Weak Lensing (and other) Measurements from Ground and Space Observatories

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1. Present State of the Art: New Results from the CTIO Weak Lensing Survey.
   
   **Mike Jarvis**
   GMB, Phil Fischer, Deano Smith, Tony Tyson & Dave Wittman

2. Improved Methods for Measurement of Weak Lensing in the Presence of PSF Systematics (GMB, Mike Jarvis)

3. Weak Lensing and Transient Survey speeds for ground- and space-based observatories of the future (GMB)
Present State of the Art: New Results from the CTIO Weak Lensing Survey

The Challenges:

- Full measurement of power spectrum will require images of $\sim 10^7$ galaxy shapes!

- Typical shear due to large-scale structure is a few tenths of a percent. Measuring this with precision requires that any systematic contamination be reduced to <0.01%.

- Any coherent stretching of the images masquerades as a lensing signal. Optical aberrations and atmospheric distortions cause just such an effect, at a typical level of 10%.

So we want to measure to $10^{-4}$ distortion in the face of a $10^{-1}$ systematic signal!
CTIO Weak Lensing Project:

- ~25 nights with BTC and Mosaic CCD cameras on Cerro Tololo 4-meter telescope.

- Each field is 2.5° square, subtending ~20 Mpc at peak lens distance. Sensitivity thus crosses from linear to non-linear regimes.

- Each galaxy is observed in multiple exposures in different parts of the CCD mosaic to enable tests for systematic errors.

- 12 fields complete, to cut cosmic variance with 24 samples of ellipticity.

- With >10^6 galaxies measured, signals on 20 Mpc scales is detected, only 0.2% distortion.

- Shallower survey (R<23) means redshift distribution is measured with <10% calibration uncertainty.
CFRS and CRS Predictions for CTIO Lens Sensitivities
How much data is it?
Comoving Radius at Lens Distance (h^{-1} Mpc)

$\gamma^2$ vs. Square Size (arcmin)

$\Lambda$CDM, $\sigma_8=1$
Foreground mass sinusoid produces ellipticity pattern at same k-vector.

Lensing cannot produce ellipticity pattern at 45 degrees to k-vector.
van Waerbeke et al. 2001 results
Where is the B-mode contamination coming from? Probably PSF Effects…

Ellipticity of Stellar Images in Representative Exposure

1% Ellipticity
A Short Introduction to Shape Measurements:

Simple indicator of ellipticity are unweighted second moments of the galaxy image:

\[
I_{ij} = \iint d^2x \, I(x)x_i x_j
\]

\[
e_+ = \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}}
\]

\[
e_- = \frac{2I_{xy}}{I_{xx} + I_{yy}}
\]

Unweighted moments simply add under convolution, so it is easy to correct observed ellipticities to intrinsic values after convolution by a PSF:

\[
e_{\text{intrinsic}} = \frac{e_{\text{observed}}}{1 - R}
\]

\[
R = \frac{\langle r^2 \rangle_{\text{psf}}}{\langle r^2 \rangle_{\text{observed}}}
\]

Unweighted moments have divergent noise properties, among other practical difficulties. Necessary to put a weight function inside the second-moment integral. A Gaussian is a practical and nearly-optimal weight:

Kaiser, Squires, & Broadhurst (KSB) method: size of weight function matched to object. Our method: size and shape of weight function matched to object. **Correction of weighted 2\textsuperscript{nd} moments for PSF convolution no longer has simple form.**
Past techniques for PSF corrections:

KSB: Effects of infinitesimal shear and infinitesimal convolution kernel upon moments can be analyzed with a differential of the weighted integral. **Polarizability** can be calculated for each object, which is a **quartic** Gaussian-weighted moment.

Fischer/Tyson/Bernstein: Infinitesimal anisotropic convolution can be cancelled by applying an orthogonal convolution to the image.

Both of these methods are formally valid only for infinitesimal PSFs or for Gaussian PSFs/objects (the Gaussians work because they’re generated by infinitesimal displacements).

These methods can be shown to fail in more realistic cases, but are good enough approximations to be used successfully for >1% shears or for phase-sensitive measurements such as galaxy-halo lensing.

Present techniques also not equipped for analysis of finite-sampled images.
New methodology (Bernstein & Jarvis 2001) developed to deconvolve away the undesirable aspects of PSF.

- Decompose image & PSF into Gaussian-based orthogonal functions:
  \[ I(r, \theta) = \sum b_{pq} \Psi_{pq}, \]
  \[ \Psi_{pq} = (-1)^q \sqrt{\frac{q!}{\pi p!}} r^m e^{im\theta} e^{-r^2/2} L_{(m)}^{(q)}(r^2) \]
  (eigenfunctions of 2d quantum harmonic oscillator)

- Image is represented by vector \( b_{pq} \). Convolution can be expressed as a matrix operation. Deconvolution is now the inverse matrix.

- Truncation of the deconvolution matrix determines tradeoff between fidelity and noise, i.e. between systematic and random errors).

- The raising/lowering operators of the 2dQHO may be combined to generate all the relevant point transformations of the image (translation, rotation, scale, shear). Effect upon the moment hierarchy is simple. Rapidly-calculable matrices for the effects of finite transformations as well.

- 2dQHO eigenfunctions are also eigenfunctions of the Fourier transform, hence the elements of the convolution matrix are also rapidly calculable.

- Refregier (2001) has also introduced the 2dQHO eigenfunctions, and Kaiser (2000) has a different approach to exact correction for effects of finite PSF.
CTIO Lens Survey uses a subset of new techniques:
Ellipticity of Stellar Images - After Correction

1% Ellipticity

jars 3-Aug-2000 12:38
Does it work? A rigorous test:

Evidence for Residual Systematic Effects in "Corrected" Galaxy Images

Though this is better than any algorithm to date, we can see that galaxies still “remember” the PSF distortions even though we have made the stars circular to high accuracy.
Increase order of PSF correction:

PSF shape rejected by ~100x
Subtle Systematic #1: Selection Bias

Though we have made the PSF round, the galaxies are typically selected in an image with elliptical PSF, which favors the detection of objects shaped like the PSF. Even after perfection shape correction, the population is biased (Kaiser 2000).

**Solution:** Select galaxies with some “isotropic” detection criterion.

Subtle Systematic #2: Centroid Bias

In making the PSF round, we have made the noise spectrum anisotropic. Errors in the centroid tend to be larger in one direction than the other, which induces a tendency to measure 2nd moments aligned with the original PSF (Bernstein & Jarvis, in prep).

**Solution:** Either re-isotropize the noise, or make a correction for the (nearly) calculable bias.
Kaiser's Selection Bias

Before Seeing:

STAR | e1>0 | e1<0

- [Diagram with color gradients and ellipses representing the distribution of variables before seeing]
Kaiser's Selection Bias

Before Seeing:

Convolved with PSF:
### Kaiser's Selection Bias

<table>
<thead>
<tr>
<th>STAR</th>
<th>$e_1 &gt; 0$</th>
<th>$e_1 &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Seeing:</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Convolved with PSF:</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>After Correction:</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**BELOW SURFACE BRIGHTNESS THRESHOLD**

**MEAN $e_1$ RETAINS PSF SHAPE!**

Before Seeing:

\[ \text{STAR} \]

\[ e_1 = 0 \]

In presence of noise, centroid is found somewhere in this error circle. Centroid error induces ellipticity - but isotropically.
In presence of noise, centroid is found somewhere in this error circle. Centroid error induces ellipticity - but isotropically.
Before Seeing:

In presence of noise, centroid is found somewhere in this error circle. Centroid error induces ellipticity - but isotropically.

Convolved with PSF:

After Correction:

Anisotropic deconvolution elongates centroid errors in PSF direction. Measured ellipticity tends to align with PSF!
The nature of the weak lensing signal:
How well can the underlying shear be extracted from the shape distribution, given our ignorance of the unperturbed shape distribution?
Weak Lensing Systematics Summary:

- Current techniques show uncorrected PSF power at fraction of a percent.
- New techniques should show very large improvements; no known bounds to accuracy of shear measurements right now. Even partial implementation has given improvement in accuracy.
- Future limitation is ability to measure PSF – how many stars, how stable is PSF?
- Calibration of shear from shapes is trivial at few-percent level; 1% calibration will take a little bit of work.
- Calibration of mass from shear requires knowledge of N(z) distribution. This will be well known from spectroscopic surveys at R<24 mag, maybe R<25 mag in 5 yrs or so. At fainter magnitudes this will remain a few-percent calibration uncertainty.
The Ideal Instrument for Gravitational Lensing:

Maximal Throughput = product of telescope aperture and field of view.

Essentially equivalent to size of CCD array, independent of telescope aperture.

Angular resolution must be fine enough to resolve galaxies. Hubble Deep Field shows that diffraction-limited 2-meter telescope does the job for nearly all visible galaxies.

High-quality and STABLE point spread function.

Our back-of-the-envelope proposal: 2-meter telescope in high orbit with ~1 degree field of view tiled with CCDs. High orbit for thermal stability and ease of pointing.
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Wide Area Space Telescope (WASTE)
Weak Lensing and Transient Survey speeds for ground- and space-based observatories of the future

What are the relative merits and strengths of orbiting observatories (SNAP) vs large ground-based survey telescopes (LSST) for weak lensing observations?

What about for photometric projects (supernova hunting/photometry, microlensing, planetary transits) or astrometric projects?

Effects that need to be considered in the calculation:
- Diffraction limitations
- Atmospheric seeing
- Zodiacal (space) vs atmospheric (ground) background emission
- Undersampling from finite pixel scale
- Dithered sampling
- Detector read noise and dark current
- Intra-pixel variations in detector response
- Charge diffusion within the detectors
- Loss of information from cosmic rays
- Field of view of camera and optical aberrations
- Duty cycle from weather/daylight/moonlight (ground) or eclipse (space)

All of these are incorporated by GMB PASP paper (January 2002 issue).
Figures of Merit for Nyquist-sampled, background-limited observations:

Photometry or detection of point sources:

\[ A_{S/N} = \left| \int \int \, d^2 k \, P^2(k) R^2(k) \right| \]

Where \( P(k) \) and \( R(k) \) are the FT’s of the optical PSF and the pixel response function.

Astrometry of point sources:

\[ A^2_{\text{centroid}} = \left| \int \int \, d^2 k \, k^2 \, P^2(k) R^2(k) \right| \]

Measurement of galaxy ellipticities – \( g(k) \) is FT of galaxy profile:

\[ \sigma_e^{-2} \propto \left| \int \int \, d^2 k \, k^2 \, P^2(k) R^2(k) \left| \left( \frac{\partial g}{\partial |k|} \right)^2 \right| \right| \]
Billion-Pixel Observatories:

Large Synoptic Survey Telescope (LSST) and Supernova Acceleration Probe (SNAP)

<table>
<thead>
<tr>
<th></th>
<th>LSST</th>
<th>SNAP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Mirror Diameter</strong></td>
<td>8 meters (6.5-meter equivalent)</td>
<td>2.0 meters</td>
</tr>
<tr>
<td><strong>CCD Field of View</strong></td>
<td>7 square degrees</td>
<td>1 square degree</td>
</tr>
<tr>
<td><strong>Number of CCD pixels</strong></td>
<td>$1.3 \times 10^9$</td>
<td>$1.3 \times 10^9$</td>
</tr>
<tr>
<td><strong>Angular Resolution</strong></td>
<td>0.5”-0.7” (atmospheric seeing)</td>
<td>0.05”-0.1” (diffraction-limited)</td>
</tr>
<tr>
<td><strong>Platform</strong></td>
<td>Ground</td>
<td>Space</td>
</tr>
<tr>
<td><strong>Nominal Exposure</strong></td>
<td>20 sec.</td>
<td>300 sec.</td>
</tr>
</tbody>
</table>
LSST generates ~2 Terabyte of imaging data per night!
• LSST would greatly expand the “throughput” – product of telescope area and field of view – of astronomical imaging.
• LSST will survey the entire available sky every 4 nights to 26th magnitude.
• In a few months per year, LSST would discover and determine orbits for 10^5 Kuiper Belt Objects of diameter 70 km or larger.
• In 10 years, catalog >90% of all Earth-crossing asteroids of D>300 meters (capable of city-destroying impacts).
• Discover ~10^4 supernovae at z<0.8.
Supernova survey efficiency for SNAP and LSST

Bernstein (2001)

Brightness and V band wavelength of SNe Ia at peak
Discovery brightness to prevent Malmquist bias
Relative Survey Speeds for Weak Gravitational Lensing

Median Sizes of Faint HDF Galaxies

\begin{itemize}
  \item m=29
  \item m=27
  \item m=25
\end{itemize}
Galaxy Counts from Hubble Deep Field:

**FIG. 29.** Galaxy counts as a function of $AB$ magnitude in the F814W band. FOCAS total and isophotal magnitudes are shown for $22 < I_{814} < 29$. Aperture magnitudes are shown only for galaxies fainter than $I_{814} = 26$. 

**TABLE 10.** HDF galaxy counts — F606W and F814W bands.

<table>
<thead>
<tr>
<th>$AB$ mag</th>
<th>$N$</th>
<th>$\log(n)$</th>
<th>$\log(n)$</th>
<th>$N$</th>
<th>$\log(n)$</th>
<th>$\log(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{606}$</td>
<td>isophotal</td>
<td>total</td>
<td>isophotal</td>
<td>total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{814}$</td>
<td>mag$^{-1}$ deg$^{-2}$</td>
<td>mag$^{-1}$ deg$^{-2}$</td>
<td>mag$^{-1}$ deg$^{-2}$</td>
<td>mag$^{-1}$ deg$^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.25</td>
<td>7</td>
<td>3.97</td>
<td>3.97</td>
<td>14</td>
<td>4.27</td>
<td>4.20</td>
</tr>
<tr>
<td>22.75</td>
<td>8</td>
<td>4.03</td>
<td>4.12</td>
<td>18</td>
<td>4.38</td>
<td>4.42</td>
</tr>
<tr>
<td>23.25</td>
<td>15</td>
<td>4.30</td>
<td>4.33</td>
<td>28</td>
<td>4.57</td>
<td>4.60</td>
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<tr>
<td>23.75</td>
<td>28</td>
<td>4.57</td>
<td>4.64</td>
<td>27</td>
<td>4.55</td>
<td>4.64</td>
</tr>
<tr>
<td>24.25</td>
<td>43</td>
<td>4.76</td>
<td>4.72</td>
<td>48</td>
<td>4.80</td>
<td>4.85</td>
</tr>
<tr>
<td>24.75</td>
<td>41</td>
<td>4.74</td>
<td>4.78</td>
<td>70</td>
<td>4.97</td>
<td>4.96</td>
</tr>
<tr>
<td>25.25</td>
<td>82</td>
<td>5.04</td>
<td>5.08</td>
<td>84</td>
<td>5.05</td>
<td>5.13</td>
</tr>
<tr>
<td>25.75</td>
<td>90</td>
<td>5.08</td>
<td>5.10</td>
<td>118</td>
<td>5.20</td>
<td>5.19</td>
</tr>
<tr>
<td>26.25</td>
<td>139</td>
<td>5.27</td>
<td>5.26</td>
<td>134</td>
<td>5.25</td>
<td>5.28</td>
</tr>
<tr>
<td>26.75</td>
<td>145</td>
<td>5.29</td>
<td>5.33</td>
<td>174</td>
<td>5.36</td>
<td>5.40</td>
</tr>
<tr>
<td>27.25</td>
<td>191</td>
<td>5.40</td>
<td>5.43</td>
<td>196</td>
<td>5.42</td>
<td>5.43</td>
</tr>
<tr>
<td>27.75</td>
<td>193</td>
<td>5.41</td>
<td>5.47</td>
<td>232</td>
<td>5.49</td>
<td>5.60</td>
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<tr>
<td>28.25</td>
<td>330</td>
<td>5.64</td>
<td>5.68</td>
<td>343</td>
<td>5.66</td>
<td>5.71</td>
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<tr>
<td>28.75</td>
<td>344</td>
<td>5.66</td>
<td>5.76</td>
<td>391</td>
<td>5.71</td>
<td>5.78</td>
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<tr>
<td>29.25</td>
<td>439</td>
<td>5.77</td>
<td>5.83</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

(11)
Practical Notes:

- Ground-based observatory has larger aperture/FOV, is faster for photometry of large/bright objects and most UV/blue observations.
- SNAP will gain for photometry of objects fainter than sky or in near-IR, by a large factor.
- Ground-based, natural-seeing observatory cannot observe ellipticities fainter than about R<25 mag, which limits density of sources to ~50 arcmin^-2 or less. But LSST can survey entire N hemisphere in multicolors to this level, 1.8x10^9 galaxies.
- SNAP can survey galaxies to R~30 where there are ~500 arcmin^-2 sources, in multiple colors as byproduct of SN search. High density of z>2 sources will permit measure of structure at z~1. Space is better for gauging evolution and getting high-S/N on individual structures.
- Systematic errors easier to reduce on orbit: stable PSF can be mapped over multiple exposures. SNAP high orbit reduces thermal cycling of HST.
- Kaiser/Tonry/Luppino WFHRI concept could permit much better resolution from ground; PSF will always be variable in time and space, hence ability to reduce PSF errors will depend upon sky density of bright stars.
- PSF estimation is critical for photometry as well as weak lensing.
- Canada-France-Hawaii Legacy Survey, then VISTA survey, will cover 100’s then >1000 square degrees for lensing and measure low-z power spectrum well.
- *These measurements CAN be done, but must be done carefully.*
<table>
<thead>
<tr>
<th>Survey</th>
<th>Observing Dates</th>
<th>Sky Coverage (deg$^2$)</th>
<th>Resolved Galaxies per arcmin$^2$</th>
<th>Filter Bands, Nominal Depth</th>
<th>Total Galaxy Shapes ($\times 10^6$)</th>
<th>Median Seeing (arcsec FWHM)</th>
<th>Publications/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTIO Survey</td>
<td>1996-2000</td>
<td>75</td>
<td>4</td>
<td>R$&lt;$23</td>
<td>1.0</td>
<td>1.0</td>
<td>Fully reduced, Jarvis et al., to be submitted late 2001</td>
</tr>
<tr>
<td>Sloan Digital Sky Survey (SDSS)</td>
<td>1999-2004</td>
<td>10,000</td>
<td>1.8</td>
<td>$ugriz, r&lt;22$</td>
<td>70</td>
<td>1.2</td>
<td>McKay et al. 2001 (3% of data); too shallow for cosmic shear.</td>
</tr>
<tr>
<td>SDSS Southern Cap</td>
<td>2001-2004</td>
<td>300</td>
<td>5-10</td>
<td>$ugriz, r&lt;23.5?$</td>
<td>5-10</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Red Cluster Survey (RCS)</td>
<td>1999-2002</td>
<td>100</td>
<td>10</td>
<td>Rz, R$&lt;$24</td>
<td>4</td>
<td>0.75</td>
<td>Hoekstra, et al. (2002) is best 25% of R data.</td>
</tr>
<tr>
<td>VIRMOS/CFHT</td>
<td>1999-2002</td>
<td>16</td>
<td>18</td>
<td>$UBVRI, I_{AB}&lt;$24.5</td>
<td>1.0</td>
<td>0.8</td>
<td>van Waerbeke et al. (2001) is 25% of I data.</td>
</tr>
<tr>
<td>Hawaii/CFHT</td>
<td>1998-2002?</td>
<td>9</td>
<td>30</td>
<td>VI, I$&lt;$24</td>
<td>0.7</td>
<td>0.8</td>
<td>Kaiser, Wilson, &amp; Luppino (2000) is 20% of data.</td>
</tr>
<tr>
<td>Deep Lens Survey (DLS)</td>
<td>1999-2003</td>
<td>28</td>
<td>20-30</td>
<td>$BVRz, R$&lt;$25?$</td>
<td>2</td>
<td>0.7-0.9</td>
<td>50% of data taken.</td>
</tr>
<tr>
<td>CFHT Legacy Wide Synoptic</td>
<td>2002-2007</td>
<td>208</td>
<td>20-30</td>
<td>$ugriz, I_{AB}&lt;$24.3</td>
<td>15-20</td>
<td>0.7?</td>
<td>Approval is imminent.</td>
</tr>
<tr>
<td>VISTA</td>
<td>2005-??</td>
<td>1000?</td>
<td>20-30</td>
<td>I$&lt;$24</td>
<td>70-100</td>
<td>0.6?</td>
<td>Dedicated 4-meter; funded, survey parameters not set.</td>
</tr>
<tr>
<td>Large Synoptic Survey Tel. (LSST)</td>
<td>2008?</td>
<td>10,000</td>
<td>30</td>
<td>$UBVRIZ, R$&lt;$25?$</td>
<td>1000</td>
<td>0.6?</td>
<td>Not yet funded or fully defined</td>
</tr>
<tr>
<td>Supernova Acceleration Probe (SNAP)</td>
<td>2008?</td>
<td>25</td>
<td>&gt;500</td>
<td>B thru H, I$&lt;$30</td>
<td>45</td>
<td>0.1</td>
<td>Not yet funded.</td>
</tr>
<tr>
<td>SNAP/Wide</td>
<td>2010?</td>
<td>1000</td>
<td>~200</td>
<td>I$&lt;$28</td>
<td>700</td>
<td>0.1</td>
<td>Possible lensing survey mode.</td>
</tr>
</tbody>
</table>

Table 1: Present and future largest weak-lensing surveys.