LSST Camera Mixed Focal Plane Option

November 13, 2015

Introduction and Purpose

The baseline plan is that all 189 science sensors installed in the LSST Camera will be from a single vendor, *i.e.*, a homogenous focal plane. To mitigate various risks, two vendors are currently under contract to develop the science sensors. As sensors from both vendors will meet the performance requirements, and as there could come a time when enough sensors of both types combined could be in hand to complete the camera, schedule risk can be mitigated with an option to install sensors of both types, *i.e.*, a mixed focal plane.

Although both types of sensors will meet the performance requirements, there will be some small systematic differences. Specifically, from the perspective of science performance, we anticipate:

- differences in the quantum efficiency (QE) curves, as shown in figure 1,
- differences in average height (Z position), which can be compensated to better than $2.5\,\mu m$ (TBR) in the mounting of the rafts,
- differences in electronics optimization, and
- possible small differences in thermal properties, which could result in somewhat more complex thermal gradients across the focal plane.

The most significant potential impacts on science are due to the QE differences, so we concentrate on those. Figure 1 can be compared with figure 2, which shows throughput variation induced by atmospheric effects.

The differences between the two sensor types are measurable and will be stable throughout the science survey. LSST Data Management (DM) is already planing to handle specific categories of sensor-to-sensor variations[1]. Most of the potential performance issues, therefore, are related to systematics from residuals *after correction*. Having sensors of different types can, in principle, help us to measure some of these residuals and/or their effects.

The mixed focal plane option has been discussed by the PST and in other venues. A memo was sent to the LSST SAC in June, 2015, along with a follow-up phone call, inviting suggestions for any additional issues to study. As a result of these discussions, several studies were undertaken to assess the potential risks of the mixed focal plane option.

This note summarizes the studies. We first define the range of options and then turn to the issues and the results. Note that other practical considerations, such as potential decreased operating temperature range, optimization of exposure and readout times, and increased characterization effort, are also under discussion but are not the focus of this note.

[1] Including likely sensor-to-sensor QE curve variations from the same vendor. As more is learned about the detailed characteristics and distributions of the actual sensors, additional effects may be uncovered and taken into account.

Definition of studies

Recall[1], the LSST Camera focal plane is modular, comprising 21 science *rafts*, each with a 3x3 array of sensors. All 9 sensors on an individual science raft will have sensors of the same type. To bracket the effective range of options, we considered cases in which as few as 4 rafts are of one type (17 of the other) as well as approximately equal populations (10 rafts of one type, 11 of the other). The spatial distribution is also uncertain and may depend in part on production schedule details. The configurations are given with each of the studies below.

Issues

The issues considered were

1. limiting magnitude average and variation,
2. spatial structure of the co-added depth map,
3. image subtraction and false transient rates,
4. photo-z impacts,
5. potential 'print-through' of residuals of the mixed focal plane pattern on the angular power spectrum of galaxy shear.

As already noted, in some cases the main concerns are the systematic errors arising from residuals after correction. In those cases, we make explicit assumptions about the sizes of the residuals and then assess the potential impacts. When the QE differences are important, we simply treat the different sensor types as two different band sets to allow the most straightforward and conservative estimates of the impacts. In a similar manner, we also considered potential impacts on early survey science, as it could require additional time for a given object to be sampled sufficiently in both types of detectors.

Limiting magnitude average and variation

Using the full LSST system throughput, estimated separately for each sensor type, the limiting magnitudes were recalculated[2], as shown in figure 3. The m5 limiting magnitudes for the two cases are shown in table 1. For one sensor type the u-band limiting magnitude is deeper by approximately 0.34 mag. For the other bands, although the shapes are slightly different, the limiting magnitudes are essentially the same. As the anticipated allocated time for the u band is small ($\sim 6\%$), the time to achieve baseline coadded depths is about the same for both sensor types.

Table 1: m5 limiting magnitudes for the two sensor types.

	u	g	r	i	z	y
vendor 1	23.66	24.91	24.46	24.00	23.43	22.51
vendor 2	24.00	24.95	24.47	24.02	23.44	22.50

Spatial structure of the co-added depth map

The different u-band single-visit limiting magnitudes convolve with the mixed focal plane layout and the observing cadence to produce early-survey sky non-uniformities. To quantify this, the same survey visit set was run[4] with different focal plane configurations (labelled A, B, C, D, E, and F), shown in figure 4. The depth distribution for configuration A is shown in figure 5, and the rms of the distribution is similar for all configurations (0.37-0.39). However, the different focal plane configurations produce different angular scale non-uniformities. The distributions after year 1 for each of the focal plane configurations are shown in figures 6 and 7 for the cases in which the red rafts of figure 4 are less or more sensitive, respectively, than the gray rafts. It is interesting to note that in figure 7, configuration E is the worst case and configuration C is the best – even better than the homogeneous focal plane case. This is due to the overlap of spatially adjacent visits: placing the lower-sensitivity rafts at the edge of the focal plane reduces the sky non-uniformity. As expected, the situation is reversed in figure 6.

These effects, which are simply due to the extra sensitivity of one sensor type, will be taken into account with object selection to uniform depth. Furthermore, as shown in figure 8, by ten years the raw depth differences on the sky are negligible.

Transient alert analysis impacts

The transient analysis is based on comparisons with templates that are built up over time. As the detailed SEDs of individual objects are not known, merely compensating for the band-integral throughput (zero-point difference) will not generally yield the same magnitude of the same object in the two sensor types, introducing additional noise (beyond the other throughput variation effects, which are generally flatter in wavelength) in the transient results and complicating the template definition. The simplest approach, therefore, is to treat the mixed focal plane as two LSST instruments with somewhat different effective bands. The main consequence of this approach is a slower rate of template formation, potentially delaying early survey alerts. To quantify this, the same survey visit set was run[4] with different focal plane configurations, shown in figure 4. For each of these configurations, the time to build the templates relative to homogeneous focal plane case is shown in figure 9. Here, it is assumed that a minimum of four visits are required for image differencing and that image differencing cannot be performed with different CCDs.

The build-up of sky coverage is slower for the configurations with equal numbers of rafts of the two types. For configuration B, for example, the sky coverage in u band is 48%, 86%, and 98% after years 1, 2, and 5, respectively. One option to accommodate the slower rate would be to build the templates using data from the trailing two-year period, instead of the trailing one-year period. The major impact would be during the first year of the survey, when there would not be sufficient input images to perform differencing over the whole survey area. This could be mitigated by devoting more time in commissioning to building the initial u-band templates. No additional impacts on other areas of science have been identified. The impact on the Data Management system should be minimal to none, as the bookkeeping tracking the input data does not assume one-year templates.

We have also considered the case in which we give up on image differencing in the u band. The major impact would be on the science cases that depend on detections in u band, *i.e.*, transients that are only (or predominantly) detectable in the u band. The discovery volume would be affected as well, though not significantly: given the lower sensitivity compared to other bands, and the relatively small observing time, the loss in the actual explored volume is small (below 5%) and is comparable to losses due, *e.g.*, to uncertainties in the weather.

Impacts on photo-z estimation

To investigate mixed focal plane effects on photo-z estimation, a continuous distribution of mock galaxy SEDs was generated[5]. The mixed focal plane was treated as two separate effective u-band filters, in a half-half checkerboard focal plane pattern, dividing the observing time between them. As the shapes of the two effective filters are different, there are $0.02 - 0.1$ magnitude differences for many galaxies. This, together with the increased number of non-detections and noisier u-band magnitude estimates, leads to biases and catastrophic photo-z errors.

A detailed analysis would start with training a state-of-the-art photo-z code using photometry from seven bands (g r i z y and the two u bands). As a worst-case estimate, the u-band measurements in the two types of sensors were instead simply combined[2]. As noted in the Introduction, it is the residual uncorrected errors that lead to systematic effects. To bound the potential size of the effects, the BPZ analysis used a different set of templates from the generation of the mock galaxies. Figure 10 shows the mean photo-z scatter, σ_z, bias, and the percentage of catastrophic outliers ($|z_p - z_s| > 0.15(1 + z_s)$) using this pessimistic, but straightforward, approach. Note that the bias can be calibrated statistically. The most significant remaining systematic is the outlier fraction, which can be mitigated with deeper u-band photometry.

Print-through of the mixed focal plane pattern on the sky

The uneven u-band depth and residual photo-z errors from the previous section, combined with the mixed focal plane spatial distribution and the observing pattern, can in principle leave an imprint on the sky that could complicate the analyses of large scale structure and limit the cosmology results from LSST. To check for these effects, observations were simulated using the dithering scheme of reference [6]. The residual photometric bias was then used to calculate the resulting induced angular power spectrum of galaxy shear, for $0.2 < z < 0.5$. The result, extrapolated to the full survey, is shown in figure 11. The impacts are negligible compared with the requirement in this range (effectively 3.2×10^{-4}): at 30 arcmin the induced fractional error is around 0.2% of the requirement.

Summary and Conclusions

The science performance impacts of a potential mixed focal plane have been considered.

The u-band throughput differences of the two sensor types would result in a 0.34 mag limiting magnitude difference. As the allocated time for u-band observations is relatively small, the time to achieve baseline co-added depths is about the same for both sensor types.

Sky uniformity has been investigated for a bracketing range of mixed focal plane layouts. The effects are negligible after ten years, however they would be noticeable in the first few years of the survey.

Impacts on u-band transient analyses have also been studied. With the conservative assumption that u-band image differencing would be done only with CCDs of the same type, there could be an early-survey delay in u-band transient detection over part of the sky while the templates are being built up. This might be mitigated with additional u-band observations during commissioning.

The impacts on photo-z and induced galaxy shear have been estimated and shown to be subdominant.

[2] As the sensor type for each observation of each object is known, the weight (for effects of the mixed focal plane) is known precisely.

The Project Science Team (PST) discussed the results of these studies on 25 September and agreed unanimously that a mixed focal plane would be acceptable, with some preference for a homogeneous focal plane. Furthermore, a mixed focal plane might be beneficial for estimating systematics, but it might also provide additional constraints for the scheduler and imply some tweaks to the commissioning plan.

References

[1] *LSST: FROM SCIENCE DRIVERS TO REFERENCE DESIGN AND ANTICIPATED DATA PRODUCTS*, Z. Ivezic et al., http://arxiv.org/abs/0805.2366

[2] L. Jones et al., based on LSST SE throughput calculations (C. Claver et al.) available in github `https://github.com/lsst-pst/syseng_throughputs`.

[3] Provided by C. Stubbs.

[4] Analysis by P. Yoachim, A. Connolly, and Z. Ivezic.

[5] Analysis by S. Schmidt, J. Jee, and J.A. Tyson.

[6] C.M. Carroll et al., arXiv:1501.04733v2 (2015).

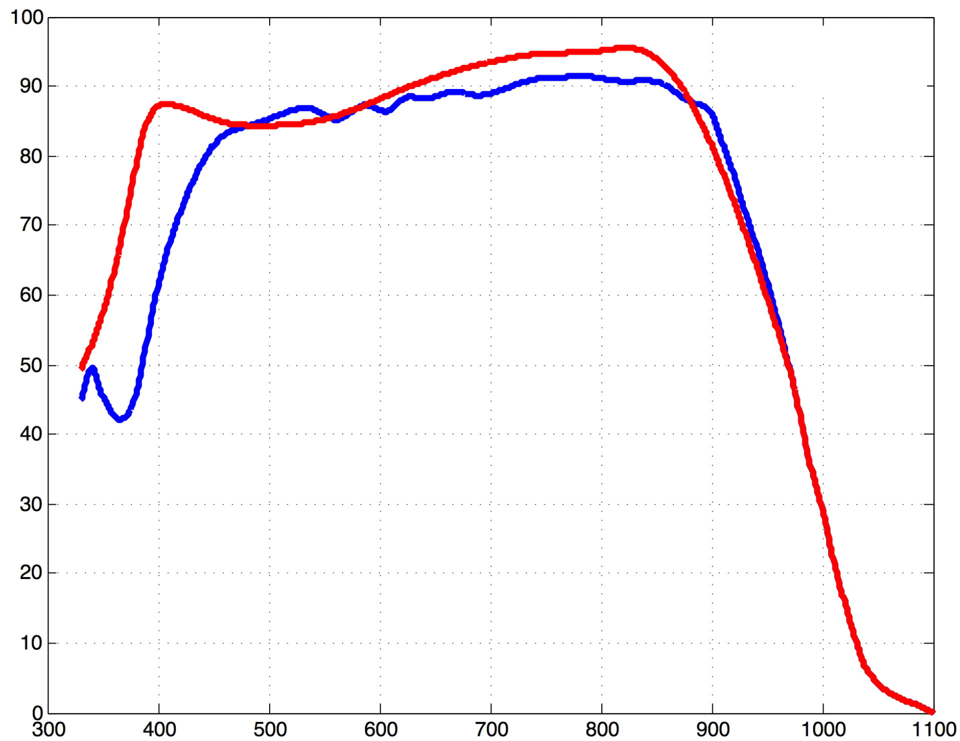

Figure 1: Representative quantum efficiency (QE vs wavelength (nm)) curves for each of the two different types of science sensors, as measured by LSST.

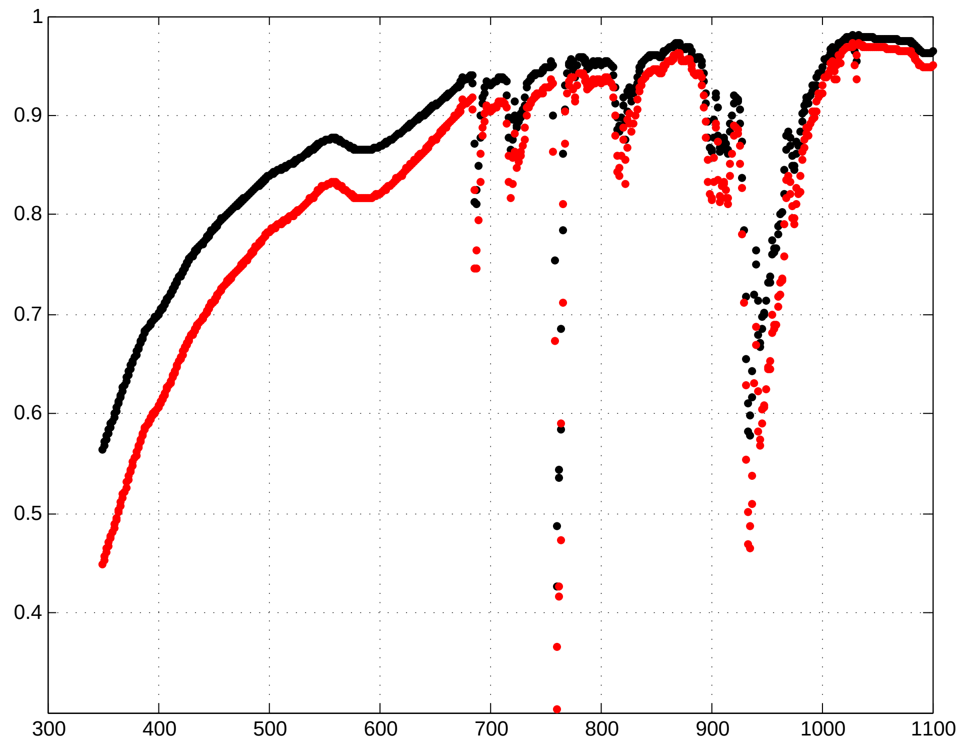

Figure 2: For comparison with figure 1, atmospheric transmission (black is at airmass 1.0, red 1.4) vs. wavelength[3].

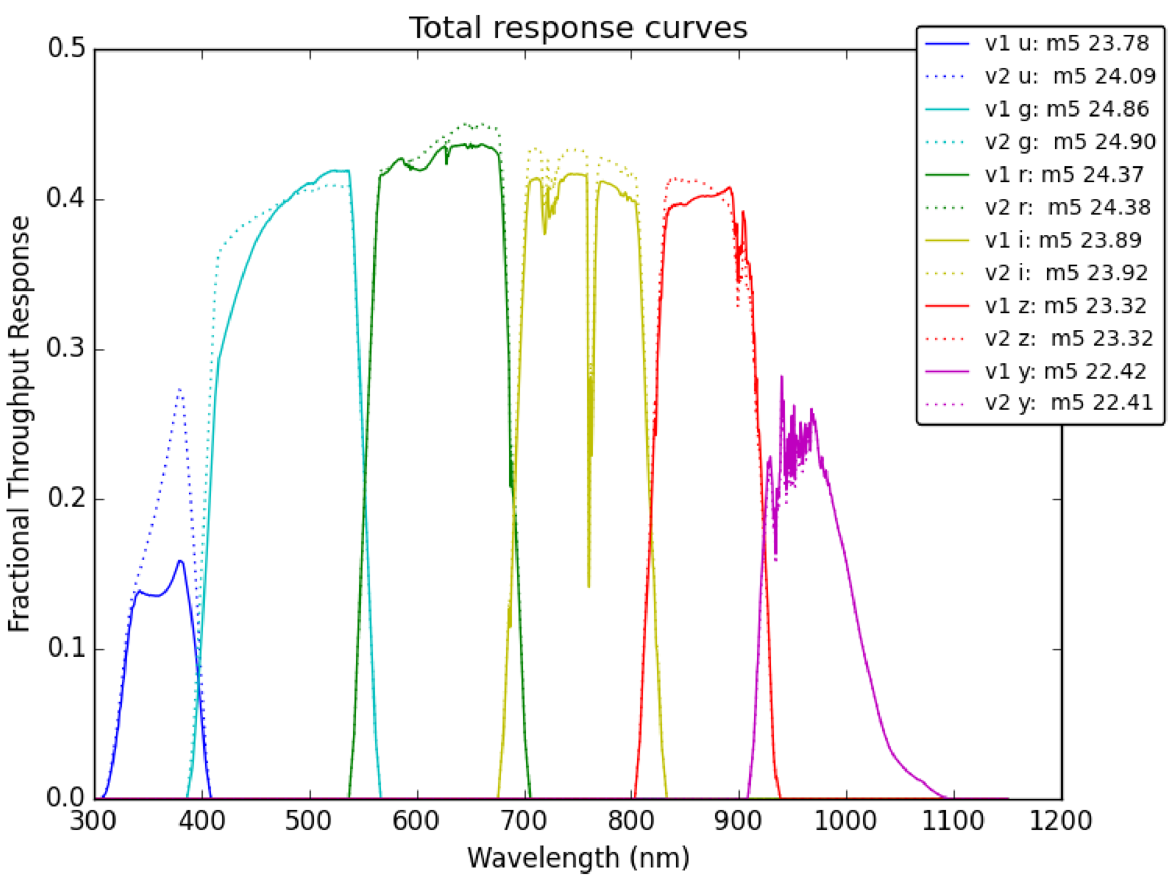

Figure 3: Total throughput for each of the two sensor types. The difference in the shape of the u band is particularly pronounced.

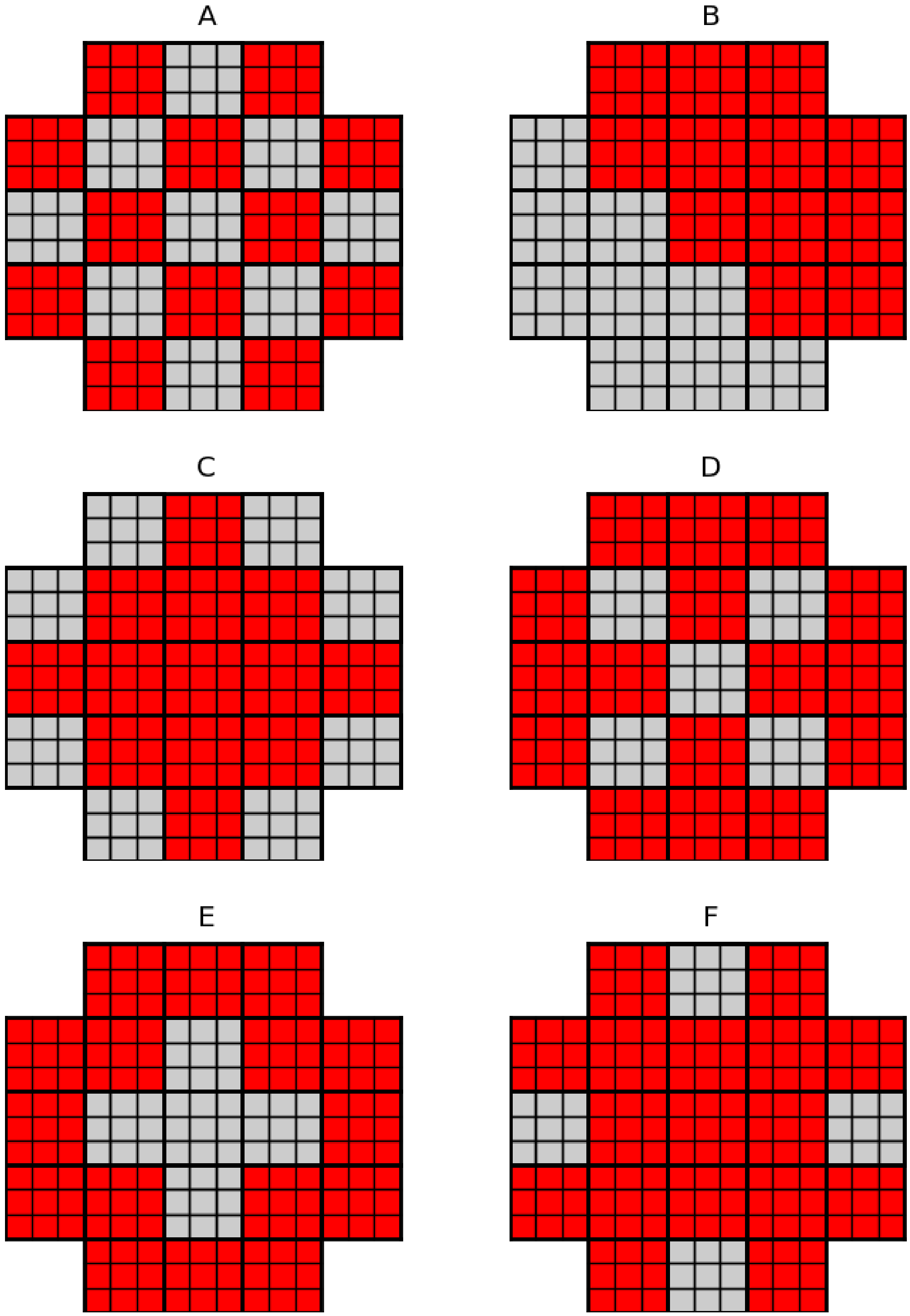

Figure 4: Mixed focal plane configurations used in the studies of spatial structure of the co-added depth map and transient alert template build-up times. The complementary cases (red rafts more sensitive or gray rafts more sensitive in u band) were simulated for each spatial configuration.

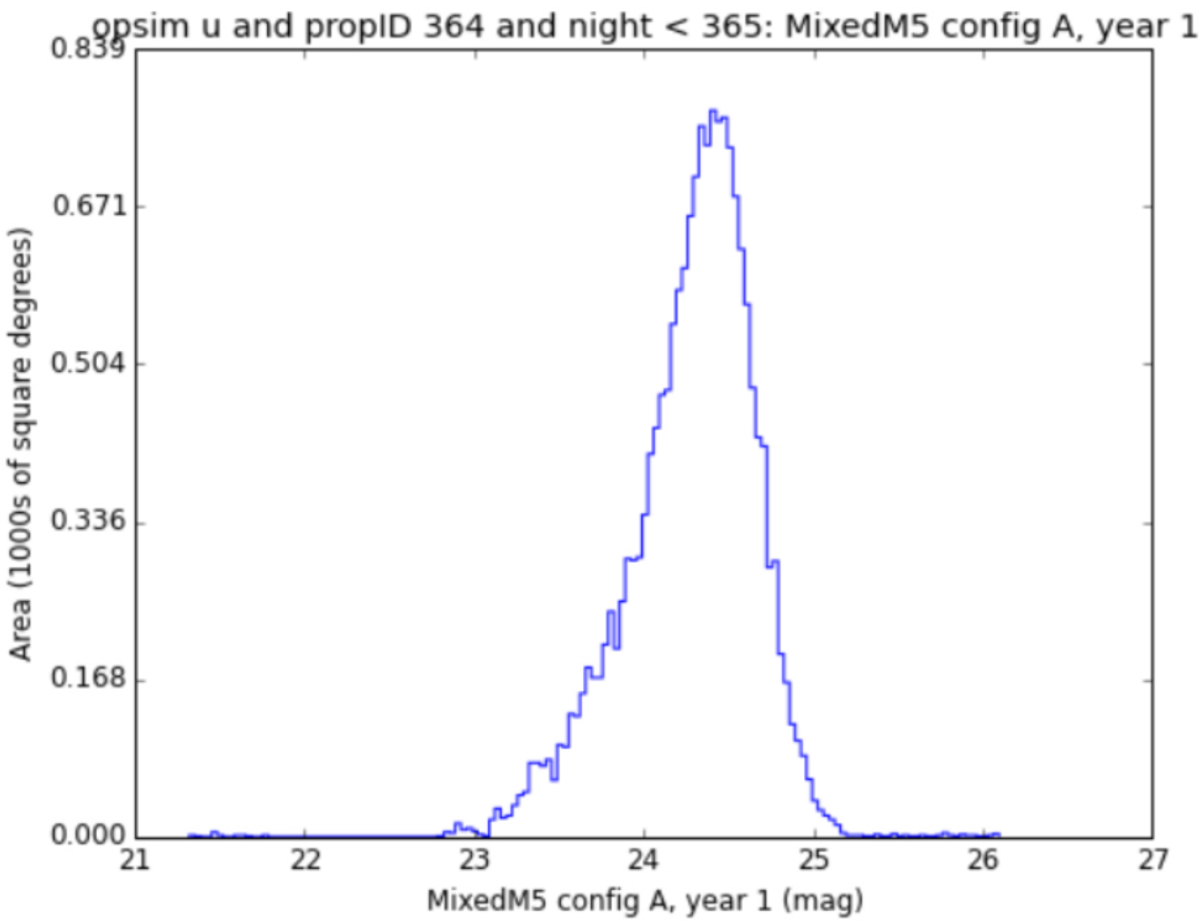

Figure 5: Distribution of year-1 u-band depth over the sky for focal plane configuration A. The rms values of the distributions for all of the focal plane configurations are similar.

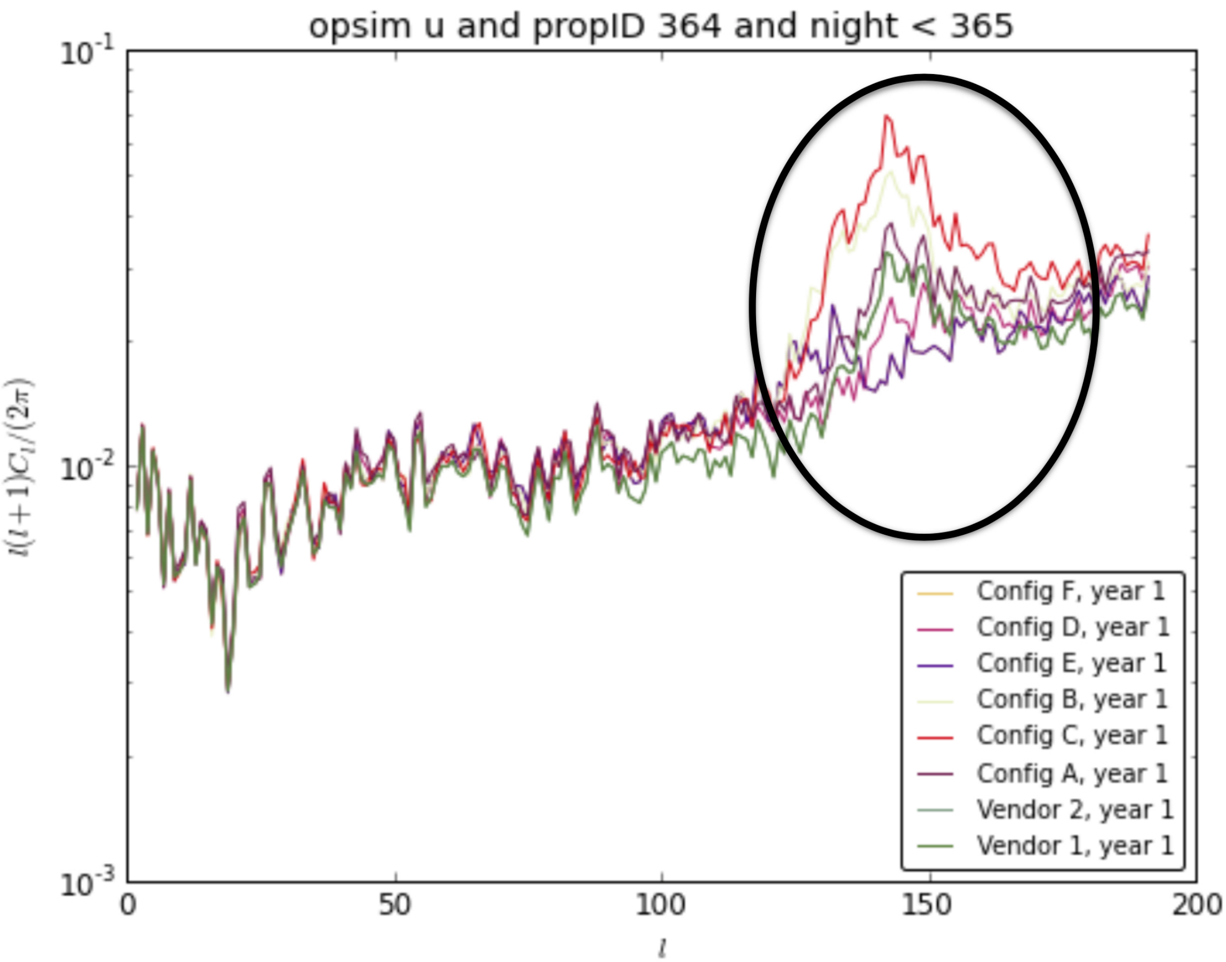

Figure 6: Year-1 u-band sky exposure angular power spectrum for each of the mixed focal plane configurations of figure 4. In this case, the red rafts of figure 4 have relatively lower u-band throughput.

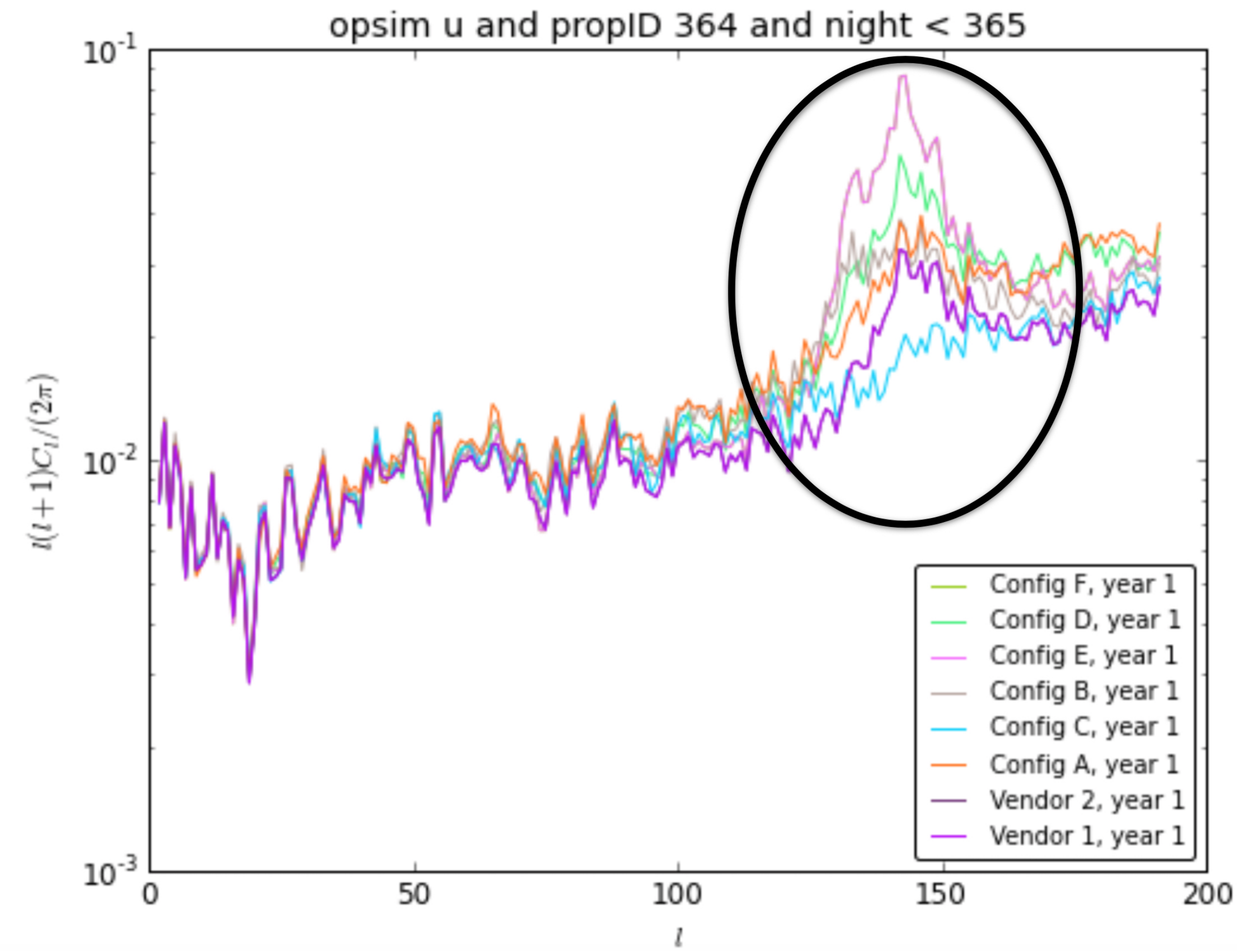

Figure 7: Year-1 u-band sky exposure angular power spectrum for each of the mixed focal plane configurations of figure 4. In this case, the red rafts of figure 4 have relatively higher u-band throughput.

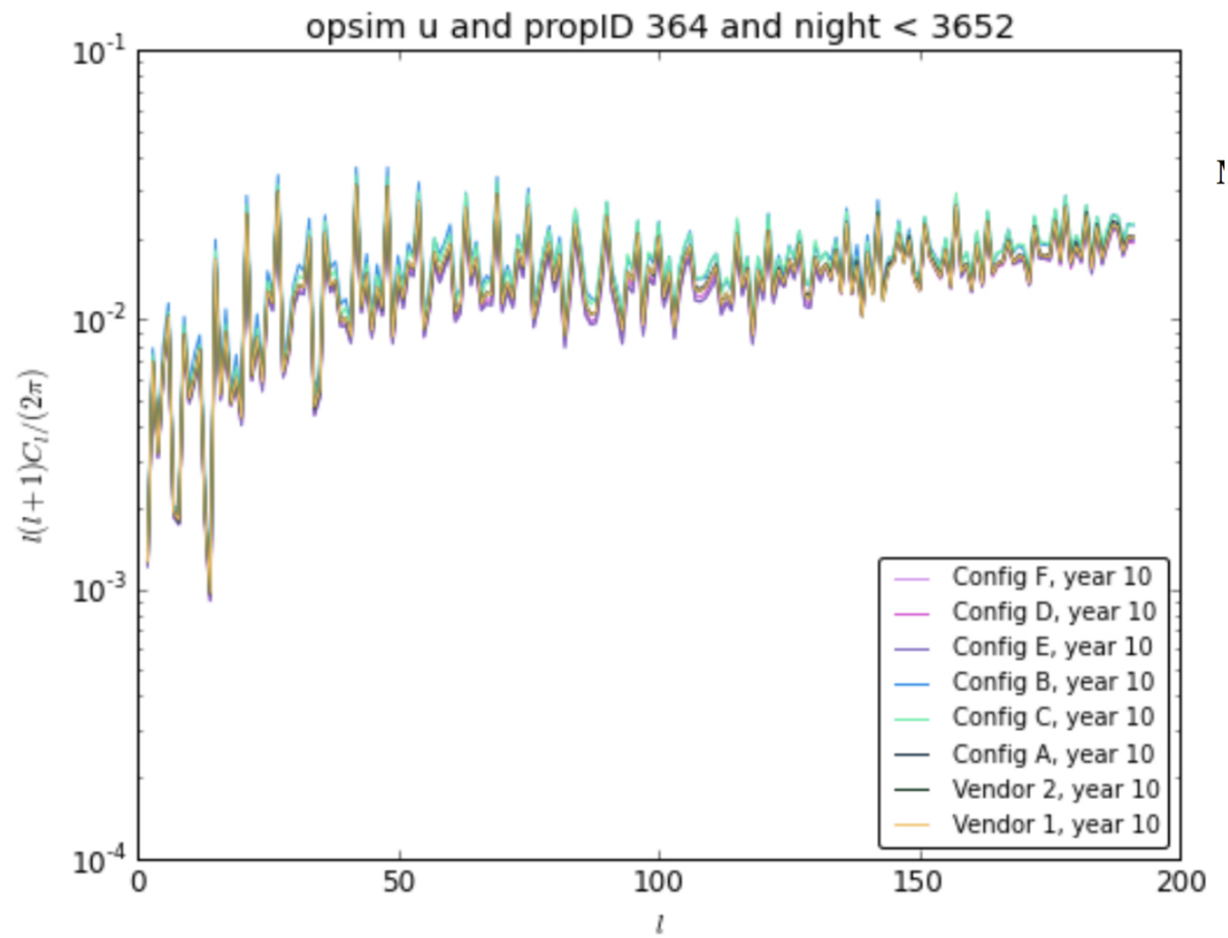

Figure 8: The angular power spectrum of u-band sky exposure for each of the mixed focal plane configurations after ten years. The impacts of the mixed focal plane are negligible.

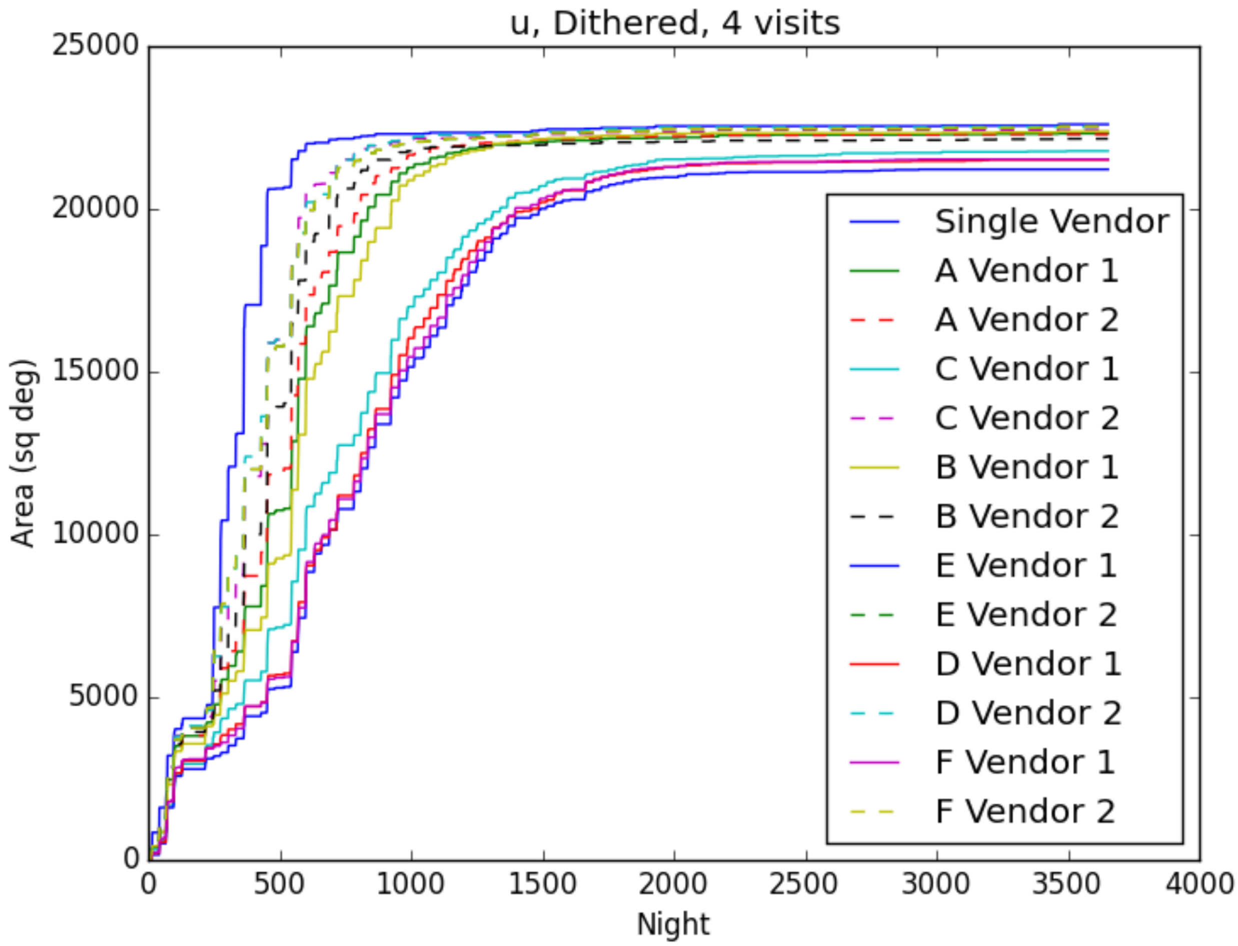

Figure 9: For each of the focal plane configurations in figure 4, the sky area with the fiducial value of at least 4 visits in a given sensor type. The curves for the different configurations should be compared with the single-vendor curve (solid blue line). Due to the slower template build up, data from the trailing two-year period, instead of the trailing one-year period, may be used.

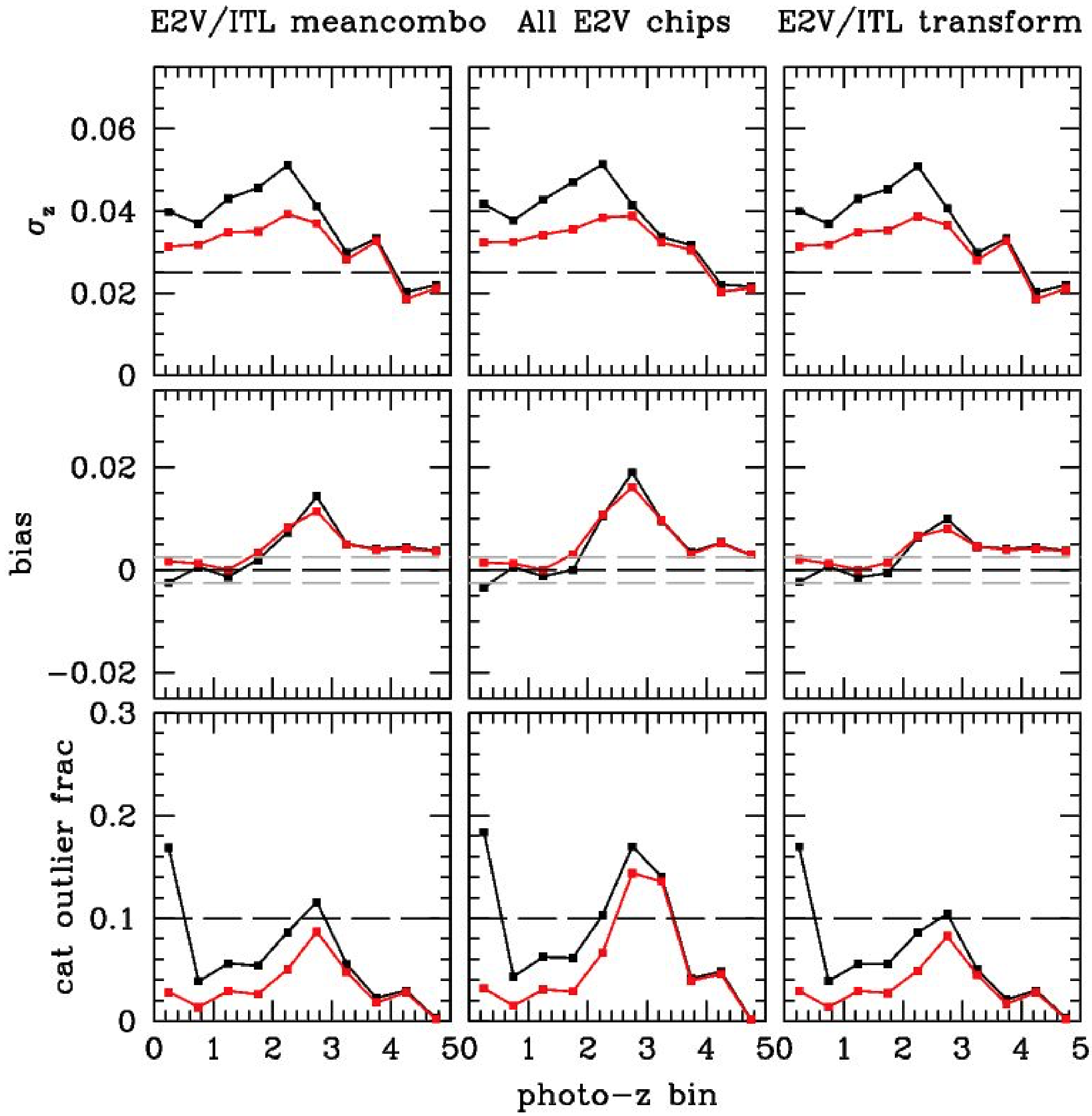

Figure 10: The mean photo-z scatter, bias, and catastrophic outlier fraction [5] for three of the scenarios described in the text: a 50-50 checkerboard mixed focal plane, a homogeneous focal plane composed of sensors with the lower u-band throughput, and a mixed focal plane after the analysis combining information from both types. The black curve represents the entire gold sample, while red represents a quality cut of ODDS > 0.65.

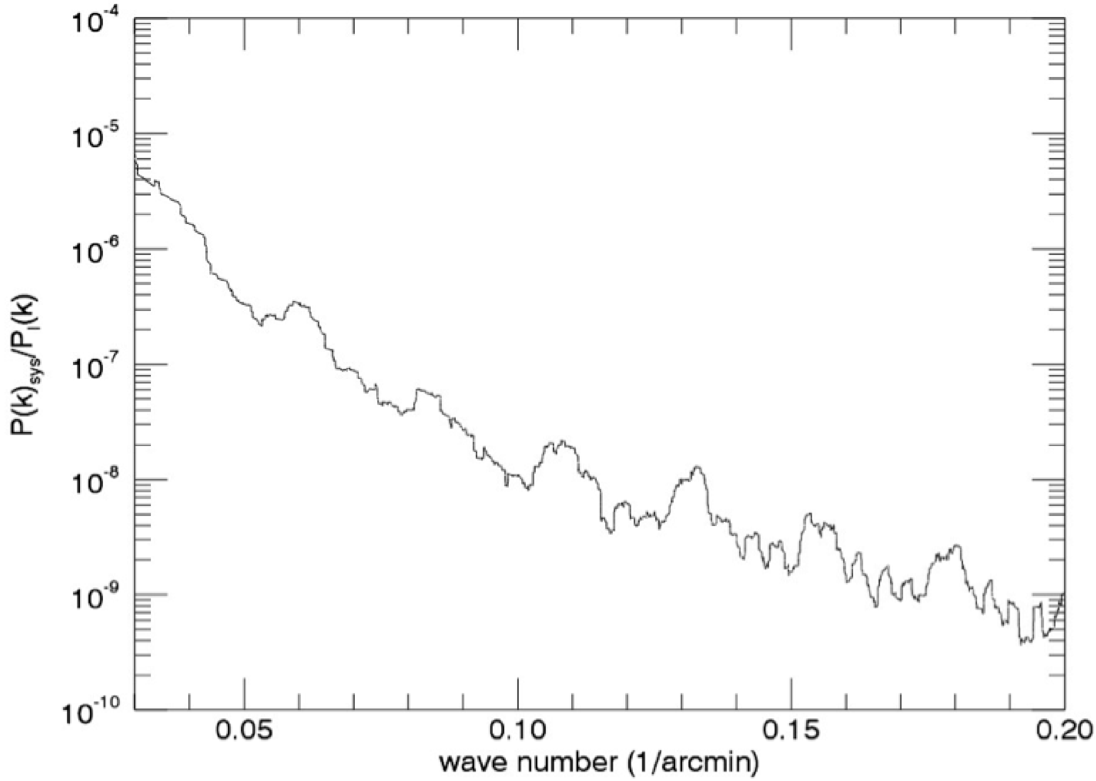

Figure 11: Residual shear power spectrum due to residual photo-z errors with the mixed focal plane and dithering scheme described in the text. The impacts are negligible: at 30 arcmin the induced fractional error is around 0.2% of the requirement (effectively 3.2×10^{-4} on this plot).