LSST Survey Footprint in the Galactic Plane and Magellanic Clouds

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1 Introduction

At least 13 of the 46 survey cadence White Papers[1] submitted by the community in 2018 highlighted the broad range of science that would result from surveying the Galactic Plane and Magellanic Clouds with the Rubin Observatory, at higher cadence than what was proposed for the Wide-Fast-Deep (WFD) survey. A broad range of stellar astrophysics can be served by observations within a footprint centered at low galactic latitudes that also encompasses additional regions of special scientific interest. Science drivers highlighted in the White Papers included detecting transiting white dwarfs and exoplanets [1]; analysing the distribution and population occurrence frequencies of all forms of stellar variability and binarity [2, 3, e.g.], particularly pulsating variables and Cataclysmic Variables [4, 5, 6]; fulfilling LSST's main science driver to map the Milky Way, providing detailed insights into stellar populations, their evolution and galactic structure [7, 5, 8]; transient phenomena such as stellar flares and microlensing [6], which promise to map the population of isolated black holes and could even discover exoplanets in the Magellanic Clouds [9] and Bulge and Disk [10]. We note that [11] demonstrated that enhanced coverage of the Galactic Plane can dramatically improve orbital period measurements for low-mass X-ray binaries. Most of this science depends strongly on time-series photometry, where cadence is more important than co-added limiting magnitude. We also note that since the 2018 White Papers were submitted, the *Gaia* Mission has made profound advances in galactic science, but probes to a limiting magnitude of ∼19–20 mag. Deeper, timeseries observations from Rubin over the 10yr LSST will complement and extend *Gaia*'s contributions to galactic structure.

However, although the filter selection, cadence and exposure time can be optimized for each science case, we emphasize that **the single most important factor in the success of all of these science cases depends on the extent of the survey area included.** The survey footprint is therefore of crucial importance. How this impacts different science cases is explored in a number of parallel Cadence Notes including those by Prisinzano et al., Abrams et al. and others.

We note that the Project's report about survey strategy [12] used "fast microlensing" as a proxy for galactic science to gauge the impact of different strategies. Although it is impossible to fully capture the complexities of all possible science cases in the Galactic Plane in a single Figure of Merit (FoM), in order to arrive at a coherent strategy, we recognize the utility of general-purpose proxy metrics. To that end, we have reviewed the survey regions, filter selections and cadences proposed in the White Papers cited above, and offer the following method as a means to arrive at a more generally representative FoM.

To be clear: almost all of these science cases would be best or at least reasonably-well served by extending the Wide-Fast-Deep (WFD) survey to the whole Southern Sky including the Galactic Plane and Magellanic Clouds, such as in the footprint_gp_smooth simulations.

The Galactic Plane represents a large sky region and the time dedicated to surveying it must be carefully orchestrated to maximize the science return while ensuring that the science requirements for the WFD survey

[1] https://www.lsst.org/submitted-whitepaper-2018

are not compromised. The operational simulation experiments (OpSims) performed to date have considered a number of alternative footprints, many of which include the Galactic Plane, Magellanic Cloud and other regions of scientific interest to various degrees. The impact of these experiments on different science cases are being evaluated in separate Cadence Notes (e.g. Bonito et al., Abrams et al., Buckley et al.). It is likely that a trade-off will have to be made between cadence and survey footprint, and at that point it will be helpful to know which regions are of highest scientific priority. The goal of this Cadence Note is to try to identify those regions, in the form of a proxy FoM.

2 Survey Footprint

We compiled a list of the survey regions of interest, filter sets and cadences requested in the White Papers cited above, and summarize them in Table 1. It should be noted that the filters listed in each case are those most important to the science case, chiefly g, r, i, z. This should not be interpreted to mean that *no* data is required in u or y but rather that it is preferable for the majority of the data to be taken in the indicated bands. The overlap between these regions is extensive. We therefore explored whether a common survey region could be derived, comprised of the regions of highest priority for the science cases concerned. For the fields in the Galactic Plane and Bulge, and the Magellanic Clouds, the regions of greatest interest closely follow the sky regions of highest stellar density, owing to the nature of the science concerned. But the stellar density varies strongly across the Plane and in general the regions of extreme extinction and lower stellar density are of lower scientific priority. There are, however, a number of regions of special scientific interest, such as stellar clusters and star forming regions (SFR [12]), which are not adequately represented by a simple function of $N_{\rm stars}/{\rm deg}^2$.

By optimizing the Galactic Plane region surveyed, we hope to reduce the overall time commitment necessary to achieve our science goals and improve the efficiency of LSST overall.

We combined the overlapping survey regions in Table 1 in the form of a HEALpix map (NSIDE=64). Firstly, we use a map of stellar density in r-band derived from the TriLegal galactic model, and identified regions of highest interest by selecting sets of HEALpix with densities greater or equal to 60%, 70% and 80% of the maximum stellar density over the whole sky. The pixels in these regions were assigned priority weightings of 0.8, 0.9 and 1.0 respectively. This map highlighted the Galactic Plane, Bulge and Magellanic Clouds.

We then added to this map the other regions of special interest, such as star forming regions etc, which were also assigned a priority weight of 1.0.

Different science cases require observations in different pass-bands. Although in the Galactic Plane especially, redder bands (g, r, i, z) tend to be preferred, we note that it is important to obtain regular observations in u, y as well for spectral typing and characterizing young star variability. We opted to represent this as weighting factors assigned to each filter separately for each science case, and generate a HEALpix priority map for each filter by iterating over the science cases and assigning a priority for each HEALpix that is effectively the product of the HEALpix' stellar-density map priority and the filter weighting factor, summed over all science cases considered. In this way, each science case effectively constitutes a 'vote' towards the priority of observations of a given HEALpix in a given filter.

The code used to generate these priority maps, as well as the maps themselves in FITS and PNG form, can be found in the TVS Github repository[2]. We emphasize that at time of writing, the relative weighting factors used to calculate the priority are preliminary, and more work is planned to ensure that they adequately represent the priorities of the community.

Code has also been developed to make these maps available as a MAF metric[3].

This footprint metric is designed to be combined with other metrics to produce FoMs which incorporate the different cadences and exposure time requirements of different science cases. For example, the product of this footprint metric and the VisitGapMetric will give a direct indication of how well an OpSim will perform for a wide range of galactic transients. Similarly, the footprint metric factored by existing metrics for evaluating period recovery will indicate how well the survey performs for a wide range of periodic variables.

We propose that broadly-applicable proxy FoMs could be produced to represent much of time-domain stellar astrophysics by splitting the timescale of variability into four categories:

[2]https://github.com/LSST-TVSSC/software_tools
[3]https://github.com/LSST-TVSSC/software_tools/blob/master/GalPlaneFootprintMetric.py

Table 1: Summary of the larger area survey regions included in this study. Due to space constraints the full list of Globular Cluster and star forming regions included in the footprint map is provided through the TVS Github repository[5]

White Paper	Region	Gal long (l°)	Gal lat (b°)	Filters
Bono+ (deep survey)	Gal. Plane center	20 − +20	-3 − +3	izy
Bono+ (shallow survey)	Gal. Plane	20 − +20	-15 − +10	ugriyz
Gonzalez+	Gal. Plane center	15 − +15	10 − +10	i, grizy
Street+	Gal. Plane	-85.0 − +85.0	-10.0 − +10.0	griz
Prisinzano+,Bonito+	Gal. Plane/SFRs	-90.0 − +90.0	-5.0 − +5.0	gri
Poleski+, Street+ Clementini+	LMC	277.8 − 283.2	-35.2 − -30.6	griz
Street+	Gal. Plane	-85.0 − +85.0	-10.0 − +10.0	griz
Poleski+, Street+ Clementini+	SMC	301.5 − 304.1	-45.1 − -43.6	griz
Street+(a)	Gal. Bulge	2.216	-3.14	griz
Clementini+	M54	5.60703	-14.08715	gri
Clementini+	Sculptor	287.5334	-83.1568	gri
Clementini+	Carina	260.1124	-22.2235	gri
Clementini+	Fornax	237.1038	-65.6515	gri
Clementini+	Phoenix	272.1591	-68.9494	gri
Clementini+	Antlia2	264.8955	11.2479	gri

- <10 d, including exoplanet, White Dwarf transits, stellar flares, short period stellar binaries, pulsating stars (inc. RR Lyrae, Cepheids), some microlensing (e.g., by free-floating planets, bound planet anomalies, brown dwarfs), variability in young stars, short-term accretion variability
- 10–100 d, includes most microlensing by galactic stellar-mass lenses, intermediate pulsation periods, disk instability in Cataclysmic Variables, novae
- 100–365 d, includes microlensing by black holes, long-timescale pulsations,
- >365 d, includes long-period variables, e.g. Miras.

We note that the MAF already includes metrics to evaluate whether sufficient observations are obtained within these timeframes, e.g. the VisitGapMetric[6] and also to determine how well periodicities can be recovered from the data, e.g. periodicDetectMetric[7].

We anticipate performing further work to explore how well these FoM would represent the interests of our difference science cases, and our goal is to complete this by the end of Q2, 2021.

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.

The survey area of the WFD could be expanded to include the regions outlined above, while following a very similar cadence and filter selection, and accomplish the majority of the science we propose. OpSim footprint_gp_smooth, for example, explores this option, while mw_heavy_v1.6 provides good coverage of the Bulge and Magellanic Clouds but neglects the wider Galactic Plane. We are grateful for more recent OpSim experiments, such as footprint_6_v1.7, in which some additional regions within the Plane are included and the footprint takes extinction into account.

However, we propose that further optimization is possible by prioritizing the footprint as described above and surveying these regions more frequently in g, r, i, z filters than in u, y to account for their scientific utility and increased extinction. For operational simplicity, it may be easiest to implement this strategy by

[6] https://github.com/lsst/sims_maf/blob/master/python/lsst/sims/maf/metrics/cadenceMetrics.py
[7] https://github.com/lsst/sims_maf/blob/master/python/lsst/sims/maf/metrics/periodicDetectMetric.py

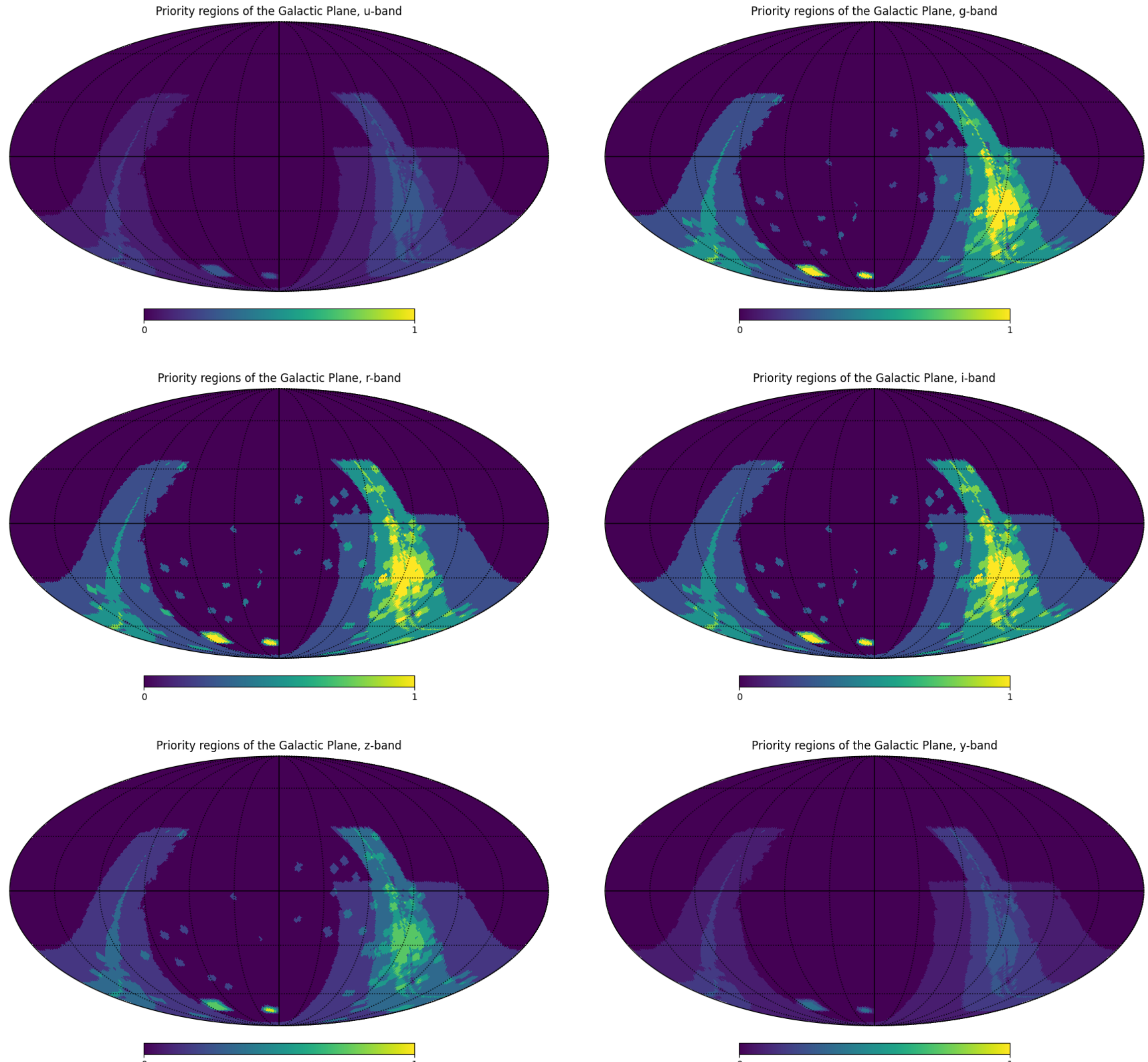

Figure 1: Sky maps where each HEALpix is weighted according to a priority metric for a broad combination of Galactic Plane science, presented for each filter.

retaining the current WFD survey and instead adding a distinct survey of the Galactic Plane and Magellanic Clouds.

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.

We advocate for dedicating a significant fraction of this time to a survey of the footprint described above on the grounds that it will deliver an unparalleled dataset that will yield a wide range of science that cannot be achieved by any other facility. This survey will be essential for LSST to complete three of its primary science drivers: exploring the transient optical sky, mapping the Milky Way and probing dark matter.

Many sources of stellar transients, such as microlensing, accretion outbursts and flares, occur overwhelmingly within the Galactic Plane and Magellanic Clouds. Without adequate multi-band timeseries photometry of this region, our understanding of the populations producing these transients will remain incomplete. The same time-series data is also essential for the full characterization of RR Lyrae, which will be critical to efforts to map the structure and evolution of the Milky Way and its satellite galaxies. Last but not least, LSST has the potential to complete the first deep, high cadence and long-baseline *microlensing* survey of the Galactic Plane, Bulge and Magellanic Clouds. This unique combination of characteristics makes it sensitive to microlensing by intermediate-mass black holes and so able to probe an otherwise-unexplored regime in the hunt for dark matter [13, 14, 15]. A Galactic Plane survey would also deliver a diverse range of science, as outlined above and in the 2018 White Papers, revolutionizing the field of large segments of the Rubin Science community, both in the US and Chile, and internationally.

We note that much of this science has some flexibility regarding the distribution of observations throughout the 10-yr survey, since in general high-cadence observations are beneficial but we also highlight the importance of early-time observations. We discuss this topic further in answer to question 6.

3 Exposure time per visit

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.

The relatively high extinction at low-latitude fields argues in favor of longer exposures in the bluer filters, especially u. While observations in this filter are scientifically valuable for estimating spectral type, metallicity and distinguishing variable classes, it is not necessary to obtain u-band exposures at high cadence.

4 Allocation of observing time per band

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.

Although our science drivers require timeseries photometry in all 6 filters to achieve their goals, higher cadence data in g, r, i, z filters (i.e. 2–3 d or higher) are particularly valuable for much of the science, while lower cadence observations in u, y are needed.

The priority maps described above are normalized across all passbands, and so could also be used to determine the relative frequency of observations in different filters. It should be noted that we only propose that these optimizations be made within the survey footprint for galactic science. How this region is surveyed - whether as part of a modified WFD strategy or as a distinct survey - is a decision we leave to the Project.

5 Time sampling and revisit offsets

Q5: Are there any science drivers that would strongly argue for, or against, obtaining 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.

Street et al. [6] outlined one potential strategy to obtain higher cadence observations in i, while also maintaining survey cadence in other bands, and ensuring regular color measurements are obtained. Their "paired-i" strategy requested that one of the two initial visits per night would be in i-band, while the other visit would use one of the other filters. That White Paper suggested limiting the filterset to g, r, i, z, but the new priority maps could be used to cycle through all of the remaining filters at different cadences.

Using the same filter for both visits per night can be beneficial for some of the science. For example, microlensing would benefit from having repeated measurements in r, i or z-bands. But this would negatively impact other galactic science drivers, for example variability in young stars or Cataclysmic Variables, where the phenomenon being studied is intrinsically color-variable. This can be particularly important for outbursts and other transient phenomena, where color information cannot be inferred from earlier or subsequent observations.

Obtaining three visits per field per night has pros and cons. Most of our science cases benefit from higher cadence lightcurves, as this allows us to better quantify the morphology of the lightcurves for classification purposes and improves the early identification of transient targets. However, the same strategy would necessarily increase the revisit time to all fields, leading to gaps in the lightcurves in which critical features of variable behavior will be lost. This is more detrimental to the shorter timescale categories described above (<30 d) than for the longer-term variability, and we intend to conduct further investigations to quantify this impact over the next few months.

For microlensing, we note that this question is explored more fully in a parallel Cadence Note led by Abrams 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.

The rolling cadence has the potential to strongly benefit many TVS science drivers in the Galactic Plane, by delivering higher-cadence lightcurves. This is particularly true for the shorter timescale categories. However, we note that there are limitations that depend on the length of the rolling cadence 'season'. Preliminary investigations (described more fully in the cadence note Abrams et al.) suggest that discovery rates decline when the season length is shorter than the timescale of the phenomenon being studied, such as black hole microlensing and Mira stars. These topics benefit from at least a minimal cadence continuing through gaps in the rolling seasons.

For this reason we are continuing to evaluate the impact of the new rolling cadence simulations that extended the footprint in the Galactic Plane, e.g. bulge_roll_scale0.90_nslice2_fpw0.9_nrw1.0v1.7_10yrs, full_disk_v1.7_10yrs and full_disk_scale0.90_nslice3_fpw0.9_nrw1.0v1.7_10yrs. We anticipate drawing more detailed conclusions before the end of Q2, 2021.

We also note the importance of early-time observations to many of the science cases included here. Baseline photometry of ∼1 yr with WFD-like cadence is necessary before transient events such as microlensing can be accurately classified [16], so early-time timeseries observations are essential in order to maximize the scientific yield of the rest of the survey. We note that early-time observations in all passbands are also important for the measurement of proper motions [8].

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.

Our science drivers have no strong requirements for spacial dithering, though we note that dithering can help to reduce aliasing in timeseries data and hence improve the unambiguous measurement of periodicities, which is important in the studies of pulsating variables such as RR Lyrae, as well as eclipsing binary and Cataclysmic Variable orbital period determination.

6

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