Vera C. Rubin Observatory
Data Management

Calculations of Image and Catalog Depth

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DMTN-296

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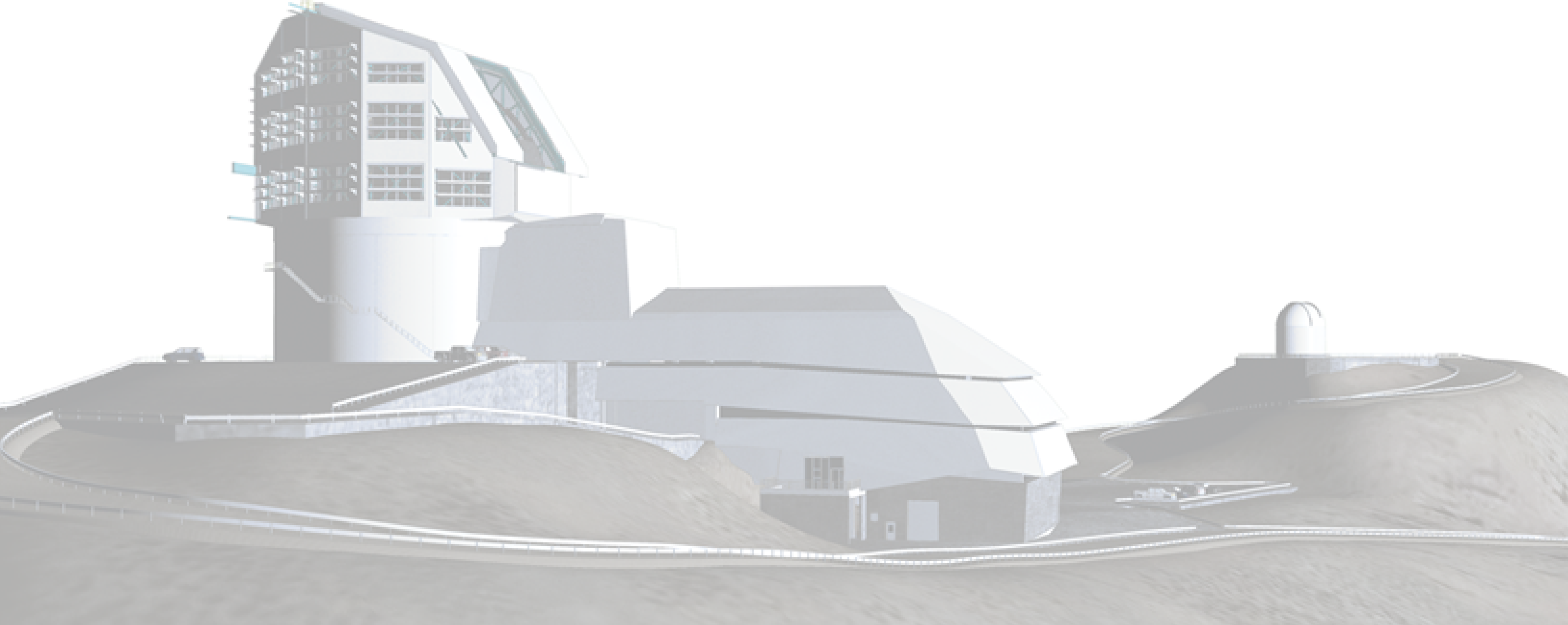

Abstract

We describe several avenues toward assessing the depth of LSST observations using source catalogs and exposure summary statistics. We validate these estimates against each other, and against predicted depth estimates from the LSST Operations Simulator.

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1 Introduction

The "depth" of a survey is colloquially used to describe the faintest astronomical object that can be detected and accurately measured. However, because astronomical objects cover a broad range of shapes and sizes, and surveys have variable performance along many avenues (angular resolution, sky brightness, instrumental noise, etc.), there is no unique definition for "depth". Thus, it is conventional to specify precise depth metrics that can be uniquely defined in terms of the properties of the survey. Although several metrics have been proposed and used by astronomical surveys (e.g., Rykoff et al., 2015; DES Collaboration, 2021), LSST has focused primarily on measurements of the limiting magnitude for unresolved point-like sources detected at a signal-to-noise ratio (SNR) of 5. This metric is canonically referred to as "$m5$" or in common speech as the "5σ limiting magnitude" (e.g., Jones, SMTN-002). Of course, the depth can be calculated at an arbitrary SNR, although $SNR = 5$ ($m5$) and $SNR = 10$ ($m10$) are the most common values chosen.

Several documents have laid out the approach to calculating $m5$ in terms of the properties of the LSST system. In particular, Ivezić et al. (LSE-40) provided a quantitative derivation of $m5$, which has been used to set the LSST System Requirements (LSR) (Claver & The LSST Systems Engineering Integrated Project Team, LSE-29). More recently, Jones (SMTN-002) provided a framework for predicting $m5$ given current LSST system throughputs and rapidly calculating $m5$ for the LSST Operations Simulator (OpSim). Here, we translate the established framework for calculating $m5$ into the LSST Science Pipelines in order to provide self-consistent estimates of 5σ limiting magnitude.[1] In particular, we estimate the depth in two different and complementary ways: (1) directly from the catalogs by selecting point-like sources that have measured $SNR \approx 5$, and (2) from summary statistics (i.e., seeing, sky brightness, transparency, read noise) that are calculated on a per-exposure basis. While these are different techniques for measuring the noise, they both share the same analytic calculation of the variance (i.e., the catalog flux uncertainties come from the variance plane, which is calculated from the same information as the exposure summary statistics). Inaccuracy in the analytic variance would thus be manifested in both estimates. A third complementary and more independent technique would be to measure the variance directly from repeated observations of faint (or sky) sources. This direct variance measurement is an important validation of the analytic variance

[1] The code for the analyses described here can be found in `DM-45573_Depth_Estimates.ipynb`.

calculation; however, it is subject to biases from the presence of sub-threshold sources (e.g., Eckert et al., 2020). The direct estimation of the variance from repeat observations is left to future work.

2 Depth Estimates Using Object Catalogs

The most straightforward mechanism for estimating the 5σ limiting magnitude, $m5$, comes from selecting sources with $SNR \approx 5$, where SNR is defined as

$$SNR = \frac{f}{\sigma_f}, \tag{1}$$

where f is the flux of the source and σ_f is the flux uncertainty. Estimating $SNR \approx 5$ can be done most directly with a simple cut (e.g., $4.75 < SNR < 5.25$), as implemented by the `FiveSigmaPointSourceDepthMetric` in `analysis_tools`.

An alternative approach involves solving Pogson's equation (Pogson, 1856) to express the SNR in terms of the magnitude uncertainty, and estimating the minimum magnitude at which the mean or median measured magnitude uncertainty for point-like sources exceeds this value (Rykoff et al., 2015). Following the derivation in Rykoff et al. (2015), the magnitude uncertainty at a given magnitude limit, σ_m, is

$$\sigma_m = \frac{2.5}{\ln 10}\left(\frac{\sigma_f}{f}\right) = \frac{2.5}{\ln 10}\left(\frac{1}{SNR}\right). \tag{2}$$

For the most commonly chosen depth estimates of $SNR = 5$ and $SNR = 10$, this yields the familiar limiting magnitude uncertainties: $\sigma_{m5} \approx 0.2171$ and $\sigma_{m10} \approx 0.1086$. In this case, a common algorithmic approach is to fit the relationship between magnitude error and magnitude for point-like sources, and then interpolate/extrapolate to the magnitude at which the magnitude error matches the desired value (i.e., σ_{m5} or σ_{m10}). Examples of these two approaches are shown in Figure 2 using simulated data from Operations Rehearsal 4 (OR4).

While catalog-based depth estimates are a direct way to estimate the depth of a survey, they have several drawbacks: (1) To accurately estimate $m5$ it is necessary to select point-like sources. This can be challenging to do robustly for faint sources (i.e., at $SNR \sim 5$). (2) For small regions of the sky, the number of sources selected may be small, leading to statistical noise (and possibly algorithmic failures) in the measurements. (3) Catalogs must be accessed

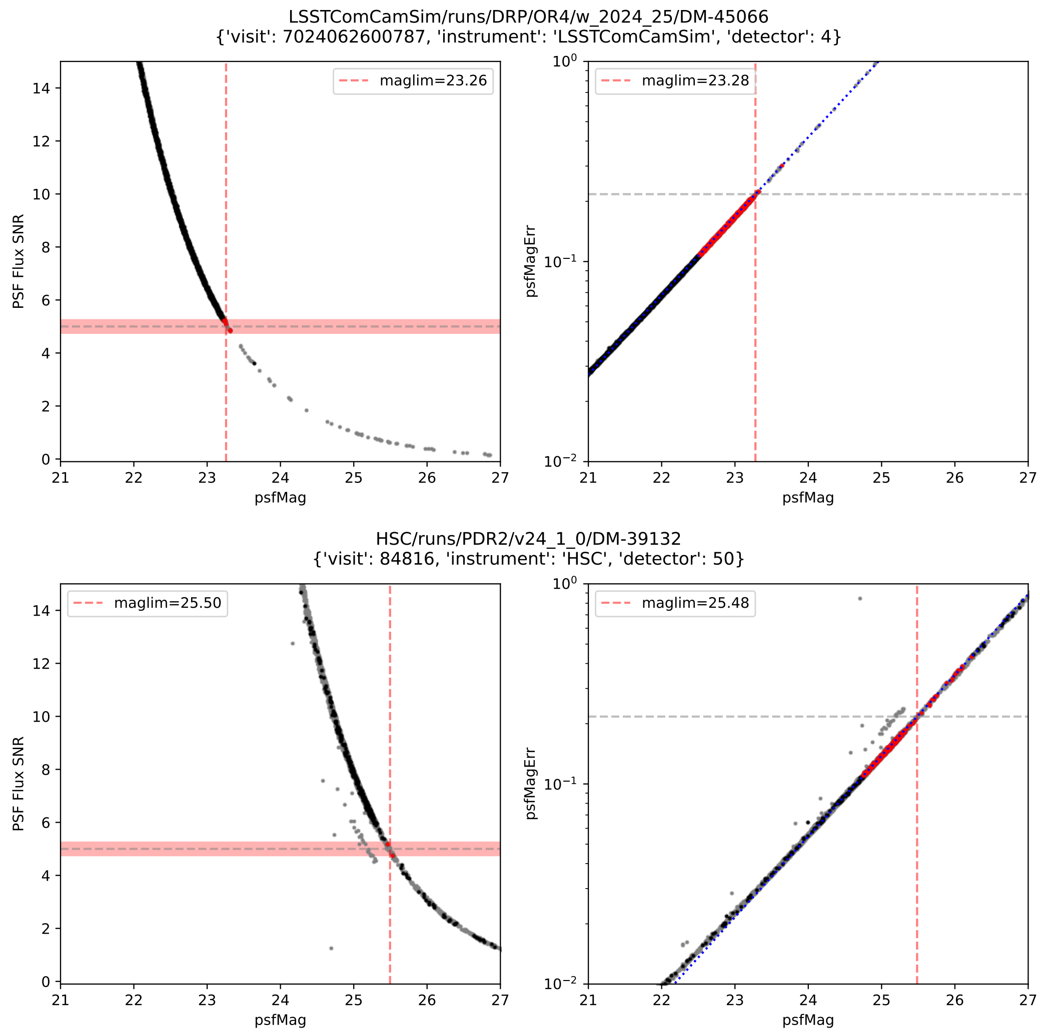

FIGURE 1: Depth estimates derived from the `psfFlux` measurements from the `SourceTable`. All sources are show in gray, while point-like sources (selected with the `extendedness` parameter) are shown in black. Left panels show a SNR-based selection ($4.75 < SNR < 5.25$). Sources in this range are colored in red, while the magnitude limit is shown with the red dashed line. Right panels show a linear fit to the logarithm of the magnitude error vs. magnitude. The linear fit (blue dotted line) is performed using sources with magnitude errors close to the magnitude error threshold (red points). The linear fit is then solved for the magnitude at which magnitude error matches the desired value ($\sigma_{m5} = 0.2171$), which is shown with the red dashed line. The top panels shows results from a 30 s simulated observation in OR4, while the bottom shows the results from a 200 s observation from HSC PDR2.

and analyzed to determine these metrics, which can be a disk and memory intensive task.

3 Depth Estimates Using Exposure Summary Statistics

A second approach to calculating the limiting magnitude of an exposure utilizes summary statistics (i.e., seeing, sky brightness, transparency, read noise). This closely follows the approach derived in Ivezić et al. (LSE-40) and described in Jones (SMTN-002). We summarize this approach and apply it to the output of the Science Pipelines for OR4.

We start by defining the relationships between image-level measurements and fluxes. The total counts from an astronomical source in an image, C (ADU), can be expressed in terms of the top-of-the-atmosphere flux, f (ADU/second), atmospheric transmission coefficient η, and exposure time t (seconds),[2]

$$C = f \times \eta \times t. \tag{3}$$

The counts in an image coming from the sky, B (ADU/pix), are generated from the atmosphere itself, and can be expressed in terms of the sky flux, b (ADU/pix/second) and exposure time,

$$B = b \times t. \tag{4}$$

As described in Ivezić et al. (LSE-40), the uncertainty on the measurement of the source counts can be assembled from the variance of the total source counts, the variance of the sky background counts per pixel,[3] the instrumental noise per pixel, $\sigma_{\rm instr}$ (ADU/pix), and the effective number of pixels in the source footprint (i.e., the sum of pixel weights defined in Eq. 26 of Ivezić et al. LSE-40), $n_{\rm eff}$,

$$\sigma_C^2 = C/g + (B/g + \sigma_{\rm instr}^2) n_{\rm eff} \tag{5}$$

The instrument gain, g (e^-/ADU), enters because Poisson statistics apply to photo-electrons rather than to ADU. For a point-like source, $n_{\rm eff}$ is equivalent to the effective area of the PSF.

The SNR of a source in an image can be estimated in terms of image-level properties following

[2]Expressed in the nomenclature of SMTN-002, $f = \frac{1}{\eta_{\rm fid}} 10^{-\frac{2}{5}(m - ZP_{1,{\rm fid}})}$ where m is the AB magnitude of the source, $ZP_{1,{\rm fid}}$ is the fiducial zeropoint for a 1-second exposure listed in the "Photometric Zeropoints" section of SMTN-002, and $\eta_{\rm fid}$ is the fiducial transmission coefficient corresponding to the "standard atmosphere" applied in that table.

[3]We have followed Ivezić et al. (LSE-40) in ignoring the contribution of uncertainties in determining the sky background (i.e., $\sigma_B = 0$). In reality, the determination of the mean background level can have significant uncertainty coming from spatial structure in the sky, especially at red wavelengths.

Jones (SMTN-002),[4]

$$SNR = \frac{C}{\sigma_C} = \frac{C}{\sqrt{C/g + (B/g + \sigma_{\rm instr}^2) n_{\rm eff}}}, \tag{6}$$

From the relation between counts and flux in Eq. 3 and the property of the variance of a random variate multiplied by a scalar,

$$\sigma_C^2 = \eta^2 t^2 \sigma_f^2, \tag{7}$$

it can be seen that

$$\frac{C}{\sigma_C} = \frac{f}{\sigma_f}. \tag{8}$$

Solving for the positive root of the quadratic SNR equation for C, it can be shown that the source counts can be expressed as,

$$C(SNR, n_{\rm eff}, B, \sigma_{\rm instr}) = \frac{(SNR)^2}{2g} + \left(\frac{(SNR)^4}{4g^2} + (SNR)^2 \sigma_{\rm tot}^2 n_{\rm eff} \right), \tag{9}$$

where we have defined $\sigma_{\rm tot}^2 = (B/g + \sigma_{\rm instr}^2)$ to be the variance coming from background sources (i.e., the sky and instrument read noise). The limiting magnitude can then be determined as,

$$m(SNR, n_{\rm eff}, B, \sigma_{\rm instr}, ZP) = -2.5 \log_{10}\Big(C(SNR, n_{\rm eff}, B, \sigma_{\rm instr}) \Big) + ZP, \tag{10}$$

where ZP is the zeropoint magnitude estimated including the exposure time. Following this convention, $m5 = m(SNR = 5)$ and $m10 = m(SNR = 10)$. As can be seen from Eq. 9 and 10, the source counts and magnitude limit can be estimated assuming that we have access to the following summary measurements for an observation:

- B (`skyBg`): the sky background level [ADU or e$^-$]
- $n_{\rm eff}$ (`psfArea`): the effective number of pixels in the PSF [pixels]
- ZP (`zeroPoint`): the zeropoint for the exposure [mag][5]
- $\sigma_{\rm instr}$ (`readNoise`): the instrumental read noise [ADU or e$^-$]
- g (`gain`): the gain (or average gain) of the detector(s) [e$^-$/ADU]

All of these parameters are available at the point of computing the exposure summary statistics. The environmental variables (i.e., `skyBg`, `zeroPoint`, and `psfArea`) are expected to vary

[4]Eq. 6 can be used without loss of generality if C, B, and $\sigma_{\rm instr}$ are in units of e$^-$ and $g = 1$ e$^-$/ADU.

[5]The Science Pipelines `zeroPoint` currently include the exposure time and thus $ZP = ZP_1 + 2.5\log_{10}(t_{\rm exp})$, where ZP_1 is the zero point for a corresponding 1-second exposure and $t_{\rm exp}$ is the exposure time. There are discussions about changing `zeroPoint` to correspond to ZP_1 instead.

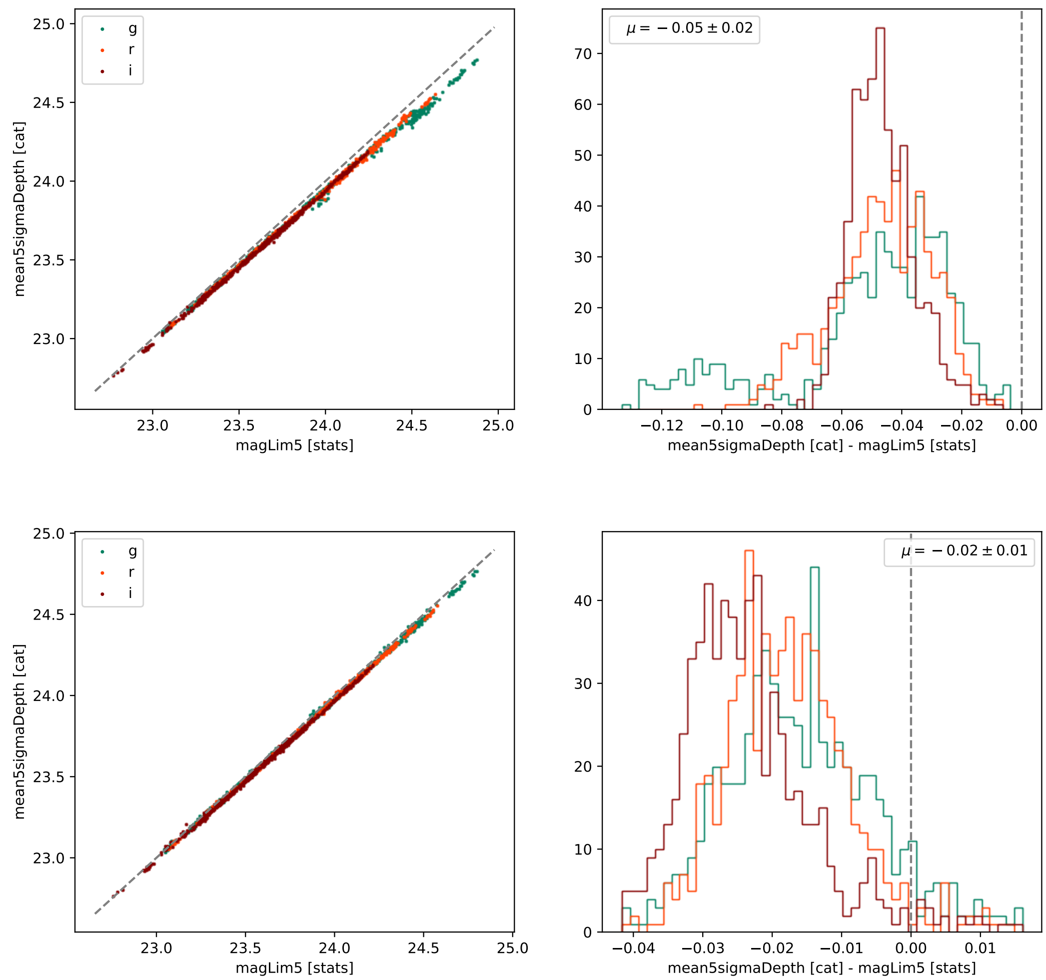

FIGURE 2: Comparison between the $SNR = 5$ point-source magnitude limit for OR4 estimated from the source catalog vs. an estimate using exposure summary statistics. The top panel shows the comparison correctly estimating the noise variance from the image and read noise both in ADU. A deviation is seen for the deepest observations (largest magnitude limit) in the g and r bands. This is due to the fact that the OR4 variance plane was incorrectly calculated using the image variance in ADU and the read noise in electrons (see DM-45976). The bottom panel uses this same (incorrect) prescription for the summary statistic depth, giving much better agreement with the catalogs.

based on observing conditions, while the other variables (i.e., `gain` and `readNoise`) are expected to be more stable from exposure-to-exposure (though this is not required). As expected, Fig. 2 shows good agreement between the $m5$ values calculated from the exposure summary statistics and those calculated directly from the catalogs. A similar consistency check should be performed during commissioning.

4 Comparison with OpSim

Jones (SMTN-002) gives a detailed prescription for how the magnitude limit is predicted by OpSim and used for the LSST scheduler. The simulated OR4 data set gives us an opportunity to compare these predicted depth to the delivered depth estimated from the summary statistics generated with the Science Pipelines. In general, we find good agreement between the predicted depth from OpSim and the measured depth from the Science Pipelines with a scatter of ~ 0.04 mag (Fig. 3). Furthermore, it is possible to compare the individual components going into the depth estimates (i.e., seeing, sky background, zeropoint) to see where the OpSim predictions differ from the measurements from the Science Pipelines (Appendix A).

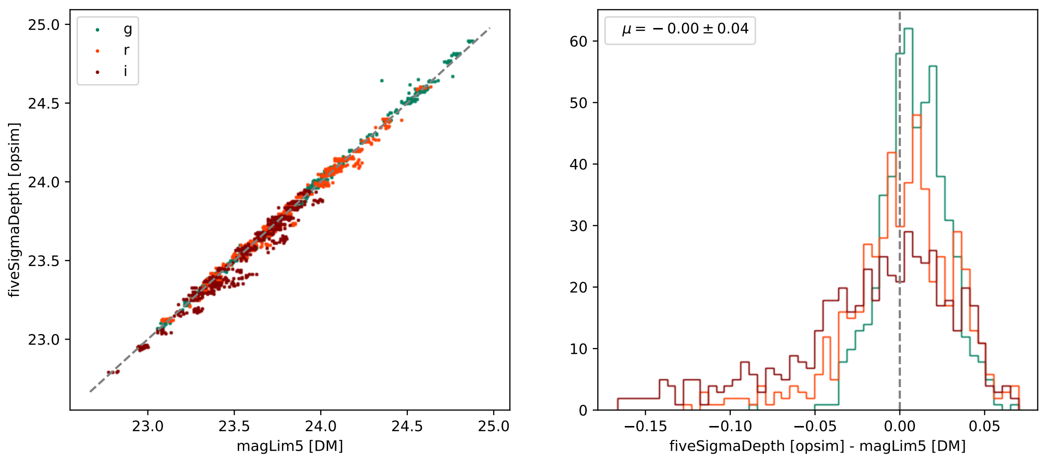

FIGURE 3: Comparison between the $SNR = 5$ point-source magnitude limit in OR4 predicted from OpSim following the prescription in Jones (SMTN-002) and the measured magnitude limit from exposure summary statistics computed by the Science Pipelines (using correct units for the image and read noise variance). The scatter between these estimates is found to be ~ 0.04 mag.

5 Fiducial Values and Delta Magnitudes

The previous discussion focused on deriving the magnitude limit for an observation without incorporating any prior knowledge about the fiducial performance of the system. However, it is often convenient to leverage fiducial values to facilitate the calculation of $m5$ (i.e., see the discussion of C_m and dC_m^{inf} in the final sections of Jones SMTN-002) or to monitor data quality relative to some fiducial expectations of the telescope system. The fiducial depth, $m5_{\rm fid}$, can be determined from Eq. 10 by solving

$$m5_{\rm fid} = m(SNR = 5, B_{\rm fid}, n_{\rm eff,fid}, ZP_{\rm fid}, \sigma_{\rm instr,fid}). \quad (11)$$

While the fiducial values can be chosen arbitrarily, we often find it most useful to define them in terms of the expected performance of the system for an observation taken at zenith in clear, dark condition with the characteristic atmospheric seeing. These fiducial values can be set in a number of ways — in the context of Rubin, they can be taken from the SRD, from the current best estimates of the expected system performance (Jones, SMTN-002), or from actual observations during nominal conditions. However, it is important to minimize the redefinition of fiducials in order to preserve the relative differences between the observed data and the fiducials.

We refer to the difference between the depth of an observation, $m5$, and the fiducial depth, $m5_{\rm fid}$, as the "delta magnitude",

$$\Delta m5 = m5 - m5_{\rm fid}. \quad (12)$$

If the fiducial values are set based on the nominal conditions, then $\Delta m5$ will generally be negative, though this need not always be the case. Furthermore, the impact of each individual observational component (i.e., seeing, sky background, transparency, read noise) can be assessed independently by calculating the delta magnitude holding all other components fixed at their fiducial values. For example, the importance of the sky can be isolated by calculating $\Delta m5_{\rm sky} = m5_{\rm sky} - m5_{\rm fid}$, where we define $m5_{\rm sky} = m(SNR = 5, B, n_{\rm eff,fid}, ZP_{\rm fid}, \sigma_{\rm instr,fid})$ to be the depth estimated fixing all components at their fiducial values except the measured sky background.

6 Coadded depth and effective number of exposures

The $m5$ depth of a coadded image can be easily computed from the depth of individual images assuming that the uncertainty on the (top-of-the-atmosphere) flux of a source, f, is uncorrelated between the individual images that contribute to the coadd. In this case, we can use the standard formula for propagation of errors in an inverse-variance-weighted mean to get the coadd uncertainty,

$$\sigma^{-2}_{f,\rm coadd} = \sum_i \sigma^{-2}_{f,i}. \quad (13)$$

This formula holds when $\sigma_{f,i}$ is the standard deviation in the top-of-the-atmosphere flux, f, for input image i. In this situation, the flux is independent of exposure time, and Eq. 13 makes it clear that two exposures of different exposure times but the same uncertainty ($\sigma_{f,i} = \sigma_{f,j}$) will have the same contribution to the coadded flux uncertainty, $\sigma_{f,\mathrm{coadd}}$.

Transforming our equation for the limiting magnitude (Eq. 10) from counts in the image, C, to flux, f,

$$m(SNR) = -2.5\log_{10}(C) + ZP \tag{14}$$

$$= -2.5\log_{10}(f) - 2.5\log_{10}(\eta \times t) + ZP \tag{15}$$

$$= -\frac{5}{2}\log_{10}(SNR \times \sigma_f) + m_0, \tag{16}$$

where t is the exposure time, η is the atmospheric transmission (fraction of photons that make it through the atmosphere), and in the last line we have defined a scaled zero point that is independent of exposure time and extinction (i.e., the zero point for an exposure time of 1 s and no atmosphere), $m_0 = ZP - 2.5\log_{10}(\eta \times t)$. Working with the scaled zero point m_0 is convenient so the same value can be used for both the coadd and all of the contributing exposures, independent of exposure time. Re-arranging, we get

$$\sigma_f = \frac{1}{SNR} 10^{-\frac{2}{5}(m_{SNR} - m_0)}. \tag{17}$$

If we substitute σ_f above into the propagation of errors formula (Eq. 13) and solve for m_{SNR}, we get,

$$m_{SNR,\mathrm{coadd}} = \frac{5}{4}\log_{10}\Big(\sum_i 10^{\frac{4}{5}m_{SNR,i}}\Big). \tag{18}$$

Note that both SNR and m_0 cancel out completely; the above formula is independent of the magnitude zero point and applies to any SNR.

This relationship between the coadd depth and the depth of contributing exposures is not linear, and common questions regarding depth are difficult to intuit from $m5$ alone without resorting to using a computer. For example, given the depth of a coadd, it is difficult to intuit what fraction of progress has been made toward a target depth, or how much an additional exposure with a known $m5$ will improve the coadd depth. Such estimates are easier to intuit with a linear measure of progress.

Inspection of the propagation of errors equation (Eq. 13) indicates that there is such a linear metric, σ_f^{-2}. Its scaling and units (inverse flux squared) are not particularly intuitive; however, as a linear quantity, we can scale it to something more convenient. Let us define a new value, τ, that is σ_f^{-2} scaled such that an exposure with a nominal exposure time taken under fiducial conditions has $\tau = 1$. In this case, τ for a given exposure represents its contribution to the SNR of a coadd relative to a nominal exposure, and τ for a coadd represents the number of nominal exposures that would need to be coadded to achieve the same $m5$:

$$\tau = \sigma_{f,\mathrm{nom}}^2 \sigma_f^{-2} \tag{19}$$

$$\sigma_f = \sigma_{f,\mathrm{nom}} \tau^{-\frac{1}{2}} \tag{20}$$

Substituting τ in place of σ_f in the equations for m_{SNR} as a function of σ_f and its inverse:

$$m_{\mathrm{SNR}} = \frac{5}{4}\log_{10}(\tau) + m_{\mathrm{SNR,nom}} \tag{21}$$

$$\tau = 10^{\frac{4}{5}(m_{\mathrm{SNR}} - m_{\mathrm{SNR,nom}})}, \tag{22}$$

where $m_{SNR,\mathrm{nom}}$ is the nominal magnitude limit at a given SNR—i.e., $m_{SNR,\mathrm{fid}}$ evaluated for the nominal WFD exposure time (e.g., $t_{\mathrm{WFD}} = 30\,\mathrm{s}$). So, for the standard $SNR = 5$:

$$\tau = 10^{\frac{4}{5}(m5 - m5_{\mathrm{nom}})} \tag{23}$$

$$m5 = \frac{5}{4}\log_{10}(\tau) + m5_{\mathrm{nom}} \tag{24}$$

$$\tau_{\mathrm{coadd}} = \sum_i \tau_i. \tag{25}$$

Conceptually, τ_{coadd} for a coadd (including a coadd of just one exposure) is the number of nominal WFD exposures (i.e., exposures taken in fiducial conditions and instrument sensitivity and nominal WFD exposure time) that it would take to achieve the same $m5$ as that coadd. So, one can think of the accumulated τ of a coadd as a number to compare with the accumulated number of exposures in order to take data quality into account.

7 Effective Exposure Time

An alternative interpretation of the linear metric, σ_f^{-2}, is as an effective exposure time (Neilsen et al., 2016). Starting from the expression for SNR in terms of the image counts (Eq. 6) and converting to fluxes (Eq. 3 and 4), we can express the SNR in terms of the flux as,

$$\mathrm{SNR} = \frac{C}{\sigma_C} = \frac{f\eta t}{\sqrt{\frac{f\eta t}{g} + \frac{bt}{g}n_{\mathrm{eff}} + \sigma^2_{\mathrm{inst}}n_{\mathrm{eff}}}} \tag{26}$$

$$= f \times \sqrt{\frac{\eta^2 t^2}{\frac{f\eta t}{g} + \frac{bt}{g}n_{\mathrm{eff}} + \sigma^2_{\mathrm{inst}}n_{\mathrm{eff}}}} \tag{27}$$

$$= f \times \sqrt{\frac{\eta^2 t^2}{\sigma^2_C}} = \frac{f}{\sigma_f}. \tag{28}$$

Rearranging a bit, we find

$$\sigma_f^{-2} = \left[\frac{g\eta^2}{f\eta + bn_{\mathrm{eff}} + \frac{g}{t}\sigma^2_{\mathrm{inst}}n_{\mathrm{eff}}}\right] \times t. \tag{29}$$

If we are in the regime where the sky background dominates, then the middle term in the denominator dominates over the others, and we are left with

$$\mathrm{SNR} \approx f \times \sqrt{\frac{g\eta^2}{bn_{\mathrm{eff}}} \times t}. \tag{30}$$

DES *aficionados* will recognize Eq. 30 as the starting point for defining the effective exposure time, t_{eff}, as described in Neilsen et al. (2016). So long as σ_{inst} is small (i.e., the noise is dominated by the Poisson shot-noise from the source and sky), then σ_f^{-2} is proportional to the exposure time. This gives another way to scale σ_f^{-2} to make it more intuitive: a hypothetical equivalent exposure time under fiducial conditions assuming that there is only noise from Poisson statistics.

If we define t_{eff} to be another scaling of σ_f^{-2} such that:

$$t_{\mathrm{eff}} = \sigma^2_{f,\mathrm{nom}}\sigma_f^{-2} \times t_{\mathrm{WFD}} = \tau \times t_{\mathrm{WFD}} \tag{31}$$

where t_{WFD} is the nominal WFD exposure time, then t_{eff} will be approximately equal to the exposure time it would take to get an exposure of equivalent $m5$ depth, where the approximation "breaks down" when σ^2_{inst} is significant. Following the discussion in Section 6, the relation between t_{eff} and $m5$ is,

$$t_{\text{eff}} = 10^{\frac{4}{5}(m5 - m5_{\text{nom}})} \times t_{\text{WFD}} \tag{32}$$

$$m5 = \frac{5}{4}\log_{10}(t_{\text{eff}}) - \frac{5}{4}\log_{10}(t_{\text{WFD}}) + m5_{\text{nom}} \tag{33}$$

$$t_{\text{eff,coadd}} = \sum_i t_{\text{eff},i}. \tag{34}$$

These relations between t_{eff} and $m5$ hold even when σ_{inst} is significant: a significant σ_{inst} only breaks the metaphor with exposure time, not the relationship between a scaled σ_f^{-2} and limiting magnitude.

8 Summary

Measuring the depth of astronomical observations is important for the purposes of modeling system performance, estimating survey progress, and selecting subsets of exposures for further downstream processing. The depth can be calculated independently of any fiducial system performance values (assuming that a zero point can be determined); however, the comparison against fiducial values provides convenient metrics for monitoring operational performance. In this note, we have described the calculation of the limiting 5σ point-source magnitude, $m5$, from source catalogs and exposure summary level statistics. The two provide a useful crosscheck, and show good agreement in the OR4 simulated data (once known issues are accounted for). However, this agreement is expected since the flux uncertainties in the source catalog come from the same variance calculation as is used in the summary statistic calculation. Another useful independent assessment of the depth and photometric uncertainties will come from repeated measurements of faint (and/or sky) sources. While more difficult to implement, such a check is important to validate the analytic variance calculation.

A OpSim Comparison

This appendix shows comparisons between the seeing, sky brightness, and zeropoints predicted from OpSim vs. those estimated from the Science Pipelines using the central detector (`detector=4`) of OR4. It is necessary to do some translations to convert from the native OpSim parameters and DM measurements, which we describe below:

- $\text{psfArea}_{\text{opsim}} = 2.266 \times (\text{seeingFwhmEff/pixscale})^2$
- $\text{skyBg}_{\text{opsim}} = \text{skycounts/gain}$
- $\text{zeroPoint}_{\text{opsim}} = \text{zeropoint} + 2.5\log_{10}(\text{expTime}) - 2.5\log_{10}(\text{gain})$

where `seeingFwhmEff`, `zeropoint`, and `skycounts` are native quantities provided by OpSim, and gain $\approx 1.67\ \text{e}^-/\text{ADU}$, pixscale $= 0.2$ arcsec/pix, and expTime $= 30$ seconds for OR4. Once these translations are performed, we find that the OpSim predictions and the DM measurements agree to within $\lesssim 10\%$. The sky brightness predicted by OpSim is found to be $\sim 7\%$ smaller (fainter) than that measured by DM with a clear trend from bluer to redder bands. Similarly, the `zeroPoint` predicted by OpSim is smaller (shallower) by ~ 0.05 mag ($\sim 0.05\%$) relative to the measured value from DM.

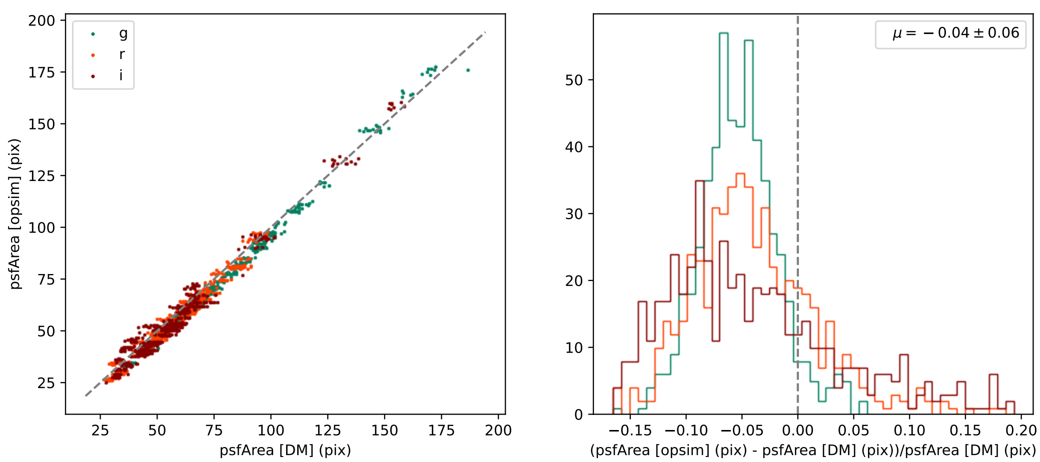

FIGURE 4: Comparison between the effective size of the PSF (in pixels) predicted by OpSim and that measured by DM.

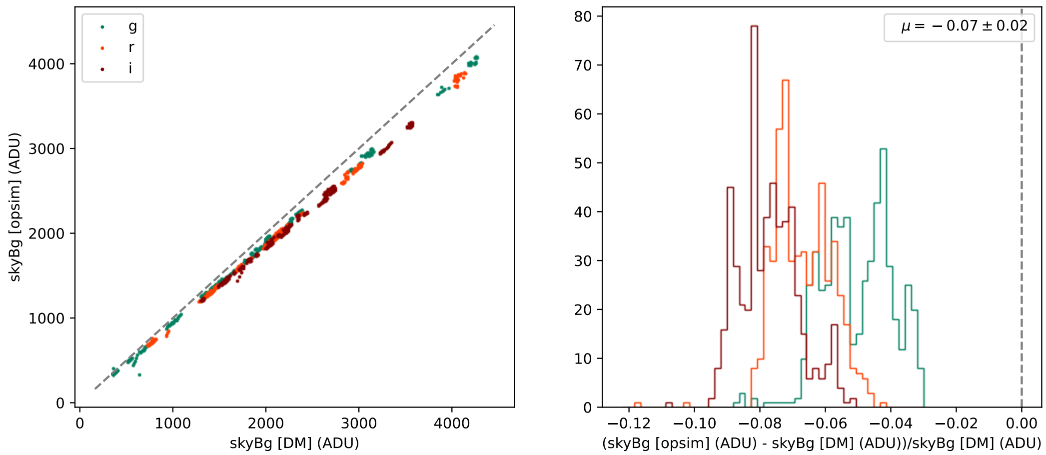

FIGURE 5: Comparison between the sky background (in ADU) predicted by OpSim and that measured by DM.

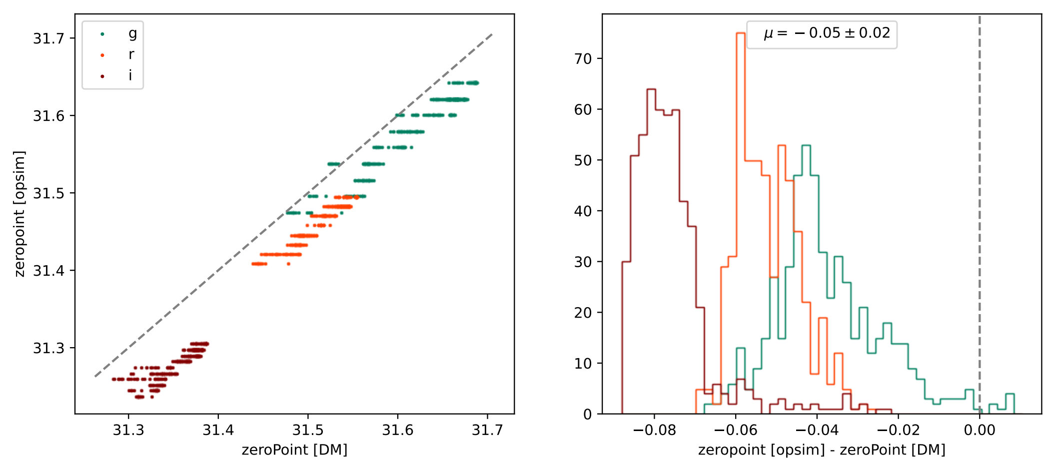

FIGURE 6: Comparison between the zero point (in ADU and including the exposure time) predicted by OpSim and that measured by DM.

B References

[LSE-29], Claver, C.F., The LSST Systems Engineering Integrated Project Team, 2017, *LSST System Requirements (LSR)*, Systems Engineering Controlled Document LSE-29, NSF-DOE Vera C. Rubin Observatory, URL `https://ls.st/LSE-29`

DES Collaboration, 2021, ApJS, 255, 20 (`arXiv:2101.05765`), doi:10.3847/1538-4365/ac00b3, ADS Link

Eckert, K., Bernstein, G.M., Amara, A., et al., 2020, MNRAS, 497, 2529 (`arXiv:2004.05618`), doi:10.1093/mnras/staa2133, ADS Link

[LSE-40], Ivezić, v., Jones, R.L., Lupton, R.H., 2010, *Photon Rates and SNR Calculations*, Systems Engineering Controlled Document LSE-40, NSF-DOE Vera C. Rubin Observatory, URL `https://ls.st/LSE-40`

[SMTN-002], Jones, R.L., 2025, *Calculating LSST limiting magnitudes and SNR*, Simulations Team Technical Note SMTN-002, NSF-DOE Vera C. Rubin Observatory, URL `https://smtn-002.lsst.io/`

Neilsen, E., Bernstein, G., Gruendl, R., Kent, S., 2016, *"Limiting magnitude, τ, T_{eff}, and image quality in DES Year 1"*, Tech. Rep. FERMILAB-TM-2610-AE-CD, Fermi National Accelerator Laboratory, URL `https://www.osti.gov/biblio/1250877`, doi:10.2172/1250877

Pogson, N., 1856, MNRAS, 17, 12, doi:10.1093/mnras/17.1.12, ADS Link

Rykoff, E.S., Rozo, E., Keisler, R., 2015, arXiv e-prints, arXiv:1509.00870 (`arXiv:1509.00870`), doi:10.48550/arXiv.1509.00870, ADS Link

C Acronyms

Acronym	Description
ADU	Analogue-to-Digital Unit
B	Byte (8 bit)
DES	Dark Energy Survey

DM	Data Management
DMTN	DM Technical Note
DR2	Data Release 2
HSC	Hyper Suprime-Cam
LSE	LSST Systems Engineering (Document Handle)
LSR	LSST System Requirements; LSE-29
LSST	Legacy Survey of Space and Time (formerly Large Synoptic Survey Telescope)
OpSim	Operations Simulation
PDR2	Public Data Release 2 (HSC)
PSF	Point Spread Function
SNR	Signal to Noise Ratio
SRD	LSST Science Requirements; LPM-17
WFD	Wide-Fast-Deep