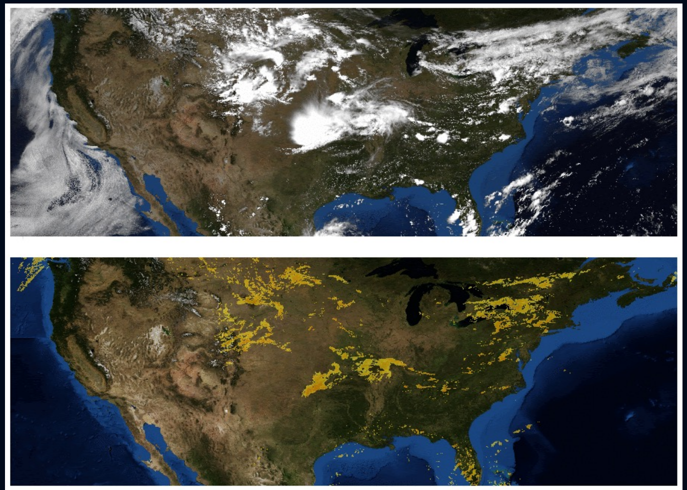
Environmental Monitoring

Satellite image showing wildfires in California's Klamath National Forest (WorldView-3, 3.7m SWIR). Image © MAXAR.

Land Use and Land Cover Mapping

Satellite image of Dubai's urban area (2016) using Pleiades-1A with 2M DEM. Image © AIRBUS Defence & Space. Processed by Satellite Imaging Corp

Weather Forecast



Top: Cloud coverage detected by geosynchronous satellites. Bottom: Rainfall locations mapped by Doppler radar. (Credit: NOAA, NWS, NSSL)

INCREASING SATELLITE DATA AVAILABILITY

Projections (2026-2029)

Credit: Terrawatch Space

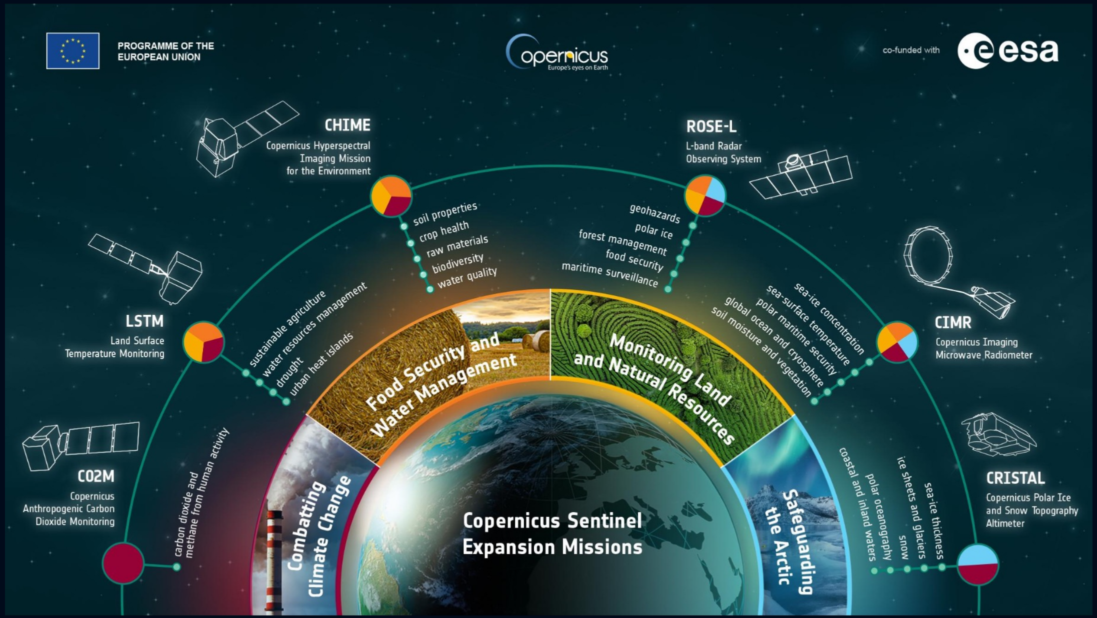
~1100
EO satellites expected to launch

~40
Countries with plans to launch EO constellation

~70
Companies with existing or future plans for EO constellations

~50TB
Daily estimate of data downlinked from Sentinel, Landsat & PlanetScope

E.g., Copernicus expansion Sentinel missions will greatly increase data availability, strengthening the current Sentinel fleet



ESA, "Future of Copernicus Expansion Missions secured" https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Future_of_Copernicus_Expansion_Missions_secured

TerraWatch Space, CDSE Review Meeting, ESA LPS 2025, https://dataspace.copernicus.eu/sites/default/files/media/files/2025-07/0930_terrawatch_the_state_of_earth_observation_forpublication.pdf

EXTRACT KNOWLEDGE FROM EO DATA

ACQUISITION

Capture remote sensing data from space

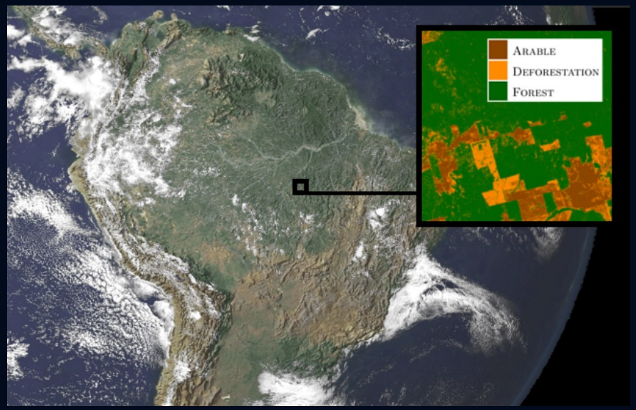
PROCESSING

Transform data into structured, exploitable information

MAXAR: https://www.maxar.com/products/satellite-imagery

INTELLIGENCE

Ready-to-use EO products to tackle specific problems and support decisions



Ribana Roscher, Advanced Machine Learning for Remote Sensing course, https://www.youtube.com/playlist?list=PLzvRrSe1_bqjGthl2s_FG6AnNYjihUIMS

From pixels to impact: data needs to be interpreted in a fast, automatic and objective way. We are searching for quantum advantage.

2

HYBRID QUANTUM-CLASSICAL ALGORITHMS FOR EARTH OBSERVATION APPLICATIONS

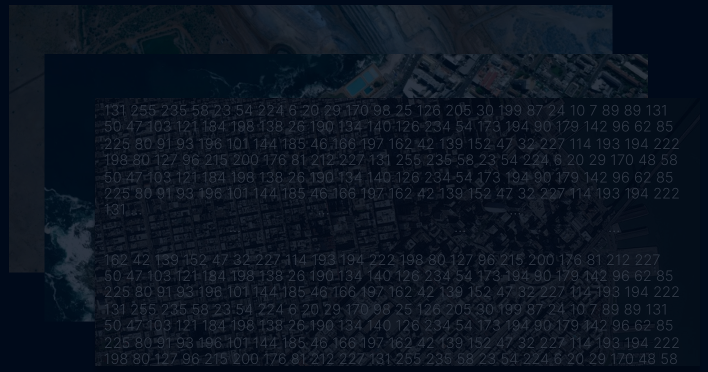
EO VALUE CHAIN TO EXTRACT KNOWLEDGE FROM DATA

ACQUISITION

Capture remote sensing data from space

PROCESSING

Transform data into structured, exploitable information



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INTELLIGENCE

Ready-to-use EO products to tackle specific problems and support decisions

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Physical infrastructure and the operational logistics.
Quantum could contribute through optimization of logistics and novel sensing physics.

SATELLITE ACQUISITION SCHEDULING

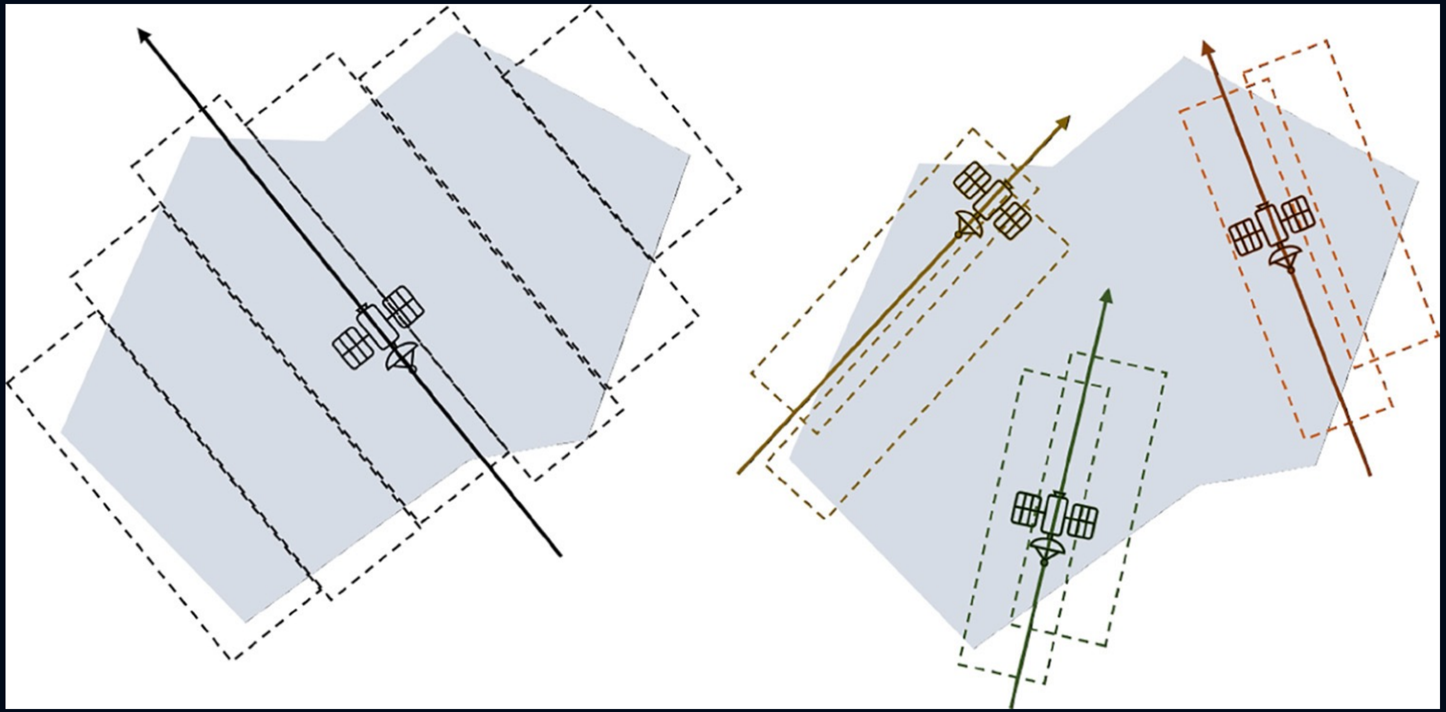
Oversubscribed problem

Number of requests from customers largely exceeds the number of observations that a satellite system can provide

B. Ferrari, J.-F. Cordeau, M. Delorme, M. Iori, and R. Orosei, “Satellite Scheduling Problems: A survey of applications in Earth and outer space observation,” Computers & Operations Research, vol. 173, no. 106875, 2025, http://doi.org/10.1016/j.cor.2024.106875

SATELLITE ACQUISITION SCHEDULING

- Simplest Problem Setup
  - a set of requests must be selected and scheduled on a satellite or constellation of satellites
  - to maximize the observation profit, while satisfying a set of complex operational constraints.

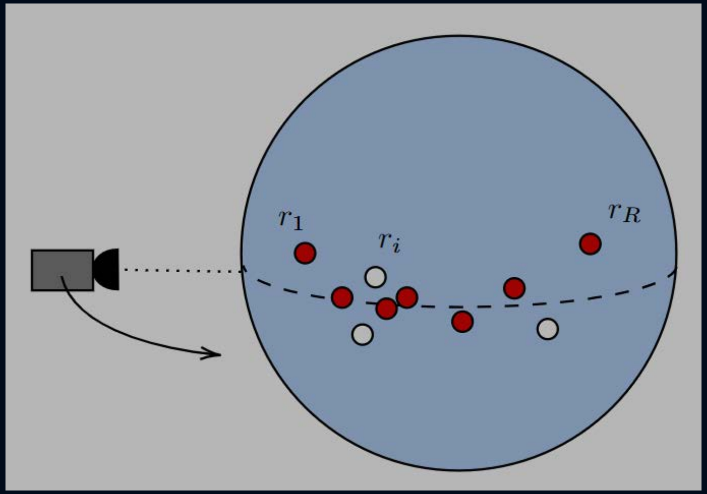


- Each satellite has different characteristics in terms of storage capacity, energy consumption, manoeuvrability, etc
- Each request has its priority and concerns some specified area on the Earth's surface.

B. Ferrari, J.-F. Cordeau, M. Delorme, M. Iori, and R. Orosei, "Satellite Scheduling Problems: A survey of applications in Earth and outer space observation," Computers & Operations Research, vol. 173, no. 106875, 2025, http://doi.org/10.1016/j.cor.2024.106875

SATELLITE ACQUISITION SCHEDULING – EXAMPLE

Find the optimal acquisition plan given a list of requests, maximizing the acquired (economic) value given a sensor rotation constraint (one satellite)



$$\max_{x \in \{0,1\}^R} \sum_{i=1}^{R} x_i v_i - p \cdot \sum_{i=1}^{R-1} \sum_{j=i}^{R} x_i x_j \cdot c(i,j)$$

- Circles → acquisition requests r_i
- Red Circles → identified subset of requests that maximizes value and satisfies satellite constraint

Solution space growing exponentially with problem size!

NP-HARD PROBLEM

A. Delilbasic, M. Riedel, K. Michielsen, and G. Cavallaro, "Towards Large-Scale Satellite Acquisition Scheduling with Hybrid Quantum-Classical Optimization", Proceedings of the First International Conference on Quantum Engineering Sciences and Technologies for Industry and Services (QUEST-IS), Springer, 2025, https://link.springer.com/book/9783032138514 (best paper award). Open access proceedings are available: https://conference-questis.org/quest-is-2025/program/proceddings/

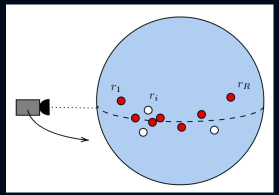
HYBRID OPTIMIZATION APPROACH

With High-Performance Computing and Quantum Annealing

$$\max_{x \in \{0,1\}^R} \sum_{i=1}^{R} x_i v_i - p \cdot \sum_{i=1}^{R-1} \sum_{j=i}^{R} x_i x_j \cdot c(i,j)$$

Problem definition

In QUBO form



Acquisition plan

with maximum value

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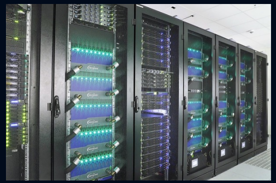

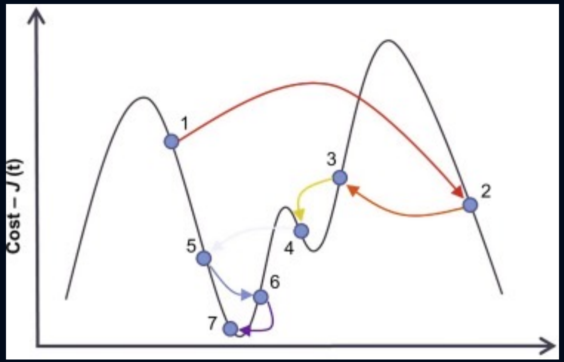

Classical heuristic search

finds a candidate solution

full problem

Sub-problem selection

Loop until conditions met

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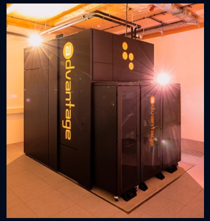
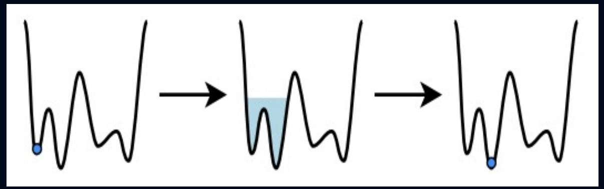
D-Wave Advantage™ System JUPSI





Quantum annealing

locally explores the solution space

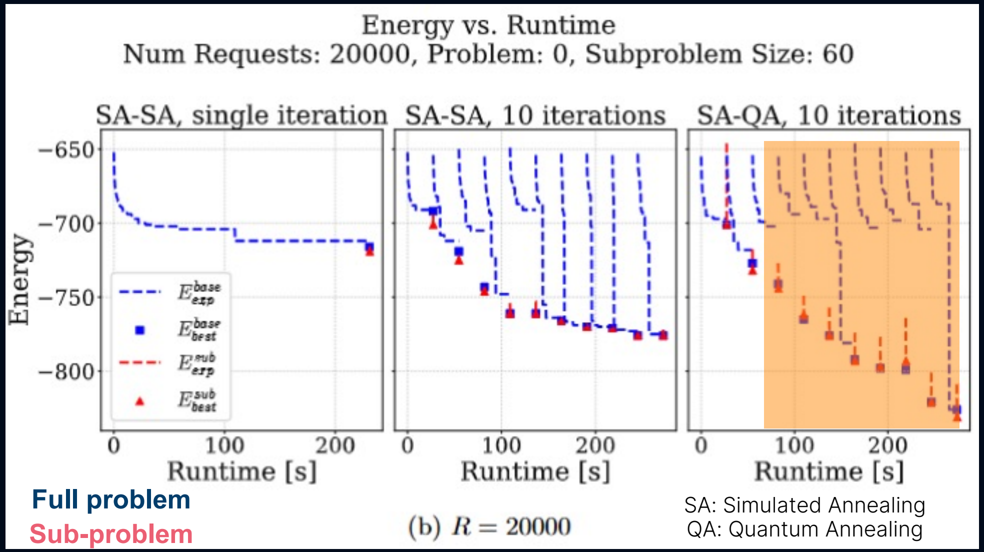
reduced problem

A. Delilbasic, M. Riedel, K. Michielsen, and G. Cavallaro, "Towards Large-Scale Satellite Acquisition Scheduling with Hybrid Quantum-Classical Optimization", Proceedings of the First International Conference on Quantum Engineering Sciences and Technologies for Industry and Services (QUEST-IS), Springer, 2025, https://link.springer.com/book/9783032138514 (best paper award). Open access proceedings are available: https://conference-questis.org/quest-is-2025/program/proceddings/

QUANTUM ADVANTAGE?

SOLUTIONS

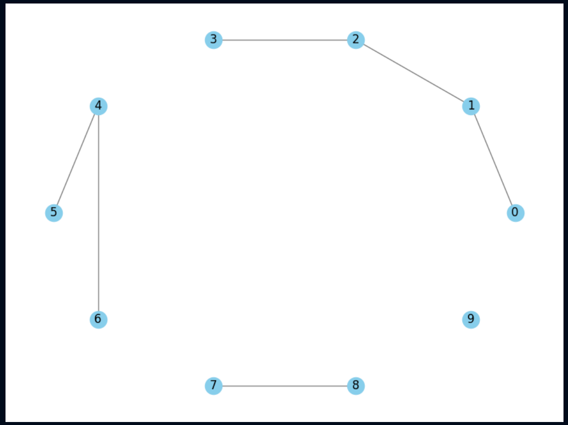
Quantum annealing can improve on classically obtained initial solutions

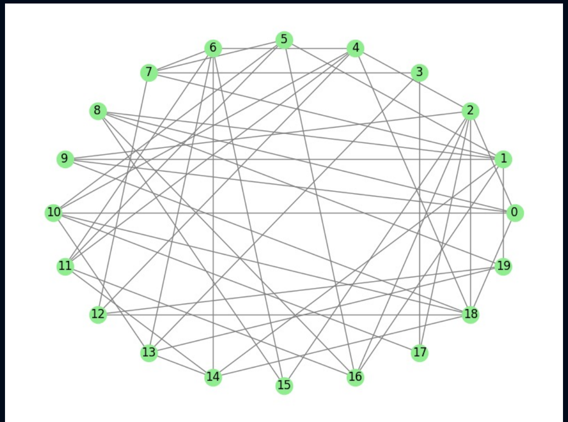


- Two algorithms' combinations: (SA-SA, SA-QA)
- Best and expected energies recorded for full problem and sub-problem (blue and red, respectively)

TIME

Advantage with a higher number of requests





- Why? More requests → requests are closer on average → higher density problem graph → more complex problem with more local minima
- Quantum annealing can help where classical heuristic methods may fail

A. Delilbasic, M. Riedel, K. Michielsen, and G. Cavallaro, "Towards Large-Scale Satellite Acquisition Scheduling with Hybrid Quantum-Classical Optimization", Proceedings of the First International Conference on Quantum Engineering Sciences and Technologies for Industry and Services (QUEST-IS), Springer, 2025, https://link.springer.com/book/9783032138514 (best paper award). Open access proceedings are available: https://conference-questis.org/quest-is-2025/program/proceddings/

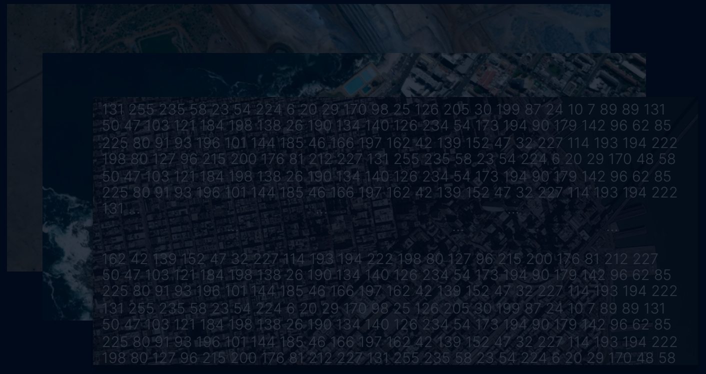
EO VALUE CHAIN TO EXTRACT KNOWLEDGE FROM DATA

ACQUISITION

Capture remote sensing data from space

PROCESSING

Transform data into structured, exploitable information

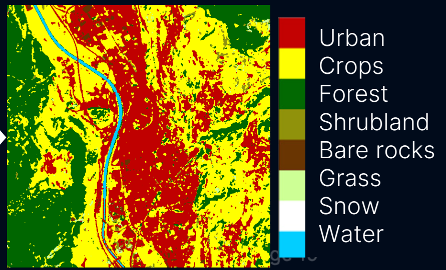


MAXAR: https://www.maxar.com/products/satellite-imagery

INTELLIGENCE

Ready-to-use EO products to tackle specific problems and support decisions

SATELLITE DATA



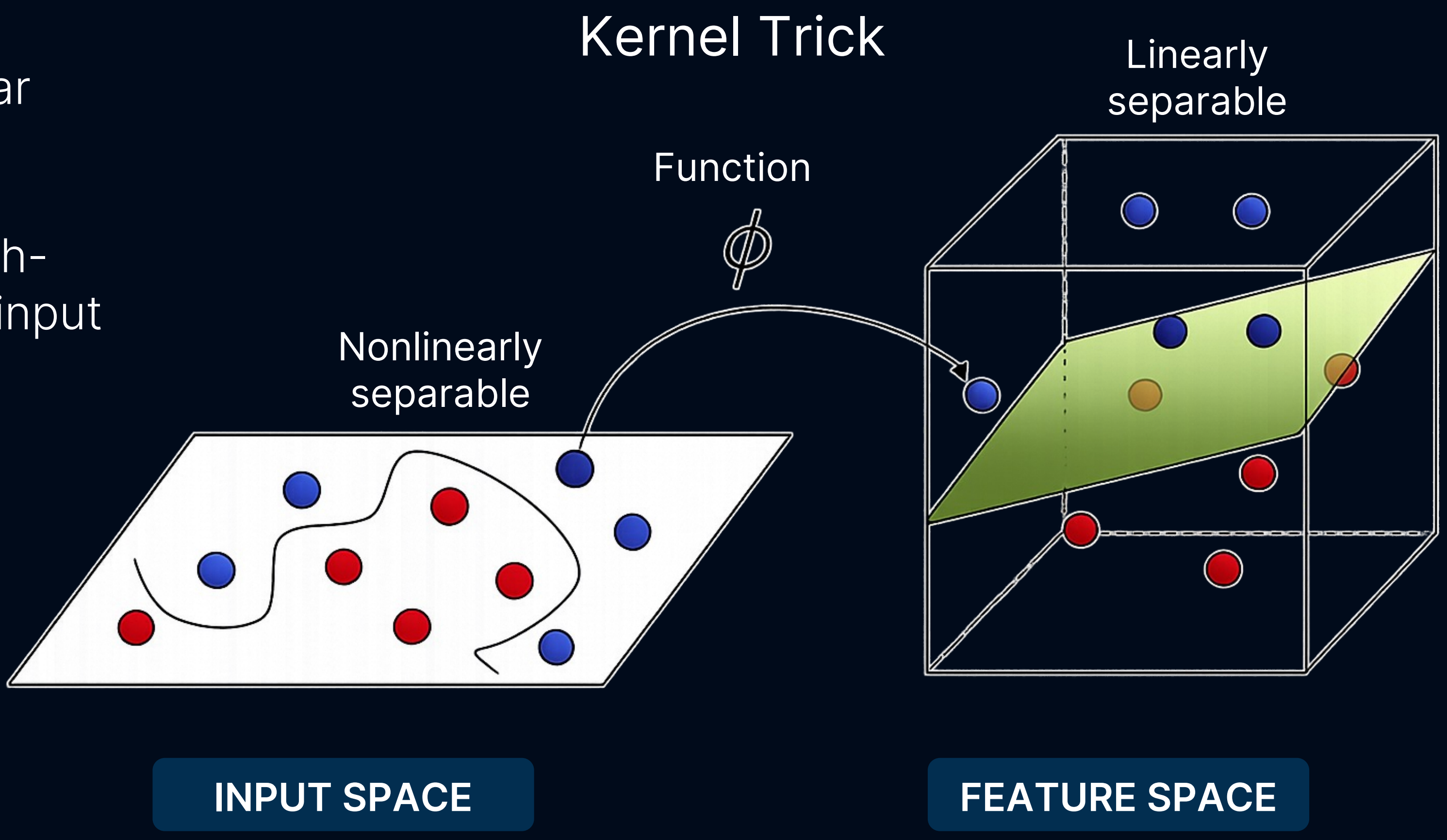
PRODUCT

Generate specific thematic insights and decision-support applications.
Quantum could contribute through service-oriented hybrid solvers.

KERNELS IN MACHINE LEARNING

- Allows linear classifiers to handle non-linear problems
- Computes similarities (dot products) in high-dimensional space using low-dimensional input
- It avoids explicitly calculating the new coordinates of data points

Could quantum computing allow access to exponentially large and novel feature spaces?



G. Camps-Valls, L. Bruzzone, "Kernel Methods for Remote Sensing Data Analysis", Wiley, 2009, 9780470722114

COULD QUANTUM KERNELS…

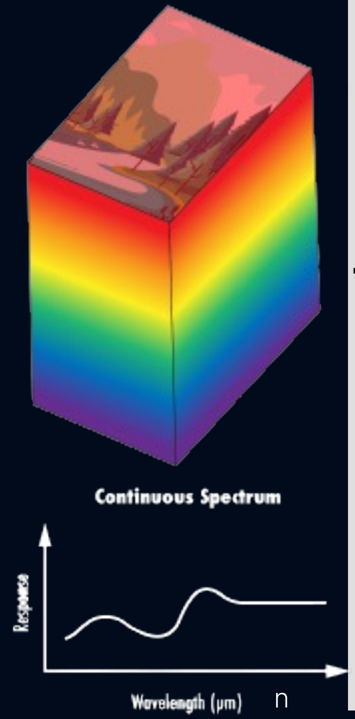
- Enhance separability? Better distinguish complex data patterns using high-dimensional spaces that are computationally expensive or impossible for classical computers to replicate.

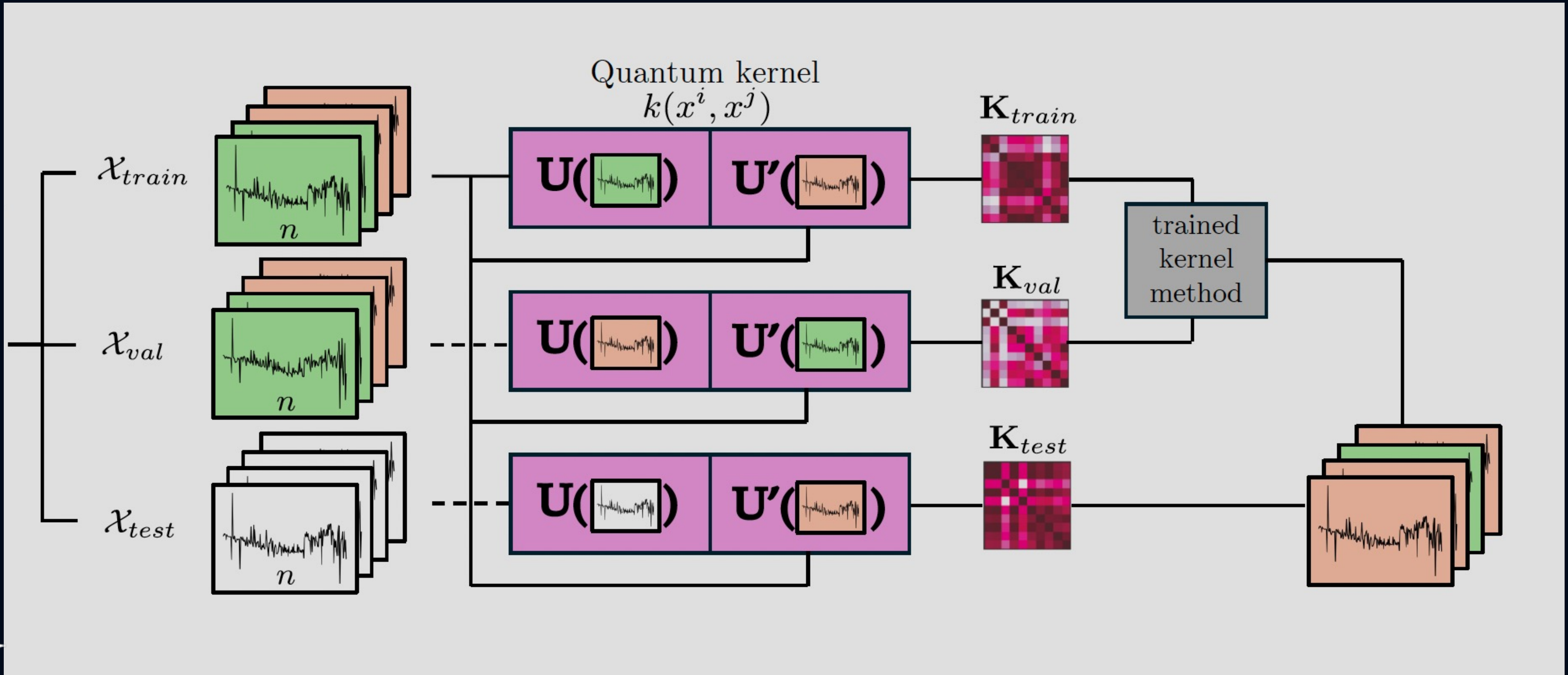
- Exploit unique inductive bias? Utilize a distinct preference for how to fit data, which can outperform classical kernels when optimized.

- Achieve quantum advantage: solve problems using kernel functions that are classically intractable to estimate.

QUANTUM KERNELS FOR HYPERSPECTRAL REMOTE SENSING DATA CLASSIFICATION

Hyperspectral Data

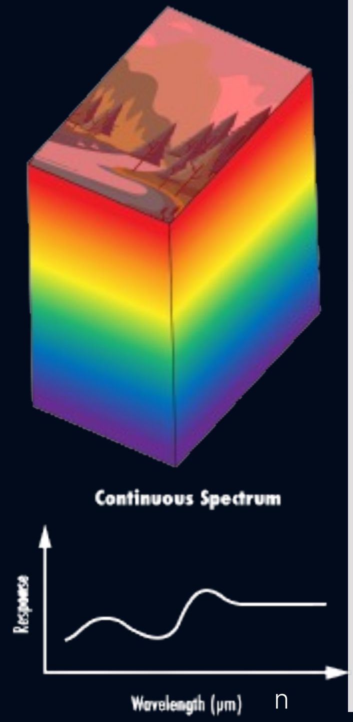


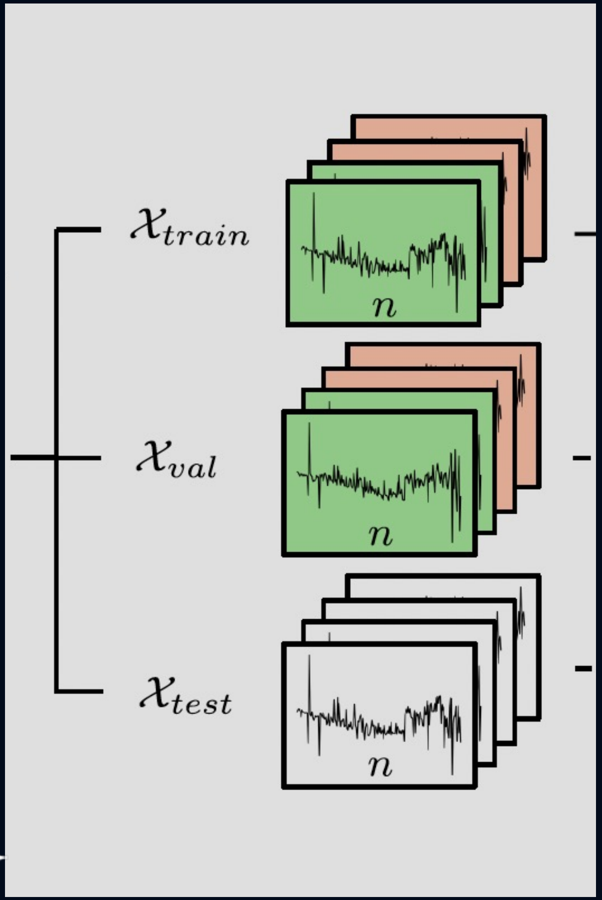


A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, “Large-Scale Quantum Kernels for Hyperspectral Data Classification,” manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

1. DATA PREPARATION

Hyperspectral Data



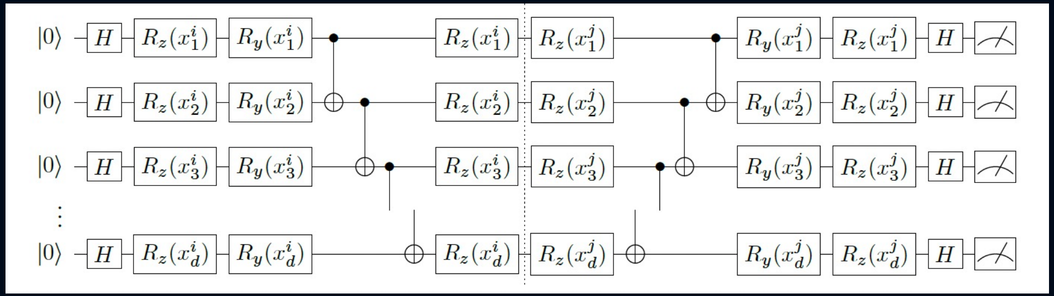


- Input full hyperspectral dataset (with hundreds of spectral bands) and map each band directly to a qubit

A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, "Large-Scale Quantum Kernels for Hyperspectral Data Classification," manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

2. QUANTUM CIRCUIT CONSTRUCTION

- Construct a fidelity quantum kernel using Loschmidt echo (allows to calculate similarity between two data points using only n qubits)
- Circuit: rotation gates to encode features and CNOT gates to introduce linear entanglement
- Obtain a feature map where the number of qubits matches the high dimensionality of the data



3. QUANTUM KERNEL SIMULATION

- Compute the kernel matrices using tensor network contraction to avoid calculating of the full quantum state vector
- Computational complexity from $O(2^n)$ to $O(n^2)$, allows to simulate hundreds of qubits

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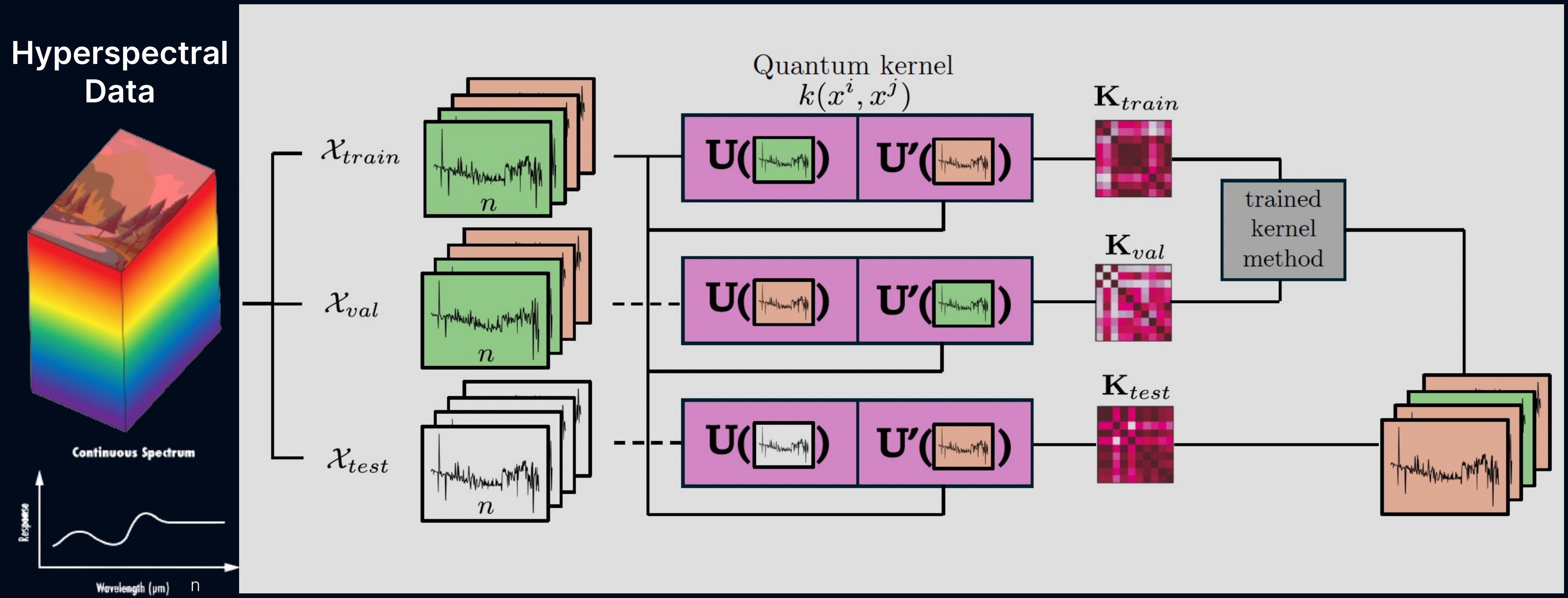
Qiskit

NVIDIA | NVIDIA cuQuantum

cuTensorNet: A High-Performance Library for Tensor Network Computations
https://docs.nvidia.com/cuda/cuquantum/latest/cutensornet/index.html
Qiskit SDK, https://www.ibm.com/quantum/qiskit

A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, "Large-Scale Quantum Kernels for Hyperspectral Data Classification," manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

4. TRAINING AND OPTIMIZATION

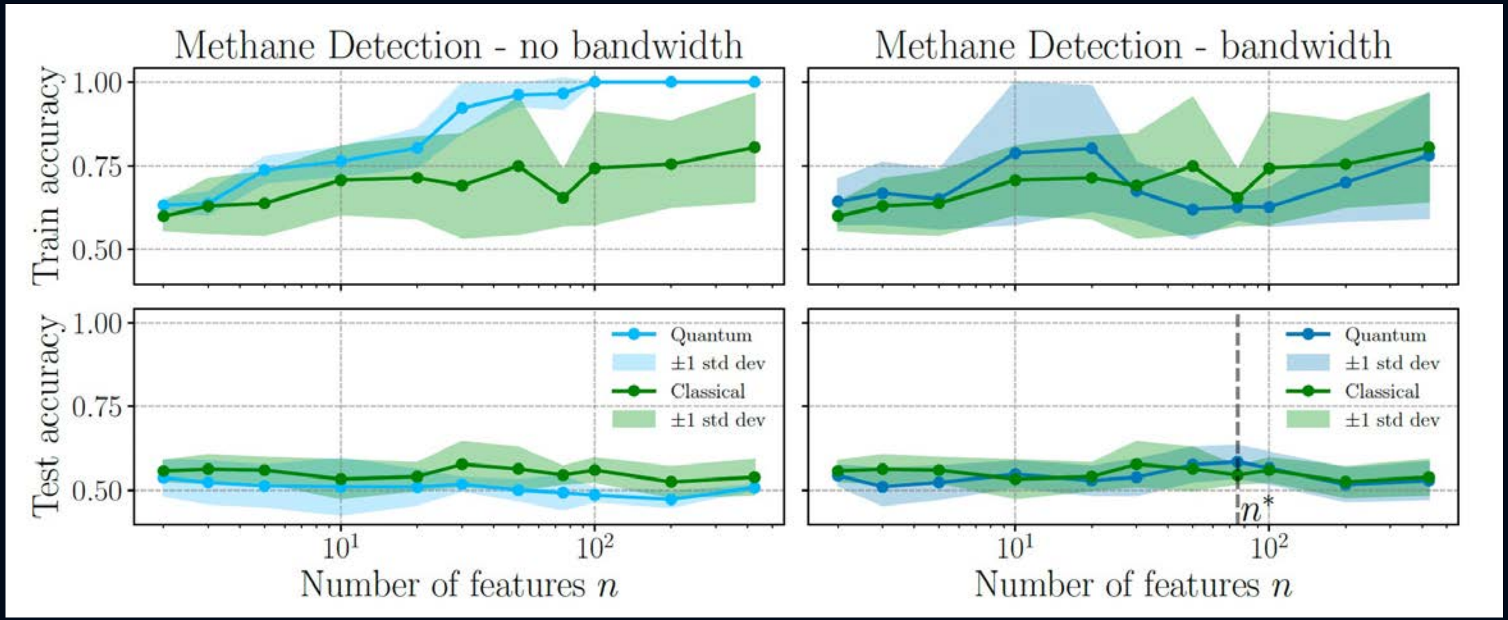


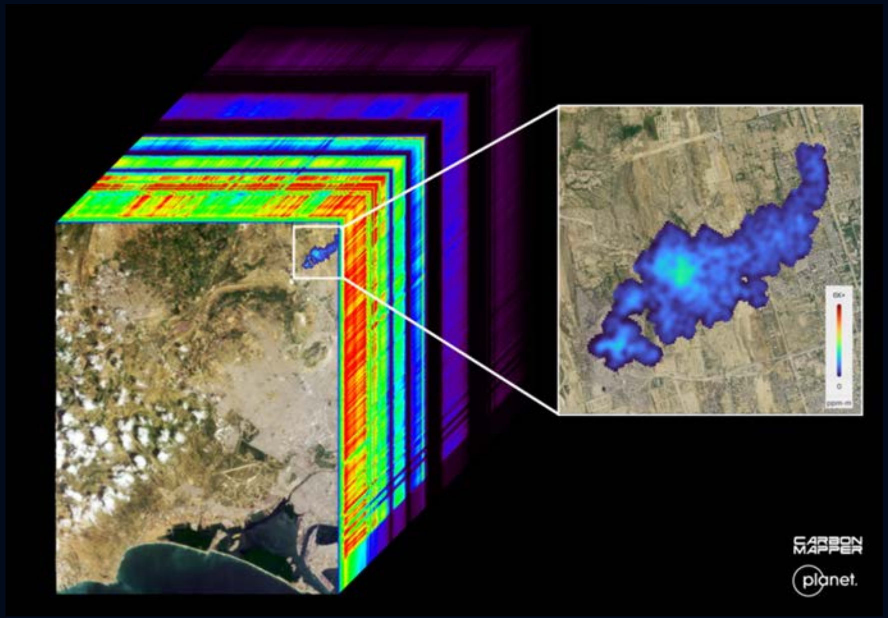
- Train a Support Vector Machine (SVM) model using the computed kernel. Use Bayesian optimization to tune hyperparameters (penalty term and kernel bandwidth)

A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, “Large-Scale Quantum Kernels for Hyperspectral Data Classification,” manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

5. EVALUATION: METHANE DETECTION

- Binary classification of the background and methane data points





- Accuracy as function of the number of features (quantum vs. classical model)

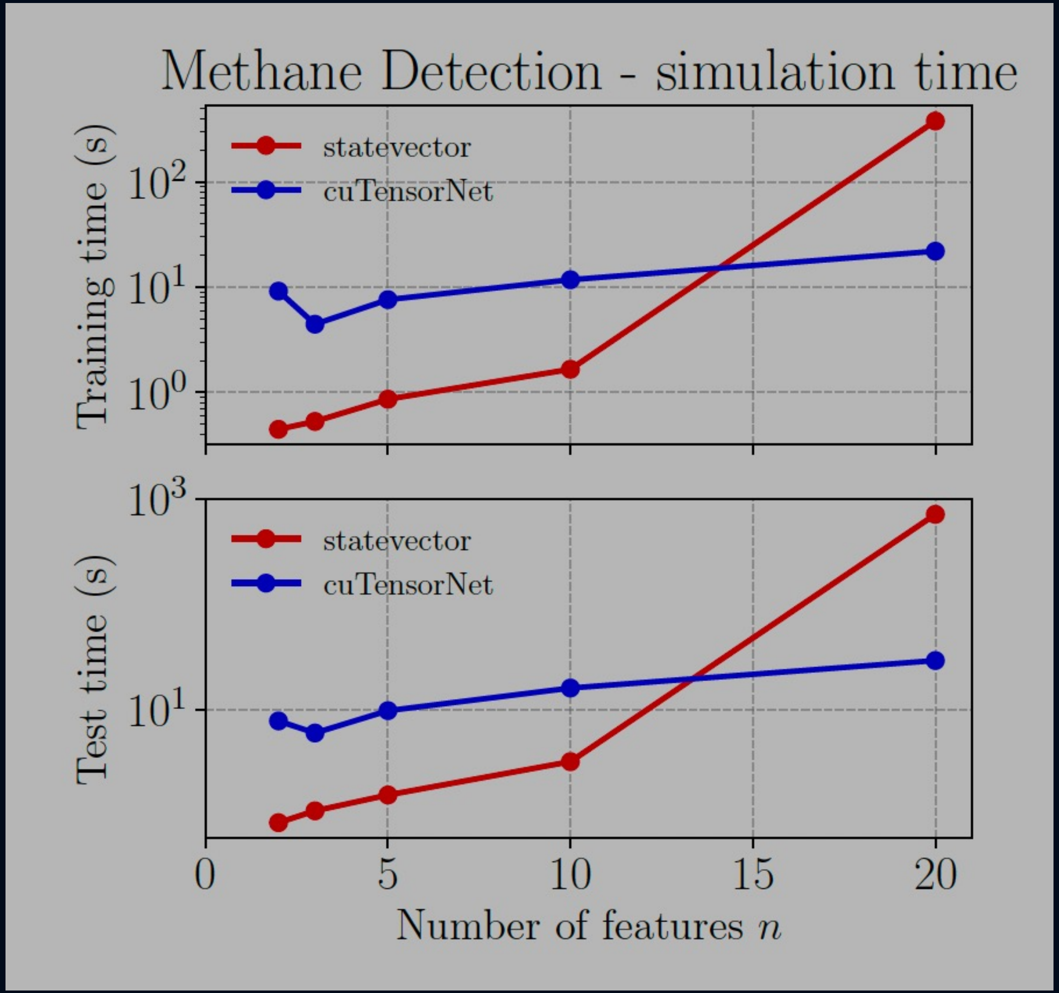
Credit: Planet Labs PBC (Carbon Mapper Releases First Emissions Detections from the Tanager-1 Satellite, https://www.planet.com/pulse/carbon-mapper-releases-first-emissions-detections-from-the-tanager-1-satellite/)

A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, "Large-Scale Quantum Kernels for Hyperspectral Data Classification," manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

NO DEFINITIVE QUANTUM ADVANTAGE, HOWEVER:

- Observed trends suggest that datasets where **classical and quantum kernels diverge most** strongly are promising candidates for future demonstrations.

- Future work
  - use of more entangled embeddings
  - quantum-native explainability
  - systematic identification of EO tasks most likely to benefit from high-qubit quantum kernels



Example with Methane Detection—run time for statevector and cuTensorNet quantum circuit simulation (up to 20 qubits) for generating Ktrain and Ktest for a Methane Detection training split.

A. Delilbasic, A. Miroszewski, A. Wijata, J. Nalepa, J. Mielczarek, M. Riedel, and G. Cavallaro, “Large-Scale Quantum Kernels for Hyperspectral Data Classification,” manuscript under revision, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS).

3

INTERNATIONAL EFFORTS AND OUTLOOK

IEEE GEOSCIENCE AND REMOTE SENSING SOCIETY (GRSS)

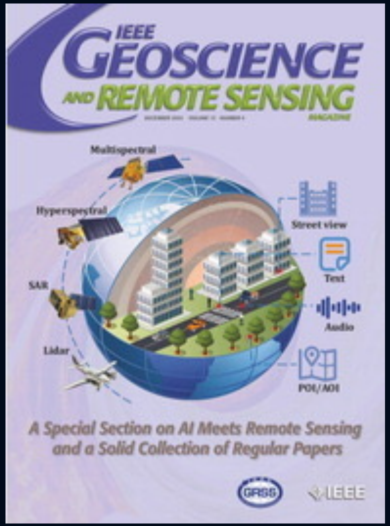
Technical Committees to promote the knowledge and application of high-performance and innovative computing methods in geosciences and remote sensing

Schools and Tutorials

GRSS HDCRS School 2025 https://www.grss-ieee.org/community/groups-initiatives/high-performance-and-disruptive-computing-in-remote-sensing-hdcrs/hdcrs-summer-school-2025/

Webinars

Publications



G. Cavallaro, D. B. Heras, et al., "High-Performance and Disruptive 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

GRSS Quantum Earth Science and Technology Technical Committee (QUEST TC), https://www.grss-ieee.org/technical-committees/quantum-earth-science-and-technology-quest/

GRSS Earth Science Informatics Technical Committee (ESI TC), https://www.grss-ieee.org/technical-committees/earth-science-informatics/

EUROPEAN SPACE AGENCY (ESA)

Funded studies on quantum computing for EO

- Quantum Computing for Earth Observation Study (QC4EO study)
  - Mission Planning for EO applications
  - Multiple-view Geometry on Optical Images
  - Optical Satellite Data Analysis
  - SAR Raw Data Processing

Information

Domain
AI4EO

Prime contractor
FORSCHUNGSZENTRUM JUELICH GMBH (DE)

Subcontractors
IQM Deutschland GmbH (DE)
ISTITUTO NAZIONALE FISICA NUCLEARE (IT)
THALES ALENIA SPACE FRANCE (FR)
THALES ALENIA SPACE ITALIA SPA (IT)

Summary

Earth Observation (EO) satellites generate a growing amount of data every year and highlight the need for scalable algorithms and adequate computational resources. However, the question about how to leverage quantum computing for enhancing the required computational steps is still largely unanswered. The QC4EO study proposes insightful answers and potential solutions to this question. The study has been conducted in the period March 2023 – October 2023 by a consortium led by Forschungszentrum Jülich, with Thales Alenia Space Italy/France, INFN and IQM, and supported by the European Space Agency. The scope of the study covers 12 use cases and a 15-year timeframe, evaluating a potential practical advantage of quantum computing in specific computational tasks and the availability of the required hardware in the near future.

https://eo4society.esa.int/projects/qc4eo-study/

- Quantum Advantage for Earth Observation Study (QA4EO study)
- Variational quantum algorithms for EO Image processing
- Climate adaptation digital twin HPC+QC workflow
- Feature selection for environmental monitoring hyperspectral imagery
- Uncertainty quantification for remotely-sensed datasets.

Information

Domain
AI4EO

Prime contractor
DLR – GERMAN AEROSPACE CENTER (DE)

Subcontractors
"ETOS" CENTRUM EDUKACJI I DORADZTWA (PL)
CSC – Tieteen tietotekniikan keskus (FI)
SYDERAL Polska sp. z o.o. (PL)
UNIV JAGIELLONIAN (PL)
VTT TECHNICAL RESEARCH CENTRE OF FINLAND LTD (FI)

HYPERSPECTRAL

Summary

The main scope of the QA4EO project (Quantum Advantage for Earth Observation) is to identify three to five intractable Earth Observation Use-Cases (EO UCs) of practical importance based on their computational advantage as well as strategic value that can be usefully expressed and solved by a quantum computing approach on quantum computers (QC). The proposed EO UCs are:

- UC1) Variational quantum algorithms for EO Image processing,
- UC2) Climate adaptation digital twin HPC+QC workflow,
- UC3) feature selection for environmental monitoring hyperspectral imagery, and
- UC4) Uncertainty quantification for remotely-sensed datasets.

To assess the selected EO UCs, we evaluate their hardness by using the computational complexity measures, and their hardness implies that conventional classical computers cannot solve efficiently our identified EO UCs but QC promise to tackle them efficiently.

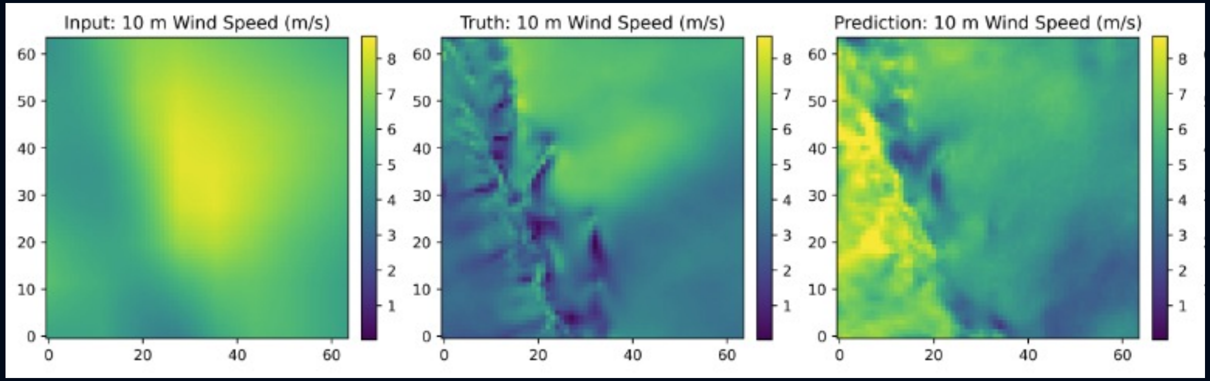
esa Φ-lab
https://philab.esa.int/

https://eo4society.esa.int/projects/qa4eo-study/

EUROPEAN SPACE AGENCY (ESA)

Follow-up funded project: Quantum Readiness for Earth Observation Study (QR4EO study)

- Preidentified use cases:
  - Optimal scheduling of satellite observations
  - **Digital Twin Earth domain (climate modelling)**



Wind Speed prediction with Hybrid quantum-classical diffusion model

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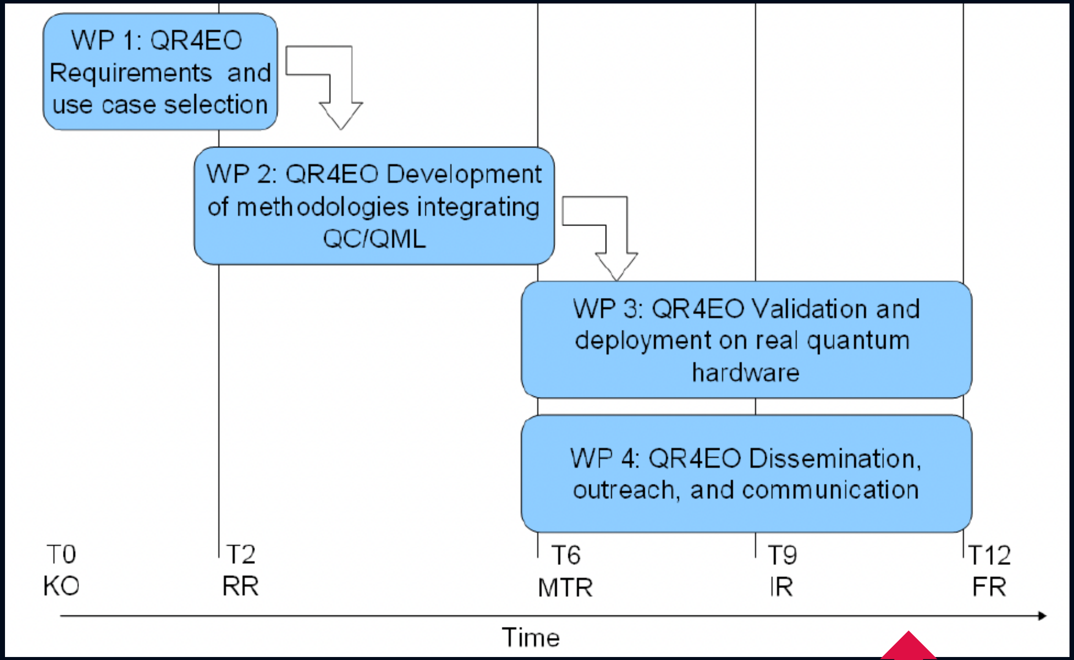

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ThalesAlenia Space – a Thales / Leonardo company

Pasqal

STAGES OF QUANTUM APPLICATIONS RESEARCH

Stage 0	Fundamental research in quantum information science
Stage 1	Discovery of new quantum algorithm in abstract setting
Stage 2	Identification of problem instances exhibiting quantum advantage
Stage 3	Establishing quantum advantage in a real-world application
Stage 4	Optimization, compilation and resource estimation for a use case
Stage 5	Application deployment

Quantum computing for EO and space applications

For Benchmark without applications

R. Babbush, R. King, S. Boixo, et al., "The Grand Challenge of Quantum Applications", 2025, https://doi.org/10.48550/arXiv.2511.09124

WHY QUANTUM COMPUTING FOR EO AND SPACE?

Motivations shared across other disciplines

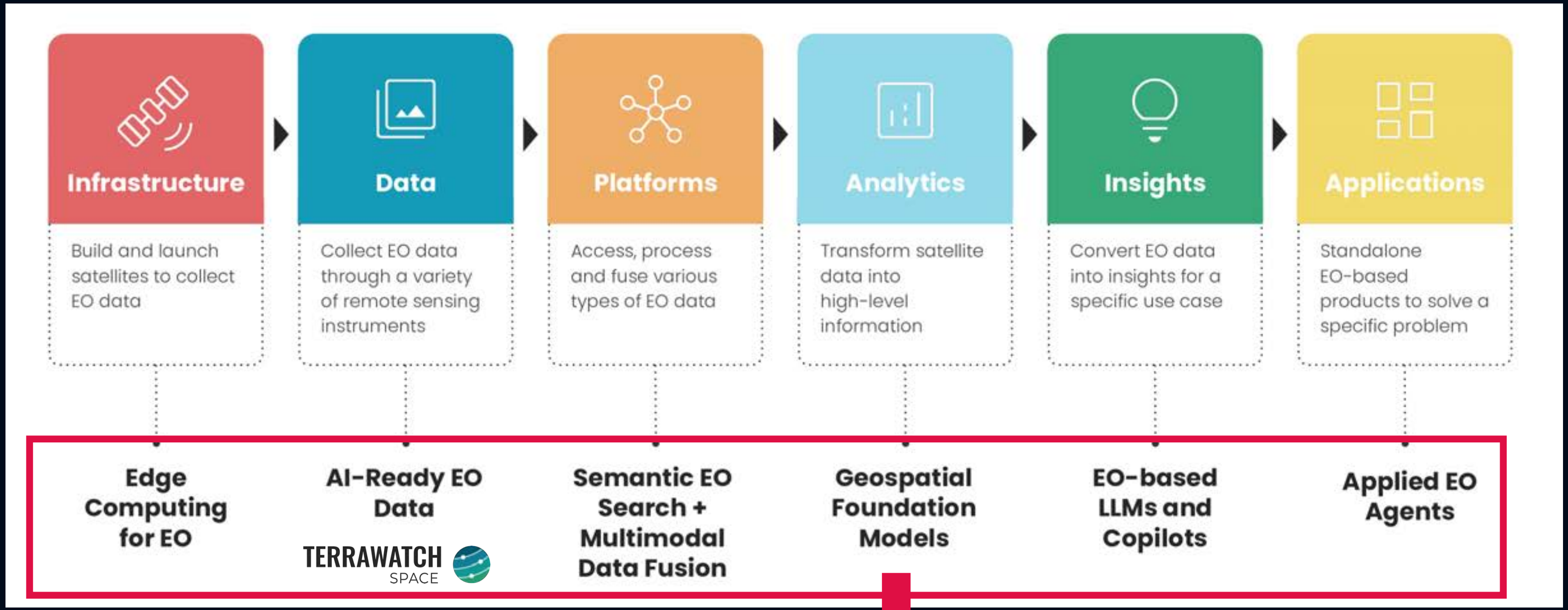
COMPLEX PROBLEM NOT TRACTABLE IN HUMAN TIME WITH HPC → New Operational Capacities and Services

EXISTING PROBLEM FASTER RESOLUTION THAN WITH CLASSICAL COMPUTERS → Performance Improvement by Augmented Engineering

COST, WEIGHT AND ENERGY ADVANTAGE OF QUANTUM COMPUTING → CO_2 Footprint Reduction and Energy Frugality

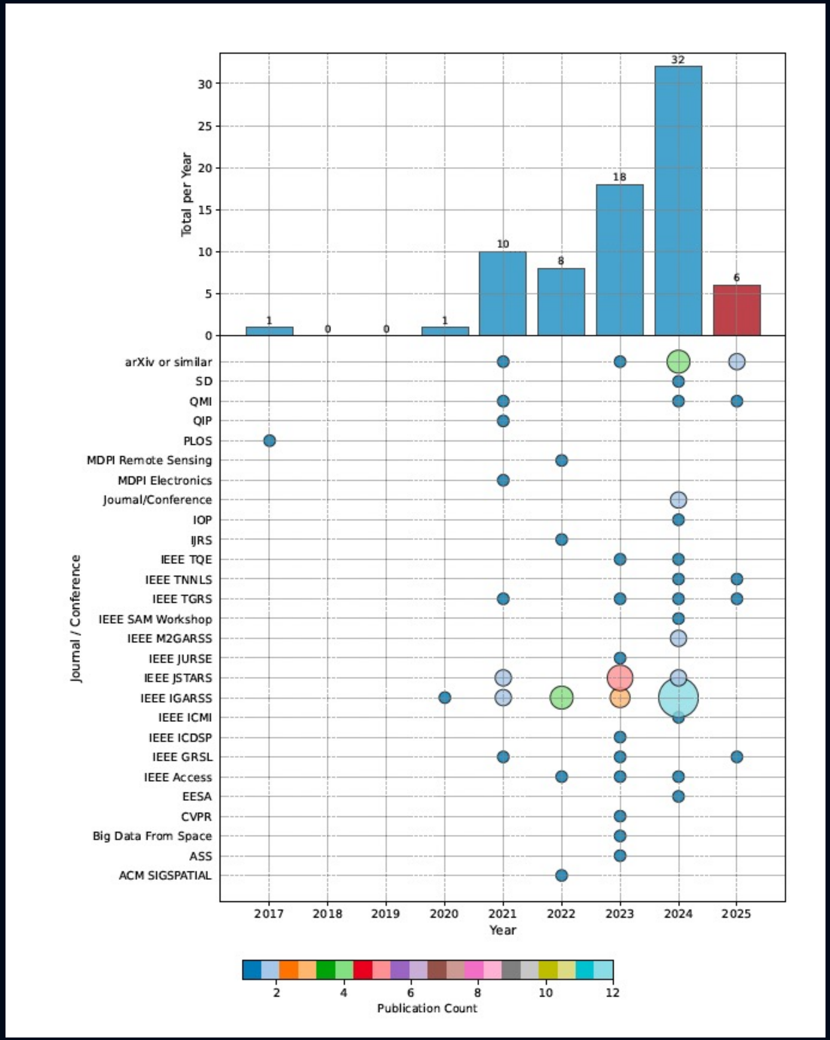
Q2B 2023 Paris | Quantum Algorithms applied to Satellite Mission Planning | Pinto & Barbaresco https://youtu.be/V2CsIzICmoY?si=aLi033lJYQ5eZkty

AI FOR EARTH OBSERVATION



For example

https://www.fast-eo.eu/terramind



Number of papers on QML4EO over the last 8 years, distributed over different journals (steady positive growth)

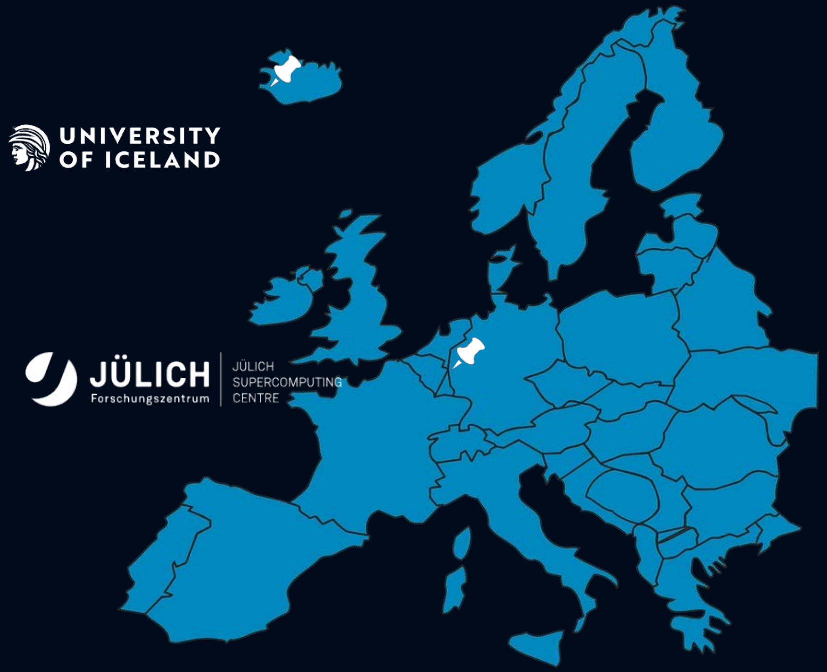
TerraWatch Space, CDSE Review Meeting, ESA LPS 2025, https://dataspace.copernicus.eu/sites/default/files/media/files/2025-07/0930_terrawatch_the_state_of_earth_observation_forpublication.pdf

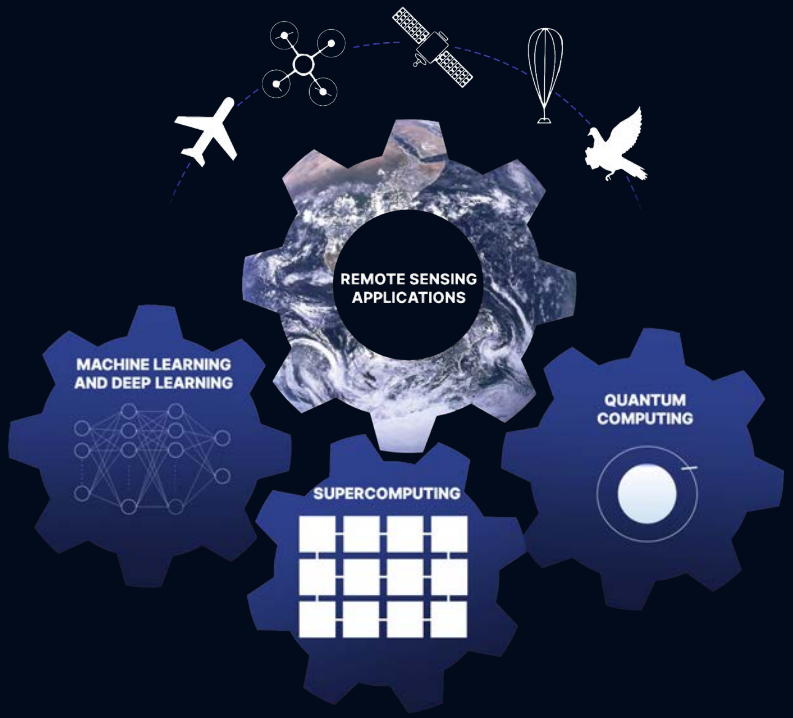
A. Sebastianelli, F. Mauro, A. Delilbasic, P. Di Stasio, F. Fan, G. Meoni, G. Cavallaro, X. X. Zhu, P. Gamba, and S. Ullo, "Quantum Machine Learning for Earth Observation: A Review and Future Prospects," in IEEE Geoscience and Remote Sensing Magazine (GRSM) (submitted on 3 April 2025, recommended for publication subject to satisfactory response to major revisions on 24 July 2025, it is now resubmitted and under revision). Pre-print: https://www.techrxiv.org/doi/full/10.36227/techrxiv.176594306.61753887

CONCLUSION

- **Necessity of Fault Tolerance**: while current "NISQ" devices can outperform supercomputers on specific tasks, unlocking broad commercial and scientific value requires building fault-tolerant machines capable of billions of gates through quantum error correction.
- **Overall feasibility and uncertainty**: practical deployment of quantum computing for EO and space applications remains hypothetical and to significant scientific, technological, and economic uncertainties.
- **Quantum advantage and performance limits:** achieving quantum advantage is not guaranteed and depends on hardware scalability, qubit quality, error correction, gate speed, and realistic end-to-end computing time.
- **Algorithmic and system-level dependencies:** viability further relies on advances in quantum algorithms, data encoding and preparation, processor interconnection, and large-scale parallelization across affordable systems.
- **Timeline and predictability**: due to the diversity of challenges, solution paths, and long development cycles, reliable predictions are difficult, and widespread practical impact is likely to take considerable time.

THANK YOU FOR YOUR ATTENTION





- **Simulation and Data Lab "AI and ML for Remote Sensing"**, Jülich Supercomputing Centre (Forschungszentrum Jülich) and School of Engineering and Natural Sciences (University of Iceland)

  https://www.fz-juelich.de/en/ias/jsc/about-us/structure/simulation-and-data-labs/sdl-ai-ml-remote-sensing

  https://ihpc.is/simulation-and-data-lab-remote-sensing/

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