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Letter to the Editor

Feasibility of adaptive telescope with laser probe

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SUMMARY

Adaptive optic promises huge gains for large telescopes, but is not applicable to faint fields. We discuss the possible use of laser pulses to create artificial reference stars. Backscattered laser light from atmospheric layers at 15 to 100 km altitudes appears to provide enough photon events to activate a fast seeing correction system. With an array of projected spots, the isoplanatic field can be substantially improved. Further investigations are desirable, using laboratory simulation and computer models.

Keywords: Adaptive optics, seeing, telescope, high angular resolution.

I. INTRODUCTION

Adaptive optics can improve enormously the performance of optical telescopes, especially those of 15-25 meter equivalent aperture currently studied in different countries. It has indeed been shown that close-loop corrections of the atmospheric disturbances can produce diffraction-limited images in narrow fields spanning a few arc-seconds. A major limitation of this approach, however, arises from the requirement that enough photon events be recorded from the observed source during the seeing lifetime to map the corrugations of the optical wave. Estimates of the corresponding limiting magnitude range from 10 to 13 (Hardy, 1981; Woolf, 1984; and Foy, 1984). The probability to find a bright enough source within the isoplanatic field around a given object is very low, mainly above the galactic plane. It is quite unfortunate that the technique fails to be applicable for those faint objects on which it would be most beneficial.

Is it feasible to use a laser probe as a reference source providing the required information on instantaneous seeing ? We present preliminary evidence suggesting that such may be the case. Because this potentiality can influence the philosophy of VLT's, NTT's or projects for very high resolution imaging (Racine, 1984), it deserves to be investigated in some detail.

II. PROPERTIES OF BACKSCATTERED LASER LIGHT

If pulses of laser light are emitted from a point source near the focal plane of the telescope, towards the sky, a small proportion of the light is backscattered into the telescope aperture by atmospheric layers up to altitudes of 100 km. Mie scattering from dust, Rayleigh scattering from molecules or resonance scattering from sodium atoms are expected to return enough light to activate an adaptive seeing correction system (section IV).

A shutter can select light returning from any desired altitude range and reject the light from undesired layers. At 100 km altitude, the laser beam can be focused into a spot of 50 cm transverse size, under conditions of 1 arc-second seeing.

If emitted by the large aperture, rather than by an auxiliary telescope, the laser spot will contain many speckles. The coherence of the backscattered light is however strongly degraded, owing to the velocities of the scattering particles, and to the thickness of the scattering layer. The artificial reference source thus created therefore appears as an extended incoherent source featuring many speckles. The size of this apparent source, and its speckled structure, do not significantly affect the adaptive optics schemes usually discussed. The Hartmann method, modified by Schack (1971) to allow the real-time mapping of wavefronts, uses subapertures of a size comparable to seeing cells, and therefore tolerates a source size comparable to the seeing angle. Shearing interferometer schemes also tolerate extended sources.

We did not find a simple analytical description of the returned image, near the focal plane of the telescope. Yura and Churnside (1984) have investigated properties of the speckle pattern of laser light backscattered by aerosols, having a much longer lifetime than speckles from molecular scattering. So we have verified through simple laboratory simulations that no unexpected effect occurs. With a stationary scatterer simulating the high altitude atmosphere, the returned image of the laser spot is comparable in size to the seeing angle, and exhibits speckles having the usual appearance. Their lifetime is similar to the seeing lifetime, as would be the case on a stellar source. With a fast moving or fluctuating scatterer representing more realistically the upper atmosphere, the returned image features fast moving speckles, according to expectations. The lifetime of these speckles in the real case should be on the order of nanoseconds, owing to the radial velocities of atmospheric atoms in the scattering layer. With its comparatively slow response, the Hartmann camera will see a smoothed image of these speckles, and the laser spot will therefore appear as an extended incoherent source.

In practice, the main foreseeable difficulties are the apparent magnitude of this reference source, which will be shown to be just bright enough (section IV), and the slight difference between the conical propagation path of the laser beam, having a focus around 90 km altitude, and the cylindrical path of the stellar beam.

This latter problem has no practical influence on the correction of low-altitude seeing, but degrades the correction of higher seeing at altitudes on the order of 10 km. We discuss in the next section possible solutions involving several laser spots.

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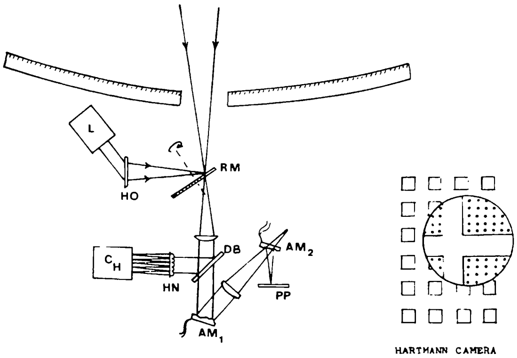

Figure 1. Adaptive optics with multi-spot laser probe for an 8-meter telescope. A pulsed laser L projects light spots focused at 15 km altitude, using the full telescope aperture. Backscattered light from these spots serves for real time Hartmann analysis and correction of wavefronts, in a field wider than the normal isoplanatic patch. A 10 x 10 array of spots is generated by the holographic optical element HO. Its projection at the working altitude is an array of spots spanning an area slightly larger than the telescope aperture. Rotating mirror/shutter RM (suitably concave in order to reimage the hologram onto the aperture) is synchronized with the laser pulses. Dichroic beam-splitter DB feeds returning laser light to Hartmann screen HN, made of a lens array containing 100 x 100 elements. The Hartmann camera has electronic shuttering to select the desired altitude range of the backscattered light. Active mirrors AM1 and AM2 correct respectively the low and high-altitude components of seeing, for improved isoplanaticity. A diffraction-limited image is expected on the photographic plate PP. On the Hartmann camera CH, each of the 100 x 100 images provided by the subapertures is itself an array of 10 x 10 points (see insert)

III. ISOPLANATICITY AND CONE EFFECT IMPROVEMENTS

In order to correct the cone effect and at the same time increase the isoplanaticity field, it can be envisaged to project several laser spots onto the high-altitude scattering layer. Figure 1 shows how a square array of spots can be projected with the full pupil of the telescope. With each Hartmann subaperture observing only one spot, the one located "in front" of the particular subaperture, the cone problem is solved for the particular direction corresponding to the "in front" relationship just mentioned. Indeed, the up-going projected array of spots is not significantly distorted by seeing, since the projecting aperture, which is the telescope itself, is much larger than seeing cells. This can in principle be achieved in several slightly different directions simultaneously, so as to increase the isoplanatic patch. If the full array of spots is seen by each Hartmann subaperture, processing adequately the camera image, which contains an array of spot arrays, can yield the correction pattern for all directions in a field wider than the isoplanatic patch.

The available photons from the artificial source are shared by these many spot images, so that the number of photon events per spot appears too low for operating the system. Fortunately, there is a high redundancy and room for comprimising the number of spots. Instead of 100 x 100 spots projected by a 8-meter telescope 10 x 10 could probably suffice. Indeed, their apparent angular spacing would be comparable to the isoplanatic patch. Thus groups of 10 x 10 Hartmann subapertures could use a single spot as a common source. It is unclear yet whether such compromises will prove suitable for a workable system. In particular, the Hartmann camera should have about 10^8 pixels for correcting a 8-meter aperture, and its response time should be as short as a few milliseconds.

At least two "rubber mirror" elements, correcting respectively the low and high-altitude seeing, appear necessary to extend the isoplanatic patch. Whether the corresponding correction for non-isoplanaticity can be rigorous, or only approximate, and in what field, deserves to be investigated.

A side benefit of the multi-spot technique is that the scattering layer utilized does not have to be as high as with a single spot. Indeed, the correction of the cone effect makes it possible to work on scattering layers only slightly higher than the highest "seeing" to be corrected. 15 km could thus be adopted instead of 90 km, thereby improving the amount of laser light returned into the telescope.

IV. REQUIRED TECHNOLOGY

The simplified presentation given is not very accurate since the situation is in fact rather complex. Digital simulations can probably clarify the exact applicability and feasibility of the laser shooting technique, but experimental tests will be required for a realistic feasibility study.

A practical version of the single-spot laser probe system of adaptive seeing corrector could work as follows: laser pulses lasting 0.1 millisecond or less are emitted every 5-10 milliseconds from a source located slightly behind the focal plane, for optimum beam concentration at the working altitude. Using mechanical or electronic shutter techniques, the returning beam is diverted towards the lens array serving as the Hartmann screen.

An intensified camera sees the Hartmann pattern, and an associated fast processor activates the phase correction element (Hardy, 1981; Fontanella, 1985) as required to compensate the seeing-induced pattern of phase defects.

Different types of lasers appear suitable. The intensity of the backscattered light depends sharply upon the scattering mechanisms involved. Possibilities are Mie and Rayleigh scattering, particularly strong at violet and ultra-violet wavelengths; resonance scattering on atoms such as sodium, for which the scattering cross-section reaches about 0.3 square micron at the yellow wavelength; molecular absorption scattering in the ozone layer, or in visible molecular lines.

Particularly attractive is the resonance scattering by sodium atoms at NaID wavelength, because it occurs at the highest altitude: the effect of conical propagation is then minimum. According to Megie and Pelon (1985), who operate a LIDAR system at Observatoire de Haute-Provence for high altitude atmospheric studies, they detect 5 photoelectrons from a 300 m thick layer in the maximum efficiency layer; they use a 80 cm aperture telescope and a YAG laser of 0.5 J pumping a dye laser, for which the efficiency is 40% at 5891 Å and the pulse frequency is 10 Hz. If the integration time is increased to 70 μs (which corresponds to a thickness of 10 km, the detected backscattered flux is expected to range around 200 photoelectrons per pulse, taking into account the efficiency of the resonance scattering with respect to the altitude. This flux could rise up to 300-400 photoelectrons if the laser operates from a high altitude site.

According to Bely (1983) and Racine (1984), seeing conditions as good as 0".5 are not exceptional on the Mauna Kea site. The corresponding mean size of turbulent cells is $r_0 = 20$ cm at 5900 Å. The detected backscattered flux is 5 photoelectrons per seeing cell, or per Hartmann spot. One or two more orders of magnitude would be necessary, and it can probably be achieved with more powerful lasers (a gain by a factor of 5 is easily attainable).

Another possibility is to work at shorter wavelengths. Rayleigh scattering is then the main source of backscattered photons. At Observatoire de Haute-Provence, 0.4 J pulses of green light provide a detected backscattering into the 80 cm collecting aperture of about 100 photoelectrons from altitudes between 40 and 46 km. This is quite low from the point of view of the conical propagation effect, but the atmospheric density rapidly decreases at these altitudes, so that Rayleigh backscattering from higher layers is a lot weaker. Excimer lasers operating in the near ultra-violet reach 1 J per pulse with repetition rates of 100 Hz, and 1 KW average power, with repetition rates of 1 KHz is expected to become available. Rayleigh scattering is about 6 times more efficient at UV wavelengths (λ 3500 Å) than in green light, but a large proportion of this gain is lost because of the increased Mie scattering on atmospheric dust. For a low altitude site the resulting gain is ≅ 2.5, leading to ≅ 600 photoelectrons with a 1 J laser. Is is again larger, by a factor of at least 3, for a high-altitude site, because of the decrease with altitude of the column density of dusts and aerosols. The resulting flux per Hartmann subaperture, under seeing conditions of 0".5, is expected to be ≅ 20 photoelectrons, taking into account for the smaller size of r_0 (13 cm) at UV wavelengths. This flux appears almost adequate with existing lasers. With a 10 x 10 spot array backscattered by 15-20 km altitude layers, the flux is expected to be about 2 photon events per laser spot per Hartmann subaperture, taking in account the higher scattering. The one-kilowatt excimer lasers which have been announced should improve things by one order of magnitude.

V. CASE OF LONG BASELINE INTERFEROMETERS

Arrays of several telescopes organized for coherent recombination can probably also benefit from laser shooting techniques. Reaching diffraction-limited light concentration within each aperture is already a huge improvement. Active phasing of the apertures relative to each other is more difficult since it would require that a single artificial reference source be observed by all apertures. Owing to the moderate altitude of the apparent source, and to the wide spacing of the telescopes, difficult field problems would arise. Because of the small number of apertures involved in the large systems currently planned (4 in the VLT case), lack of multiaperture phasing does not degrade very much the limiting magnitude. It however makes it more complicated to generate reconstructed images through aperture synthesis. In the VLT case therefore, it is perhaps not justified to attempt multiaperture phasing, in view of the considerable gains in limiting magnitudes achievable if laser shooting techniques can be implemented separately on each 8-meter telescope. The gain would enhance conventional observing, diffraction-limited observing with individual telescopes and long-baseline interferometric observing. Infra-red interferometry should also benefit from visible or ultra-violet laser shooting.

CONCLUSION

Preliminary estimates for the use of a laser probe as a reference star suitable for adaptive optical corrections of seeing suggest that the approach may be feasible. Laboratory simulations show that the laser spot can serve as a Hartmann source. Levels of backscattered light to be expected are adequate with some of the most powerful lasers currently available. Isoplanaticity corrections should be possible, although they require significant technical developments. Considerable gains in sensitivity and limiting magnitude can be expected for large ground based telescopes such as the VLT and the NNTT if laser shooting techniques can be implemented.

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