Measuring Wigner functions of quantum states of light in the undergraduate lab

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Measuring Wigner functions of quantum states of light

Measuring the state of light

Understand the temporal behaviour of electrical signals on detectors, to characterize light:

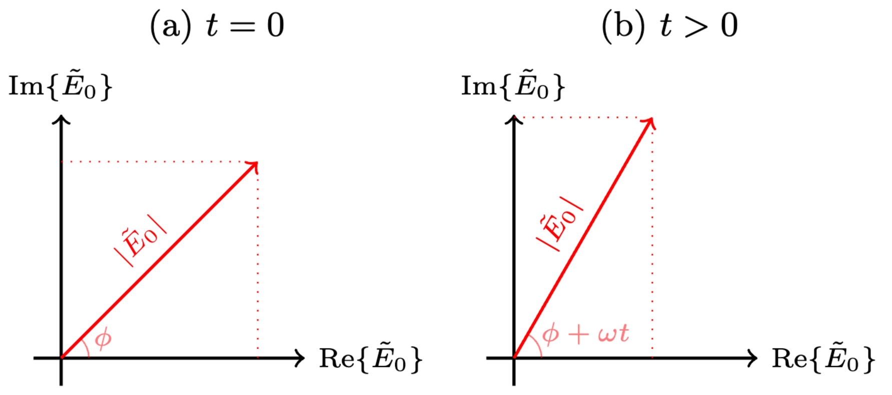
Quadratures

Description of a monochromatic wave (polarization $\hat{e}$, frequency ω) in terms of complex amplitude $\tilde{E}_0$

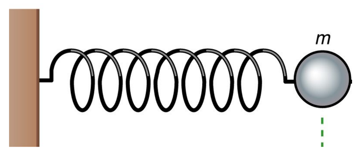
$$\vec{E}(t) = \mathrm{Re}\left[\tilde{E}_0 e^{i\omega t}\right]\hat{e}$$

Rewrite in terms of **quadratures** (the real and imaginary parts of complex amplitude):

$$\vec{E}(t) = [X\cos\omega t - Y\sin\omega t]\hat{e}$$



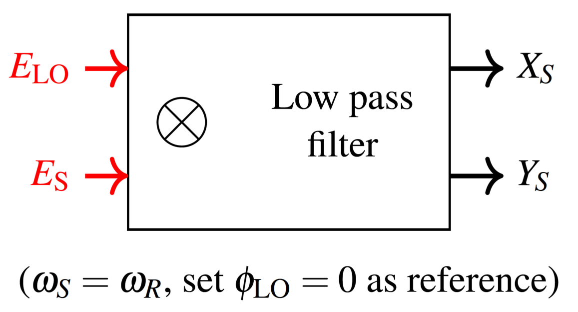
X and Y: Analogous to position and momentum in a mechanical oscillator.



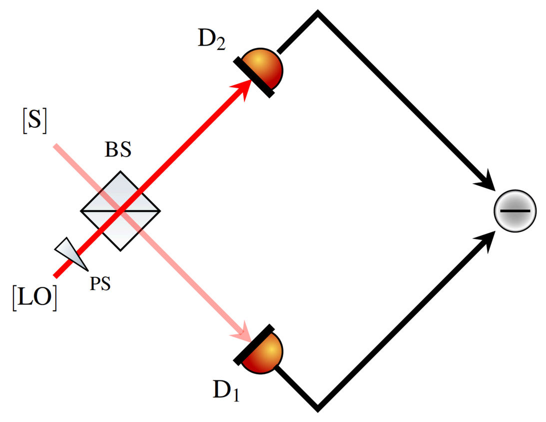
Quadratures are **conjugate variables** (Fourier transforms of each other)

Measuring quadratures

Combine signal of interest with a well-known local oscillator (LO), and vary the phase ϕ_{LO}:



Lock-in amplifier (kHz and MHz) Mix by modulation



Homodyne detection (Optical regime, THz) Mix into beam splitter

PS defines the phase of the Local Oscillator, ϕ_{LO}

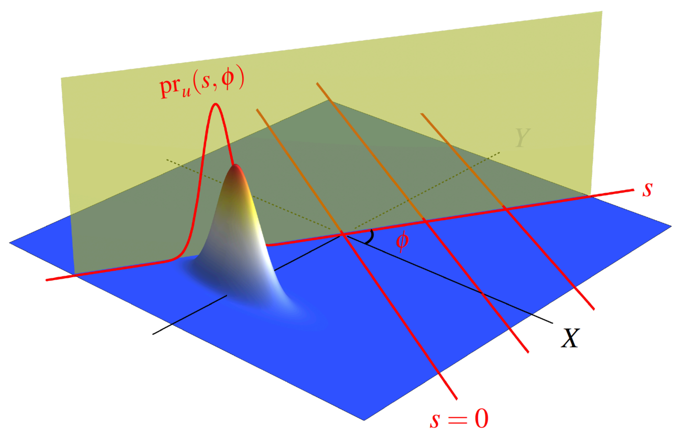
Wigner Distribution Function (WDF)

Represent a signal in phase space

$$W_u(X,Y) = \int u\left(X - \frac{X'}{2}\right)u^*\left(X + \frac{X'}{2}\right)e^{-2\pi i X'Y}\,dX'$$

Projections are performed with respect to a conjugate variable

$$\mathrm{pr}_u(X,\phi) = \int_{-\infty}^{\infty} W_u(X\cos\phi - Y\sin\phi, X\cos\phi + Y\sin\phi)\,dY.$$



Recovery of WDFs, a pipeline

Radon inverse transformation:

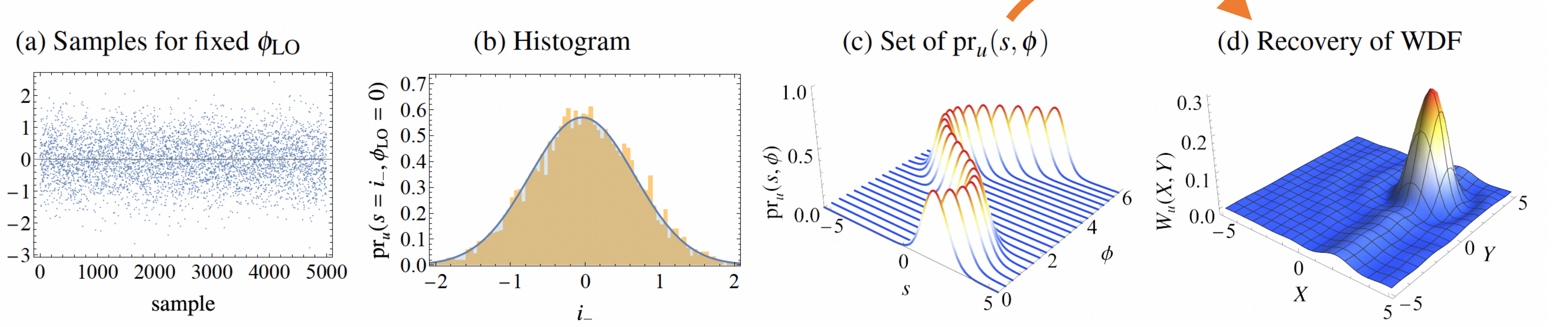
$$W_u(X,Y) = \frac{1}{2\pi^2}\int_{\phi=0}^{\pi}\int_{s=-\infty}^{+\infty}\mathrm{pr}_u(s,\phi)K(X\cos\phi + Y\sin\phi - s)\,ds\,d\phi$$

K is the kernel of the Radon inverse transform:

$$K(s) = \frac{1}{2}\int_{-\infty}^{+\infty}|\xi|\,e^{i\xi s}\,\mathrm{d}\xi$$

Filter kernel by truncating ξ by k_c

Radon inverse transformation



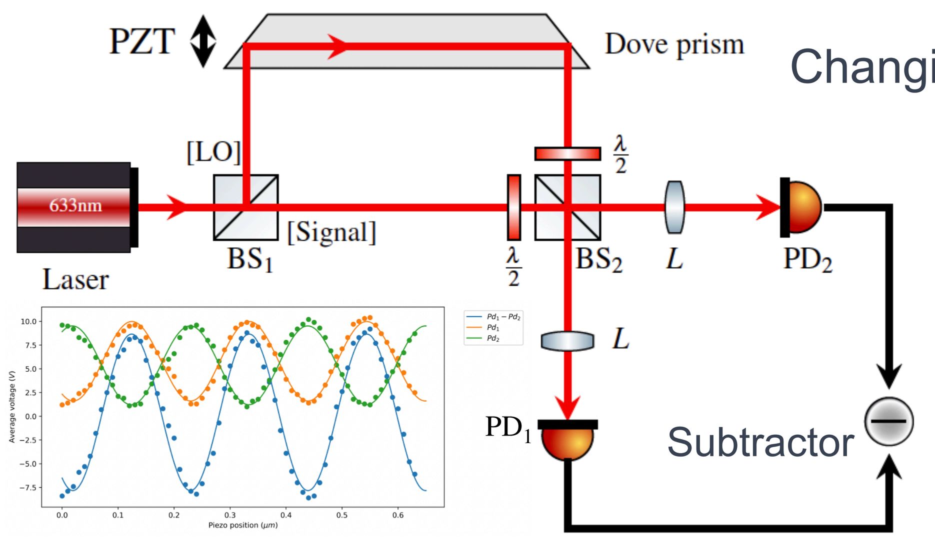
In the undergraduate lab

Undergraduate physics curriculum @ UniAndes

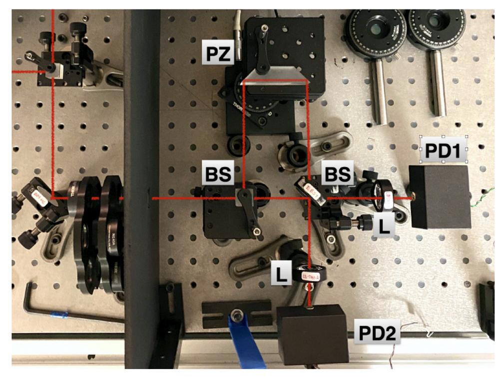
7th semester 2019-2 Intermediate laboratory	8th semester 2020-1 Undergraduate research project	2021-1 Test run Quantum optics course

By students — **For students**

Student activity #1: Building experimental setup

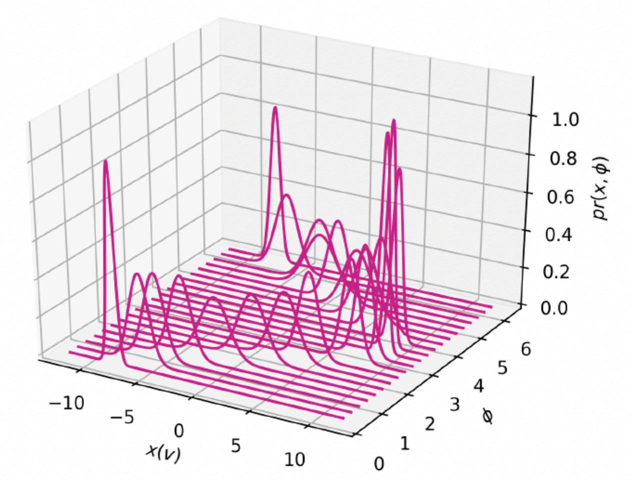


Changing the phase every $\pi/12$.

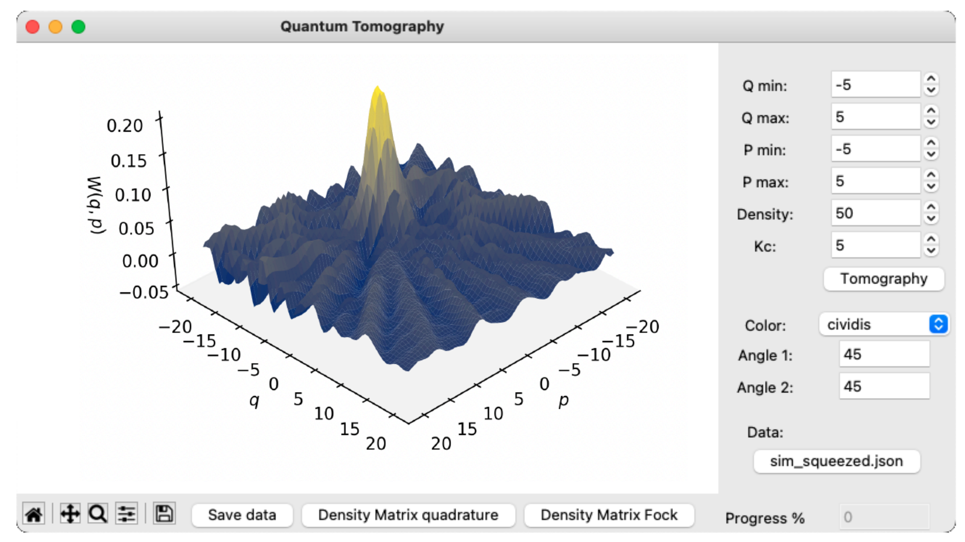


Student activity #2: Undergraduate research project

Used experiment to measure quadratures by changing ϕ_{LO}:



Algorithm and GUI development for WDF reconstruction

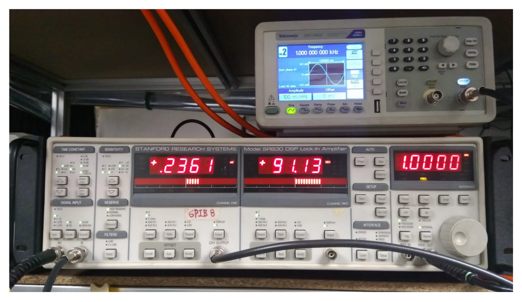


Openly available Windows & Mac Can generate own simulated data

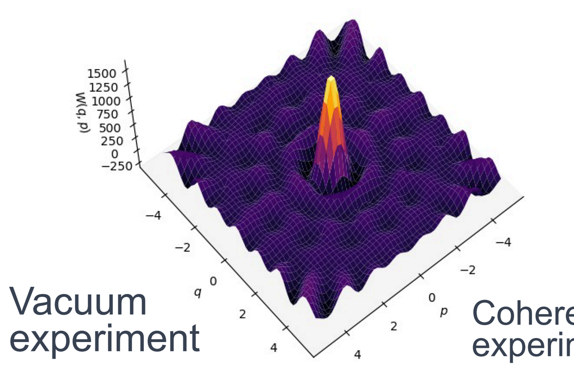
https://github.com/amartinez1224/quantum-tomography

Test run: Application of the activity in quantum optics class

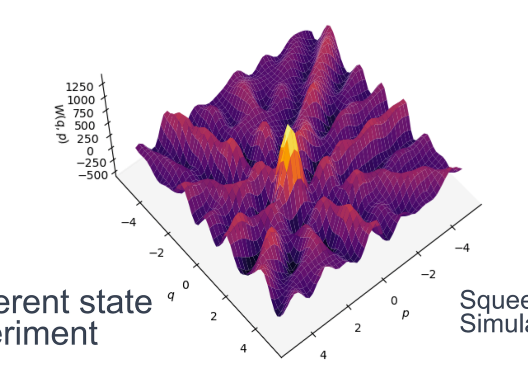
- Theoretical and practical, taught with experiments for the last two editions of the course.
- Book lab to work in pre-aligned setup for two-hour experimental runs
- Due to COVID, some students used simulated data to reconstruct more exotic states
- Usage of lock-in amplifiers and optical homodyne detection



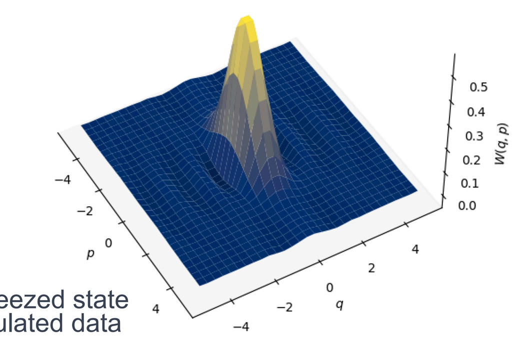
Function generator and lock-in amplifier



Vacuum experiment



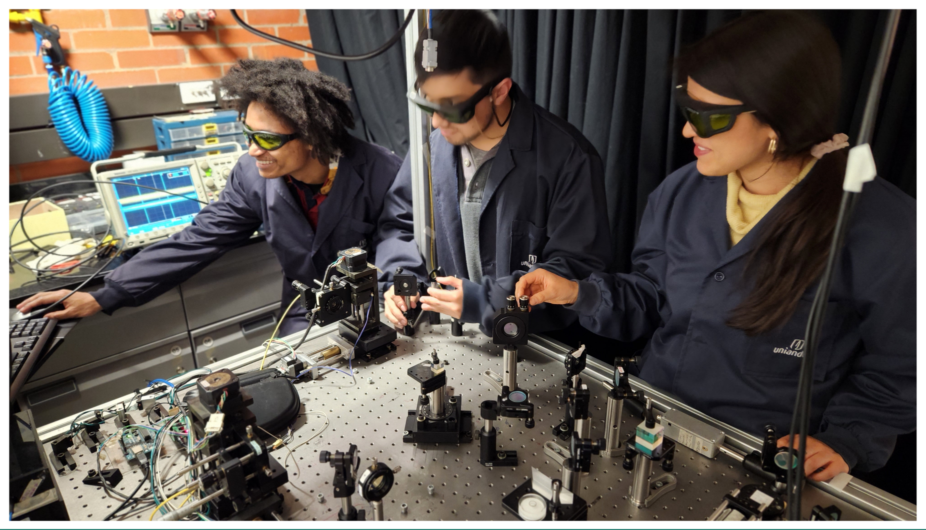
Coherent state experiment



Squeezed state Simulated data

Conclusions

- Activity by students and for students
- Demystifying quadratures using lock-in amplifiers and optical homodyne detection in class
- Recovery of Wigner functions: use of techniques applicable in other areas of physics.
- Designed with distance learning in mind



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