LSST AGN SC Cadence Note: Type-1 Quasar Colors in the Context of Photometric Redshifts

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1. EXECUTIVE SUMMARY

We have developed two metrics to evaluate the 10yr co-added depths expected for each band in the context of photometric redshifts for type-1 quasars as function of OpSim runs from FBS 1.5, 1.6 and 1.7. Each metric focuses on a different aspect. The first one focuses exclusively on the depth expected for u-band with the aim of detecting the SED break short of Lyα. The second one compares the depths of contiguous bands in wavelength to the expected colors of type-1 quasars. In both cases, while we find that some OpSim runs perform better than others, we do not find any of them to be critically detrimental for type-1 quasar photometric redshifts in the context of these metrics, although we remark on the usefulness of having as deep u-band coverage as possible.

2. THE METRICS

Below we discuss the two metrics we developed to assess the performance of the different OpSim runs in the context of photometric redshifts for type-1 quasars when considering the respective 10 yr coadded depths. We note that for type-2 quasars and for low-luminosity AGN the UV/optical colors are mostly dominated by the host-galaxy, so the problem of photometric redshifts reduces to that of regular galaxies, which is already being addressed in depth by DESC.

2.1. *u-band Depth*

The strongest feature in type-1 AGN UV-through-NIR broad-band SEDs is the strong deficit of light shortward of Lyman-α at 1216Å, produced by a combination of neutral hydrogen absorption in the intervening IGM and the Lyman break at 912Å. Given the lack of other strong broad-band features due to their power-law SEDs, detection of this feature can greatly increase the accuracy of photometric redshifts. In the redshift range $1.7 \lesssim z \lesssim 3.0$, this feature will produce a noticeable break in the LSST broad-band SED between the u and g bands, shifting into redder band combinations at higher redshifts. The redshift range $1.7 \lesssim z \lesssim 3.0$ encompasses the period of cosmic time when quasar activity peaks (e.g., see Assef et al. 2011, and references therein), highlighting how important it is for quasar science.

We consider that a constraining detection of the break should be at least at the 3σ level. Assuming that all objects will be detected at a much higher SNR in g than in u, we can approximate that constraining detections of the break can be achieved for objects as faint as those that have a 3σ detections in the u-band. Hence, we can quickly discriminate between OpSim runs simply by looking at the distribution of their 3σ u-band depths. We estimate the latter by first estimating the 5σ depths for u-band using the `ExgalM5` MAF metric, slightly modified to avoid regions with foreground reddening $E(B-V) > 1$ mag, which are not ideal for extragalactic observations and could bias our results. We then convert these 5σ depths to 3σ depths by assuming Gaussian statistics. This last step does not affect the ranking of the OpSim runs, but it is useful for interpreting the expected depths.

2.2. *Color Excess*

Type-1 quasars typically have power-law SEDs that lack strong features in their broad-band SEDs that permit to anchor their photometric redshifts with ease, with the exception of the break short of Lyman α (see §2.1). Most of the photometric information will come from deviations to the power-law SED shapes caused by their broad, high-equivalent-width emission lines. Estimating the total effects of a given OpSim run on the accuracy of type-1 quasar photometric redshifts would be very costly, as the accuracy will not only depend on the depth of the observations, but also on redshift and the emission line properties. Instead, however, we can express as a general rule that depths between bands that are in the same ratio as typical type-1 quasar fluxes will tend to produce better photometric redshifts. Specifically, we defined the color excess index between bands a and b as

$$C_{\rm Ex}^{ab} = \left[m_a^{5\sigma} - m_b^{5\sigma}\right] - \left[m_a^{\rm qso} - m_b^{\rm qso}\right], \quad (1)$$

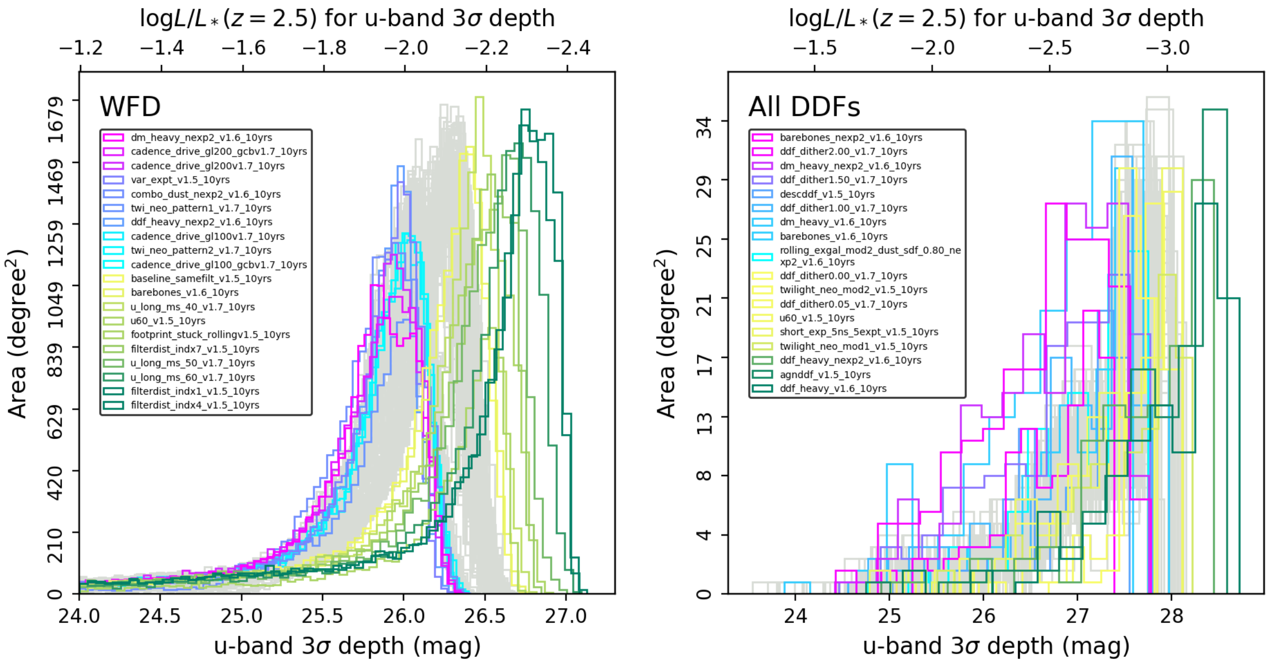

Figure 1. Expected 3σ u-band depths expected for all 190 OpSim runs in FBS 1.5, 1.6 and 1.7 for the WFD (*left*) and for the combination of all DDFs (*right*). The color-coded OpSim runs correspond to the top and bottom 5% ones when ranked by their median depth. The rest are shown in light gray. The top axis shows the luminosity reached as a fraction of $L*$, assuming the QLF of Shen et al. (2020, model A) and the quasar composite template of Vanden Berk et al. (2001)

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such that a value of $C_{\rm Ex}^{ab}$ closer to 0 means that the 5σ depths of the bands are in the same ratio as the expected colors of a type 1 QSO at a given redshift. We consider only pairs of contiguous bands in wavelength, as they are the most sensitive to the SED features. The "true" quasar colors in the LSST bands as a function of redshift are taken from the empirical models of Temple et al. (in prep.). We assume the colors of $m_i = 24.5$ quasars according to the models of Temple et al. (in prep.), but note that the changes with i-band magnitude are subtle, particularly given the broad strokes of our analysis. As before, we estimate the 5σ depths by using the `ExgalM5` MAF metric and avoiding regions with foreground reddening $E(B-V) > 1.0$ mag.

3. ANALYSIS OF RESULTS

The left panel of Figure 1 shows the distribution of u-band depths of the different OpSim runs. We remind the reader that deeper u-band limiting magnitudes are better in the context of this metric. The Figure shows that a handful of OpSim runs reach significantly deeper $u-$band magnitudes, and a handful have broad shoulders towards shallower depths, while the great majority result in broadly similar depths. The shallowest OpSim run has a median depth that is only 0.27 mag brighter than the $50^{\rm th}$ percentile one, suggesting that the worst case scenario would not be critically detrimental for this metric. We find the same qualitative result if we include the non-DDF mini-surveys (i.e., GP, NES and SCP) in addition to the WFD. The best performing OpSim runs are the `filterdist_indx4` and `filterdist_indx1`, which respectively correspond to the "u heavy" and "Uniform" strategies of the `filterdist` family, which is aimed at improving photometric redshifts. Additionally, the `u_long` and `u60` families perform well too, as would be expected. The worst performing OpSim runs correspond to those that sacrifice u-band depth due to increased airmass coverage (`dm_heavy`), increased g-band cadence (`cadence_drive`), uniform depth (`var_expt`), increased coverage of dusty regions (`combo_dust`), twilight WFD observations (`twi_neo_pattern`) and improved DDF coverage (`ddf_heavy`).

The right panel of Figure 1 shows the same but for the combination of all DDFs. The worst performing OpSim runs have median depths about 0.6 mag shallower than the typical OpSim run, which is considerably worse than in the WFD case. It is noteworthy that *among the DDF specific OpSims, that designed for AGN science,* `agnddf_v1.5_10yrs`*, is*

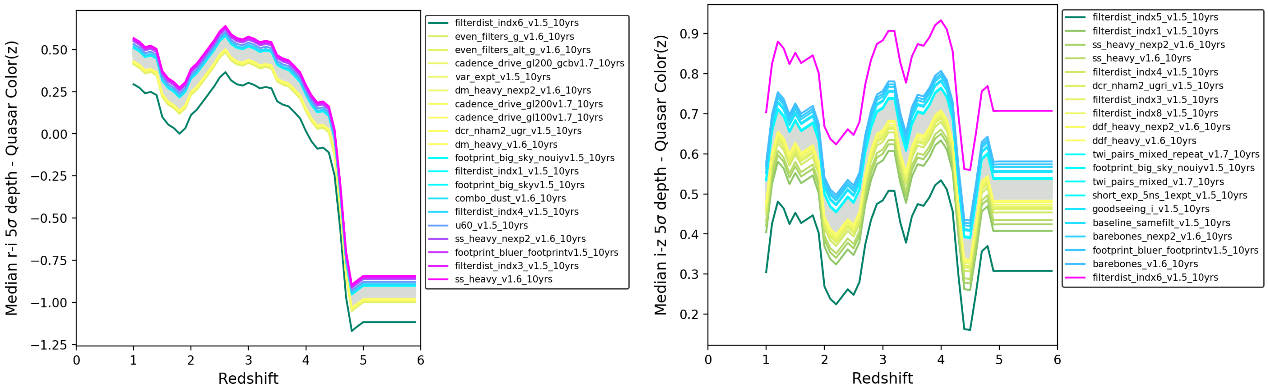

Figure 2. Color excess in r–i (*left*) and i–z (*right*) for all 190 OpSim runs in FBS 1.5, 1.6 and 1.7 for the WFD. The color-coded OpSim runs correspond to the top and bottom 5% ones when ranked by their median color excess. The rest are shown in light gray. We remind the reader that better performing OpSim runs have color excesses closer to 0 for a given band combination.

ranked second best, while the `descddf_v1.5_10yrs` *one is among the worst ranked in this metric.* Only one of the OpSim runs, however, `dm_heavy_nexp2_v1.6_10yrs`, under-performs considerably in both the DDF and WFD surveys. This OpSim, however, may prove useful for modeling the DCR properly, and thus may have complementary merits for type-1 quasar photometric redshifts that balance out its perceived faults. In general, as in the WFD survey, we can conclude that no OpSim run considered in FBS 1.5–1.7 would be critically detrimental for AGN photometric redshifts in the context of their achieved $u-$band depths in the DDFs.

Figure 2 shows, as an example, the r–i and i–z color excesses as a function of redshift for all OpSim runs. We select three very broadly typical redshifts, 1.0, 2.0 and 3.0, on which to slice these color excesses and get a more detailed analysis of them. For each redshift range, we rank the OpSim runs with their absolute combined color excess, $\Sigma_{\rm Ex}$, defined as the sum of the absolute values of the color excesses found in u–g, g–r, r–i, i–z and z–y. The u–g color excess is usually the largest contributor to $\Sigma_{\rm Ex}$. For all three redshift ranges we find that the 50$^{\rm th}$ percentile OpSim run corresponds to an OpSim run of the `rolling_cadence` family. While there is a significant variation between the color excess of different contiguous band combinations, the combined deviation seems to have a fairly narrow range. This narrow range indicates that while different OpSim runs could have significantly different effects at different redshifts, no OpSim run is clearly favored nor clearly detrimental for broad population studies.

4. ANSWERS TO QUESTIONS

> Q1: Are there any science drivers that would strongly argue for, or against, increasing the WFD footprint from 18,000 sq. deg. to 20,000 sq.deg.? Note that the resulting number of visits per pointing would drop by about 10%. If available, please mention specific simulated cadences, and specific metrics, that support your answer.

We do not see that the larger area OpSim runs ($\gtrsim$20,000 deg^2) perform significantly better or worse than the typical OpSim run in either metric.

> Q2: Assuming that current system performance estimates will hold up, we plan to utilize the additional observing time (which may be as much as 10% of the survey observing time) for visits for the mini-surveys and the DDFs (with an implicit assumption that the main WFD survey meeting SRD requirements will always be the first priority). What is the best scientific use of this time? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

It is generally preferable from the point of view of quasar photomeric redshifts to devote the extra time to observe the DDFs. The DDFs, due to the large number of additional multi-wavelength and spectroscopic observations, are fundamental for calibrating the numerical techniques we will need to use in the WFD. Furthermore, as shown in Fig. 1, the DDFs will reach much fainter than the WFD, which is ideal for a calibration sample.

> Q3: Are there any science drivers that would strongly argue for, or against, the proposal to change the u band exposure from 2x15 sec to 1x50 sec? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

As seen in the results above, those simulations in which there is a longer u-band exposure can be beneficial for type-1 quasar photometric redshifts in the range $1.7 \lesssim z \lesssim 3.0$. In particular, the `u_long_ms` family of OpSims performs very well in the u-band depth metric, unsurprisingly, but also does not cause a poor performance in the color-excess metric at any of the redshifts studied.

Q4: Are there any science drivers that would strongly argue for, or against, further changes in observing time allocation per band (e.g., skewed much more towards the blue or the red side of the spectrum)? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Our color-excess metric shows that none of the OpSim runs are heavily favored nor disfavored, implying that the science case presented here does not strongly argue for changes in the time allocation per band.

Q5: Are there any science drivers that would strongly argue for, or against, obtained two visits in a pair in the same (or different) filter? Or the benefits or drawbacks of dedicating a portion of each night to obtaining a third (triplet) visit? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Not applicable here, but see our cadence note on the effects of variability in quasar photometric redshifts by Assef et al.

Q6: Are there any science drivers that would strongly argue for, or against, the rolling cadence scenario? Or for or against varying the season length? Or for or against the AltSched N/S nightly pattern of visits? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Not in the context of the metrics tested here.

Q7: Are there any science drivers pushing for or against particular dithering patterns (either rotational dithers or translational dithers?) If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Not in the context of the metrics tested here.

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