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Extending the pyramid WFS to LGSs: the INGOT WFS

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ABSTRACT

Laser Guide Stars are, in spite of their name, all but "stars". They do not stand at infinite distance, neither on a plane. If fired from the side of a large telescope their characteristics as seen from various points on the apertures changes dramatically. As they extend in a 3D world, there is need of a WFS that deploy in a similar 3D manner, in the conjugated volume, resembling the approach that MCAO required long time ago to overcome the usual limitations of conventional AO. We describe a class of a novel kind of WFS that employ a combination of refraction and reflection, such that they can convey the light from an LGS into a limited number of pupils, making the device compact, doable with a single piece of glass, and able to feed a minimum sized format detector where the information is collected maximizing the information depending from which part of the LGS the light is coming from, and on which portion of the telescope aperture the light is landing. They represent, in our opinion, the best-known adaptation of the pyramid WFS for NGS to the LGS world. As in the natural reference case the practical advantages come along with some fundamental advantages. Being a pupil plane WFS with the perturbator placed on the (3D) loci of focus of the various portions of the source of light they have the potentiality to extend WFS to a number of issues, including the ability to sense the islands effect, where non-contiguous portions of the main apertures are optically displaced. Further to their description and the main recipes we speculate onto possible variations on cases where the LGS is fired from the back of the secondary mirror and we exploit some potential features when implementing onto an extremely large aperture.

Keywords: WaveFront Sensing, Adaptive Optics

1. INTRODUCTION

Words are important. They shape our knowledge in manners that sometimes are subtle. In the early days of Adaptive Optics the use of the term beacon for a mesospheric resonant scattering excitation of the Sodium layer by means of a powerful laser propagated from the ground was surely a proper word. The sodium populations act as a beacon and send back some of the energy channeled from the ground. As an extension of the wide use of the term "Guide Star", or GS, a distinction has now to be made, between the NGS, the Natural Guide Star, that is one of the unresolved source that populate our own galaxy, and the LGS, or Laser Guide Star where the way the light is formed (and in fact the beacon nature of such a reference) is implicitly lost. An LGS is, in fact, all but a "star", at least in the optical sense. It is located at finite distance, it is actually a well resolvable source, and it extends not only angularly but also radially from the observer. In fact it is a 3D column with a complex (and often time-varying) structure. It is a rough cylinder illuminated by a beam that, as it crossed upward our turbulent atmosphere, is the cylindrical projection of a far-field distribution of light characterized by speckles evolving with time. The vertical distribution is depending upon the local density of the Sodium atoms and the efficiency of the return flux depends upon the relative geometry of the Earth magnetic field and the direction of propagation

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of the exciting light flux, further to other details including the matching of the Maxwellian doppler population with the optical bandwidth of the laser employed.

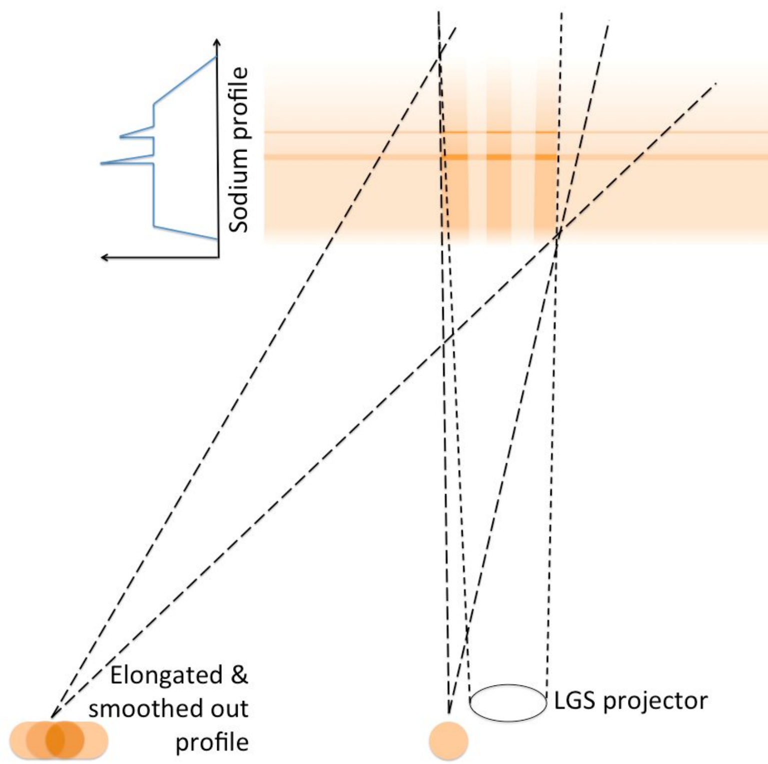


Figure 1 - In this simplified scheme it is shown that the structure of an LGS, both because of the upward turbulence and because of the Sodium density profile, will appear as elongated and smoothed out.

This "cigar in the sky" (or maybe LGC: Laser Guide Cigar) is approximately a cylinder whose edges span a height over the Earth of about 10 km on an average of 92 km. If projected from an LGS projector the size of a few r_0, as usually it is, its angular size is of the order of the seeing disk and it is seen from the ground with different elongations (but never smaller than ~1.4 the seeing disk, if observed without any adaptive compensation) depending upon the geometrical configuration. Its internal structure, both vertically and horizontally, is basically smeared out, unless it is observed at large distance from the place where the LGS is being fired.

Attempting to use a conventional WFS, designed and conceived to be used with unresolved stellar sources, with such a kind of reference and pretending the solution is optimal is definitively a gamble.

2. WAVEFRONT SENSING IN 3D AND THE INGOT CONCEPT

As it has been widely recognized [1], the pyramid WFS [2] is nowadays among the best solutions in terms of sensitivity and design compactness. Its use on an extended source jeopardize its ability to achieve performances better than other conventional WFS employed in astronomy [3] but still exhibits a number of advantages when coupled to an LGS. The detector exploitation is by far more efficient and the island effect, that has no signal propagated onto the detector in the case of a Shack-Hartmann, is measurable with the Pyramid one. This led to the concept of extending the pyramid concept to the LGS as reimaged onto the focal volume behind the line where infinite references are focused in a large optical telescope.

The concept has been outlined and described in [4,5] while its configuration took shape into a fashion exhibition as well [6] and simulation code has been assembled [7] specifically to study it from the numerical perspective. Basically it consists of a combination of refractive and reflective surfaces arranged onto a somehow complex prismatic shape (nicknamed “ingot”) that extends in three dimensions along the locus where the reference beacon deploy in the focal volume. This allows for an optimum detection of the signal along the axis transverse to the apparent beacon elongation while the signal from the axis coherent with the elongation is due basically to the signal coming from the edges. While on some hand this is similar to the “dark WFS” approach [8], one has to realize that this imply that one gives up using any structure in the LGS apparent brightness variation as a source of signal. On the other hand the pixel occupation is paramount much more efficient than in the Shack-Hartmann version making almost nil the chance of any effect related to spot truncation. Furthermore, as being the ingot WFS a pupil plane one, any effect that formally gives no signal on the subaperture (like the so-called island effect) is detected with such a kind of device.

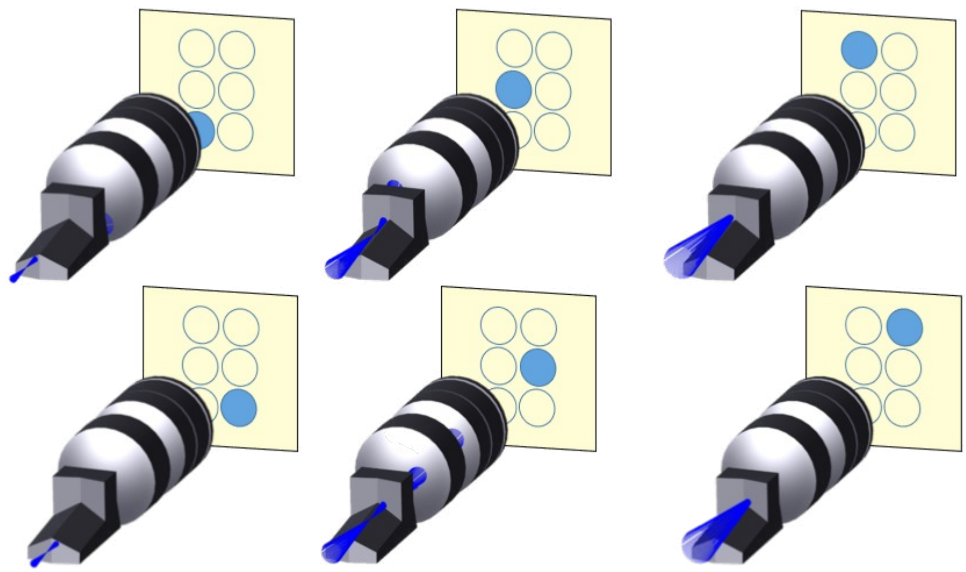


Figure 2 In this figure an ingot WFS is shown with the LGS light coming from the lower left side, away from the focal plane where NGS are focused. Depending upon the relative position along the prism all the six faces are illuminated. In contrast with the pyramid WFS, and also because of the extended nature of the reference, the illumination of the six pupils under no turbulence is not uniform and reflects the different elongation as seen from different points on the pupil. For instance, in the points closer to where the LGS is propagated most of the light is split into four pupils as in the conventional pyramid, allowing for a uniform sensing on both axes.

Because the beacon is monochromatic, the problems related to the chromatism [9] of the pyramid are irrelevant here. On the other hand, a combination of reflective and refractive solutions, as the described baseline, is more sensitive to the misalignment than a conventional refractive pyramid where, at the first order, a tilt of the pyramid itself has almost no effect on the image formation. Finally, in order to keep reasonable the length of the ingot one is tempted to illuminate it with e relatively fast focal ratio, requiring an optical system complex enough to cope with the equivalent field of view. In some cases, the use of cylindrical shapes into some of the refractive surfaces of the ingot could be of some help.

3. SIMPLIFIED VERSIONS

The ingot WFS actually represents a class of WFSs where, from a schematic viewpoint, the light coming from the LGS, although deploying into a 3D space, is subdivided into a certain number of regions and each of them is conveyed onto a pupil image, possibly onto a common plane where it can be accommodated onto a suitable detector. Splitting the light into different directions is another obvious solution, however, given the great pixel efficiency of this kind of device it sounds like an unnecessary complication and is not being treated here, although for some special cases there could be some advantages for such a solution. In particular one has to deal with complexity and degradation of performances because of the augmented requirements on the optical device as a whole with respect to the quality of the signal involved. In all the cases where the contribution from the laser photon shot noise is negligible one should consider a significantly simplified version of the ingot device. In its more extreme form this is done through a single knife edged prism [10] that has been preliminarily conceived as a Rayleigh-beacon WFS, where one gives up a priori at all into making any sensing orthogonal to the elongation direction.

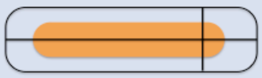
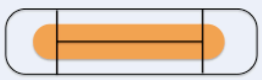
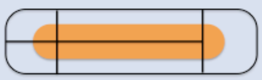
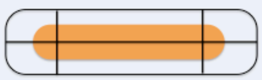
Configuration	No. of pupils	Signal along x	Signal along y	Notes
	2	Nil (-)	Full (+++)	Rayleigh compliant
	3	Only one edge (+)	All but one edge (++)	Simplest with both x & y
	4	Only one edge (+)	Full (+++)	Doable with conventional prisms
	4	Both edges (++)	All but both edges (+)	Complex ingot construction Required (--)
	5	Both edges (++)	All but one edge (++)	
	6	Both edges (++)	Full (+++)	

Table 1 A synoptic subdivision of ingot-like WFSs. The orange LGS beacon is here represented onto the paper plane through how it is subdivided. Although the comments and related pros and cons are somehow arbitraries, one should recall that the light distribution is not symmetric. The x axis is placed along the elongation direction while the y axis is orthogonal.

Further splitting of the beams leads to a range of options that can be divided into cases where a full symmetry is retained and others where such a choice is not satisfied. In some cases, the loss of signal is just due to not using the full extension of the light for a certain scope, while in other it is deliberately given up a certain portion of the light for that specific purpose. One should keep in mind that the two edges of the beacon are non-symmetric, as the lower edge is much sharper than the highest one. This means that refusing to use the less efficient one to sense the signal along the direction aligned with the elongation represents a deterioration of less than a factor of two in terms of light involved. The technical complexity of the beacon, furthermore, can be greatly reduced with a minimum reduction of the efficiency, if enough high margin of fluxes is taken into account.

4. SELECTING THE RIGHT RAYS

Once photon shot noise from the LGS and other effects like islands and spot truncations are rules out, in the overall error budget of the Adaptive Optics loop, especially for larger telescopes, one of the dominating term could turn out to be the one related to the geometry of the beacons and to the ability to cope with the tomographic solution involved in the process. Under these special conditions a number of ideas and concepts popular at the time of the layer-oriented [11] concepts could become of new relevance. Abundance of beacon photons could be simply used to cancel out any conical, tomographic and related effects just by deliberately selecting the rays with the angle of arrival compatible with the scientific Field of View or somehow related with that (for instance augmenting them by the equivalent isoplanatic patch, depending upon which layer is being aimed the correction). This of course requires the multiplication of the beacon making it somehow ubiquitous over the large pupil entrance of the telescope. While this can be easily obtained through some grating device, thanks to the monochromatic nature of the propagated beam, one could consider solutions where the beacon is swept over the sky during the observations [12,13]. In the latter case the amount of optical perturbators and the relatively huge field of view capabilities required to the pupil reimager are eliminated by a proper choice of synchronous movements of some optical components in the launch and sensing areas. A physical diaphragm selecting the proper rays can be made interchangeable or of varying size and shape depending upon the scientific case. For MOAO one could consider even the possibility to make multiple selections onto different pupil planes, both in a spatial and temporal subdivision.

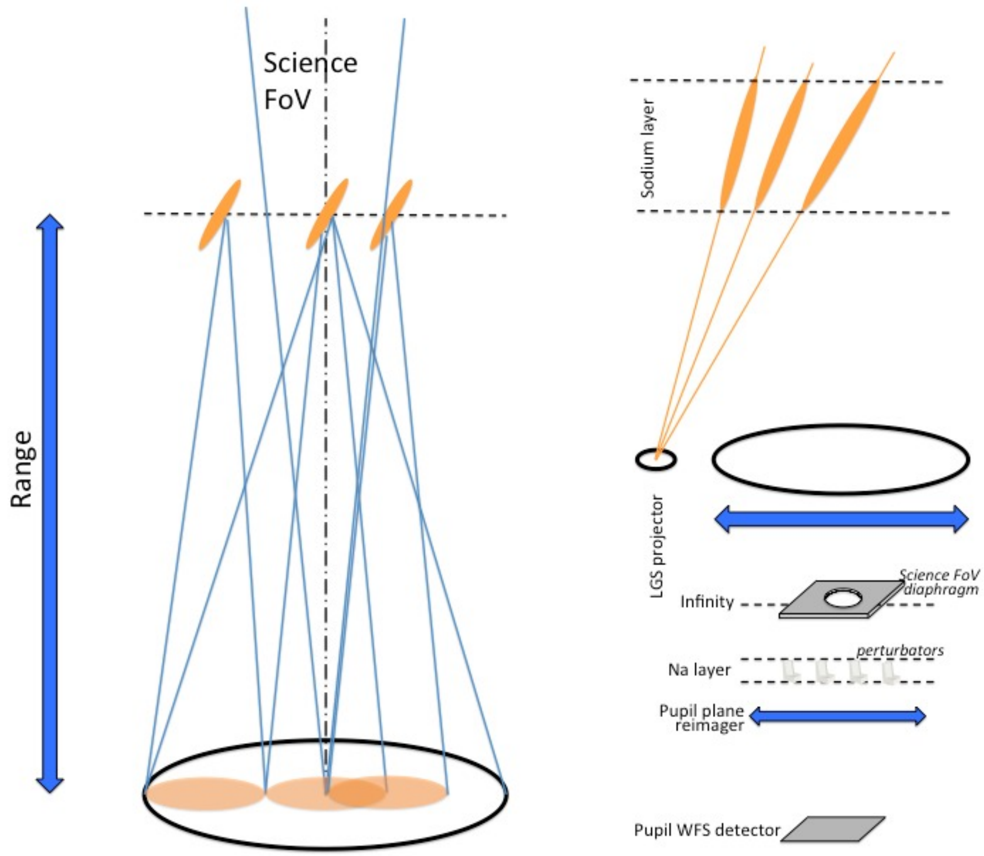


Figure 3 On the right side an illustrative way on how rays are selected in order to match the required scientific FoV. Pupil coverage depends upon the size of such diaphragms in a way that a smaller FoV would requires a larger density of beacons. Proper choice should be given to the number and density of these as depicted in the illustrative example on the left side where two pupil patches just smack each other or exhibits a significant overlap for a proper stitching.

Again, the single wavelength employed on the Sodium beacon would allow for a clear subdivision of the wavefront sensing area where the full set of light is being collected. The sub-optimality in terms of usage of the photons collected from the ground can be seen again as a sort of mild dark wavefront sensing where the light coming from too off-axis has the only effect of augmenting the photon shot noise of the background light. This also suggests a way of wavefront sensing where the sensing of multiple layers is actually achieved by a physical selection of rays in multiple planes, but the development of this approach is beyond the limits of this paper.

5. CONCLUSIONS

Extending the pyramid to the Sodium reference beacon, namely said LGS, is not just treating the LGS itself as an extended source, but it is deploying it in a 3D manner. This is somehow more complex and allow for a certain number of choices to be taken, including the way to sense the derivative of the wavefront along the direction of apparent propagation. In contrast with the SH the occupation of pixels in the detector is optimal and the edge ruling the derivative orthogonal to the elongation is always placed in the proper position. This gives to the ingot wavefront sensor an intrinsically better sensitivity that is to be traded out with the lack of information assuming no structure in the Sodium layer being used to sense the derivative along the direction of apparent elongation. Such structure is often smoother out unless of very extreme cases.

Such a new class of wavefront sensors allow for the detection of island modes where groups of subapertures shift in a piston-manner with respect to others and allow for feeding relatively small detector because of the very efficient pixel usage. Further numerical and optomechanical studies on this kind of devices are urgently needed in order to be employed in the coming generation of extremely large telescopes, although with some form of on-sky demonstration to figure out effects not being considered here.

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