How Future Space-Based Weak-Lensing Surveys Might Obtain Photometric Redshifts Independently

R. Sorba and M. Sawicki

Department of Astronomy and Physics and Institute for Computational Astrophysics, Saint Mary’s University, 923 Robie Street, Halifax, Nova Scotia, B3H 3C3, Canada; rsorba@ap.smu.ca, sawicki@ap.smu.ca

Received 2011 February 7; accepted 2011 April 28; published 2011 May 26

ABSTRACT. We study how the addition of onboard optical photometric bands to future space-based weak-lensing instruments could affect the photometric redshift estimation of galaxies and hence improve estimations of the dark energy parameters through weak lensing. Basing our study on the current proposed Euclid configuration and using a mock catalog of galaxy observations, various onboard options are tested and compared with the use of ground-based observations from the Large Synoptic Survey Telescope (LSST) and Pan-STARRS. Comparisons are made through the use of the dark energy figure of merit, which provides a quantifiable measure of the change in the quality of the scientific results that can be obtained in each scenario. Effects of systematic offsets between LSST and Euclid photometric calibration are also studied. We find that adding two optical bandpasses (U and G) or even solely the U bandpass to the space-based infrared instrument greatly improves its photometric redshift performance, bringing it close to the level that would be achieved by combining observations from both space-based and ground-based surveys while freeing the space mission from reliance on external data sets.

Online material: color figures

1. INTRODUCTION

Over the past few years, it has been shown that approximately 74% of the energy density of the universe is in the form of dark energy (DE). Often represented as the cosmological constant $\Lambda$ in Einstein’s theory of general relativity, DE causes the expansion of the universe to accelerate (see Copeland et al. 2006 for a review). A great deal of effort is being put into constraining the DE equation-of-state parameters in order to better understand the phenomenon. One promising method of placing high-accuracy constraints on the DE parameters is through weak lensing, which involves measuring the shape of numerous galaxies over a large area of the sky (e.g., Blandford et al. 1991; Bartelmann & Schneider 2001; Réfrégier 2003).

An important source of error in the weak-lensing analysis comes from uncertainties in the photometric redshift (photo-$z$) estimation to each galaxy, which is required to form a threedimensional map. While they are less accurate than spectroscopic redshifts (spec-$z$), the extremely large area (20,000 deg$^2$) planned for future dark energy surveys necessitates the use of photo-$z$ (see Hildebrandt et al. 2010 for a summary of current photometric redshift techniques and capabilities). The effects of photo-$z$ uncertainties on weak lensing were studied by Huterer et al. (2006), who placed stringent constraints on the degree of accuracy and precision required in order for the redshift estimations to be useful in tomography. Indeed, current goals state that the standard deviation of the photo-$z$ must be less than 0.05 ($1+z$) and that any bias in the photo-$z$ must be known to a degree of 0.002 ($1+z$). Ma et al. (2006) found that in order to satisfy these criteria, a large spectroscopic survey (on the order of $\sim 10^5$ galaxies) must be carried out to properly calibrate the photometric redshifts. Several works since then have found that the amount of spectroscopy needed can be reduced by optimizing the spectroscopic survey to cover important redshift ranges (Ma & Bernstein 2008; Sun et al. 2009; Berstein & Huterer 2010), while Bordoloi et al. (2010) studied how the photo-$z$ themselves can be used for calibration.

Because of confusion between breaks, photometric redshifts are especially prone to catastrophic outliers, which can greatly impact the weak-lensing analysis (Sun et al. 2009; Bernstein & Huterer 2010). It was found that the number of catastrophic outliers can be greatly reduced if ground-based photometry ($u, g, r, i, z, y$) is complemented with near-infrared (NIR) photometry (Abdalla et al. 2008; Nishizawa et al. 2010). To this aim, both Wide-Field Infrared Survey Telescope (WFIRST) and Euclid, two space-based instruments that will study weak lensing, will include a NIR channel to facilitate accurate photometric redshifts. However, in their current state, neither instrument can obtain accurate photo-$z$ by itself. Instead, they must rely on complementary observations from ground-based instruments (such as the proposed Large Synoptic Survey Telescope [LSST] or the Panoramic Survey Telescope and Rapid Response System [Pan-STARRS]). Various complications may arise from trying to combine such a large amount of data from two or more
observatories, and it may be beneficial if a space-based instrument could produce its own optical observations.

In this work, we study how future space-based weak-lensing missions may benefit from the addition of onboard optical photometry. We do this in the context of the current Euclid design in order to ground our results in reality, but the conclusions could apply just as well to WFIRST or any other future weak-lensing instrument. Euclid is comprised of both a visual (VIS) channel and a NIR channel. The proposed VIS channel is made of a very broad filter (RIZ) that covers the wavelength range 0.55–0.92 μm and will be used primarily to measure galaxy shapes for weak lensing. The NIR photometric channel includes three bandpasses (Y, J, and H) and spans wavelengths from 1.0 to 1.6 μm.

While one could design a highly optimized, multielement onboard filter system, our aim is to instead explore simple scenarios that result in relatively small perturbations to the current Euclid instrument and mission design. To this end we explore the impact of adding two onboard optical bandpasses (U and G) to Euclid and compare them with the results one would obtain by augmenting Euclid observations with ground-based optical observations. In § 2, we detail the method with which we simulate a catalog of observed galaxies and generate photometric redshifts for each of the galaxies. In § 3 we present the photometric redshift distribution of various filter combinations and compare these with the expected results of combining observations from Euclid with either LSST or Pan-STARRS using the dark energy figure of merit (FOM). Finally, we discuss the effects of any systematic offsets between the Euclid and ground-based observations on the weak-lensing analysis.

2. METHOD

2.1. Mock Catalog

In order to study the effect of space-based optical observations, we first needed a catalog of galaxies to be observed. Ideally, this catalog would have realistic redshift, color, and luminosity distributions in order to accurately model the galaxy population and its photometric redshift distribution. To this aim, we chose to use the COSMOS Mock Catalog (CMC; Jouvel et al. 2009). This catalog draws upon observations from the COSMOS Deep Field (Capak et al. 2007) and the photometric redshift catalog of those galaxies (Ilbert et al. 2009). By combining the best-fitting redshift and extinction with observable properties such as galaxy type and half-light radius (Leauthaud et al. 2007), the CMC construction is representative of a real galaxy survey.

The CMC best-fitting spectral energy distribution (SED) templates were generated similarly to those of Ilbert et al. (2009), which used template libraries of both Polletta et al. (2007) and Bruzual & Charlot (2003). The Polletta et al. (2007) templates include SEDs of elliptical and spiral galaxies, whereas the Bruzual & Charlot (2003) templates model starburst galaxies with ages ranging from 3 to 0.03 Gyr. Additional extinction was applied to the templates using the Calzetti et al. (2000) extinction law with $E(B-V)$ values of 0, 0.05, 0.1, 0.15, 0.2, 0.35, 0.3, 0.4, and 0.5.

In summary, the CMC provides best-fitting spectra and observed properties of 538 000 galaxies from the COSMOS-ACS catalog and covers an effective area of 1.24 deg$^2$. It has a maximum redshift of $z = 3.64$ and a median redshift of 0.96. The COSMOS mock catalog is limited by the completeness of the COSMOS imaging ($i'_{AB} \sim 26.2$ for 5-σ detection; Capak et al. 2007).

2.2. Simulating Observations

The proposed observational strategy for Euclid involves taking four dithered exposures of each field, with the total integration time of each dither being approximately 700 s (Duvet 2010). Euclid is designed such that the VIS and NIR channels can observe simultaneously. In order to limit the number of moving parts during the VIS integration, the NIR spectrometer and the VIS channel will observe first (with an integration time of $\sim 540$ s), after which the NIR photometry bands will observe sequentially (integration times given in Table 1). All of our simulations for Euclid observations assume this observational strategy.

We studied photo-z performance with several Euclid $U + G$ channel configurations, as outlined in a recent study (Rowlands et al. 2011) sponsored by the Canadian Space Agency. We first assumed a best-case scenario in which two dichroics split the VIS channel light such that the RIZ, G, and U filters can all observe simultaneously (i.e., three separate detectors). However, we also tested other scenarios: one in which we removed one detector and dichroic and put the U and G filters on a filter exchanger so that they must share integration time and another in which all the filters are on an exchanger and all feed the same single detector. Finally, we also considered scenarios in which only one additional onboard filter—either $U$ or $G$—is used.

| Filter | Wavelength (nm) | Obs. time (s) | Total throughput (%) |
|--------|-----------------|---------------|----------------------|
| $U$    | 300–440         | 542$^a$       | 0.35                 |
| $G$    | 440–550         | 542$^a$       | 0.5                  |
| RIZ    | 550–920         | 542           | 0.59                 |
| $Y$    | 920–1146        | 88.5          | 0.45                 |
| $J$    | 1146–1372       | 107.4         | 0.45                 |
| $H$    | 1372–2000       | 61.8          | 0.45                 |

$^a$Total throughput is estimated to include all photon losses through the system. Each filter is approximated as a box function.

$^b$The $U$ and $G$ observation times listed are for the scenario where each of these filters feeds a dedicated detector; $U$ and $G$ observation times are shorter for other scenarios, as described in the text.
Assuming that the best-fitting SED from a galaxy in the CMC is the true signal from the galaxy, we simulated the observed magnitude of each galaxy in each of the Euclid filters (properties shown in Table 1) by adding a random noise component to the true signal measured through each filter.

Our method of estimating noise closely follows that described in the appendix of Jouvel et al. (2010), but a brief outline is given here. First, we calculated the expected signal-to-noise ratio (S/N). For space-based observations, the S/N can be found by

$$
\frac{S}{N} = \frac{e_{\text{signal}}}{\sqrt{e_{\text{signal}} + e_{\text{sky}} + N_{\text{pix}} N_{\text{exp}} e_{\text{RON}} + N_{\text{pix}} N_{\text{exp}} e_{\text{obs}} e_{\text{dark}}}.
$$

(1)

Here, $e_{\text{signal}}$ is the number of electrons produced in the device by the galaxy flux. The noise contributions in the denominator include Poissonian noise from the source and the background zodiacal light ($e_{\text{sky}}$), the dark current caused by the thermal radiation of the instrument ($e_{\text{dark}}$), and the readout noise (RON) of the detector ($e_{\text{RON}}$), which follows a Gaussian statistic. $N_{\text{pix}}$ is defined to be the number of pixels contained within a circular area of 1.4 times the observed full width at half-maximum of the galaxy, $N_{\text{exp}}$ is the number of exposures (four, as planned in the Euclid survey), and $t_{\text{obs}}$ is the exposure time. For the VIS channel, we use $e_{\text{dark}} = 0.03 \, e \, s^{-1}$, $e_{\text{RON}} = 6 \, e$, and assume 0.1" pixel$^{-1}$, whereas for the NIR we assume $e_{\text{dark}} = 0.05 \, e \, s^{-1}$, $e_{\text{RON}} = 5 \, e$, and 0.3" pixel$^{-1}$. The onboard optical $U$ and $G$ channel is assumed to have the same pixel scale as the NIR channel (0.3" pixel$^{-1}$), but the RON and dark current of the VIS channel.

Once the theoretical S/N is determined, we simply add an error term to the true magnitude of the galaxy, which is drawn from a Gaussian distribution of mean $\mu = 0$ and standard deviation $\sigma = [2.5 / \ln(10)] / [1 / (S/N)]$. In this way, realistic observational uncertainties are included in our final simulated observations, as is demonstrated in Figure 1. By comparing Figure 1 with results from other radiometric performance simulations of Euclid (Duvet [2010] predicts a S/N of 14.3 for the RIZ filter at a magnitude of 24.5 and a S/N of 7.1 for the IR filters at magnitude 24), we are confident that our noise generation procedure produces reasonable results.

For ground-based LSST observations our error simulations followed a different approach. In accordance with Ivezic et al. (2008), the expected photometric error for a single observation of a galaxy is given by

$$
\sigma_{\text{LSST}}^2 = \sigma_{\text{sys}}^2 + \sigma_{\text{rand}}^2,
$$

(2)

where $\sigma_{\text{sys}} = 0.003$, and $\sigma_{\text{rand}}$ is given by

$$
\sigma_{\text{rand}}^2 = (0.04 - \gamma) x + \gamma x^2,
$$

(3)

with $x = 10^{0.4(m - m_0)}$. Here, $m_{\text{5}}$ is the 5-$\sigma$ depth for point sources in a given band, and $\gamma$ is based on factors such as the sky brightness and readout noise. Values for $m_{\text{5}}$ and $\gamma$ can be found in Table 2. To account for repeat observations, $\sigma_{\text{rand}}$ is divided by 10 to give the error after 100 observations.

In a similar fashion to the preceding space-based observations, an error term was added to each of the model magnitudes, which is drawn from a Gaussian distribution, but now with $\sigma = \sigma_{\text{LSST}}/10$. Gaussian errors for Pan-STARRS are assumed to have the same form as those for LSST, but have been adjusted to match the sensitivities given in Abdalla et al. (2008) for a Pan-4-like scenario (Table 2).

From the true signals of the CMC, we thus created a catalog of realistic observations for LSST, for Pan-STARRS, and for Euclid combined with a proposed onboard $U + G$ optical channel.

---

**FIG. 1.**—Uncertainty versus observed magnitude for objects with RIZ magnitude less than 24.5. Horizontal lines mark the 10-$\sigma$ and 5-$\sigma$ uncertainties.

**TABLE 2**

| Filter | $m_{\text{5}}$ (LSST) | $\gamma$ | $m_{\text{10}}$ (Pan-4) |
|--------|-----------------------|---------|------------------------|
| $u$    | 23.9                  | 0.037   | ...                    |
| $g$    | 25.0                  | 0.038   | 25.9                   |
| $r$    | 24.7                  | 0.039   | 25.6                   |
| $i$    | 24.0                  | 0.039   | 25.4                   |
| $z$    | 23.3                  | 0.040   | 23.9                   |
| $y$    | 22.1                  | 0.040   | 22.3                   |

2011 PASP, 123:777–788
2.3. Photometric Redshifts

From the noisy observations, we then calculated a photometric redshift to each galaxy for various filter combinations. The photometric redshifts were estimated by comparing the simulated observed broadband photometry with a grid of the model SEDs from the CMC. While this creates a situation in which our model SED templates perfectly match the reality of the CMC galaxies, and therefore overestimates the photo-z quality, we feel that this is an unavoidable approach. While some systematic effects of choice of SED templates are known (for example, the BCO3 templates are thought to underestimate stellar mass, due to a poor treatment of the thermally pulsating asymptotic giant branch phase [Bruzual 2007]), most are not well understood. It would therefore be very difficult to realistically model the scatter and possible bias of the photometric redshift estimates as a consequence of our choice of model templates. We chose to instead focus on contributions to the photo-z error resulting from random photon statistics and possible systematic instrument calibration errors, but we acknowledge that the photo-z given here may be slightly worse, in reality, because of imperfect SED templates.

To calculate the photometric redshifts, we used the SEDfit software package (Sawicki & Yee 1998; Sawicki 2011, in preparation). This software redshifted the CMC model spectra onto a grid of redshifts spanning \(0 \leq z \leq 6\) in steps of 0.02 and attenuated them using the Madau (1995) prescription for continuum and line blanketing, due to intergalactic hydrogen along the line of sight. It then integrated the resultant observer-frame model spectra through filter transmission curves to produce model template broadband fluxes. In order to match the model template fluxes to the simulated observations, the observed fluxes of each object were compared with each template in the grid by computing the statistic

\[
\chi^2 = \sum_i \frac{[f_{\text{obs}}(i) - sf_{\text{tpt}}(i)]^2}{\sigma^2(i)},
\]

where \(f_{\text{obs}}(i)\) and \(\sigma(i)\) are the observed flux and its uncertainty in the \(i\)th filter, and \(sf_{\text{tpt}}(i)\) is the flux of the template in that filter. The variable \(s\) is the scaling factor between the observed and template fluxes and can be computed analytically by minimizing the \(\chi^2\) statistic with respect to \(s\), giving (Sawicki 2002)

\[
s = \frac{\sum_i f_{\text{obs}}(i) f_{\text{tpt}}(i)/\sigma^2(i)}{\sum_i f^2_{\text{tpt}}(i)/\sigma^2(i)}.
\]

For each object, the most likely redshift is determined by the smallest \(\chi^2\) value over all the templates. Error bars are generated by refitting the object 200 times with slightly perturbed photometry and finding the range in which 68% of the fits lie.

2.4. Figure of Merit

In order to objectively compare the different observational scenarios, we employ the DE FOM proposed by the Dark Energy Task Force. This number is the inverse of the area of the \(2\sigma\) uncertainty ellipse in the plane of the DE parameters \(w_0\) and \(w_a\). The FOM is thus a statement on the precision of the DE measurements, not necessarily the accuracy.

We used the iCosmo package (Rérégier et al. 2008) to calculate the FOM for each of our survey scenarios, assuming a flat cosmology with fiducial cosmological parameters of \((\Omega_m, w_0, w_a, \Omega_b, \Omega_s, n_s, \Omega_\Lambda) = [0.3, -0.95, 0, 0.7, 0.045, 0.8, 1, 0.7]\), an intrinsic ellipticity dispersion of 0.25, and 10 tomographic redshift bins. The calculations are done using only the weak-lensing power spectrum, which is summed over \(10 \leq \ell \leq 20,000\), and the \(w_0 - w_a\) uncertainty is marginalized over the other five parameters without any external priors.

To orient our comparisons, Rérégier et al. (2010) state that the current FOM is on the order of 10, which is generated using WMAP observations combined with baryon acoustic oscillation and Type Ia supernova distance measurements, as well as a prior adopted in accordance with big bang nucleosynthesis (Komatsu et al. 2009). This is the FOM value currently achieved by combining several available DE probes; in contrast, in the rest of the article we present FOM values attainable from weak-lensing observations alone, without the inclusion of other probes that are available now or in the future.

A FOM generated solely from a weak-lensing survey using both space-based and ground-based observations is expected to be approximately 180 (see Table 4.1 in Rérégier et al. 2010), over an order of magnitude greater than the current figure. However, values can vary depending on the parameters and methods used to estimate the expected FOM. For example, Amara & Rérégier (2007) obtain a FOM of only 50 for a survey with properties similar to what is expected with Euclid plus ground-based observations (20,000 deg\(^2\) area, 35 gal arcmin\(^{-2}\) and median redshift of 0.9). Regardless, if all cosmological probes observable with Euclid are utilized, then the FOM increases to \(-400\) and to well over 1000 with the use of external prior constraints derived from Planck.

It is informative to discuss how various parameters of the photometric redshift distribution affect the FOM. Amara & Rérégier (2007) have shown that the FOM is almost directly proportional to the number density of galaxies in the photometric redshift catalog. However, there is a tradeoff between a wide and a deep survey, as they show that the FOM also depends strongly on the median redshift of the photo-z distribution (FOM \(\propto z_{\text{med}}^2\)). The figure of merit also degrades as the precision of the photometric redshifts decreases (FOM \(\propto 10^{-1.69cz_{\text{med}}}\)) and as the fraction of objects with catastrophic redshift errors (\(F_{\text{cata}}\)) increases (FOM \(\propto 10^{-0.75F_{\text{cata}}}\)). It is clear that accurate and precise photo-z are important if a respectable FOM is to be obtained.
3. RESULTS

In this work, we used the preceding procedure to create a catalog of observations for each galaxy in the mock catalog, but limited ourselves to analyzing only those galaxies that have an AB magnitude of less than 24.5 in the RIZ channel. We studied three options for a weak-lensing survey: (1) using only the filters currently planned for the Euclid instrument (RIZ shape channel, Y, J, and H); (2) the Euclid filters plus additional onboard optical filters U and G; and (3) the Euclid IR filters (Y, J, and H) plus ground-based observations from either Pan-STARRS (grizy) or LSST (ugrizy). The first scenario was done strictly for comparison and is not expected to yield usable photometric redshifts, since it has no optical observations. The second scenario was divided into several subcases in which we examined the impact of different exposure times with the two optical filters and also the effect of not using the RIZ shape channel for photometry. For the last case we preferentially used LSST for the ground-based observations, since we found similar (although slightly worse) photometric redshift results using Pan-STARRS (see also Abdalla et al. 2008). A summary of the scenarios and results is presented in Table 3. The median redshift for all cases is 0.8.

3.1. Euclid Alone

The currently proposed strategy for Euclid was chosen to rely on other ground-based projects to obtain optical measurements for photometric redshift estimation. The optical wavelength observations are required in order to obtain accurate low-redshift photo-z by detecting the various breaks in a galaxy’s SED as they appear in our observer frame. It is well understood that without any optical bandpasses, virtually no constraints can be placed on the redshifts of low-z galaxies. Thus, it is no surprise that the plot shown in Figure 2 contains a large number of catastrophic redshifts, as galaxies with $z \leq 1$ are scattered upward to higher redshifts. Note also that the standard deviation $\sigma_z/(1+z)$ is well above the required level of 0.05 at nearly all redshifts, and the FOM is less than the present-day value. Obviously, results can be improved by culling galaxies that have low-quality photometric redshift estimates, as shown in Figure 3, where any galaxy with an uncertainty $\Delta z_{\text{phot}}$ greater than 0.5 has been removed. Removal of poorly constrained galaxies can be a tradeoff, as it tightens up the spread of the photo-z and thus raises the FOM, but it also reduces the number density of galaxies, which acts to lower the FOM. However, in this scenario, culling of poorly fit galaxies results in the removal of almost all galaxies needed for weak lensing in the target range of $0.3 \leq z \leq 2$, resulting in a poor FOM.

The point of this exercise is to emphasize that when it is said that Euclid will rely on ground-based observations, it is fully reliant, in that a weak-lensing DE survey will not be possible without optical photometry from other telescopes.

3.2. Addition of an Onboard U and/or G Channel

Figure 4 shows the drastic improvement in photometric redshifts that can be found with the addition of two onboard optical bandpasses to Euclid. The ability to discriminate low-z galaxies from high-z galaxies is invaluable. While the overall standard deviation is still rather high $[\sigma_z/(1+z) > 0.05]$ due to the number of catastrophic failures at low redshift, a simple culling of untrustworthy galaxies ($\Delta z_{\text{phot}} < 0.5$) brings this down to below the required level, as shown in Figure 5. The right panels of

| Scenario     | Filters | Culling$^*$ | $N_{\text{gal}}$ | $\sigma_{\Delta z/(1+z)}$ | $F_{\text{auto}}$ | FOM   |
|--------------|---------|------------|-----------------|--------------------------|------------------|-------|
| Euclid       | RIZ, Y, J, H | N         | 32.2           | 0.951                    | 0.3985           | <5    |
| Euclid       | RIZ, Y, J, H | Y         | 2.3            | 0.114                    | 0.0126           | <5    |
| Euclid+optical | U, G, RIZ, Y, J, H | N         | 32.2           | 0.052                    | 0.0043           | 122   |
| Euclid+optical | U, G, RIZ, Y, J, H | Y         | 31.6           | 0.037                    | 0.0016           | 126   |
| Euclid+optical (50:50 U : G time split) | U, G, RIZ, Y, J, H | N         | 32.2           | 0.071                    | 0.0090           | 113   |
| Euclid+-optical (50:50 U : G time split) | U, G, RIZ, Y, J, H | Y         | 30.8           | 0.046                    | 0.0029           | 119   |
| Euclid+U only | U, RIZ, Y, J, H | N         | 32.2           | 0.126                    | 0.0414           | 85    |
| Euclid+U only | U, RIZ, Y, J, H | Y         | 25.7           | 0.062                    | 0.0063           | 100   |
| Euclid+G only | G, RIZ, Y, J, H | N         | 32.2           | 0.199                    | 0.0019           | 58    |
| Euclid+G only | G, RIZ, Y, J, H | Y         | 19.7           | 0.059                    | 0.0047           | 67    |
| Euclid+Pan-1  | g, r, i, z, y, Y, J, H | N         | 32.2           | 0.299                    | 0.098            | 41    |
| Euclid+Pan-1  | g, r, i, z, y, Y, J, H | Y         | 24.8           | 0.102                    | 0.027            | 72    |
| Euclid+Pan-4  | g, r, i, z, y, Y, J, H | N         | 32.2           | 0.175                    | 0.039            | 70    |
| Euclid+Pan-4  | g, r, i, z, y, Y, J, H | Y         | 30.1           | 0.070                    | 0.010            | 105   |
| Euclid+LSST   | u, g, r, i, z, y, Y, J, H | N         | 32.2           | 0.030                    | 0.0011           | 131   |
| Euclid+LSST   | u, g, r, i, z, y, Y, J, H | Y         | 32.2           | 0.024                    | 0.0003           | 133   |
| Euclid+LSST with ZP errors | u, g, r, i, z, y, Y, J, H | N         | 32.2           | 0.032                    | 0.0011           | 130   |
| Euclid+LSST with ZP errors | u, g, r, i, z, y, Y, J, H | Y         | 32.2           | 0.025                    | 0.0004           | 132   |

$^*$ Culling is defined as removing any objects with photo-z error bars greater than 0.5.
Figures 4 and 5 demonstrate that even if the overall standard deviation is high, the standard deviation as a function of redshift can still be below the required value in the key redshift range for weak lensing ($0.3 \leq z \leq 2$). The resulting FOM of 122 and 126 for the raw and culled scenarios, respectively, make it clear that the addition of onboard optical bandpasses could make Euclid self-sufficient for weak lensing. Although observations from other instruments could, of course, still be used, Euclid would no longer be completely reliant on them.

In the preceding scenario, both the $U$ and $G$ filters feed dedicated detectors and so have the maximum exposure time available ($\sim 500$ s, the same as the $RIZ$ shape channel). If the two optical bands cannot observe simultaneously, but instead have to share observation time, as might be the case if a single detector plus a filter exchange mechanism were used, this will have a negative impact on the photometric redshift estimations. Although observations from other instruments could, of course, still be used, Euclid would no longer be completely reliant on them.

In the preceding scenario, both the $U$ and $G$ filters feed dedicated detectors and so have the maximum exposure time available ($\sim 500$ s, the same as the $RIZ$ shape channel). If the two optical bands cannot observe simultaneously, but instead have to share observation time, as might be the case if a single detector plus a filter exchange mechanism were used, this will have a negative impact on the photometric redshift estimations. Although observations from other instruments could, of course, still be used, Euclid would no longer be completely reliant on them.

The FOM stays at roughly the same level ($115 < \text{FOM} < 119$) until the observing time percentage drops below 30% in either band. At the extreme ends of sharing scenarios, it is clear that $U$-band observations are more critical than $G$-band observations, as the FOM with nothing but $G$ is 67.4, much less than the FOM = 100.1 for solely $U$-band observations. The larger FOM comes from the better constraints that the $U$ band can place on the lowest redshift galaxies. In order to determine if two optical filters are absolutely necessary, we also tested a scenario with a broad filter that combined the $U$ and $G$ wavelengths, which resulted in a FOM of 87.86. While being able to estimate the photo-$z$ of low-redshift galaxies better than just the $G$ band, the broadness of this merged filter led to ambiguity as to where the 4000 Å break falls within the filter, and hence it was not able to break the degeneracy between low-$z$ and high-$z$ objects, as well as simply the $U$ filter. These results show that both $U$ and $G$ filters are required for optimal photometric redshifts. Note, however, that using just the $U$ filter gives a fairly adequate FOM of $\sim 100$ that, while not optimal, may prove to be the best compromise between the instrument’s weight and complexity and the best obtainable DE constraints.

As a final scenario for Euclid, we tested the effects of splitting the broad shape channel $RIZ$ filter into two separate filters, hereafter called $R$ and $Z$, and adding $U$ and $G$ filters as well. In this scenario, all the filters feed one detector and would be mounted on a filter wheel. Euclid’s planned total observing time per dither is fixed at $\sim 700$ s, which was divided among the $U$, $G$, $R$, and $Z$ filters, allowing 10 s to account for the time taken to change filters. We found that using four filters ($U$, $G$, $R$, and
in this finite amount of time was not beneficial, as the short observing time increased the signal-to-noise ratio. The best case we found used three filters (\(U\), \(R\), and \(Z\)) with the observing time split roughly evenly between the three, although slightly favoring the \(U\) band (40\%, 30\%, and 30\% of the observing time in the \(U\), \(R\), and \(Z\) bands, respectively). This layout yields a FOM of 105, lower than the scenarios with one broad shape channel and two optical bands, but slightly higher than one
broad shape channel and the $U$ band alone. However, this figure is an upper limit at best, as it is uncertain if accurate shape measurements will be attainable in the $R$ or $Z$ bands with this little observing time. If the shape channel were to be split up, a different survey strategy that allows more observation time per object may be preferable in order to increase the S/N in the observations, both for photometry and shape measurements.

### 3.3. Euclid’s IR Plus Ground-Based Observations

For comparison, we now show what is expected to be obtainable with the use of ground-based telescopes plus the IR bands from Euclid. In these scenarios, all surveys are assumed to overlap completely and cover the same 20,000 deg$^2$ area. This yields a best-case result, and if the overlap between Euclid’s space-based survey and ground-based surveys turns out to be smaller, then the FOM would be negatively affected. In fact, the FOM scales linearly with the survey area (Amara & Réfrégier 2007) so that if only half of the space-based survey overlaps with the ground-based component, then the expected FOM will also be cut in half.

Figures 8 and 9 show the results for Pan-4 and LSST, respectively. The Pan-4 scenario is slightly worse than the Euclid plus $UG$ case, while the LSST results are slightly better, due to its deeper observations relative to Pan-STARRS. We will hence use the LSST observations for all future discussion. Abdalla et al. (2008) note that in order to obtain reliable photo-$z$, shallower surveys such as DES or Pan-STARRS are not well matched to the Euclid survey and show similar effects on the FOM, due to the increased photo-$z$ scatter from these shallower surveys.
In the interest of establishing a time frame for the desired lensing results, we investigated how long it would take LSST plus Euclid to reach the same FOM as the Euclid plus onboard optical scenario, and we found that LSST needs to observe each galaxy at least 45 times to have the same FOM (126) as Euclid plus optical filters (approximately 6 months of observations.

**Fig. 7.**—Same as Fig. 2, except using bandpasses $U, G, R, I, Z, Y, J,$ and $H$, where the $U$ and $G$ bands each observe for only 271 s (50% of the $RIZ$ band) and galaxies with photo-$z$ error bars greater than 0.5 have been culled. See the electronic edition of the *PASP* for a color version of this figure.

**Fig. 8.**—Same as Fig. 2, except using bandpasses from both Euclid and Pan-STARRS with all four mirrors and culling galaxies with photo-$z$ error bars greater than 0.5. See the electronic edition of the *PASP* for a color version of this figure.

2011 PASP, 123:777–788
with LSST). After this point, the FOM will increase as LSST makes more and more observations. We now have a simple means of estimating how many LSST observations are needed if equation (2) turns out to be overly generous in reality. For example, if the LSST photometric errors turn out to be twice as large as predicted, then four times as many observations (i.e., 180 observations or ∼2 yr) are needed to match the Euclid plus onboard optical FOM.

We also studied two scenarios that could detrimentally affect the LSST observations: random photometric zero-point errors, and systematic zero-point offsets between ground and space observations.

The error formulation given in equation (2) for LSST specifically does not include any terms for miscalibration of the zero-point (ZP) magnitudes from field to field. To study how any field-to-field ZP errors could negatively affect the photometric redshifts (shown in Fig. 10) and thus slightly decreasing the FOM (though not significantly) to 132. The small deviations expected from field-to-field ZP errors are, for the most part, dominated by the random photometric errors. Additionally, the ZP errors are independent and thus add in quadrature with the photometric errors, leading to only slight effects in the best-fitting photometric redshifts. Their contribution is therefore almost negligible, and we conclude that field-to-field ZP offsets in ground data are not likely to be an issue in DE weak-lensing surveys.

There is also a possibility that the LSST ZP magnitudes could be systematically offset from the ZPs derived for the Euclid instrument. We found that this has the effect of worsening the photometric bias \( \mu_z \), specifically, at redshifts greater than ∼1.5 when the 4000 Å break starts to fall between the LSST filters and Euclid’s IR filters. Figure 11 demonstrates how this effect worsens as the systematic offset increases. The steep dropoff in bias (present in nearly all the figures) above redshift

![Graph showing the relationship between zspec and zphot with LSST data and FOM calculations.]

**Fig. 9.**—Same as Fig. 2, except using bandpasses from both Euclid and LSST and culling galaxies with photo-z error bars greater than 0.5. See the electronic edition of the *PASP* for a color version of this figure.

| Band | \( \sigma_{ZP} \) |
|------|------------------|
| u    | 0.05             |
| g    | 0.02             |
| r    | 0.02             |
| i    | 0.02             |
| z    | 0.03             |
| y    | 0.03             |

**Table 4:** Standard Deviations of Random Zero-Point Offsets
3 is a result of our brightness restriction, leading to small numbers of galaxies at this redshift and a bias toward galaxies that are erroneously bright in the $RIZ$ bandpass, due to photometric errors. The dropoff should not be confused with a failure of LSST, as the sharp decline in bias is also seen in Figure 4.

The rise in photo-$z$ bias can have detrimental effects to the weak-lensing analysis, which requires the central redshift of each tomographic redshift bin to be known to better than $0.002(1+z)$. While many photo-$z$ codes can correct for systematic offsets between bandpasses (e.g., Ilbert et al. 2006; Coe et al. 2006), this requires spectroscopic redshifts for comparison. This highlights the importance of a spectroscopic redshift survey in order to properly calibrate the photometric redshifts. Such a survey is not without its own difficulties, in that it has to overcome cosmic variance (van Waerbeke et al. 2006) and selection biases in order to obtain a fully representative sample. The calibration of any systematic ZP offsets might be greatly aided if the instruments shared similar bandpasses, such as $U$ or $G$, and avoided entirely if space-based surveys could be independent.

4. CONCLUSIONS

In this work, we have used the currently proposed Euclid design to study how future space-based weak-lensing missions might be able to estimate photometric redshifts independently, i.e., without the use of complementary ground-based observations. We found that the addition of two optical bandpasses (or even one bandpass) to Euclid could greatly improve the fidelity of photometric redshifts that the telescope can attain by itself. If the $U$ and $G$ filters are added, the constraints that Euclid will be able to place on dark energy from weak lensing...
(FOM = 119–126) will be comparable with those using a combination of Euclid and ground-based LSST observations (FOM = 132). Additionally, quite acceptable dark energy constraints can be obtained if only the $U$ bandpass is added to the baseline Euclid design (FOM = 100).

In their present form, to fulfill their weak-lensing-goal, missions such as Euclid and WFIRST must rely on external ground-based observations. Including such ground-based observations entails many of the difficulties of combining two very large and different data sets, including, but not limited to, logistical complications, mismatch or potential delays in construction timescales, changes is planned survey designs, or data access limitations. Furthermore, if the survey area of the space-based observations does not overlap entirely with that of the ground-based survey, then the FOM will be negatively affected. For example, if Euclid and LSST only share $10,000 \text{ deg}^2$, then the FOM obtainable by combining the observations will be only $\sim 66$ instead of $\sim 132$ in the case of full overlap. The addition of onboard optical imaging through two filters (or even one filter) would avoid most of such complications. It would allow future space-based instruments to meet their scientific requirements for weak lensing without having to risk relying on external data.

We thank our colleagues on the Canadian Dark Energy Mission Study team for useful discussions and suggestions: Neil Rowlands, Ludo van Waerbeke, Justin Albert, Michael Balogh, Ray Carlberg, Pat Côté, John Hutchings, and Dae-Sik Moon. We acknowledge funding from the Canadian Space Agency (CSA) and the Natural Sciences and Engineering Research Council (NSERC) of Canada. High-performance computing resources for this work were supplied by the Atlantic Computational Excellence Network (ACEnet).

REFERENCES

Abdalla, F. B., Amara, A., Capak, P., Cypriano, E. S., Lahav, O., & Rhodes, J. 2008, MNRAS, 387, 969
Amara, A., & Réfrégier, A. 2007, MNRAS, 381, 1018
Bartelmann, M., & Schneider, P. 2001, Phys. Rep., 340, 291
Bernstein, G., & Huterer, D. 2010, MNRAS, 401, 1399
Blandford, R. D., Saust, A. B., Brainerd, T. G., & Villumsen, J. V. 1991, MNRAS, 251, 600
Bordoloi, R., Lilly, S. J., & Amara, A. 2010, MNRAS, 406, 881
Bruzual, A. G. 2007, preprint (arXiv:astro-ph/0703052)
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Capak, P., et al. 2007, ApJS, 172, 99
Coe, D., Benítez, N., Sánchez, S. F., Jee, M., Bouwens, R., & Ford, H. 2006, AJ, 132, 926
Copeland, E. J., Sami, M., & Tsujikawa, S. 2006, Int. J. Mod. Phys. D, 15, 1753
Duvet, L. 2010, ESA Standard Document (SRE-PA/2010.030; Noordwijk: ESA)
Erben, T., et al. 2009, A&A, 493, 1197
Hildebrandt, H., Pielorz, J., Erben, T., Van Waerbeke, L., Simon, P., & Capak, P. 2009, A&A, 498, 725
Hildebrandt, H., et al. 2010, A&A, 523, A 31
Huterer, D., Takada, M., Bernstein, G., & Jain, B. 2006, MNRAS, 366, 101
Ilbert, O., et al. 2006, A&A, 457, 841
———. 2009, ApJ, 690, 1236
Ivezic, Z., Tyson, J. A., Allsman, R., Andrew, J., Angel, R., et al.for the LSST Collaboration 2008, preprint (arXiv:0805.2366)
Jouvel, S., et al. 2009, A&A, 504, 359
———. 2010, preprint (arXiv:1003.4294)
Komatsu, E., et al. 2009, ApJS, 180, 330
Leauthaud, A., et al. 2007, ApJS, 172, 219
Ma, Z., & Bernstein, G. 2008, ApJ, 682, 39
Ma, Z., Hu, W., & Huterer, D. 2006, ApJ, 636, 21
Madau, P. 1995, ApJ, 441, 18
Nishizawa, A. J., Takada, M., Hamana, T., & Furusawa, H. 2010, ApJ, 718, 1252
Polletta, M., et al. 2007, ApJ, 663, 81
Réfrégier, A. 2003, ARA&A, 41, 645
Réfrégier, A., Amara, A., Kitching, T., & Rassat, A. 2011, A&A, 208, 33
Réfrégier, A., Amara, A., Kitching, T., Rassat, A., Scaramella, R., Weller, J., & Euclid Imaging Consortium 2010, preprint (arXiv:1001.0061)
Rowlands, N., Lin, H., & Aldridge, D. 2011, Com Dev Executive Report (RPT/CSA/50148/1005 (Cambridge: Com Dev)
Sawicki, M. 2002, AJ, 124, 3050
Sawicki, M., & Yee, H. K. C. 1998, AJ, 115, 1329
Sun, L., Fan, Z.-H., Tao, C., Kneib, J.-P., Jouvel, S., & Tilquin, A. 2009, ApJ, 699, 958
Van Waerbeke, L., White, M., Hoekstra, H., & Heymans, C. 2006, Astropart. Phys., 26, 91