

# Report on Winter2014 Production: Image Differencing

March 19, 2014

The goals of this Winter 2014 (W14) task are to investigate the effects of differential chromatic refraction (DCR) on the rate of false positives in image differences. We quantify this by using a suite of image simulations that contain no intrinsic variability, and run the images through the LSST Data Management image subtraction pipeline, which includes detection and measurement of false positives (both positive-going and negative-going) in the differences. As demonstrated in a similar analysis in Winter 2013 (W13), we are able to achieve a false detection rate consistent with random Gaussian fluctuations in the background. We compare the results of DCR with theory to validate both the amplitude and orientation of the effect in our simulations.

Since the underlying image simulation software (`phoSim`) has evolved from our W13 work (v3.2.2 to v3.3.2), our first subtask was to recreate the results of W13, which involve a suite of 15s *i*-band images taken at zenith angle of 20.2° and in seeings of 0.66, 0.8, and 1.2 arcseconds. These are differenced against a 300s *i*-band image generated at the same airmass with seeing 0.8". The focus of this analysis is the image-vs-template seeing dependence of the rate of false positives, and how pre-filtering of the science `Exposures` with their `Psf`s affects this rate. We limit our analysis to the 9 sensors of central raft 2,2 for this analysis. The second subtask involves the generation of *g*-band and *r*-band images in the same observing configuration, to verify there is not wavelength dependence to our results. For both these first and second subtasks, the simulated catalog includes stars of a single spectral energy distribution (SED) covering a narrow range in (high S/N) brightness. We find that our results are quantitatively similar to those of the W13 analysis. We do not see substantial issues with DCR in these data, as expected.

Our third subtask involved creating a similar suite of *gri*-band images, but generated at 5 airmasses throughout a single night, using a star catalog with 3 discrete SEDs. The data include 2 observations before meridian crossing at airmasses 1.55 and 1.16, one observation near zenith, and then 2 observations after the meridian crossing at airmasses 1.16 and 1.55. Observations at the same airmass, before and after meridian crossing, will have different parallactic angles, and thus different directions of DCR. This will directly test whether or not the parallactic angle needs to be a consideration when designing templates for image subtraction during LSST operations. We difference each of 5 per-airmass templates against each of the 15 science images (binned 5 in airmass and 3 in seeing), and do this for each of the 3 passbands. We find that the difference images where the parallactic angles are aligned yield false positives consistent with the rates seen above, at all airmasses. However, when differencing images taken at one parallactic angle with a template taken at another, we find a significantly enhanced rate of false positives. This rate is both passband and seeing dependent, in the sense that the false positives are more enhanced in the *g*-band than in the *i*-band, and higher in the better seeing data than in the worse seeing data. We validate that the amplitudes and orientations of DCR "dipoles" are similar both to theory and to the effects designed into the simulations. We also find that joint-Psf dipole measurements in the difference images tend to overestimate the amplitude of the effect. A fourth subtask – investigating the false positive rates using a more realistic mixture of stars and galaxies in the input catalog – was deferred to later analysis, as this is not central to resolving the DCR issue.

Finally, we provide extensive documentation on the running of the image simulations, how to design DCR into the data, and how to interpret the results.

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# 1 Production Scope and Goals

The primary goal of this W14 production was to investigate the effects of DCR on the image differencing process, with the expectation that this inform the requirements on image differencing templates. The current DM baseline is that LSST will have up to 9 templates per passband per region of sky, binned 3x3 in airmass and seeing. The airmass bins are currently segmented *only* on the zenith distance of the observation, and are designed to minimize mismatch between the DCR effects on a science image and on the nearest (in terms of airmass and seeing) template. However, this design does *not* account for the angle that DCR takes through an image, which will be different for every observation, and which ideally requires a per-image (in orientation) and per-object (in amplitude) correction to properly compensate for it.

To examine these effects, we designed a staged analysis where each successive stage builds on the results of the previous stage, but adds an additional layer of complexity. Starting with the base input catalog and simulation configuration used in the previous W13 analysis, our second subtask includes multi-passband sims, while the third subtask additionally includes multi-airmass and multi-parallactic angle sims. This final stage is sufficient to characterize the effects of DCR on the false positive rate. Technical details on each of the subtasks are provided in Appendix 7.2.

We generated images in three passbands corresponding to the LSST *g*-band, *r*-band, and *i*-band filters. Fifteen-second “snaps” were generated at 3 discrete seeings: 0.6”, 0.88”, 1.2”. One accompanying image subtraction template was also generated (as opposed to assembled via coaddition) with an effective 300 second exposure time and a seeing of 0.88”. All 4 sets of images were generated for each airmass-filter combination.

After generation we ran the simulated **eImages** through single frame measurement (SFM) using the script `processEimage.py`. Note that we did not use the raw per-amplifier simulated images, instead choosing to operate on the **eImages** because the former would have required the generation of calibration products and instrument signature removal (ISR). Had we run in this mode, SFM would have proceeded using script `processCcd.py`.

We next ran the images through image differencing, using the 300s image as the image subtraction template. For this reason, the derived class `Winter2013ImageDifferenceTask` (so-called as it was initially designed for the W13 production cycle) was used, as this includes a specific flag to use a visit as the template, instead of an extraction from the coadd repository. We next ran detection and measurement on the difference image to extract the **DiaSources** from the image. We look at detections of both positive and negative polarity, and at a detection threshold of 5-sigma. Dipoles were identified and measured, and their separation and orientation compared to what was expected from theory, and what was expected based on the inputs to `phoSim`. The numbers of false positives were recorded as a function of filter, image seeing, image airmass, and (where applicable) template airmass. In the following, we reference the 3 bins in seeing as **Seeings 1,2,3** for seeing = 0.6”, 0.88”, 1.2”, respectively, and the 5 visits at different airmasses as **Visits A,B,C,D,E**.

We briefly summarize each of the proposed and performed subtasks below, and elaborate on the tickets developed during this production.

## 1.1 Subtask 1: Reproduce W13 Results Using Current PhoSim

Starting with the W13 `phoSim` configuration, we produce simulated images at a single airmass (1.07) and in a single passband (*i*). Science images are simulated at each of the 3 seeing values described above, and a single template image as described above. We simulated images for the 9 CCDs of the central raft 2,2. We perform image differencing, and source detection and measurement, and validate that the average numbers of false positives are consistent with the results of W13. We also

analyzed the actual W13 data using the current version of the DM pipeline, and validated that the total numbers of false positives were similar to the W13 analysis, with minor differences. Results of these analyses are described in Section 3 below.

Trim files for this subtask are contained in subdirectory `sims3/` of this repository. Work on this subtask resulted in Ticket #3143, described in Section 1.6 below.

## 1.2 Subtask 2: Simulate Starfield using Multiple SEDs at a Single Airmass

Starting with the input trim files to subtask 1 above, we replace the SEDs used for the starfield with 3 discrete SEDs chosen to span a range in color. We choose a G0V star to be our reference source, and replace 80% of the source SEDs with those of SED `km20_6000.fits_g30_6020.gz`. When performing the image differencing, *only* these objects will be used for the creation of the Psf-matching kernel. This effectively makes this set of sources the reference for the differential refraction. We then replace 10% of the SEDs with those of a “blue” source – spectrum `kp01_9750.fits_g45_9830.gz` representing an A0V star – and 10% of the SEDs with those of a “red” source – spectrum `m2.0Full.dat.gz` representing an M2.0V star. We modified the brightnesses of the sources in the *i*-band trim file to have approximately the same S/N as the original sources, given the color of each star.

We then re-ran the image differencing analysis, and validated that we were able to difference the *i*-band data to a similar quality as in subtask 1 above. The trim files for this are contained in subdirectory `sims5/` of this repository.

We further generated sets of simulations in the *g*-band and *r*-band using the exact same set of trim files except for the requested `Opsim_filter`. Analysis of these images showed no color-dependence to our results. However, because we did not modify the input brightness distributions for the stars to have similar S/N in each passband, the results are somewhat compromised due to the different signal-to-noise distributions. We do not expect this to substantially modify our conclusions. Results of these analyses are described in Section 4 below.

The trim files for this are contained in subdirectory `sims5gr/` of this repository. Work on this subtask resulted in Ticket #3128, described in Section 1.6 below.

## 1.3 Subtask 3: Simulate Starfield using Multiple SEDs at Multiple Airmasses

Starting with the `sims5/` trim files referenced above, we further modify the simulations by first moving the star field to pass through zenith on the night of simulation. This required a shift in declination of approximately 20°, applied to the coordinate of each star and the requested boresight pointing of the simulations. We next evaluated the times that this starfield would pass through 5 discrete zenith angles: 50°, 30°, 0°, 30°, 50°, corresponding to visits A, B, C, D, and E. We note that 50° is the approximate airmass cutoff of the LSST Universal Cadence. We further modified the brightnesses of each star in each filter’s trim files such that each object was rendered at approximately the same S/N in each filter.

To examine how a mismatch between the effects of DCR in the template and science affects the false positive rate, we perform each permutation of differencing the template visit ABCDE with science visit ABCDE. The “on diagonal” components (AA, BB, etc) reflect an exact match between the airmass and parallactic angle of the template and science image. Combinations AE and BD (as well as EA and DB) reflect a match between the airmass of the observations, but a mismatch of parallactic angle. All other permutations reflect a mismatch between both airmass and parallactic angle of the images. We perform differences of all 5 template visits with all 5 science image visits, for all 3 filters and all 3 seeing values. Results of these analyses are described in Section 5 below.

The trim files for this are contained in subdirectory `sims8/` of this repository. Work on this subtask resulted in Ticket #3161, described in Section 1.7 below.

#### 1.4 Subtask 4: Include Realistic Mix of Stars and Galaxies

This subtask was not undertaken, and was deferred to a future analysis.

#### 1.5 Development Work: Ticket #3128

This ticket was opened to allow the user to select the sample of “red” and “blue” stars to be added to the control sample. This enabled after-the-fact diagnostics of the different populations of objects.

#### 1.6 Development Work: Ticket #3143

This ticket was opened to fix a bug in the settings of the deconvolution kernel sizes. A variable that was unused during the process of deconvolution was unintentionally causing a misconfiguration of the *gr*-band, seeing 1 data during postfiltering. This resulted in a factor of 10–100 increase in the deconvolution false positives, compared to the *i*-band. This indicates that deconvolution may indeed be compensated for kernel configuration, resulting in an acceptable false positive rate, although the variance in the images ends up being much higher (and the effective detection threshold much lower) compared to the prefiltering route.

#### 1.7 Development Work: Ticket #3161

This ticket was the most extensive implemented in this W14 work. Joint-Psf dipole measurement (simultaneously fitting for a positive and negative-going Psf, 6 terms including two x,y centroids and two fluxes) in the original subtask 3 differences used a very coarse “minimization” routine originally implemented in W13. This routine effectively took half pixel steps in the 4 centroid positions, and performed a linear fit for the two fluxes at each step, returning the fit that yielded the lowest  $\chi^2$ . However, the dipole separations expected from DCR were in general far smaller than the default step size, and thus the measurements were too coarse for this task. In addition, this process was expectedly slow, making measurement of more than  $\sim 200$  dipoles in a given image unfeasible.

In Ticket #3161 we implemented a fully non-linear joint Psf fit, using the `Minuit` package. This substantially sped up the per-dipole measurement process, by a factor of 20–30, from 1–2 measurements per second to 20–60 per second. This speed-up analysis was performed using script `python/compareMeasurementTiming.py` in this repository.

## 2 Review of Wavelength Dependent Refraction

We first review the expected signature of differential chromatic refraction in the image simulations. We use the formalism of ? throughout.

The wavelength-dependent index of refraction of the atmosphere,  $n(\lambda)$ , may be represented as

$$n_0(\lambda) - 1 = 10^{-6} \times \left[ 64.328 + \frac{29498.1}{146 - \lambda} + \frac{255.4}{41 - \lambda} \right] \quad (1)$$

where  $\lambda$  is the wavelength in microns. Temperature, pressure, and water vapor corrections may be expressed as:

$$C1(P, T) = P \times \frac{1 + (1.049 - 0.0157 T) \times 10^{-6} P}{720.883 * (1 + 0.003661 T)} \quad (2)$$

$$C2(f, T) = 10^{-6} \times f \times \frac{0.0624 - 0.000680/\lambda^2}{1 + 0.003661 * T} \quad (3)$$

$$n(\lambda) - 1 = (n_0(\lambda) - 1) * C1 - C2 \quad (4)$$

where  $P$  is the ambient pressure in mm of mercury,  $T$  is the temperature in Celsius, and  $f$  is the water vapor pressure in mm of mercury. The index of refraction is larger for shorter wavelength light, meaning that photons from the blue end of the spectrum are refracted more than ones from the red. Accordingly, this effect is dependent on the zenith distance  $Z$ , such that:

$$R(\lambda) = \frac{n(\lambda)^2 - 1}{2 n(\lambda)^2} \tan(Z) \quad (5)$$

where  $R$  is the deflection angle in radians. This deflection is expressed along the direction of increasing altitude, such that blue sources will appear higher in the sky, compared to red sources, when seen through the atmosphere.

What this means in practice is that there will be a SED-dependent, per-object deflection whose amplitude depends on the source color, and whose orientation depends on the angle towards zenith in the image. We examine the amplitude of this effect for 5 discrete spectra, 3 of which are used in the `phoSim` analysis. Because we are using the same spectra for our theoretical analysis as we are using for running `phoSim`, we expect concordance between the amplitude and orientations of the DCR effect in the simulated images.

In Figure 1, we show along the top the spectra, in units of  $f_\nu(\lambda)$ , of 5 sources. Left to right, these represent a “blue” AOV star, a reference GOV star, a red M2.0V star, and an active galactic nucleus at redshift  $z = 0$  and then at  $z = 0.5$ . We also show the transmission profiles of the LSST  $g$ ,  $r$ , and  $i$ -bands along the left side of the figure, along with the product of these two curves which represent the effective spectrum of each source as viewed through each LSST filter. Figure 2 shows the flux-weighted refraction of each SED as a function of zenith distance. This is presented in units of arcseconds; note that at the Universal Cadence limit of  $50^\circ$  zenith angle, the refraction of all sources approaches 1 arcminute. In Figure 3, we show the *differential* refraction of each spectrum, DCR, with respect to the GOV star. Note that the maximum amplitude of DCR is approximately  $0.1''$  at  $50^\circ$ , or approximately half an LSST pixel. Is this effect we wish to explore in this sequence of analyses.

### 3 Analysis of Subtask 1

### 4 Analysis of Subtask 2

### 5 Analysis of Subtask 3

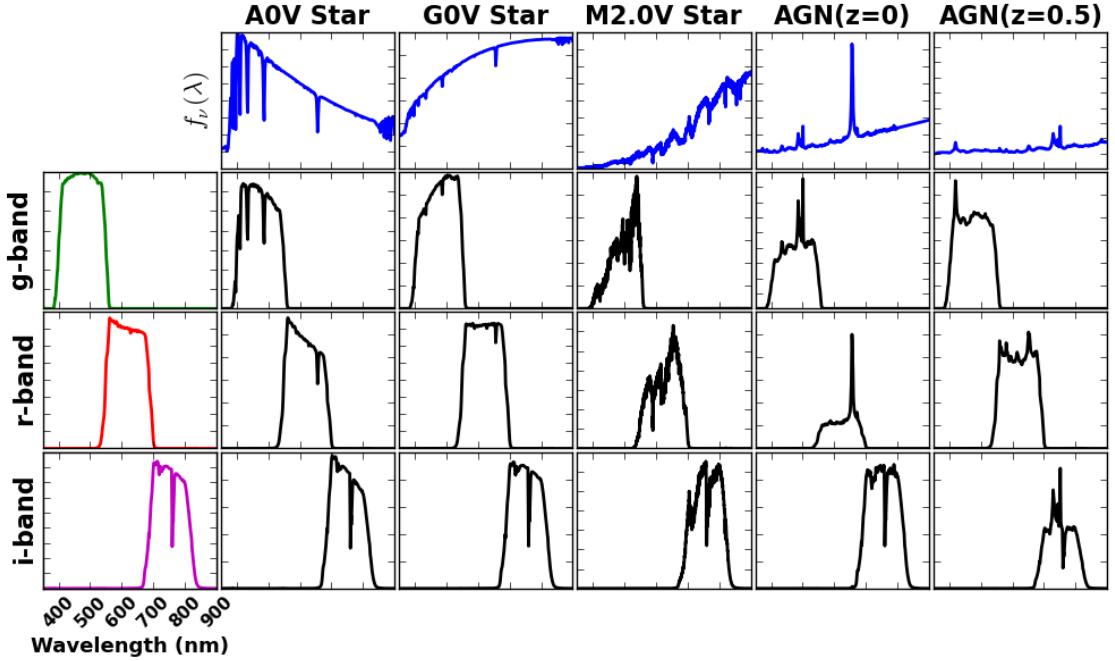
### 6 Possible Solutions to DCR Issue

We outline possible resolutions to the DCR issue. Classes that need to know about DCR include the `WCS` class, for astrometric modeling, and the `Psf` class, for its contribution to color-dependent

point spread functions. The consumers of this information include the image coaddition and differencing tasks. The latter has a double dependency on DCR, since it uses coadded templates whose generation itself depends on an adequate treatment to DCR. We expect to work towards this resolution in the upcoming Summer 2014 production (S14) cycle. Possible solutions include:

- Remapping each template image pixel by pixel, depending on color  
Color-dependent Psf matching kernel (does not fix template issue)  
Dipole fit that restricts the angle of separation to be along Dcr vector

In any case, it is likely that any resolution will require a per-object treatment, similar to that described in Section 3.3 of ?, who use a per-pixel color map to compensate for DCR. A key improvement over this technique is the need to undertake this operation in a way that preserves the PSF.



**Figure 1: Effective Spectral Energy Distributions :** The effective spectra of 5 reference objects – a “blue” A0V, a reference G0V, and a “red” M2.0V star, along with a QSO at redshift  $z = 0$  and  $z = 0.5$  – filtered through 3 transmission profiles corresponding to the LSST  $g$ ,  $r$ , and  $i$ -bands. The top row shows the input spectral energy distribution  $f_\nu(\lambda)$ , while the leftmost column shows the LSST filter transmission profile in units of the normalized system response  $\phi$ . The inner row/column figures show the effective spectrum of each SED (along columns) when multiplied through the respective filter (along rows). In all subpanels, the x-axis is wavelength. The A0V, G0V, and M2.0V spectra correspond to CAT\_SHARE\_DATA files `kp01_9750.fits_g45_9830.gz`, `km20_6000.fits_g30_6020.gz`, and `m2.0Full.dat.gz` respectively, and were used as the SEDs of the stars in the W14 image simulations. This figure may be recreated using the script `python/DCR.py`.

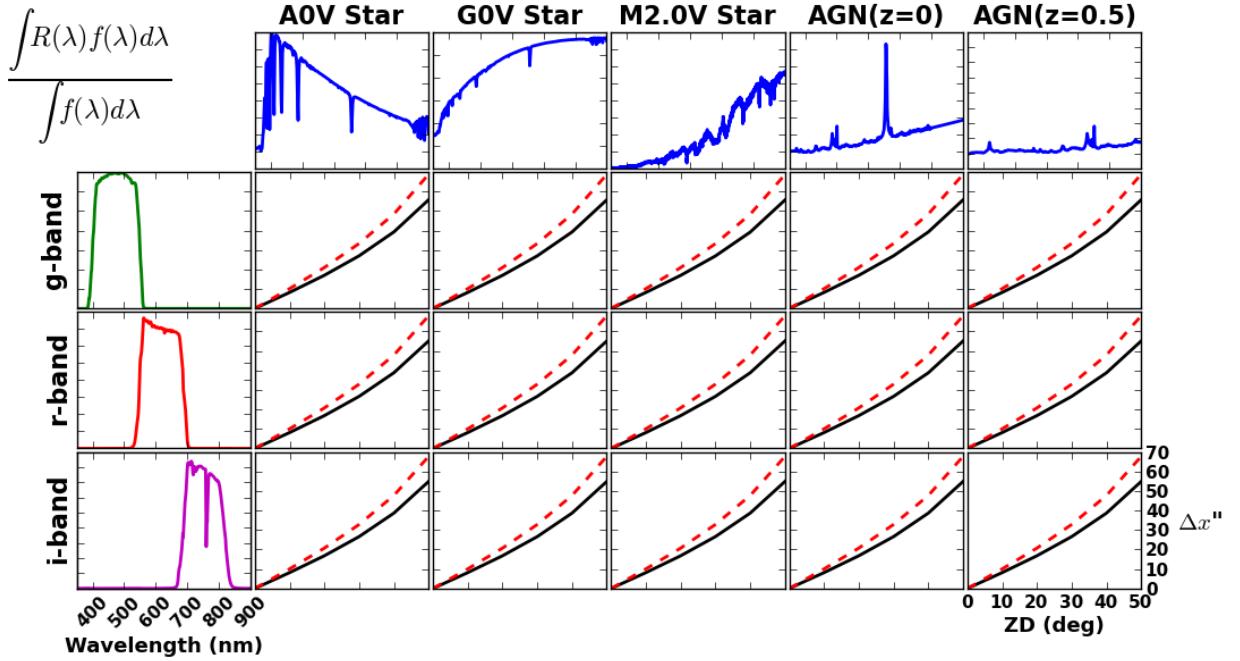
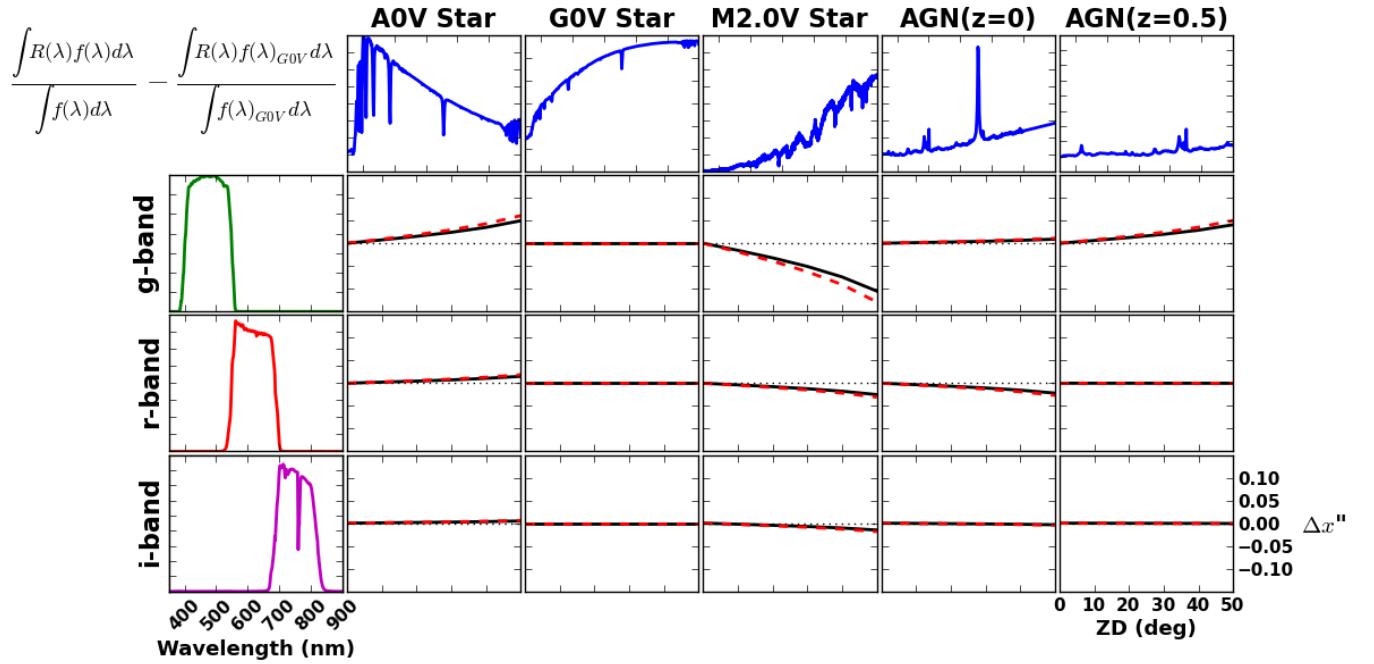
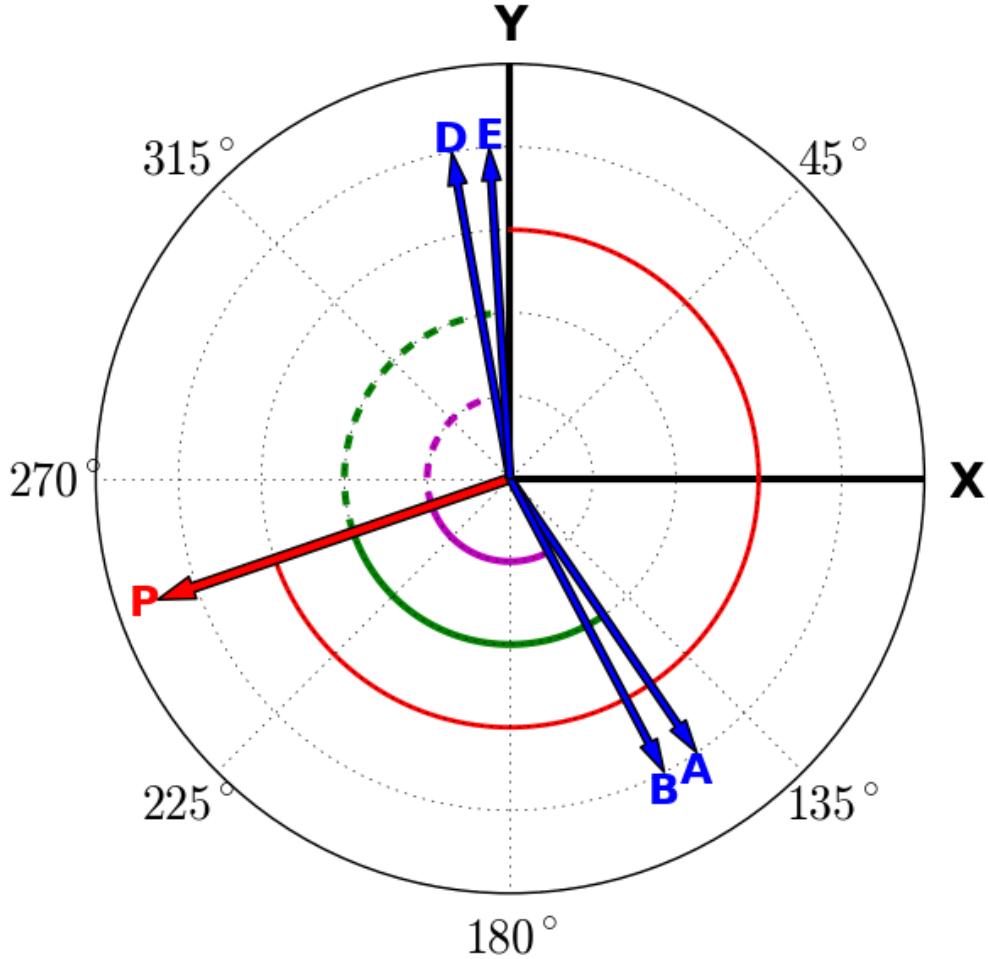


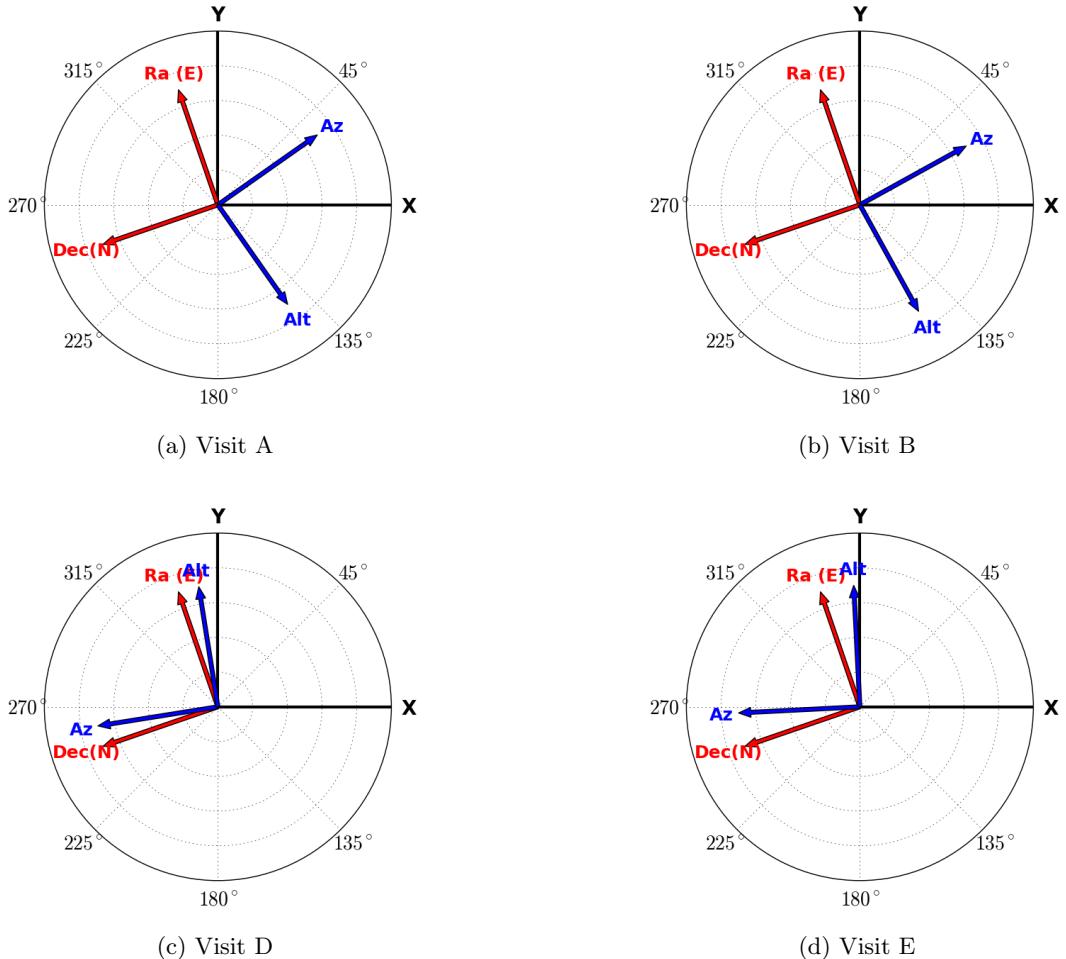
Figure 2: **Refraction Amplitude vs. Filter and Spectral Energy Distribution:** The flux-weighted amplitude of refraction (in arcseconds) for each of the filtered SEDs in Figure 1, as a function of zenith distance in degrees along the x-axis. The solid black line is the nominal result from Eqn ??, while the dashed red line ignores the corrections for temperature and pressure. Note the maximum amplitude of refraction reaches nearly 1 arcminute. This figure may be recreated using the script `python/DCR.py`.



**Figure 3: Differential Chromatic Refraction vs. Filter and Spectral Energy Distribution:** The differential chromatic refraction of all sources from Figure 1 with respect to the reference G0V star, with respect to zenith distance. The maximum amplitude of DCR reaches  $0.1''$ , or approximately half an LSST pixel. This figure may be recreated using the script `python/DCR.py`.



**Figure 4: Designed Orientation of Dcr in W14 Phosim Runs:** This figure represents the anticipated orientations of Dcr in the W14 phoSim data. The x,y coordinate system is depicted, as well as the convention that angles (`rotTelPos`, `rotSkyPos`) are clockwise with respect to the positive y-axis in the image coordinate system (counterclockwise in the camera coordinate system). The `rotTelPos` of 251 degrees specified for all simulations, which reflects the direction to the pole, is shown with the red vector P and the red arc at  $y=0.6$ . The derived `rotSkyPos` for visits A,B,D,E are shown with the blue vectors, and reflect the angle towards zenith (the angle of increasing altitude). Dcr is expected to happen along these vectors. The angles PA,PE are similar, and represented by the green arcs; the angles PB,PD are also similar, and represented by the purple arcs. This is expected as observations A and E are taken at airmass 1.55 (zenith distance of 50 degrees) but at opposite sides of the meridian crossing of the star field; a similar situation was designed for observations B and D, which are taken at airmass 1.15 (zenith distance of 30 degrees). Visit C is not depicted as it was taken at zenith. This figure was created using the script `python/dcrSchematic.py`.



**Figure 5: Wcs-Derived Orientations of Phosim Data:** These figures show the orientations of the Right Ascension and Declination axes (red), and Altitude and Azimuth axes (blue) of visits A,B,D,E. Arrows represent the directions of *increasing* coordinate value. The Ra,Decl axes are the same in all images since they were designed to have a common `rotTelPos`. Ideally, the directions of increasing Alt will correspond to the `rotSkyPos` depicted in Figure 4. All coordinate system orientations were derived from the fitted Wcs of the `calexp` of the  $g$ -band observation of seeing values 2, i.e. the worst seeing image. To determine the orientations empirically, small steps were taken in each coordinate starting at the center of the image, and the `Wcs` and topocentric corrections used to map these back into offsets in the pixel plane. This figure was created using the script `python/compareDcrFromSims.py.py`.

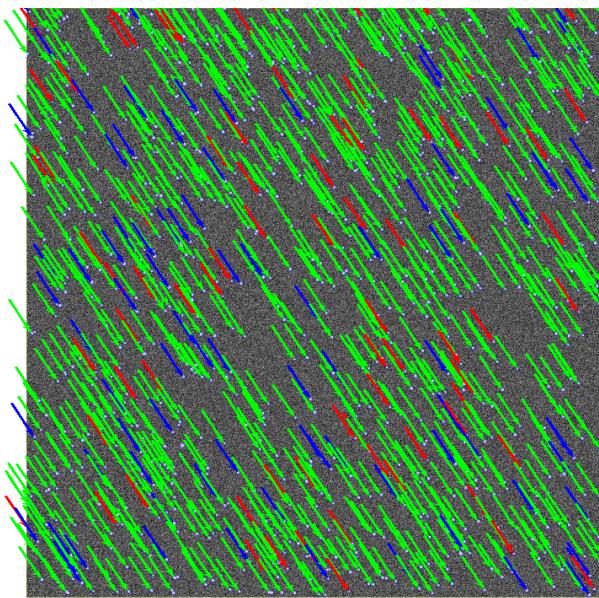
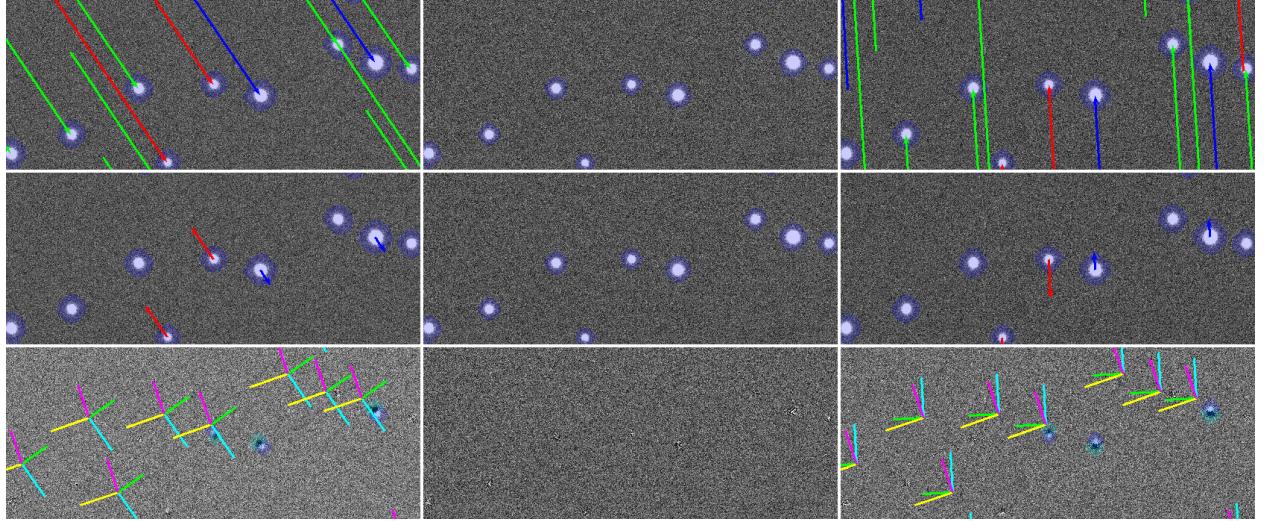
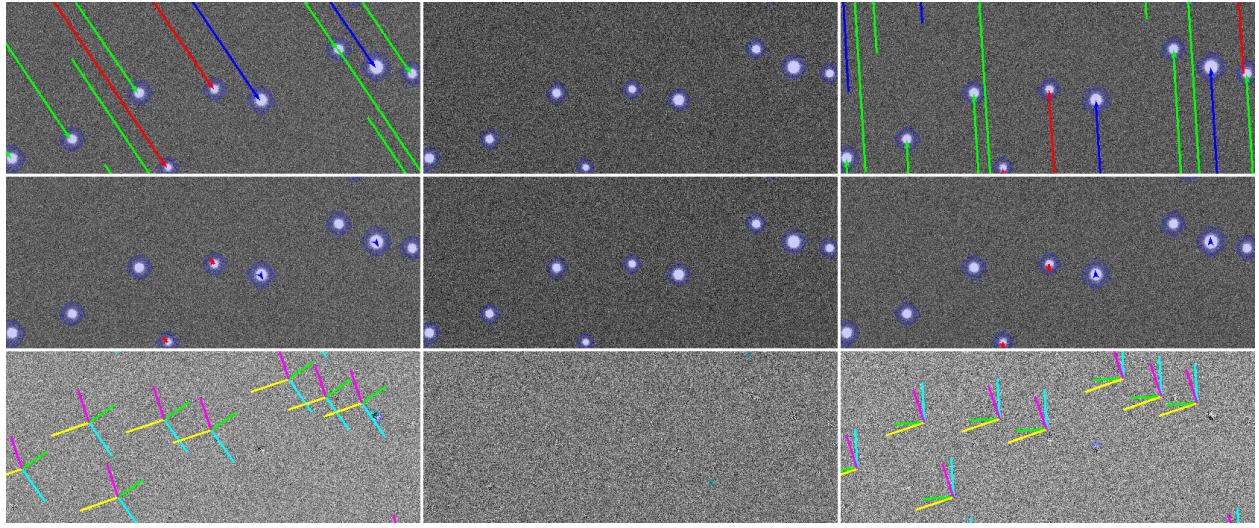


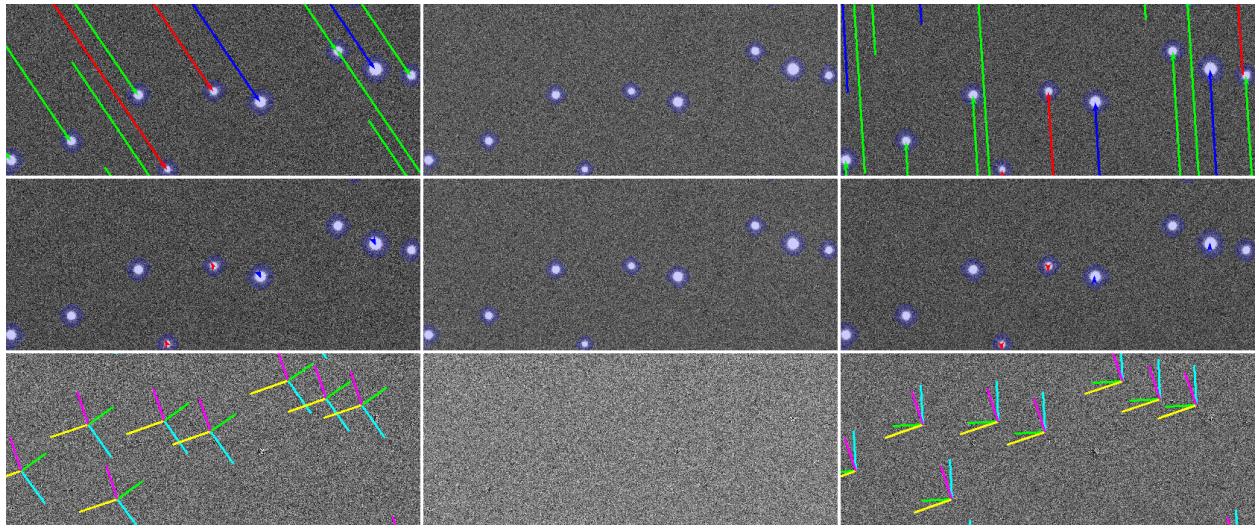
Figure 6: **Refraction:** This figure depicts the amplitude and orientation of the refraction vector in the visit A, `raft=2,2 sensor=1,1 filter=g`, seeing value 2 data. The vectors point from the unrefracted locations to the realized locations in the image. The SEDs of the sources are indicated with colors `blue`, `green` and `red` for AOV, GOV, and M2.0V respectively. This figure was created using the script `python/compareDcrFromSims.py`.



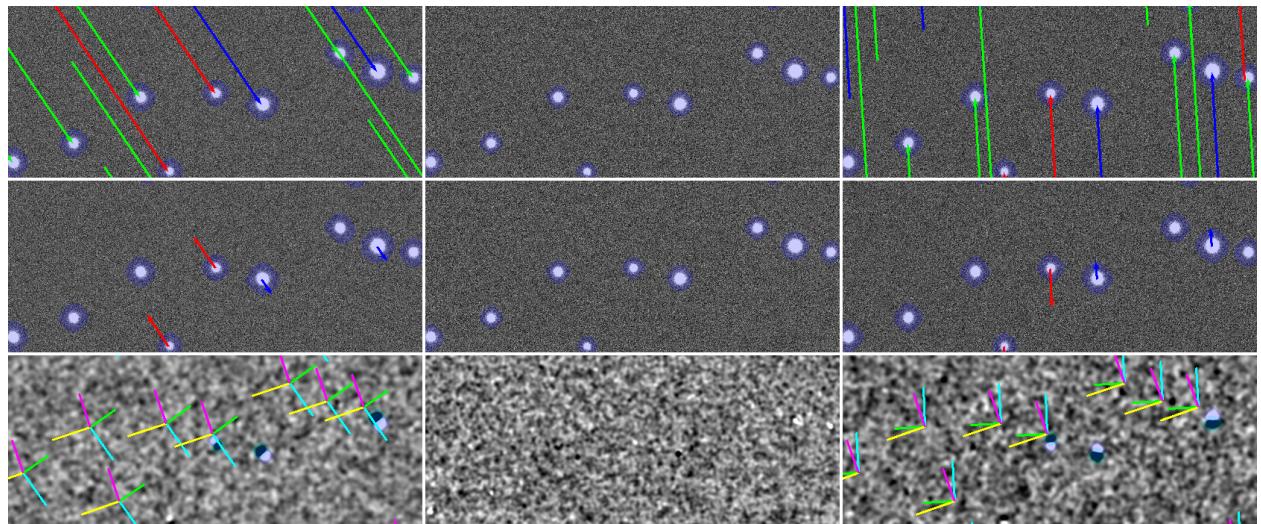
**Figure 7: Differential Chromatic Refraction and Difference Image Quality,  $g$ -band:** This set of panels demonstrates the amount of refraction (top row), differential refraction with respect to the GOV star (middle row), and the quality of the difference image (bottom row) for three sets of image differences. The first column uses science visit A, the middle C, and the third E. In all cases the template used was taken at zenith, i.e. visit C. The top rows effectively present the same information as Figure 6, but zoomed in on a particular cluster of stars. The second row subtracts off the green vector from all vectors. The residual refraction of the blue,red vectors represents differential chromatic refraction. These residual lengths have been multiplied by a factor of 100 for readability. Note that the blue vectors point along the vector to zenith, indicating the blue stars appear higher in the sky than their green counterparts, compared to an unrefracted observation. The red stars are not refracted as much and thus will appear lower in the sky. On the bottom row, we show the realized difference image quality. Note that the blue stars have positive lobes pointing along the direction to zenith, meaning the stars are “higher” in the sky w.r.t. the green stars when compared to the zenith template, while the dipoles of the red stars have the opposite polarity. For completeness, the Wcs-derived orientation of the Ra,Decl and Az,Alt coordinate axes are shown in the difference image (Ra,Decl,Az,Alt are magenta,yellow,green,cyan); see Figure 5 for more detail. This figure was created using the script `python/compareDcrFromSims.py`.



**Figure 8: Differential Chromatic Refraction and Difference Image Quality,  $r$ -band:** Same as Figure 7, but for  $r$ -band data. This figure was created using the script `python/compareDcrFromSims.py`.



**Figure 9: Differential Chromatic Refraction and Difference Image Quality,  $i$ -band:** Same as Figure 7, but for  $i$ -band data. This figure was created using the script `python/compareDcrFromSims.py`.



**Figure 10: Differential Chromatic Refraction and Difference Image Quality, Prefiltering:**  
Same as Figure 7, but using prefiltering of the science image with its Psf. This figure was created using the script `python/compareDcrFromSims.py`.

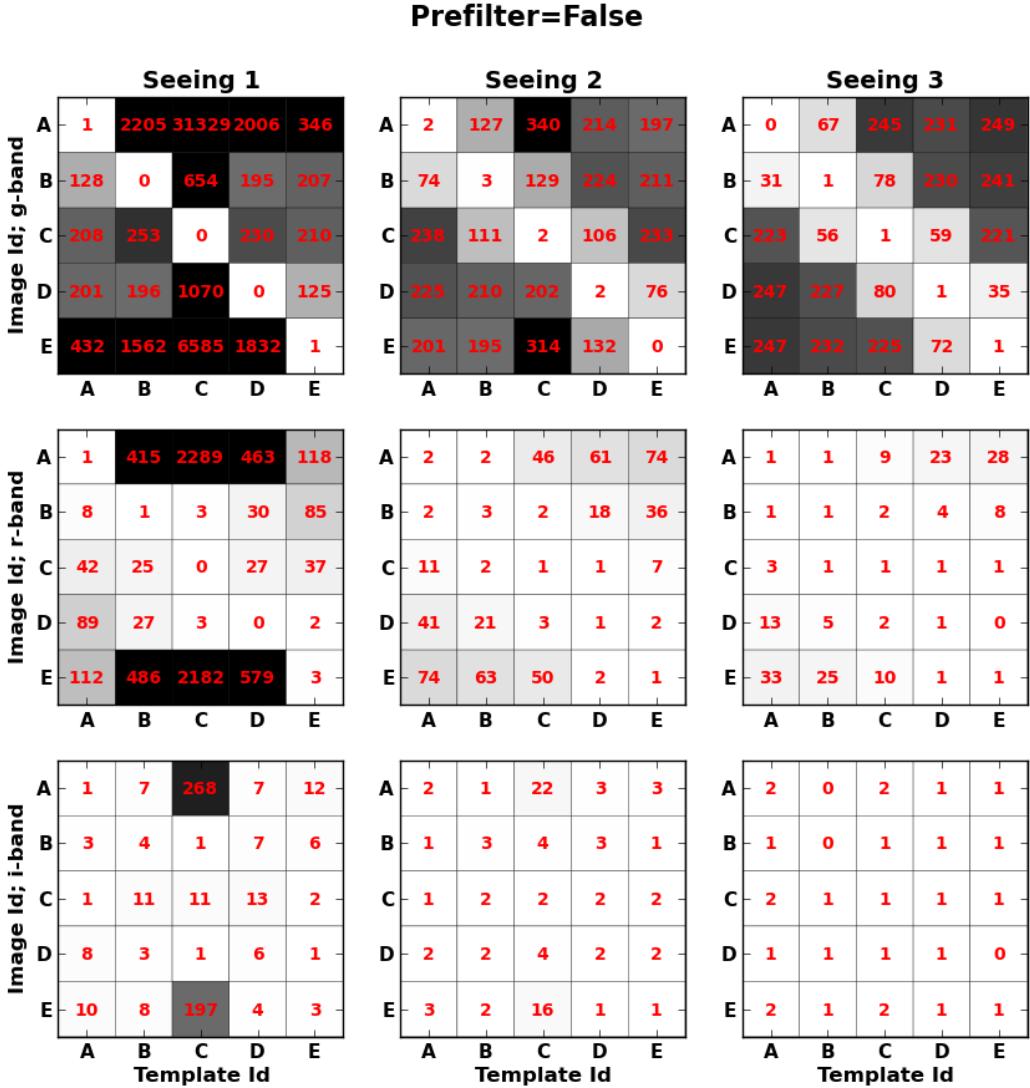


Figure 11: **Number of False Positives, Postfiltering:** This figure shows the median number of false positives across the 9  $\text{raft}=2, 2$  CCDs. The first row of information shows these “heat-maps” for  $g$ -band data, the second for  $r$ -band, and the third for  $i$ -band. The first column represents the good-seeing images, the second the medium-seeing images (same quality as template), and the third the poor-seeing images. Within each filter-seeing combination, the heat-map represents the median number of false positives as a function of the template airmass (visit ABCDE) along the x-axis, and image airmass (visit ABCDE) along the y-axis. The diagonal elements represent the situation where the template and science image are taken at the same airmass and have the same orientation w.r.t. zenith. The off-diagonal elements represent a mismatch between the template and science image in terms of airmass *and* parallactic angle. The general trend is that the numbers of false positives decrease with decreasing differences in the airmass,angle attributes of the template and science image, decrease with increasing seeing, and decrease with increasing wavelength. The  $i$ -band data in poor seeing do not appear sensitive to Dcr. This figure was created using the script `python/heatMap.py`.

### Prefilter=True

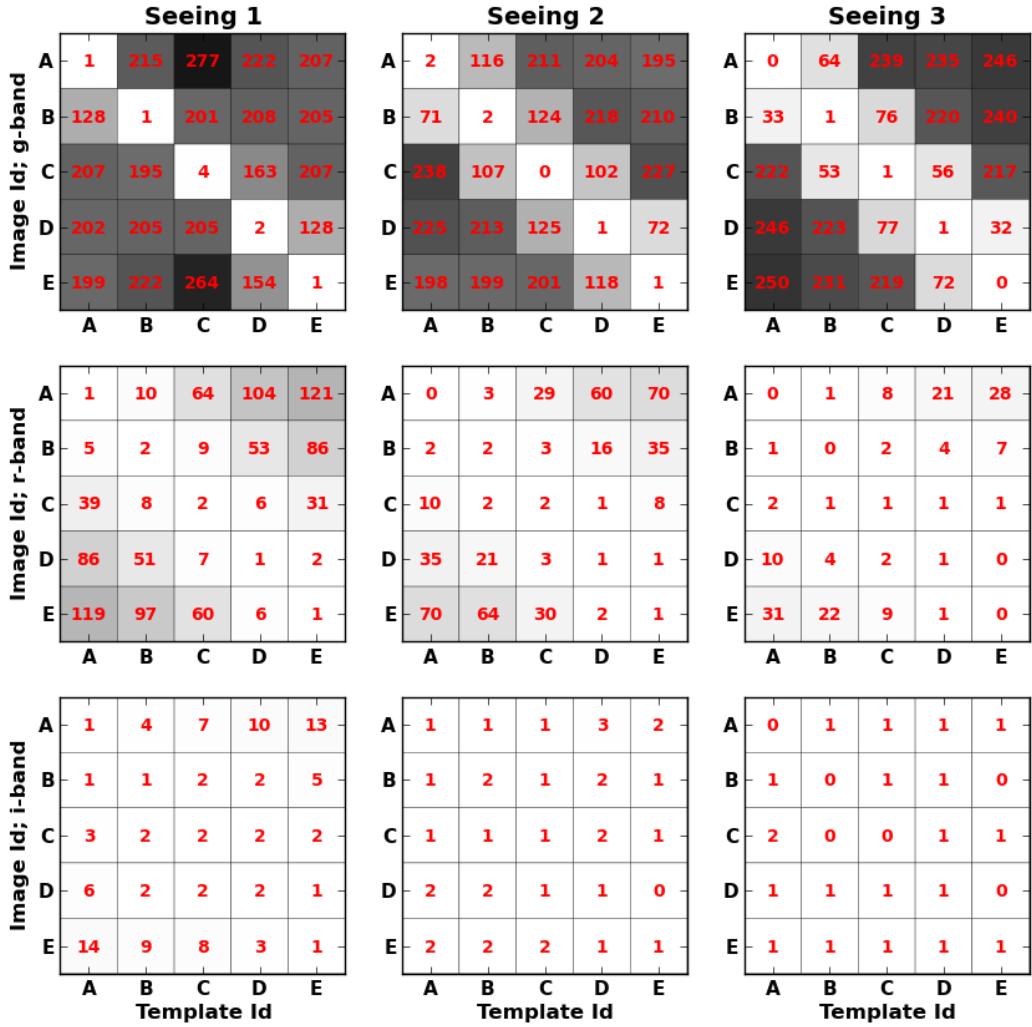


Figure 12: **Number of False Positives, Prefiltering:** Same as Figure 11, but using prefiltering of the science image with its Psf. The numbers of false positives is overall far lower than in the postfiltering case (Figure 11). This figure was created using the script `python/heatMap.py`.

PhoSim Visits					
Visit	MJD	rotSkyPos	rotTelPos	Altitude	Airmass
A	51130.111719	251.0689567	145.7139810	40.1	1.55
B	51130.176302	251.0689567	152.2708405	59.9	1.16
C	51130.272830	251.0689567	341.0975816	89.9	1.00
D	51130.272830	251.0689567	349.8619334	59.9	1.16
E	51130.433247	251.0689567	356.4181128	40.1	1.55

Table 1: Summary of the configuration parameters that define each phoSim visit ABCDE. Observations were designed to follow a single star field through zenith on a single night, and observed twice before and twice after crossing the meridian, as well as at zenith. Each visit was simulated using the same random seed (153555399), in 3 filters ( $g$ ,  $r$ ,  $i$ ), and under 4 observing conditions. These correspond to the template image (`Opsim_rawseeing` = 0.878") and `SIM_VISTIME` = 300) and then 3 bins in seeing for the science image corresponding to `Opsim_rawseeing` = 0.6", 0.878", and 1.2" for seeing bins 1, 2, 3, respectively. All science images were simulated with `SIM_VISTIME` = 15.

Overall, this yielded  $5 \times 3 \times 4 = 60$  runs of phoSim, which are encoded as `visitId=X00Y00Z` where X represents the phoSim filterId  $gri=123$ , Y represents the visit `ABCDE= 01234`, and Z represents the seeing: 0 for the template and 123 for the science images. All 9 CCDs within `raft=2,2` were simulated. All trim files used to generate the sims for this analysis may be found in the `sims8/` directory.

Orientation of Dcr				
Visit	SED	rotTelPos	Wcs + Topo	Measured Dipole Orientation
A	AOV	145.7°	144.9°	145.7°
	M2.OV	325.7°	324.9°	325.6°
B	AOV	152.3°	151.1°	151.7°
	M2.OV	332.3°	331.1°	331.8°
D	AOV	349.9°	351.0°	349.3°
	M2.OV	169.9°	171.0°	170.0°
E	AOV	356.4°	357.1°	355.2°
	M2.OV	176.4°	177.1°	176.2°

Table 2: The expected and measured orientations of Dcr, using the coordinate conventions depicted in Figure 4. These numbers represent the orientation of the *positive* lobe of any dipole arising from the Dcr effect. Numbers are reported as a function of visit A–E, and the spectral energy distribution of the source. For the `rotTelPos` and `Wcs` columns, the numbers for the red M2.OV stars are simply 180° from those of the blue AOV stars, which should be in the direction of zenith. The numbers under `rotTelPos` reflect the designed orientation of Dcr that was input to phoSim. The numbers under `Wcs` reflect the empirically determined direction to zenith in each image, using the `calexp` fitted `Wcs` and topocentric corrections appropriate for each visit. Finally, we report the measured median orientation of DiaSources in each image difference, when differenced against the template taken at zenith (visit C). Here the red and blue populations are considered separately.

These numbers come from analysis of *g*-band data, seeing bin 1, which have the most dipoles. We only show results for 1 filter since the orientation should be filter-independent. Results in the *r*-band, in cases where there are more than 10 dipoles measured, show quantitatively similar results. In addition, we only report numbers from the postfiltered data, where dipole measurement is known to operate correctly. We do not see any dependence of these orientations on the seeing. Full results may be found in the file NOTES.

Amplitude of Dcr							
Visit	SED	Filter	Theory	Wcs Offsets	Dipole Amplitude Seeing Bin 1	Dipole Amplitude Seeing Bin 2	Dipole Amplitude Seeing Bin 3
A	AOV	<i>g</i>	0.049"	0.042"	0.167"	0.259"	0.208"
		<i>r</i>	0.015"	0.013"	0.049"	...	...
		<i>i</i>	0.005"	0.005"	...	...	...
	M2.OV	<i>g</i>	0.105"	0.077"	0.144"	0.204"	0.293"
		<i>r</i>	0.025"	0.020"	0.230"	...	...
		<i>i</i>	0.015"	0.012"	...	...	...
B	AOV	<i>g</i>	0.024"	0.020"	0.183"	0.243"	...
		<i>r</i>	0.007"	0.006"	...	...	...
		<i>i</i>	0.002"	0.002"	...	...	...
	M2.OV	<i>g</i>	0.051"	0.038"	0.222"	0.266"	...
		<i>r</i>	0.012"	0.010"	...	...	...
		<i>i</i>	0.007"	0.005"	...	...	...
D	AOV	<i>g</i>	0.024"	0.020"	0.201"	0.251"	...
		<i>r</i>	0.007"	0.006"	...	...	...
		<i>i</i>	0.002"	0.002"	...	...	...
	M2.OV	<i>g</i>	0.051"	0.038"	0.201"	0.254"	...
		<i>r</i>	0.012"	0.010"	...	...	...
		<i>i</i>	0.007"	0.006"	...	...	...
E	AOV	<i>g</i>	0.049"	0.042"	0.169"	0.235"	0.360"
		<i>r</i>	0.015"	0.013"	0.135"	...	...
		<i>i</i>	0.005"	0.005"	...	...	...
	M2.OV	<i>g</i>	0.105"	0.077"	0.158"	0.213"	0.267"
		<i>r</i>	0.025"	0.020"	0.262"	...	...
		<i>i</i>	0.015"	0.011"	...	...	...

Table 3: The expected and measured amplitudes of Dcr, in arcseconds. These numbers represent the differential offset between positions of an object at zenith (visit C) and at the airmasses associated with visits ABDE, with respect to the positions of the reference GOV stars, which define the astrometric reference system in this study. The Theory column is the expected amplitude as described in Section 2, using the reference SEDs described in Section ???. The Wcs column represents the mean offsets between stars of the given SED and the astrometric reference solution, determined using calexp’s Wcs and Source products. Residuals of the reference GOV stars are smaller than 0.002" in all cases. The dipole amplitudes are determined using the same fits that yield the dipole orientations in Table 2, and represent the offset between the fitted positive and negative lobes of the dipole. These numbers are only reported for data sets that contain more than 10 measurements. Because we see a seeing dependence on these numbers, we report them for each of the seeing bins 1,2,3. Full results may be found in the file NOTES.

## References

# Appendices

## A Use of PhoSim

I describe here the end-to-end process of generating instance (or trim) files for `phoSim`, running these images to create output `eImages`, creating `astrometry.net` index files for astrometric calibration, and running these images through `processEimage.py`. This does *not* include the process of generating instance catalogs from a master base catalog, or the process of using calibration data to run the simulated images through `processCcd.py`, which does (amongst other operations) the assembly of amp images into CCD images and instrument signature removal. The process is described for `phoSim` version 3.3.2.

### A.1 Setting up PhoSim

### A.2 Generation of Instance Catalogs for W14

#### A.2.1 General

exposure times single snap control file header seeing

#### A.2.2 Subtask 1

We describe our first step in the `phoSim` process, the generation of the input configuration. We start with the trim files used in W13 processing, which consist of a random star field populated by stars of SED `km50_5000.fits_g20_5140.gz`, and covering a range of magnitudes  $19 < r < 21$ . Observations were designed to be at a zenith distance of  $20.2^\circ$ , with a boresight pointing of (Ra, Decl) =  $(79.68926^\circ, -9.70229^\circ)$ . Observations were simulated in the *i*-band. These trim files are stored in the `sims3/` directory in this repository.

#### A.2.3 Subtask 2

We chose spectrum `km20_6000.fits_g30_6020.gz` for our reference GOV-star, and replaced 80% of the objects in the original trim file with this SED. We then selected the bluest object contained in the base catalog, `kp01_9750.fits_g45_9830.gz`, for every tenth object starting at object #0, and the most populous red object in the catalog `m2.0Full.dat.gz` for every tenth object starting at object #5. These correspond to spectral types AOV and M2.OV, respectively.

Because the magnitudes in the trim files represent a 500nm magnitude (approximate *g*-band), it was required to make color corrections to the requested magnitudes of the objects to preserve the relative brightness distribution of the as-simulated, multi-SED sources. This was done using their respective *i*-band magnitudes (i.e. a correction of  $-2.5 \log_{10} (f_i; \text{SED} / f_i; \text{GOV})$ ). Accordingly, the brightness distributions in the *gr*-bands were not optimal (this was fixed in Task C). The colors of each spectral type were calculated using `python/colors.py`. Script `makeNewTrims.py` was used to make these modifications to the `sims3/` trim files, yielding `sims5/` trim files (*i*-band). The only modifications made to the input trim files to simulate images in the *gr*-bands were to change the `Opsim_filter` field to indicate  $gri = 123$ ; these are stored in the `sims5gr/` directory.

#### A.2.4 Subtask 3

First, to have similar brightness distributions in all data, we make a SED-dependent *and* passband-dependent magnitude correction to the trim files used for this task. These corrections are made in

script `generateTrimFilesDcr.py`, which ran on the *i*-band trim files from `sims5`.

Second, the original observations do not pass through zenith on the given night of simulated observations. To design the observations to pass through zenith at the LSST site, which is at southern latitude  $-29.67^{\circ}$ , we first subtracted  $19.96437^{\circ}$  from all coordinates in the input trim files so that the field is centered at a declination equal to the Southern latitude of the site. This includes both the per-object coordinates and the boresight pointing `Unrefracted_Dec` in the trim file header.

We simulated this star field throughout the night of MJD 51130 (the night of the fiducial image simulations) to establish the times at which it was at an altitude of 40 and 60 degrees (zenith distance of 50 and 30 degrees; airmass of 1.55 and 1.15), and when it was closest to zenith. We chose 5 specific times at which to simulate the images: before meridian crossing at airmass 1.55; before meridian crossing at airmass 1.15; closest to zenith; after meridian crossing at airmass 1.15; after meridian crossing at airmass 1.55).

Because the instance catalog inputs to `phoSim` form an overcomplete set (e.g. the user specifies Ra, Decl, altitude, azimuth, and time of observation), it is possible to request a simulation configuration that is not physically possible. For this reason, we used

`lsst.sims.catalogs.measures.example_utils.makeObsParamsRaDecSky` subroutine `makeObsParamsRaDecSky` to generate a self-consistent set of observation parameters given the Ra and Decl of the field, and the times of observation established above.

In addition, this script synchronized the values of `Opsim_rotskypos` and `Opsim_rottelpos`. `Rotskypos` sets the orientation of Ra and Decl of the catalog, effectively a rotation of the Pole away from the Zenith. When `rotskypos=0` the Ra direction is “up”, along the y-axis. This value was kept the same for all images, so that the star field was always rendered in approximately the same orientation. `Rottelpos` is defined as (`rotskypos`-180+parallactic angle), such that the angle of DCR should be along this axis. This will also be the angle of increasing Altitude in the Az,Alt coordinate system. This value is observation dependent, and was determined using `makeObsParamsRaDecSky`. Trim files for this run are found in the `sims8/` directory of this repository.

### A.3 Running `phosim.py`

### A.4 Creating Astrometry Index Files

```
setup -r /lsst/home/krughoff/lsst/lsst_devel/Linux64/astrometry.net-0.38/astrometry text2fits.py  
2002000.ref 2002000.fits setenv P 1402120 build-index -i 2002000.fits -o index-P00.fits -IP00 -  
P 0 -S r -n 100 -L 20 -E -j 0.4 -r 1 build-index -1 index-P00.fits -o index-P01.fits -I P01 -  
P1 -Sr -L20 -E -M -j 0.4 build-index -1 index-P00.fits -o index-P02.fits -IP02 -  
P 2 -S r -L 20 -E -M -j 0.4 build-index -1 index-P00.fits -o index-P03.fits -I P03 -P3 -  
Sr -L20 -E -M -j 0.4 build-index -1 index-P00.fits -o index-P04.fits -IP04 -P 4 -S r  
-L 20 -E -M -j 0.4 ls index-1402120* — awk 'printf("modhead setup astrometry.net 0.30 cp -r  
/nfs/lsst/home/becker/Winter2014/astrometry.net_data/ups . edit andConfig.py setup -k -r .
```

### A.5 Running `processEimage.py`

## B ImageDifferenceTask

We used `$PIPE_TASKS_DIR/bin/imageDifferenceWinter2013.py`, which has an additional flag that allows us to use a particular visit ID as the template, instead of extracting one from the template archive.