Near-Diffraction-Limited Visible Imaging on 10-30 M Telescopes with EMCCDs

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Abstract: Lucky Imaging routinely produces near diffraction limited images from the ground in the visible over arc minute fields of view. Our data suggest that models of atmospheric turbulence need to be improved as they show adaptive optics systems will be much harder to realise and had been appreciated. We mainly discuss a novel approach which should allow near diffraction limited images to be obtained in the visible using telescopes in the 10-30m class using techniques borrowed from radio aperture synthesis techniques. It uses an array of photon-counting EMCCDs using Lucky Image selection. It promises to offer much larger isoplanatic patch sizes as well as being markedly cheaper than adaptive optics/laser guide star methods.

Keywords: atmospheric turbulence, optical aperture synthesis, EMCCDs.

1. INTRODUCTION

The quality of science that will come from extremely large telescopes (ELTs) will be determined largely by the imaging quality of the telescope both in terms of point spread function and isoplanatic patch size diameter. Atmospheric turbulence limits the resolution that can be obtained on ground-based telescopes with long exposures to around one arc second, or slightly better under the best conditions and on the best sites. Virtually all attempts to improve image quality and telescope resolution have used adaptive optics systems where a reference star close to the science target is used to determine the phase errors in the wavefront entering the aperture of a telescope. These methods do work provided one can use a bright reference star. The high order correction achieved with the US Air Force Telescope in Maui is impressive. Unfortunately there are very few bright enough reference stars in the sky even for the relatively low order correction systems that are presently being developed. This limits very greatly the fraction of sky that can be observed using adaptive optics systems based on natural guide stars. Considerable effort has also been devoted to laser guide star systems that rely on creating an artificial star at high altitude that can be used to provide wavefront error information when no natural guide stars are available. The best adaptive optic systems such as those on the VLT and on Keck are able to produce an image resolution in K-band (2.2 µ) similar to that of the Hubble Space Telescope (HST), typically 0.1 arc seconds. In the visible no adaptive optics systems have been able to produce similar resolution even on Hubble size telescopes (2.5 m), despite the very considerable sums of money spent on these technologies.

Adaptive optics when it does work is still very limited because of the rather small isoplanatic patch size, typically four arc seconds radius in I-band at Paranal (Sarazin & Tokovinin, 2001). This is barely useful for real astrophysical studies as the point spread function varies markedly across the field in a poorly defined manner. Most adaptive optics studies are content to demonstrate that objects can be resolved from one another. Real astrophysics requires that we can measure their magnitudes and compare brightnesses in different parts of the field. Unless we can do this routinely, the appeal of adaptive optics systems to astronomers must be extremely narrow. It is often claimed that multi-conjugate adaptive optics systems will be much better at achieving this level of performance since they have the potential to correct for turbulence in different layers. Unfortunately, the results of Wilson (2002) using SLODAR systems on La Palma to measure C_n^2 as a function of altitude suggests that the turbulence is generally not well stratified. It is likely, therefore, that MCAO systems will deliver, at best, a modest improvement in performance.

In Cambridge we have been developing a different approach to obtaining near-diffraction limited performance on ground-based telescopes in the visible. Fried (1978) originally described "Lucky Imaging" which relies on taking images fast high enough to freeze the atmospheric turbulence. Provided there are not too many turbulent cells across a telescope (so that $D/r_o < 5\text{-}7$), a few percent of images will be near-diffraction limited. The sharpest selected images are shifted and added to produce a composite output picture. The larger the percentage of images used the poorer the resolution. We find we are routinely able to achieve 0.1 arc second resolution on 2.5 m telescope in I-band (850 nm) with 10% selection (Law et al, 2005). Deconvolution techniques on the less good images should allow increasing percentages of images to be used without markedly degrading the resolution.

These studies have produced very large numbers of short exposure (10-50 ms) images of stars and star fields taken under a variety of conditions. They have provided considerable insight into the nature of atmospheric turbulence as it applies in astronomy. Most importantly our results call into question some of the basic assumptions that underlie the design of most adaptive optic systems, assumptions critical to the design of ELTs.

2. ATMOSPHERIC TURBULENCE AT THE TELESCOPE

It is surprising how little systematic data has been accumulated on atmospheric turbulence on large telescopes. Perhaps the most comprehensive dataset comes from the JOSE experiments that recorded Shack-Hartmann data on an 8 x 8 array on the William Herschel 4.2 m telescope on La Palma. These results have been reported in detail by Wilson et al (1999). More recent studies on Paranal to characterise the atmosphere using the VLTI the had been reported by di Folco et al (2003) and reported at the Mini Workshop on Atmosphere and AO for Large Telescopes, Garching, 2003. All these results show that the turbulent spectrum has a power law significantly shallower from that predicted by the Kolmogorov model. A consequence of this is that many derivations of the turbulent outer scale, L_o, which depend on a measurement of turbulence over a relatively small-scale together with the knowledge of the total turbulent power and assumption of Kolmogorov turbulence greatly underestimate the size of the outer scale.

Although astronomers happily accept the Kolmogorov theory as a universal truth, other researchers are far from accepting it. In the fluid dynamics community it is widely agreed that the physics of turbulent dissipation in the atmosphere on the scales that matter to astronomers continue to be one of the most challenging problems. Astronomers concluded incorrectly that because the turbulent power spectrum is close to that predicted by Kolmogorov then the turbulence is indeed purely Kolmogorov. Our lucky imaging data help us to understand why this is much too simple. What we often see, even under conditions of the very best seeing, are steps in the phase front across the pupil. These phase steps change only very slightly the measured power spectrum and so are easy to ignore.

Astronomers often think of atmospheric turbulence as caused by a mechanical churning in the atmosphere. This is probably how it is generated at the edges of the jet stream but these motions are dissipated within a few turning times. The atmosphere is then made up of cells that are essentially isothermal and so of relatively constant refractive index next to other cells of slightly different temperature and of slightly different refractive index. Between them will be a step in phase as these cells move across the telescope aperture. The reality is more complex than this but it is widely acknowledged in a geophysics community (for example Wyngaard, 1992 and Sreenivasan & Antonia, 1997) that energy dissipation in the smaller scales of turbulence is unevenly distributed in space. This effect is called intermittentcy and increases steadily with Reynolds number. Turbulent atmospheric flows are characterised by enormous Reynolds numbers. What intermittentcy essentially means is that the probability of large amplitude fluctuations is greatly increased relative to what might be expected for a normally distributed random variable. This effect will increase the turbulent power at high frequencies and increase it at low frequencies, exactly what is found in the most detailed astronomical studies of turbulence. This is also found in the wide range of data published by a geophysics community, for example by Beyer et al, 2003 and by Dole et al, 2001) who also find that atmospheric turbulence has a power spectrum somewhat shallower than Kolmogorov with a transition to a yet more shallow slope on scales of 20-200m.

The consequence of these studies is that a strategy such as used by adaptive optics systems that assume the phase across the pupil is always continuous and where each time element t_o evolves in a well-behaved fashion towards the next time element is going to have problems in dealing with very sharp steps in the phase pattern across the pupil. Deformable mirrors cannot cope with such steps and so those regions around a step will be seriously mis-corrected. What is needed is some strategy for quality control of each and every moment that an adaptive optics system is functioning to make sure that only well-behaved parts of the telescope aperture are used to construct the final image.

3. THE IMPORTANCE OF IMAGE SELECTION

Our Lucky Imaging studies show that even under good seeing conditions there are times when images are quite dreadful. Data taken under those conditions reduce both the resolution and in particular the isoplanatic patch size of the final dataset. Under all conditions, even poor conditions, we find that image selection gives at least a factor of three improvement over the long exposure image resolution. We would expect that any adaptive optics system would also benefit greatly if they also used image selection. A different method of minimising the effects of poorly corrected elements in the pupil plane of an adaptive optic system has been simulated by Morossi et al (2002), though it may be difficult to implement. Image selection combined with an adaptive optics system should lead to a much higher percentage of the frames being usable than if no adaptive optics system was in use. It would also allow Lucky Imaging strategies to be used effectively on larger telescopes where otherwise the probability of a sharp image would be vanishingly small. It would be very easy to try this in practice and could allow much better image quality to be achieved than hitherto.

Lucky Imaging works very well on 2.5 m class telescopes and I-band and so should work just as well on 7-10 m class telescopes in K-band. Both will give close to HST resolution. Lucky Imaging behind an adaptive optic system working at wavelengths shorter than K-band on 7-10 m class telescopes should allow significantly better resolution to be achieved from the ground. However what we really need to look at are ways to achieve resolution much better than is obtained with HST. Unfortunately Lucky Imaging will not work in its basic form on telescope apertures where $D/r_o > 7$ because the probability of a nearly flat wavefront becomes vanishingly small. There are just too many turbulent cells across the aperture of the telescope. We need D to be large to give us good resolution but we do not want too many turbulent cells otherwise we have no chance of getting good images.

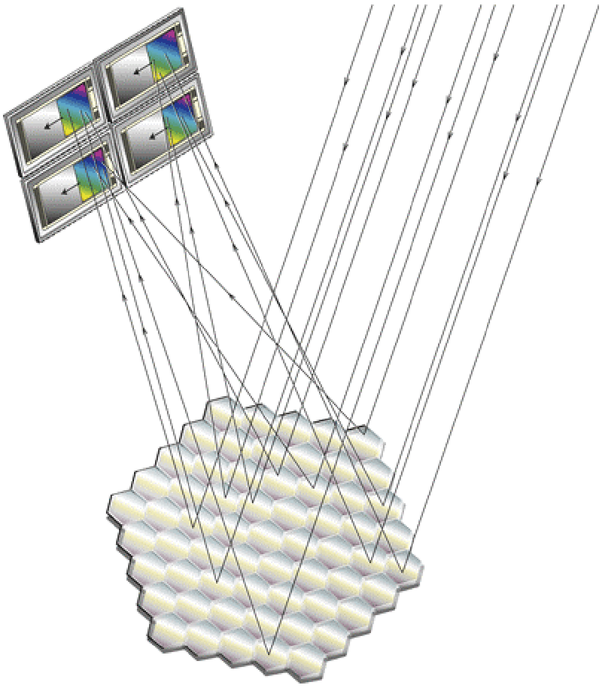

Figure 1: Groups of four sub-apertures of a segmented telescope pupil plane are directed onto separate EMCCD detectors.

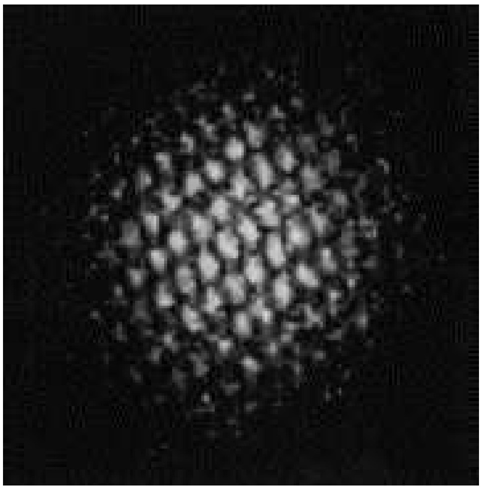

Figure 2: Each star image is seen here crossed with Michaelson interference fringes corresponding to the separation of

4. SEGMENTED APERTURE HIGH RESOLUTION IMAGING

We have examined arrangements where the pupil of a large telescope is divided into sub-apertures and only a small number of those sub apertures, usually four, have their light directed onto a single detector (figure 1). If the total area of those four sub-apertures is about the same as the 2.5 m telescope then it is clear that the number of turbulent cells across these apertures is very similar to that in a single 2.5 m telescope. If the sub apertures are well separated then there will be an additional turbulent component which corresponds to the larger scales with well separated apertures. The images that will be seen by the detector will then be the star field seen by each sub-aperture with every star crossed with Michaelson interference fringes, with a fringe period and orientation corresponding to the spacing and orientation of the baselines connecting each pair of apertures (figure 2). Using closure phase techniques (Baldwin et al, 1986, and Haniff, 1989) it is possible to derive the relative phases of several components of the Fourier transform of the two-dimensional sky brightness distribution. Directing other groups of sub-apertures onto other detectors allow more Fourier components to be measured. With a complete set of sub-apertures that fully fill the telescope pupil, and appropriate selection of the positions of the sub apertures so that the Fourier plane is well-sampled, it is possible to record all the information needed to allow a two-dimensional Fourier inversion to produce a high resolution image of the sky.

This method is, for all practical purposes, identical to aperture synthesis in radio astronomy. Essentially, with Lucky Imaging, we check the quality of each and every frame recorded at the telescope to choose those which are sharpest (in the present context, those images which have the highest fringe visibility). The fringe visibility is measured using a reference star within the field and the limiting magnitude of such a reference star will be very similar to that which we need for conventional Lucky Imaging, typically I=16.5-18, depending on the quality of the mirror of the telescope. Frames with lower fringe visibility may be corrected by scaling the fringe visibility on the reference star. The probability of getting a high fringe visibility frame will be very similar to that of Lucky Imaging under the seeing conditions at that time. The additional turbulent power on the larger scales corresponds to phase offsets that move the fringes relative to the peak of the star. Achieving the highest visibility when working with broad bands may require piston corrections so as to maintain the white light fringe in the centre of the star. These piston corrections are relatively slow and can be derived from the measured fringe positions on a frame to frame basis. Frames have to be taken quickly enough to freeze the turbulence on the smaller scales which is changing most rapidly and therefore it is a relatively straightforward matter conceptually to track the fringes and make the piston corrections with good accuracy.

5. OPERATIONAL CONSIDERATIONS

Despite the additional complexity of such an optical layout system set up and operation turns out to be relatively straightforward. While reading out at high speed (typically 30 Hz in I-band), each of the four elements (we use four because that gives us the best combination of closure phase redundancy and signal-to-noise) are autoguided so that the images overlap on the detector. One sub aperture has its piston setting changed until fringes are found. This is adjusted until maximum visibility is achieved. Then the third sub aperture is moved in the same way to maximise its contribution to fringe visibility and so also with the fourth. These piston corrections correspond to drifts on a timescale set largely by the wind crossing time of the telescope and so occur over fractions of seconds. The images now obtained will be the normal image of the sky as seen with a single aperture with each unresolved or partially resolved object crossed with fringes. Diffuse objects will show no such fringing but are not resolved out by the system since the total amount of light is still recorded.

The detectors of choice are high-speed noiseless CCDs, electron multiplying CCDs such as the L3CCDs from E2V Technologies (Chelmsford) or the Impactron devices from Texas Instruments. These detectors are essentially normal CCDs except that they can be run at high pixel rates (up to 20 MHz for the L3CCDs and up to over 35 MHz for the Impactrons) allowing frame rates of up to 100 Hz relatively conveniently. The only downside of this approach is that the aggregate data rate is very high, particularly when we realise that a telescope the size of the VLT might require 16 detectors working in parallel giving a data rate approaching 1 GB per second continuous and sustained. Larger telescopes require correspondingly more detectors. Inevitably the processing that is required on each frame has to be done in real time with DSP array processor hardware.

It is worth noting in passing that the is no reason why any science image should not be directed on to an integral field unit connected to a spectrograph. The spectrograph detector would also have to read out at high speed and selection criteria would be used to identify which images were particularly sharp. This additional mode of operation will not be discussed further here but it is important to appreciate that these techniques may indeed be applied effectively to spectroscopy as well as to imaging.

6. CONCLUSIONS

It is being a long, hard struggle to develop adaptive optic systems that just now are beginning to produce images with a resolution equal to that of the HST. Our experience with taking very large numbers of star images at high speed has given an insight into the nature of atmospheric turbulence as it affects astronomy which is significantly different from the accepted Kolmogorov model of turbulence. These differences help to explain why adaptive optics systems have been so difficult to make work well and our experience suggests that it will be even harder to make adaptive optics, even multi-conjugate adaptive optics, work on extremely large telescopes. Lucky Imaging routinely produces HST resolution of ground-based telescopes in the visible, something that no adaptive optics system has yet achieved. These results have been achieved with very little expenditure and very little technical skill. The much larger isoplanatic patch achieved with Lucky Imaging is particularly attractive for real astrophysical applications. The prospects of using Lucky Imaging techniques in conjunction with the current generation of adaptive optic systems look very encouraging.

A new method of achieving much higher resolution is proposed here whereby the pupil plane is divided into sub apertures. The light from groups of four sub-apertures are then combined coherently to give star images crossed with fringes. Those data allow a full aperture synthesis to be carried out after Lucky Imaging selection of the sharpest frames. The technique offers a real possibility of achieving much high resolution images from the ground on current large telescopes and on the next generation of even larger ones. Preliminary design work suggests that not only will this method be successful but that the cost of implementing it on a typical telescope will be an order of magnitude less than that for an adaptive optic system. It is undoubtedly radical but advances in detector technology now make it realistic and potentially highly competitive with existing technologies.

REFERENCES

1. Baldwin, J. E., Haniff, C. A., Mackay, C. D. and Warner, P. J., *Nature*, 320, (1986) p. 595-597.
2. Beyer, J.T., Roggemann, M.C., Otten, L.J., Schulz, T.C. and Brown, W.W., *Applied Optics*, 42 (2003), 908.
3. Dole, J., Wilson, R., Dalaudier, F. and Sidi, C, *Annales Geophysicae*, 19 (2001), 945
4. di Folco et al, *Proceedings of the SPIE*, 4838,(2003)
5. Fried, D. L. *Optical Society of America Journal*, **68**(1978), 1651.
6. C. A. Haniff. "Phase closure imaging - theory and practice". In D. M. Alloin and J.-M. Mariotti, editors, Diffraction-limited Imaging with Very Large Telescopes, volC.274 of NATO ASI, 171,13-23 September 1988, Cargèse, Corsica, Kluwer, 1989.
7. N.M. Law, C.D. Mackay, and J.E. Baldwin (2005) (accepted *Astron & Astrophys*)
8. Mackay, C. Basden, A. and Bridgeland, M., , 2004, *Proceedings of the SPIE*, 5499 (2004),203.
9. Morossi, C.; Franchini, M.; Furlani, S., *Pubs. Ast. Soc. Pacific*,114 (2002),187
10. D. St-Jacques, G. C. Cox, J. E. Baldwin, C. D. Mackay, E. M. Waldram, and R. W. Wilson. *Mon. Not. R. astr. Soc.*, 290 (1997), 66.
11. Sarazin, M. and Tokovinin, A., (2001), *Venice Conf " Beyond Conventional Adaptive Optics"*, paper entitled " The Statistics of the Isoplanatic Angle and Adaptive Optics Time Constant Derived from DIMM Data"
12. Sreenivasan, K. R.; Antonia, R. A, *Annual Review of Fluid Mechanics*, 29 (1997), 435
13. Wilson, R. W., O'Mahony, N., Packham, C. and Azzaro, M, *Mon. Not. R. astr. Soc.*,309 (1999), 379
14. Wilson, R. W. *Mon. Not. R. astr. Soc.*,337 (2002), 103
15. Wyngaard, J. C., *Annual Review of Fluid Mechanics*, 24(1992), 205.