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Deliverable 3.7.1: Report on optimal metrics for measuring the impact of the LSST pipeline sky subtraction on low-surface-brightness flux at different spatial scales

WP 3.7: Low-surface-brightness science using the LSST

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Author(s) inc. institutional affiliation	Aaron Watkins (LJMU) Chris Collins (LJMU) Sugata Kaviraj (Hertfordshire)
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1 Executive Summary

To expand LSST's scientific reach into the low surface brightness (LSB) regime, where nearly all of its extragalactic discovery space lies, an accurate sky subtraction is paramount. The current LSST pipeline sky subtraction routine must therefore be optimized for LSB work. The first step in this optimization is to test the current implementation and determine how much improvement is required for LSB work to proceed. This requires the development of metrics for measuring the over-subtraction currently induced by the sky subtraction.

We have devised such a metric using model galaxy injections: the difference in model magnitudes pre- and post-sky subtraction, or Δm. Using this metric, we have tested both the final, local sky subtraction done at the deep coadd level, as well as the full focal plane sky subtraction done to remove night sky emission. While both show systematic over-subtraction below μ_λ~26 mag/arcsec^2, the final local sky subtraction's effect is significantly worse, and also shows a trend with model size for high surface brightness models that is absent from the full focal plane sky subtraction. Though these tests only established a baseline, it is already apparent that the final sky subtraction step makes LSB work infeasible with LSST, and even heavily impacts high surface brightness objects with scales larger than 10". In future work, we will expand the parameter space to include more realistic galaxy profiles to determine the full scope of the problem, and then begin devising mitigation strategies.

2 Introduction

Our statistical understanding of how the Universe evolves is strongly determined by the objects and structures that are brighter than the surface-brightness limits of wide-area surveys. While huge strides have been made in comprehending galaxy evolution over the last few decades, using surveys like the SDSS, our understanding is naturally constrained by aspects of the Universe that are actually observable in such datasets. For example, the completeness of galaxies in surveys like the SDSS decreases rapidly for surface brightnesses fainter than ~24.5 mag arcsec^{-2} (e.g. [5]). However, the low-surface-brightness (LSB) regime, defined as the domain that is invisible in past wide-area surveys, contains a wealth of information that is essential for understanding how the observable Universe evolves over cosmic time.

First, both theory [6] and observation [3] indicate that the bulk of the galaxy population actually resides in the LSB regime. For example, ~50 (85) per cent of galaxies down to 10^8 (10^7) M_* inhabit this regime (see Table 2 in [6]). Second, there are key LSB components around high-surface-brightness galaxies that offer fundamental constraints on the evolution of the observable Universe. Two examples are merger-induced LSB tidal features, galactic stellar haloes, and intra-cluster or intra-group light (ICL, IGL). Tidal features encode the assembly histories of galaxies and constrain our structure-formation model. However, the surface-brightness of tidal features is a strong function of merger mass ratio. Given that low-mass galaxies far outnumber their massive counterparts, most mergers involve low mass ratios (i.e. are 'minor' mergers), which produce faint tidal features that are largely undetectable in past wide-area surveys (e.g. [4]). Nevertheless, both theory and observation suggest that minor mergers are key drivers of galaxy evolution, making the analysis of LSB tidal features an essential component of our galaxy-evolution effort. In a similar vein, ICL is a significant component of galaxy clusters, which are important tests of our cosmological model. Since the ICL contributes anything up to 40% of the baryonic mass budget of clusters at low redshift, a larger fraction than the contribution from the central brightest cluster galaxies in many cases [2], the utility of clusters as cosmological probes is closely linked to our ability to detect and characterize the diffuse ICL over cosmic time.

Under ideal conditions, LSST is capable of reaching depths fainter than $\mu_\lambda \approx 31$ mag arcsec^{-2} over around 20,000 square degrees. *The LSB Universe thus represents virtually all the extra-galactic discovery space of this transformational survey.* However, LSB structures are acutely sensitive to sky over-subtraction. Preservation of LSB flux in LSST images is, therefore, a key requirement of the data-processing pipeline, without which LSST will not be capable of providing access to this revolutionary regime.

2.1 Purpose

The purpose of this project is to: (1) define metrics which probe how the Rubin data management (DM) pipeline treats LSB flux and quantify the level of sky over-subtraction (2) develop strategies to use the DM architecture itself to improve the preservation of LSB flux and (3) develop bespoke algorithms that maximise LSB preservation in the DM pipeline where needed. This report focusses on the metrics that quantify the preservation of LSB flux in the DM pipeline. Throughout this project we have worked closely with the DM pipeline team in Princeton: Lee Kelvin, Yusra Al-Sayyad, Robert Lupton, and Sophie Reed.

2.2 Glossary of Acronyms

DM: data management

HSC: Hyper Suprime-Cam

ICL: intracluster light

IGL: intragroup light

LSB: low surface brightness

HSB: high surface brightness

3 Methodology

To measure the impact of the current pipeline's sky subtraction algorithm, we devised metrics that employ simple, single Sérsic component model galaxy injections. The reason for this is two-fold: (1) using simple models, with easily measurable parameters (total magnitude, effective radius, and central surface brightness) makes for a convenient ground-truth, and (2) we must rely on the DM team's source injection software, which initially was only able to inject Sérsic models into the HSC pipeline.

First, we provide here a brief overview of the different sky subtraction routines that we tested. The current iteration of the LSST data-reduction pipeline does two different kinds of sky subtraction: a full-focal-plane subtraction using interpolation across a low resolution mesh to remove night-sky emission and correct for filter transmittance variations across the field of view, as well as variations in pixel-level response across CCDs [1]; and a very localized second sky subtraction taking place on the co-adds using a 128x128 pixel mesh, tuned to flatten the background around bright sources to aid in de-blending for weak-lensing science (a version of this is to be implemented in the third public data release). For the first round of testing, the injections were done at the level of the deep co-add, just prior to the small-mesh sky subtraction. In the second round of testing, the models were injected much earlier in the pipeline, post-instrumental signature removal but prior to the full-focal-plane sky subtraction.

We injected the same set of models to test both sky subtraction procedures, built to explicitly measure the impact of each as a function of surface brightness, size, and on-sky separation. These consisted of three grids of flat (Sérsic index n=0.3, the lowest allowed by the injection code) and face-on (circular) single-component galaxies. These grids are as follows:

- 36 model galaxies with effective radii of 50 pixels (~8.5" at the HSC pixel scale), separated by 250 pixels, with varying central surface brightness (μ_0 = 16—28 mag/arcsec^2, an identical range across photometric bands).
- 36 model galaxies with identical central surface brightness (μ_0 = 21 mag/arcsec^2), separated by 1000 pixels, with varying effective radii (4 pixels – 100 pixels, or 0.7"—16.8").
- 36 pairs of identical model galaxies (effective radius 8.5", μ_0 = 21 mag/arcsec^2) separated by varying factors of effective radius (0.3R_{eff}—11R_{eff}, or ~2.6"—93.5").

In both injections, the models' coordinates were the same, hence the impact of any interloping astrophysical objects was controlled for between runs.

To avoid ambiguity, we measured the resulting models ourselves directly from the images. Each model can be isolated by subtracting the image without the model (from a previous reduction) from the image containing the model. Likewise, both the model and the sky subtraction can be obtained by subtracting the image without the model, pre-sky-subtraction, from the image containing the model, post-sky-subtraction. We then perform surface photometry on both the pre- and post-sky-subtraction models in order to compare the total magnitude of each with the input catalogue magnitudes. The difference in magnitudes between those measured via surface photometry and the input catalogue values, which we call simply Δm, is our primary metric for measuring the amount of over-subtraction.

4 Results

Here we provide plots detailing the impact of both kinds of sky subtraction on object surface brightness, size, and separation, and discuss how we use these kinds of plots to provide useful metrics to the DM team.

4.1 First injections, small-mesh sky subtraction

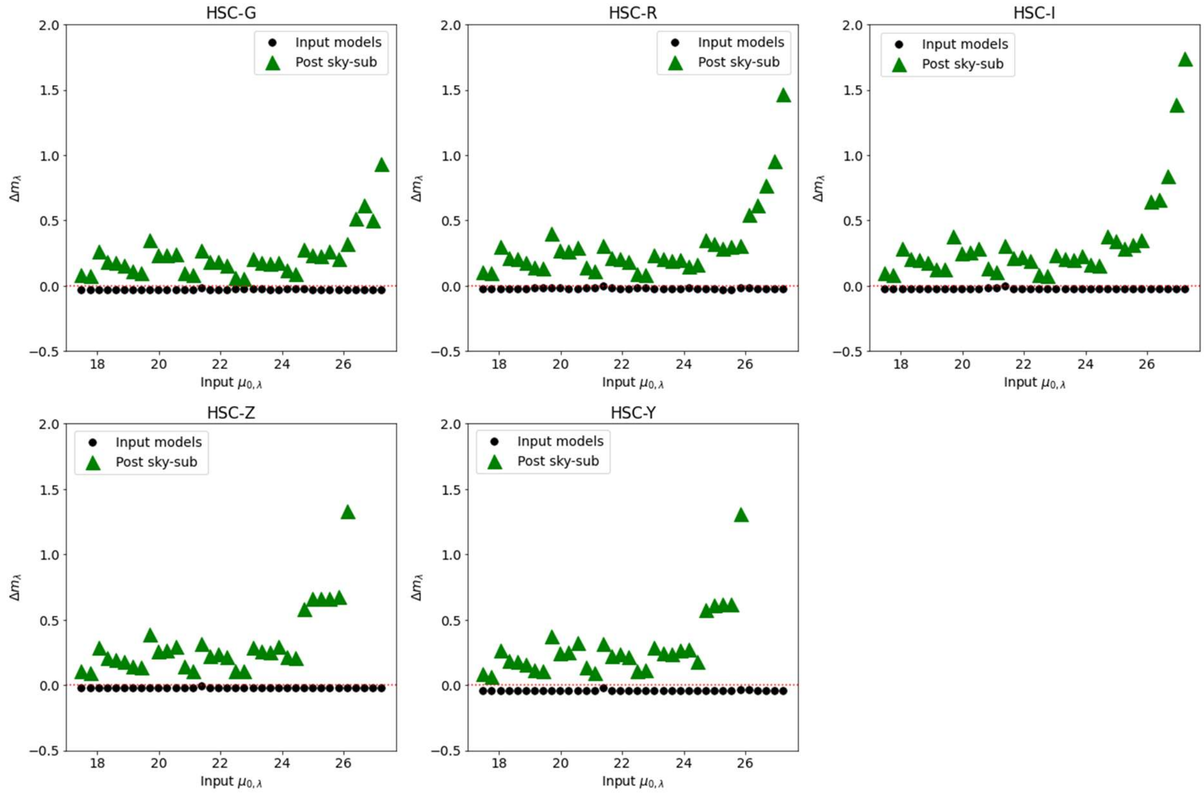

Figure 1 Surface brightness vs. magnitude deficit 1st injections

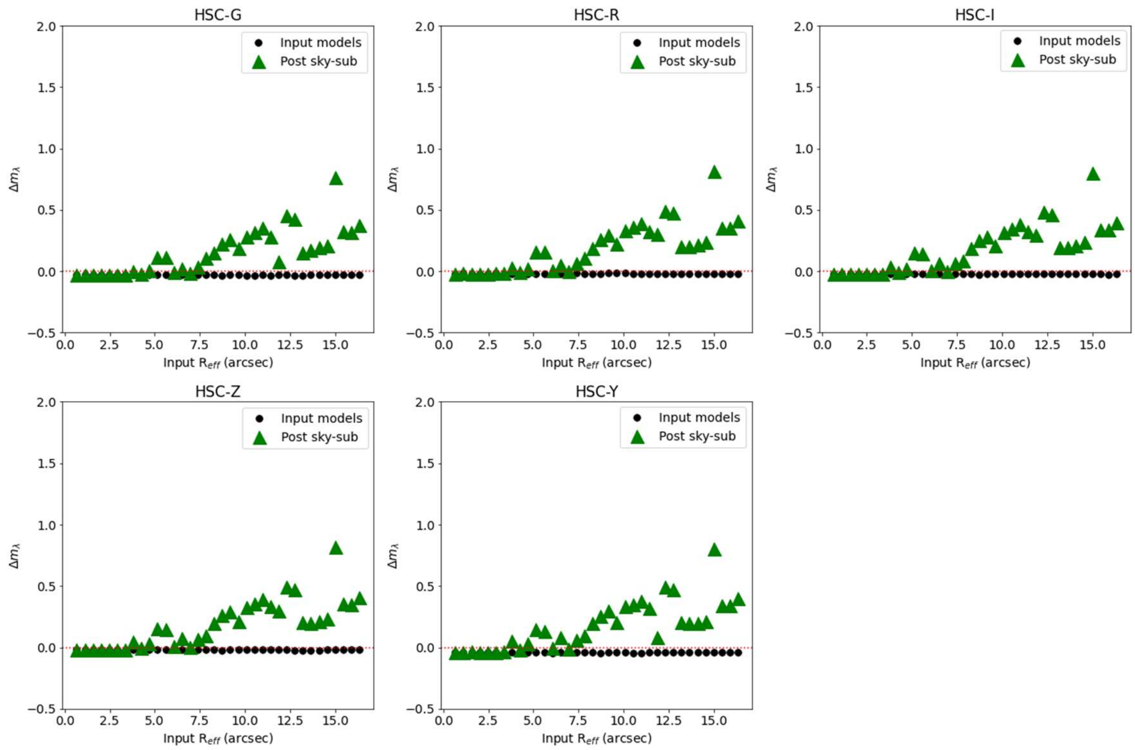

Figure 2 Effective radius vs. magnitude deficit, 1st injections

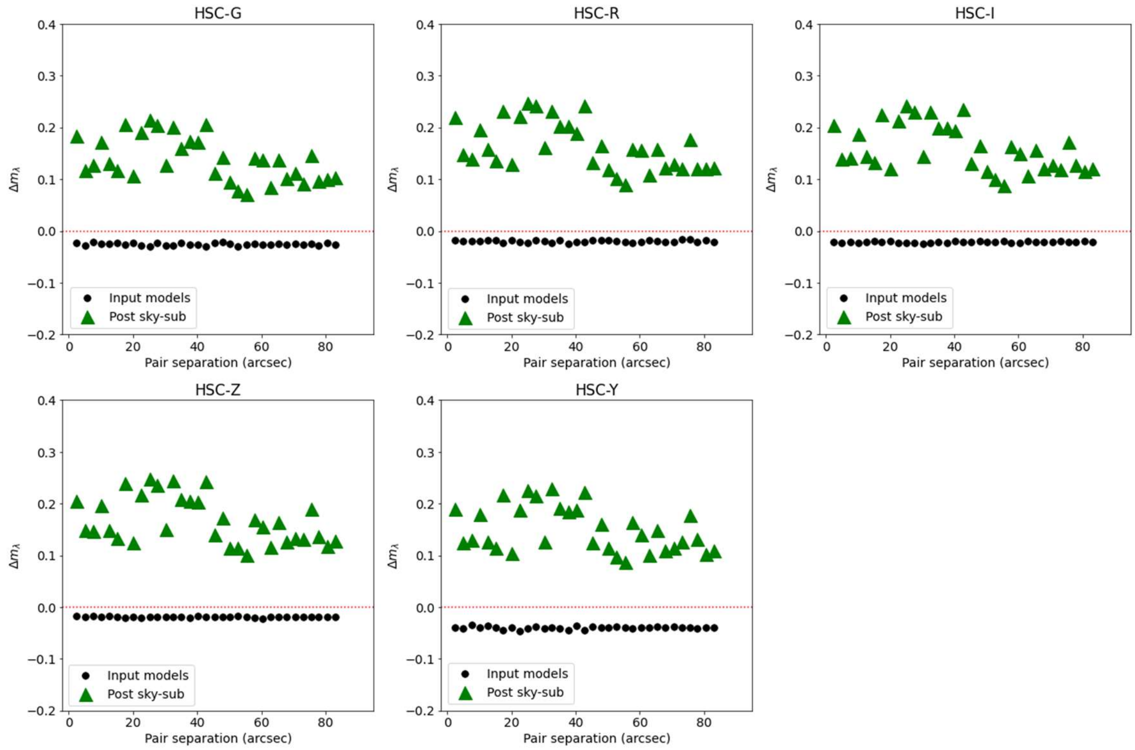

Figure 3 Separation vs. magnitude deficit, 1st injections

Figure 1, Figure 2, and Figure 3 show the effect of the 128x128 pixel mesh sky subtraction as a function of model surface brightness, size (effective radius), and object separation, respectively. In each plot, the y-axis is the difference between the magnitude of each model as measured by the process described above from the model's input catalogue magnitude. Black points denote models pre-sky-subtraction (note that due to subtleties in the model injection procedure, the pre-sky-subtraction model magnitudes are never exactly equal to the input catalogue magnitudes), while green triangles denote models post-sky-subtraction. Using these plots, we can pinpoint both a common surface brightness and common size at which systematic over-subtraction occurs, values we then provide to the DM team.

For example, regarding surface brightness (Figure 1), systematic over-subtraction occurs in most photometric bands at around 26 mag/arcsec^2, with more severe over-subtraction at lower surface brightness. The problem is worse in the z and y bands, where this systematic over-subtraction occurs closer to μ_0 = 24.5 mag/arcsec^2. Most models below μ_0 = 26 mag/arcsec^2 are over-subtracted (in terms of total flux) by more than half a magnitude, while the lowest surface brightness models are over-subtracted by upwards of 2 magnitudes (a factor of six difference in total flux compared to the input catalogue). Evidently, if this small-mesh approach to sky subtraction is consistently removing significant flux below 26 mag/arcsec^2 (five magnitudes, or a factor of 100 in flux, above the theoretical limit of 31 mag/arcsec^2 achievable by LSST), this algorithm is not tenable for LSB work of any kind.

Similar behaviour occurs regarding model size, where a systematic over-subtraction begins at R_{eff} ~ 7.5" (~45 pixels), with more severe over-subtraction occurring for larger objects (with some scatter). In the worst cases, this over-subtraction is nearly 1 magnitude (a factor of 2.5 difference in flux). These models are fairly standard in brightness compared to real galaxies (μ_0 = 21 mag/arcsec^2), hence this small-mesh based approach to sky subtraction degrades not only LSB science, but any astronomy involving objects greater than ~10" in size (e.g., ICL, low-redshift galaxies, Galactic cirrus, etc.).

On the other hand, we find no clear correlation between object separation and magnitude deficit. Over-subtraction of these models is the same (with small variation) as for all other models with μ_0 = 21 mag/arcsec^2 and R_{eff} = 50 pixels. We discuss this further in the following sections.

4.2 Second injections, full-focal-plane sky subtraction

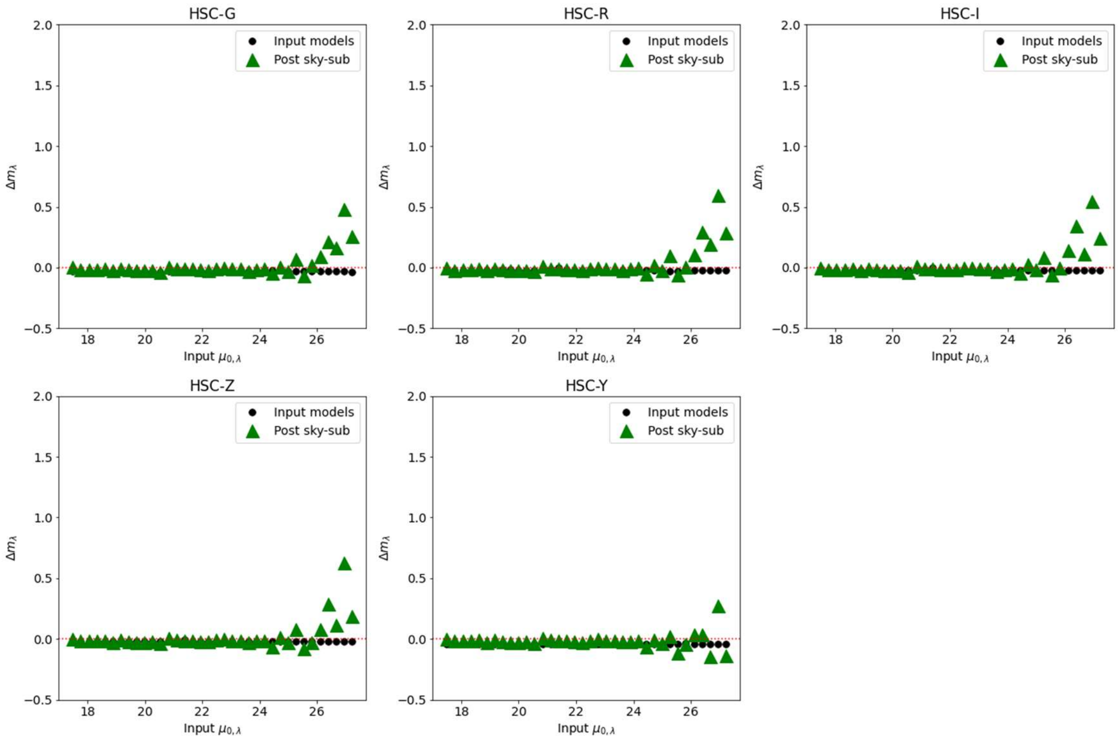

Figure 4 Surface brightness vs. magnitude deficit, 2nd injections

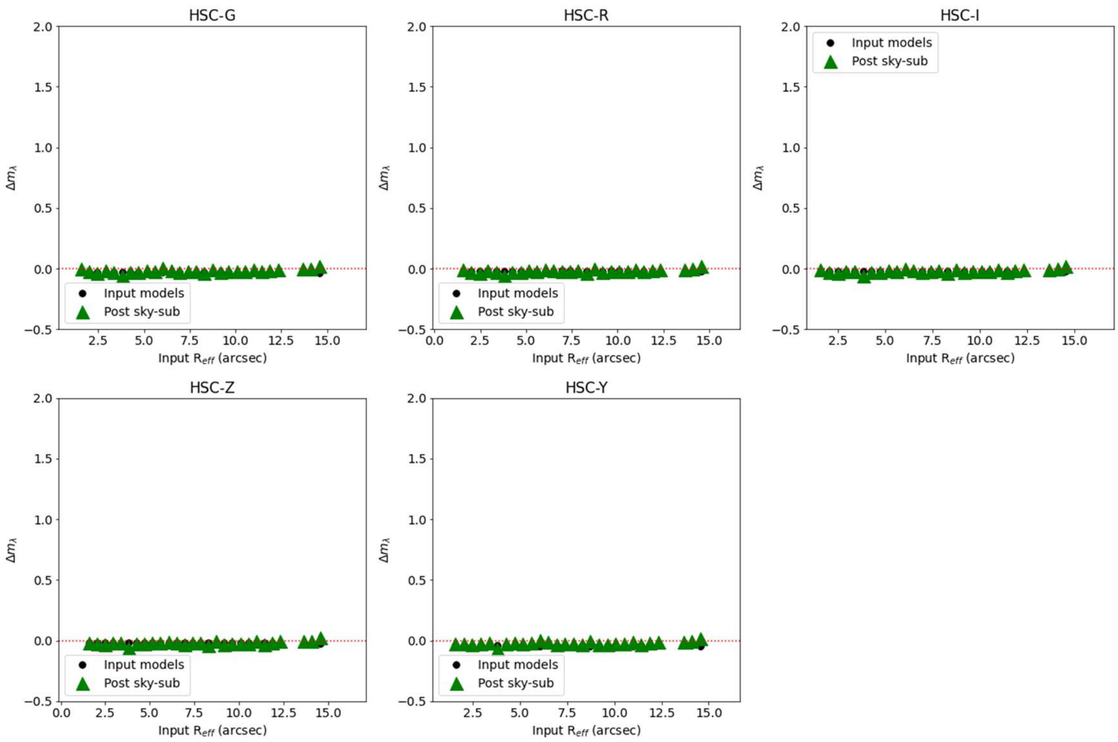

Figure 5 Effective radius vs. magnitude deficit, 2nd injections

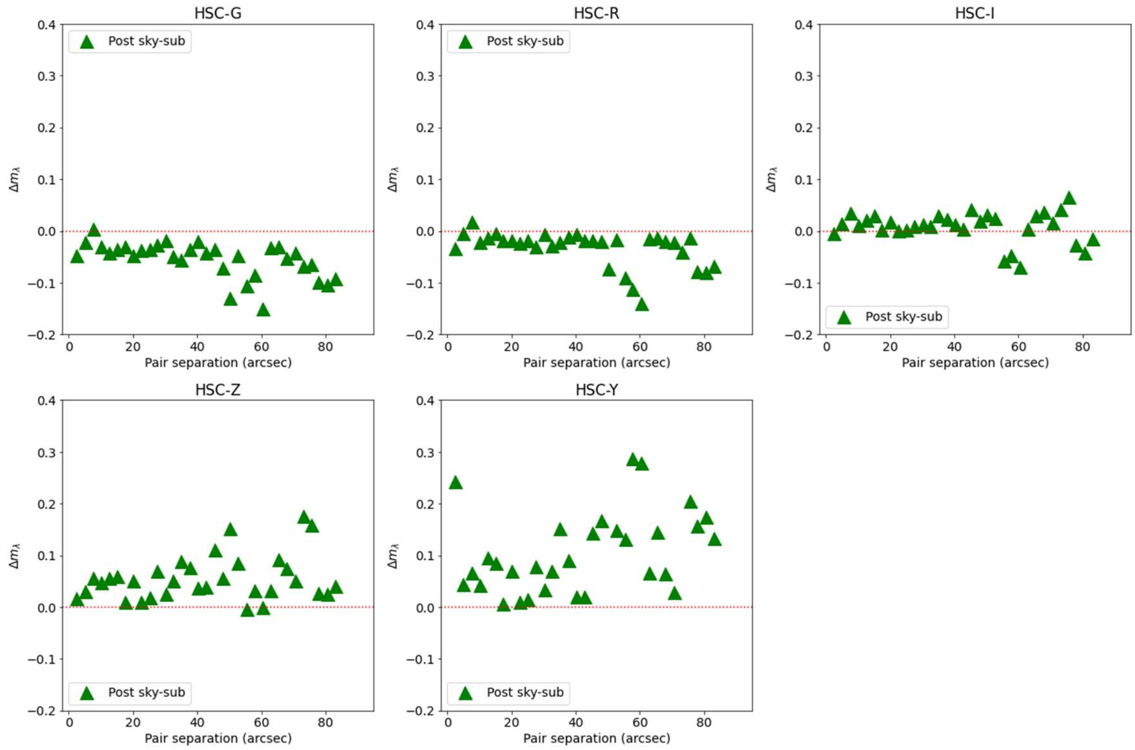

Figure 6 Separation vs. magnitude deficit, 2nd injections

Figure 4, Figure 5, and Figure 6 are the same as Figure 1, Figure 2, and Figure 3, but are showing the impact of the full focal-plane sky subtraction on our model galaxies.

Figure 4 demonstrates that the full-focal-plane sky subtraction's impact on LSB objects is lessened but not removed. Objects with $\mu_0 > 26$ mag/arcsec^2 are still systematically over-subtracted, albeit upwards of only half a magnitude in the worst cases. While this is an improvement, it appears that LSB science still suffers under this sky subtraction routine, in a similar way as under the smaller mesh approach.

From Figure 5, we see that the over-subtraction trend with model size is almost completely mitigated when using the full-focal-plane method. Finally, Figure 6 demonstrates again no clear trend in over-subtraction with model pair separation, though low-level (of order 0.1 mag) flux differences from the catalogue values are still visible among these models.

4.3 Injections summary

In total, while the details of the sky subtraction algorithms are constantly changing, we can conclude from this first round of model injections that one primary source of over-subtraction is the choice of mesh size used in measuring the sky. While over-subtraction even at high surface brightness is severe in the first round of injections (testing the small-mesh-based sky subtraction approach), in the second round of injections, testing the full-focal-plane sky-subtraction (which uses a larger mesh), the trend of over-subtraction with model size mostly vanishes. Examination of individual images in the first round of injections shows that most of the variation in over-subtraction for galaxies with a similar size results from where the galaxies are placed relative to the mesh grid. We demonstrate this effect in Figure 7, using the variable R_{eff} models. Galaxies located near the centre of one mesh box (e.g., fifth row, second column of Figure 7, or index 11 in Figure 2) compose most of that box's "sky" and are therefore more severely over-subtracted compared to models that straddle two or more mesh boxes. The least over-subtracted of such models appear to land at the corners of these mesh boxes (e.g., second row, fifth column of Figure 7, or index 26 in Figure 2). This in turn explains why object separation has comparatively little impact; what seems to matter most is the mesh size and placement of each object within the mesh grid itself.

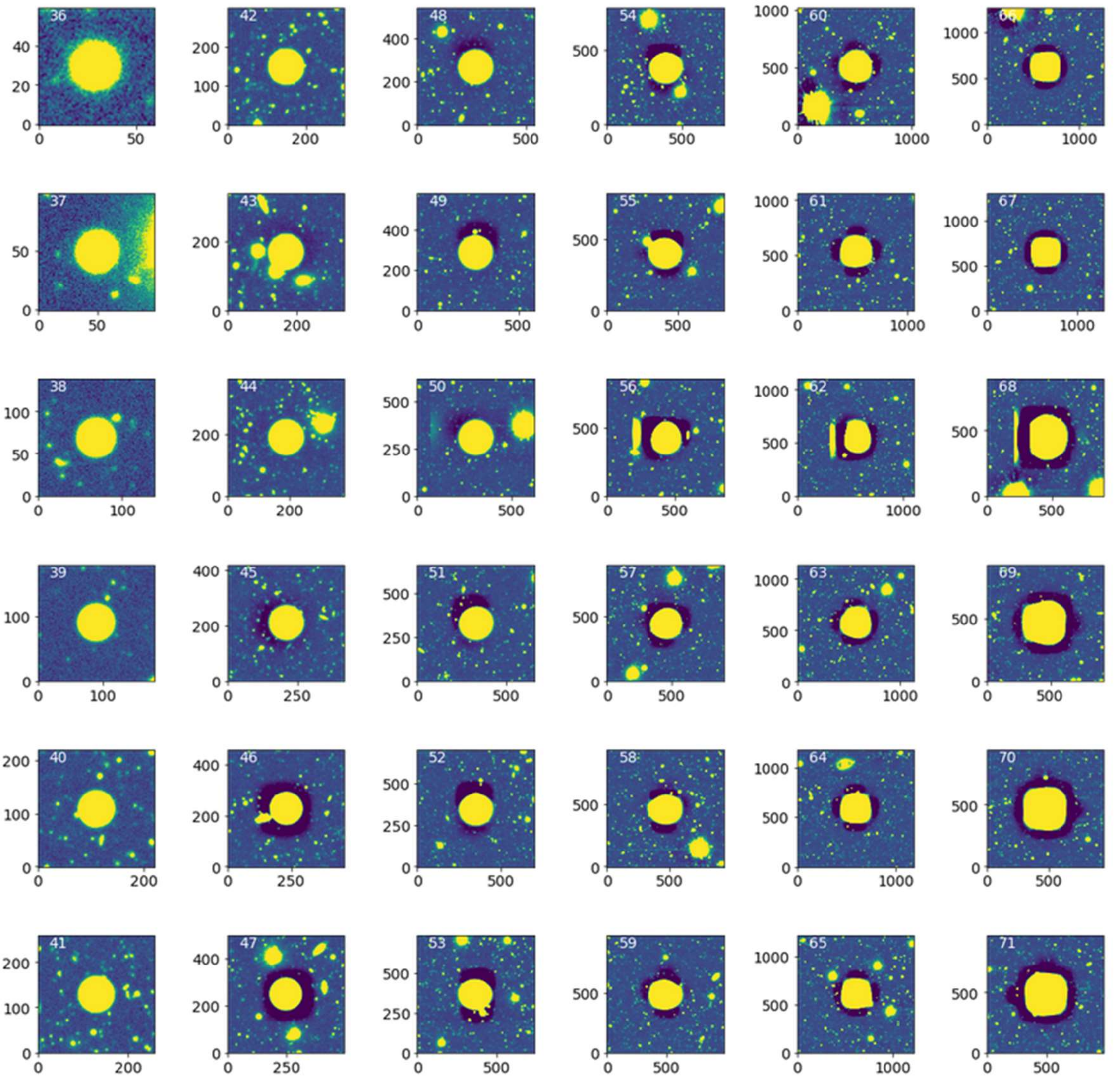

Figure 7 Examples of local sky over-subtraction due to the small-mesh approach, revealing the shape of the mesh. Each panel shows one of the 36 variable size models (Fig. 2) as it appears in the final, sky-subtracted co-add (g-band). Axis units are cutout coordinates in pixels. To compare with Fig. 2, model index increases starting from the top-left panel going down each row (such that the first panel in the second row is index 7).

The trends with model surface brightness are harder to explain without knowing the full details of the sky-subtraction algorithms, but we have shown that over-subtraction begins at roughly the same surface brightness in both algorithms, suggesting a common cause. For example, improper masking of LSB flux will tend to result in an over-estimation of the background, no matter what size of mesh is used. This in turn leads to over-subtraction of LSB flux. Additionally, even if no mesh is used, estimation of the full-focal-plane sky via a large-order polynomial can lead to over-subtraction of small-scale (limited by the polynomial order) flux as well when LSB objects are not properly masked.

Therefore, our metrics help identify not only the quantitative impact of the sky subtraction on LSB flux, but can also help pinpoint the causes of the over-subtraction. This in turn will allow us to propose solutions.

4.4 Next steps

From these initial flat model injections, we have established a baseline measure of the amount of over-subtraction produced by each sky-subtraction algorithm in the DM pipeline. We are therefore now able to intelligently expand this baseline to cover most of LSB science using a revised model injection which includes a larger parameter space.

For example, we have yet to establish whether the amount of over-subtraction we have measured with these injections is the same for models with different kinds of surface brightness profiles, parametrized by magnitude (brightness), effective radius (size), and Sérsic index (light concentration). Our next round of model injections will therefore be much larger and will be designed to cover a much wider breadth of parameter space, in order to test how our metrics vary for a wide range of realistic galaxies. Also, alongside simply varying the models' central surface brightnesses, we will expand our metric to include the impact of the pipeline on individual profiles, determining at what specific surface brightnesses over-subtraction begins to occur for all profile shapes. Additionally, we will include models of ICL, as well as a handful of images of galaxies with tidal debris taken from simulations. Including these will help generalize any trends we find using the simpler model galaxies to a much broader range of LSB science cases, and will help constrain the potential sources of the over-subtraction in the pipeline itself.

5 Summary

- LSB science composes most of the potential discovery space for LSST, but it relies on the accurate measurement of fluxes far below the night sky surface brightness over large areas of the sky.
- This in turn requires an extremely careful sky-subtraction algorithm, without which LSB science simply cannot be done using LSST.
- Using idealized model galaxy injections at varying stages of the DM pipeline, we have devised a simple metric for estimating the impact of the current LSST sky-subtraction routines on LSB science, by comparing the total fluxes of the model galaxies pre- and post-sky-subtraction.
- We have found that the DM pipeline's final sky-subtraction step, built to optimize weak-lensing science, degrades LSB flux considerably.
  - Objects with surface brightnesses below μ_0 = 26 mag/arcsec^2 in all bands are systematically over-subtracted, with increasing over-subtraction at lower surface brightness.
  - Objects with sizes larger than R_{eff} ~ 10", even at high surface brightness, are also consistently over-subtracted, with increasing over-subtraction at larger size.
- Likewise, we have found that the sky-subtraction step just prior to this (removing the full-focal plane night sky), while an improvement, still results in some over-subtraction.
  - While the trend of over-subtraction with object size is greatly mitigated, objects with central surface brightnesses below 26 mag/arcsec^2 are still being systematically over-subtracted by this sky-subtraction step.
- These preliminary model injections have established a baseline measure of the current level of over-subtraction in the DM-pipeline, therefore we will next generalize these trends by expanding the parameter space probed via the next round of model injections and by including several examples of ICL and tidal debris.

6 References

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Annex A. Acknowledgements

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