Title

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Author

Ragazzoni, Roberto

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Roberto Ragazzoni

INAF - Osservatorio Astronomico di Padova, Vicolo dell'osservatorio 5, Padova, Italy

ABSTRACT

The concepts and considerations that could leads to the development of a novel kind of classes of wavefront sensors in which the information is retrieved by the absence of photons rather than from their presence are shown. In quantum optics the concept of ”sensing” an object without actually having photons interacting with it is already known. The potentiality in terms of sensitivity has been already pointed out. Under the conditions that background counts are small enough (something that evolved with time with respect to a couple of decades ago, as today close to zero RON detectors are available, although sky background would continue to impose some limit to this approach) detecting ”no photons” can be made with an SNR larger than detecting a ”given amount of photons” in a number of practical situations. While we review the case of the coronograph coupled with a conventional WFS -a case already proposed in the literature- we explore variations on the theme of the Smartt wavefront sensor and in particular we explore the case of a double channel WFS where two images of the pupil are exploited and the flat wavefront is perceived as no photons on the pupils. The presence of a signal on subapertures on one pupil or the other indicates the sign of the wavefront perturbation. The system can be tuned in its sensitivity and -potentially- adjusted in order to have the two detectors working with close to zero flux on them while in closed loop operations. As the ”signal” is coming from the condition of no photons I described these as a ”Dark” WFS.

Keywords: Wavefront Sensing

1. INTRODUCTION

In an outreach paper published about 20 years ago [1] summarizing most of the results obtained one year earlier [2] it has been demonstrated that once can actually produce an interferometer that would be able to “sense” an obstruction on one of the two arms with a certain a-priori defined fidelity (i.e. probability to detect such an obstruction) with –in principle- as low as desired amounts of photons actually hitting the obstruction itself. Although the description of such an experiment as “seeing an object without actually throwing photons to it” is somehow deceptive, it is, in its asymptotic meaning, accurately true. In fact the experiment does not deal with any kind of manipulated or specifically generated photons (like entangled ones), and does not invoke any exotic quantum physics principle. In fact it is merely a very clever way to arrange an interferometer in order to produce a certain probability to achieve detection using as multiplication the progressive rotation of the polarizing angle of an optical beam. Although the principle quoted in this paper is not directly used in the following, as this has been very influential in a number of techniques that are described in the following I think it was relevant to point out to the Adaptive Optics community its possible relevance. Generally speaking, while it has been shown that you can “see” something “without” photons, can the same be said for “sensing” a wavefront actually getting “no” photons? The use of quotation marks is here much more than just a mere descriptive trick. A wavefront sensor that would offers no photons when everything is fine will work, in closed loop, with basically zero (or maybe as small as one desire, or as small as much is practically possible) photons. Sometime you just need to pose a very good question in order to find some answer, so... is this doable in some way?

2. THE RELEVANCE OF DARKNESS

When any kind of device is exploiting the duty of wavefront sensing, a certain portion of the incoming light is finally handled into a detector, that would translates light -specifically photons coming from starlight- into electronic, and finally digital signal that are somehow treated with a specific algorithm in order to reconstruct, with a certain degree of accuracy, the incoming wavefront shape. Whatever detector is employed and optical device is used, photons will finally obey, under most if not all of the conditions one have to deal in Adaptive Optics for Astronomy, Poissonian statistics. This means that, even in presence of perfect detector (Quantum Efficiency reaching the unity, no Read Out, no Dark

Counts) and perfectly efficient optics, a certain degree of uncertainty must be contemplated. Usually, the largest the number of involved photons, the highest the accuracy. However, it has been already pointed out that one should carefully consider which portion of the photons are actually producing a signal useful to determine the incoming signal and which part is not. The latter are just contributing to the noise and not to the signal. While in several conditions, both from the practical and the fundamental viewpoint there is no way to remove, or not to consider these non-collaborating photons, surprisingly these can be easily avoided in a number of occasions. The main aim of this paper is to describe a few examples, including some operational perspective, as the border between photons actually piling up in order to produce a significant signal and the non collaborating one can be variable with time and it can occasionally happen the division cannot be attained any longer. Only a detailed analysis can tell if one can deal with such events. Another interesting consideration is that only recently detector with small enough dark counts are available to be able to effectively recognize "no photons" with high fidelity.

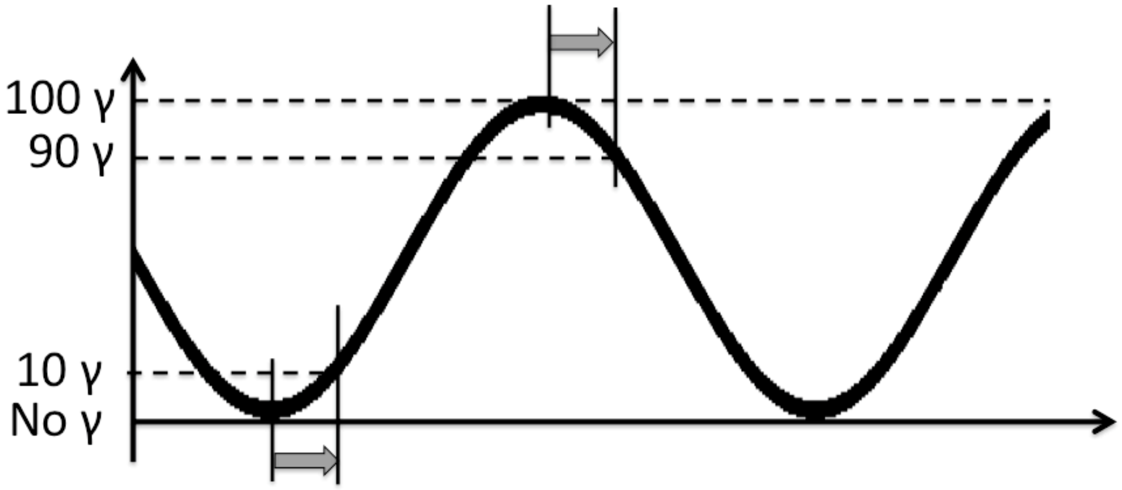

Figure 1 **In an interferometric type of light detection the same optical path difference, in this pictorial example materialized by the solid block arrow, will translates into some variation of the detected light in a certain point of the interferometry. In this illustrative example we assume a total of 100 photons per unit of integration, both spatial and temporal. The difference of 10 photons is to be distinguished with respect to the very dark and to the full amount of light. It is easy to convince ourselves that, whenever no dark counts are employed in a perfect detector, the SNR of the measurement around the darkness is characterized by an SRN that is three times larger than the one around the full illumination.**

This is of course a basic point. A detector with such a characteristic will be able to recognize the presence of, say, 10 photons out from the full dark with a nominal SNR~3 (assuming the square root rule in the number of photons is a good enough approximation of the Poissonian shot noise) while detecting the same lack of 10 photons from a bulk of about 100 can only be assessed with an SNR~1 under the same conditions. Dark detection is a more robust measurement than the same perturbation to a predefined flux.

3. A DARK TIP-TILT SENSOR

In several LGS based systems the actual sky coverage is often dominated by the limiting magnitude of the tip-tilt sensing of the involved NGSs. The latter, being compensated by the high-order, LGSs driven, AO system are relatively high Strehl, well defined in size spots on the focal plane. This makes the definition of the ultimate tip-tilt sensor under these conditions potentially a valuable one in the framework of the current artificially referenced adaptive optics systems on large and extremely large telescopes.

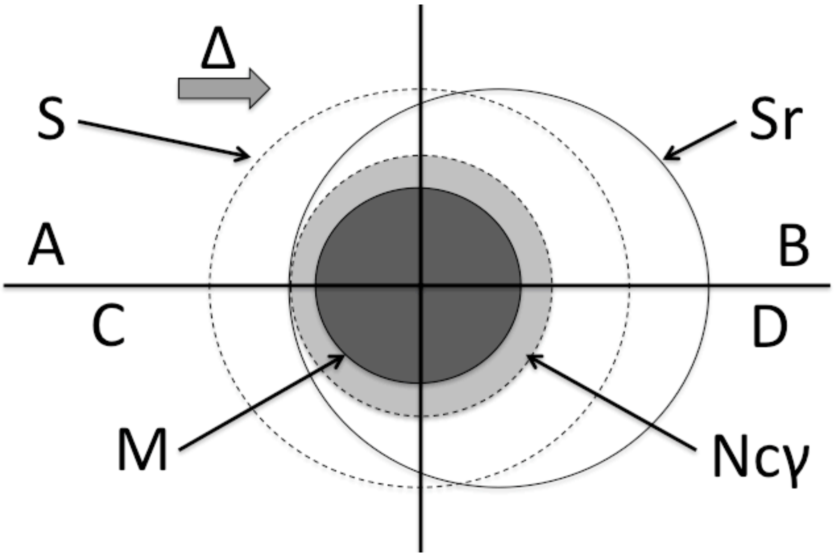

Figure 2 **In this illustrative example a four quadrants (quadrants are named A, B, C and D) tip-tilt sensor is shown along with a centered spot S. The typical maximum displacement of the spot, assumed working in closed loop with a certain degree of accuracy, is given by the block arrow. Sr is a representative display of the spot once maximum displaced to the right. This would lead to define the photons falling in the Nc light-gray circle as non cooperative ones. A mask M, in this case with a certain margin of safety, will avoid most of these photons to contribute to the noise.**

The direct elimination of the non cooperative photons can be accomplished in a four quadrant tip-tilt sensor with a mask placed in the focal plane, where the detection is actually accomplished. This has been proposed in an early concept [3] coupled with a Wavefront Sensor, however the reimaging of the focal plane (into a pin in the case of a pyramid, or in a second focal plane in the case of a Shack-Hartmann) will carry on diffraction effects from the mask. In the case of a dark spot physically located on the detector plane all these trouble vanish and we can simply compute the light distribution on the focal plane without considering the mask itself. One option is to assume the mask is actually an area of the detector where the Quantum Efficiency drops to zero. In Fig.2 a naive approach show that in order to be effective one has to decide which is the maximum practical expected displacement of the star. This of course poses two problems:

- How to bootstrap[4] the system because when not in closed loop the wander of the spot is likely to be much larger than the spot size;
- How to deal with spikes of poor seeing leading to momentarily underperforming of the loop closure and loss of locking of the tip-tilt signal.

To deal with both one can easily envisage a system in which the incoming starlight is split into two wildly different fractions (like 99% and 1%) in which the largest portion of the light is sent to the masked four quadrant WFS and the remaining is sent to a conventional four quadrant WFS clocked at a lowest temporal bandwidth, hence unable to achieve the required high performance of correction but surely able to acquire the star, to place in the center of the four quadrants and to deal with momentarily loss of locking. The best ratio between the two split beams and the potential usage of the masked light (for instance by using a reflective mask) in order to have a signal able to timely warn about the lock of loss (and at this stage one can even envisage to momentarily sent all of the light through the conventional four quadrant tip-tilt sensor in order to minimize the recovery time) are well beyond the conceptual descriptions reported here and are left to a further detailed analysis in which clearly the results will depends upon the environmental conditions (seeing, and its temporal spectral behavior) and quality of the high-order, artificially referenced, compensation at the wavelength used for the tip-tilt sensing.

4. HIGHER ORDER DARK WFS

Further to the concept presented elsewhere [3] we can trace which would be the outcome of a sort of idealized WFS in which the concept of exploiting darkness is fully accomplished. In order to do so let us imagine that –with an ideal detector completely free of dark counts- and neglecting sky background (both will inhibit the ability to sense the darkness, of absence of photons, with high accuracy) we envisage a system working in closed loop in which the issues of bootstrapping or to deal with momentarily lapse of locking are taken into account in some (at least for this initial phase of conception) irrelevant manner.

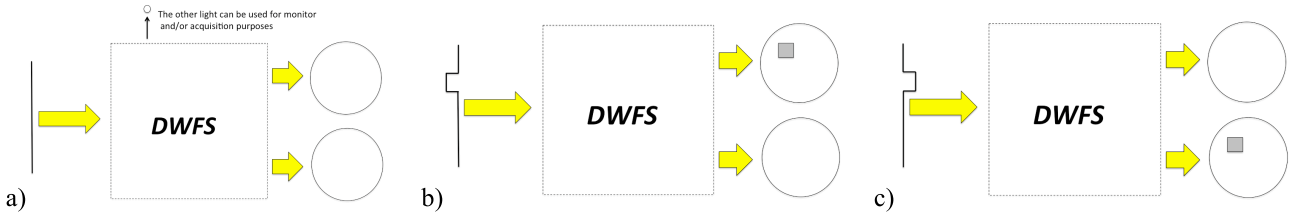

***Figure 3 From left to right: a)* The ideal DarkWFS will lead to two completely dark pupil images. Eventually the collected light can be used to monitor the status of locking of the AO system; *b)* in case of a perturbation the related portion of the pupil will get some light *c)* depending upon the sign of the incoming perturbation.**

The ideal Dark-Wavefront Sensor (hereafter DWFS) should be made in a way that, whenever the incoming wavefront is flat (or identical to the *non-common path* aberration shape desired) the outcome is just a completely dark pupil image. Of course this would be undetectable from simply a DWFS that is not receiving any light at all, so one can envisage that the whole part of the collected light will be used in some manner just to monitor the status of the DWFS, in a similar manner to the light eventually reflected by the reflective mask in the case described in the previous section about the tip-tilt. Once some perturbation is experienced in the wavefront some light should appears in the detectable pupil plane. This would however lead to a sign issue. In principle quadratic wavefront sensing could be used in this case [5] via a *bang-bang* approach, ut this would lead to a non-linear behavior of the DWFS that would be –in most if not all the practical cases- prevent its use. In order to overcome such a problem the idealized DWFS could have just two pupil planes, and the actual perturbation will plow some photons just in one of the two, depending upon the sign of the incoming perturbation. This, again as in the case for the tip-tilt sensor, leads to the idea that such a DWFS works actually well only in closed loop operation and within a predefined range of actual displacement of the wavefront from the nominal position. As for the tip-tilt sensor, continuing the analogy, a sort of Automatic Gain Control could lead the DWFS to operate in the right regime depending upon the quality of the controlled loop. We note that AGC has been widely used in curvature wavefront sensor [6].

5. TOWARD A PRACTICAL IMPLEMENTATION

How to actually build such a DWFS? Continuing the analogy with the quantum “seeing in the dark” sketched at the beginning of this paper, let me stress that, in principle, one should declare ourselves happy not actually making an ideal DWFS, but making an “as ideal as practically possible one”. As the key here is to have completely dark pupils we try to figure out an “almost DWFS” employing pupils that are not completely dark but with a low illumination, with the caveat that, at least in principle, such illumination could be kept as low as practically possible. In order to explain how to reach such a goal let’s start from a simple Mach-Zender interferometer in which in one of the two arms light is artificially flattened. This can be achieved, for instance, by placing a lens focusing onto a spatial filter (just a pin-hole of the right size) and hence producing a flat wavefront, whatever the incoming one is. The interference between the internally generated flat wavefront with the incoming one would produce, assuming the initial wavefront is actually flat, onto the two exit ports an amount of light that would depends, following a sinusoidal behavior, the difference in pathlength of the two arms. If this difference is zero one of the two exit ports will actually exhibits a dark pupil image, and any perturbation will deploy some illumination, unrelated with the sign of the incoming perturbation. A solution to this issue is to deliberately displace one arm with respect to the other in order to produce a low level of illumination. Depending upon which side of the differential displacement has been opted for, the same small perturbation will produce a net enlighten of the pupil's interested portions in one case, and a further dimming of the light in the other (this assuming the perturbation is within the displacement introduced). This means that one can imagine to have the incoming light split toward two similar Mach-Zender interferometers, each adjusted to the same slight inequality but with different directions. The same small perturbation will make dimmer the pupil on one size and brighter on the other.

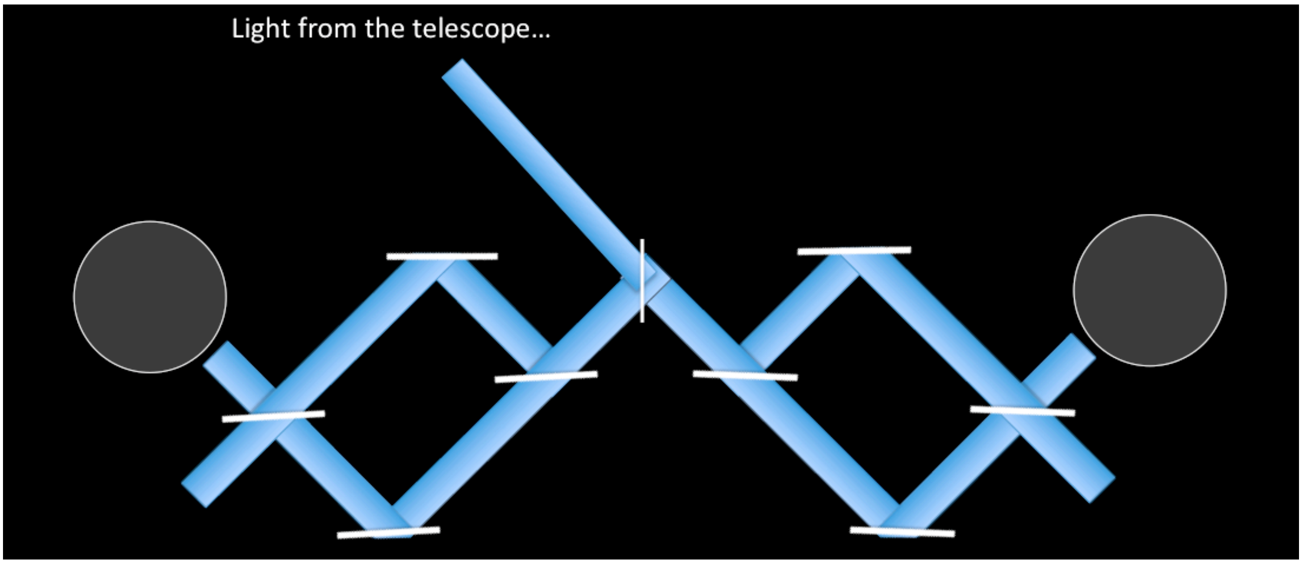

Figure 4 **In this example of a practical implementation of a DWFS the starlight is split into two Mach-Zender interferometers of unequal path arms lengths. Into each of the two splitted arms a spatial filter (not shown in the drawing) is introduced. The two are adjusted to show a small amount of light on their pupil planes in one of each arm (the other not being used here). The two interferometers, however, are adjusted in order to exhibits variations of the light depending upon two different signs of the incoming perturbed wavefront being adjusted to a small fraction of wavelength in a positive and negative manner in the two interferometers.**

6. TECHNICALITIES AND PARADIGMS

The approach described so far would requires a complex arrangement of several optical elements, beam splitters, and will likely be extremely hard to align. Inequality of the paths just by moving 45deg mirrors would introduce relative displacement of the pupils, that would unavoidably leads to even more complex optomechanics, like trombones, cat's eyes or refractive media that could be controlled in some way, for instance by superposition of two refractive wedges. A first way of simplifying the whole approach would be to make everything in a sort of solid structure just gluing together glass blocks making up prisms, beam splitters and using internal total reflections. Such systems has been build up for a number of optomechanical solutions and they could even be controlled thermically in order to adjust differentially the optical path lengths. Making them very small so that they could be coupled directly toward their detectors can be a twofold solution allowing for a relatively speed of response when trying to adjust the optical path lengths via temperature. Another completely different approach that would basically incorporate some of the two arms into a single layer deposited on a face of a beam splitter is by using a couple of Smartt interferometers, as depicted in Fig.5. Also, this approach assumes the use of a single wavelength or, in other words, to build up a monochromatic DWFS. It is interesting to note that an ideal DWFS build up in an interferometric fashion could offer zero light regardless of the interference (a white light interferometer) but its practical variations will exhibits a low light level pair of pupils that would be strongly chromatic. A possible way to overcome such a problem is to build up optical devices that would exhibits the same optical pathlength difference, expressed in wavelength units, at their related wavelengths. Such achromatic systems has been actually designed and built in other adjacent realms.

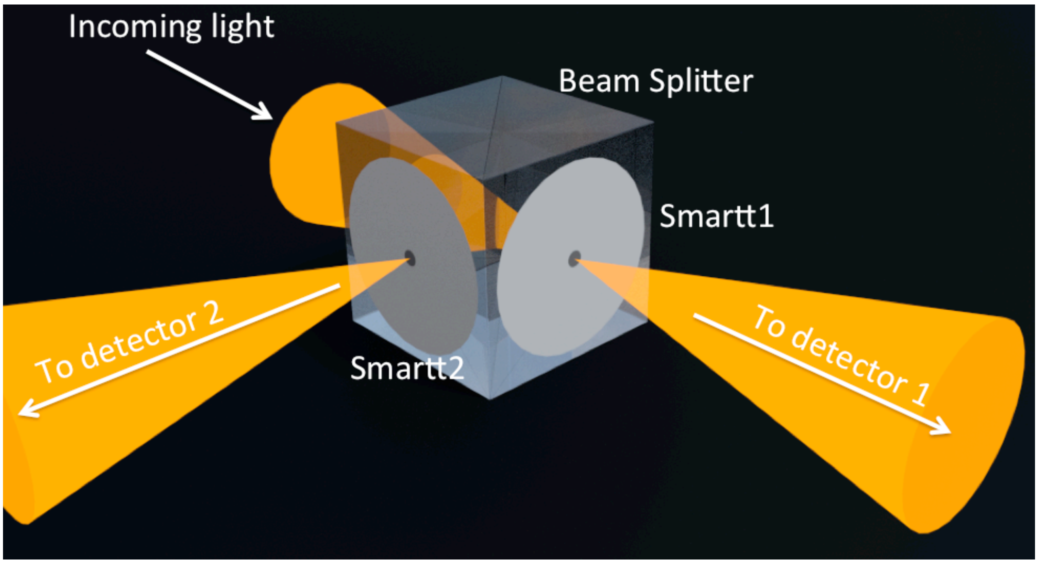

Figure 5. **A possible practical realization of a DWFS is just employing a beam splitter on whose two faces two Smartt interferometers are deposited. In this case the adjustment of the optical path length different would be driven by the thickness of the deposited material. While this is surely doable at level of design a possible way to control automatically is by changing the refractive index of the material by some electrically sensitive material or by changing the thickness by adjusting the local temperature of the two faces. As both these approaches would carry on a number of complications it is likely that this, very compact, design would be of practical interest only for systems whose gain is fixed in advance. If detectors cost would be negligible one could even envisage an array of such a DSWF each with a different gain (difference on the optical length of the two arms) and light is injected into the proper one depending upon the degree of achieved wavefront compensation.**

A completely different approach is instead shown in Fig.5 where a couple of Smartt interferometers are layered onto the two faces of a solid beam splitter. Interesting enough the DWFS approach is not in fact a single concept of WFS, but it carry on a somehow new category of new devices, that are characterized by offering a signal that is, under the most favorable conditions, absence of light. The reason why such an approach should exhibits a better performance with respect to existing WFS has been outlined, but of course it must “fight” against the fundamental assumptions made in its respect. The one that has the major option, from a purely scientific viewpoint, to diminish the effectiveness of DWSF is the sky background. Even in closed loop fashion the entrance diaphragm cannot be lowered below a certain threshold to avoid it effectively works as spatial filter washing out the signal it is supposed to sense with such high efficiency. Its size is hence defined by the seeing or at least by the finest sampling of the compensation introduced. Hierarchical approaches [7] here would be of little help. However, this scientific approach [8] is probably not really relevant for the spreading of novel concepts. Although LGSs slowly evolved into working systems in the last couple of decades with brilliant results, we are still sensing them with conventional WFSs using their light as it would come from an unresolved source and new attempts to introduce new classes of solutions, like the z-invariant [9], basically faded out and no other devices following the similar concept has been conceived. It is interesting by tracing these and similar concepts in the relatively small circle of Adaptive Optics community as fashion, or paradigms [10], actually drive the spreading of innovating (and not necessarily “better”) concepts.

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