Top

Left side

TEST

Right side

bottom

Correlation functions in optics; classical and quantum 4.

TUW, Vienna, Austria, April 2018
Luis A. Orozco
www.jqi.umd.edu

UNIVERSITY OF MARYLAND 18 56

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Some review papers on this topic:

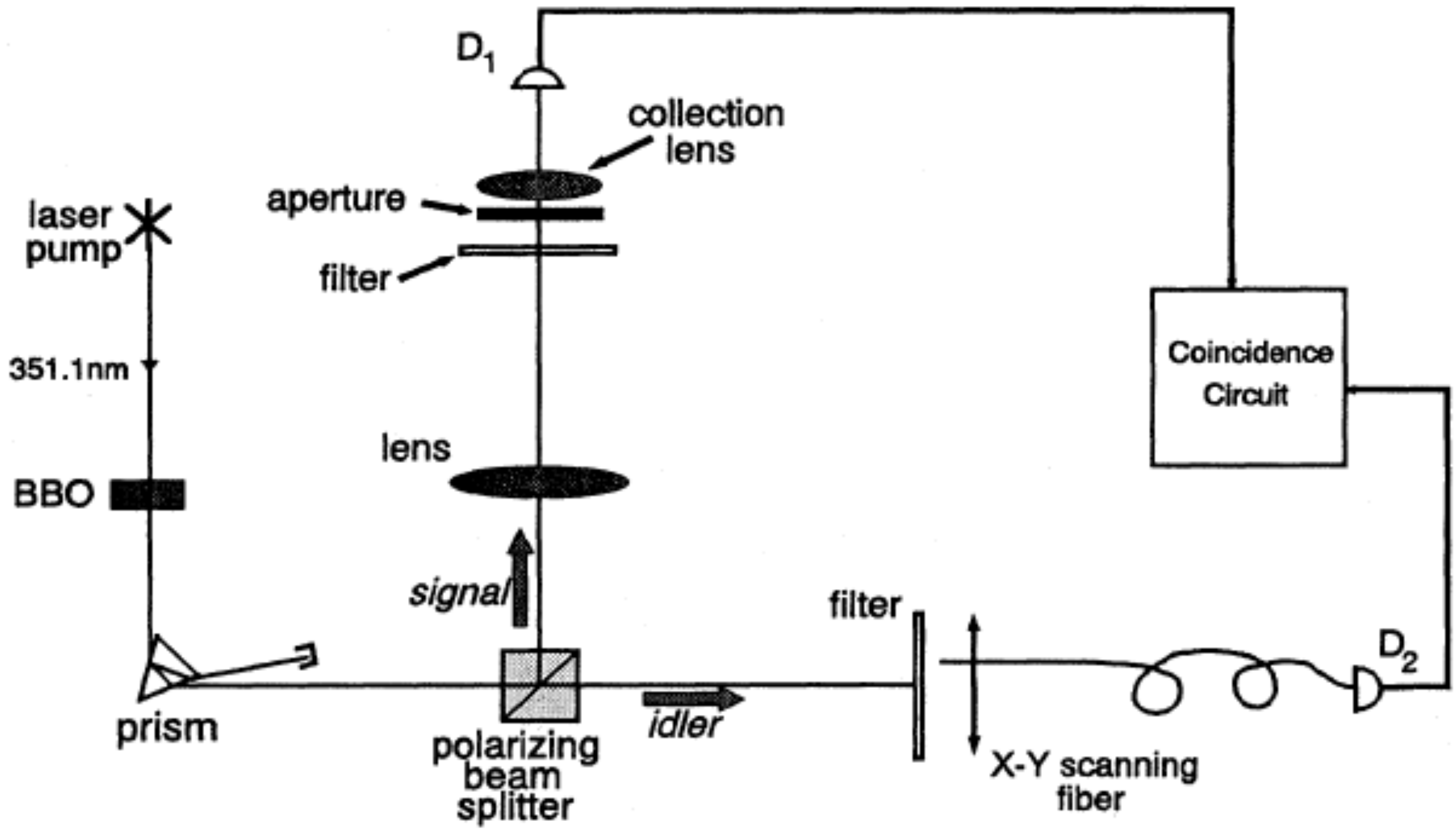
Baris I. Erkmen and Jeffrey H. Shapiro, “Ghost imaging: from quantum to classical to computational,” Advances in Optics and Photonics **2**, 405 (2010). doi:10.1364/AOP.2.000405.

Miles Padgett, Reuben Aspden, Graham Gibson, Matthew Edgar and Gabe Spalding, “Ghost Imaging,” Optics and Photonics News, p. 40, October 2016.

Ghost imaging is also known as Single Pixel Imaging: (Rice University in the 1990’s.) See for exampe: Marco F. Duarte, Mark A. Davenport, Dharmpal Takhar, Jason N. Laska, Ting Sun, Kevin F. Kelly, and Richard G. Baraniuk “Single-Pixel Imaging via Compressive Sampling” IEEE Signal Processing Magazine **25**, 85 (2008) DOI:10.1109/MSP.2007.914730

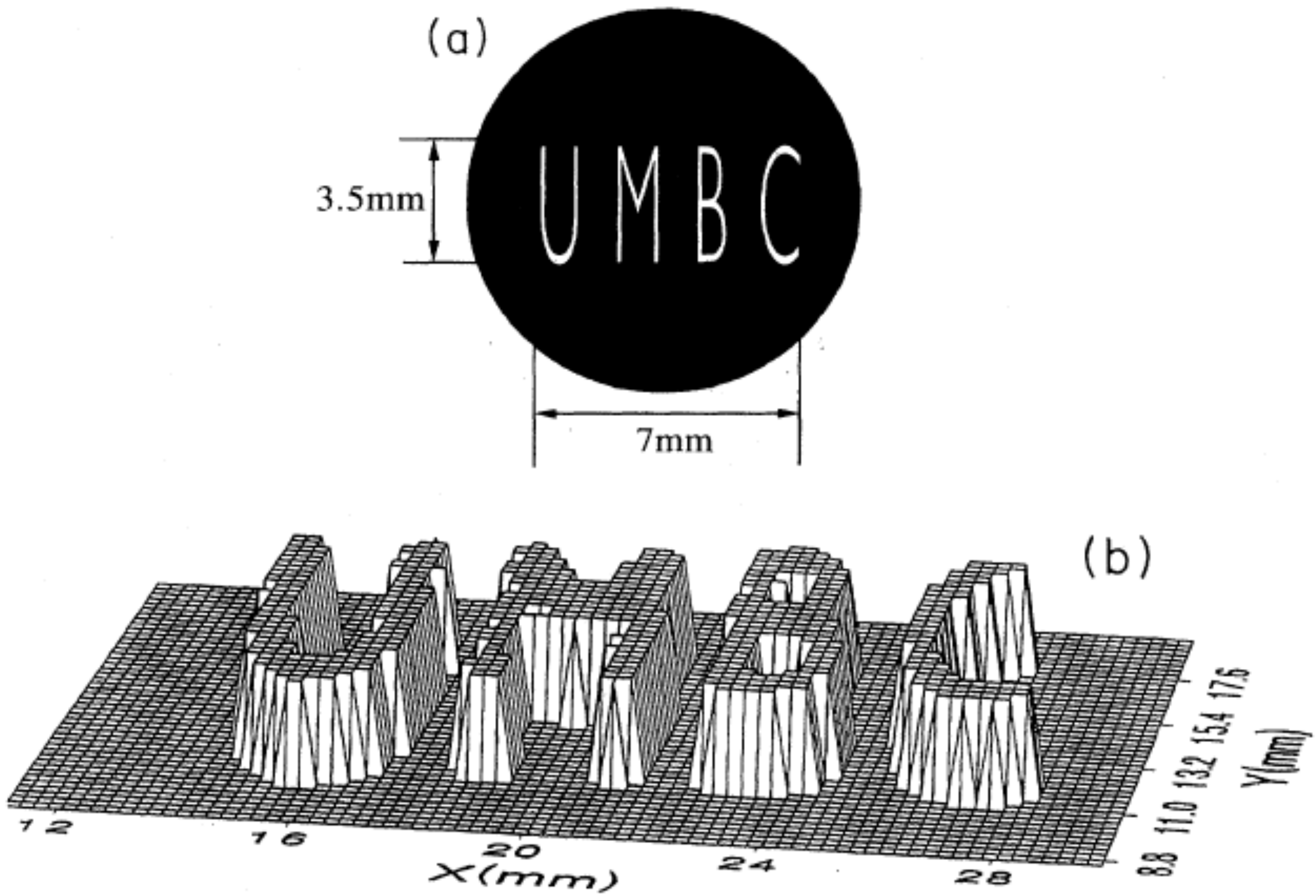
What is ghost imaging?

An experiment:



1. T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, "Optical imaging by means of two-photon quantum entanglement," Phys. Rev. A **52**, R3429–R3432 (1995).

The image



T. B. Pittman, et al. Phys. Rev. A **52**, R3429 (1995).

Correlated photons

Source: Spontaneous Parametric Down Conversion [SPDC]: non linear process where the pump frequency at 2ω becomes two beams at frequencies ω_s and ω_i (signal and idler).

Conservation of energy requires: $2\omega= \omega_s+\omega_i$
Conservation of momentum requires: $k_{2\omega}=k_s+k_i$
Conservation of angular momentum requires that the polarization of s and i have to be related.

The photon pair can be entangled.

Entanglement implies a high correlation between two properties or two particles (please be aware of the recent discussions on classical entanglement).

R. J. C. Spreeuw, “A classical analogy of entanglement,” Found. Phys. 28, 361 (1998).
R. J. C. Spreeuw, “Classical wave-optics analogy of quantum information processing,” Phys. Rev. A 63, 062302 (2001).
F. Töppel, A. Aiello, C. Marquardt, E. Giacobino, and G. Leuchs,“Classical entanglement in polarization metrology,” New J. Phys. 16, 073019 (2014).
X. F. Qian, B. Little, J. C. Howel, J. H. Eberly, “Shifting the quantum-classical boundary: theory and experiment for statistically classical optical fields,” Optica, 2, 611 (2015).

The correlation is independent of the basis used to measure it. Can be generalized for n particles

The state can not be written as an external product.

With two polarizations and two photons: $|H>_{1,}$ $|V>_1$, $|H>_{2,}$ $|V>_2$

$$\Psi=\alpha|H>_1|H>_2+\beta|V>_1|V>_2+\gamma|H>_1|V>_2+\delta|V>_1|H>_2$$

Bell states:

$$\Phi^{\pm} = (|H>_1|H>_2 \pm |V>_1 |V>_2)/(1/2)^{1/2}$$

$$\Psi^{\pm} = (|H>_1 |V>_2 \pm |V>_1|H>_2)/(1/2)^{1/2}$$

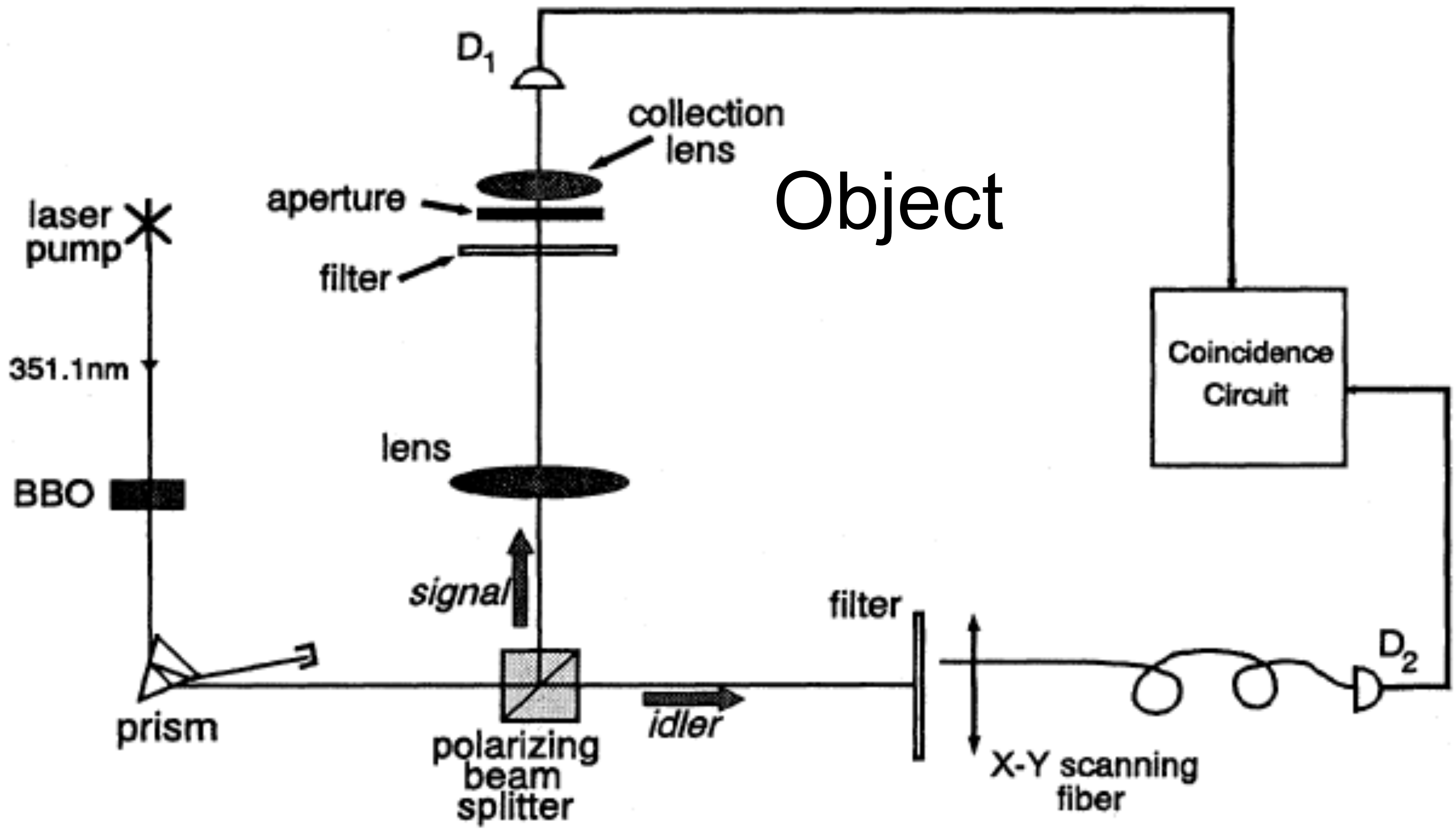
If we know the polarization of one, then we are sure of the polarization of the other.
In the circular basis |+>,|-> the same happens, this is what is strange.

The photon source gives highly correlated photon pairs.
However in each realization the individual result is random.

If we condition the detector of many pixels to detect a single click on the one pixel detector, it is possible to reconstruct the image.

Single pixel detector (bucket)

The lenses are not necessary

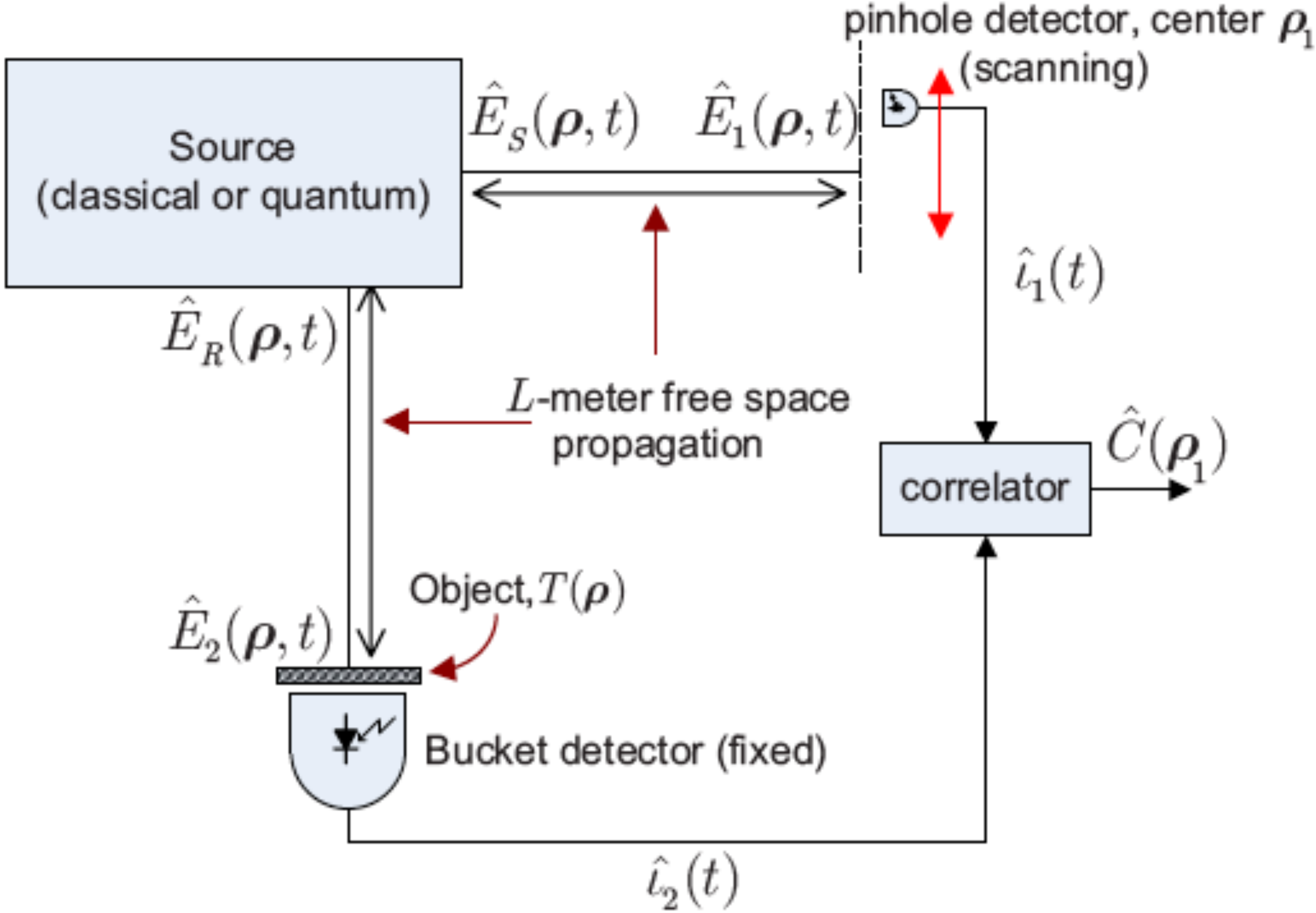


Multi pixel detector (scanning)

Coincidence (correlation, trigger)

T. B. Pittman, et al. Phys Rev. A **52,** R3429 (1995).

A generalization of the apparatus.



Baris I. Erkmen and Jeffrey H. Shapiro, "Ghost imaging: from quantum to classical to computational," Advances in Optics and Photonics **2**, 405–450 (2010).

Is it necessary to have entangled photons?

Correlation on the displacement of a classical beam

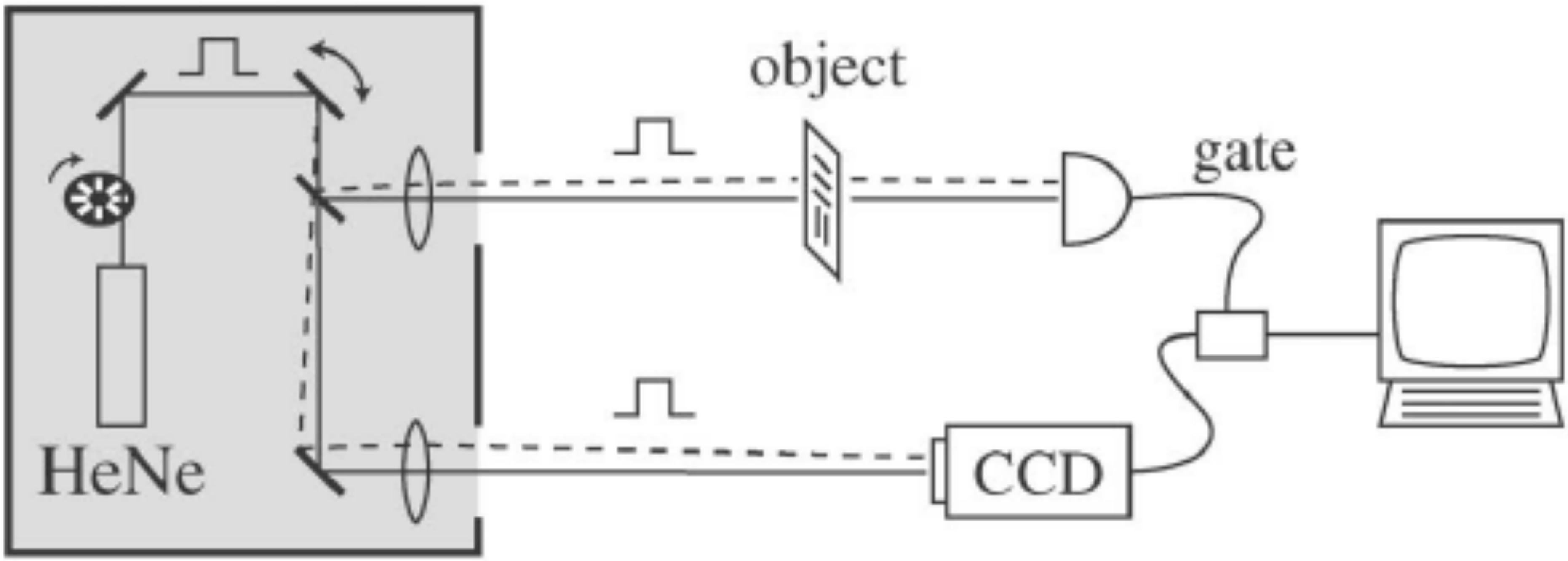


FIG. 2. The experimental setup used to perform coincidence imaging with a classically correlated source (shaded box).

R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Two-photon” coincidence imaging with a classical source,” Phys. Rev. Lett. **89**, 113601 (2002).

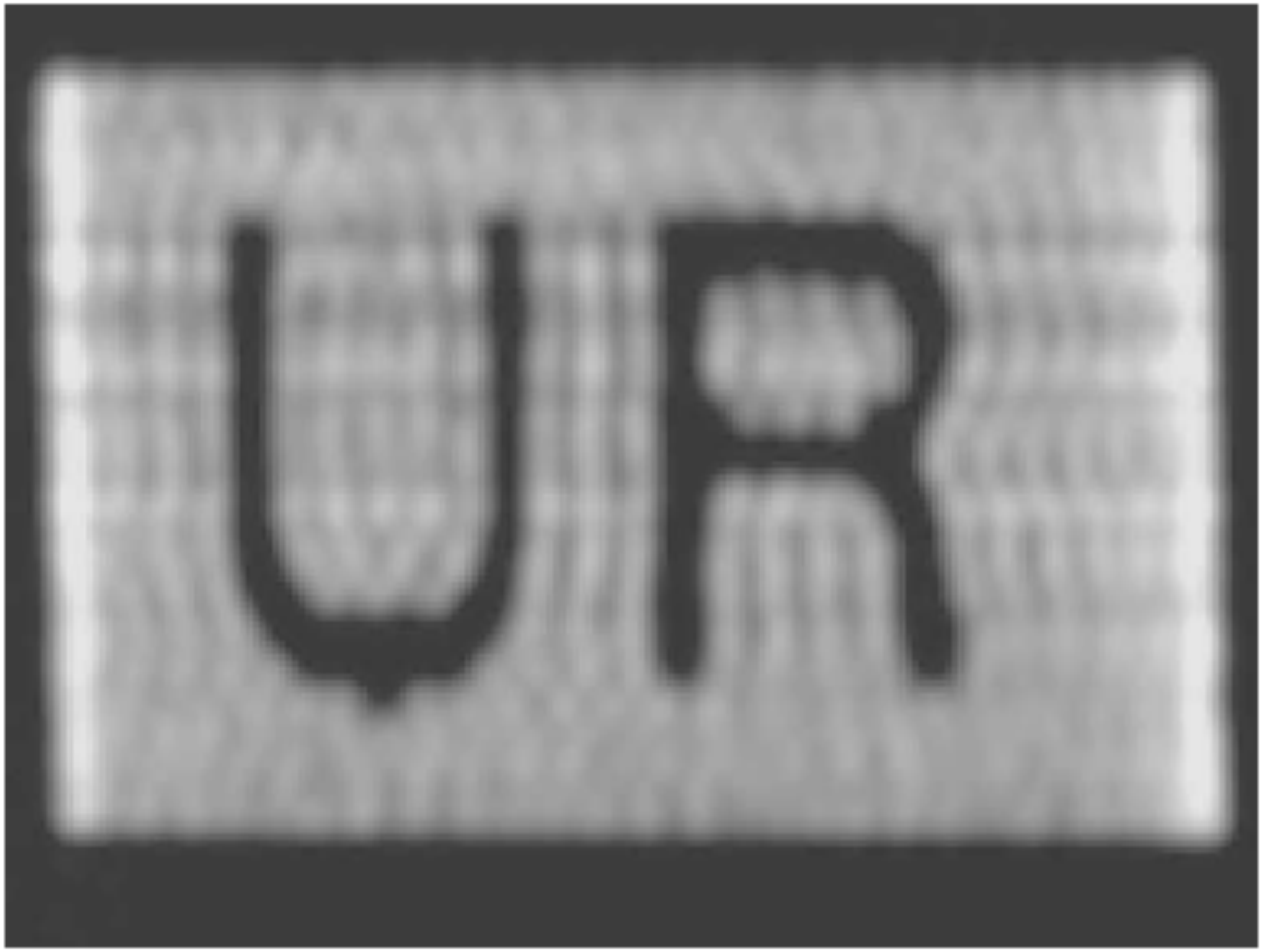


FIG. 3. The image formed in the reference arm when gated by the detector in the test arm. Such an image corresponds to the marginal probability distribution.

R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Two-photon” coincidence imaging with a classical source,” Phys. Rev. Lett. **89**, 113601 (2002).

Generalization as a probability problem.

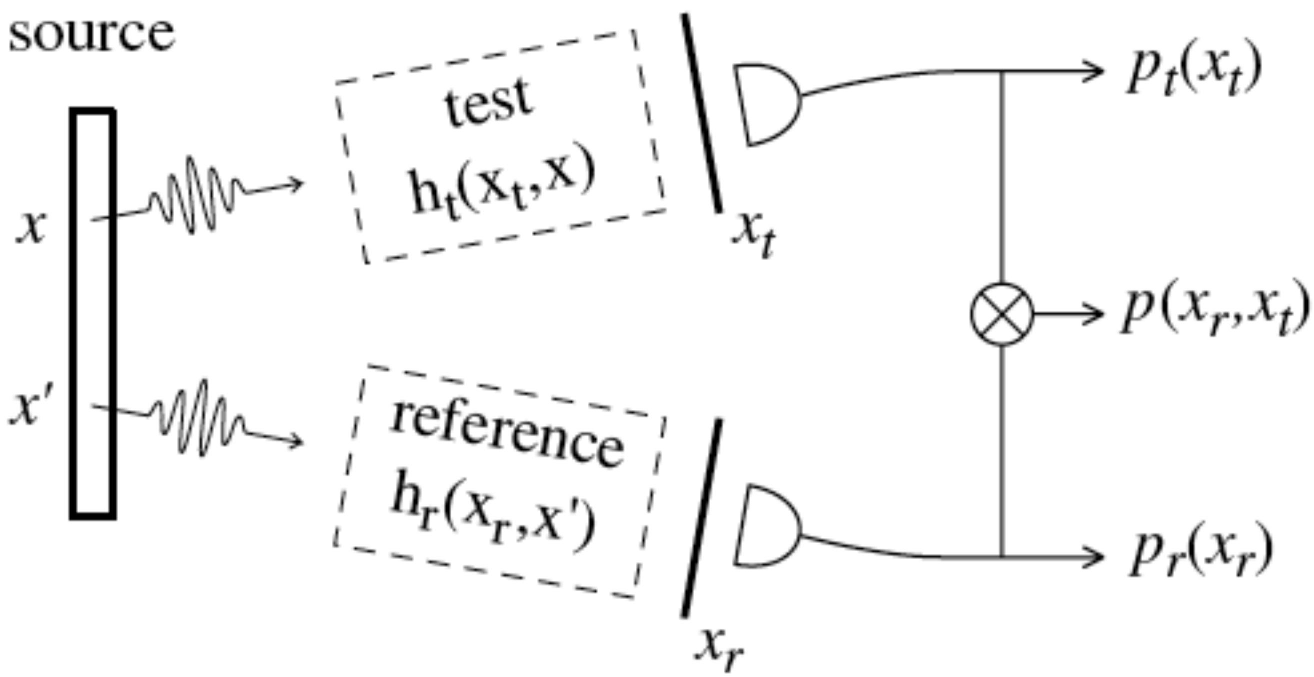


FIG. 1. (adapted from [12]) Two-photon coincidence imaging. The transfer function of the test system is to be obtained from the joint detection statistics using knowledge of the reference system.

R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Two-photon” coincidence imaging with a classical source,” Phys. Rev. Lett. **89**, 113601 (2002).

The probabilities given the source distribution

$$p_t(x_t) = \int dx' \left| \int dx h_t(x_t, x) \varphi(x, x') \right|^2,$$

$$p_r(x_r) = \int dx \left| \int dx' h_r(x_r, x') \varphi(x, x') \right|^2,$$

$$p(x_t, x_r) = \left| \int dx dx' h_t(x_t, x) h_r(x_r, x') \varphi(x, x') \right|^2,$$

h is the appropriate transfer function and it is crucial ϕ has correlations

The correlation functions satisfy the same wave equation (including diffraction) that the appropriate electromagnetic wave.

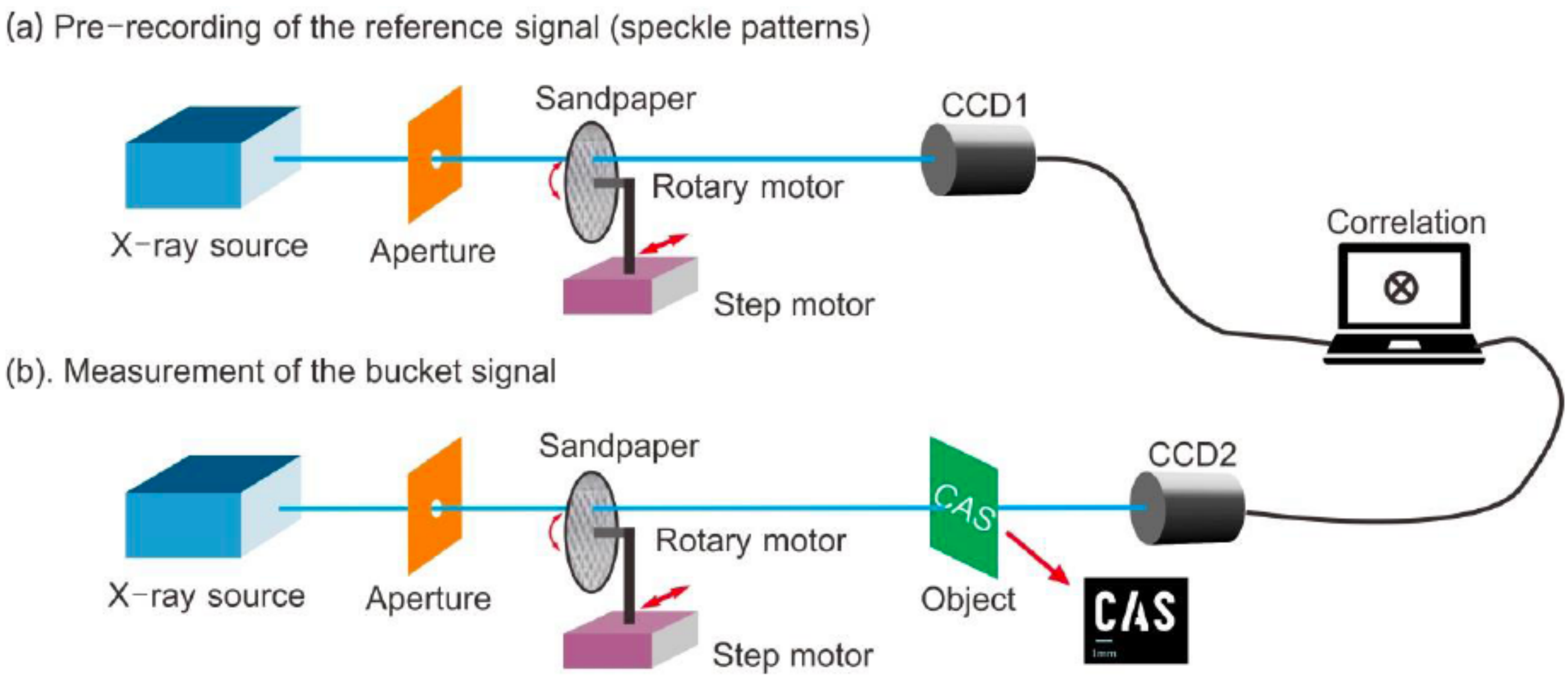
Classical sources have (random interference) speckle

Table-top X-ray Ghost Imaging with Ultra-Low Radiation

Ai-Xin Zhang[*], Yu-Hang He[*], Ling-An Wu[†], Li-Ming Chen[†], Bing-Bing Wang

Institute of Physics, Chinese Academy of Sciences, Beijing 100191, China

University of Chinese Academy of Sciences, Beijing 100049, China



Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation”, ArXive 1709.01016

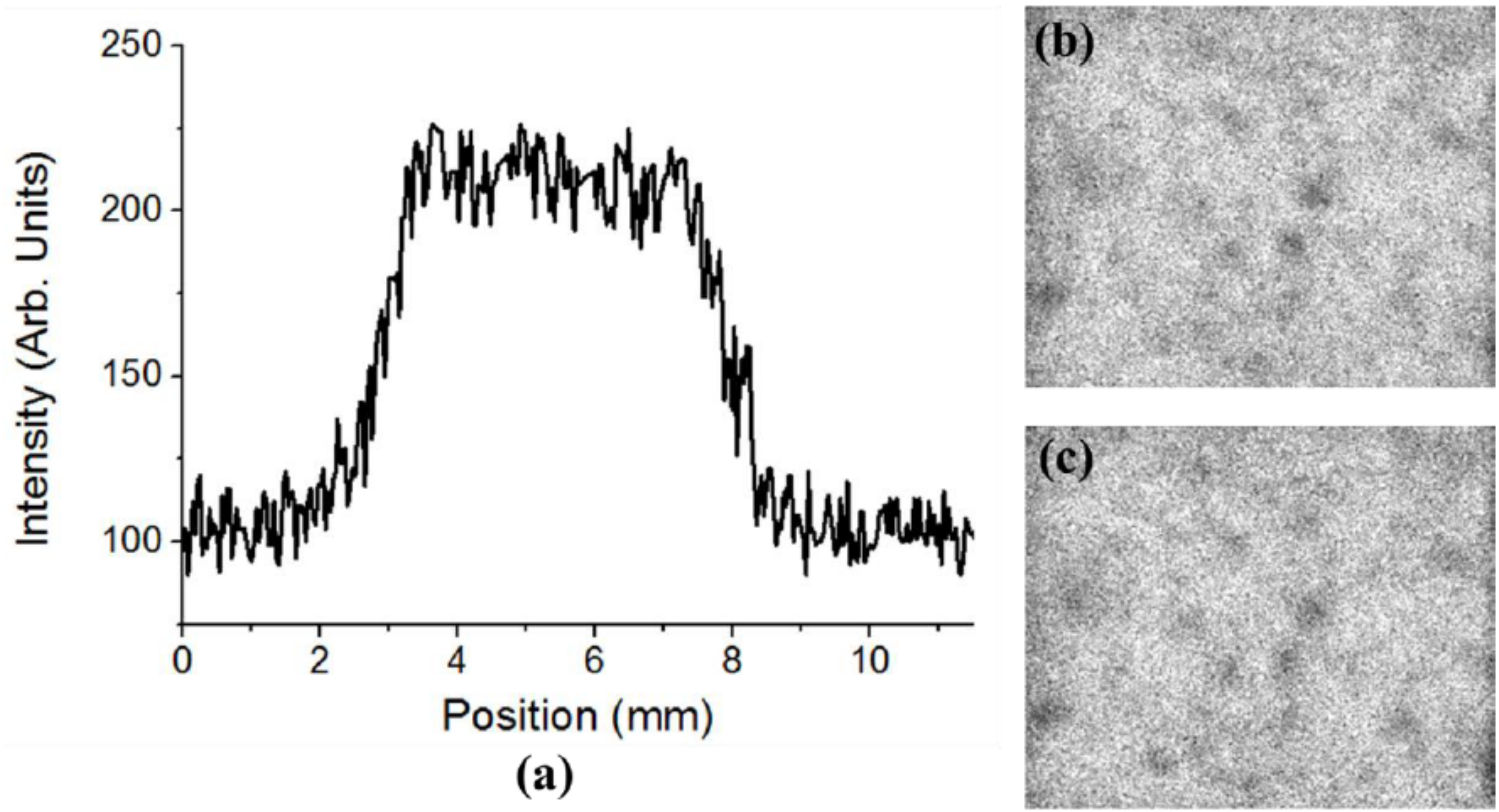
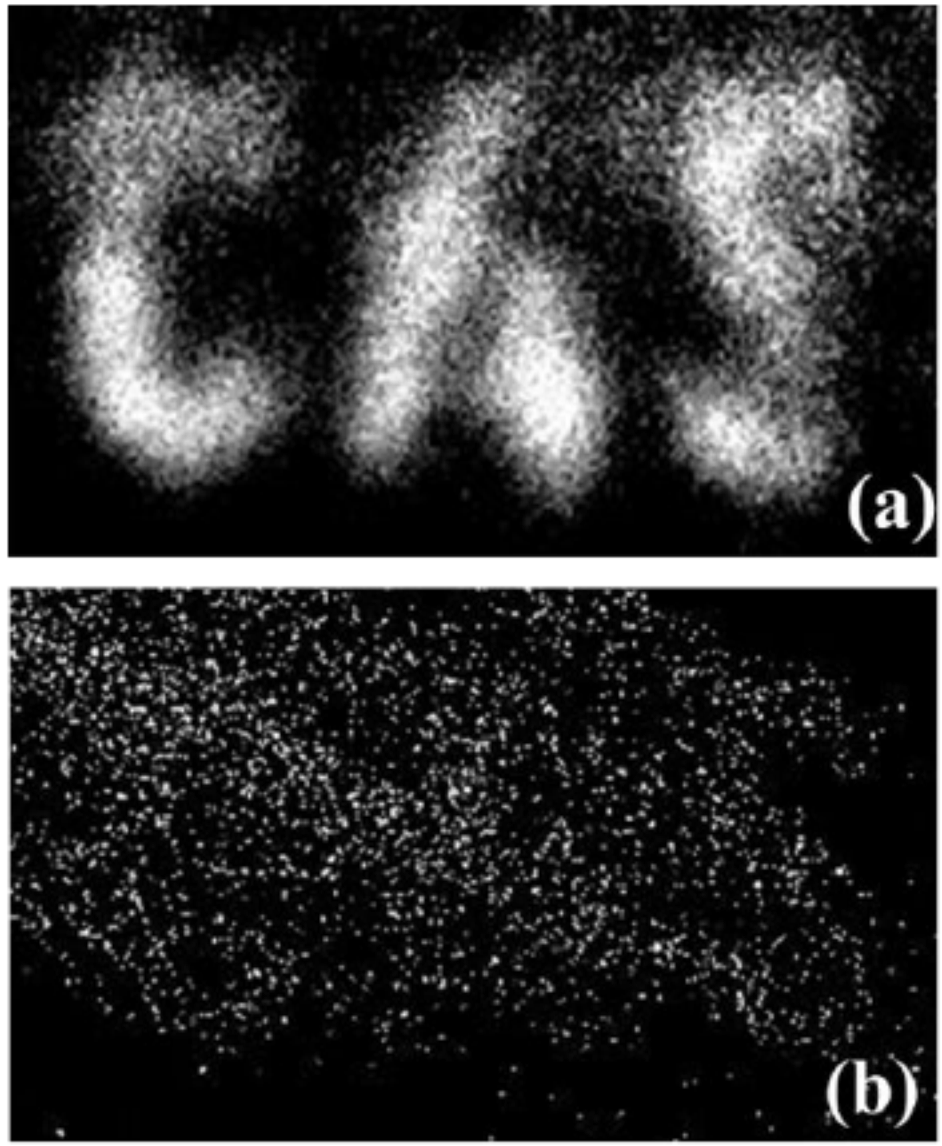


Fig. 2(a) Intensity profile of the direct x-ray beam; (b) Pre-recorded speckle pattern I_1; (c) Speckle pattern I_1' in the second series of positions.

Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation”, ArXive 1709.01016



Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation”, ArXive 1709.01016

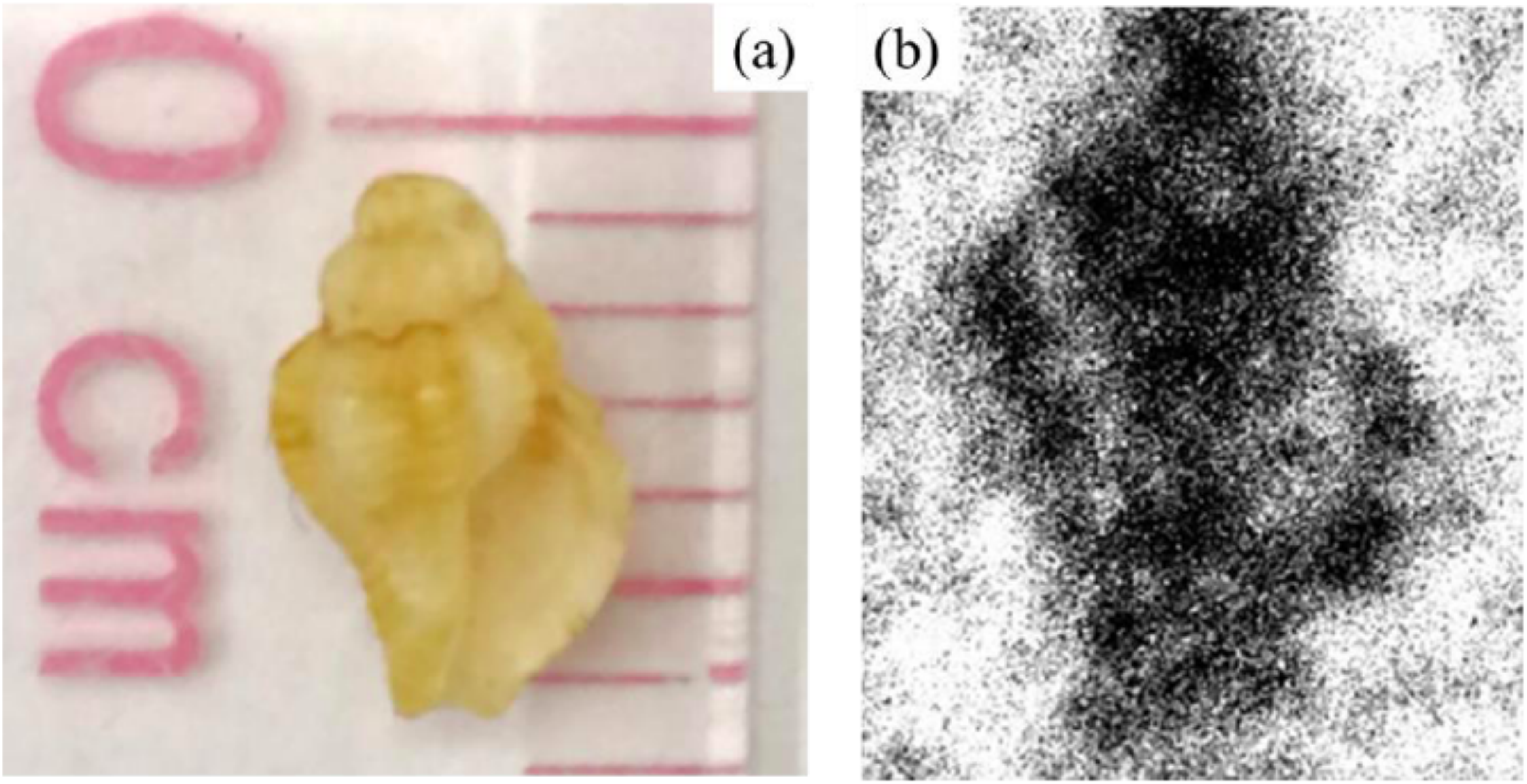
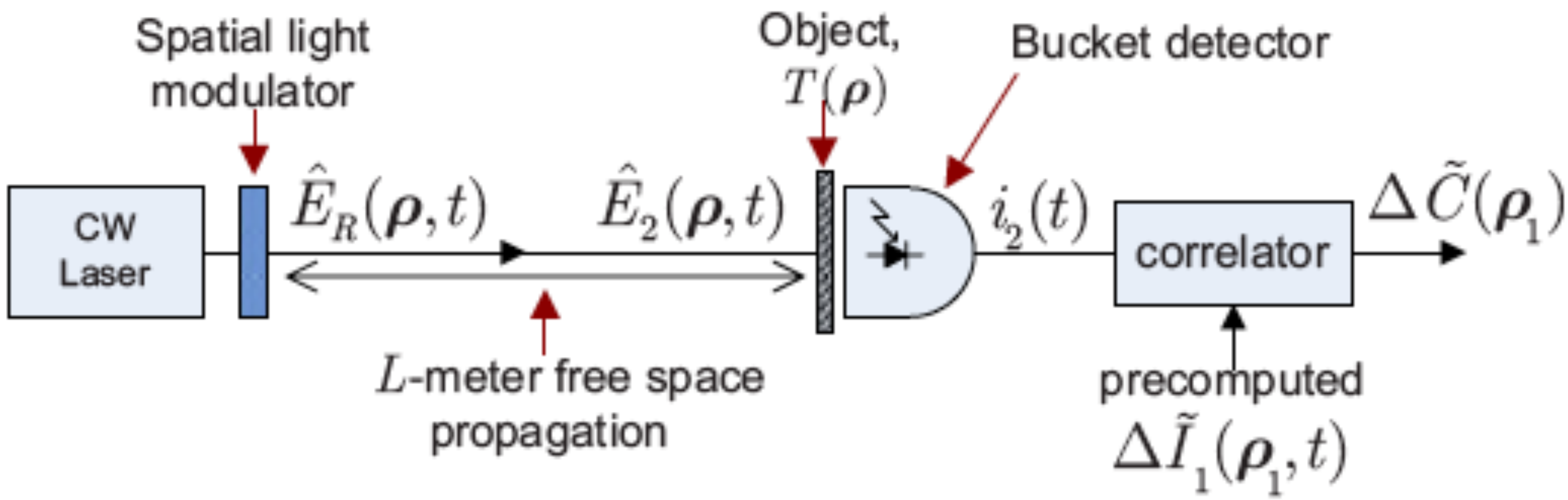


Fig. 4. (a) Ordinary photo of the shell; (b) XGI gray-scale transmission image.

Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation”, ArXive 1709.01016

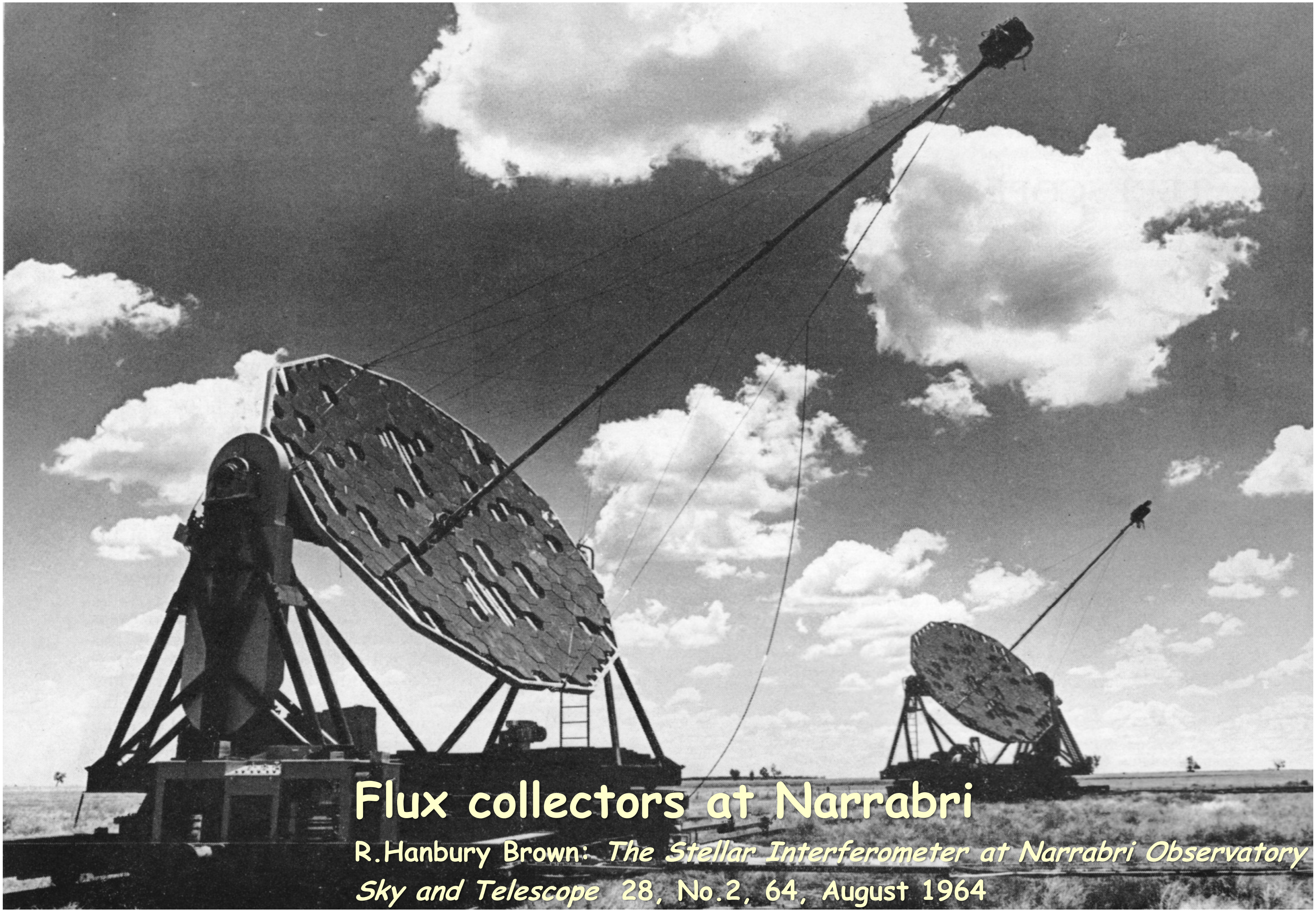


Computational ghost-imaging setup.

There is no lens, only one source.

Baris I. Erkmen and Jeffrey H. Shapiro, "Ghost imaging: from quantum to classical to computational," Advances in Optics and Photonics **2**, 405–450 (2010).

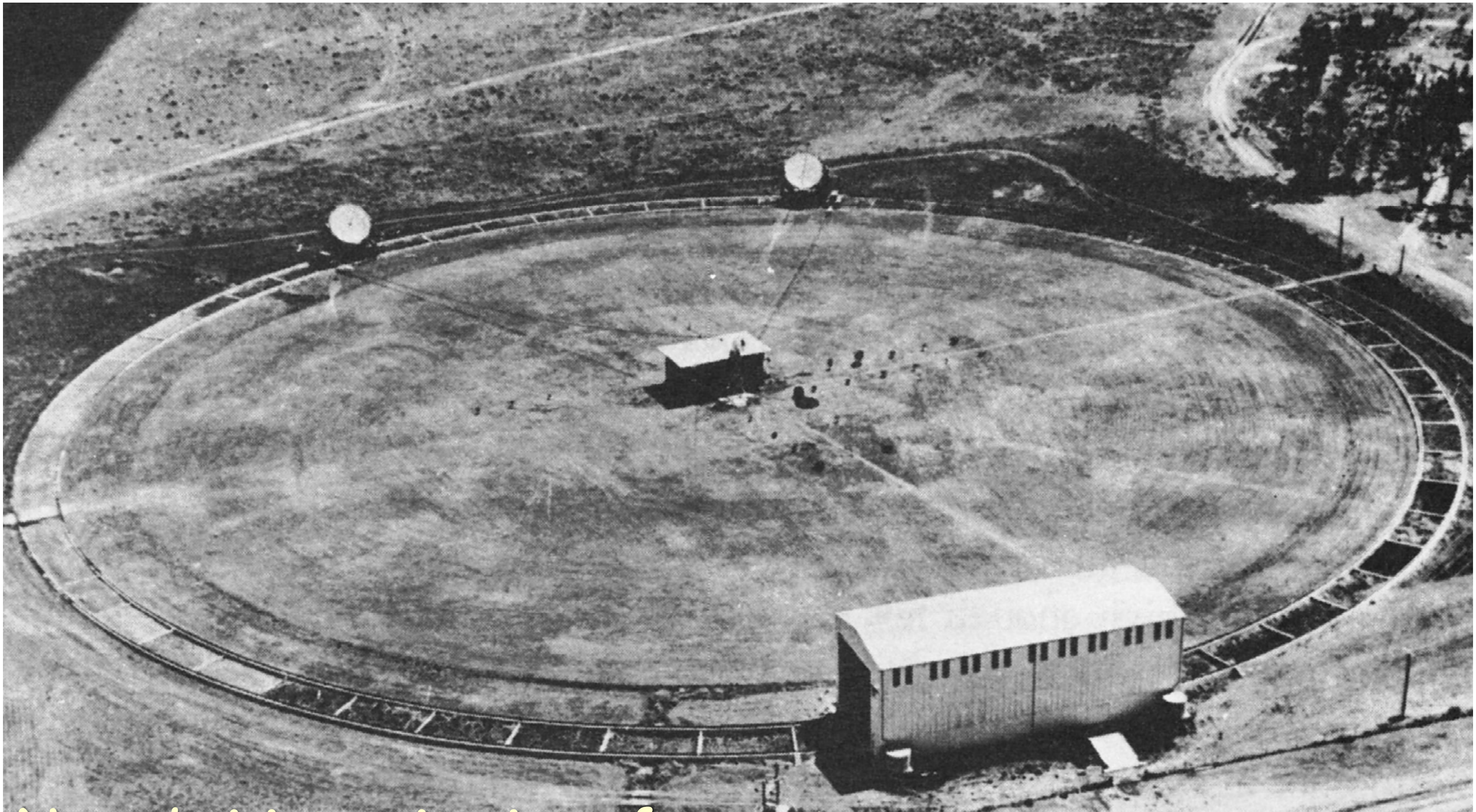
Handbury Brown and Twiss



Flux collectors at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*

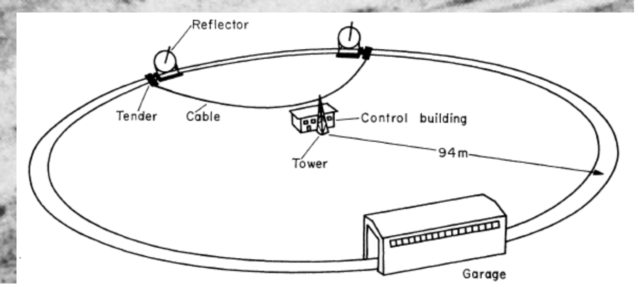
Sky and Telescope 28, No.2, 64, August 1964



Narrabri intensity interferometer

with its circular railway track

R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



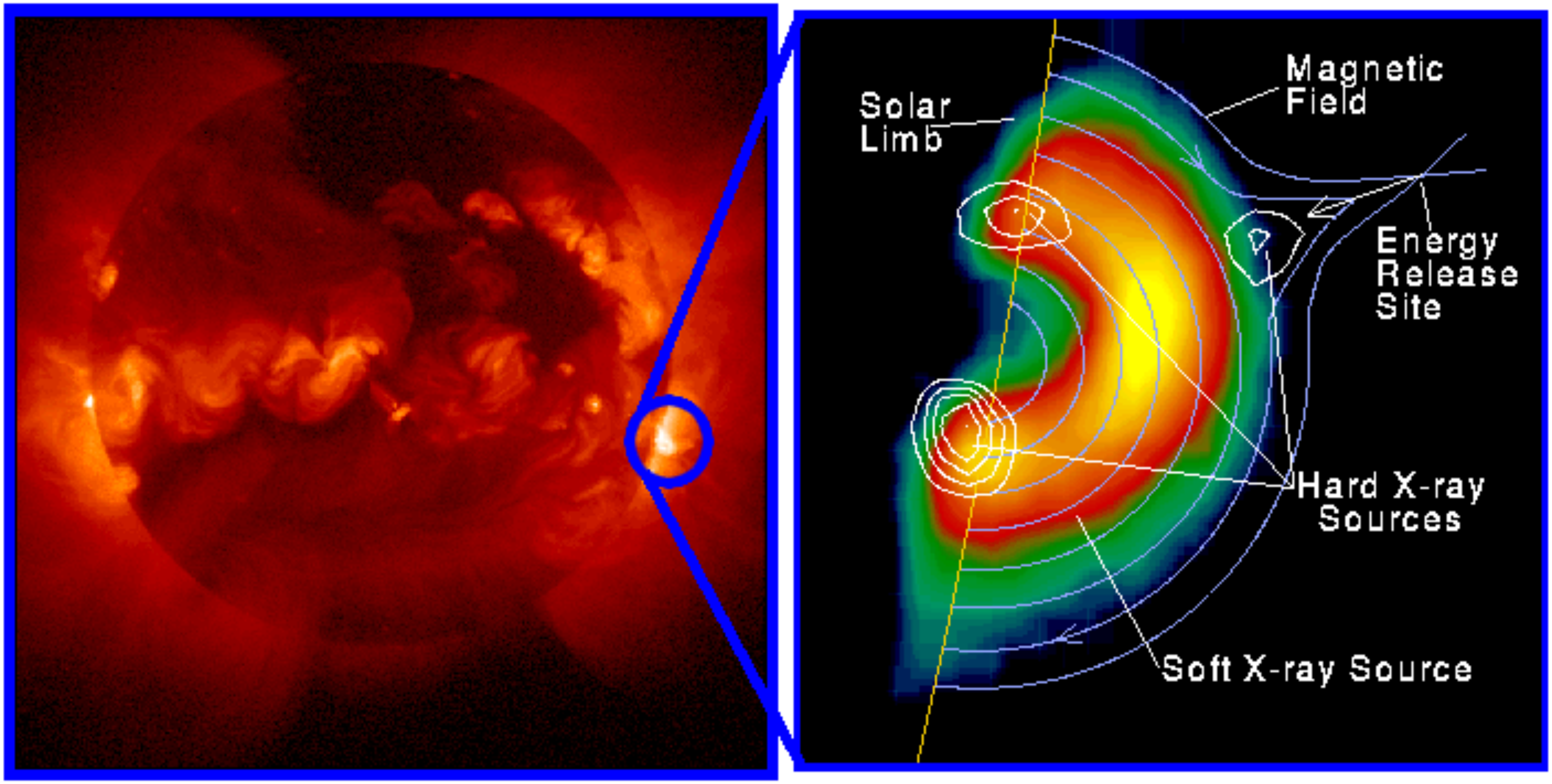
RHESSI mission

How to create an image with a single pixel detector?

Rotational Modulation Collimators

1975 Minoru Oda

Take a sample (counting) with an aperture to know the amplitude of a certain Fourier Component. Change the shape of the aperture (filter) to obtain enough Fourier Components to reconstruct the image.



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

Questions:

- What is the limit of resolution of this type of images?
- How does the resolution scale with the spatial correlation of the source?
- Is there a favored kind of correlation in the source?
- Could one use the correlation $h_\theta(\tau)$ (Field-Intensity) to get an image of both the intensity and the phase?
- Which kind of spectral analysis could be done with this images?
- How can you use this on a Telescope?

Use correlations!

Gracias