

“GHOST IMAGING”: FUNDAMENTAL AND APPLICATIVE ASPECTS

Nota del s.c. LUIGI A. LUGIATO (*)

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SUNTO. – Il cosiddetto *ghost imaging* rappresenta una tecnica innovativa per acquisire immagini, appropriata specialmente per ottenere immagini di oggetti in posizioni difficili da raggiungere o immersi in mezzi torbidi. Venne proposta come una nuova tecnologia quantistica che sfrutta la proprietà quantistica cruciale che viene denominata *entanglement*. Successivamente, è stato dimostrato sia teoricamente sia sperimentalmente che la stessa tecnica può essere realizzata anche usando fasci luminosi correlati classicamente. Per lungo tempo il tema del *ghost imaging* è stato oggetto di un dibattito accademico concernente la questione se l'*entanglement* quantistico sia necessario o no per realizzarlo. In questa presentazione ci focalizziamo sulla questione concreta se ci siano o no casi in cui il *ghost imaging* fornisce prestazioni superiori a quelle dell'*imaging standard*, e descriviamo lo stato dell'arte in questo ambito.

ABSTRACT. – The so - called ghost imaging represents a novel imaging technique which is especially appropriate to obtain images of objects located in positions difficult to reach or immersed in turbid media. It was first proposed as a novel quantum technology which exploits the key quantum property which is called entanglement. Subsequently, it has been shown theoretically and experimentally that the same technique can be realized also using classically correlated light beams. For a long time the topic of ghost imaging has been the object of an academic debate concerning the question whether quantum entanglement is necessary or not to realize it. In this talk we focus on the concrete question whether there are or not cases in

(*) Università degli Studi dell'Insubria-Como, Italy.
E-mail: luigi.lugiato@uninsubria.it

which ghost imaging can offer better performances than standard imaging, and describe the status of the art in this matter.

1. WHAT IS GHOST IMAGING

This short article describes some of the results obtained in collaboration with Alessandra Gatti and with the experimental activities carried in the laboratory led by Fabio Ferri at Dipartimento di Scienza e Alta Tecnologia of Università dell'Insubria in Como[1].

The first issue which is necessary to address is, of course, to explain what is ghost imaging.

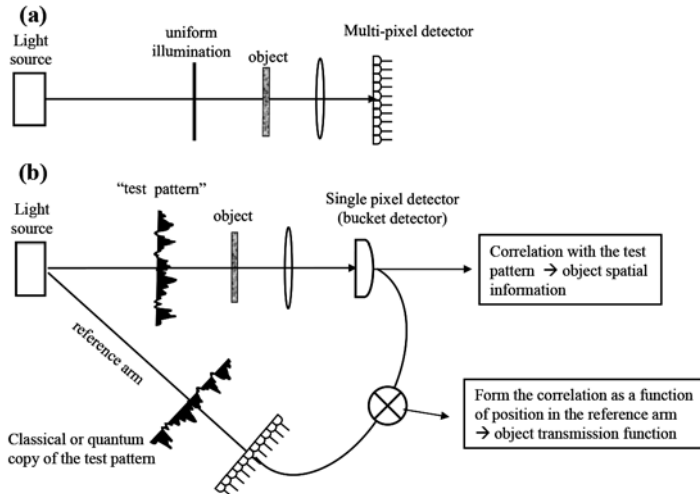


Fig. 1 – a) Scheme for standard imaging; b) scheme for ghost imaging.

In standard imaging (Fig. 1a) one utilizes a light source to illuminate an object which is observed in transmission. In order to obtain an image of the object, one utilizes a multi-pixel detector, e.g. a digital camera, to resolve the details of the object. In the case of ghost imaging (Fig. 1b), instead, one follows a scheme with a two-arm configuration, the object is located in the test arm and the other is called reference arm. The object is illuminated by a light pulse (flash) that we call test pattern. In this case on the other side of the object one does not locate a multi-pixel

detector, but a single-pixel detector, which is called bucket detector because it collects all the light transmitted by the object, and therefore measures the total intensity of the transmitted light and does not provide an image of the object. On the other hand, in the reference arm one sends a light pulse which is a quantum or a classical copy of the test pattern, and one locates a multi-pixel detector which, however, does not provide an image of the object either, because the reference beam does not cross the object. One can demonstrate, however, that an image of the object can be retrieved by correlating the signal measured by the bucket detector with the signals measured by the pixels of the multi-pixel detector, and performing a statistics over a large number of test patterns. Such a procedure was called ghost imaging because the multi-pixel detector reveals light which never interacted with the object.

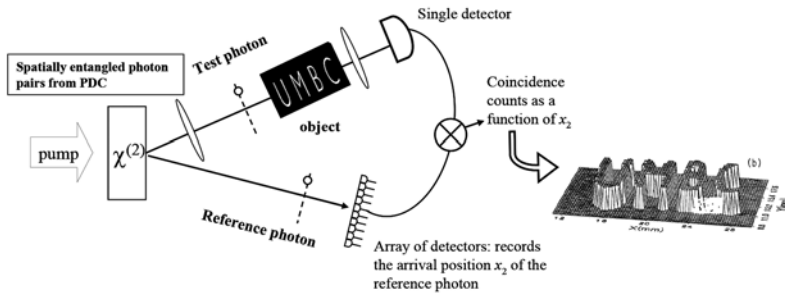


Fig. 2 – Ghost imaging realized by using pairs of entangled photons. $\chi^{(2)}$ indicates a nonlinear crystal with a quadratic nonlinearity.

This technique was theoretically formulated by Belinsky and Klyshko [2] for the case of quantum correlated test and reference light beams, and was subsequently realized experimentally by Shih and collaborators [3]. In this case the test and reference beams are obtained by a process which is called optical parametric down-conversion, in which a fraction of the photons of a pump beam are converted by a nonlinear crystal into pairs of photons which are called twin photons and arrive at the detectors in the two arms one by one. In this case one detects the coincidences between the arrival of a photon at the bucket detector and the arrival of a photon at one of the pixels of the multi-pixel detector (Fig. 2). The process with which a pump photon splits into a pair of twin photons occurs with conservation of total energy and total momentum (Fig. 3). The two twin photons of a photon pair are linked

by a special correlation which is called quantum entanglement and, according to Schroedinger, quantum entanglement is the essence of quantum physics. Thanks to this property, if one measures any observable of any of the two photons, *e.g.* its energy, or its momentum, or its polarization, from the result of the measurement one is capable of inferring with certainty the value of the same observable for the other photon. And this remains true even when the two photons get largely separated from each other.

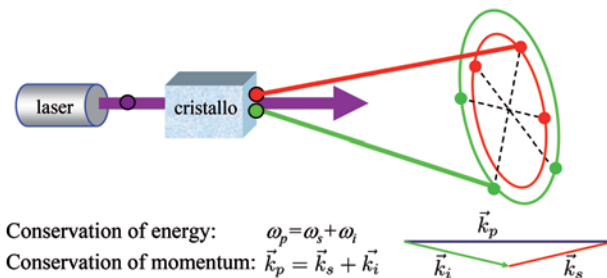


Fig. 3 – This figure shows the process of optical parametric down-conversion, in which pairs of twin photons in a state of quantum entanglement are generated. The process conserves the total energy and momentum.

A decade after the experimental realization of ghost imaging by quantum illumination (pairs of entangled photons), it was shown theoretically [4] and experimentally [5] that the same technique can be realized even by classical illumination. In this case one injects (*Fig. 4*) the pulses emitted by a laser into a rotating ground glass, which transforms the coherent light of the laser into incoherent light as that emitted by a standard lamp, but with values of the parameters which can be engineered at will. Next, the incoherent light pulses are sent to a 50/50 beam splitter, which produces two speckle patterns which are classical copies of each other. In this case the two light beams are not perfect quantum copies of each other as it is ensured by quantum entanglement, but they are correlated in an excellent way, which is enough to realize ghost imaging very nicely. The quantum procedure produces in principle results of better quality but, at the present state of the art in technology, the performance of classical ghost imaging is superior and, in addition, is obtained with a much simpler experimental setting which utilizes off-the-shelf elements.

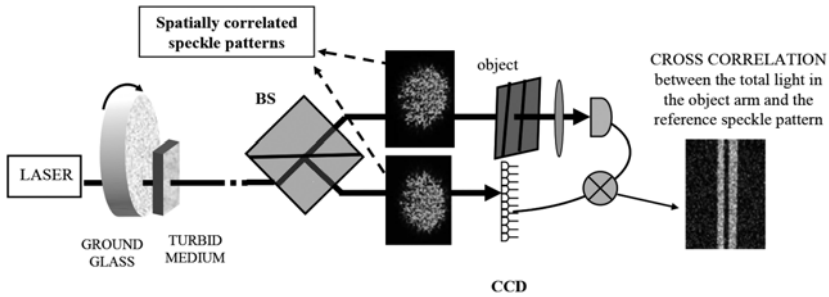


Fig. 4 – Ghost imaging realized by using classically correlated thermal beams.

Fig. 5 shows the result of a classical ghost imaging experiment, in which one obtains the image of a detail of the “Birth of Venus” by Sandro Botticelli. One sees the results obtained by conventional ghost imaging and by an improved ghost imaging technique which is called differential ghost imaging [6].

Recently also 3D ghost images have been realized [7].

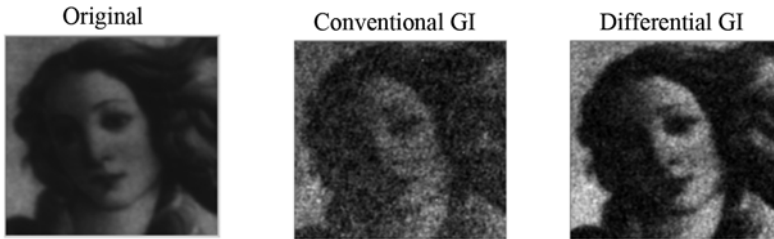


Fig. 5 – Ghost image of a detail of the “Birth of Venus” realized by conventional ghost imaging and by differential ghost imaging.

2. THE DEBATE ON QUANTUM VERSUS CLASSICAL GHOST IMAGING.
ON THE OTHER HAND, A VERY CONCRETE QUESTION

The literature on the topic of ghost imaging includes a long debate on the question whether quantum entanglement is necessary or not for this kind of imaging, and on the comparison of quantum and classical ghost imaging, overviews of this can be found in [8,9]. Thus the topic of ghost imaging has led to quite interesting theoretical and experimental investigations, but it mainly remained the forum for academic discussions on quantum vs classical.

In this presentation, instead, we want to address a very concrete question: can ghost imaging, in some special cases, work better than standard imaging?

An especially promising case is illustrated in *Fig. 6*, in which the object is followed by a turbid medium, *i.e.* a medium in which the light rays are randomly scattered in all directions. In such a situation, it is hard to obtain an image of the object using standard imaging.

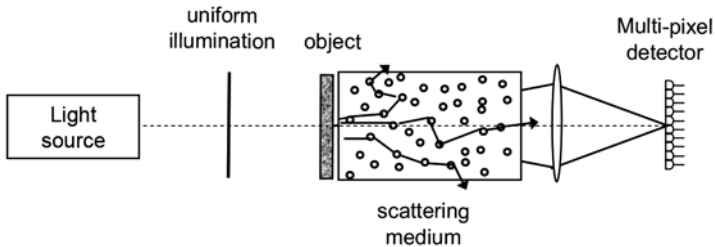


Fig. 6 – If the object is followed by a scattering medium, standard imaging is not capable of providing a good image.

On the other hand the situation can notably improve, instead, if the image is obtained using ghost imaging (*Fig. 7*), because the object is observed by a bucket detector which collects the scattered light, so that the random change of direction of the light rays becomes immaterial.

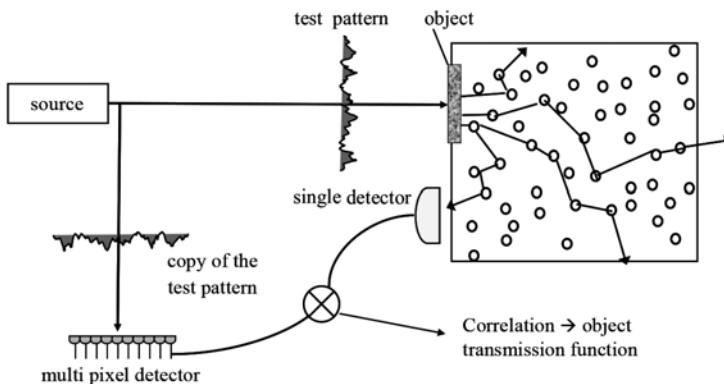


Fig. 7 – Since in ghost imaging one utilizes a bucket detector, which can collect the scattered light, the situation is notably improved.

The scheme of *Fig. 7* can be implemented, for example, for a possible biomedical application such as the detection of a tumor in the skin (*Fig. 8*). In this case the test pattern is injected in the tumor, and the light transmitted by the tumor is scattered by the epidermis.

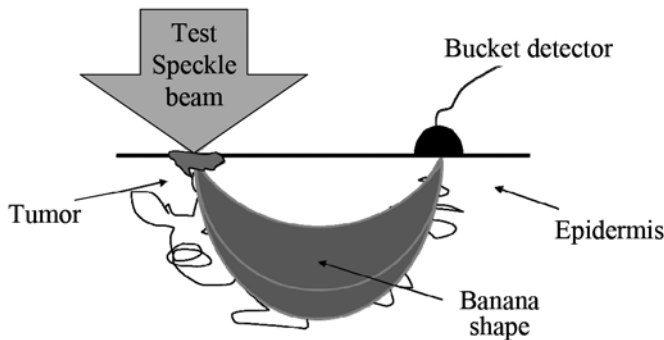


Fig. 8 – Scheme for the detection of a skin tumor using ghost imaging.

3. COMPARISON OF STANDARD IMAGING AND GHOST IMAGING

In [1] we report on the results of an experiment inspired by *Fig. 8*, with the aim of comparing the performances of ghost imaging with those of standard imaging. In this case the object is a thin black cardboard, so that the transmission is equal to 0 in the stripe where the cardboard is, and is equal to 1 on the two sides (*Fig. 9*). *Fig. 9* illustrates the comparison of the results obtained by standard imaging (third column) and differential ghost imaging (first column). The second column shows the results obtained by a variant of the standard imaging technique that we call diffusive imaging and that is illustrated later. The last column (Cross sections) is obtained by measuring the transmission in the cross section of the stripe and averaging over all possible cross sections. There are three sets of figures in correspondence to three different depths h_1 , h_2 and h_3 at which the object is located.

One can see that the performance of ghost imaging is definitely better than that of standard imaging because, for example, the transmission is much closer to 0 inside the stripe. When the depth is increased, the result worsens for both techniques, but the comparison remains basically the same.

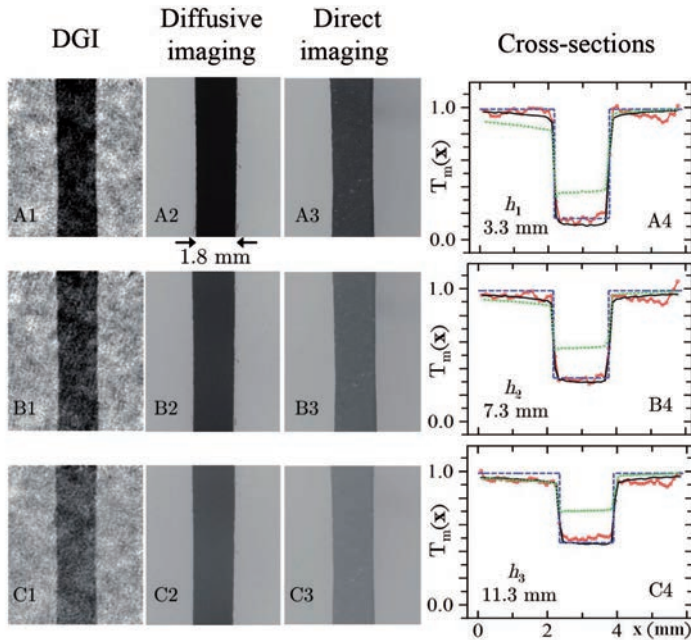


Fig. 9 – Comparison of differential ghost imaging (first column), diffusive imaging (second column) and standard imaging (third column). In the last column (Cross sections) the broken line indicates the ideal result (transmission equal to 0 in the stripe, to 1 out of the stripe), the solid line the result of diffusive imaging, the irregular line the result of differential ghost imaging and the dotted line the result of standard imaging. There are three sets of figures, corresponding to the three indicated values of the depth with which the object is immersed in the turbid medium.

On the other hand, Ferri and collaborators have conceived a variant of the standard imaging which produces results of the same quality as those obtained by differential ghost imaging. This technique, that they call diffusive imaging, is illustrated in Fig. 10.

In the case of standard imaging the object is illuminated directly and the light is observed in reflection using a multi-pixel detector. In the case of diffusive imaging, instead, we locate in the path of the light beam a stopper which blocks the central part of the beam. In this way, the light illuminates the sides of the object and not the object directly. The incident light is then diffused in all directions by the scattering medium and, in particular, is diffused backwards, so that diffusive

imaging basically corresponds to a backward illumination of the object (Fig. 11).

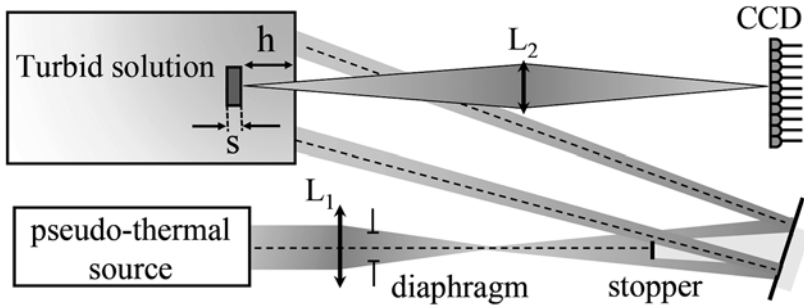


Fig. 10 – Scheme for the diffusive imaging technique.
In this case the object is illuminated on the sides.

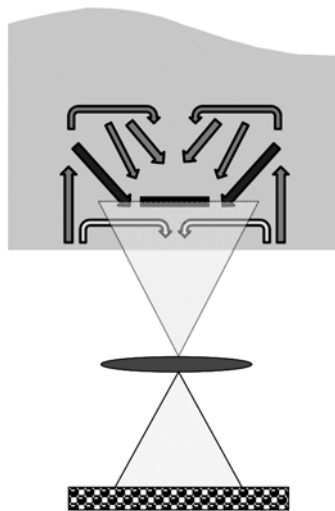


Fig. 11 – Diffusive imaging corresponds to a retro-illumination of the object.

The main conclusion is that in our experiment the performance of standard imaging is indeed inferior to that of ghost imaging, but a variant of standard imaging, *i.e.* diffusive imaging, produces results of quality comparable to those of differential ghost imaging. Hopefully some

future improvement of the ghost imaging technique will carry its results to a level of quality superior not only to those of standard imaging but also of its variants.

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