LSST Strong Lensing Science Collaboration response to the Survey Cadence Optimization Committee Call on Cadence

Timo Anguita[1,2], Aprajita Verma[3] and Thomas Collett[4] for the LSST Strong Lensing Science Collaboration

[1]*Departamento de Ciencias Fisicas, Universidad Andres Bello Fernandez Concha 700, Las Condes, Santiago, Chile.*
[2]*Millennium Institute of Astrophysics, Nuncio Monseñor Sotero Sanz 100, Of. 104, Providencia, Santiago, Chile.*
[3]*Sub-department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK.*
[4]*Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK.*

Abstract

Strong Lensing requires good seeing and depth in the gri-bands primarily over a wide area. Our key goals are (1) Wide area with reasonable sensitivity in all bands (2) Good (sub-arcsecond) image quality in general, but particularly in the blue (g-band) (3) Blue sensitivity. In particular, we advocate that g-band image quality should not be compromised in favor of higher image quality for the redder bands. Given these requirements we find that some of the filterdist and goodseeing simulations best match the requirements. These simulations are discussed in the cadence note as part of our answers to all of the LSST Survey Strategy questions.

1. Introduction:

This cadence note summarizes the thoughts and analyses of the Strong Lensing Science Collaboration (SLSC) regarding the questions posed about the LSST survey strategy.

Gravitational strong lenses have a broad range of cosmological and astrophysical applications, however, our ability to effectively utilize them is currently hampered by the small number of lenses known. Rubin's WFD survey with its combination of wide area, image quality, sensitivity and cadenced observations has the potential to revolutionize strong-lensing science in the 2020s by increasing the number of known strong lenses from order of hundreds to hundreds of thousands. Such statistically large samples will allow us to realize the huge promise of strong lenses to advance a broad range of fields, including the detailed mass distributions of lensing galaxies, groups and clusters; new regimes of sensitivity and resolution in high redshift lensed galaxies; testing detailed predictions of CDM on sub-galaxy scales, corresponding to the most likely failure modes of CDM and best constraints on WDM contributions; competitive constraints on cosmological parameters including H0 from lensed quasars and supernovae (e.g. Suyu et al. 2013) and w from double-source plane lenses (Collett & Auger 2014); and the discovery and study of optical counterparts to strongly-lensed gravitational waves (GWs; Smith et al. 2018a,b).

We expect to discover ~ 105 galaxy-scale lenses, ~ 104 strongly lensed quasars and ~ 500 lensed type Ia SN (Goldstein & Nugent 2017) of which 100s will be suitable for time-delay analysis, and 1000s of group- and cluster-scale lenses. Selecting complete and pure samples of strong lenses is not trivial, mainly owing to the large number of false positives that 'robots' (e.g. ArcFinder More et al. 2012 & RingFinder Gavazzi et al. 2014) and machine learning (ML) codes (e.g. deep convolutional or residual neural networks) currently deliver. Furthermore, none of the lens discovery methods are 100% complete and are generally optimized to probe different (but overlapping) parameter spaces (in terms of e.g. source brightness, lens redshift, lens mass, and Einstein radius). The SLSC and DESC-SLWG are working towards developing an efficient discovery system for all regimes of strong lensing (galaxy-, group and cluster-scale), incorporating catalogue and images based selection using robots, sophisticated CNNs and citizen powered visual inspection. However, there are observational considerations (e.g. seeing, depth/area, footprint) that would impact the numbers of lenses discovered in the WFD survey, and therefore impact the resultant science, that are mentioned in this response. We do not focus our analysis in specific night to night cadence but rather on the static "lens-discovery" parameters. We note that the impact of the observing strategy on cosmography from strongly lensed time delay sources have been summarized in the Lochner et al. (2021) and mentioned in the DESC cadence note - we do not repeat those findings here.

The predominant population of strongly lensed sources are drawn from the numerous star forming “faint blue galaxy” population dominating the faint end of the galaxy luminosity function. The predicted distribution of image separations based on simulated galaxy luminosity functions to LSST WFD depths show that the majority of lenses have Einstein radii 0.5” (Collett, 2015, Fig. 1) and the intrinsic (unlensed) magnitude of most sources is i ~ 27. DES chose to optimise observing strategies for weak lensing: prioritising good seeing time in r and i (Diehl et al. 2014). However, making the same choice for LSST would severely hamper the ability to identify strongly lensed galaxy candidates from the LSST data. The very blue nature of lensed sources means that **good r and i-band seeing is no substitute for good g-band seeing**. Our optimal observing strategy would allow for good median seeing in all three of the gri-bands, and we strongly prefer this over strategies preserving ri only.

Current OpSim observing strategies show that the median seeing is around ~1.0” in all gri-bands (See e.g. figure A.1). Forecasts using the code of Collett (2015), suggest that relaxing the g−band median seeing to 1.2” would lead to a significant loss of ~40% of galaxy-galaxy strong lenses while improving it to 0.9” would lead to ~15% more lenses found, rising to ~40% at median g-band seeing of 0.8”.

In general the requirements for strong lens discovery are:

- **Wide area with reasonable sensitivity in all bands** increases sample size, the larger the area the more lensed systems will be discovered
- **Good (sub-arcsecond) image quality in general, but particularly in the blue (g-band)** to discern faint blue lensed images from the bright red lensing galaxies, better Θ_E sampling, accurate image positions
- **Blue sensitivity** detect typically blue SFGs and probe lower down the luminosity function

2. Question 1: Footprint

Holding everything else constant, if we exchange 10% longer exposure time per unit area for 10% less total area means we will find 4% fewer lenses (based on the forecasting model of Collett 2015). Notably, in this scenario the discovered lenses are on average slightly fainter and so they are harder to study and follow-up. We therefore generally prefer extragalactic area over depth, but this effect is not a strong driver. Another driver for wider area would be increased overlap with Euclid, where the enhanced spatial resolution greatly benefits lens confirmation, modelling and deblending of source and lens light to improve photo-z estimates.

Crowded and/or high extinctinction fields are not useful for discovering lenses. As such, trading extragalactic depth for additional area within the galaxy is bad for strong lensing science.

3. Question 2: Additional Observing Time

As the area is one of the most, if not the most important parameter for strong lens discovery, assuming depth and image quality remaining constant, any increase in (low extinction) area would linearly increase the number of systems to be discovered. Our science goals would favour increasing the area of the WFD over other options allocating more time to the DDFs or mini-surveys. The specifics of image quality and depth for these larger area simulations are discussed in Question 4.

4. Question 3: U-Band Exposure Time

Since lensed sources are primarily blue star forming galaxies at z~3, g-band depth (with good seeing) is the primary driver for discovery. The deeper u-band data suggested is not deep enough to improve the discovery of LSST strong lenses. Losing ~0.1 mag of the g-band depth results in 5% fewer lens discoverable lenses.

However, lens discovery is challenging and the presence of detectable arcs does not guarantee we will find them with high completeness and purity. A photometric redshift for lens and source will be extremely helpful to convince ourselves that the blue ‘arc’ and the red ‘lens’ are at different redshifts and therefore will help to rank lens candidates selecting the best for follow-up.

Significant higher depth of the u-band observations could improve photometric redshift estimates. These are particularly important for low redshift early type lens galaxies at redshifts (4000 Å dropouts) as well as typical redshifts for the late type lensed sources (Ly break dropouts). However, given that the typical lensed source has g~23, the deeper u-band data suggested is unlikely to significantly help with source photometric redshifts as most sources will be at best marginally detected in u-band.

Overall, it is difficult to make a direct comparison between the loss of potential lenses against the benefit of more accurate photo-z's in ranking our strong lens candidates. Therefore, whilst the deeper u-band strategies are not catastrophic, strong lensing prefers the baseline allocation of u-band time.

5. Question 4: Filter Distribution

As mentioned in the introduction, even when good image quality across all bands is of major importance for identifying strong lens systems, due to the typical redshift and nature of lenses and sources, in particular the g-band image quality should not be compromised in favor of higher image quality for the redder bands. We have explored the median and best seeing images per band in each of the (~20000 sq. deg.) filterdist family opsim experiments given our general preference for a larger WFD area. As it can be seen in Figure 1, compared to the "baseline-like" filterdist_indx2 run, both median seeing and median "best epoch" seeing do not vary significantly within the family.

Final coadded depth over the whole survey, shown in Figure 2, does, however, show a significant difference when number of visits favor certain specific filters: up 0.35 and 0.5 magnitudes deeper coadds in the g and u-bands for g and u heavy distributions, respectively (see Figure 2). We thus propose a compromise with minimal impact in the number of visits and depth of the redder (r, i, y and z) bands (~10% less visits in them and slight depth difference compared to the "baseline-like" filterdist_indx2 run)[1] but a >0.1 deeper coadd in g and u by favoring the "blue skewed" filterdist_indx7 simulated run.

In Verma et al. (2019), we proposed an early "all sky reference image": This would ensure that all the available extragalactic sky observed in at least g, r and i-bands with excellent seeing to single visit depth at the beginning of the survey operations. This would be very powerful for a broad range of transient and non-transient science, including discovery of strong gravitational lenses, because single visit g, r and i-band depth is sufficient for discovery of the brightest strongly lensed sources. Knowing the location of all the bright lensed sources early on in the WFD survey will allow us to identify lensed supernovae and other transients faster, enabling time-critical follow-up to be triggered. Discovery of lensed kilonovae/NS-NS as described in the white paper by Smith et al. (2019) also benefits from single-visit depth early reference imaging.

As such, we have explored the filterdist family with this in mind: conservatively assuming that the whole footprint will be at least observed once in all bands within the first year[2], we have explored the median per visit and median best epoch seeing during the first year of operations. As with the full 10 year survey, no significant difference can be observed (see Figure 3).

Nonetheless, if the final strategy does not follow a "large area" footprint like the filterdist family, a significant improvement in the median best epoch seeing during the first year of operations can be seen in the goodseeing family when compared to baseline_v1.5. The improvement amounts to >10% better seeing in the g-band in some of the experiments (see Figure 4). This comes at the cost of image quality in the y-band data but only marginal depth trade off. As such, assuming a baseline_v1.5 survey footprint we would suggest following something along the lines of the goodseeing_gi and goodseeing_gri simulated strategies only for the first year of the survey to obtain an early reference survey with exceptional image quality to search for the brightest strong lenses with minimal impact on the image quality in the z-band in the long run. A similar good seeing early reference survey is also supported by the Galaxies SC, as described in their cadence note (Ferguson et al.).

---

[1] https://github.com/lsst-pst/survey_strategy/blob/master/fbs_1.7/SummaryInfo.ipynb

[2] Driven by the available sky and completed at around 9 months for most opsim experiments, Lynne Jones, private communication

6. Question 5: Visit Pairs and Triplets

While there is not any direct impact for non-variable/static lenses, there is an important effect for lensed SNe where colors can provide information on microlensing and lightcurve fitting (colors are particularly important for SN Ias where the evolution is well understood). This has also been mentioned in the DESC observing strategy paper (Lochner et al. 2021) and accompanying cadence note. However, we have not done a benefit analysis taking account of the increased overheads arising from filter changes.

7. Question 6: Rolling Cadence, Season Length and Altsched

Even though the present cadence note focuses on static science and thus quite agnostic on nightly cadence but rather cumulative results, we again refer to the DESC observing strategy paper (Lochner et al. 2021) and accompanying cadence note for specifics. We would like to note, anyway, that the number of identifiable lensed transients have shown a strong correlation with season length. As such, extreme rolling cadences that result in shorter than baseline season lengths would limit these science cases. Furthermore, as shown by Neira et al 2020, identifying high quasar microlensing events in lensed quasars benefits from uniform cadences.

8. Question 7: Dithering

The dithering strategy is of minimal importance to static strong lensing in the WFD survey, save that it should not compromise the image quality of the reduced images.

9. References

Collett & Auger, 2014, MNRAS, 443, 969
Collett 2015, ApJ, 811, 20
Diehl et al., 2014, Proc. SPIE, 9149, 91490V
Gavazzi et al., 2014, ApJ, 785, 144
Goldstein & Nugent, 2017, ApJ, 834, L5
Lochner et al. 2021, arXiv: 2104.05676
More et al., 2012, ApJ, 749, 38
Neira et al. 2020, MNRAS, 495, 544
Smith G. P., Jauzac M., et al., 2018a, MNRAS, 475, 3823
Smith G. P., Bianconi M., et al. 2018b, arXiv:1805.07370
Smith et al. 2019, arXiv: 1902.05140
Suyu et al., 2013, ApJ, 766, 70
Verma et al. 2019, arXiv: 1902.05141

10. Figures

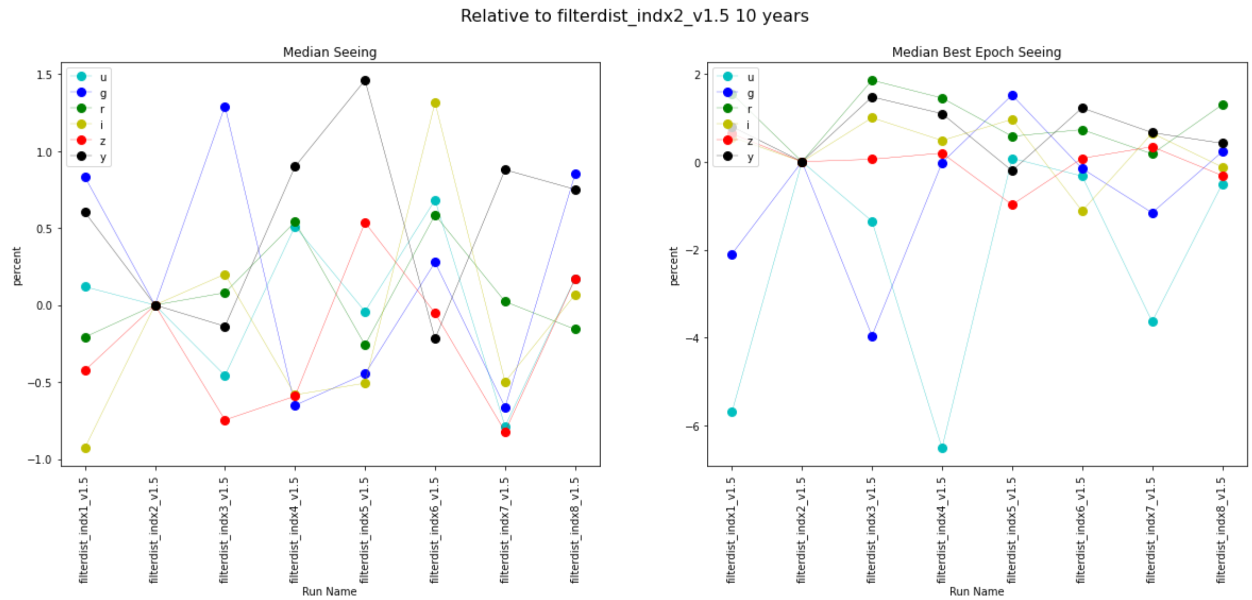

Figure 1. *filterdist* family performance of seeing metrics relative to the “baseline-like” *filterdist_indx2* considering the 10 year long survey. Left: relative median (per visit) seeing. Right: median best epoch (visit) seeing.

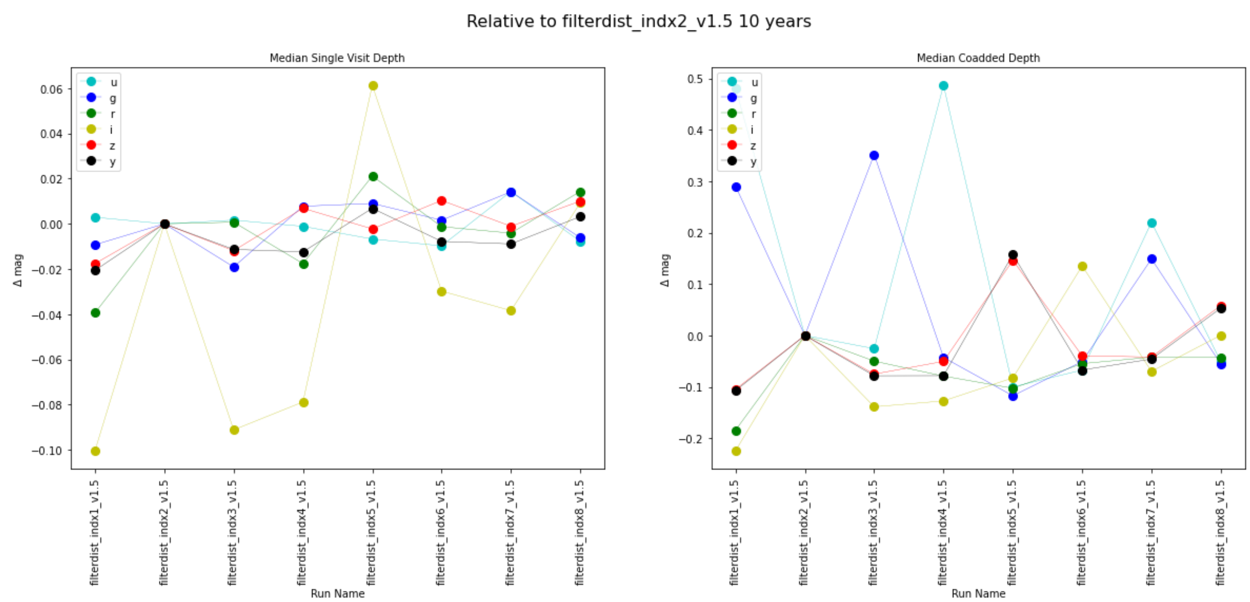

Figure 2. *filterdist* family performance of depth metrics relative to the “baseline-like” *filterdist_indx2* considering the 10 year long survey.

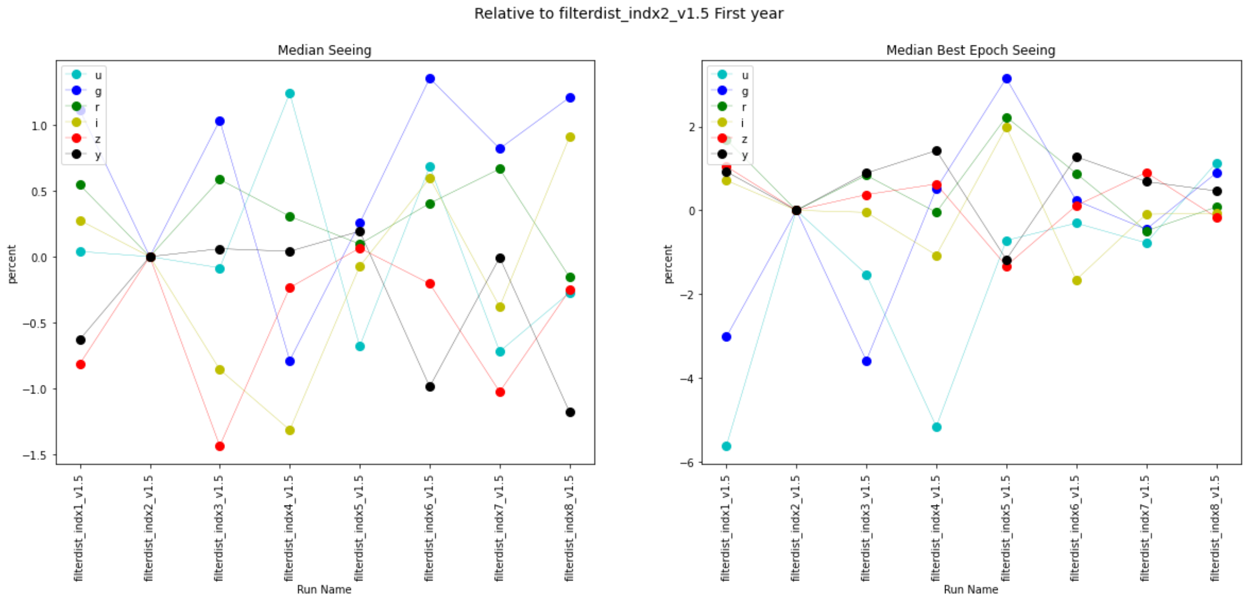

Figure 3. *filterdist* family performance of seeing metrics relative to the "baseline-like" *filterdist_indx2* considering just the first year of the survey. Left: median (per visit) seeing. Right: median best epoch (visit) seeing or best single depth early reference.

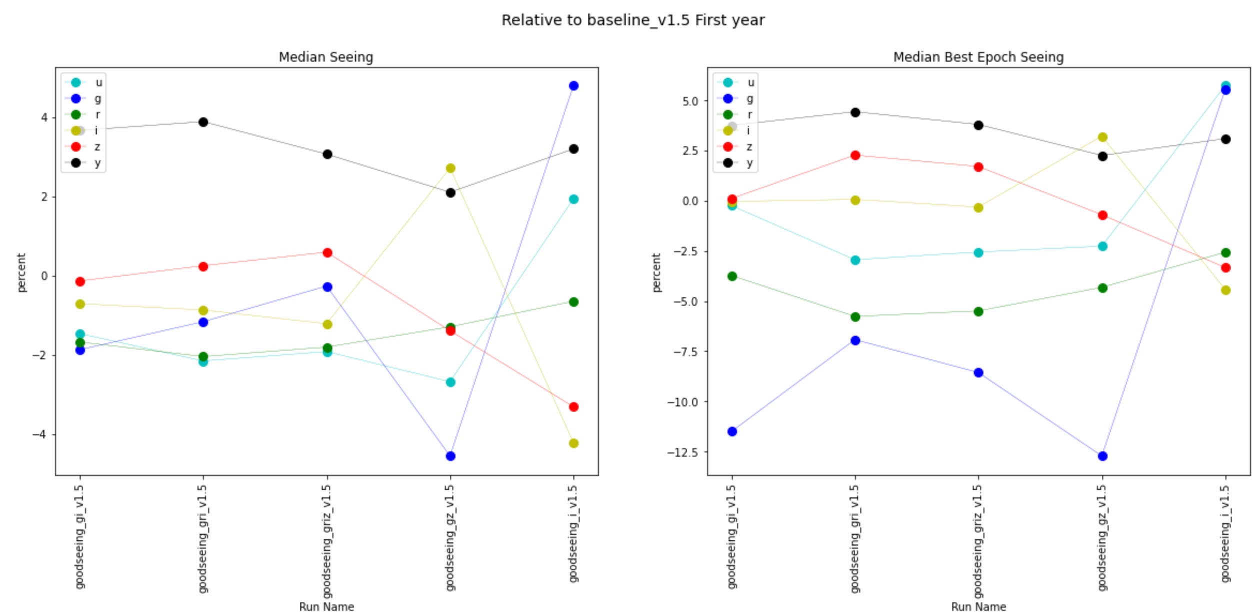

Figure 4. *goodseeing* family performance of depth metrics relative to the *baseline_v1.5* considering the first year of the survey.

11. Appendix

In order to give context to the relative values presented in the figures and the text shown in our answer to question 4, the following figures show the absolute performance of the metrics used for the selected opsim experiments.

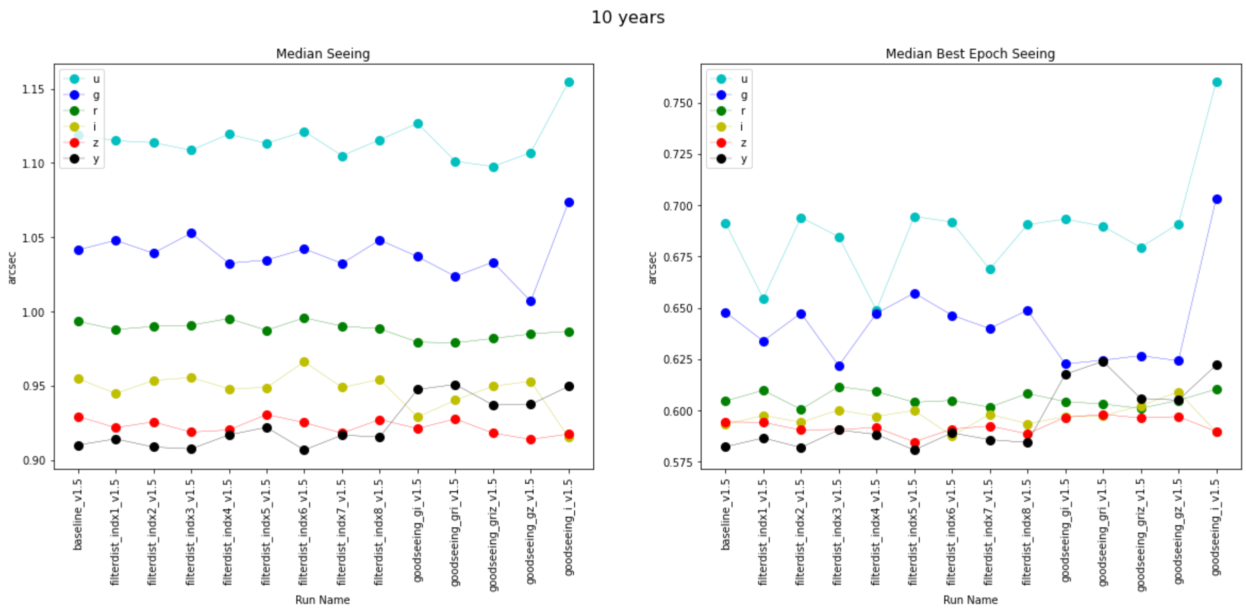

Figure A.1. Absolute performance of seeing metrics for the full 10 year survey. Left panel shows the median (per visit) seeing. Right panel shows the median best epoch (visit) seeing.

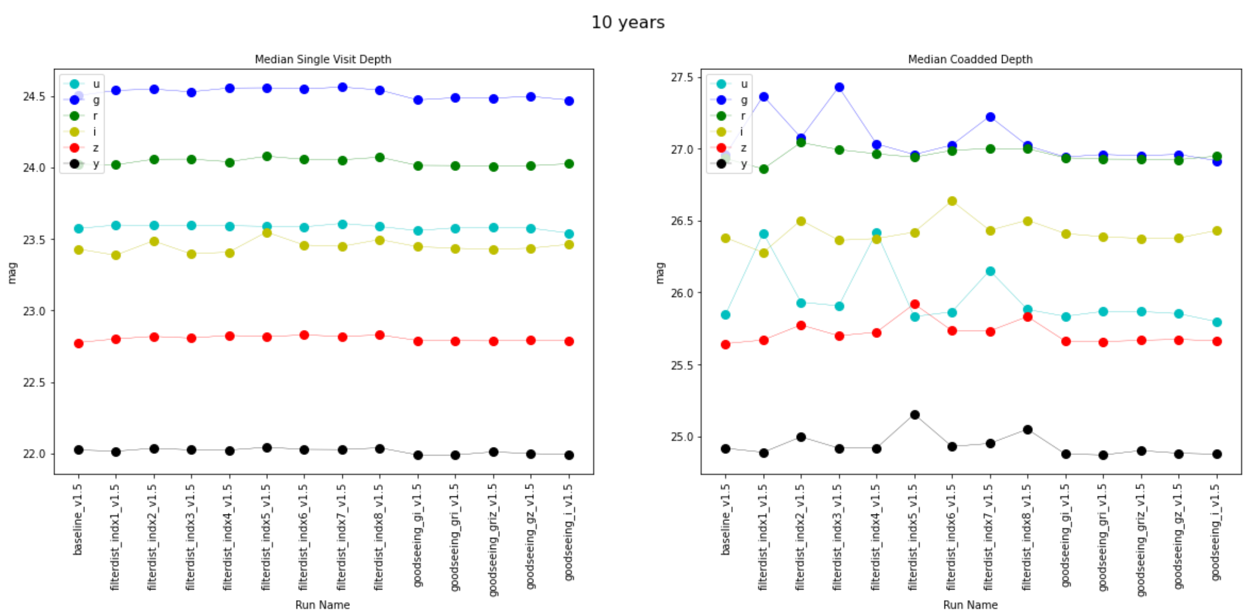

Figure A.2. Absolute performance of depth metrics for the full 10 year survey. Left panel shows the median single visit depth. Right panel shows the median coadded depth

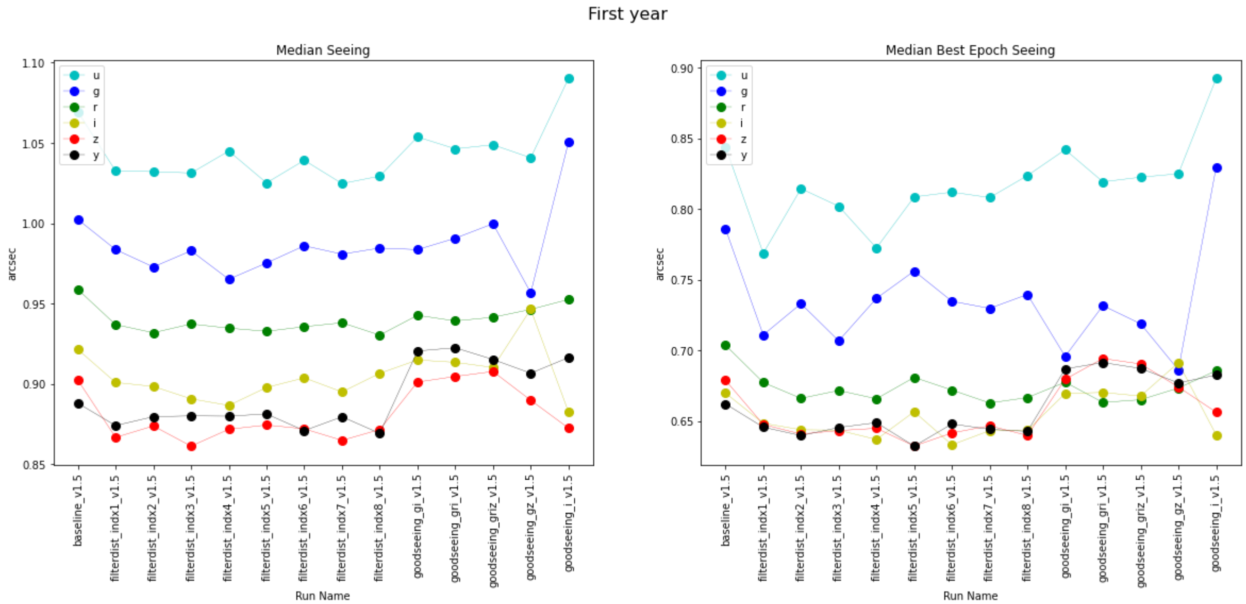

Figure A.3. Absolute performance of seeing metrics for the first year of survey. Left panel shows the median (per visit) seeing. Right panel shows the median best epoch (visit) seeing.