Ariadna - Super-Resolution via Spatial Mode Demultiplexing and its Applicability to Observational Astronomy

Executive Summary

Authors: J. Řeháček[1], Z. Hradil[1], B. Stoklasa[1] , M. Paúr[1], L. Moťka[1], L.L. Sánchez-Soto[2,3], J. Grover[4], A. Kržič[4]

Affiliation: [1] Palacký University Olomouc, [2] Universidad Complutense Madrid, [3] Max-Planck-Institut fur die Physik des Lichts, Erlangen, [4] ESA ACT

Date: December 20, 2018

ACT research category: Physics

Contacts:

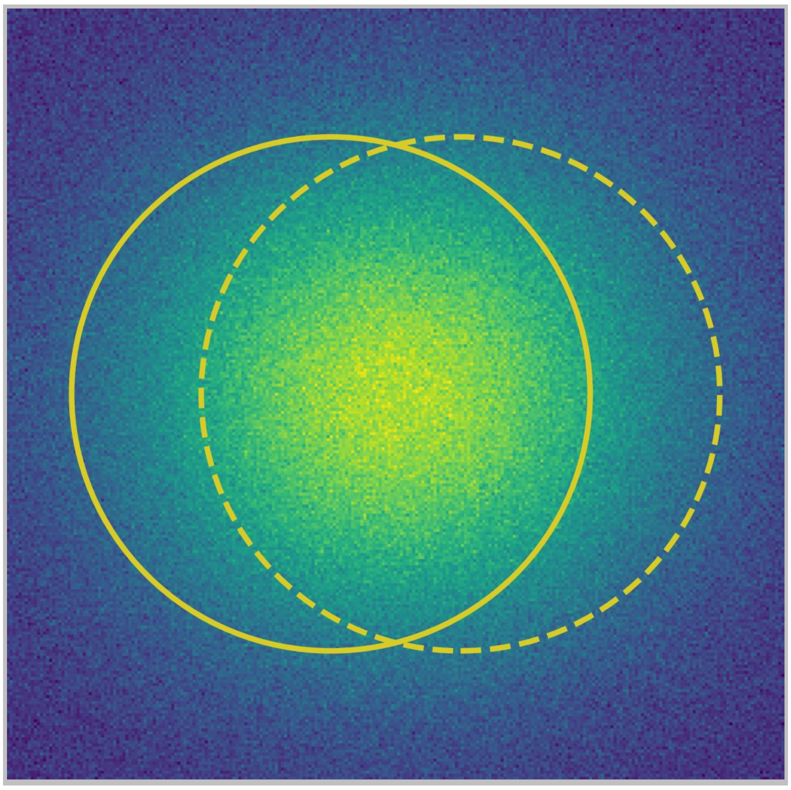
Jaroslav Řeháček, Dept. of Optics, Palacký Univerzity, 17. listopadu 12, 77146 Olomouc, Czech Republic
Tel: +420 585634257
e-mail: rehacek@optics.upol.cz

Leopold Summerer (Technical Officer)
Tel: +31(0)715654192
Fax: +31(0)715658018
e-mail: act@esa.int

Ariadna ID: 17/1501
Ariadna study type: Standard
Contract Number: 4000120780/17/NL/as

Available on the ACT website
http://www.esa.int/act

Picture:



Motivation:

We aim to explore the concept of indirect super-resolution imaging based on spatial mode demultiplexing, perform theoretical and experimental assessments of the method and study its applicability to observational astronomy, with special reference to binary star systems and exoplanet detection.

Methodology:

When resolving two incoherent point sources, our objective is to measure their separation and other relevant parameters (centroid, intensities). For conventional intensity detection, the precisions of the parameters drop to zero as the separation of the point sources goes to zero. This loss of information can be avoided or greatly reduced by changing the detection scheme. The following steps have been followed in the project to develop these ideas:

- Choosing suitable theoretical models.
- Determining quantum resolution limits by evaluating the quantum Fisher information.
- Finding optimal detection schemes both analytically and by numerical simulation.
- Developing detection schemes based on spatial light modulation.
- Translating the problem from spatial to time-frequency domain.
- Performing proof-of-principle experiments and verifying quantum improvements.

Results:

- *Multiparameter quantum metrology of incoherent point sources.* Fundamental quantum limits were derived for the first time for two unequally bright light sources. The limits apply e.g. to binary stars and star-exoplanet systems.
- *Optimal measurements for quantum spatial superresolution.* Explicit construction of the optimal quantum detection scheme was found for any telescope PSF providing the best performance on two unequally bright sources.
- *Tempering Rayleigh's curse with PSF shaping.* A class of PSFs was identified suffering less loss of information at very small separations than most PSFs. Reshaping a given PSF into the desired form was demonstrated experimentally with the help of spatial phase modulation resulting in a robust super-resolution utilizing conventional intensity detection.
- *Quantum-Limited Time-Frequency Estimation through Mode-Selective Photon Measurement.* The problem of spatial resolution was translated into time and frequency domains. Optimal quantum detection was realized experimentally for both equally and unequally bright time- and frequency-separated light pulses.

Publications:

- J. Rehacek, Z. Hradil, B. Stoklasa, M. Paur, J. Grover, A. Krzic, and L.L. Sánchez-Soto: Multiparameter quantum metrology of incoherent point sources: Towards realistic superresolution, Phys. Rev. A **96**, 062107 (2017).
- J. Rehacek, Z. Hradil, D. Koutny, J. Grover, A. Krzic, and L.L. Sánchez-Soto: Optimal measurements for quantum spatial superresolution, Phys. Rev. A **98**, 012103 (2018).
- M. Paur, B. Stoklasa, J. Grover, A. Krzic, L.L. Sánchez-Soto, Z. Hradil, and J. Rehacek: Tempering Rayleigh's curse with PSF shaping, Optica **5**, 1177 (2018).
- J. M. Donohue, V. Ansari, J. Rehacek, Z. Hradil, B. Stoklasa, M. Paur, L.L. Sánchez-Soto, and C. Silberhorn: Quantum-Limited Time-Frequency Estimation through Mode-Selective Photon Measurement, Phys. Rev. Lett. **121**, 090501 (2018).
- M. Paur, B. Stoklasa, D. Koutny, J. Rehacek, and Z. Hradil, J. Grover, A. Krzic, L. L. Sánchez-Soto: Reading out Fisher information from the zeros of the PSF. Submitted for publication in Optica.

Highlights:

New quantum-inspired metrology was developed based on spatial light modulation with phase-only masks. Through PSF shaping or realizing complex mode projections these techniques can outperform conventional detection of closely-spaced binary sources. This has been demonstrated in controlled experiments. Translated into time-frequency domain such ultra-precise sensing is well within the grasp of current technology with natural applications in, for example, splitting nearly degenerate stellar spectral lines, time-of-flight ranging, or probing ultrafast system dynamics.