Flatting the lightwave on a 100m scale
Towards the Goal of Performing Adaptive Optics
on the Apertures of Future Giant Telescopes

Roberto Ragazzoni\textsuperscript{a,b}

\textsuperscript{a}Astronomical Observatory of Arcetri
Largo E. Fermi 5, I-50125 Firenze, Italy
\textsuperscript{b}Max Planck Institut für Astronomie
Konigstuhl 17, D-69117 Heidelberg, Germany

ABSTRACT
Performing Adaptive Optics on a 100m scale is not only a formidable engineering goal for nowadays. It requires also to look for ideas, concepts, and ways of sorting out technicalities, that are beyond the current visions about Adaptive Optics aboard 8–10m class telescopes. Different physical regimes require to have different metrics when weighting pros and cons of one approach with respect to another. My current, and maybe very personal view, is here exposed, along with the reasons why I think one should face such a target recalling in his mind that the solution can comes together with options that can look irrespective of apparently well established configurations. Substantially, a road–map including Laser Guide Stars whose light is treated as it is the Natural Guide Stars one, is sketched.

Keywords: Adaptive Optics, multi-conjugation, Extremely Large Telescopes

1. INTRODUCTION
Operating an Adaptive Optics (AO hereafter) system feeding a Near InfraRed camera on a 3.5m telescope in Canary\textsuperscript{1} (but the situation is not too much different from what one can get by a survey of results obtained so far with Adonis in the Chilean deserts) occasionally one realizes that, although the improvement in the image quality can be remarkable in relative terms, the absolute results (for instance, obtaining a 0.2\textendash0.3arcsec FWHM under a poor seeing of one arcsec) are, without any doubt, a bit frustrating. The usual phrase "a resolution obtainable under good conditions atop Mauna Kea" usually can be heard in the control room of the telescope. Recent results pushing the limits toward 8m class telescope and toward smaller wavelengths (and the comparison with HST images, that are finally surpassed by the deeper exposures, for instance, obtained by NAOS–CONICA aboard VLT\textsuperscript{2}) are giving a feeling of how much the AO gain scales with the telescope diameter. Following the example with the 4m class telescope given above I would say that finally 8–10m-class telescopes equipped with AO are able to obtain images that can never be obtained with superb seeing conditions in any place on the Earth (maybe with the exception of Dome–C in Antarctica, a place in competition with the outer space, in terms of difficulty of erection and operation of relatively large facilities). The current efforts to push for larger Field of Views (FoVs hereafter) and shorter wavelengths can only further enlarge such a gap. I think this is one of the key points to understand the currently widespread opinion that telescopes aperture much larger than the current 8–10m class ones, the so-called Extremely Large Telescopes\textsuperscript{3,4} (ELTs hereafter) will essentially need AO to make a reason of their existence. Gains in terms of resolving power and depth of imaging, just to mention a couple of issues, are so large that a 100m telescope without AO and one with AO are really two different facilities, offering completely different views of the Universe. The time to trace a road–map to obtain a realistic way to get almost full-sky diffraction limit capabilities from the ground over a decent FoV, even at short wavelengths, has finally come.

E-mail: ragazzoni@arcetri.astro.it
2. MCAO AND DMS, IS THERE REALLY AN ISSUE?

The obvious answer to AO on ELTs is MCAO\(^6\). The latter statement is actually too vague for what concern the way WFS is done, while it is rather clear on how the correction is done. Unless some emerging technology still provide chromatic-free transparent correcto, there is little hope that solutions different from simply having a certain number of DMs in the optical train will be more effective. Several optical design for ELTs incorporates into their design mirrors that are conjugated to convenient ranges in the atmosphere. Also, there is a somewhat general consensus that, other than having a DM conjugated to, or very close to, the ground, the others can be placed at ranges lying in the 4 to 15km spans without huge variations in the expected performances. It is interesting to point out that secondary adaptive mirror technologies\(^7\) could be exploited into this quaternary or so mirrors, even in a segmented fashion.\(^8\) Most of the current emerging technologies refers to DMs with very small pitches that are, to some extent, unusable aboard ELTs because of the Lagrange invariant problem (but give a look to one of the next subsections). Current secondary adaptive mirror technologies have been proven in the lab with sizes and number of actuators comparable to what would be required by a single segment of an ELTs in order to conceive correction in the NIR. Extension to the visible band would require a moderate development in this technique, likely in the material to be used as flexible shell. Sure, the technology still need to be demonstrated on the sky and much more feedback is needed, but there is nothing of conceptually new in all this. It is an hard statement to say that for ELTs the issue of DM is virtually solved, and in fact it isn’t. Let say that with current, only laboratory demonstrated, technology, one can easily conceive an ELT with adaptive capability up to the NIR. Extension to the visible or adoption of more exotic approaches (like making the primary mirror an adaptive one) are going to be studied in the next years.

3. LARGER CONTRACTS OR DIFFERENT PHYSICAL REGIME?

A reductive approach to the problem of performing AO on ELTs could be limited to a mere fact of number of actuators, parallelization of real time computing, and splitting the light of the wavefront sensor into a number of existing detectors, just not to mention the more than duplication of planned or existing LGSs systems\(^9\).\(^10\). This brute force approach makes apparently the AO@ELTs problem virtually solved on the conceptual point of view, just raising concern on the industrial capability of performing such a task. A further reductive view can be represented by the question: placing a call for tender for a 10\(^6\) actuators DM and related AO, would this finally end in a placed contract to the same company?

However I would like to point out that jumping from a 10 to 100m scale the AO@ELT is going to work under different physical regime. In order to convince the reader I hereby mention a few points in a list not exhaustive at all:

- The typical FoV times the average turbulence height is much smaller than the telescope aperture. This means that essentially the footprint of the light beam at the altitude of the highest turbulence layers is marginally larger than the telescope aperture. This has important consequences: just to mention a few lower modes are correlated over the FoV; reference light, regardless its nature, is not spread on the telescope aperture significantly more than what happens on the ground layer; a change in height conjugation does no longer requires a change in the overall number of sampling points, or a compromise over its sampling.

- The telescope aperture is larger or at least of the same order of the outer scale. This parameter, \(L_0\), that occasionally played a marginal role in the study of AO performances on current telescopes, can have a substantial impact on the AO@ELTs design. Just two consequences among the others would be that the required stroke on DMs is largely lower than for an infinite outer scale, and that there are serious concerns about the point if the tip-tilt correction is really an issue or simply there is essentially no tip-tilt to correct at all.

- LGSs, even Sodium ones, illuminate the pupil with an arrival angle that is larger or at least of the same order of the largest FoV conceived for these types of telescopes. A bunch of LGSs able to illuminate the footprint for a FoV of the order of a couple of arcmin really invest the pupil with angles that are
several times larger, making the need for larger FoV if one wants to collect all the light and, maybe more important, to smooth focused layers with a degradation that is more steep once the turbulence is not exactly located on the reimaged layer. This effect, at least when linear reconstructions are considered, is independent from the technique used for the Multi Conjugated Adaptive Optics (MCAO) reconstruction. Sodium LGS elongation becomes much larger than the seeing disk. The effect jump from one to two arcsec for current generation telescopes (where already such effect is an issue) to several tens of arcsec in ELTs, raising the point about gating the LGSs, as one is forced to do in Rayleigh for today telescopes, and placing constraint on the type and pulse format of the LGSs firing system, if any.

- The ratio \((D/r_0)^2\) scales from values of the order of \(\approx 100\) of current AO systems, to something of the order of \(\approx 10^6\) for the MCAO systems aboard ELTs we are speaking about. This place the concept of partial adaptive optics correction in a somewhat new light. The brightness ratio \(\eta\) of a companion giving in its core the same flux in the corresponding area occupied from the halo of a partially corrected star (neglecting diffraction effects) is of the order of:

\[
\eta \approx \frac{1 - S}{S(D/r_0)^2}
\]

Because of such a huge jump in terms of the \(D/r_0\) a poor \(S \approx 0.1\) figure for an ELT translates into having on the detectability of faint objects around a bright one, the same behaviour than a \(S > 0.99\) for a high-order system can play now for an 8m class telescope. This also means that our actual ideas about the scientific requirements for AO on 8m telescopes does not apply as they are to ELTs and need a reformulation too.

As there are new physical boundary conditions for AO on ELTs there should be little surprise in learning of MCAO concepts that are suitable to work only with ELTs and that would fails into 8m class telescopes. Although we present at this conference just one of these\(^{11}\), it would be an easy bet to assume that much others are on the way.

4. ARE THERE FUNDAMENTAL LIMITS?

As dealing with a different physical regime, in a certain sense one is forced to exploit new concepts that are uncommon, at least in the astronomical adaptive optics community. Once one of this concept is found there is need of some time to really understand it and an exhaustive search for the ways to implement such a novel idea should be pursued. Noticeably, variations on the theme of a new concept can sometimes offers more possibilities than the original finding. In the meantime there is a relatively large probability that someone, more or less authoritative, will explain, based upon some fundamental physical law, that the proposed concept is wrong, practically impossible to achieve, or its extrapolation to 100m aperture exhibits strong drawbacks.

Apparently there is a very small but vigorous fraction of the community that spends most of his time in finding how and why this or that technique will never work. Very often the criticism is really very smart and subtle and it is understood from a few among the people in the field. As any adaptive optics project (just not to mention the ones for 100m scale apertures...) costs millions of Euros/Dollars and several dozens of man-year, it is clear that these negative concerns are well paid of strong attention. It is interesting that pointing out a show-stopper of a technique is a risky business. If the concern will turn out to be wrong or overconstrained, its owner will become famous for having delayed of years some new development, while in the opposite case the knowledge of the community will be only marginally affected. In spite of such an extreme low rewarding this activity pops up for any novel concept, although in the long time span the right assessment will firmly takes place.

The usual plot of a show-stopper is to take the new concept, to place it in some well established framework, and to get to conclusions that are linked not only to the new concept under examination but also to all the explicit or implicit assumptions made to establish the framework where the concept is seen. In the following I list a few examples of situations where some strong statement places an apparently unavoidable upper limit on
performances and capabilities of different techniques, just to convince the reader to be at least strongly diffident to these show-stoppers and, in the best case, to take such a criticism as a starting point to find out techniques to overcome the problem pointed out.

I will make often reference to my current more popular way to perform MCAO, that is to the Multiple Field of View variation\textsuperscript{12} of the Layer–Oriented one\textsuperscript{13} (M–FoV). Although the interested reader should give a look to the proper references I here recall that the basic idea is to collect photons from a relatively large FoV in order to sense (and to correct) for the ground–layers, while a smaller FoV but with a coarser sampling of the pupil should be used to 	extit{counter} the mid– and high–altitude turbulence. In this way a significant sky coverage can be obtained as, although for different reasons, both the loops, specific to different altitudes in the atmosphere, take some advantage with respect to the straightforward application of the layer–oriented concept.

4.1. How much bright is the sky?

NGS–based wavefront sensing aims to collect photons from a wide range of reference sources, including possibly a number of faint stars, where 	extit{faint} here is to be intended as for usual AO reference sources. In the case such stars has a magnitude of the order of 19 and fainter an issue regarding the relevance of the sky background is usually pointed out. In fact, by placing a diaphragm stop of the order of a few arcsec, each reference will carry along some sky background photons that can turn out to be far from negligible. Under a full moon a sky brightness of 19 per arcsec square can easily grow to an equivalent magnitude of \( \approx 15 \) when collecting something like five stars onto a diaphragm of the order of 3 x 3arcsec. As this is an extreme example, one could place nevertheless some limits on the faintness of usable stars, negating, in a certain sense, the original spirit of the layer–oriented approach, that is to use all the possible sources of informations available. While the interested reader should give a look to a specific paper\textsuperscript{14} in order to get a reliable estimation of how much and how bright are expected NGs in such configurations, we are not exempted to further get insight into the mentioned matter.

In fact one can easy see that by placing a diaphragm of the order of \( \lambda / r_0 \) there is little, if any, impact on the wavefront sensing capability of any pupil–plane wavefront sensor, in closed loop. This is a different situation with respect to a Shack–Hartmann wavefront sensor, at least to a certain extent. A further reduction of the diaphragm hole will further hamper the reimaging of the pupil at the largest spatial frequencies (and this will translates into a loss of SNR at the very highest modes corrected, something that should be traded off with the improved overall SNR because of the smaller sky background collected by the WFS). For a Shack–Hartmann WFS a reduction of the entrance diaphragm to a fraction of the seeing disk will leads almost no signal to correct.

As the situation described above rely to the closed–loop situation care is to be given to the bootstrap process. Although in the past we already described variable diaphragm configurations, it is noticeable that the most preliminary simulations show how the bootstrapping phase can easily overcome the lack of information because of the light spilling out of the diaphragm, with the proper actions. Specifically it is required that the slopes information are obtained by an un–normalized four–quadrant style information over the four pupils reimaged by the pyramid WFS. To be convinced one should imagine a simplified geometrical model. In such a framework some rays initially are not going through the hole and the related portion of pupil is not illuminated in any of the four reimaged pupils. As long as these rays fall, by chance, inside the diaphragm, their signal is obtained and the closed loop system keep them in place. To be correct this requires that non–common path aberrations are within the range imposed by the diaphragm. Moreover, one should also note that by performing a modal correction, several portions of the pupil will be strongly 	extit{pushed} to fall into the diaphragm.

4.2. Giuseppe Luigi Lagrange

As an example of how scaling up a system using straightforwardly physical law can lead to erroneous conclusions I want to mention the limitations introduced in the optical design by the Lagrange invariant. The latter is also known as invariance of the product \( A \times \Omega \) or as \textit{etendue} law (the latter French term spreading the sensation that Giuseppe Luigi Lagrange was French, although he actually was born in Torino). Whenever a pupil image where light coming from a certain FoV is obtained, the full angle formed by the collecting beam scales inversely to how much the pupil is shrinked. That means that reimaging a 100m pupil onto a 10mm detector, as it produces

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a reduction of a factor 10⁴ will lead to a corresponding amplification of the angles of rays insisting on the pupil. This means that observing a FoV of the order of a couple of arcmin would translates into something of the order of more than 300 degrees, and even a FoV of mere 30 arcsec will translates into an aperture angle on the small pupil of the order of 80 degrees. As this would require some impossible super-fast optical system this result has been sometimes referred to as a limit to how small the pupil can be when reimaging a relatively large FoV on a large telescope. As this result has been obtained from a physical law, this result has been for a few time interpreted as one of fundamental nature or, in other words, unavoidable unless one breaks the physical law (an attractive option, indeed, but we are not yet ready for such a big leap). The results mentioned so far does apply to both pupil-plane wavefront sensors (as the layer-oriented one) as well as to the physical size of DMs. This conclusions, however, turn out to be false without requiring any exotic variation. The Lagrange invariant, in fact, does apply only when the full FoV is reimaged through the pupil in a continuous way. It can be easily shown that by changing the pupil size locally around the few object of interest (the reference stars) the pupil can be shrunk with very conventional optics (as the covered FoV around the target can be as low as less than one arcsec) and later the set of beams so shrunk can be reimaged into a single beam. This concept is applied in the layer-oriented wavefront sensor we build up in the laboratory as well as for the design of MAD and for NIRVANA. The same procedure applies to DMs. Let us assume one has a relatively small DM where he/she can realistically convey starlight only from a certain relatively small FoV that is going to be used for scientific purposes. Illuminating the DM with starlight coming from stars in an even significantly larger annulus around such central FoV would again look unfeasible. There are at least two ways to overcome such a problem. The first is to enlarge again the focal ratio of such stars and by introducing them into a marginally larger annulus around the scientific FoV, so that the corresponding beam can be interested by the DM and hence used to have some closed loop signal; another option is to optically translate such stars into an homometric copy characterized by a smaller physical size. Both examples show how the assumption made in the conclusion outlined using the Lagrange invariant were much larger than the real one (reimaging of the whole FoV instead of reimaging of only a limited number of non-continuous, small patches) and hence the conclusions where, to some extent, incorrect.

4.3. Where are the Laser Guide Stars?

As MCAO with solely NGSs has to deal with relatively poor seeing, shorter wavelength, and Strehl requirements that becomes larger and larger, there is some chance that, in spite of the possible uncovered variations that could be exploited in the near future, sky coverages would becomes acceptably low. This raises the question of how to efficiently use LGSs in such a situation. Current views about LGSs wavefront sensing badly scales up with telescope diameter. I just recall here the main problems:

- Perspective elongation becomes of sizes of the order of 10 arcsec;
- Differential aberration introduced by the limited range of the source are of the order of several dozens of μm and has to be carefully calibrated;
- Dependence of the latter from the effective height of the LGS beacon has to be fully measured in real-time;
- The inclination of rays originating from a close LGS can be very large, requiring the optical system to convey such a large FoV onto the focal plane (and it is interesting that in such a situation the FoV can easily become much larger than what required by M-FoV; with solely NGSs, also one should recall that in this way the correctable thickness of atmosphere can become very small);
- Focal plane position where LGS beacon images form can become physically much distant from the conventional focal plane.
- Depending upon the design of the telescope, an image of object as close as 100km can simply never forms as such a distance is too small. LGS reimaging for an ELT is really macrophotography, as it has been sometimes mentioned by Philippe Dierickx.

All these (and others more subtle that are not going to be discussed here) effects can be attacked one by one by revisiting the design of the telescope, by assuring the proper physical places in the focal plane volume.
and by, very likely, using gated LGSs. All these problems can be solved in a single shot by using a completely different approach. Here we show one of these but there is no evidence that this would be the only one.

Let us assume to collect the light coming from a Sodium beacon with an ELTs by physically limiting the light as coming from a virtual infinite source of circular shape (see also Fig.2). This corresponds into having on the focal plane conjugated to infinity a single circular slit. Not all the portion of the pupil will be interested by such rays. Several circular slits, corresponding to several circular virtual sources at infinity can be made in place. We'll assume that these will cover the whole telescope pupil, even with severe overlaps (that is that a point on the pupil can be interested by a number, even large, of virtual sources). This light, as coming from infinity, will exhibits the same aberrations as the ones coming from the sky in the given off-axis. When the linear obstruction ratio of the telescope is significant (for instance approach the usual $\varepsilon \approx 0.3$) the coverage of the pupil can be obtained with a reasonable number of virtual rings spanning a FoV of the order of one to two arcmin, depending upon details on the beacon and on the telescope aperture.

A reimaging of the pupil after such selection will leads to an illumination map that, not surprisingly, will be proportional to the second derivative of the wavefront as measured radially. In other words, establishing normalized coordinate polar system over the telescope pupil $\rho$ and $\theta$ the illumination of the pupil will be of the type:

$$I \approx I_0 \left(1 + k \frac{\partial^2 W}{\partial \rho^2}\right)$$  \hspace{1cm} (2)

where $I_0$ is the illumination of the pupil without any aberration, depending upon how is the distribution of illumination of the beacon and on how and where the circular slits are placed or, in other words, from the geometry of the layout. This can be easily understood if one think that a curvature of the wavefront along a radial direction will translates into feeding into the circular slit of a smaller or larger portion of the beacon.
length, translating directly into a modulation of the light. In order to conceive information also along the angular direction a reflective rod can be placed in the system, similarly to what has been conceived for the so-called $z$-invariant wavefront sensor. The resulting effect is that the reimaging of a pupil through a reflective rod can give a Laplacian signal of the wavefront, as it is described in polar rather than rectangular coordinates (as it is for instance in the conventional curvature WFS). The value for the proportionality constant $k$ can be easily computed and one can see that deformation of the wavefront of the order of a wavelength gives a strong modulation on the light intensity. Also, it is noticeable that the fraction of light collected by a circular slit, at least in the region of the pupil illuminated, is of the same order of the fraction one would get for a pulse timing gating approach on the same beacon. However multiple gating is straightforward (it is enough to place a larger number of circular slits) and does not require any pulse format on the LGS (actually it works as well with CW LGSS). It is interesting that one can reformulate such an approach describing the process as an angular gating, as opposite to the conventional timing one.

5. A SHAMELY COMPARISON WITH MICROSCOPY

The pyramid wavefront sensor,\textsuperscript{15} is a phase-contrast microscope, the layer-oriented wavefront sensor is a confocal microscope,\textsuperscript{16} so you can maybe think that I spent most of my time reading the Journal of Optical Microscopy and my interest toward the German language is due to the potential goldmine in Zeitschrift für wissenschaftliche Mikroskopie und mikroskopische Technik. As depicted from Tyson in his famous Adaptive Optics book, the technology to perform Adaptive Optics dates back to the 50s, but the strong interdisciplinarity among different fields (and, I would add, some orders of magnitude of further complexity with respect to a wide range of other optical systems) make the development in this field significantly slower than others, so looking for what microscopist did and are doing, is just an extension of the process that led to the current and future generations of Adaptive Optics systems. Future prediction is not an easy task but there is clearly a topic potentially hot for astronomers: super-resolution. The Rayleigh limit, as dictated by the Heisenberg uncertainty relation is almost routinely overcome in optical microscopy and, although I'm not enough in the field to be sure this record is a current one, an improvement of a factor 23 has been achieved in optical microscopy.\textsuperscript{17}

Of course there is no any breaking of the Heisenberg uncertainty relation. The latter can be reformulated in a way that a photon collected by a telescope of aperture $D$ can be localized onto the focal plane with an angular accuracy of $\approx \lambda/D$. This turns out because the entrance pupil imply a measure of position in the plane normal
Figure 3. Leftmost box: an optical system with an aperture $D$ collecting a single photon of wavelength $\lambda$ should give an uncertainty in the momentum along the pupil plane corresponding to an uncertainty in its arrival direction equal to $\lambda/D$ and in fact the corresponding probability expectation distribution should give such an uncertainty, as depicted by the width of the small bar below the focal plane of the pictured telescope. Center box: when a larger number of photons are collected the uncertainty on the position of arrival of the source is known with a better accuracy, as the width of uncertainty scales with the inverse square root of the number of collected photons; for instance collecting 100 photons the uncertainty Heisenberg relationships allow to estimate the angle of arrival with a resolution ten times better than the Rayleigh limit. Rightmost box: an inefficient system needing 100 photons coming from the same source to deliver a single photon on the focal plane with a expectation distribution that is 10 times smaller than the conventional one does not break the uncertainty Heisenberg principle; a viable solution to achieve such a task with an astronomical telescope is, however, still to be found.

to the line of sight while the angular direction implies a measurement of the photon momentum in the same plane. However the Heisenberg uncertainty principle, as quantum law, is substantially of statistical nature. The latter formulation apply to a single photon. In fact accumulating $N$ photons the angle of arrival can be estimated with an accuracy $\sqrt{N}$ times better. This is not the only way to fulfill the Heisenberg uncertainty principle: instead of a cluster of $N$ photons scattered over a $\lambda/D$ region, a single photon associated in some way to $N$ photons (and this translates into a lower throughput or efficiency of the optical system, by a factor $N^{-1}$) reaching the focal plane with an uncertainty equivalent into the angular space of $\lambda/(\sqrt{N}D)$ will fulfill as well the quantum physics law. There will be no difference, for instance, in terms of accuracy of centroiding of a spot. There will be also no difference in detecting an object against a uniform background, so the limiting magnitude will be the same (but with exposure times proportionally longer, a factor favouring nevertheless ELTs) but a net increase in resolving power will be obtained. The concept described above is, in a certain sense, just a reformulation of the DeBroglie interferometer where a set of $N$ photons, if they are made to act collectively (for instance, at a beam splitter, they are all reflected, or all transmitted), has the same energy as a photon of wavelength $\lambda/N$. This will translate into a dependence upon the efficiency going linearly rather than with the square root as this last case would happen when the behaviour of the photons are supposed to be individually uncorrelated.

Finally I would like to remark that optical systems giving super-resolution are known in the literature\textsuperscript{18,19}, although a detailed and severe criticism is often required but it is beyond the limit of this paper. Sometimes for these upper, apparently fundamental, limits are reported. These refer to the practical way they are implemented and there is no proof that these limits (that, usually, exhibits efficiency by several orders of magnitude lower than the rough rules I explained a few lines above) can be overcome by different techniques. It is interesting that the various techniques differs, and maybe can be classified (a technique useful to discover new techniques) by the way the photons are lost, because of the low efficiency. For example, in some cases these are confined
into an annular region around the line of sight (placing practical limits to the covered FoV), sometime the light is reflected back toward the observed object, and several other examples could be formulated.

In the comparison with microscopist, other than a pure matter of positive interdisciplinary competition, one should be warned that in the near-field case the object can be actively illuminated, and observed from all around, a couple of possibilities well explored by microscopist that are inherently not allowed to our starry community. It is noticeable that micro-lithography, in order to produce electronic (and, in a somewhat near future, optical) micro-circuits is as well in the business of super-resolution with a much larger capabilities of translating new finding into economical improvements. As a final comment concerning a non-astronomical community that in the past played a great role for Adaptive Optics, one should mention that, if these techniques are known to military scientists, these are, very likely, classified.

6. CONCLUSIONS
I summarize hereafter which is my current roadmap for achieving AO on ELTs, or at least what would be my starting point in the development of a concept for such a goal, with a time-framework compatible with current schedules circulated in the literature about ELTs:

- Use, initially, NGs as much as possible: they are easier, cheaper and more reliable, than any other artificial sources (maybe with the exception of the sky background, for which a suitable wavefront sensor is still pending to be discovered, if any); the use of NGs will also educate to take care of any single precious photon, making the use of any further artificial reference system less demanding and more reliable (for instance, requiring lasers with less output power);

- When switching to artificial references, adopt schemes that uses such references in parallel beams coming from infinity, within a FoV not larger than what is required by NGs;

- Do not use approaches that places any restriction on the pulse format. This would be left free to be eventually used to maximize the photon return. In other words there is enough constraints from the NGs firing system itself, that additional constraints coming from the concept would limit further and likely in an unacceptable manner, the NGs firing system;

- Any concept based upon a Rayleigh LGS other than a Sodium one is clearly better in terms of availability and reliability of the LGS system. Of course this statement could be made a surpassed one whenever the current plans for Sodium LGSs actively pursued at Gemini, Keck and VLT will prove successful. A knowledge we’ll have in a few years from now. I’m afraid to say that in the current, inverse Bessel beam scheme I proposed, I rely on Sodium LGSs. A solid solution, if any, with Rayleigh beacon, could turn out to be superior;

- Gate in a static optics fashion way, that is in other words not to introduce further constraints onto the detector or super-fast shutters. Several concepts requires detectors acting on picoseconds scale, clearly such detectors has still to come and likely will not be as efficient as current ones.

The rationale behind this roadmap is essentially to develop NGs based system and then use concepts that takes advantage of all the development (in the areas of optics, reconstruction techniques and detectors) obtained so far. I recall again here that 8m-class demonstration programs are possible and should be actively pursued. It is noticeable, however, that the proper scaling would assume to use Rayleigh beacons on 8m class telescopes to mimic Sodium ones aboard ELTs. Starting to act now we should have in a few years convincing experiments carried out on the currently largest telescopes showing how effective is MCAO and LGSs wavefront firing and sensing. How much the following times will be exciting and will push toward one, or more, concepts to achieve diffraction limited imaging on Extremely Large Telescopes is just a matter of how much efforts the AO community will spend in such a direction.
Acknowledgements

Thanks are due to a number of people for the endless discussions about the topics discussed here: Roger Angel, Carmelo Ardiciono, Guido Brusa, Philippe Dierickx, Emiliano Diolaiti, Simone Esposito, Jacopo Farinato, Wolfgang Gaessler, Adriano Gnedina, Roberto Gilmozzi, Stefan Hippler, Enrico Marchetti, Guy Monnet, Erez Rütak, Armando Riccardi, François Rigaut, Piero Salinari, Elise Vernet

Special thanks are due to the Alexander von Humboldt foundation that made possible for me to share a 50/50 position between Italy and Germany through the Wolfgang Paul prize.

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