

Geometrical effects of the source size in correlation imaging

Giuseppe Lerario *Dipartimento Interuniversitario di Fisica, Università degli Studi di Bari, Via Giovanni Amendola, 173, 70125 Bari, Italy*Milena D'Angelo ^{*} and Gianlorenzo Massaro *Dipartimento Interuniversitario di Fisica, Università degli Studi di Bari, Via Giovanni Amendola, 173, 70125 Bari, Italy
and Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Giovanni Amendola, 173, 70125 Bari, Italy*

(Received 23 December 2025; accepted 13 April 2026; published 7 May 2026)

Correlation imaging (CI) is an emerging approach to imaging aimed at overcoming the limitations of conventional, intensity-based imaging modalities. In this paper, we focus on a peculiarity of chaotic-light-based CI: the strict link between image properties, and source size and geometry. We will show that the light source acts as a limiting aperture, whose geometrical properties significantly affect image formation, hence, the defocused resolution and depth of field. In ghost imaging, the image quality is typically associated with the speckle size, namely, with wave-optics effects; here, we evaluate the second-order correlation function of an out-of-focus CI system and demonstrate that the out-of-focus point-spread function is governed by a geometrical circle of confusion determined by the illumination numerical aperture. Both analytical results and numerical simulations indicate that this geometrical effect dominates the optical response of CI systems both in out-of-focus conditions and when large sources are employed. Even more, in correlation plenoptic imaging, the axial resolution is found to be directly linked to the illumination geometry, as the source size is found to constrain both the quality of the refocused images and the axial sectioning capability. The presented analysis applies to all CI architectures, thus providing a comprehensive framework for understanding and optimizing source-dependent effects in CI.

DOI: [10.1103/6g9j-5xx3](https://doi.org/10.1103/6g9j-5xx3)

I. INTRODUCTION

Correlation imaging (CI) exploits correlations between photons to overcome conventional limitations in sensitivity and resolution [1–8]. This class of imaging modalities has gained much attention in recent years, leading to novel and promising approaches such as imaging with undetected photons [9–12], sub-shot-noise imaging [13–17], imaging under turbulence and scattering conditions [18–20], as well as under low photon flux [21,22]. Unlike conventional imaging, where a single photodetector is used to acquire the light intensity distribution coming from the scene of interest, CI is based on the measurement of the correlation function resulting from light impinging on two detectors, often placed at remote locations from one another [5,6,23–25]. Among CI methods, ghost imaging (GI) is surely one of the most extensively studied. A typical GI scheme employs two detectors: a spatially resolving reference detector and a single-pixel bucket detector. The bucket detector measures the total intensity of light transmitted, reflected or scattered by the object, with no

spatial resolution, while the reference detector provides the spatial information of correlated photons that do not interact with the object. By correlating the two measured intensities, a spatially resolved image of the object is retrieved. The first experimental demonstration of GI was performed in the 1990s by employing entangled photons from spontaneous parametric down conversion (SPDC) [23]. It was later proven that GI could also be achieved by replacing SPDC with chaotic light sources, such as thermal and pseudothermal, with the relevant difference of reduced visibility and signal-to-noise ratio [26–29]. Chaotic light has subsequently been employed within numerous other imaging techniques based on photon-number or intensity correlations, with the advantage of achieving higher photon flux, with less demanding light sources [5,24,25,30,31].

In recent years, advances in quantum and quantum-inspired imaging have lead to the introduction of many other CI modalities, as well as developments toward different application scenarios ranging from remote sensing to biomedical imaging and security [30,32–40]. One of these approaches, which will be analyzed in some detail in our work, is correlation plenoptic imaging (CPI). CPI was originally introduced as a generalization of GI, with either thermal [41] or entangled [42] light, as the bucket detector was simply replaced by a high-spatial resolution detector. Soon after, it was extended to self-emitting objects [43–46], thus greatly enlarging the pool of possible use cases. The additional information over GI, allows CPI to gain multiple points of view of the object, thus

^{*}Contact author: milena.dangelo@uniba.it

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

enabling both three-dimensional (3D) imaging and changing the focusing plane, in postprocessing. Most interestingly, CPI overcomes one of the main limitations of conventional, intensity based light-field imaging, namely, the direct conflict between image resolution and 3D imaging performance [41–43,45–49].

In this work, we will deepen the exploration into the physics of CI by considering the role played by the source size and geometry on the image quality, both for focused and for out-of-focus imaging systems. A general formal context, which can be applied to any CI technique, will allow us to outline a general analytical description of CI, which will then be applied to describe the two example cases of GI and CPI. As we will elaborate extensively in our paper, the effects of the source geometry on the final correlation-based image is typically associated to wave-optics phenomena, such as the coherence area (or speckle size). Here, we will prove that CI is affected by other concurrent geometrical effects, which are related with the source size and that, in defocused conditions, can even dominate speckle-induced wave-optics effects. The presented results deepen our understanding of CI while offering a particularly useful tool for optimizing the design of CI optical setups.

The paper is structured as follows. In the next section, we introduce the formal framework used to derive the second-order correlation function. After deriving its general form, we then specialize it to the CI schemes of interest. In this section, we also provide the analytical tools for interpreting the geometric optics features of the correlation function, and clarifying the role of the source size and geometry within CI. The third section is devoted to the analysis of the role played by the source in both GI and CPI. In the last section, we summarize the main findings of the paper and outline future developments.

II. SECOND-ORDER CORRELATION FUNCTION IN CORRELATION IMAGING SCHEMES

CI retrieves the image of a sample by exploiting the correlation of light intensities measured at two photodetectors. The design of the optical system naturally depends on the specific CI implementation. To provide a unified description, we introduce a general formalism describing the two-dimensional intensity distribution at the two detectors, thus obtaining a four-dimensional correlation function between light intensities at two arbitrary transverse planes in space. This general formulation can be subsequently adapted to various CI scenarios through straightforward transformations, i.e., by specifying the detection strategy. It will be shown that the specific correlation function for any given CI techniques can always be derived from this formulation.

Let us start by considering a generic CI scheme made of two optical paths and two generic photodetectors placed at the end of each path. As shown in Fig. 1, we can consider two possible configurations: in the first one, light from the source is split into two optical arms, and only one of the beams illuminates the object, as typically occurs in GI-like setups [Fig. 1(a)]; in the second one, light illuminates—or is emitted by—the object before being split, and photons emerging from the object reach both detectors [Fig. 1(b)]. Figure 1

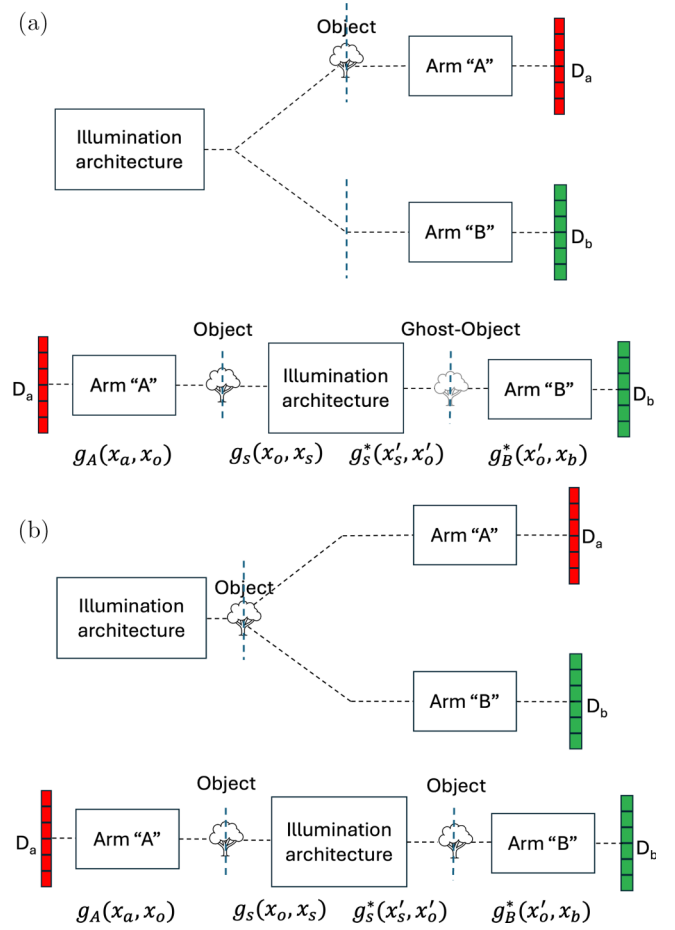


FIG. 1. Generic schemes of the possible CI architectures, which we name: (a) $m = 0$, and (b) $m = 1$, in line with the notation employed in Eq. (2). In both panels, we report, in the top part, the correlation imaging setups, and, in the bottom part, the corresponding unfolded Klyshko pictures.

shows the unfolded Klyshko picture for the two considered configurations; the unfolded versions are very similar to each other, with the only difference that, in arm B, the object plane of case $m = 1$ is replaced, if $m = 0$, by a ghost image plane, namely, a plane correlated to the object plane. The formulation applies regardless of whether the measured correlations originate from quantum [42,49,50] or classical [43,45,49,51] light. However, in the present paper, the discussion will be restricted to classical correlations generated by thermal (or pseudothermal) light sources; the analogies with the quantum case will be discussed in the conclusions. For CI architectures employing thermal light illumination, the second-order correlation function is given by the covariance of the field intensity distributions evaluated in the transverse planes corresponding to the detectors surfaces [43,45,50], namely

$$\Gamma^{(2)}(\rho_a, \rho_b) = \langle I_A(\rho_a) I_B(\rho_b) \rangle - \langle I_A(\rho_a) \rangle \langle I_B(\rho_b) \rangle, \quad (1)$$

where $I_A(\rho_a)$ and $I_B(\rho_b)$ are the resulting intensity distributions, also known as speckle patterns, and $\rho_i = (x_i, y_i)$, with $i = a, b$, are the 2D vector coordinates on the transverse planes occupied by the detectors D_A and D_B ; the angular brackets denote the ensemble average resulting from all the

statistical realizations of the random source [52,53]. From this point onward, for the sake of simplicity, the four-dimensional dependence of the correlation function will be neglected. This implies, when intensity detection will be included in our formalism, considering the detectors as monodimensional, with x_a and x_b representing the detector coordinates. Assuming the object is a thin 2D mask with complex field transmittance $A(x_o)$, the correlation function reads:

$$\Gamma^{(2)}(x_a, x_b) = \left| \int A(x_o) g_A(x_o, x_a) \int [A^*(x'_o)]^m g_B^*(x'_o, x_b) \times \int \Phi(x_o, x'_o) dx_o dx'_o \right|^2, \quad (2)$$

where the coefficient m is 0 for GI-like setups [Fig. 1(a)], and 1 when both detectors collect light from the object [Fig. 1(b)] [53]. This equation comprehensively describes the propagation of the electric field from the object position x_o to the detector coordinates $x_{a,b}$ throughout the optical setup, up to the sensor planes. In both configurations, the field propagation towards D_A and D_B is described by means of the Green's functions g_A and g_B , respectively. In setups characterized by $m = 1$, the Green's functions propagate the field from the source through the object plane to the detectors placed in arms A and B. In contrast, for $m = 0$, field propagation occurs from the source through the object and to the detector, in the arm containing the sample (A), and from the source through the ghost image and to the detector, in the arm with no sample (B). The function Φ in Eq. (2) is, in the case $m = 1$, the mutual degree of spatial coherence on the object plane [52], and, in the case $m = 0$, the mutual degree of spatial coherence between the object and ghost-image planes. To maintain generality, no assumption is made at this stage regarding the analytical form of Φ , as it depends on the optical design responsible for the transmission of light from the source to the object. In particular, the illumination architecture in Fig. 1 may consist of either free-space propagation over the distance separating the source from the sample, or direct emission from the object itself, or any other more elaborate configuration employing optical elements to shape light with specific properties (e.g., far-field lens, relay optics, etc.). To account for all these possible illumination modalities, we will express Φ as

$$\Phi(x_o, x'_o) = \int g_s(x_o, x_s) g_s^*(x'_o, x'_s) \langle E_s(x_s) E_s^*(x'_s) \rangle dx_s dx'_s, \quad (3)$$

where g_s indicates the Green's function describing field propagation from the source to the object plane, and E_s is the field on the source plane, identified by the transverse coordinate x_s . In $m = 0$ configurations, where the object is present in one arm only [Fig. 1(a)], g_s describes propagation from the source to the object plane, in the arm containing the sample, and propagation from the source to the ghost-image plane, in the other arm.

Equation (3) indicates that the mutual degree of spatial coherence at the object plane depends both on the statistical properties of the emitted light, as described by the mutual degree of spatial coherence on the source plane $\langle E_s(x_s) E_s^*(x'_s) \rangle$, and on the illumination architecture, as described by g_s . From

now on, we will assume negligible coherence area at the emission surface, so that the statistical properties on the object (and ghost-image) plane are entirely defined by the illumination strategy. With this assumption

$$\langle E_s^*(x_s) E_s(x_s) \rangle \sim S(x_s) \delta(x_s - x'_s), \quad (4)$$

where $S(x_s)$ is the intensity emission profile of the source. Equation (3) thus becomes

$$\Phi(x_o, x'_o) \sim \int g_s(x_o, x_s) g_s^*(x'_o, x_s) S(x_s) dx_s. \quad (5)$$

To conclude the introduction of the formalism, it should be emphasized that a CI technique does not directly measure the correlation function introduced so far, which corresponds to the second-order correlation of the fields at two transverse planes. Such a situation would occur only if detectors D_A and D_B were capable of sampling the intensity of the electric field with pointlike resolution, which is typically neither the case nor required (e.g., the bucket detection in GI). The intensity measured at the detector coordinate x_i is the integral of the intensity collected over the entire pixel of size d_i , centered in x_i , during the integration time, which is

$$\mathcal{I}_{A,B}(x_i) = \int_{x_i-d_i/2}^{x_i+d_i/2} I_{A,B}(x'_i) dx'_i \quad (6)$$

with $i = a, b$. Based on Eq. (1), the measured correlation function is thus the spatially integrated version of the correlation function discussed so far, namely

$$\Gamma_{\text{meas}}^{(2)}(x_a, x_b) = \int_{x_a-d_a/2}^{x_a+d_a/2} \int_{x_b-d_b/2}^{x_b+d_b/2} \Gamma^{(2)}(x'_a, x'_b) dx'_b dx'_a. \quad (7)$$

Geometric optics description of the second-order correlation function

Equations (2) and (3) fully describe the propagation of the electric field from the source plane, x_s , to the detection planes, $x_{a,b}$, and their combination gives the complete analytical expression of the second-order correlation function of CI protocols.

Valuable insights about the general features of the correlation function will now be obtained by working in the geometrical optics approximation, namely, by evaluating the second-order correlation function in the so-called stationary phase approximation [53,54]. In this limit, the correlation function associated with a generic CI scheme involving N limiting apertures $P_J(x_J)$, with $J = 1, \dots, N$, reduces to:

$$\begin{aligned} \Gamma_{\text{geom}}^{(2)}(x_a, x_b) &= |A(\alpha(z)x_a + \beta(z)x_b)|^{2(1+m)} S^2(s_a x_a + s_b x_b) \\ &\times \prod_J |P_J(p_{J,a} x_a + p_{J,b} x_b)|^2. \end{aligned} \quad (8)$$

This expression is almost identical to the one reported in Ref. [53] for the case of a self-emitting object. The only crucial difference is the inclusion of an additional multiplying term $S^2(s_a x_a + s_b x_b)$ representing the squared intensity profile of the source, with the specific value of the parameter $s_{a,b}$ depending on the illumination strategy.

In the geometrical approximation, the correlation function thus takes the form of a product between the object intensity profile (squared, if $m = 1$) and the squared modulus of all the apertures involved in the optical design, including the source size. Each of these factors is evaluated at a rescaled coordinate given by the linear combination of the detector coordinates, x_a and x_b , with coefficients $\alpha(z)$ and $\beta(z)$ determined by the specific optical setup, z being the axial location of the object. In particular, these coefficients govern the dependence of the object on the detector coordinates, and are determined by the focusing conditions. Specifically, if $\alpha = 0$, the object term in the correlation function depends only on x_b and the sample is focused on the detector D_b (directly, if $m = 1$, and through GI, if $m = 0$). Analogously, the focusing condition on D_a happens when $\beta = 0$ [53]. In the most general case, both α and β are non-null, and none of the detectors can retrieve a focused image of the object.

Another interesting feature of the geometrical correlation function of Eq. (8) is its support: since all apertures are compactly supported functions, their role is to delimit the overall support. More precisely, since the aperture functions appear as multiplicative factors, the nonzero part of the correlation function in the (x_a, x_b) space is determined by the intersection of their supports. These, in turn, are defined both by the aperture size (larger apertures imply a larger support), and by the coefficients $p_{j,A}$ and $p_{j,B}$, which are defined by the optical design. Interestingly, also the source aperture appears as a multiplying factor; its influence can thus be neglected only in the limit of infinitely extended emitters ($S \sim 1$). In all realistic situations, the geometrical properties of the correlation function are defined by both the size of the source, as encoded in the support of $S(x_s)$, and the illumination strategy, which determines the coefficients s_a and s_b . Hence, even in scenarios where the impact of finite lenses is negligible, the correlation function still retains a finite support dictated by the source size.

III. EFFECT OF THE SOURCE IN CORRELATION IMAGING

We now examine how the source term appearing in the geometrical approximation of the correlation function [Eq. (8)] governs the imaging behavior of correlation-based techniques. In particular, we highlight its role in GI, where the object arm is measured through bucket detection, and in CPI, which exploits the full four-dimensional correlation between two transverse intensity distributions.

A. Effect of the source in ghost imaging

As anticipated, GI is a class of CI techniques where only one sensor (i.e., the bucket detector) collects light from the object (case $m = 0$ in Fig. 1). The ghost image is retrieved by correlating the intensity measured by the bucket detector, in the sample arm (A), with the spatially resolved intensity retrieved in arm B; for the ghost image to be sharply focused, detector D_a must be optically conjugated to the object plane. The analytical expression of the ghost image is given by Eq. (7), which we will simplify by considering ideal detectors, namely, a bucket detector having infinite size, and a reference

detector with pointlike pixels [55], thus getting:

$$\Sigma_{\text{GI}}(x_a) = \lim_{\substack{d_a \rightarrow 0 \\ d_b \rightarrow \infty}} \Gamma_{\text{meas}}^{(2)}(x_a, x_b) \sim \int \Gamma^{(2)}(x_a, x_b) dx_b, \quad (9)$$

where $\Gamma^{(2)}$ is given by Eqs. (1) and (2).

In chaotic light GI, the image resolution is well known to be defined both by the Airy disk associated with the system limiting aperture, as in conventional imaging, and by the size of the coherence area—or speckle—of the illuminating field in the sample plane [30,56–59]. However, for optimal SNR, it is generally preferred to work in the speckle-limited domain, where the speckle size is significantly larger than the Airy disk; in fact, the signal-to-noise ratio (SNR) of GI is well known to scale inversely with the total number of speckles transmitted through the object [60–62]. The role of the speckle size becomes even more prominent in lensless ghost imaging, a peculiar architecture enabled by thermal and pseudothermal light sources [26,28], where sharp imaging is achieved without any focusing element and, consequently, without the formation of an Airy disk.

As we will now prove, the above description is not complete, as the GI resolution cannot be entirely understood in terms of diffraction (Airy disk) and lateral coherence (speckle size). In particular, we will show that such physical and statistical optics effects, respectively, represent a good description only when GI is close to perfect focus, namely, when the object is located exactly in the plane optically conjugated to the reference detector. However, in more realistic situations where the object placement deviates from this ideal positioning, the GI behavior is found to be effectively explained through geometric optics arguments, without the need for statistical optics or diffraction theory. Equation (8) is thus found to be a powerful tool for characterizing the optical performance of out-of-focus GI, such as resolution, point-spread function (PSF), and depth of field (DOF). Notably, in lensless GI, where the imaging behavior is not governed by a physical lens, careful attention must be devoted to the design and optimization of the illumination stage. Let us consider a lensless GI setup, as shown in Fig. 2(a). Light from the source is separated in two paths by means of a beam splitter and propagates over a distance z in free space before being transmitted through the sample and collected by the bucket detector, in arm A. In arm B, it is collected by the reference detector after propagating over a distance $z + \delta$ from the source, with the parameter δ accounting for defocusing: when $\delta \neq 0$, the ghost image retrieved by correlating the signals from D_a and D_b is blurred [63]. To study the effect of the source size on the GI resolution and DOF, we will now evaluate the analytical form of Eq. (9) in the considered setup.

For the described GI scheme, Eq. (5) reads

$$\Phi(x_o, x'_o) = \int \exp \left[\frac{i\pi}{\lambda z} [(x_s - x_o)^2 - (x_s - x'_o)^2] \right] S(x_s) dx_s, \quad (10)$$

with λ the illumination wavelength. For convenience, we will model the source with a Gaussian intensity profile, namely,

$$S(x_s) = \exp \left[-\frac{x_s^2}{2\sigma_s^2} \right]; \quad (11)$$

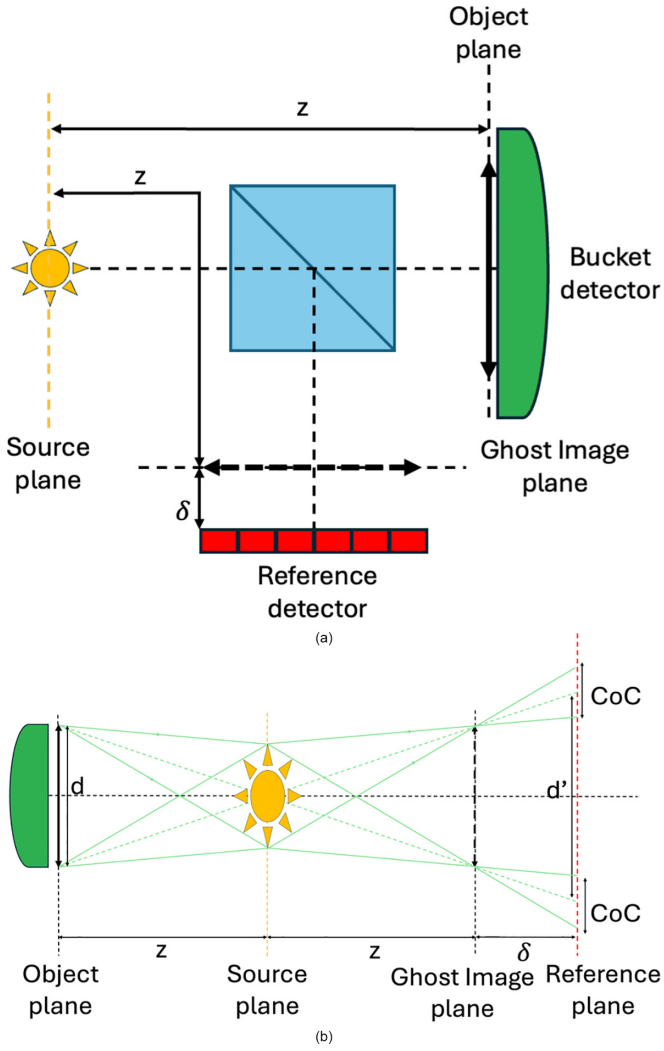


FIG. 2. (a) Lensless ghost imaging scheme with illumination via an extended source and free space propagation. The object is placed only in the arm B, at a distance z from the source. The object is replicated in arm A through correlations, giving rise to a ghost image (dashed arrow in arm A), at the same distance z from the source. The reference detector is placed at a distance δ from the ghost image plane, thus yielding an out-of-focus ghost image. (b) Unfolded Klyshko picture of the setup of panel (a).

the parameter σ_s will from now be regarded as the source transverse size. By plugging Eq. (10) into Eq. (2), and then into Eq. (9), one obtains a well-known result: GI can be described through a PSF, as for any incoherent imaging modality [64,65]. In fact, the resulting analytical expression for the ghost image is the convolution between the object intensity profile and the system PSF

$$\Sigma_{\text{GI}}(x) = \int |A(x_o)|^2 \exp \left[-\frac{(x_o - x/M(\delta))^2}{\sigma_{\text{speckle}}^2 + \sigma_{\text{CoC}}^2} \right] dx_o, \quad (12)$$

where $M(\delta) = 1 + \delta/z$ is a defocusing-dependent geometric magnification,

$$\sigma_{\text{speckle}} = \frac{\lambda z}{2\pi \sigma_s} \quad (13)$$

is the speckle size on the object plane, and

$$\sigma_{\text{CoC}} = |\delta| \frac{\sigma_s}{z + \delta} \quad (14)$$

is the circle of confusion (CoC) [64], namely, a loss of resolution proportional to both the defocusing δ and the source numerical aperture: $\text{NA}_s = \sigma_s/(z + \delta)$.

To summarize, apart from a geometrical magnification term—which does not affect the resolution of the system—the PSF of GI system is defined not only by the well-known speckle-induced contribution, but also by a CoC, which is indeed typical of defocused incoherent imaging systems [64]. Interestingly, while the speckle-related resolution loss is a wave-optics effect dominating at focus, both the magnification and the CoC only enter into play in defocused conditions and can be entirely understood in terms of ray optics. This can be seen in the unfolded Klyshko picture reported in Fig. 2(b) [26]: the green lines represent the correlated photon paths, and play the role of effective light rays emitted—from the object, reflected by the conjugate mirror represented by the thermal source, and propagating toward the reference detector. The dimension of the image on the reference plane is $d' = \frac{z+\delta}{z}d$, as predicted. The same conclusion can be reached by evaluating Eq. (9) in the stationary phase approximation, namely,

$$\Sigma_{\text{GI}}^{\text{geom}}(x) = \int |A(x_o)|^2 \exp \left[-\frac{(x_o - \frac{x}{M(\delta)})^2}{2\sigma_{\text{CoC}}^2} \right] dx_o; \quad (15)$$

which is identical to Eq. (12), with the only difference that the σ_{speckle} term is now absent.

Typically, the circle of confusion can dominate over speckle-limited resolution (i.e., $\sigma_{\text{CoC}} \gg \sigma_{\text{speckle}}$) both for large defocusing distances δ and in high-resolution applications, where a very large source is employed to reduce the speckle size. In this last case, the source NA increases proportionally to the source size, giving rise to a larger CoC, and hence, to a smaller DOF, making the system sensitive to even modest defocusing. In such configurations, both resolution and DOF end up being entirely defined by often neglected geometrical effects. This is in line with the focusing capability that the source acquires, in lensless GI, through correlation measurements, as clearly appears by the unfolded setup of Fig. 2(b).

To validate the above theoretical predictions, we will present the results of a numerical simulation. We will consider the thermal field propagating in free space from the source to both detectors; in particular, we will keep the object and the bucket detector fixed at a distance z from the source, while we vary the distance of the reference detector, thus leaving the defocusing distance δ as a varying parameter (see Appendix A and Ref. [66] for further details on the simulation). In Fig. 3, we report the intensity distribution retrieved by the reference detector for three simulated speckle patterns. As can be observed, the speckle size on the reference detector plane increases with the propagation distance δ , in line with the analytical expression of σ_{speckle} [Eq. (13)]. The speckles on the plane of the bucket detector will always have the same size as the ones shown in Fig. 3(a). Hence, for speckle-limited

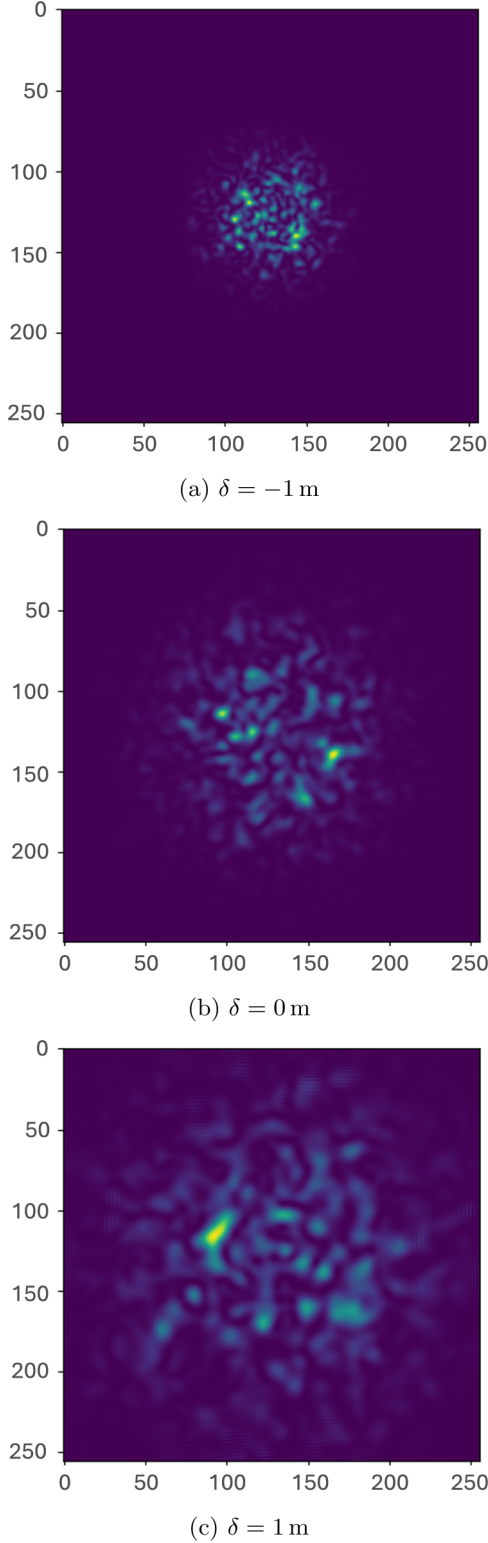


FIG. 3. Images of simulated speckle patterns on the reference detector, after propagation in free space over a distance $z + \delta$ from the source.

resolution, this would employ a PSF increasing linearly against δ , on the reference detector, and constant, on the bucket.

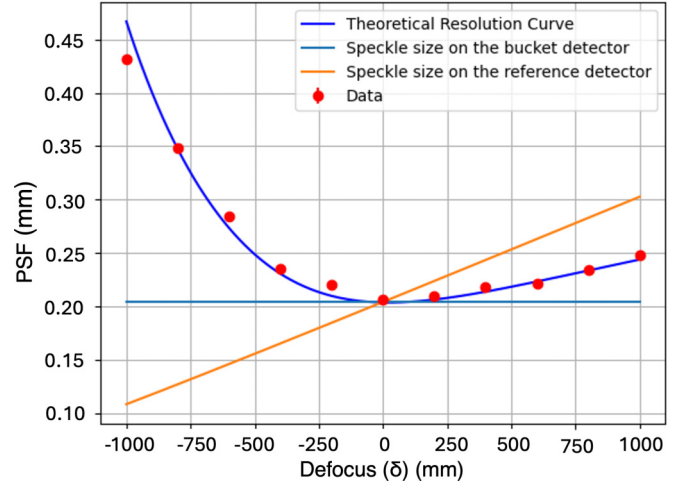


FIG. 4. Plot of the simulated PSF width for defocused ghost imaging for varying defocusing parameter δ . The plot is obtained by considering eleven defocusing distance δ , in a range covering 2 m of distances. The source-to-object distance z is set to 2 m, in such a way that the source-to-reference distance $z + \delta$ varies from 1 m to 3 m. The number of simulated frames is $N = 3000$ and the wavelength and pixel size are $\lambda = 532$ nm and $60 \mu\text{m}$, respectively.

In Fig. 4, we report the result of the simulated PSF (red points), which we compare with the speckle sizes at both the object (cyan line) and the reference plane (orange line). The trend of the simulated PSF width clearly matches the theoretical resolution curve (blue line). The plot clearly confirms the theoretical predictions by showing that the system PSF is limited by the speckle size only for $\delta = 0$, namely, in focusing conditions, where the CoC term is 0 [see Eq. (14)]. Limiting to speckle-limited resolution conditions, the PSF would either be constant or vary linearly with the defocusing parameter δ . However, both the theoretical and simulated PSF width deviate from these trends for any $\delta \neq 0$, thus ensuring that geometrical contributions, represented by the CoC term, are not negligible when performing out-of-focus ghost imaging. This behavior is also found in incoherent intensity-based imaging whenever the illumination aperture is the limiting element, and the DOF is thus defined by the illumination NA [64]. However, the underlying physical mechanism is fundamentally different. In fact, in GI, defocusing-induced blurring is an asymptotic geometrical effect that can easily be understood, in Klyshko picture, as a consequence of the diffractive role played by the source on electric field back propagating from the bucket detector [see Eqs. (3) and (4)]. Intrinsically, this behavior cannot exist in intensity-based imaging. The striking similarity between the performance of a defocused GI system and that of a defocused conventional imaging system, both affected by CoC-induced blurring, should instead be attributed to the fact that both techniques are spatially incoherent imaging modalities. Recent results [53] show that, in incoherent imaging, the loss of resolution can be explained through diffraction only in the in-focus condition (the Airy disk in conventional imaging and, as we have shown, the coherence area in GI). Conversely, the loss of resolution out of focus is understood purely in geometrical terms, i.e., through the CoC,

whether induced by the source or by the imaging optics. The fact that this phenomenon is specific to incoherent imaging, and not related to correlation imaging itself, will be confirmed in the next section. We will show that CPI, which must be regarded as a spatially coherent imaging technique [44], does not suffer from source-size-induced loss of resolution under defocusing.

B. Effect of the source in correlation plenoptic imaging

In GI, the spatial integration over the surface of the bucket detector D_b entails the loss of significant information, as well as incoherent imaging behavior [Eq. (9)]. However, when both detectors are spatially resolving, correlation measurements retrieve the full 4D function of Eq. (2), which is richer in information and describes spatially coherent imaging [44,64]. This is exactly what is done in CPI [41], whether it is based on GI-like architectures ($m = 0$) [41,42,50] or on schemes where light from the object reaches both detectors ($m = 1$) [43,46,49]. Due to its coherent nature, CPI's imaging capabilities cannot be described through a PSF [65,67], as for GI, and no defocusing-induced blurring occurs [65]; in addition, a much weaker compromise between DOF and resolution holds [43,49]. Even more, the availability of the whole 4D correlation function leads to a key capability of CPI: changing the focused plane *a posteriori* through a so-called refocusing algorithm [68]. In this paper, we will focus on the case of a planar sample with unknown axial location; multiple axial slices will be calculated, and the final image and corresponding axial location shall be identified by the sharpest reconstruction [69].

The working principle of the refocusing algorithm is easily understood in the geometrical optics approximation [Eq. (8)], where the transmittance of the object $A(x_o)$ is mapped onto the function $|A(\alpha x_a + \beta x_b)|^{2(1+m)}$; in other words, the detail of the object located at the coordinate x_o is mapped, in the space of the measurement coordinates (x_a, x_b) , onto a line of equation:

$$\gamma(x_o, z) : \alpha(z)x_a + \beta(z)x_b = x_o, \quad (16)$$

where the coefficients α and β depend on the axial coordinate of the object z . The refocusing algorithm for retrieving the refocused image of an object located at an axial position z , consists in summing all contributions to the correlation function arising from the same axial coordinate, as effectively done by the path integral

$$\Sigma_z(x_o) = \int_{\gamma(x_o, z)} \Gamma^{(2)}(x_a, x_b) d\ell \quad (17)$$

extended to all x_o coordinates within the FOV.

Upon refocusing, a relevant metric is the achievable axial resolution. To evaluate it, we will consider an object placed at an axial position z , not known *a priori*, and calculate the image fidelity of all reconstructions at axial coordinates z' , namely [69],

$$F_A[\Sigma_{z'}](z', z, \sigma_o) = \int \sqrt{\Sigma_{z'}(x_o, z, \sigma_o)} |A(x_o)|^{m+1} dx_o, \quad (18)$$

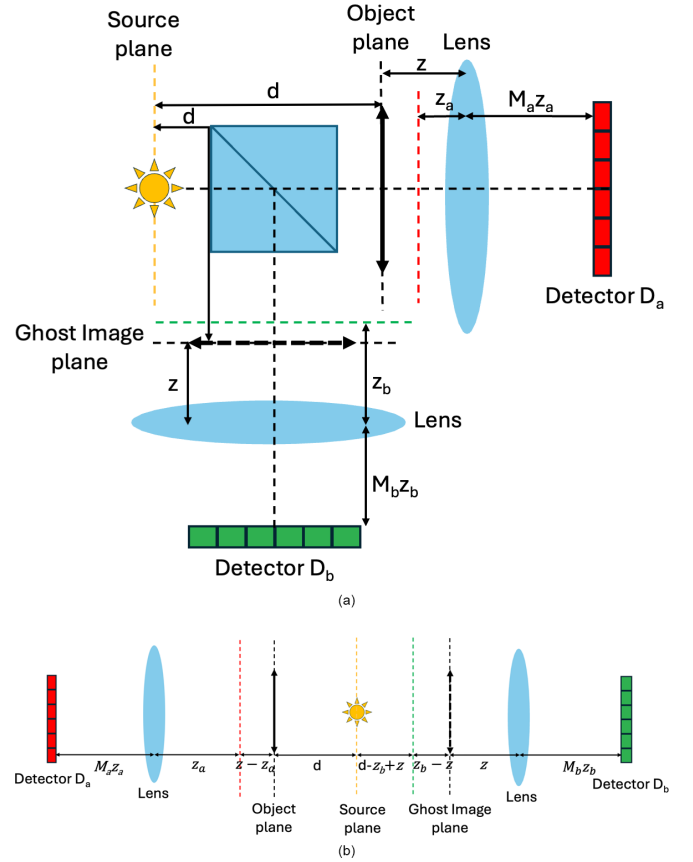


FIG. 5. (a) CPI-AP scheme with illumination via an extended source and free space propagation. The object is placed only in the arm A, at a distance d from the source. The object is replicated in arm B through correlations, giving rise to a ghost image (dashed arrow in arm B), at the same distance d from the source. The red and green dashed lines identify the two transverse planes that are optically conjugated to the detectors D_a and D_b , respectively, by means of the two identical lenses. Both the object and the ghost image planes are at a distance z from both imaging lenses, and are thus out of focus ($z \neq z_{a,b}$). (b) Unfolded Klyshko picture of the setup of panel (a).

where σ_o is the width of the object, which is assumed to be Gaussian. The fidelity clearly enables direct comparison between the refocused image and the intensity transmittance of the object, without invoking PSF blurring or any other physical degradation mechanisms [64]. By setting fidelity thresholds for defining acceptable image quality, fidelity curves can be drawn in the parameter space to get an effective tool for assessing CPI performance in terms of resolution and DOF. As demonstrated in Ref. [69], the image fidelity analysis leads to demonstrate that the CPI axial resolution is governed by the extent of the support of the correlation function, which is, by the system NA; this can be understood by considering that larger NA of the optical components produces longer object lines in Eq. (17), thus improving the axial sectioning capability. Here, we will examine how the source aperture affects the CPI axial resolution. To do so, we will focus on the CPI setup shown in Fig. 5(a): an extended source illuminates an absorptive sample through free-space propagation, while optics and detectors are placed such that two different arbitrary planes in the surrounding of either the sample or its ghost

image are imaged onto two detectors, a scheme known as CPI between arbitrary planes (CPI-AP) [49]. The corresponding unfolded Klyshko picture is reported in Fig. 5(a).

The analytical expression of the correlation function for this scheme is obtained from Eq. (2), by considering $m = 0$ and plugging in the following expressions:

$$g_j(x_o, x_j) = \int \exp \left\{ i \frac{\pi}{\lambda} \left[\frac{(x_o - x_l)^2}{z} - \frac{x_l^2}{M_j/(1+M_j)z_j} + \frac{(x_l - x_j/M_j)^2}{M_j z_j} \right] \right\} \cdot P_j(x_l) dx_l, \quad (19)$$

$$\Phi(x_o, x'_o) = \int \exp \left[i \frac{\pi}{\lambda d} [(x_s - x_o)^2 - (x_s - x'_o)^2] \right] S(x_s) dx_s, \quad (20)$$

with M_j the optical magnifications on detector D_j , P_j the iris function of the lens j , with $j = a, b$ identifying quantities and/or optics in arm A, B , respectively. In Eq. (20), S describes the Gaussian shape of the source intensity profile [Eq. (11)], as already done in GI. By performing a stationary phase approximation, in the hypothesis of identical lenses in both arms ($P_a = P_b = P$), one gets:

$$\Gamma_{\text{geom}}^{\text{CPI}}(x_a, x_b) = \left| A \left(-\alpha_{\text{CPI}}(z) \frac{x_a}{M_a} - \beta_{\text{CPI}}(z) \frac{x_b}{M_b} \right) \right|^2 S^2 \left(-s_a \frac{x_a}{M_a} - s_b \frac{x_b}{M_b} \right) \left| P \left(p_a \frac{x_a}{M_a} - p_b \frac{x_b}{M_b} \right) \right|^4, \quad (21)$$

where

$$\begin{aligned} \alpha_{\text{CPI}}(z) &= \frac{z - z_b}{z_a - z_b}, & \beta_{\text{CPI}}(z) &= 1 - \alpha_{\text{CPI}}(z), \\ s_a &= \frac{d}{z_a - z_b} + \alpha_{\text{CPI}}(z), & s_b &= \frac{d}{z_a - z_b} - \beta_{\text{CPI}}(z), \\ p_a &= \frac{z_b}{z_a - z_b}, & p_b &= 1 + p_a. \end{aligned}$$

The expressions of these coefficients indicate that, when the object is focused on D_A ($z = z_a$): $\alpha_{\text{CPI}}(z_a) = 1$ and $\beta_{\text{CPI}}(z_a) = 0$, as expected; conversely, when $z = z_b$: $\alpha_{\text{CPI}}(z_b) = 0$ and $\beta_{\text{CPI}}(z_b) = 1$, indicating that a focused ghost image is formed on D_B , upon correlation measurements.

Equation (21), similar to Eq. (8), clearly indicates that the source indeed plays the role of a limiting aperture, similar to the two lens irises P . Let us now study how the source parameters and illumination architecture affect the axial resolution of the refocused images. We will assume that the source represents the dominating aperture function, namely, in Eq. (21), the contribution of $|P|^4$ in determining the support of the correlation function is negligible with respect to S^2 . In these conditions, the refocused image at the axial coordinate z' is given by [68]:

$$\Sigma_{z'}(x_o) = \int_{-\infty}^{+\infty} \Gamma^{(2)} \left(R^{-1}(z') \begin{bmatrix} x_o \\ x' \end{bmatrix} \right) dx', \quad (22)$$

where $R^{-1}(z')$ is the inverse of the refocusing matrix

$$R(z') = \begin{bmatrix} \frac{\alpha_{\text{CPI}}(z')}{M_a} & \frac{\beta_{\text{CPI}}(z')}{M_b} \\ \frac{s_a}{M_a} & \frac{s_b}{M_b} \end{bmatrix}.$$

In general, due to coherence, the analytical expression of Eq. (22) cannot be described by a PSF, namely, by a function $f(x)$ such that

$$\Sigma_{z'}(x_o) = \int |A(x')|^2 f \left(x' - \frac{x_o}{M'} \right) dx'.$$

However, as already mentioned, the tomographic performances of CPI are not governed by coherence, but rather by the CoC defined by the limiting aperture of the imaging

system [69]. In fact, by plugging into Eq. (22) the geometrical correlation function of Eq. (21) and assuming lenses with infinite NA ($P = 1$), the refocused image comes out to be described by an effective PSF, whose shape is defined by the source profile, namely:

$$\Sigma_{z'}(x_o) = \int |A(x')|^2 \exp \left\{ \frac{(x' - x/M'(z'))^2}{\left[1 + \frac{d}{z-z'} \right]^{-2} \sigma_s^2} \right\} dx', \quad (23)$$

where $M'(z') = 1 + (z - z')/d$ is a geometrical magnification and z is the unknown position of the object. Based on Eq. (23), the optimal reconstruction of the object is achieved for $z' = z$.

The above result is analogous to Eq. (15) for GI, with the key difference that the blurring in CPI arises exclusively in postprocessing, upon refocusing. Despite small discrepancies from the typical expression of a CoC, the denominator of the PSF in Eq. (23) describes an analogous phenomenon, which we identify here, in the realm of CI. In fact, when the misfocusing $|z' - z|$ is small compared to the illumination distance d , one has

$$\left(1 + \frac{d}{z - z'} \right)^{-2} \sigma_s^2 \simeq (z' - z)^2 \left(\frac{\sigma_s}{d} \right)^2,$$

which is the exact expression of a CoC, where the role of the numerical aperture is played by the ratio between the source size and the illumination distance, as already seen in GI.

The impact of the source NA on the axial resolution is reported in Fig. 6, where we plot the fidelity curves associated with a refocused-image fidelity of 95%. The brown region corresponds to sharp CPI reconstructions of the object profile, as obtained by refocusing with $z = z'$ [i.e., $F_A[\Sigma_{z'}](z' = z, z, \sigma_o)$ in Eq. (18)]. The light green, red, and purple regions describe the axial sectioning capability of CPI, and correspond to a z' scan around the position of the object z . Specifically, the green and purple regions correspond to objects placed at the two conjugate planes of the detectors ($z = z_a$ and $z = z_b$, respectively), while the red region refers to the object located in the middle, $z = \frac{z_a + z_b}{2}$. For a given object detail size σ_o , the difference between the maximum and minimum z values within the brown region represents the DOF achievable by

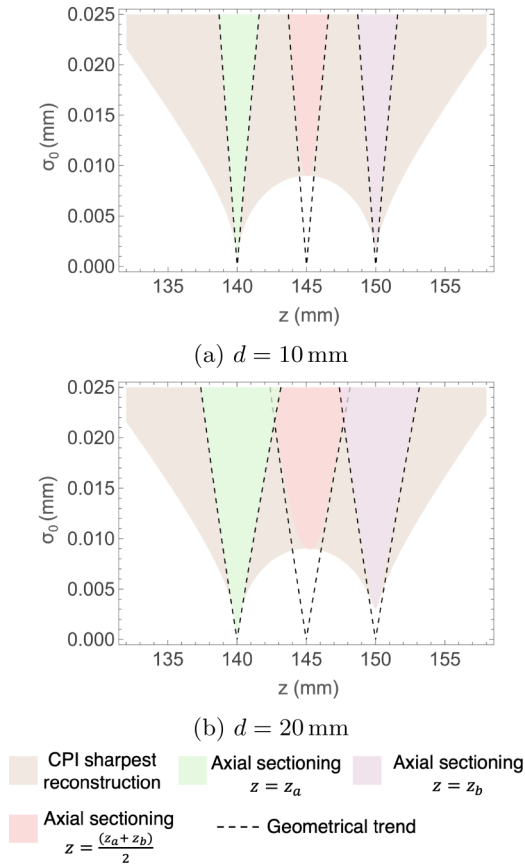


FIG. 6. Fidelity curves corresponding to a threshold of 95% for two different values of the illumination distance d in the CPI setup of Fig. 5(a).

CPI, while within the colored cones corresponds to the axial resolution at the given transverse resolution σ_o . Also in this case, the source is the only limiting aperture, as the lens pupils are considered to be infinite.

In Figs. 6(a) and 6(b) we report the fidelity curves for decreased source NA, as obtained by increasing the source-to-object distance d while keeping fixed the source size σ_s ; comparison of the two plots clearly shows that axial resolution is entirely defined by the illumination NA. The black dashed lines in both plots illustrate the ray-optics limit ($\lim_{\lambda \rightarrow 0} F_A$), confirming that axial sectioning is governed by geometrical effects. As a final remark, while the green and brown regions approach zero at $z = z_a$, the resolution at $z = z_b$ is lower due to coherence effects. In the proposed CPI scheme, where the object lies in arm A, when $z = z_b$, the refocused image corresponds to a ghost image, whose in-focus resolution is limited by the speckle size [Eq. (12)], as already pointed out. This effect is more pronounced in Fig. 6(b), where the speckle size on the object plane, $\sigma_{\text{speckle}} = \frac{\lambda d}{2\pi\sigma_s}$ [analogous to Eq. (13)], is significantly larger.

Interestingly, the results of Fig. 6 bear a strong resemblance to Fig. 4 of Ref. [69]. However, the latter were obtained in a scenario where the lens is the limiting aperture, while, in this paper, similar effects have been found by considering a finite-size source.

In conclusion, in scenarios where the lens aperture is neglected and the finite source dominates, the fidelity analysis indicates that the source NA plays an equivalent role in setting the axial performance. Since the source intensity enters the geometrical correlation function as a multiplicative factor [Eq. (21)], its size critically affects both refocused-image quality and axial sectioning. Poor source design can therefore severely compromise CPI performance. The presented fidelity analysis provides a quantitative assessment of source-induced constraints on correlation imaging, offering a more comprehensive framework for optimizing experimental setups.

IV. DISCUSSION AND CONCLUSIONS

The presented analysis shows the crucial role played by the geometry of the illumination stage in correlation imaging, and in particular on the depth of both GI and CPI refocused images. In particular, we have found that, in GI, the resolution is governed by the coherence area on the object plane (i.e., the speckle size), only in conditions of perfect focusing; in fact, outside the focused plane, resolution has been shown to be governed by the geometrical circle of confusion, as defined by the NA of the overall imaging system. In CPI, the illumination geometry has been shown not to limit the overall DOF, but rather to determine the axial resolution of refocused images.

From a formal point of view, both results have been obtained by considering the source as a limiting aperture in the correlation function and considering the geometrical approximation of the correlation function. Due to the general formal context considered throughout the paper, the presented results are easily generalized to any CI architecture. As an example, extension of our studies to the case of far-field illumination is reported in the Appendix. Most importantly, both the considered arguments and formal context can be applied to quantum illumination schemes, such as entangled photon sources [2,9,14,42]. In fact, by removing the complex conjugate from the propagators in Eqs. (2) and (3), the formalism readily applies to the quantum case, and analogous conclusions can be drawn [42,50].

As a final remark, we note that the formalism introduced at the beginning of this work [leading to Eq. (2)] is considerably more general than the specific scenarios analyzed here. In particular, it can also capture coherence-induced, source-related effects in correlation-based imaging systems operated away from focus. In this paper, we restricted our attention to geometrical-approximation effects, obtained via a stationary-phase analysis of the model.

To the best of our knowledge, the influence of a partially coherent source is well understood only at the in-focus plane (e.g., speckle-limited resolution in GI), whereas a broader, unified description remains largely unexplored. Future work will aim to characterize the role of transverse partial coherence more comprehensively, with the goal of extending the present framework to more general and realistic illumination conditions.

ACKNOWLEDGMENTS

The authors acknowledge funding from Università degli Studi di Bari under project ADEQUADE. Project

ADEQUADE has received funding from the European Defence Fund (EDF) under Grant Agreement No. EDF-2021-DIS-RDIS-ADEQUADE (n. 101103417).

Funded by the European Union. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: VALIDATION THROUGH NUMERICAL SIMULATIONS

The numerical results shown in Fig. 4 of the main text are obtained through a computer simulation of the setup sketched in Fig. 2. The strategy to adopt requires using a pointlike object to measure the psf evaluated for different planes out of focus, i.e., for different values of the parameter δ . Bearing in mind that the setup has been constructed in such a way that the reference detector is placed out of focus, this implies that the object has to stay in the same axial position, while the reference detector has to be scanned. It should be noted that in a laboratory experiment the pointlike object would be a pinhole or a point object with transverse dimensions that would ideally match the pixel size of the camera. This concept can be naturally extended to the case of the simulation, in which, if we imagine the camera to be composed of $M \times M$ pixels, the object would be represented by a single pixel. The following lines have to be intended as a detailed description of the steps required to perform the simulation. The procedure here summarized follows the methodology established in Ref. [66].

(i) *Generation of a thermal source.* The first step requires simulating a speckle pattern. The computational strategy involves the generation of a complex random phase matrix, where each element is defined as $e^{i2\pi\phi}$, with ϕ uniformly distributed in the interval $[0,1)$. This field is then convolved with a PSF, typically modeled as a two-dimensional Gaussian whose variance determines the transverse coherence properties of the source. The resulting complex field represents the amplitude distribution of the simulated thermal source. The corresponding speckle pattern is obtained by computing the intensity distribution, i.e., the squared modulus of the field. Moreover, the shape of the initial field must reflect the desired coherence properties at the detection plane. According to the Van Cittert-Zernike theorem [70], the spatial coherence in the far field is related to the Fourier transform of the source's spatial profile. Therefore, to simulate a source with a Gaussian coherence area at the detector, the initial random phase matrix must also exhibit a Gaussian envelope. This modeling approach is not only theoretically consistent but also aligns with typical experimental implementations, where pseudothermal sources are generated by illuminating a rotating ground glass disk with a TEM00

laser mode, inherently Gaussian in shape. In summary, the simulated thermal source is constructed as the product of a random speckle field and a two-dimensional Gaussian envelope representing the source profile.

(ii) *Vacuum propagation of the fields.* This step consists of two independent field propagations in free space: one from the source to the reference detector (A) at distance $z + \delta$ and the other to the bucket detector (B) at distance z . In the context of the simulation, the object is modeled as a single central pixel of the initial 2D matrix. Consequently, the bucket signal is intrinsically defined as the intensity at this central pixel. The field propagation is most efficiently implemented in the Fourier domain, where free-space propagation can be expressed as a pointwise multiplication of the field's Fourier transform by the corresponding transfer function.

(iii) *Measurement of the intensity.* This step requires measuring the intensity in both arms, A and B, over N frames, i.e., the number of independent statistical realizations. It is expected that the signal-to-noise ratio (SNR) depends on the square root of N [60–62].

(iv) *Calculation of the correlation function.* Once the intensities are measured, the ghost image is obtained by correlating them. The procedure requires calculating the ghost image, Eq. (9) of the main text. The statistical average present in Eq. (1) has to be performed over the number of frames N .

The outcome of this process is a two-dimensional matrix representing the system's PSF. This distribution is expected to approximate a two-dimensional Gaussian profile projected onto the image plane.

(v) *Gaussian fitting of the PSF.* The final step involves creating a single-parameter fit of the computed PSF to a two-dimensional Gaussian model, with the aim of extracting the standard deviation σ .

Steps (i)–(v) are repeated for each value of the defocusing parameter δ within a specified range. The final step consists in plotting the extracted results to obtain the points of Fig. 4 of the main text together with the theoretical prediction curve.

The plot of Fig. 4 has been obtained considering 11 defocusing points in a range covering 2 m of distances. The parameter z (source-to-object distance) has been set to be 2 m, in such a way that $z + \delta$ (source-to-reference distance) would vary from 1 m to 3 m. The number of frames used was $N = 3000$ and the wavelength and pixel size were set as $\lambda = 532$ nm and 60 μ m, respectively.

For definitiveness, it should be pointed out that, given the construction of the simulated thermal source, the coherence area at the source plane is nonzero [as discussed in step (i)], indicating that the source is partially coherent. Under these conditions, the approximation of negligible coherence area at the emission surface [see Eq. (4) of the main text] is no longer strictly valid, as it does not account for the effects of partial spatial coherence. Therefore, although Eq. (12) of the main text has been obtained considering a spatially incoherent source, the blue curve of Fig. 4 has a modified analytical expression.

Under these hypothesis, the new expression for the variance of the PSF of the defocused ghost imaging system is as

follows:

$$\sigma^2 = \frac{z^2 [z^2(z+\delta)^2 \lambda^4 \sigma_c^4 + 8z^2(z+\delta)^2 \lambda^4 \sigma_c^2 \sigma_s^2 + 16\lambda^2(z^2(z+\delta)^2 \lambda^2 + \pi^2(2z^2 + 2z\delta + \delta^2) \sigma_c^4) \sigma_s^4]}{16\pi^2(z+\delta)^2 \sigma_s^2 (\sigma_c^2 + 2\sigma_s^2) (16\pi^2 \sigma_c^2 \sigma_s^4 + z^2 \lambda^2 (\sigma_c^2 + 4\sigma_s^2))} + \frac{z^2 [64\pi^2(2z^2 + 2z\delta + \delta^2) \lambda^2 \sigma_c^2 \sigma_s^6 + 64\pi^2(\delta^2 \lambda^2 + 4\pi^2 \sigma_c^4) \sigma_s^8]}{16\pi^2(z+\delta)^2 \sigma_s^2 (\sigma_c^2 + 2\sigma_s^2) (16\pi^2 \sigma_c^2 \sigma_s^4 + z^2 \lambda^2 (\sigma_c^2 + 4\sigma_s^2))}.$$

APPENDIX B: CPI WITH FAR-FIELD ILLUMINATION

To comprehensively characterize the effect of the source aperture on CPI, in addition to the free-space propagation case, another widely used experimental configuration can be considered. Figure 7 shows the optical setup of CPI having the object illuminated by the source through a far-field lens. This implies placing the object and the source in the focal planes of the lens. With respect to the free-space propagation case, the transfer function here incorporates the Green's functions accounting for the propagation towards the lens. The formalism describing the propagation in the two optical arms is identical. The expression for the mutual coherence function Φ becomes:

$$\Phi(x_o, x'_o) = \iint_{-\infty}^{+\infty} \exp \frac{i\pi}{\lambda f} [(x_s - x_f)^2 - x_l^2 + (x_f - x_o)^2 + x'_f - (x'_f - x_s)^2 - (x'_o - x'_f)^2] S(x_s) dx_f dx'_f dx_s$$

f being the focal length and where we indicated the coordinate of the far-field lens as x_f or x'_f whether it is seen from the arms A or B. x'_o is the coordinate of the ghost-object plane in the arm B. To further clarify the notation and the physics involved, one can refer to the unfolded Klyshko picture, depicted in Fig. 8.

Analogously to what was done in the previous section, we can look at the expression of the source intensity profile in the correlation space, obtained applying a stationary phase approximation.

$$S(x_a, x_b) = \exp \left[-\frac{\left(\frac{x_a}{M_A} - \frac{x_b}{M_B} \right)^2}{2 \left(\frac{\sigma_s(z_A - z_B)}{f} \right)^2} \right].$$

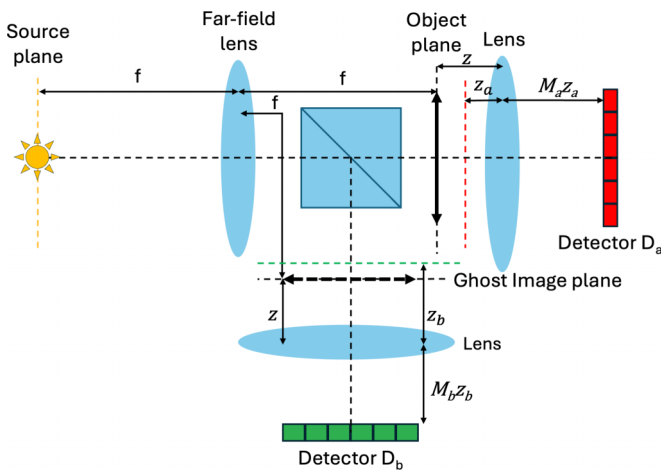


FIG. 7. Optical scheme of a CPI-AP setup with a far-field illumination.

This is still a Gaussian in the space defined by (x_a, x_b) . The key difference with respect to Eq. (21) of the main text lies in the inverse dependence of the variance on the focal length of the far-field lens, as opposed to the propagation distance d . This implies that, in order to maximize the support of the correlation function, one should minimize the focal length f , assuming all other parameters are held constant. From a practical standpoint, this suggests that lenses with shorter focal lengths are preferable for experimental implementations aiming to enhance the extent of spatial correlations.

The expression of the refocused image for the axial sectioning analysis is

$$\Sigma_{z'}(x) = \exp \left[-\frac{x^2}{\sigma_o^2 + \left(\frac{z-z'}{f} \right)^2 \sigma_s^2} \right].$$

A comparison with Eq. (23) of the main text is instructive. The second term of the variance corresponds again to a CoC; however, in this case, the effective numerical aperture depends on the focal length f of the far-field lens, rather than on the propagation distance d .

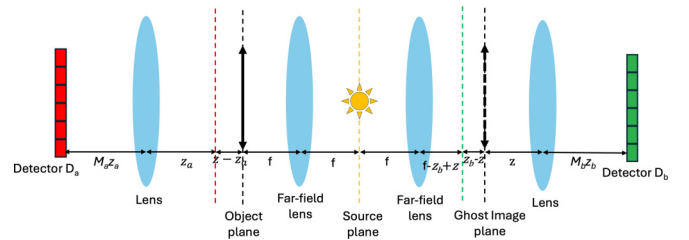


FIG. 8. Unfolded Klyshko picture of the optical setup of Fig. 7.

- [1] P. A. Moreau, E. Toninelli, T. Gregory, and M. J. Padgett, Imaging with quantum states of light, *Nat. Rev. Phys.* **1**, 367 (2019).
- [2] M. Genovese, Real applications of quantum imaging, *J. Opt.* **18**, 073002 (2016).
- [3] Y. Shih, Quantum imaging, *IEEE J. Select. Topics Quantum Electron.* **13**, 1016 (2007).
- [4] M. Gilaberte Basset, F. Setzpfandt, F. Steinlechner, E. Beekert, T. Pertsch, and M. Gräfe, Perspectives for applications of quantum imaging, *Laser Photon. Rev.* **13**, 1900097 (2019).
- [5] A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Correlated imaging, quantum and classical, *Phys. Rev. A* **70**, 013802 (2004).
- [6] B. E. A. Saleh and M. Carl Teich, Noise in classical and quantum photon-correlation imaging, in *Advances in Information Optics and Photonics*, Vol. PM183, edited by A. T. Fr berg and R. Dändliker (SPIE Press, Bellingham, WA, 2008), Chap. 21, pp. 423–436.
- [7] S. Vernekar and J. Xavier, Quantum correlation enhanced optical imaging, *Quantum Beam Sci.* **8**, 19 (2024).
- [8] G. Massaro, F. V. Pepe, and M. D'Angelo, Correlation hyperspectral imaging, *Phys. Rev. Lett.* **133**, 183802 (2024).
- [9] G. B. Lemos, V. Borish, G. D. Cole, S. Ramelow, R. Lapkiewicz, and A. Zeilinger, Quantum imaging with undetected photons, *Nature (London)* **512**, 409 (2014).
- [10] M. Lahiri, R. Lapkiewicz, G. B. Lemos, and A. Zeilinger, Theory of quantum imaging with undetected photons, *Phys. Rev. A* **92**, 013832 (2015).
- [11] J. H. Shapiro, D. Venkatraman, and F. N. Wong, Classical imaging with undetected photons, *Sci. Rep.* **5**, 10329 (2015).
- [12] M. Gilaberte Basset, R. Sondenheimer, J. Fuenzalida, A. Vega, S. Töpfer, E. A. Santos, S. Saravi, F. Setzpfandt, F. Steinlechner, and M. Gräfe, Experimental analysis of image resolution of quantum imaging with undetected light through position correlations, *Phys. Rev. A* **108**, 052610 (2023).
- [13] G. Brida, L. Caspani, A. Gatti, M. Genovese, A. Meda, and I. R. Berchera, Measurement of sub-shot-noise spatial correlations without background subtraction, *Phys. Rev. Lett.* **102**, 213602 (2009).
- [14] G. Brida, M. Genovese, and I. R. Berchera, Experimental realization of sub-shot-noise quantum imaging, *Nature Photon.* **4**, 227 (2010).
- [15] N. Samantaray, I. Ruo-Berchera, A. Meda, and M. Genovese, Realization of the first sub-shot-noise wide field microscope, *Light: Sci. Appl.* **6**, e17005 (2017).
- [16] A. Meda, E. Losero, N. Samantaray, F. Scafirimuto, S. Pradyumna, A. Avella, I. Ruo-Berchera, and M. Genovese, Photon-number correlation for quantum enhanced imaging and sensing, *J. Opt.* **19**, 094002 (2017).
- [17] I. R. Berchera and I. P. Degiovanni, Quantum imaging with sub-Poissonian light: Challenges and perspectives in optical metrology, *Metrologia* **56**, 024001 (2019).
- [18] P. Zhang, W. Gong, X. Shen, and S. Han, Correlated imaging through atmospheric turbulence, *Phys. Rev. A* **82**, 033817 (2010).
- [19] G. Scala, G. Massaro, G. Borreggine, C. Lupo, M. D'Angelo, and F. V. Pepe, Robustness of chaotic-light correlation imaging against turbulence, *Eur. Phys. J. Plus* **139**, 1010 (2024).
- [20] Wenlin Gong and W. Gong, Correlated imaging in scattering media, *Opt. Lett.* **36**, 394 (2011).
- [21] G. Lubin, D. Oron, U. Rossman, R. Tenne, and V. J. Yallapragada, Photon correlations in spectroscopy and microscopy, *ACS Photon.* **9**, 2891 (2022).
- [22] B. Ndagano, H. Defienne, D. Branford, Y. D. Shah, A. Lyons, N. Westerberg, E. M. Gauger, and D. Faccio, Quantum microscopy based on Hong–Ou–Mandel interference, *Nature Photon.* **16**, 384 (2022).
- [23] 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 (1995).
- [24] R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Two-photon” coincidence imaging with a classical source, *Phys. Rev. Lett.* **89**, 113601 (2002).
- [25] R. S. Bennink, S. J. Bentley, R. W. Boyd, and J. C. Howell, Quantum and classical coincidence imaging, *Phys. Rev. Lett.* **92**, 033601 (2004).
- [26] A. Valencia, G. Scarcelli, M. D'Angelo, and Y. Shih, Two-photon imaging with thermal light, *Phys. Rev. Lett.* **94**, 063601 (2005).
- [27] F. Ferri, D. Magatti, A. Gatti, M. Bache, E. Brambilla, and L. A. Lugiato, High-resolution ghost image and ghost diffraction experiments with thermal light, *Phys. Rev. Lett.* **94**, 183602 (2005).
- [28] G. Scarcelli, V. Berardi, and Y. Shih, Can two-photon correlation of chaotic light be considered as correlation of intensity fluctuations? *Phys. Rev. Lett.* **96**, 063602 (2006).
- [29] J. H. Shapiro and R. W. Boyd, The physics of ghost imaging, *Quantum Info. Proc.* **11**, 949 (2012).
- [30] J. H. Shapiro and B. I. Erkmén, Ghost imaging: From quantum to classical to computational, *Adv. Opt. Photon.* **2**, 405 (2010).
- [31] Y.-H. Zhai, D. Zhang, L.-A. Wu, and X.-H. Chen, Correlated two-photon imaging with true thermal light, *Opt. Lett.* **30**, 2354 (2005).
- [32] S. Han, H. Yu, X. Shen, H. Liu, W. Gong, and Z. Liu, A review of ghost imaging via sparsity constraints, *Appl. Sci.* **8**, 1379 (2018).
- [33] J. H. Shapiro, Computational ghost imaging, *Phys. Rev. A* **78**, 061802(R) (2008).
- [34] P. A. Moreau, E. Toninelli, T. Gregory, and M. J. Padgett, Ghost imaging using optical correlations, *Laser Photon. Rev.* **12**, 1700143 (2018).
- [35] F. Ferri, D. Magatti, L. A. Lugiato, and A. Gatti, Differential ghost imaging, *Phys. Rev. Lett.* **104**, 253603 (2010).
- [36] O. Katz, Y. Bromberg, and Y. Silberberg, Compressive ghost imaging, *Appl. Phys. Lett.* **95**, 131110 (2009).
- [37] P. Ryczkowski, M. Barbier, A. T. Friberg, J. M. Dudley, and G. Genty, Ghost imaging in the time domain, *Nature Photon.* **10**, 167 (2016).
- [38] M. Lyu, W. Wang, H. Wang, H. Wang, G. Li, N. Chen, and G. Situ, Deep-learning-based ghost imaging, *Sci. Rep.* **7**, 17865 (2017).
- [39] B. I. Erkmén, Computational ghost imaging for remote sensing, *J. Opt. Soc. Am. A*, **29**, 782 (2012).
- [40] N. D. Hardy and J. H. Shapiro, Computational ghost imaging versus imaging laser radar for three-dimensional imaging, *Phys. Rev. A* **87**, 023820 (2013).
- [41] M. D'Angelo, F. V. Pepe, A. Garuccio, and G. Scarcelli, Correlation plenoptic imaging, *Phys. Rev. Lett.* **116**, 223602 (2016).

- [42] F. V. Pepe, F. Di Lena, A. Garuccio, G. Scarcelli, and M. D'Angelo, Correlation plenoptic imaging with entangled photons, *Technologies* **4**, 17 (2016).
- [43] G. Massaro, D. Giannella, A. Scagliola, F. D. Lena, G. Scarcelli, A. Garuccio, F. V. Pepe, and M. D'Angelo, Light-field microscopy with correlated beams for high-resolution volumetric imaging, *Sci. Rep.* **12**, 16823 (2022).
- [44] G. Massaro, Analytical form of the refocused images from correlation plenoptic imaging, *Opt. Express* **32**, 35755 (2024).
- [45] D. Giannella, G. Massaro, B. Stoklasa, M. D'Angelo, and F. V. Pepe, Light-field imaging from position-momentum correlations, *Phys. Lett. A* **494**, 129298 (2024).
- [46] G. Massaro, P. Mos, S. Vasiukov, F. Di Lena, F. Scattarella, F. V. Pepe, A. Ulku, D. Giannella, E. Charbon, C. Bruschini, and M. D'Angelo, Correlated-photon imaging at 10 volumetric images per second, *Sci. Rep.* **13**, 12813 (2023).
- [47] F. Scattarella, D. Diacono, A. Monaco, N. Amoroso, L. Bellantuono, G. Massaro, F. V. Pepe, S. Tangaro, R. Bellotti, and M. D'Angelo, Deep learning approach for denoising low-SNR correlation plenoptic images, *Sci. Rep.* **13**, 19645 (2023).
- [48] I. Petrelli, F. Santoro, G. Massaro, F. Scattarella, F. V. Pepe, F. Mazzia, M. Ieronymaki, G. Filios, D. Mylonas, N. Pappas, C. Abbattista, and M. D'Angelo, Compressive sensing-based correlation plenoptic imaging, *Front. Phys.* **11**, 1287740 (2023).
- [49] F. D. Lena, G. Massaro, A. Lupo, A. Garuccio, F. V. Pepe, and M. D'Angelo, Correlation plenoptic imaging between arbitrary planes, *Opt. Express* **28**, 35857 (2020).
- [50] F. Di Lena, F. V. Pepe, A. Garuccio, and M. D'Angelo, Correlation plenoptic imaging: An overview, *Appl. Sci.* **8**, 1958 (2018).
- [51] C. Abbattista, L. Amoroso, S. Burri, E. Charbon, F. Di Lena, A. Garuccio, D. Giannella, Z. Hradil, M. Iacobellis, G. Massaro, P. Mos, L. Motka, M. Paúr, F. V. Pepe, M. Peterek, I. Petrelli, J. Řeháček, F. Santoro, F. Scattarella, A. Ulku, *et al.*, Towards quantum 3D imaging devices, *Appl. Sci.* **11**, 6414 (2021).
- [52] L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge University Press, Cambridge, 1995).
- [53] G. Massaro, F. Di Lena, M. D'angelo, and F. V. Pepe, Effect of finite-sized optical components and pixels on light-field imaging through correlated light, *Sensors* **22**, 2778 (2022).
- [54] N. Bleistein and R. A. Handelsman, *Asymptotic Expansions of Integrals* (Dover, New York, 1986).
- [55] The infinitely sized bucket detector approximation does not entail any loss of generality, as it simply implies neglecting photon loss. Likewise, the pointlike reference pixels approximation has the only effect of neglecting pixel-limited resolution, which is of no interest for this paper.
- [56] X.-H. Zhu, Y.-F. Bai, W. Tan, L.-Y. Zhou, X.-W. Huang, T.-J. Jiang, T. Jiang, S.-Q. Nan, and X.-Q. Fu, High-resolution microscopic ghost imaging for bioimaging, *Phys. Rev. Appl.* **20**, 014028 (2023).
- [57] W. Tan, Y. Bai, Y. Bai, X. Huang, T. Jiang, S. Nan, Q. Fu, X. Zou, X. Fu, and X. Fu, Enhancing critical resolution of a ghost imaging system by using a vortex beam, *Opt. Express*, **30**, 14061 (2022).
- [58] P. Zerom, Z. Shi, M. N. O'Sullivan, K. Wai Clifford Chan, M. Krogstad, J. H. Shapiro, and R. W. Boyd, Thermal ghost imaging with averaged speckle patterns, *Phys. Rev. A* **86**, 063817 (2012).
- [59] F. Ferri, D. Magatti, V. G. Sala, and A. Gatti, Longitudinal coherence in thermal ghost imaging, *Appl. Phys. Lett.* **92**, 261109 (2008).
- [60] B. I. Erkmen and J. H. Shapiro, Signal-to-noise ratio of Gaussian-state ghost imaging, *Phys. Rev. A* **79**, 023833 (2009).
- [61] E. Lantz, P. A. Moreau, and F. Devaux, Optimizing the signal-to-noise ratio in the measurement of photon pairs with detector arrays, *Phys. Rev. A* **90**, 063811 (2014).
- [62] M. N. O'Sullivan, K. W. C. Chan, and R. W. Boyd, Comparison of the signal-to-noise characteristics of quantum versus thermal ghost imaging, *Phys. Rev. A* **82**, 053803 (2010).
- [63] See Ref. [71] for the analysis of out-of-focus lensless ghost imaging in the case of far-field illumination.
- [64] G. Massaro, B. Barile, G. Scarcelli, F. V. Pepe, G. P. Nicchia, and M. D'Angelo, Direct 3D imaging through spatial coherence of light, *Laser Photon. Rev.* **18**, 2301155 (2024).
- [65] G. Massaro and M. D'Angelo, Characterization of defocused coherent imaging systems with periodic objects, *Sensors* **24**, 6885 (2024).
- [66] S. de Gioia, G. Massaro, and M. D'Angelo, A pseudo-thermal simulation strategy for correlation imaging, *Eur. Phys. J. Plus* **140**, 1097 (2025).
- [67] G. Massaro, S. de Gioia, A. Brunetti, F. V. Pepe, and M. D'angelo, Two-point resolution of a defocused imaging system based on spatially coherent illumination, *Photon.* **11**, 1203 (2024).
- [68] G. Massaro, F. V. Pepe, and M. D'Angelo, Refocusing algorithm for correlation plenoptic imaging, *Sensors* **22**, 6665 (2022).
- [69] G. Massaro, Assessing the 3D resolution of refocused correlation plenoptic images using a general-purpose image quality estimator, *Eur. Phys. J. Plus* **139**, 727 (2024).
- [70] L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge University Press, Cambridge, 1995).
- [71] G. Lerario, G. Massaro, and M. D'Angelo, Effect of the finite size of the source in correlation imaging, in *Proceeding SPIE, Quantum Communications and Quantum Imaging XXIII, 136180A*, Vol. 13618 (San Diego, California, United States 2025).