Chapter 6

Conclusions

In this chapter I hope to bring together the results presented within previous chapters, and to draw general conclusions about the advantages and disadvantages of the Lucky Exposures method. It is clear that the Lucky Exposures approach has great potential for a number of astronomical programs. A substantial amount of observational data from 2003 is yet to be processed, and hopefully this will provide a number of important science results.

The selection of short exposures based on measurements of the Strehl ratio using reference stars in the image has been demonstrated as a technique that can provide high resolution I-band images at a 2.56 m telescope. The high Strehl ratios, small FWHM and good dynamic range offered by the technique would be very valuable in a number of astronomical imaging programs. The true imaging capability and faint limiting magnitude of reference stars for Lucky Exposures can provide significant advantages over other high frame rate imaging techniques. I will list here a few of the key conclusions which have been listed at the end of individual chapters.

Sky coverage

Observations at the NOT in July 2001 indicated that the isoplanatic angle for observations using the Lucky Exposures method was 30 as. This represents a substantial improvement over the typical values expected for I-band adaptive optics. Images with FWHM as small as 130 as were obtained at this separation from a reference star. Observations in May 2000 were suggestive of a smaller isoplanatic angle at that time. Future analysis of data taken at the NOT in 2003 may give a better indication of the typical range of isoplanatic angles at the NOT site.

Observations of M13 in July 2001 indicate that good image quality can be obtained using reference stars as faint as $I = 15.9$. Observations analysed using faint reference stars from

June 2003 had image quality which was consistent with that obtained in July 2001 using reference stars of similar magnitude.

The limiting magnitude and isoplanatic angle, combined with models for galactic star counts at I-band indicate that approximately 25% of the night sky should be within range of a suitable reference star for the Lucky Exposures method.

Image quality

Using bright reference stars, the Lucky Exposures method can provide I-band images of exceptional quality from a telescope of 2.56 m diameter under good seeing conditions. The measured Strehl ratios are consistent with those predicted by numerical simulations. The images of close binaries showed very good agreement between the stars, while there was evidence for some anisoplanatism in wider binaries. Spatial autocorrelations of ζ Boötis indicate that the re-centring of short exposure images works most effectively when the short exposure Strehl ratios are high. The image resolution obtained using the Lucky Exposures method decreases gradually when the fraction of exposures is increased.

Observations of M13 indicate that high precision relative astrometry should be possible in crowded fields given good charge transfer efficiency and a suitable understanding of the plate scale and relevant aberrations.

Results from simulation

Previous theoretical studies have indicated that the timescales and isoplanatic angles relevant to speckle imaging may be larger than those for non-conjugate adaptive optics at many astronomical observatories. Numerical simulations presented here were broadly consistent with these predictions.

High Strehl ratio images would be expected from the Lucky Exposures technique even if there are aberrations in the telescope mirror, as the method will tend to select exposures at times when the atmosphere is counter-acting the mirror aberrations. Structure on the mirror surfaces which is on very different scales to the dominant atmospheric perturbations is much less likely to be corrected in this way.

Sinc-resampling of the short exposures can significantly improve the estimation of the Strehl ratio and position of the brightest speckle. In low signal-to-noise data, Fourier filtering can be used to improve the performance of the exposure selection and re-centring, and reduce the noise in the final reconstructed image.

Timescale measurements

The atmospheric coherence time for speckle imaging at I-band was found to be approximately 65 ms at the NOT in May 2000. The excellent image quality obtained using frame rates as low as 18 Hz in 2001 is consistent with this. The oscillation of the NOT telescope was found to cause slight blurring of exposures having duration longer than ten milliseconds.

L3Vision CCD performance

Theoretical modelling of L3Vision CCDs from E2V Technologies indicate that these devices have the potential to act as an image plane photon-counting array. The distribution of output electrons can be modelled numerically for any given flux of detected photons.

Experimental measurements of L3Vision CCDs in our camera both at the NOT and in the laboratory indicate that short exposures are often affected by charge transfer efficiency problems at low signal levels.

Future prospects

There are a number of modifications to the Lucky Exposures method as presented here which would make it applicable to a wider range of astronomical observations. In crowded fields, the image quality could be monitored using a number of reference stars across the field, allowing exposures to be selected on the basis of isoplanatic angle as well as overall image quality. By combining data from several different reference stars, the signal-to-noise ratio for Strehl ratio measurements could also be improved.

The Lucky Exposures method is not restricted to single-wavelength detectors – light from a science target could be directed into a spectrograph with an Integral Field Unit (IFU) while the light from a reference star was monitored on a conventional imaging detector in order to select moments of high image quality. Array detectors with spectroscopic sensitivity such as Superconducting Tunnel Junction (STJ) devices could also be used to provide spectral information. If the reference star is faint, a broader bandpass could be used for the reference star than for the observations of the science target.

The dependence of r_0 on observing wavelength described in Equation 2.9 implies that the Lucky Exposures method should work well on much larger telescopes if longer observing wavelengths are used. An 8 m telescope observing at K-band would have the same number of r_0 across its diameter as a 2.5 m telescope observing at 800 nm wavelength, and a similar probability of Lucky Exposures would be expected. Current low noise infra-red cameras can typically only be read at low frame rates, so further camera and detector development might be required to make such an instrument viable. Observations could also be performed at shorter wavelengths using smaller telescopes, although this would probably require faster camera readout rates and possibly an atmospheric dispersion corrector.

In order to improve the resolution attainable with the Lucky Exposures technique, non-circular apertures could also be exploited. If a large (diameter greater than $7r_0$) telescope were broken up into a series of slit apertures, the probability of obtaining good atmospheric conditions over one of these slits would be higher than for the telescope aperture as a whole. By repeating observations with a range of different slit position angles, high resolution data could be obtained in all orientations from an astronomical target.

Alternatively, a low-order adaptive optics system designed for long wavelength imaging might provide a substantial improvement to the probability of obtaining Lucky Exposures at short wavelengths on a large telescope, as it would eliminate the large scale structure in the atmospheric phase perturbations. This could allow high resolution imaging from large telescopes without the need for high-order adaptive optics correction (which usually requires a bright reference star).

Summary

It is clear that the Lucky Exposures method has great potential for many astronomical programs. The higher sky coverage of the Lucky Exposures method at I-band as compared to that for natural guide star adaptive optics means that this method can be applied to a much wider range of astronomical targets. If a large isoplanatic patch is frequently available during Lucky Exposures observations, it will be possible to image large fields at high resolution.

A substantial quantity of observational data taken in 2003 is waiting to be analysed. The wide range of astronomically interesting targets promise many exciting astronomical results. The dataset will also be very valuable in characterising the atmospheric conditions at the NOT over a more statistically significant period.

The development of instrumentation for Lucky Exposures is ongoing in the Institute of Astronomy, and the staff at the NOT and associated institutes have expressed a keen interest in becoming involved with this work. With a bit of Luck, this program will eventually lead to a permanent exposure selection instrument available to the whole astronomical community.