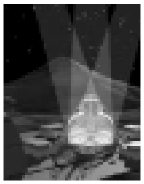
Venice 2001
**Beyond
Conventional
Adaptive
Optics**



Low power laser guide stars and wide field of view

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ABSTRACT

What is the number of photons that are required for multiconjugate adaptive optics? For sodium layer beacons, the minimum required is three or four lasers; for fringes created by a single laser, the total power is even higher. This is due to an inefficient scheme of detection and digital processing. We suggest that by processing optically the light, the efficacy of multiple wave front sensing is enhanced. Where a 12W laser was sufficient for an integrated measurement, we can use a 15W laser for two layers. This is achieved with Moiré demodulation of mesospheric laser fringes using a pyramid array. Holographic gratings can replace the pyramids and simplify the optics even further.

1. INTRODUCTION

The field of view in adaptive optics is limited. Natural guide stars can be used to measure a wider volume of atmospheric turbulence for multiconjugate correction to take place. Multiple wave front sensors are necessary to measure the light from each star and detect the turbulence it traverses. Even then, the number and intensity of stars are barely sufficient for this purpose (Ribak 2000a).

The amount of light needed to measure two turbulent layers is not much more than that needed to measure the integrated atmosphere. This is especially true if one of the layers has a larger isoplanatic area. Thus, one should expect that by using less than twice the light, the two-layer problem should be solved. Using laser guide stars, at least three are necessary around the rim of the telescope for this purpose, and there are some indications that indeed less light might still be useful (le Louarn *et al.* 2000). Thus, one should strive to improve the efficiency of wave front detection. The multiple-pyramid scheme is a step in this direction (Ragazzoni 2000).

2. FRINGES IN THE SKY

Sandler (1992), and then Baharav *et al.* (1994) and Gavel *et al.* (1998) proposed to use a powerful laser to create Rayeigh or sodium fringes. Three beams from the same laser are sent from above the central obscuration of the telescope, approximately 5cm apart in two dimensions. They open up to a cone large enough to sample the turbulence, interfering all the way up. The fringes are visible only when scattered from low dust or high sodium atoms. Light from these fringes crosses the atmospheric layers, deforming in shape as it travels down towards the telescope. The deformations are sensed and the atmospheric structure is extracted from this information. This method is known in image processing as structured light. The laser fringes can be replaced by plasma fringes, created by intensive radio beams (Ribak 1997).

Analysis of the fringe deformations is achieved by a combined optical-computational method. As with discrete laser guide stars, the images of the fringes are taken through a Hartmann-Shack lenslet array. At the focus of each lenslet in the array, a multiplicity of pixels samples the deformations in the fringes (Baharav *et al.* 1994). This method was recently adopted also for individual guide stars (previously each such star had a different lenslet array and a separate camera). High turbulence distorts the fringes in each lenslet, whereas the boundary layer just shifts the pattern as a whole. Digital Fourier demodulation of the images of the fringes separates the atmospheric layers (Baharav *et al.* 1994).

The main disadvantage of the analysis of discrete lasers and fringe patterns is their use of Hartmann-Shack sensors, which is followed by processing of the data. The large number of pixels required to sample properly the spots or fringes is large, and prohibitively so for decameter-class telescopes. The solution lies in optical

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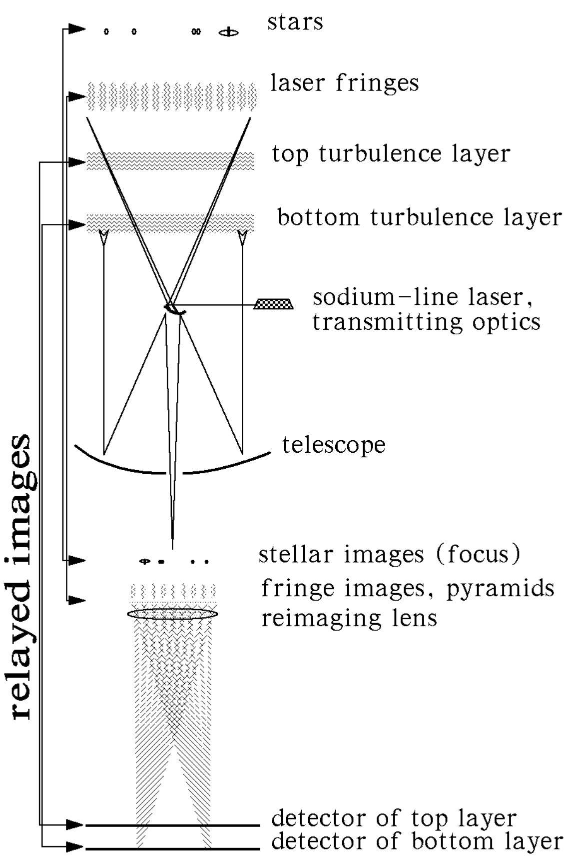

Figure 1. Fringes are formed in the sodium layer, and distort on the way down to the telescope. They are imaged on an array of pyramids, and the resulting refracted beams create separate images of the atmospheric layers with the gradient information encoded in intensity.

pre-processing of the data, which can increase the efficiency of calculation (Matik and Goodman 1989). Indeed one should be hopeful: scaling from one integrated layer to two separate ones, the product of the total number of turbulence cells and their speed, equivalent to a space-bandwidth product, increases very little, if at all. Suppose that a telescope of diameter D_0 encompasses isoplanatic cells of size r_0, to be read within a time t_0 (the inverse of the Greenwood frequency). If n photons establish the slope in this patch during this time, then $nD_0^2/r_0^2t_0$ photons are necessary for the telescope during 1 second. Breaking the atmosphere into two layers, each has a larger patch, say r_1 and r_2, to be read out more slowly, within times t_1 and t_2. At the same time, the area to be measured is somewhat larger for the low layer, say D_1 and even larger D_2. This is because the measured volume is a truncated cone, opening up by the astronomical field of view. The required number of photons will increase by a factor $\frac{t_0}{t_1}(\frac{D_1/D_0}{r_1/r_0})^2 + \frac{t_0}{t_2}(\frac{D_2/D_0}{r_2/r_0})^2$. For most observatories, this factor is close to one, hardly ever exceeding two. In those cases where it is *below* one, it is worth it to measure two layers, even if correction is made only with one mirror. If the required power for a single laser star and 10m telescope is 10-12W, the power required for will scale accordingly up to 12-15W, rather than 300-500W as required by previous analysis schemes (Baharav *et al.* 1994).

3. ANALYSIS OF THE FRINGE PATTERN

Following these arguments, an optical demodulation of sodium fringes is suggested as a replacement of the digital one (Ribak 2000b). As is well known, small deviations from a periodic pattern are achieved by multiplying the pattern at the accurate period and integrating the product - this is the essence of demodulation. Optically, this is the familiar Moiré method. Unfortunately, in astronomy we cannot afford to multiply the few arriving photons by an amplitude mask, so a new concept is introduced: Moiré loss-less demodulation. Usual Moiré

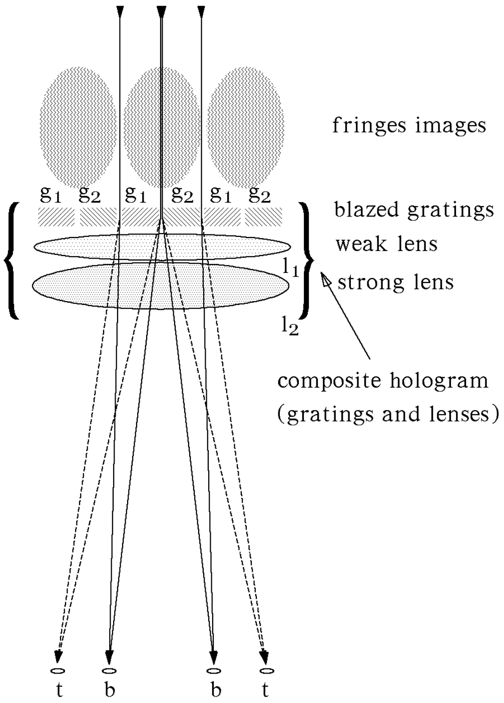

Figure 2. By using gratings g_1, g_2, quadrant sections of the fringes can be fully deflected in different directions. The two lenses l_1, l_2 for re-imaging the top and bottom layers can be incorporated into the same hologram. The separate beams for these layers are natural orders of the grating.

techniques absorb the light that does not pass through the multiplying mask. It is proposed to reflect the light, which is usually blocked, into a second detector for higher efficiency. This is achieved by a partially reflecting single mask at a slight angle to the incoming beam. Using a deflecting array simplifies matters even more, since all beams continue in the same general direction, and more than two beams are possible. Hence it also allows the application of the method to fringes at different directions.

In the simplest realization, the image of the checkered fringes is passed through an array of pyramids (Figure 1). The period of the fringes is tuned to match the pitch of the pyramids. Since the intensity is sinusoidal, small manufacturing errors in the edges of the pyramids are insignificant. These edges face the maxima of the fringes, where the intensity variations are the slowest. Four beams are produced from each pyramid, which continue and diffract, until they merge. Further down the beams, detectors are placed in the four images of the atmospheric layers to be probed. This is the adaptation of Ragazzoni's scheme from a few stars to a regular array, and hence it provides a much more regular coverage of the detected area; irregularities arise more because of patchiness in the sodium layer.

The sizes of the isoplanatic areas of the different layers and their Greenwood frequencies are not the same. This means that the pixels in the detectors have to be binned and clocked out differently according to their layer. This is where the great advantage of this method is, as calculated above.

4. OPTICAL SYSTEM

The fringes are imaged on an array of pyramids. This array is very similar to commercial lenslet arrays, except that its surfaces are flat and tilted and not curved. It is also similar to a retro-reflector array, but much shallower. Behind the pyramid array there is a beam splitter, to separate the images of the top and bottom layer. Magnification of the images according to the atmospheric turbulence is achieved by another lens before the detector. Alternatively, one can alternate between two magnifications and focus the two layers on the same detector.

Another option is to use an acoustic cell to create the refracting array (Ribak, 2001). The benefit of this array is its flexible spacing, which does not require tuning of the fringes to the array, but the other way round.

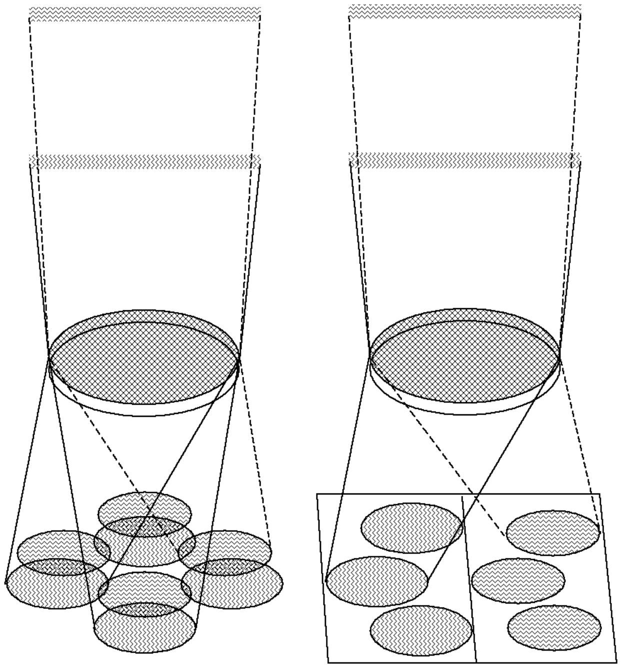

Figure 3. Left: A pyramid array creates eight successive images of the atmospheric layers, which have to be separated by beam splitters. Right: Trilateral pyramids (and fringes) produce three images of each layer, reducing even further the required laser power. A holographic array places the images of the layers side by side on the same detector.

Yet another possibility, which is not as flexible but is well suited to the monochromatic fringes, is the use of computer-generated holograms or gratings. Here all focusing, splitting and re-imaging is by such holograms (Figure 2). For even higher efficiency, the pyramids (and fringes) can be trilateral and not quadrilateral: the number of images drops from eight to six, and the laser power is reduced by further 15%.

5. SIMULATION

In order to have an understanding of the method, we ran a crude simulation of the array of fringes, of the intervening atmosphere, and of the optics. An array of 145 stars is arranged along 5 × 5 lines spaced 30 arcsec apart, with individual stars every 10 arcsec. This is a low order approximation of the set of fringes. This pattern was propagated down through the seven-layers model used by Gemini, at K band. This was using the first version of the simulation code (Ragazzoni *et al.* 2000), and it ran for 2.6 hours on a Pentium II PC. The isoplanatic patch is much larger and it can be conceived as a scaling of 5 arcsec spacing from the visible to the K band, although pupil displacement does not depend upon this (Figure 4).

The result of the simulation is indeed a very flat field (Figures 4 and 5). This is clear in the plot of the Strehl ratio as a function of the field measured on all the used stars. The stars are truncated in a quadratic shape and the wave front is not extrapolated outside the footprint of the stars. In other schemes involving few separate lasers, the correction is good next to the lasers or at chosen points (Fusco *et al.* 2000), but not at all of them.

6. SYSTEM ASPECTS

The marriage of the concepts of laser fringe projection and pyramid wave front detection should produce successful offsprings: measurement of two or more atmospheric layers with reduced laser power, with homogeneous coverage of the atmospheric volume. This homogeneity is only spoiled by the sodium layer itself not being a perfect screen. However, this blotchiness varies much slower than turbulence, and can be combined into the

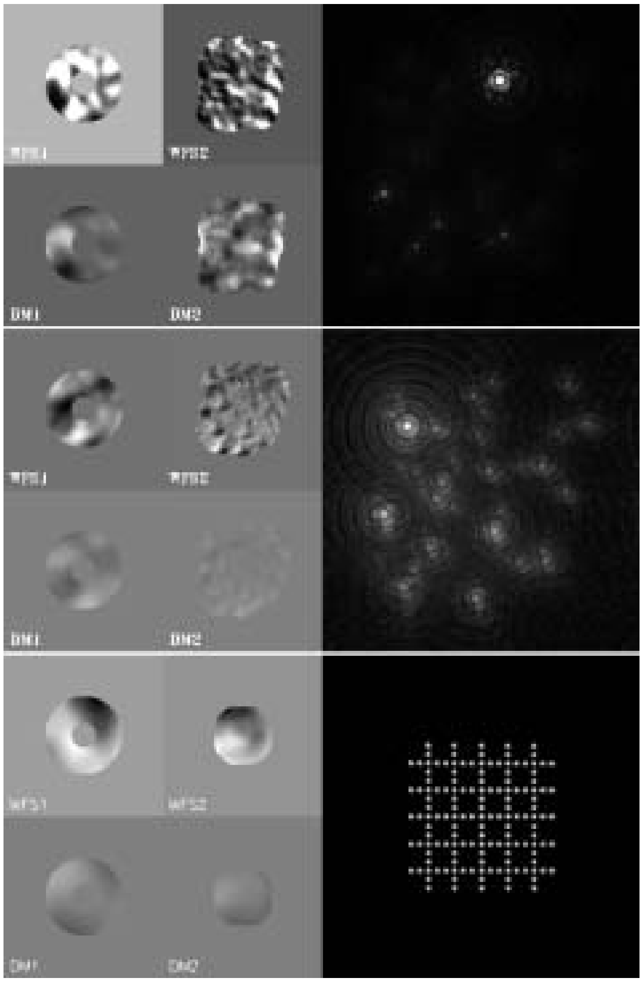

Figure 4. Three simulations are compared, with natural guide stars (top two panels) and with a laser array mimicking the fringe pattern (bottom). After compensation, the array (right subpanel) has a very smooth distribution on the high and low wave fronts (top left subpanels) and on the mirrors (bottom left subpanels).

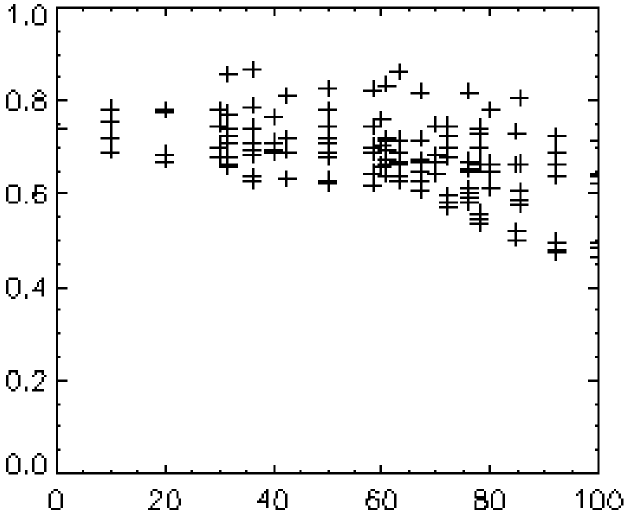

Figure 5. Strehl ratio for a noiseless case ($m_v = 0$ stars) across a field of view of 100 arcsec.

detection algorithm (at any rate it is much better than that from discrete stars). The very low power, and its spread over a much larger area, cannot lead to saturation effects as with single laser guide stars. However, all the power is required out of one laser, not three or four as with the other schemes. Sending the beams from above the secondary mean that some of the light does get entangled with the astronomical path, and some scattering might hamper faint observations.

Other benefits arise because of the optical processing of the data. The pixel size, read-out rate, and conjugation level can be changed quite easily. The prism array is easy to manufacture and its accuracy is not essential, because the fringes are coarse (1-2m period). The possible use of diffractive optics is also encouraging, but it raises the question of coherence. Since the light is monochromatic, we might get interference patterns between the combining beams on the detector.

Finally, the fringe elongation problem might probably limit the method to relatively smaller telescope. For all the fringes to move in unison, they must be projected through one isoplanatic patch. Apart from the global tilt error this raises, one should also carry in mind the fact that when observed from the side, the fringes hide each other through the thickness of the atmospheric sodium layer. For a layer extending from elevation G to H, and a distance R between the laser source and the observer, the fringes will not obscure each other if the period is $R(1-G/H)$. This period has to be in the range of 1-2m for proper atmospheric sampling. Thus, the maximum telescope *radius* is limited to 12m. This problem can be alleviated by either changing the magnification of the fringes on the pyramid array as the pulse of the laser crosses the layer, or by tuning the acoustic frequency in the flexible lenslet array (Ribak 2001). Alternatively, the spacing between the launching mirrors can be varied during the pulse to counter the widening of the fringes.

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