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LSST Dark Energy Science Final Report

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Auspices Statement

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FY06 LDRD Final Report
Dark Matter and Dark Energy Science
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Steve Asztalos, Principal Investigator

Abstract

Three decadal surveys recommend a large-aperture synoptic survey telescope (LSST) to allow time-domain and cosmological studies of distant objects. LLNL designed the optical system and also is expected to play a significant role in the engineering associated with the camera. Precision cosmology from ground-based instruments is in a sense terra incognita. Numerous systematic effects occur that would be minimal or absent in their space-based counterparts. We proposed developing some basic tools and techniques for investigating "dark sector" cosmological science with such next-generation, large-aperture, real-time telescopes. The critical research involved determining whether systematic effects might dominate the extremely small distortions ("shears") in images of faint background galaxies. To address these issues we carried out a comprehensive data campaign and developed detailed computer simulations.

Introduction/Background

Weak gravitational lensing is a powerful and relatively unbiased technique for measuring the unseen dark matter and dark energy in the universe. Light from distant objects undergoes deflection as it passes through intervening over-dense regions, inducing tangential alignment of the objects' image. Numerous cosmological parameters can be inferred from correlations in these alignments. One important lensing statistic is the correlation in ellipticity between objects as a function of their separation. For more than a decade this technique has been used to infer galaxy cluster and individual galaxy masses, two cases for which the signal is comparatively large. More recently, the lensing technique has been extended to inferring large-scale structure, where it is often referred to as cosmic shear. Here the signal is weak and many galaxies must be surveyed to overcome lack of knowledge of the intrinsic ellipticities (shape noise). Nonetheless, this technique has been yielding estimates of M, the amount of matter in the universe relative to the critical density, consistent with other techniques. The next generation of weak lensing instruments will extend these results to individual redshift intervals. From this, stringent constraints will be placed on w and w0 , the cosmological equation of state and its first derivative, respectively.

The optics, camera and atmospheric turbulence all contribute to lensing systematic errors, with the latter effect being perhaps the most serious. For a large aperture telescope, a thousand or more turbulent cells are in view at the aperture at any given time, giving rise to appreciable instantaneous ellipticity. For an intermediate length exposure of 15 s this raw ellipticity is reduced by the number of independent atmospheric realizations, which in turn depends on the wind speed. Objects which happen to lie close to one another have approximately sampled the same portion of the atmosphere and should have similar ellipticity vectors; those further apart will be less similar. In this way the atmosphere induces correlations that mimic a lensing signal. Numerous techniques have been developed to remove spurious atmospheric power, however, these techniques are dependent on the spatial distribution of fiducial objects whose point spread functions (PSFs) are known. Furthermore, these same techniques may require a degree of coherence between these objects, otherwise little can be said about the behavior of the PSF between them. In short, atmospheric turbulence affects weak lensing measurements in two ways: by introducing both spurious ellipticity and spatial coherence. It is desirable to characterize the magnitude of this effect in data and simulations.

Research Activities

Quantifying spurious atmospheric power was the main focus of our investigations during this two-year LDRD. Rather than rely solely on simulations, which are notoriously incapable of reproducing the rich time dependent turbulent behavior seen in the physical atmosphere, we instead chose to study data from a facility similar to the proposed Large Synoptic Science Telescope. Thus, to study atmospheric impacts on weak lensing science, discretionary time was sought and awarded on the Gemini Multi-Object Spectrograph (GMOS) Gemini South. Forty three R-Band images were obtained over the course of four nights spanning May 10-13, 2005. We systematically studied image ellipticities and build on earlier work by exploring image ellipticities over a range of seeing conditions with known atmospheric turbulence and wind conditions.

The second main thrust of our work concerned the fidelity of differing techniques in reproducing known, albeit gross properties of atmospheric turbulence as measured in the focal plane. The issue here is one of fidelity versus speed: for weak lensing studies one should preserve ellipticity correlation due to atmospheric turbulence. One also desires that the simulation be sufficiently fast so as to be able to simulate the PSF of a large aperture telescope with a 15 sec cadence. These requirements are, of course, conflicting. We sought to compare and contrast two disparate simulation techniques: ray-tracing versus fast Fourier transformations, the latter being appreciable faster computationally than the latter.

Results/Technical Outcome

Regarding weak lensing systematics, we found that under good seeing conditions PSF correlations persist well beyond the separation typical of high-latitude stars. Under these conditions, ellipticity residuals based on a simple PSF interpolation can be reduced to within a factor of a few of the shot-noise induced ellipticity floor. We also found that the ellipticity residuals are highly correlated with wind direction. Finally, we correct stellar shapes using a more sophisticated procedure (a noted weak lensing software pipeline) and generate shear statistics from stars (Figure 1). Under all seeing conditions in our data set the residual correlations lie everywhere below the target signal level. For good seeing we found that the systematic error attributable to atmospheric turbulence is comparable in magnitude to the statistical error (shape noise) over angular scales relevant to present lensing surveys.

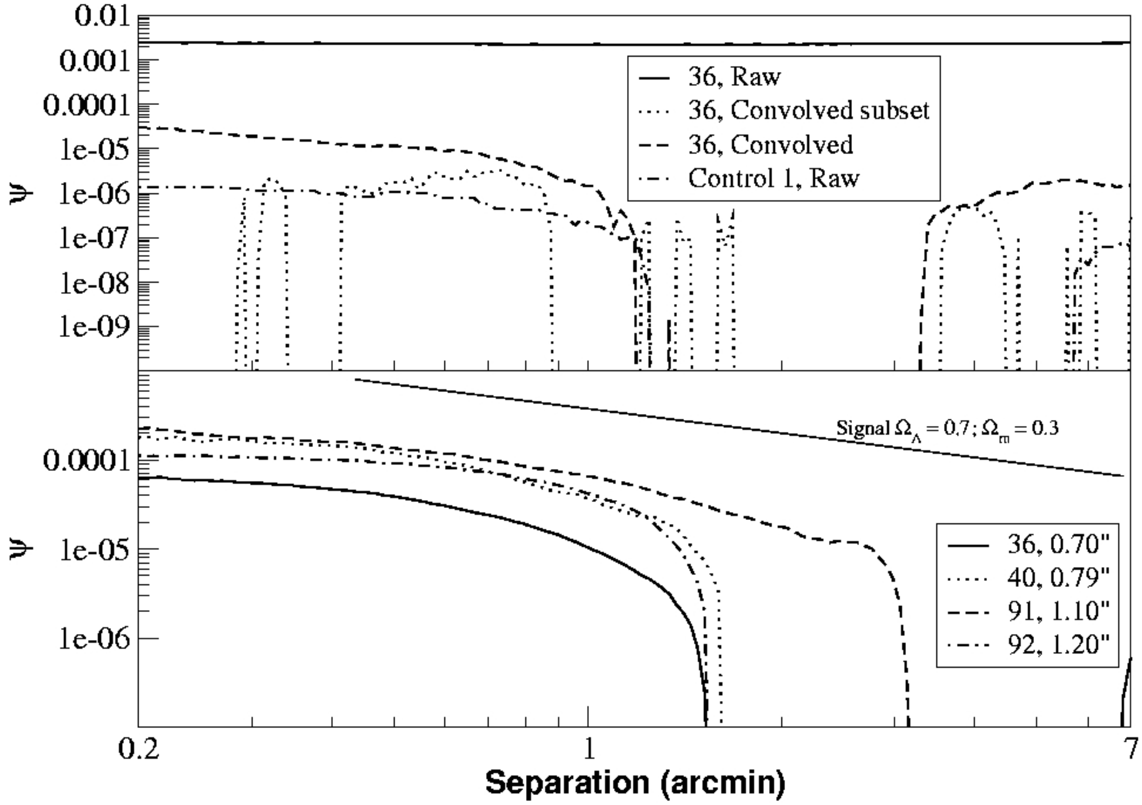
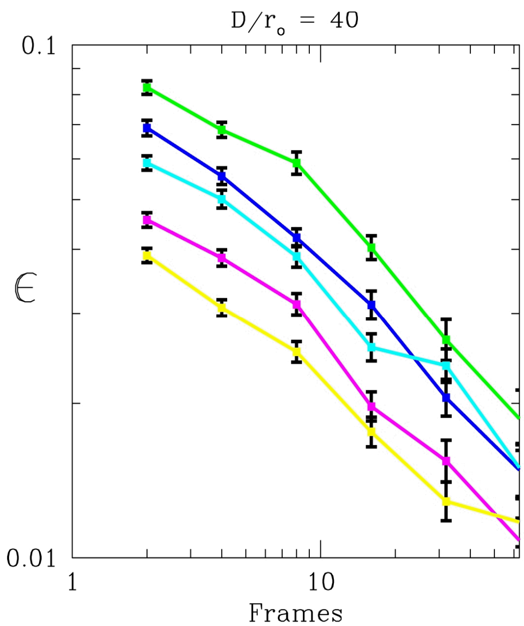


Fig. 1. [Upper panel] The two point correlation function for various object lists processed through a weak lensing pipeline. The solid, constant, line is the correlation function for 512 raw stellar objects from a frame taken under good seeing conditions. That the curve is featureless and the amplitude large is a reflection of the sizable ellipticity correlation seen in the raw image. The dotted curve is constructed from a subset of 122 rounded stellar objects (~ 25% of the total of 512). The erratic behavior observed in this curve arises from minimal statistics in numerous separation bins. The dashed curve is again the correlation function for the 512 stars, but now the 122 stellar objects have been used for rounding and interpolation. The dashed-dotted curve is the correlation function of 339 simulated stars whose magnitude distribution mimics those from the Gemini South. [Lower panel] The two-point correlation functions for frames 36, 40, 91 and 92 (good to bad seeing conditions) constructed in manner similar to the dashed curve in the upper plot, but instead using 30 of the brightest stars as the fiducial subset. Only positive values of are shown. The solid line is the level of the expected signal for a cosmology with a standard cosmology.

This work was an important confirmation and extension of earlier work and emphasized the need for new analysis techniques for the next generation of ground based instruments for precision cosmology. Promising analysis techniques have since been promulgated that may transform atmospheric systematic effects into statistical effects, though the impact of seeing and wind still need to be quantified.

Concerning our second main area of research, we also investigated the ellipticities of the PSF produced by imaging point sources with a telescope subject to the effects of atmospheric turbulence. The telescope modeling involved either a Fourier transform of the phase information in the pupil plane, or a ray-tracing approach. Using a standard method involving the Gaussian weighted second moments of intensity, we then calculated the ellipticities of the PSF patterns. We found significant ellipticities for the instantaneous patterns (as much as 10% or more and consistent with what we observed in the Cerro Pachon data). Longer exposures, which we approximate by combining multiple (N) images from uncorrelated atmospheric realizations, yield progressively lower ellipticities (~ sqrt(1/N)). We also verified that the measured ellipticity does not depend on the sampling interval in the pupil plane using the Fourier method, as long as the sampling interval exceeded the Nyquist limit. The results from the ray-tracing technique, on the other hand, did depend strongly on the sampling rate.



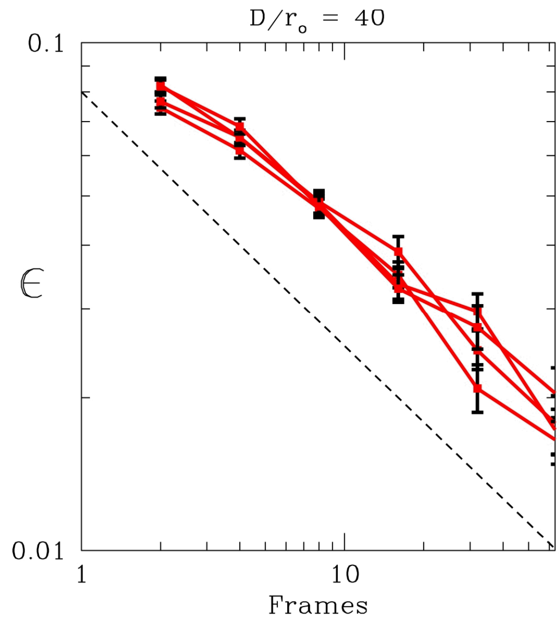


Fig. 2. Ellipticity as function of the number of independent phase screens and sampling rates. The left panel shows the results for ray-tracing, with the pupil-plane sampling rates color-coded as: r_o / 2 green, r_o / 4 blue, r_o / 5 cyan, r_o / 8 purple, and r_o / 16 yellow. The panel on the right shows the same results (except r_o / 5) for the Fourier method. The latter method clearly illustrates the expected behavior: ellipticity should be independent of pupil plane sampling rates beyond Nyquist rates. The progressive lowering of the curves for higher sampling rates in the left panel, therefore, is unphysical. The dashed line in the right panel shows a sqrt(1/N) decline.

Therefore, we conclude that the effects of interference, which are responsible for the characteristics of the speckle pattern, are a significant contributor to image ellipticities induced by atmospheric turbulence, and are not adequately accounted for in the ray-tracing case.

This result directly addresses weak-lensing simulations that attempt to include the effects of the atmosphere and telescope, and for which accurate modeling of sheared galaxy shapes are essential.

Exit Plan

This LDRD has been completed within a two-year period. Though much remains to be studied in the area of weak lensing systematic effects before the advent of next-generation precision instruments, this field is not wanting for prominent investigators. After considerable deliberation, we instead have chosen to pursue supernovae (SNe)science with LSST. Our group at LLNL has chosen to focus our efforts on systematic effects associated with ground-based measurements of SNe light curves. We have embarked on a three-year observational and simulation LDRD to address these issues.

Summary

This LDRD addressed potential limitations to the determination of dark matter and dark energy from ground-based instruments. We have demonstrated that that systematic error introduced by atmospheric turbulence will not exceed the statistical error of ongoing weak lensing surveys. In the refereed literature we have also argued that this likely cannot be said of future surveys, which will cover the night sky every few nights. There, systematic effects due to the atmosphere would likely dominate the error budget save for the introduction of interesting new analysis methods that allow one measure shapes across images. Though some work needs to be done regarding the limitation of these new techniques under very good seeing conditions and the problem of persistent winds, the field has advanced enormously since the date this LDRD was awarded.

The second topic addressed by this LDRD was one of simulations. For weak lensing the simulations need to preserve not only ellipticity, but ellipticity correlation across the image. Atmospheric turbulence mimics the sought after signal by introducing spurious correlations and it is desirable that simulations capture this effect. Again in the refereed literature we have shown that ray-tracing, though fast compared to the fast Fourier alternative, does not faithfully reproduce ellipticity due to atmospheric structure. Accordingly, much more research will have to be invested if one wishes to faithfully but expeditiously simulate an evening's worth of long-exposure images from next-generation ground-based instruments

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