Large Synoptic Survey Telescope

www.lsst.org

Shear Systematics in LSST Simulated Images

Chihway Chang[1], S. M. Kahn[1], G. Jernigan[2], J. R. Peterson[3], A. P. Rasmussen[1], Z. Ahmad[3], J. Bankert[3], D. Bard[1], A. Connolly[4], R. R. Gibson[4], K. Gilmore[1], E. Grace[3], M. Hannel[3], L. Jones[4], S. Krughoff[4], S. Lorenz[3], S. Marshall[1], S. Nagarajan[3], J. Pizagno[4], M. Shmakova[1], N. Sylvestre[4], N. Todd[3], M. Young[3]

[1]SLAC/Stanford, [2]SSL/UC Berkeley, [3]Purdue Univ., [4]U. Washington.

The Large Synoptic Survey Telescope (LSST) is a large-aperture, wide-field, ground-based telescope designed to provide a complete survey of 18,000 square degrees of sky in six optical bands every few nights. Over ten years of operation, it will measure the magnitudes, colors, and shapes of several billion galaxies. As such, LSST will probe cosmic shear down to levels far beyond those accessible with current surveys. The unprecedented statistical power of LSST will impose new requirements on the control of weak lensing systematics. Various noise sources become important in this context, associated with counting statistics, atmospheric effects, and wavefront errors introduced by the telescope and camera systems. We are studying these various noise components and their impact on shear measurements using simulated LSST images produced by a prototype high fidelity photon-by-photon Monte Carlo code. The code includes the most significant physical effects associated with photon propagation through the atmosphere, reflection off of the three mirror surfaces of the telescope, and propagation through the elements of the camera and on into the detector. We report on preliminary results from this program, including plots of residual shear error correlation functions due to errors in the object shape estimation for realistic LSST operating conditions.

Introduction

- One of the main goals for LSST is to probe the **cosmic shear** using **weak gravitational lensing** [1].
- Previous surveys were limited by **statistical errors** associated with the intrinsic shapes of galaxies. With LSST, this statistical uncertainty will be reduced by orders of magnitudes, suggesting that **systematic errors** may be the ultimate limiting factor [2].
- This is a preliminary report on a larger effort to quantitatively account for **the expected sources of systematic errors in cosmic shear measurements for LSST**.
- We invoke a high fidelity **image simulator** to quantify the uncertainties and spatial correlation of these systematic errors.

The LSST Image Simulator and Targeted Simulations

- **The LSST Image Simulator** [3] has been developed to support software development for the LSST data management effort, and to provide high fidelity LSST images for the community.
- A **photon-by-photon Monte Carlo approach** is adopted to capture subtle features in the images. Photons are generated from a realistic catalog of objects on the sky, propagated through the atmosphere and optics and finally on into the detector (see another poster for details: *"End-to-End Simulations", K. Simon et al.*). Figure 1 shows an example of the simulator output.
- Instead of using full LSST simulations that contain all physical effects and objects as in real data, in this study, we generate sets of **reduced images** that are designed to **target on testing specific problems**. Figure 2 shows examples of test images used in this work.

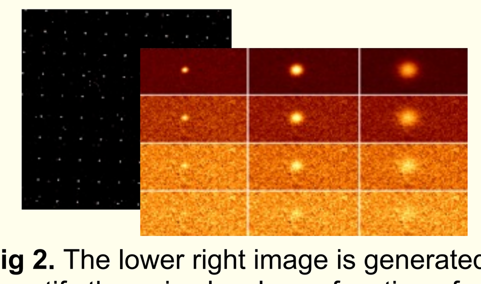


Fig 2. The lower right image is generated to quantify the noise level as a function of object size and magnitude; whereas the upper left image shows a dense grid of objects simulated to test the correlation properties of noises.

Fig 1. Output from the LSST Image Simulator. This image combines three single exposures in the g, r and i bands with no background added. The image contains all major physical effects as well as realistic stellar and galaxies.

Framework

We are interested in three major issues associated with various contributors to galaxy shape errors:

(1) *What is the quantitative contribution to the ellipticity error as a function of galaxy magnitude, size and shape?*

(2) *How are those ellipticity errors correlated as a function of angular separation?*

(3) *What are the residual shear errors after correction using our knowledge of the PSF, and how are those shear errors correlated with angular separation?*

- **There two classes of physical effects that contribute to errors on ellipticity measurements:**
  - **Non-stochastic effects**
    - aberration
    - optics misalignment
    - focal plane non-flatness

    These can be corrected using information from multiple exposures and methods such as Principle Component Analysis (PCA)
  - **Stochastic effects**
    - counting statistics
    - wavefront correction errors
    - tracking errors
    - atmosphere distortion

    These vary randomly from frame to frame and can only be corrected using information from a single exposure

By systematically turning these individual effects on and off in the simulator, we can evaluate their contributions to the three issues listed above. An illustration of the logic flow of this work can be seen in Figure 3.

We define the ellipticity and correlation function as follows:

- **ellipticity** $\varepsilon=(\varepsilon_1,\varepsilon_2)$, a combination the object's second moments, is chosen as our shape parameter
- **two-point correlation function** is used to quantify the spatial correlation properties:

$$C_{XX}(\Delta\theta) = \langle X_t(\theta)X_t(\theta+\Delta\theta)\rangle + \langle X_\times(\theta)X_\times(\theta+\Delta\theta)\rangle$$

where X=ε for ellipticity correlation and X=γ for shear correlation.

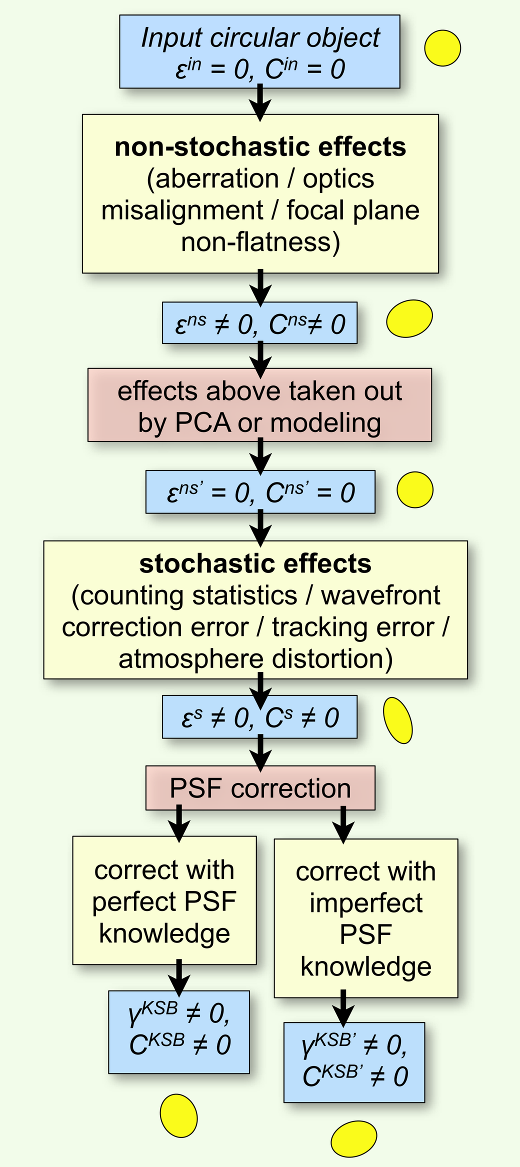


Fig 3. Overview of the processes that introduce additive systematic errors on shear measurements. Blue indicates the measured shape/shear (ε or γ) and the correlation (C). We use the superscripts later text to denote the analysis stage in this chart. Yellow describe the possible sources of noise that cause the errors; red denotes the use of an algorithm. The yellow circle illustrates the concept of shape distortion in different stages.

Results — non-stochastic effects (ε^{ns}, C^{ns})

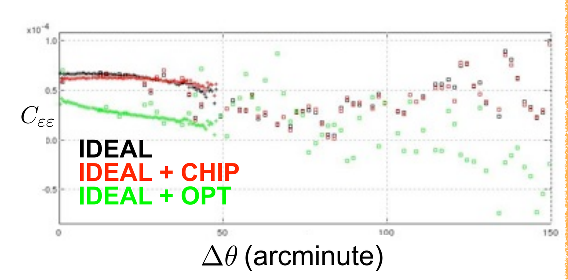


Fig 4. Ellipticity two-point correlation function for the LSST with the non-stochastic effects. Black points show the shape correlation introduced by the optical design of LSST. Adding focal plane non-flatness changes the correlation slightly, as shown in red. Optical misalignments can increase or decrease the correlation; one example is shown here in green. Note that the level remains $<10^{-4}$.

- There are three non-stochastic effects in this analysis: the pure optical aberration **(IDEAL)**, the optics misalignments **(OPT)** and the focal plane non-flatness **(CHIP)**. The raw ellipticity two-point correlation function for these three effects is shown in Figure 4.
- These spurious shape correlations can in principle be removed if treated properly with PCA [4] or similar methods and are neglected in our subsequent analyses. We show them here to illustrate the size and contributions.

Results — stochastic effects (ε^{s}, C^{s})

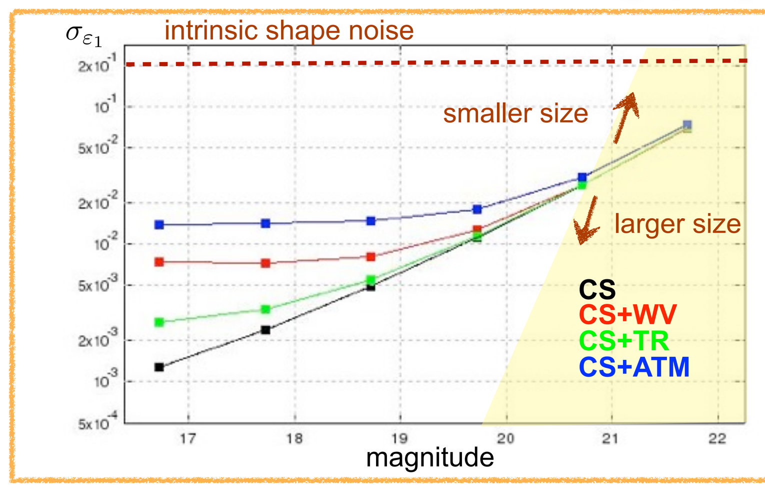


Fig 5. Noise on ellipticity measurement vs. object brightness for the four stochastic noise sources. The shaded area shows where counting statistics dominate. These curves are plotted for a Gaussian object of size ~1". The arrows point to the direction where the entire family of curves move when a larger/ smaller object is considered. Also marked is the intrinsic shape noise level ~0.21.

- There are four stochastic effects included in this analysis: counting statistics **(CS)**, residual wavefront correction errors **(WV)**, tracking errors **(TR)** and atmospheric distortions **(ATM)**.
- The errors on ellipticity measurement as a function of object brightness and size are quantified and summarized in Figure 5. The errors are defined as the **standard deviation of ellipticity measurements over an ensemble of identical input objects, ie. $\sigma_{\varepsilon 1}$, $\sigma_{\varepsilon 2}$.**
- The correlation of these errors, calculated for each individual effects, and shown in Figure 6a and combined in a more realistic situation in Figure 6b. There are features in the correlation function that are related to the atmospheric structure model and wind.

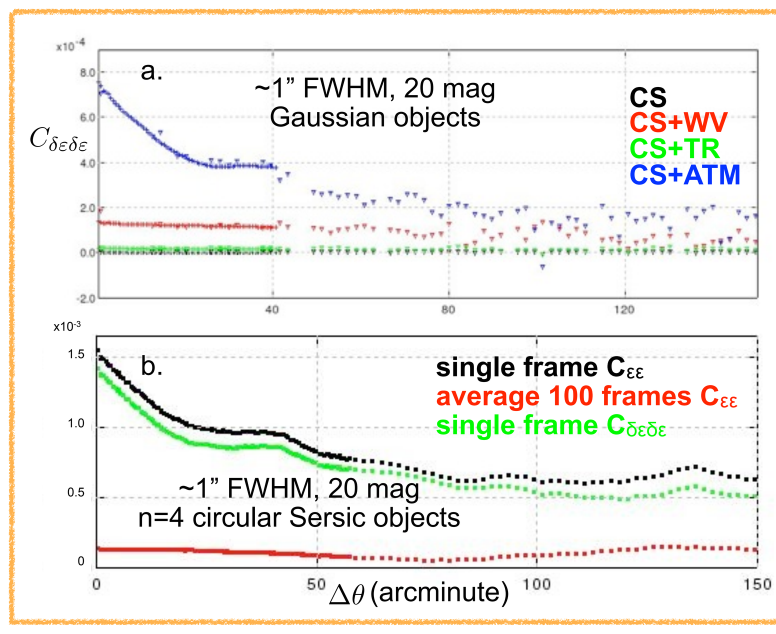


Fig 6. Ellipticity two-point correlation functions for the errors on ellipticity measurements due to the four stochastic effects separately (a) and combined (green points in b). The lower panel also shows the effect of averaging over multiple frames, which beats downs the stochastic noise as 1/N but the non-stochastic component remains the same for all frames and does not average out.

Results — residual shear / perfect PSF knowledge (γ^{KSB}, C^{KSB})

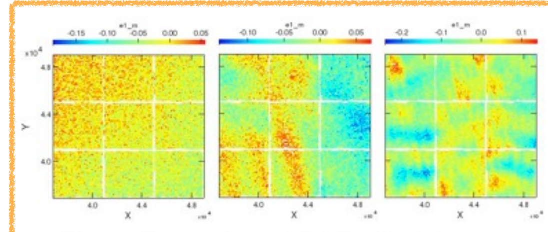


Fig 7. Examples of PSF ellipticity maps. Note that the atmospheric turbulence effects are clearly visible.

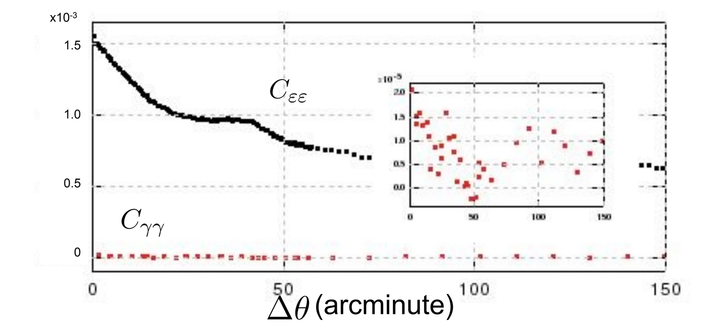


Fig 8. For a single exposure, if the PSF is known perfectly, the KSB algorithm corrects the correlated errors in ellipticity (black) and leaves residual shear correlations at $<10^{-5}$ levels as shown in the inset (red).

- We implement the **KSB algorithm** [5] as an approximation to the deconvolution process.
- Figure 7 shows examples of the PSF maps used here and the correlation of the residual shear after correction is plotted in Figure 8.

Results — residual shear / imperfect PSF knowledge ($\gamma^{KSB'}$, $C^{KSB'}$)

- In practice, the PSF is not known a priori, and must be estimated by measuring the shapes of nearby stars in the image.
- We simulate this effect using a realistic star distribution (~1 star/arcminute^2) and **interpolating** the stars with a 3rd order polynomial to get the modeled PSF.
- In Figure 9, we show the residual shear correlation corrected by the interpolated PSF using KSB. Also plotted is a comparison with the previous case with perfect PSF knowledge. There is significant **increase of correlation at small scales** for the imperfect PSF case.
- Note that Figure 9 shows the residual shear correlation for a single exposure, while we expect that averaging over multiple exposures will bring the correlation down as 1/N.

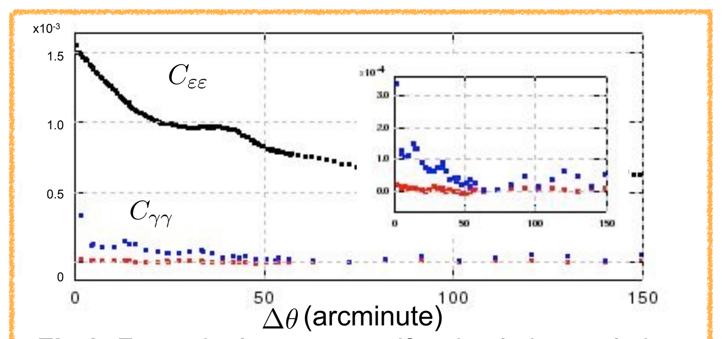


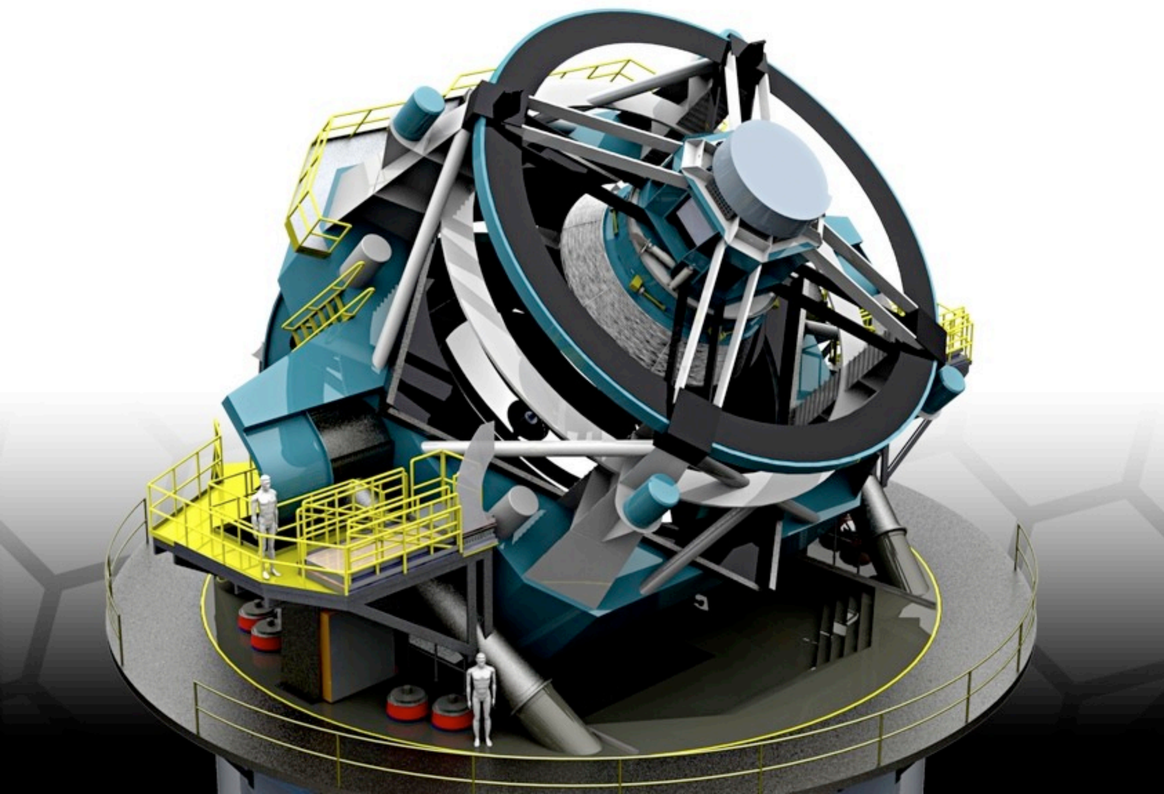
Fig 9. For a single exposure, if a simple interpolation scheme is used to obtain the PSF model, the KSB algorithm corrects the correlated errors in ellipticity (black) and leaves residual shear correlations at ~10^{-4} on small scales and $<10^{-5}$ on large scales (blue). Comparison with the previous case shows that the interpolation process causes spurious correlation on small scales.

Conclusion

- In this project, we quantify the level and correlation properties for various sources that introduce **shear systematics** in a realistic LSST survey. **The LSST Image Simulator** is well suited for this systematic study.
- For most of the cases, errors on shape measurements are dominated by **counting statistics**. For bright and small object, however, **atmospheric distortion** is the main contributor to ellipticity measurement errors.
- Correlated errors on ellipticity measurements are dominated by the atmospheric distortions. The two-point correlation function is ~10^{-3} at small scales for a single exposure, and falls off at large scales.
- Using a simple PSF correction algorithm such as KSB, the ellipticity errors can be corrected to first order, but may **introduce additional correlation on small scales due to the interpolation scheme used for PSF modeling**. The shear correlation is a factor of 10 smaller than the raw ellipticity correlation, and will decrease as 1/N for multiple exposures. For the full LSST survey, the correlation should be below 10^{-7} for all relevant angular scales.

Reference

[1] LSST Science Collaboration, et al. 2009, arxiv:09120201 [2] Huterer et al. 2005 [3] http://lsst.astro.washington.edu/
[4] Jarvis, M., & Jain, B. 2004 [5] Kaiser, N., Squires, G., & Broadhurst, T. 1995



January 2011

LSST is a public-private partnership. Design and development activity is supported in part by the National Science Foundation. Additional funding comes from private gifts, grants to universities, and in-kind support at Department of Energy laboratories and other LSSTC Institutional Members.