Quantitative microscopy requires an accurate and intuitive description of the image formation. Interpretation of the specimen properties from the fluorescent images is enabled by the linear (viz., convolution by a point-spread function) relationship between the fluorophore density and the recorded image intensity. Interpretation of the specimen’s properties from the intensities measured using some experimentally valuable microscopes (such as bright-field, dark-field, Zernike’s phase contrast, Nomarski’s differential interference contrast, and differential phase contrast) has remained difficult due to lack of an intuitive description that relates the specimen’s properties with the image intensity. Intuitive description of the above methods has been difficult due to the bilinearity (i.e., dependence of the image at a point on the pairs of points of the specimen) caused by the partially coherent illumination (i.e., use of an extended incoherent source). By describing the image formation in the joint space-spatial frequency space (using Wigner distributions), we overcome the above difficulty and provide a description equivalent to point-spread function.

Image \( I(x) \) recorded by a coherent microscope is given by \( I(x) = |t(x) \otimes h(x)|^2 \), where \( t(x) \) is the specimen transmission and \( h(x) \) is the amplitude point spread function (PSF) of the imaging system. In the Wigner space, the coherent image becomes the spatial marginal (integration along frequency) of the Wigner distribution of the field in the image space [1], i.e., \( I(x) = \int W_f(m,x)dm \). The Wigner distribution of the image field \( W_f(x) \) is given by convolution along \( x \), but multiplication along \( m \) of the Wigner distributions of the specimen \( W_s(x) \) and the PSF \( W_h(x) \), i.e., \( W_f(m,x) = W_s(m,x) \otimes W_h(m,x) \). We show that in case of the partially coherent imaging, where the imaging PSF and the extended illumination both affect the image, the above relationship can be extended as, \( \Psi(m,x) = W_f(m,x) \otimes K(m,x) \), where the kernel \( K \) is related in a simple manner to \( W_h \) and the source distribution. Analogous to the coherent case, the partially coherent image \( I(x) \) is the spatial marginal of the distribution \( \Psi \). The above kernel leads to an intuitive understanding of behavior of the above-mentioned imaging systems and an efficient algorithm for computation of partially coherent images. The above kernel can be derived from our phase-space model of partially coherent imaging systems [2] and we, therefore, call it the phase-space imager kernel. Fig. 1 illustrates the model using an example of a double-slit and a bright-field microscope with matched illumination.

![Fig. 1](image-url) (a) Wigner distribution of a double-slit (with slit separation of \( 0.6 \lambda / NA \)), when convolved along space with (b) the PSI-kernel of a bright-field microscope (with matched illumination) gives rise to (c) the distribution \( \Psi \). Integration of \( \Psi \) along frequency provides (d) the partially coherent image. The vertical lines in (d) are the double-slit. \( x \) and \( m \) are normalized space and spatial-frequency coordinates.

References