PROPERTIES OF ELLIPTICITY CORRELATION WITH ATMOSPHERIC STRUCTURE FROM GEMINI SOUTH

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ABSTRACT

Cosmic shear holds great promise for a precision independent measurement of \( \Omega_m \), the mass density of the universe relative to the critical density. The signal is expected to be weak, so a thorough understanding of systematic effects is crucial. An important systematic effect is the atmosphere: shear power introduced by the atmosphere is larger than the expected signal. Algorithms exist to extract the cosmic shear from the atmospheric component, although a measure of their success applied to a range of seeing conditions is lacking. To gain insight into atmospheric shear, Gemini South imaging, in conjunction with ground condition and satellite wind data, was obtained. We find that under good seeing conditions point-spread function (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 find that the ellipticity residuals are highly correlated with wind direction. Finally, we correct stellar shapes using a more sophisticated procedure and generate shear statistics from stars. Under all seeing conditions in our data set the residual correlations lie everywhere below the target signal level. For good seeing we find 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.

Subject headings: atmospheric effects — dark matter — gravitational lensing

1. INTRODUCTION

Weak gravitational lensing is a powerful and relatively unbiased technique for measuring the unseen dark matter and dark energy in the universe (Bartelmann & Schneider 2001). Light from distant objects undergoes deflection as it passes through intervening overdense 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 over a decade this technique has been used to infer individual galaxy (Fischer et al. 2000) and cluster masses (Tyson et al. 1990). More recently, the lensing technique has been extended to inferring large-scale structure, often referred to as cosmic shear (Mellier & van Waerbeke 2001). Here the signal is weak, and many galaxies must be surveyed to overcome the lack of knowledge of the intrinsic ellipticities (shape noise). Nonetheless, this technique has been yielding estimates of \( \sigma_{\kappa} \) (the bias factor times the amount of matter in the universe relative to the critical density) that are consistent with other techniques (Jarvis et al. 2006). The next generation of weak-lensing instruments will extend these results to individual redshift intervals. From this, stringent constraints will be placed on \( \omega \) and \( \omega' \), 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 \( \sim 15 \) s this raw ellipticity is reduced by the number of independent atmospheric realizations, which in turn depends on the wind speed. Objects that happen to lie close to one another will have approximately sampled the same portion of the atmosphere and should have similar ellipticity vectors; those farther 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 spurious ellipticity and by causing spatial decoherence. It is desirable to characterize the magnitude of this effect in data and simulations.

This paper is devoted to assessing the impact of atmospheric turbulence on weak-lensing measurements. Recently it was shown that under good seeing conditions atmospheric residuals lie comfortably below the level expected of a weak-lensing signal (Wittman 2005). The need for controlling a dominant systematic effect such as atmospheric turbulence, especially in the context of future ground-based lensing measurements, cannot be understated. Here we systematically study image ellipticities and build on that result by exploring image ellipticities over a range of seeing conditions with known atmospheric turbulence and wind conditions. In § 2 we describe the image and atmospheric data set. In § 3 we show that the wind direction can be inferred by correlations in the ellipticity residuals. We then turn to ellipticity correlations as a function of seeing and investigate how seeing affects PSF interpolation. Photon shot noise introduces an irreducible ellipticity floor that is modeled and compared to observational data. Finally,
we construct lensing statistics from the corrected ellipticities of PSF stars and compare them with a putative signal. These results may have bearing on site selection for the next generation of proposed telescopes as well as implications for their science requirements.

2. Observations

To study atmospheric impacts on weak-lensing science, discretionary time was awarded on the Gemini Multi-Object Spectrograph (GMOS) Gemini South (Hook et al. 2004). GMOS is a three-chip camera spanning 5.6′ on a side. Forty-three R-band images were obtained over the course of four nights spanning 2005 May 10–13. On three of the four nights (excepting May 11) observations were divided into two intervals, for a total of seven viewing windows. Observations were done on two different fields having bright reference stars. The first (second) field is denoted with a black (gray) date label in Figure 1. The intrinsic stellar density of the first field is approximately 3 times that of the second. The gray labels along the abscissa of the second and fifth viewing windows denote the second field.

The bottom plot in Figure 1 depicts the ground wind speed and direction extracted from the image headers. No flat-fielding was performed. The top plot shows the median seeing and source counts; the last two columns are computed values. Col. (1): Abbreviated frame number. Col. (2): Telescope azimuth. Col. (3): Wind speed. Col. (4): Date. Col. (5): Universal time. Col. (6): Wind direction. Col. (7): Source count. Col. (8): Full width at half-maximum, defined as the median FWHM of the source objects in col. (7). All angles are in degrees, north through east.

3. Analysis

Galactic stars are unresolved, and the photons they emit are relatively unaffected by intervening dark matter; hence, they are excellent zero-ellipticity calibration objects. However, the atmosphere, instrument, and shot noise all introduce spurious ellipticity that must be removed to recover the lensing signal. The success of a procedure in removing spurious ellipticity is directly tested by applying it to stars, whose PSF one knows a priori to be round: we apply it to stars, whose PSF one knows a priori to be round: we

\[ \epsilon = \frac{1 - \beta^2}{1 + \beta^2}, \]

where the images from the second and fifth viewing windows difficult to analyze, and hence they are excluded from subsequent discussion. A summary of header information from the remaining frames is contained in Table 1.

| Frame | WDir. (deg) | WS (m s\(^{-1}\)) | Date | UT | Az. (deg) | So. | FWHM (arcsec) |
|-------|------------|-------------------|------|----|-----------|----|--------------|
| 36... | 317.0      | 1.8               | 2005 May 10 | 050106 | −147.91 | 1436 | 0.718       |
| 37... | 293.0      | 1.3               | 2005 May 10 | 050210 | −147.72 | 1652 | 0.748       |
| 38... | 308.0      | 2.2               | 2005 May 10 | 050313 | −147.53 | 1543 | 0.753       |
| 39... | 318.0      | 2.0               | 2005 May 10 | 050416 | −147.34 | 1493 | 0.788       |
| 40... | 318.0      | 2.3               | 2005 May 10 | 050519 | −147.16 | 1112 | 0.818       |
| 41... | 319.0      | 2.5               | 2005 May 10 | 050622 | −146.98 | 1004 | 0.886       |
| 42... | 333.0      | 4.4               | 2005 May 11 | 011041 | 146.25   | 1553 | 0.726       |
| 43... | 317.0      | 3.2               | 2005 May 11 | 011145 | 146.42   | 1535 | 0.788       |
| 44... | 335.0      | 4.3               | 2005 May 11 | 011247 | 146.60   | 1525 | 0.825       |
| 45... | 333.0      | 4.6               | 2005 May 11 | 011350 | 147.13   | 1542 | 0.809       |
| 46... | 331.0      | 4.5               | 2005 May 11 | 011452 | 146.95   | 1613 | 0.748       |
| 47... | 281.0      | 4.6               | 2005 May 11 | 011555 | 147.13   | 1542 | 0.809       |
| 48... | 330.0      | 6.1               | 2005 May 12 | 011507 | 147.70   | 1003 | 0.710       |
| 52... | 327.0      | 6.1               | 2005 May 12 | 011610 | 147.89   | 823  | 0.840       |
| 53... | 337.0      | 5.9               | 2005 May 12 | 020037 | 158.22   | 200  | 1.101       |
| 55... | 274.0      | 5.6               | 2005 May 12 | 020140 | 158.52   | 390  | 0.830       |
| 56... | 336.0      | 5.6               | 2005 May 12 | 020242 | 158.82   | 466  | 0.784       |
| 57... | 330.0      | 5.6               | 2005 May 12 | 020345 | 159.12   | 546  | 0.772       |
| 58... | 336.0      | 5.6               | 2005 May 12 | 020448 | 159.43   | 527  | 0.726       |
| 59... | 336.0      | 5.6               | 2005 May 12 | 020550 | 159.73   | 562  | 0.802       |
| 74b...| 333.0      | 6.2               | 2005 May 13 | 013053 | 151.69   | 430  | 0.993       |
| 75... | 332.0      | 6.2               | 2005 May 13 | 013155 | 151.92   | 329  | 1.088       |
| 77... | 323.0      | 6.1               | 2005 May 13 | 013401 | 152.41   | 665  | 1.080       |
| 78... | 323.0      | 6.1               | 2005 May 13 | 013505 | 152.65   | 636  | 1.029       |
| 79... | 324.0      | 6.1               | 2005 May 13 | 013607 | 152.90   | 542  | 0.965       |
| 87b...| 323.0      | 3.6               | 2005 May 13 | 044632 | 211.57   | 1074 | 1.136       |
| 88b...| 328.0      | 4.3               | 2005 May 13 | 044735 | 211.77   | 1039 | 1.165       |
| 89... | 324.0      | 4.5               | 2005 May 13 | 044837 | 211.96   | 1058 | 1.140       |
| 90... | 327.0      | 4.8               | 2005 May 13 | 044940 | 212.16   | 947  | 1.324       |
| 91... | 326.0      | 4.4               | 2005 May 13 | 045043 | 212.35   | 1037 | 1.145       |
| 92... | 326.0      | 4.1               | 2005 May 13 | 045146 | 212.54   | 970  | 1.242       |

Notes.—The coordinates of field 1 are R.A. = 13h40m40s, decl. = −53°41′20″. The first six columns are extracted directly from the image headers; the last two columns are computed values. Col. (1): Abbreviated frame number. Col. (2): Wind direction. Col. (3): Wind speed. Col. (4): Date. Col. (5): Universal time. Col. (6): Telescope azimuth. Col. (7): Source count. Col. (8): Full width at half-maximum, defined as the median FWHM of the source objects in col. (7). All angles are in degrees, north through east.
in which $\beta$ is the ratio of the minor to major axes of the fitted ellipse. From this quantity one can construct the two independent ellipticity components $\epsilon_1$ and $\epsilon_2$,

$$\epsilon_1 = \epsilon \cos(2\phi),$$  \hspace{1cm} (2)$$

$$\epsilon_2 = \epsilon \sin(2\phi),$$  \hspace{1cm} (3)$$

where $\phi$ is the angle between the major axis of the ellipse and the $x$-axis of the detector. Systematic effects appear as correlations in ellipticity vectors across the image. To quantitatively assess the efficacy of correction procedures for removing PSF effects we define

$$\epsilon_{\text{rms}} = \frac{1}{N} \sum_{i} \left( \epsilon_{1,i}^2 + \epsilon_{2,i}^2 \right)^{1/2},$$  \hspace{1cm} (4)$$

$$\bar{\epsilon} = \frac{1}{N} \left[ \left( \sum_{i} \epsilon_{1,i} \right)^2 + \left( \sum_{i} \epsilon_{2,i} \right)^2 \right]^{1/2}$$

$$= \left( \epsilon_1^2 + \epsilon_2^2 \right)^{1/2}. \hspace{1cm} (5)$$

The first quantity, $\epsilon_{\text{rms}}$, is the rms ellipticity magnitude, while $\bar{\epsilon}$ is the average ellipticity. The sums in these equations are restricted to stars. Both quantities vanish in the round star limit; the latter likewise vanishes if the ellipticity vectors are randomly oriented.

The three panels in Figure 2 show the ellipticities of 811 stars in frame 36 derived using steps 1–3 of the measurement procedure described in § 3.3. (For reference, SExtractor identified a total of 1536 objects in the same frame.) The close agreement between $\epsilon_{\text{rms}}$ and $\bar{\epsilon}$ in the left panel reflects the high degree of correlation (presumably telescope tracking errors). A necessary next step is the removal of spurious ellipticity correlation, which otherwise mimics the weak-lensing signal. A first-order correction is to remove the common mode seen in that panel. The middle panel in Figure 2 is constructed in this manner, with $\epsilon'_{\text{rms}}$ defined as

$$\epsilon'_{\text{rms}} = \frac{1}{N} \sum_{i} \left( \epsilon_{1,i} - \bar{\epsilon}_1 \right)^2 + \left( \epsilon_{2,i} - \bar{\epsilon}_2 \right)^2 \right)^{1/2}, \hspace{1cm} (6)$$

replacing $\epsilon_{\text{rms}}$ of equation (4) and $\bar{\epsilon}_{1,2}$ defined as in equation (5). The middle panel shows the effect of subtracting off the lowest order common mode. Although $\epsilon'_{\text{rms}}$ has been reduced to 0.04, there remain persistent correlations, especially near the image corners. With this redefinition, $\bar{\epsilon}$ is identically zero. The right panel in Figure 2 shows the ellipticities after processing the image through the entire pipeline. Here $\epsilon_{\text{rms}}$ and $\bar{\epsilon}$ are reduced to 0.03 and 0.0016, respectively. More important, no obvious correlations persist. For this reason we make extensive use of the pipeline when discussing atmospheric residuals in § 3.3.

Having emphasized the preeminent role that stars play in subsequent analyses and with some idea of the ellipticity magnitudes, we now consider how their correlations depend on wind and seeing conditions.

### 3.1. Ellipticity Correlations with Wind

The next generation of weak-lensing measurements will likely include high-fidelity simulations to disentangle systematic effects from the signal. A crucial component of these will be atmospheric simulations, which require, among other things, wind speed and direction as a function of height as their input. These data may or may not be readily available at many observing sites. Even if they are, it is still nontrivial to infer an effective wind direction and speed across the aperture. It therefore would be useful to extract wind information from the image itself as one is accustomed to do for seeing.

We see no wind information in the distribution of the first moments of object intensities (seeing). However, it can be extracted by considering the second moments (ellipticities). The dominant ellipticity trend observed in the left panel in Figure 2 could well be attributed to the effects of wind transport across the aperture but may also contain nonatmospheric components such as wind shake of the telescope or guiding/tracking errors. We therefore cannot assume a priori that the dominant ellipticity trend is solely due to the wind.

To eliminate competing phenomena as the origin of the dominant ellipticity we perform pairwise vector subtraction of the raw ellipticity components of stars across the image, with the ellipticity components $\epsilon_a$ and $\epsilon_b$ derived from the shape parameter $\epsilon$ and position angle $\theta$ in the following manner:

$$\epsilon = \frac{1 - \epsilon_a}{\epsilon_b},$$  \hspace{1cm} (7)$$

$$\tan \theta = \frac{\epsilon_b}{\epsilon_a}.$$  \hspace{1cm} (8)$$

As defined above, $\epsilon_a$ and $\epsilon_b$ are the lengths of the major and minor axes of the ellipse, respectively. It follows that $\epsilon_x = \cos \theta$ and $\epsilon_y = \sin \theta$ are the ellipticity projections onto the $x$- and $y$-axes of the detector, respectively. The ellipticity residual is then defined as

$$\epsilon_{\text{res}} = \left[ (\epsilon_{x,i} - \epsilon_{x,j})^2 + (\epsilon_{y,i} - \epsilon_{y,j})^2 \right]^{1/2}. \hspace{1cm} (9)$$

In constructing this latter quantity we arrive at a distribution of ellipticity residuals from which the common-mode ellipticity has been removed.\(^{10}\) The ellipticity residuals can be projected onto the rows and columns of the detector (as in eq. [9]), along the right ascension (R.A.) and declination coordinate system, or along any other set of axes. (For an altitude-azimuth mount telescope

\(^{10}\) We expect these nonatmospheric components of the ellipticity to be extremely uniform across the detector and therefore to be removed very efficiently.
such as Gemini South a camera rotator is used to hold the instrument at a fixed position angle. For these data the position angle was such that the axes were aligned with R.A. and declination. In Figure 3, we plot the magnitude of one of these components as a function of position angle. A position angle of 0° corresponds to a basis in which the x-axis corresponds to the R.A. direction and the y-axis to the declination direction. Any positive rotation is then counterclockwise toward the east. While the total magnitude of the ellipticity is a rotational invariant, the magnitudes of the projected values are not. Figure 3 plots the projection along the vertical axis; by construction the x-axis values are offset in phase by 90°.

The curve for each frame (as indicated on the right side of the plot) has a distinctive minimum. Even though only a selected few frames are shown, all image data exhibit this behavior, albeit with lower significance for poorer seeing. Because the ellipticity residuals are at a minimum at a particular rotation, we can interpret this position angle as the direction in which the residuals are most correlated: a longer correlation length lowers the median ellipticity value as the PSFs are more similar along that direction. We believe this stretching of the correlation length in a particular direction is due to the more or less constant wind directions of the dominant wind layers (ground layer and 200 mbar jet stream layer) across the telescope aperture. In essence, this transport of the air across the telescope ensures that otherwise uncorrelated regions of the detector see the same atmosphere, resulting in more similar PSFs along this effective wind direction.

During the observations the ground layer wind direction varied from 300° to 330° (Fig. 1), with wind speeds of up to 6 m s⁻¹. The jet stream layer was blowing due east with wind speeds of about 30 m s⁻¹. If we assume that the wind directions are constant, then the only orientation variable left is the relative positioning of the telescope with respect to these winds.

Figure 4 summarizes the minima for all our image frames. It is clear that the data fall in two groups: one for which the telescope was pointed along the ground wind direction (azimuth ~150°; gray triangles) and one pointed almost perpendicular to the ground wind (azimuth ~215°; black triangles). We find that these minima are consistent over multiple days, ultimately reflecting similar observation and wind directions. The gray triangles all reflect observations of the same field taken about 2 hr before the meridian and the black triangles those 2 hr after the meridian. However, given the scatter in the data, we cannot uniquely identify these minima with a particular wind layer.

We furthermore note that for each frame the minima, even after taking out the bulk ellipticities through the pairwise subtractions, correlate with the direction of the bulk ellipticity (as given by the median ellipticity vector). The minima are found to be almost perfectly at right angles with the direction of largest ellipticity, and therefore they closely align with the ellipticity minor axis. So for these particular Gemini observations it is clear that most (if not all) of the bulk ellipticity observed in the frames is induced by the wind.

Given the predominant wind direction at Cerro Pachon and other sites, ellipticity residuals induced by the dominant wind layers are likely to persist over time. If an observing strategy involved viewing a part of the sky at similar hour angles and telescope orientations, the result would be a persistent residual that would not diminish by averaging more images.

3.2. Ellipticity Correlations with Seeing

In this section we describe how the atmosphere affects the ability to characterize a PSF at a particular location on the detector, where intrinsically round stellar objects can acquire an ellipticity for reasons set forth in § 1. Obviously, the better we can measure
statistics limit the useful range to below 4.

was extracted.

in eq. (9).

less than 1

tions the coherence distance is also finite. Coherence distances
and the PSF is known everywhere. Under finite seeing condi-
tions a stellar wave front is coherent
the stellar density and atmospheric coherence. Under perfect see-
ing (and telescope) conditions a stellar wave front is coherent

(see § 3.2.1). Using these fiducial stars we predict the PSFs of the
other fixed set of stellar objects by calculating the (distance)
weighted mean PSF derived from the fiducial set.

We use a fixed set of 150 stellar PSF positions randomly dis-
tributed across the chip. For each of these we calculate the vector
ellipticity difference between the distance weighted mean PSF,
calculated using a varying set of fiducial stars, and the actual PSF
at these 150 positions. The y-axis of Figure 6 is the median value
ellipticity residual for the fixed set of 150 stars. The number of
fiducial stars comprising the interpolation grid are varied from
about 400 down to about 5, corresponding to a spatial density
range of ~14 down to 0.2 stars arcmin⁻² (given our detector sur-
face area of 29.2 arcmin²).

In Figure 6 we plot the results for frames 36, 40, 91, and 92,
whose variables span the range of observing conditions (see
Table 1). The curve based on frame 36 represents the best ob-
serving conditions (~0.7′′ seeing) and is discussed first. This curve
is flat across spatial densities between 10 and 2 stars arcmin⁻², only
to turn upward at higher and lower spatial densities. The upturn
with decreasing spatial density is due to the gradual onset of spa-
tial decorrelation between the PSFs due to the atmosphere. With
separations of more than a few arcminutes the simple weighted in-
terpolation invoked here poorly estimates PSF shapes. The upturn
in the left part of the curve, on the other hand, is due to probable
contamination by nonstellar objects (and their large intrinsic ellip-
ticities) of the interpolation grid, as well as ellipticity measure-
ment limitations of faint stars due to shot noise. We come back to
this issue shortly.

Ignoring this high spatial density upturn, it is clear that with an
interpolation grid of at least 1 star arcmin⁻² residuals are mini-
mized within this type of interpolation scheme. As the observation
conditions worsen (as they do through frames 40, 91, and 92) ellipticity residuals rise regardless of PSF surface density, reproducing the trend seen in Figure 5. For the (seemingly) pathological cases of frames 91 and 92, for which the PSF correlation length is essentially zero, we do not see an increase in the residuals with decreasing PSF surface density. Instead, we see a decrease due to the fact that in the lowest spatial density bins we only consider the brightest stars in the frame, which happen to be those with the smallest measurement errors. The spatial PSF decorrelation in these frames is such that it does not matter what PSF we use for our model.

3.2.1. Shot Noise Contributions

To address how well this interpolation scheme performs, artificial sky images were created using a realistic observing and instrumentation setup. We use SkyMaker software\(^\text{12}\) to create three sets of images. The first (control 1 in Fig. 6) uses the brightness distribution found in frame 36. The other two images contained only stars of 20th and 15th magnitude (control 2 and 3, respectively). All stars are generated with a FWHM of 0.7", but no optical distortions are applied; hence, the PSFs are perfectly round. Consequently, the sole source of ellipticity is photon number statistics, i.e., shot noise. Furthermore, as we have perfect PSF correlation across the chip, there should not be any trend with decreasing spatial PSF density. This is indeed what is seen in both controls 2 and 3, and the offset between these histograms is exactly what is expected from shot noise calculations. The fact that control 1 slopes upward is due to the inclusion of progressively fainter stars as one goes up in spatial density (the faintest stars in control 1 are 19th magnitude), which increases the shot noise contribution.

Based on these control curves we can conclude the following. With ellipticity residuals on the order of 0.02 (frame 36), we are within a factor of a few of the shot noise limit for ~19th magnitude stars, with the difference attributed to atmospheric turbulence. Second, for stellar surface densities of less than about 1 arcmin\(^{-2}\) this interpolation scheme is less successful. However, the roll-off is gradual, both in terms of PSF surface density and seeing conditions.

3.3. Full Lensing Analysis

Ellipticity correlations as formulated above are a powerful measure of coherence and PSF behavior, but they are not expressed in a form that is readily compared with a cosmological lensing signal. Furthermore, more precise correction procedures are available than that applied above. We have chosen the Bernstein & Jarvis weak-lensing analysis software (Bernstein & Jarvis 2002) to correct stellar shapes for systematic effects. Much of the shape correction procedure is similar to that described in Jarvis et al. (2003). However, not all elements of a pipeline expressly designed to measure galaxy shapes apply here, where we restrict our attention to stellar objects. Those that do apply are described briefly below.

1. Object identification.—All our analyses adopt SExtractor as their starting points. Aperture magnitudes and the zero-point magnitude suggested for GMOS are adequate for our purposes. Only well-isolated stars having no associated error flags are selected.

2. Shape measurement.—Ellipticities measured by SExtractor serve as initial estimates for more precise shape measurements based on second moments weighted by elliptical Gaussians.

\(^{12}\) Available at http://terapix.iap.fr.
the “control 1” group of Figure 6. Recall that control 1 can be considered the same as frame 36 but without atmospheric distortions. The correlation functions generated in this manner are bounded from above by the raw ellipticities (solid line) and from below by photon shot noise (dash-dotted line), as expected.

The bottom panel in Figure 7 was generated in an analogous manner to that used to produce the dashed curve in the top panel, but was carried out for frames 36, 40, 91, and 92 using just 30 of the brightest stars in each frame as fiducial stars. The convolution was then applied to the remaining stars. The roll-off exhibited by each of the curves for separations above a few arcseconds is understood in terms of the density of fiducial stars (∼1 arcmin⁻² to match the typical density of high-latitude stars). For separations below a few arcseconds the correlations rise monotonically, reflecting the imperfect interpolation process between fiducial stars. However, even for the smallest separations this procedure results in an improvement on systematics shape 3–10 times over that in the raw images. Under all seeing conditions and for all separations the uncorrectable power is at worst a factor of 5 or so below that of the expected lensing signal (Jain & Seljak 1997). For separations relevant to present surveys (∼1′ or more) the systematic error arising from uncorrectable atmospheric power (for good seeing) is of comparable magnitude to the statistical error (∼0.003; Jarvis et al. 2006, Fig. 1). The lack of an exact one-to-one correspondence between seeing and amplitude of the two-point correlation functions is attributed to fluctuations, as well as variations in the number of test stars in the four frames.

4. CONCLUSIONS

Many systematic effects will affect data from the next generation of weak-lensing instruments. To understand the impact of the varying atmosphere we have acquired simultaneous image and atmospheric data from the Gemini South telescope. The exposure time of 15 s, site location, and mirror diameter are matched to that of the proposed Large Synoptic Survey Telescope (Tyson et al. 2005).

We have studied the effects of atmospheric turbulence using three methods of increasing sophistication and demonstrate that with seeing conditions up to ∼0.7″ the PSF is coherent over appreciable angular scales. When seeing exceeds 1″, the atmosphere is largely decoherent over all angular scales. We find that these correlations are not isotropic. Rather, there is a preferred direction, which we find to be induced by persistent wind layers. Unless somehow corrected for, this correlation will persist even after image stacking. Using a simple interpolation technique and under good seeing conditions the PSF can be predicted to within a factor of a few of the theoretical (shot noise) limit. A complete weak-lensing analysis demonstrates that for data taken under less than ideal circumstances atmospheric residuals can be reduced below that of the target cosmic shear signal. The presence of fiducial stars at a nominal density of ∼1 arcmin⁻² provides for sufficient sampling of the image plane to compensate for atmospheric decoherence. Under the best seeing conditions we confirm an earlier result (Wittman 2005) and further note that the uncorrectable systematic errors are of the order of statistical errors associated with present lensing surveys. However, future surveys will measure many more shapes, and the statistical errors will be correspondingly reduced. Thus, the present level of systematic error must also be lowered, especially in the nonlinear regime. It is not obvious a priori how one would commensurately lower the systematic error attributed to the atmosphere using the procedure outlined in this paper (since the errors are proportional to the fixed density of stellar objects used to make shape corrections). Fortunately, future surveys will revisit the same patch of sky multiple times, and one can resort to shear-shear correlations computed from shear measured across frames (first discussed in Jarvis & Jain 2004). If these frames are well separated temporally (e.g., >20 s) then the atmospheric noise is purely stochastic and will not add systematic power to shape measurements (see Jain et al. [2006] for a methodology that minimizes the information lost from not computing shear correlations within an image).

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Facilities: Gemini:South (GMOS)

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