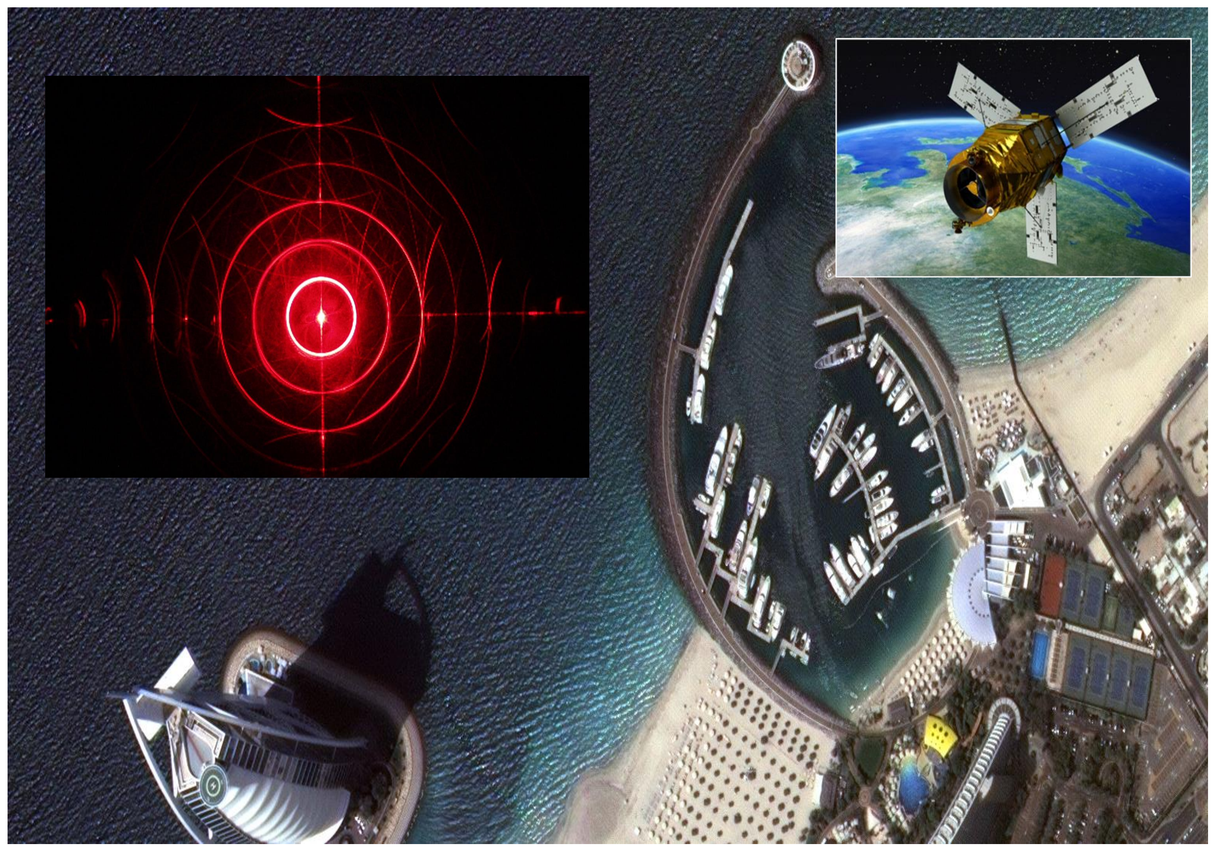
# QCOptSens

## Improving optical instruments in aerospace by optimizing diffractive structures with quantum algorithms.

This project explores novel approaches to improving optical instruments for aerospace applications. Calibration of high-resolution camera systems relies on components engineered to generate diffraction patterns according to strict target specifications. Efficiently designing these diffractive optical elements under manufacturing constraints gives rise to challenging optimization problems, which we aim to address using quantum computing approaches.

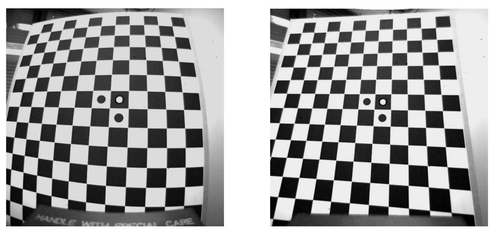
- Applications: Calibration of high-resolution cameras
- Optimisation: Diffractive grating structure design



### Motivation: Instrument Design

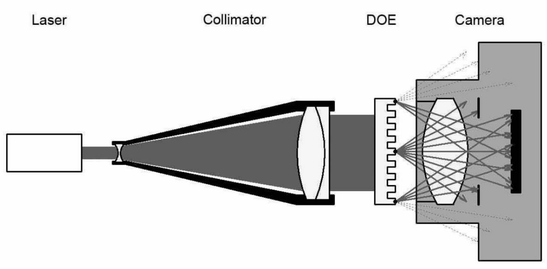
We have been successfully developing camera systems and spectrometers for aerospace, security, and transportation for many years. In this project, we are investigating hybrid quantum computing approaches to improve the next generation of optical instruments for aerospace applications.

The calibration of high-resolution hyperspectral camera systems is performed with components such as diffractive optical elements (DOEs), which are designed to generate diffraction patterns according to strict targets. The DOEs are essential elements for the geometric calibration of imaging systems, mapping between the 3D world and the 2D image sensor.



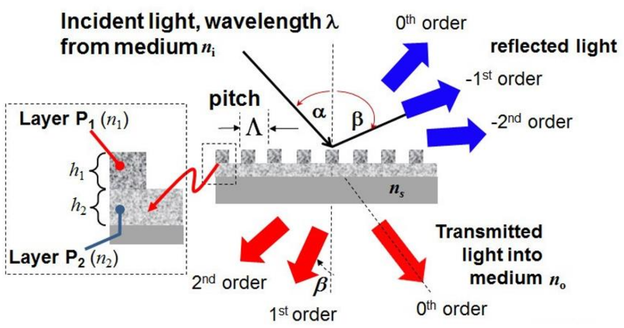
Left: Original image Right: Corrected image

For each new custom camera system developed, a specific DOE for geometric calibration is required. This depends on the operating wavelengths of the camera system and efficient design becomes more challenging as our cameras become more advanced (e.g. muti-spectral or hyperspectral cameras systems).




Optical system for camera calibration with DOE. Source: DOI: 10.1364/OE.16.020241

To create a DOE that produces a good diffraction pattern across multiple wavelengths, requires more complex designs and therefore more design parameters. The classical design of these diffractive structures is limited due to the curse of dimensionality in the number of design parameters. This calls for new long-term technologies and methods for the design of DOEs.

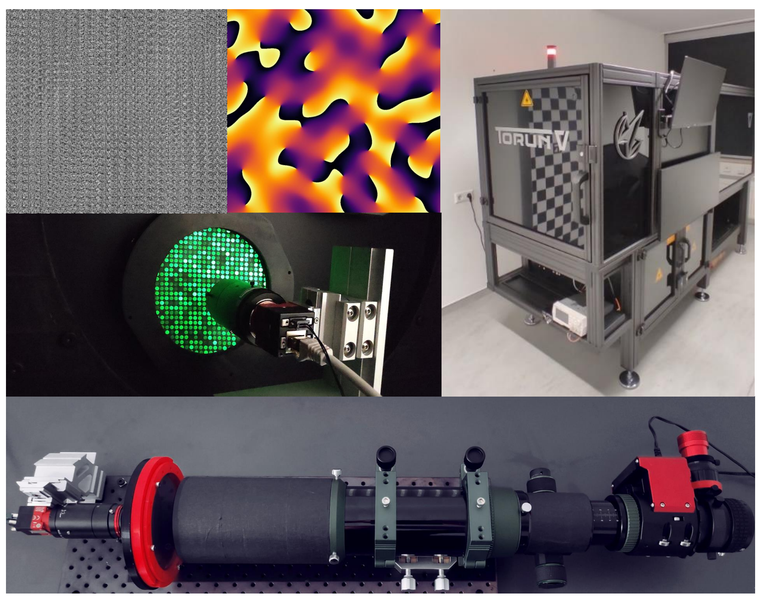



Source: https://doi.org/10.1186/1556-276X-7-645

Quantum computing represents a promising approach to overcoming these limitations and enabling the design of more complex DOEs. By mapping the optimisation of diffractive structures onto quantum algorithms, it may be possible to achieve performance improvements beyond the capabilities of classical methods

### Industry Partner: WCI (Wave-Cube Innovations)

WCI builds intelligent systems at the intersection of photonics and high-performance computing. They are experts at geometric camera calibration, by combining physics-first models of optical instruments with elegant operating concepts. This enables one to get dependable, high-quality imaging and calibration anywhere, from lab benches to orbit.




### Collaboration

Within this project WCI are providing expertise in the modelling of DOE-based geometric calibration through software and hardware (physical measurements). This is essential for providing a realistic problem formulation, that can then be mapped to quantum computing approaches.

- Software example: End-to-end optical "digital twin" for design, simulation and calibration.
- Hardware example: Measurements from compact DOE-based calibration modules and reference targets.

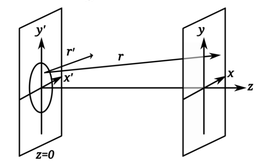
*ISS docking with a holographic reference*

Left: uncalibrated. Right: calibrated reconstruction with consistent scale, pose, and crisp edges for confident guidance. Demonstrates hologram-referenced perception for ISS docking. The top collage contrasts raw (uncalibrated) imagery with a calibration-corrected reconstruction referenced to our *TORUN-V©* phase-only hologram. The archival images document *TORUN-V©* with a DLR camera aligned for calibration (WCI hologram visible as a green pattern, recorded by a documentation camera), the *TORUN-V© Stereo-UVIR* and *TORUN-V© SMART FOCUS-DETECT* configurations for performance testing and end-to-end geometric calibration, and the ideal retrieved phase optimized with *WCI-ATLAS/WCI-MOSAIC*—forming the *digital twin* used to predict, compare, and validate the measurement.

### Scalar Integral Theory

We investigated tackling the curse of dimensionality with classical methods (Spie: https://doi.org/10.1117/12.3063950) for a full-wave solver. However optimising diffractive structures with full-wave solvers such as FDTD or RCWA requires solving Maxwell's equations in full, which makes efficient mapping to quantum computing—especially NISQ devices—highly challenging. A more tractable approach is to apply scalar diffraction models, such as Fraunhofer diffraction derived from Kirchhoff integrals.

- Field at target plane $U(x, y, z)$
- Field at DOE plane $A(x, y, z)$
- Incident monochromatic wave
- Discretise integral to propogate field:




$$U(x,y,z) \approx \frac{e^{ikz}e^{ik(x^2+y^2)/2z}}{i\lambda z} \iint_{\text{Aperture}} A(x',y')e^{-i\frac{k}{z}(x'x+y'y)}\,dx'\,dy'$$

The intensity at the target plane is $I(x,y) = |U(x,y)|^2$ and this can be optimised for by changing DOE structure weights. The field at the DOE plane is $\mathrm{A}(x,y) = \mathrm{A}'(\mathrm{x},\mathrm{y})\mathrm{w}(\mathrm{x},\mathrm{y})$, where the material distribution in the DOE cause a phase/amplitude change to the incoming light.

### Phase Retrieval Formulation of problem

The integral is discretised and the resulting discretised intensity pattern at the target plane is a function of the DOE weights $\mathrm{w}(\mathrm{x},\mathrm{y})$. The optimisation problem becomes an instance of the phase retrieval problem:

$$\min_{w} loss = ||\ |\tilde{A}w|^2 - I\ ||$$

- Goal: find the complex-valued DOE phase weights $w$ that approximate the desired target pattern $I$
- NP-complete problem
- Classic problem in optics, crystallography,diffractive imaging, signal procesing and more
- $\tilde{A}$ describes the complex linear forward propagation

### First Quantum Computing Approach: QUBO

Restricting to a phase-only DOE which can take on one of two possible phases, the problem becomes a binary decision problem. If there are N weights $w$, there are $2^N$ possible configurations. This binary grating optimisation problem can be mapped to a PUBO instance that contains quartic terms. This PUBO is then converted to a QUBO instance using the method of Verma, A et. Al. "*Optimal quadratic reformulations of fourth degree Pseudo-Boolean functions*" https://doi.org/10.1007/s11590-019-01460-7. There is a significant overhead due to higher order terms that need to be quadratised. Future work on minimising this overhead using the DFT structure of the $\tilde{A}$ matrix is being investigated, along with other possible quatum computing approaches.




**Mehr Infos zu dem Projekt finden Sie auf unserer Website.**

**A project of**

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**Contractor**

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**Get in touch.**
**We enable quantum!**