Quantum Computing for Radar Remote Sensing Applications

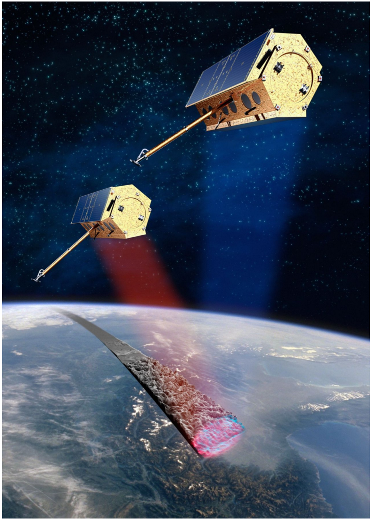
S. Huber, K. Glatting, G. Krieger, A. Moreira

German Aerospace Center (DLR)
Microwaves and Radar Institute

25. November 2021

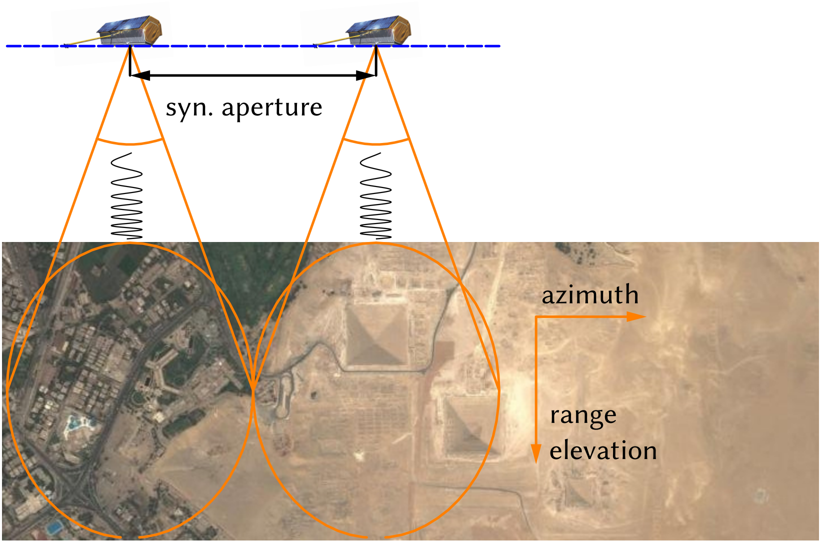
DLR

DLR - Microwaves and Radar Institute



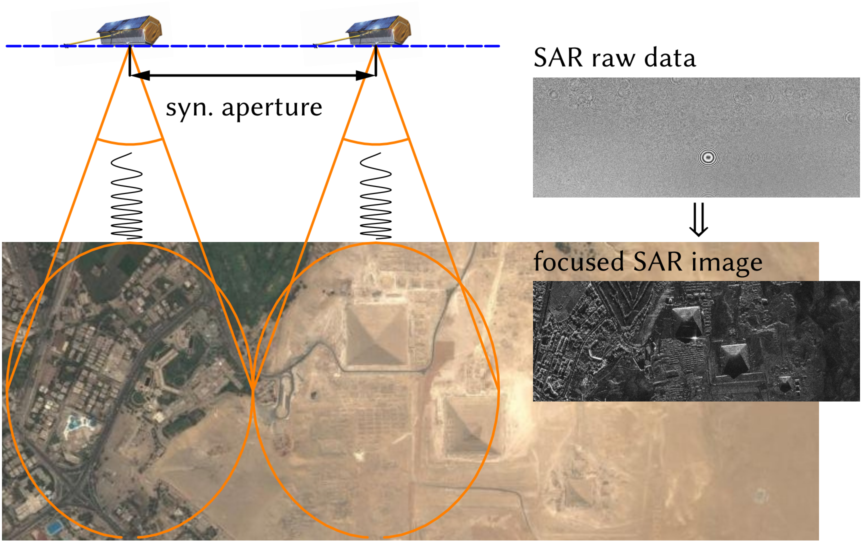
- DLR has 10.000 employees at 30 locations in Germany
- Microwaves and Radar (HR) Institute known for its expertise in microwave remote sensing
- HR Institute active in **quantum computing applications** for **radar remote sensing**

Synthetic Aperture Radar (SAR)



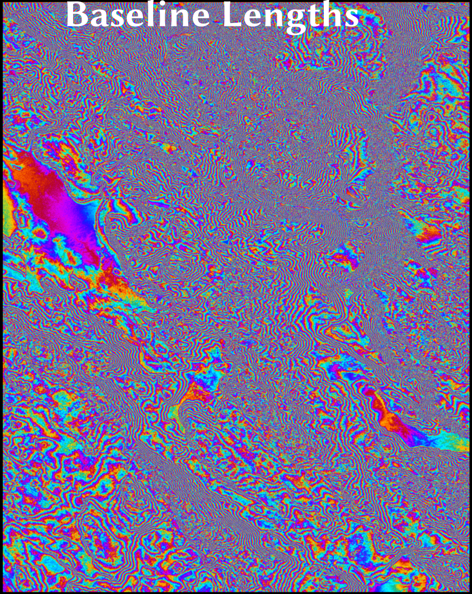
DLR

Synthetic Aperture Radar (SAR)

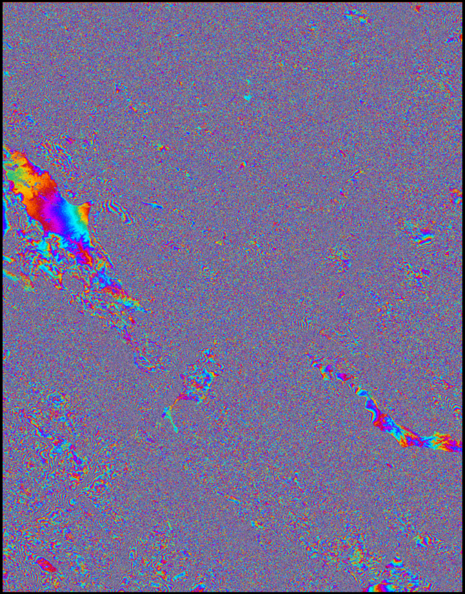


Part I: Applications

TanDEM-X Interferograms with Different Baseline Lengths

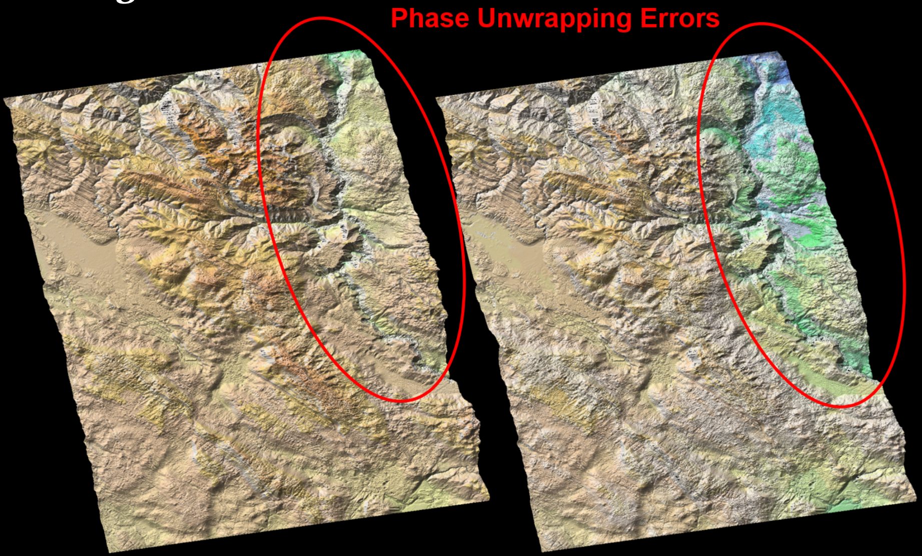


B_{eff} = 107.8 m, h_{amb} = 49.2 m



B_{eff} = 267.9 m, h_{amb} = 19.7 m

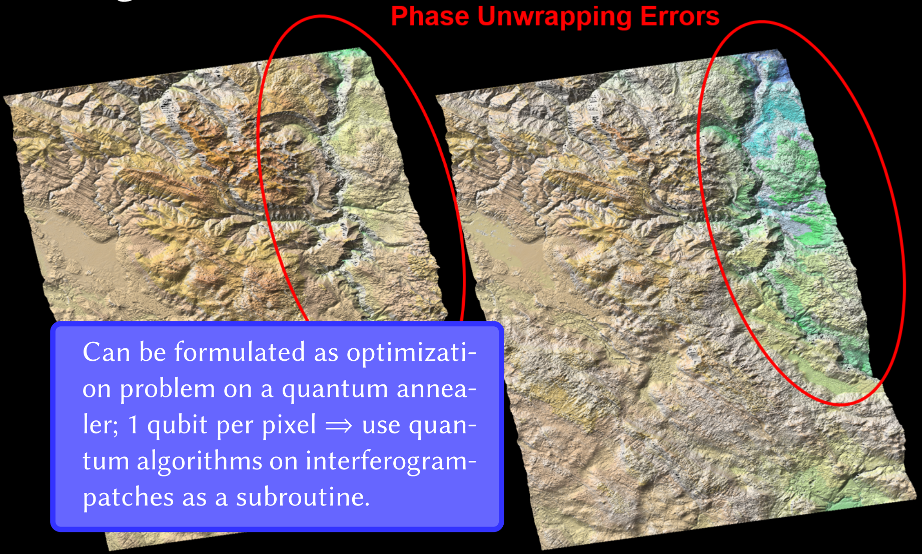
TanDEM-X DEMs with Different Baseline Lengths



B_{eff} = 107.8 m, h_{amb} = 49.2 m

B_{eff} = 267.9 m, h_{amb} = 19.7 m

TanDEM-X DEMs with Different Baseline Lengths

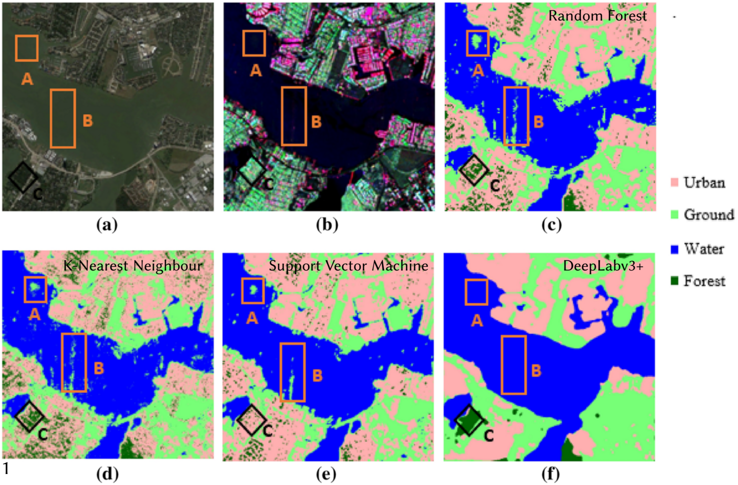


Can be formulated as optimization problem on a quantum annealer; 1 qubit per pixel $\Rightarrow$ use quantum algorithms on interferogram-patches as a subroutine.

B_{eff} = 107.8 m, h_{amb} = 49.2 m

B_{eff} = 267.9 m, h_{amb} = 19.7 m

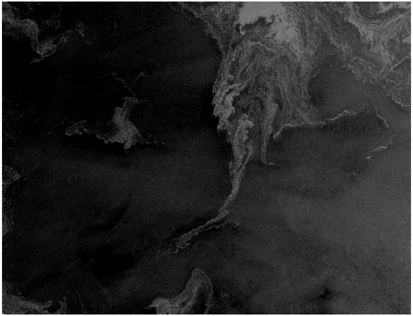
SAR Image Classification



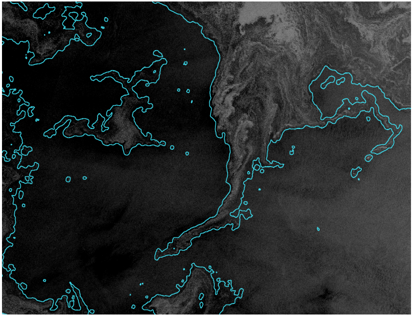
[1]

[1] Source: Semantic segmentation of PolSAR image data using advanced deep learning model

SAR Image Classification



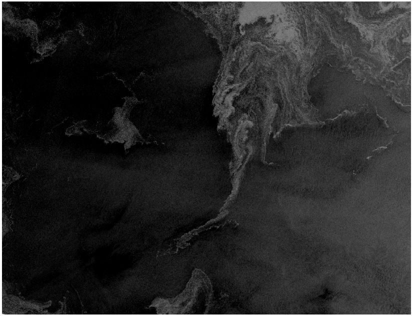
Sentinel-1 SAR image with sea ice features in the Greenland Sea representing areas of different concentrations[1]

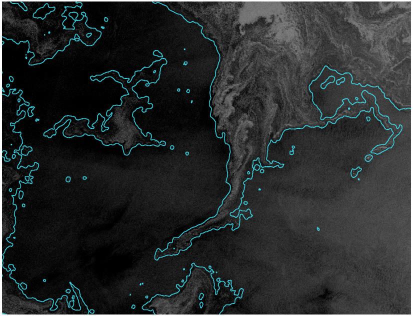


ice edge map automatically generated by deep learning algorithm[2]

[2] Source: Copernicus Sentinel-1 and Deep Learning

SAR Image Classification

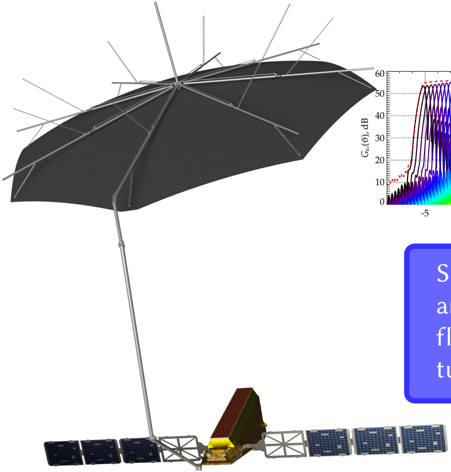


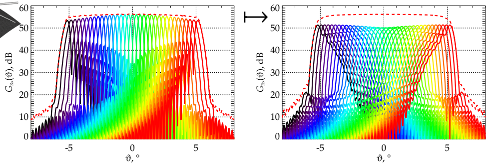


Quantum machine learning: enhanced classification and feature extraction by quantum sub-routines

[2]Source: Copernicus Sentinel-1 and Deep Learning

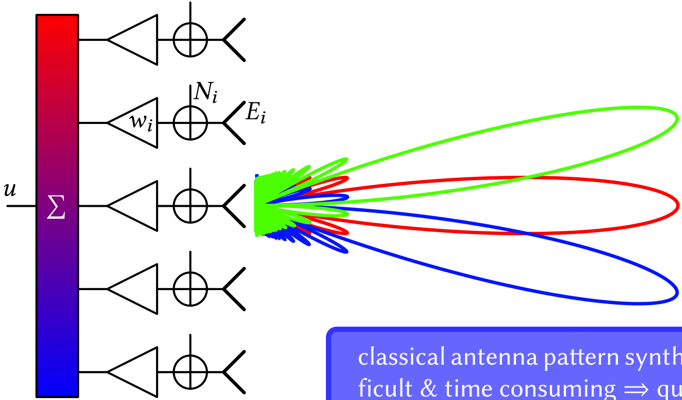
Optimization of Reflector Antennas





Shaped reflector for optimized antenna beams ⟹ discretized reflector model as input for quantum algorithm

Antennas with Electronic Beamforming

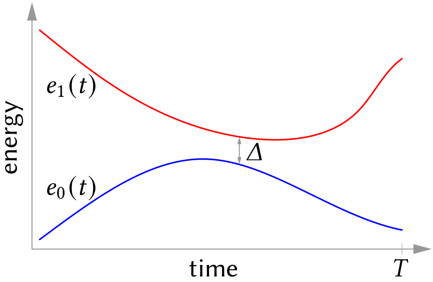


$u = \sum_i w_i(E_i + N_i)$

classical antenna pattern synthesis is difficult & time consuming ⇒ quantum algorithms may be faster and may have better potential to find global optima

Part II: Examples

Adiabatic Quantum Computation



Idea: encode solution of a problem in the ground state of the Hamiltonian

$$H(t) = A(t)H_\mathrm{i} + B(t)H_\mathrm{p}\ .$$

Slowly change initial Hamiltonian H_i towards problem Hamiltonian H_p using control functions A and B.

To each instantaneous eigenenergy $e_\mu(t)$ belongs a corresponding eigenstate $|e_\mu(t)\rangle$

$$H(t)\,|e_\mu(t)\rangle = e_\mu(t)\,|e_\mu(t)\rangle$$

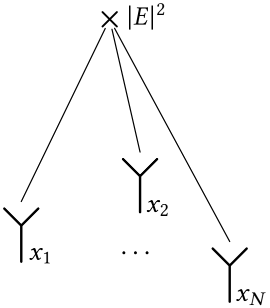
Runtime of the algorithm inversely proportional to energy gap of two lowest states

$$T \sim O(1/\Delta^3)\cdots O(1/\Delta^2)$$

Quantum Annealing implements a specific problem Hamiltonian

$$H_\mathrm{p} \sim \sum_i h_i x_i + \sum_{i,j>i} J_{ij} x_i x_j$$

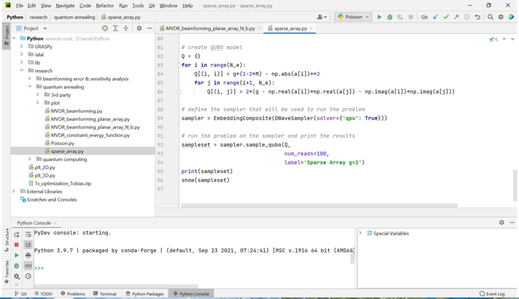
Example I: Sparse Antenna Arrays



Formulation for Quantum Annealer

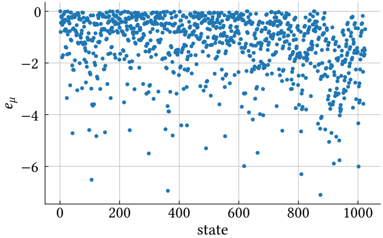
"Maximise field intensity at position X, selecting exactly M out of N elements:"

$$e_\mu = -\left|\sum_{i=1}^{N} x_i E_i\right|^2 + \gamma\left(\sum_{i=1}^{N} x_i - M\right)^2$$

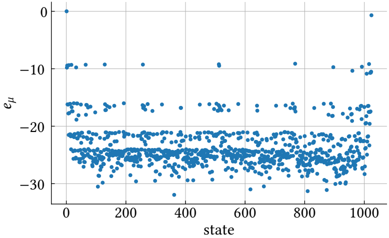


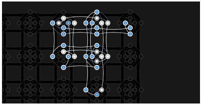
Results on D-Wave 2000Q (Chimera)

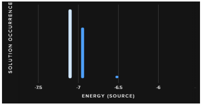
without constraint ($\gamma = 0$)

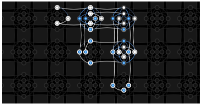


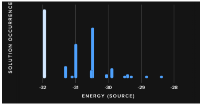
with constraint ($\gamma = 1$)











Here, 5 out of 10 elements. Challenges: Heuristic choice of parameter γ. Larger problem sizes (>20 qubits) may need error correction & post processing.

Example II: Array Antenna Beamforming

Minimum Variance Distortionless Response (MVDR) beamforming:
"Minimize noise power in receiver system, while maintaining unit signal power in a certain direction:"

$$\text{minimize} \quad \sum_{ij} r_{ij} w_i w_j^* \,, \quad r_{ij}, w_i \in \mathbb{C}\,,$$

$$\text{subject to} \quad \sum_{i} w_i E_i = 1\,, \quad E_i \in \mathbb{C}\,.$$

Formulation for Quantum Annealer

$$e_\mu = \sum_{ij} r_{ij} w_i w_j^* + \gamma \left| \sum_i w_i E_i - 1 \right|^2 \,, \quad \text{here:} \quad r_{ij} = \delta_{ij}\,.$$

A Model for Continuous Complex Variables

Complex coefficients w_i:

$$w_i = c \sum_{km} \mathrm{i}^m \left(2^k x_{ikm} - d\delta_{0k}\right) \ .$$

Heuristic choice of parameters c and d matching field E_i

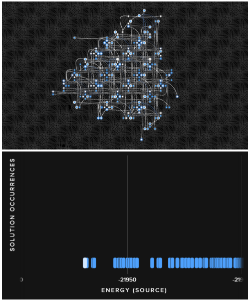
$$c = \frac{\max\{|E'_0|, \ldots, |E'_{N_\mathrm{c}-1}|, |E''_0|, \ldots, |E''_{N_\mathrm{c}-1}|\}}{\left(2^{N_\mathrm{b}} - 1 - d\right) \sum_i |E_i|^2} \ ,$$

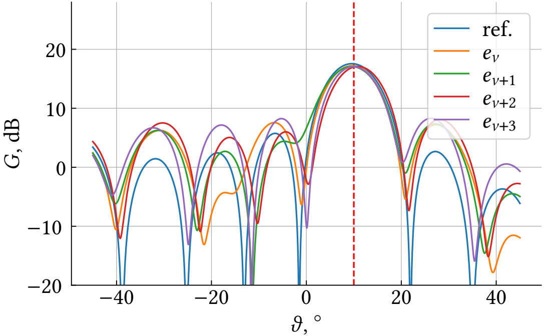
$$d = \frac{1}{2}\left(2^{N_\mathrm{b}} - 1\right) \ .$$

Required number of qubits in this example:

$$N_\mathrm{c} \times N_\mathrm{b} \times 2 = 5 \times 4 \times 2 = 40 \ .$$

Results with D-Wave Advantage 4.1 (Pegasus)





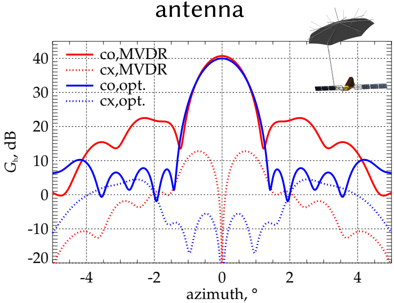
Results look promising. Reasons for deviation:

- altered optimization problem
- low weight quantization (4×2) compared to floating point arithmetic of standard digital computers
- size and topology of the solutions space as well as quantum noise might prevent the quantum computer converging to the ground state solution

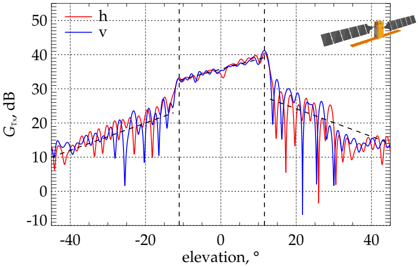
DLR

Goal: More Complicated Optimization

sidelobe control & cross-pol suppression for array-fed reflector antenna



Optimal transmit patterns for wide-swath imaging (here for Sentinel-1 NG)



- patterns have been obtained using the Python `CVXOPT` package and damped least-squares method, respectively
- implement quantum optimizers outperforming classical algorithms such as particle swarm optimization, etc.

DLR

Summary

- radar remote sensing offers a wide variety of interesting & challenging applications for quantum computation ranging from radar **system design** to **data processing** and **information retrieval**
- first examples in array processing indicate potential of quantum computation for these particular kind of problems
- research questions to be addressed in the future: How many qubits can be effectively used? Error correction for quantum annealers in order to improve results? Etc.

DLR