

## Give Me a Few Hours: Exploring Short Timescales in Rubin Observatory Cadence Simulations

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### ABSTRACT

The limiting temporal resolution of a time-domain survey in detecting transient behavior is set by the time between observations of the same sky area. We analyze the distribution of visit separations for a range of Vera C. Rubin Observatory cadence simulations. **Simulations from families v1.5–v1.7.1** are strongly peaked at the 22 minute visit pair separation and provide effectively no constraint on temporal evolution within the night. This choice will necessarily prevent Rubin from discovering a wide range of astrophysical phenomena in time to trigger rapid followup. We present a science-agnostic metric to supplement detailed simulations of fast-evolving transients and variables and suggest potential approaches for improving the range of timescales explored.

### 1. INTRODUCTION

For time-domain surveys, the temporal pattern of observations, or cadence, determines which astrophysical phenomena can be observed. Accordingly, survey designers choose cadences based on their scientific goals in conjunction with the constraints imposed by their instruments (cf. Bellm 2016).

The Vera C. Rubin Observatory (Ivezic et al. 2019) aims to conduct a Legacy Survey of Space and Time (LSST) that addresses four broad science pillars: probing Dark Energy and Dark Matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way. Given the scale of the survey and the breadth of its scientific aims (Abell et al. 2009), the project is conducting extensive simulations (Connolly et al. 2014) of potential cadences and evaluating them according to community-supplied metrics, which provide scientifically-motivated scores for evaluating the relative performance of different cadence simulations. Bianco et al. (2021) provides an overview of this process, which makes use of the OpSim simulation framework (Delgado & Reuter 2016; Reuter et al. 2016), a feature-based scheduler (Naghib et al. 2019), and the Metrics Analysis Framework (MAF; Jones et al. 2014).

As a supplement to metrics which treat specific classes of transients (e.g., Andreoni et al. 2021a), variables, and accreting sources (e.g., Bonito et al. 2021, Raiteri et al. in prep.), we present a source-agnostic analysis of the time gaps present in current cadence simulations. While detailed metrics simulating specific object classes are important in determining the science impacts of specific cadence choices, they require extensive development by domain experts and may not span the discovery space. Additionally it is challenging to weight specific object classes against one another. Simple metrics in conjunction with knowledge of the survey design can provide a useful supplement to scientifically-motivated analyses.

The (logarithmic) time separation of visits to a given sky area encapsulates the most basic information content of a time-domain survey. Our goal is to maximize the information we gain from these visits about time-varying objects. As discussed by Richards et al. (2018), for a sparsely-sampled time-domain survey, an ideal cadence for source class-agnostic discovery and variability characterization would be uniform in  $\log \Delta t$ —it would be sensitive to variations on all timescales, from the length of a single exposure up to the total survey duration.

In practice, of course, a ground-based survey cannot achieve this uniformity due to diurnal and seasonal cycles. However, the cadence families explored in LSST simulations at the time of this writing (Jones et al. 2020) are still far from effective at probing the full range of accessible timescales. In particular, the use of closely-spaced observation pairs leaves an “intra-night desert” preventing real-time discovery and timely followup of any phenomena varying on timescales of a few hours to a day. This includes stellar flares; young supernovae; gamma-ray bursts, orphan afterglows, and other relativistic transients; kilonovae; and rare new kinds of fast extragalactic transients. This also includes a variety of short-timescale accretion variability: Young Stellar Objects (YSOs) show short-timescale bursts and dipping events due to a variety of physical mechanisms, including accretion rate changes, disk warping, stellar flares, and starspots (e.g., Bonito et al. 2018). Among Active Galactic Nuclei (AGN), low-mass supermassive black holes and accreting intermediate mass black holes are expected to be most variable on **timescales of hours to days** (e.g., Burke et al. 2021). Likewise, the most dramatic active phases of extreme flaring blazars exhibit short-timescale variability that can help identify the underlying emission physics (e.g., Raiteri et al. 2021a,b). Even for purely periodic variable stars, variations in the visit separation spacing are important to reduce aliasing during period searches (e.g., Bell et al. 2018).

In this paper we present a new scalar metric for evaluating the temporal sampling of a time-domain survey on timescales of interest (§2). In §3 we evaluate this metric on current LSST cadence simulations, with particular focus on sampling at short timescales. We close in §4 with a range of ideas for diversifying the cadences of the Rubin Observatory’s LSST.

## 2. METRICS

To analyze the current simulations, we used the existing MAF metric `lsst.sims.maf.metrics.TgapsMetric` with logarithmic bins from 30 seconds to 10 years.<sup>1</sup> We computed **time separations between consecutive pairs of observations of a given sky position** (`allGaps=False`) in any filter and summed the result-

<sup>1</sup> `np.logspace(-3.46,3.54,99);` see [https://github.com/RichardsGroup/LSST\\_OpSim/blob/master/contrib/00\\_computeLogTgapsMetric.ipynb](https://github.com/RichardsGroup/LSST_OpSim/blob/master/contrib/00_computeLogTgapsMetric.ipynb)

ing histograms for an NSIDE=64 healpix grid.<sup>2</sup> We also computed a normalized cumulative distribution function (CDF) of the resulting histogram.

Using this cumulative histogram as a conceptual starting point, we defined a new metric (`TgapsPercentMetric`) which represents the percentage of observation pairs with separations between 2 hours and 14 hours (same night revisits) and between 14 and 38 hours (next-night revisits). We selected these intervals due to their importance for identifying **the classes of fast-evolving transients and variables described in §1**, but the metric can be configured to use any desired time window.

**Our chosen 2 hour lower limit is an approximate minimum over which variability of fast-evolving transients can be identified:** Andreoni et al. (2021b) defines fast extragalactic transients as changing by more than 0.3 mag day<sup>-1</sup>. Over a two hour baseline, such evolution is at the threshold of detectability for 1% photometric precision.

Our metric can also be combined with other standard MAF tools to explore the revisit fraction for subsets of survey visits taken from arbitrary spatial regions, filter selections, survey intervals, and/or survey proposals. The resulting code is publicly available in the central `rubin_sim` MAF metric repository.<sup>3</sup>

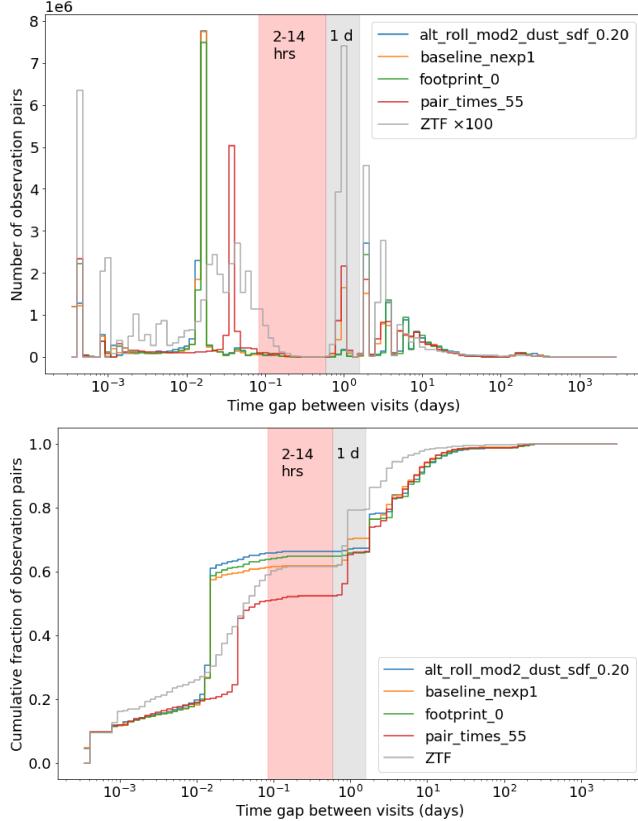
## 3. RESULTS

We evaluated our metrics on OpSim simulations from the v1.5, v1.7, and v1.7.1 simulation releases (Jones et al. 2020).<sup>4</sup> These releases each include a variety of simulation families, which explore the scientific impact of varying some aspect of the survey strategy, such as the survey footprint, im-

<sup>2</sup> This restriction to gaps between consecutive observations understates the temporal information present in more densely sampled surveys with many observations within a period less than the astrophysical timescales of interest. For instance, these histograms for a single sector of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) would consist of a single spike at the continuous 30-minute full-frame image cadence, but the data would provide temporal information over the entire 27-day interval in which TESS was pointed at the sector.

<sup>3</sup> [https://github.com/lsst/rubin\\_sim/blob/main/rubin\\_sim/maf/metrics/tgaps.py](https://github.com/lsst/rubin_sim/blob/main/rubin_sim/maf/metrics/tgaps.py)

<sup>4</sup> The v2.0 OpSim simulations (Jones 2021a) were released after the submission of this paper. This simulation set includes two families, `long_gaps` and `long_gaps_no_pair`, which respond to our Cadence Note (Bellm et al. 2021) and explicitly explore longer intra-night visit separations. They also include a revised `presto_color` family with improved triplet spacing.



**Figure 1.** Histogram (top) and normalized cumulative histogram (bottom) of the time gaps between visits to the same sky position for several representative LSST simulations as well as Zwicky Transient Facility (ZTF) observations. Shaded regions highlight the 2–14 hour and 14–38 hour ranges for which we compute metrics (Table 1).

age exposure time, filter distribution, visit pair separation, etc. Jones et al. (2020), Yoachim (2021), and Jones (2021b) describe these releases in detail. Because we are interested in the total temporal content of the survey, we included all spatial regions and survey proposals (Wide-Fast-Deep, Deep Drilling Fields, etc.). Figure 1 presents these time gap histograms for several illustrative example runs, and Table 1 summarizes the `TgapsPercentMetric` for each.

Despite the possibility of observing fields with time gaps longer than two hours but before the end of the current night, we find that less than 1% of visits are spaced in this critical timescale across all survey families. We stress that there is no inherent limitation preventing observations in this time range.

Perhaps surprisingly, given the fiducial 3-day cadence of the main Wide-Fast-Deep survey, one-night cadence timescales are somewhat better covered. Many simulation families show 7–12% of visit gaps at one-day

timescales, although a subset have sub-percent fractions at 1-day timescales as well. The latter observing strategies would be catastrophic for discovery of fast-evolving transients.

We also compared these simulations to comparable histograms from the Zwicky Transient Facility (ZTF; Bellm et al. 2019a; Graham et al. 2019). While ZTF has a field of view five times larger than LSSTCam, and therefore on average revisits a given area of sky five times more often (Bellm 2016), the ZTF surveys have also explicitly sought to span a wide range of timescales. These have included “movie mode” continuous-cadence observations, 6 visit per night transient searches, twilight searches for moving objects, as well as slower 2, 3, and 4-day cadence surveys (Bellm et al. 2019b).

### 3.1. Survey Footprint

Generally, we expected the increased number of visits in simulations which use a smaller main survey (Wide-Fast-Deep) footprint would provide more effective time sampling. However, current simulation families do not distribute the additional visits at short timescales and so do not provide a major improvement in the relevant metrics. The `wfd_depth`, `filt_dist`, and `footprint` simulations are comparable to or slightly worse than the current `baseline` simulations, with the exception of the `fbs_1.7footprint_tunefootprint_#` simulations, which have extremely low (sub-percent) coverage at 1-day timescales.

### 3.2. Visit Pairs

Paired observations need to be closely spaced (up to  $\sim$  one hour) for linking of main-belt asteroids to succeed (Jones et al. 2018) due to the  $N^2$  combinatoric explosion of source pairs to consider when constructing tracklets. Current simulation families explore the effect of varying both the visit pair separation as well as the filters used in the visit pair.

The `pair_times` family considered spaces as large as 55 minutes. The largest pair-spacing simulation, `pair_times_55`, provides the best metric values for both the 2–14 and 14–38 hour timescales of all the simulations to date.

With the exception of stellar flares, most of the classes of fast transients motivating this work above will not vary appreciably on timescales less than an hour. Accordingly this suggests that switching filters between observations in a pair (as in the current baseline) is preferable, so that the second observation provides non-redundant information (color).

### 3.3. Triplet Observations

OpSim run	TgapsPercentMetric 2–14 hours	TgapsPercentMetric 14–38 hours
baseline_nexp1* <sup>†</sup>	0.5%	8.6%
baseline_nexp2	0.5%	8.2%
third_obs_pt15	0.3%	8.5%
third_obs_pt30	0.4%	8.2%
third_obs_pt45	0.4%	8.1%
third_obs_pt60	0.5%	8.0%
third_obs_pt90	0.7%	7.6%
third_obs_pt120	0.8%	7.3%
pair_times_11	0.4%	7.5%
pair_times_55*	1.3%	<b>13.9%</b>
wfd_depth_scale0.65	0.3%	7.9%
wfd_depth_scale0.99	0.2%	8.6%
footprint_0*	0.6%	0.2%
footprint_stuck_rolling	0.4%	7.1%
footprint_big_sky	0.2%	8.8%
filterdist_idx1	0.3%	9.2%
rolling_scale0.2_nslice2	0.8%	0.1%
rolling_scale1.0_nslice3	0.8%	0.1%
alt_roll_mod2_dust_sdf_0.2*	0.5%	0.6%
roll_mod2_dust_sdf_0.20	0.3%	8.4%
rolling_nm_scale1.0_nslice2	0.6%	8.9%
rolling_nm_scale0.90_nslice3_fpw0.9_nrw1.0	0.8%	<b>12.6%</b>
Zwicky Transient Facility (observed)*	3.6%	17.7%

**Table 1.** Median percent of observations probing intra-night and 1-day timescales. We selected representative examples from within the **v1.5**, **v1.7**, and **v1.7.1** simulation families for brevity. Metric values above 10% are bolded, while sub-percent values are italicized. As-observed values for the Zwicky Transient Facility are included for comparison. **Opsim runs plotted in Figure 1 are marked with an asterisk (\*).** The **baseline\_nexp1** run plotted by band in Figure 2 is marked with a dagger (†).

“Triplet” observations (the “Presto-Color” strategy, [Bianco et al. 2019](#)) add a third nightly observation in one of the two filters of the visit pair, and so present the best means of capturing the intranight variability of fast transients. Surprisingly, the current `third_obs_pt#` simulations show almost *no* improvement in 2–14 hour timescale coverage. The **v1.5** triplet implementation thus provides little improvement over the baseline strategy, as it does not provide sufficiently wide time sampling nor enough additional visits to substantially change the fraction of observations in the intra-night desert. The **v1.5** implementation did not impose a minimum time gap between the second and third observations in the triplet, so the scheduler preferred to revisit recently-observed fields that were nearby and low airmass ([Jones et al. 2020](#); P. Yoachim, priv. comm.). Further improvements to the current LSST implementation of this survey strategy are necessary for triplet observa-

tions to reach their potential.<sup>5</sup> Owing to their longer visibility windows, sky areas that transit near zenith are likely to be preferable for observations with long time gaps without requiring high-airmass observations. Scheduling multiple images with wide spacing during the night may benefit from scheduling algorithms that optimize field selection on nightly timescales (e.g., [Bellm et al. 2019b](#)).

### 3.4. Rolling Cadences

“Rolling cadences” are observation strategies that do not distribute visits uniformly over the survey, but instead rotate between periods of enhanced and decreased sampling for a given sky area (e.g., [LSST Science Collaboration et al. 2017](#)). Rolling cadences pro-

<sup>5</sup> We note the improved performance of the `presto_color` simulation family in the **v2.0** simulations ([Jones 2021a](#)) released after the submission of this work.

vide the best means of allocating additional observations into the 2 hours–1 night window critical for rapid discovery of fast-evolving transients. Current simulations show a wide range of performance; the `rolling_scale` and `alt_roll` simulations have very poor (sub-percent) coverage of one-day timescales. `rolling_nm_scale1.0_nslice2` is close to the `baseline`, and `rolling_nm_scale0.90_nslice3_fpw0.9_nrw1` approaches the `pair_times_55` simulation in its effective timescale coverage. We suggest continued investigation into how best to distribute the rolling visits in time.

### 3.5. Per-filter Time Gaps

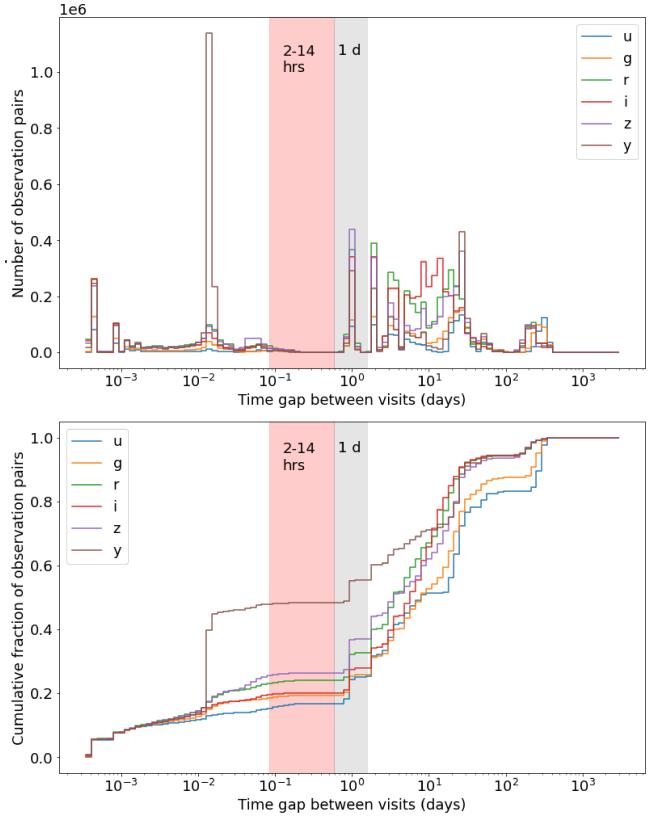
So far we have considered pairwise time gaps between observations in any pair of filters. Analysis of short-timescale variability will be more straightforward when those two visits are in the same filter, however. **Different astrophysical sources may benefit from pairs in specific filter bands; extragalactic transients and stellar flares are usually brighter in bluer filters, and kilonovae in redder filters. A broad exploration of short-timescale parameter space would suggest a balanced filter distribution. We consider here all bands independently; a user interested in only a subset of filters could use appropriate SQL constraints within MAF to limit the inputs.**

Figure 2 shows the per-band time gap histograms between observations in the same filter for the `baseline_nexp1` simulation. **For this figure only**, we excluded the Deep Drilling Fields, which observe only a small sky area and cycle through the available filter set on a daily basis.

Overall, the morphology of the per-band time-gap histograms is quite similar to the total histograms (Figure 1). There are very few observation pairs in the 2–14 hours range (`TgapsPercentMetric` ranges from 0.0% (*g* & *y* bands) to 1.6% (*u*)). The 14–38 hour interval shows a larger revisit fraction, with `TgapsPercentMetric` ranging from 6.1% (*g*) to 10.2% (*z*). The per-band sampling on one-day timescales is thus larger than expected given the notional baseline cadence, although we note that the histograms show a long tail of revisit times extending from weeks to months.

### 3.6. Comparison to ZTF

For an informative comparison to an existing sky survey, we also computed histograms and the `TgapsPercentMetric` on ZTF’s on-sky pointing history. We included pointings from all public and private surveys from March 2018–September 2021. We determined pairwise time gaps for each discrete ZTF field, neglect-



**Figure 2.** Histogram (top) and normalized cumulative histogram (bottom) of the time gaps between visits to the same sky position in the same filter in the `baseline_nexp1` simulation excluding the Deep Drilling Fields. Shaded regions as in Figure 1.

ing the overlaps at the field edges, which typically provide additional sampling on sub-hour timescales. Figure 1 shows the resulting time gap histogram, and Table 1 lists the corresponding metrics.

As discussed in Bellm (2016), the areal survey rate (the instantaneous field of view of a survey camera divided by its exposure time and any overheads) determines the number of exposures of a field a survey can obtain on average. Due to its wider field of view, ZTF obtains a factor of five more yearly exposures per field than LSST. Despite this advantage and a significant focus of a subset of the private ZTF surveys on high-cadence observations (Bellm et al. 2019b), we see that ZTF has only 3.6% of its observations in the 2–14 hour window and 17.7% in the 14–38 hour window. This is due to the presence of other large observing programs (e.g., the public 2- and 3-day cadence Northern Sky Survey). **While not an inherent technical limit**, we may thus take the ZTF numbers as a practical upper bound which LSST can achieve with its multi-faceted survey goals, and suggest that LSST target 1–2% for 2–

14 hours and 10–15% for the 14–38 hour window. **This would imply LSST would deliver tens (hundreds) of thousands of visits with long intranight (1-day) spacing. This would already enable parameter space constraints well beyond those achievable with any other survey (cf. Berger et al. 2013; Ho et al. 2021).**

#### 4. DISCUSSION

The survey simulations analyzed in §3 generally exhibit sub-percent revisit fractions within the night (Table 1). Modifications of the existing triplet and rolling cadence strategies may already be enough to improve this sampling. However, we also suggest exploration of more unique cadence modes not present in the survey families **considered here**.

Asteroid discovery drives the requirement for visit pairs spaced by an hour or less. However, most Main Belt Asteroids ( $\sim 80\%$ ; M. Juric, priv. comm) are discovered in the first three years of the survey (Ridgway et al. 2014). Accordingly a move to much wider visit pairs ( $> 2$  hours) later in the survey might enhance fast transient discovery without compromising LSST’s solar system science: with the majority of new asteroids discovered and the false-positive rate well-understood, identifying tracklets over wider temporal spacing could be tractable. Alternatively, new asteroid discovery algorithms show promise in discovering asteroids independent of the input cadence (Moeyens et al. 2021). **Since  $\sim 50\%$  of the visit separations occur at the visit pair gap (Figure 1), lengthening this spacing later in the survey could provide hundreds of thousands of observations with larger separations. Such a change would yield unprecedented sensitivity to variability at these timescales, which must be balanced against other survey goals. Allocating a few percent for longer timescales nightly and 10–15% at single-day cadence will provide an unprecedented window on variability at these timescales.**

Because the current LSST Deep Drilling Fields are scheduled as single contiguous blocks of observations, they also do not provide leverage for intra-night variability. Scheduling approaches that separated observations of a Deep Drilling Field widely within the night would be extremely valuable for identifying short-timescale variability, albeit over a limited sky area.

Throughout this work we have largely focused on pairwise time separations between observations in any pair of filters. In practice, identifying rapid short-timescale variability—especially in near real-time—is most straightforward if those observations are both

taken in the same filter. Making use of heterogeneous filters will require model-dependent assumptions about the source spectral energy distribution and extinction. Although this challenge will be present in analysis of LSST’s multi-band data at all timescales, the limited number of data points available for fast transients will make such interpretation particularly difficult. For this reason, the Presto-Color triplet strategy (Bianco et al. 2019) explicitly requests two widely-spaced visits within the night in the same filter.

Were additional visits available, we would suggest the observing time be used to provide a “variability wedding cake” survey approach that would more broadly explore the discovery space in  $\log \Delta t$ . This might include point-and-stare continuous-cadence (“movie-mode”) observations of single fields to provide sensitivity to very short timescale variability; short high-cadence campaigns on a limited sky area (e.g., Bonito et al. 2018); adding third (triplet) observations within the night to Wide-Fast-Deep fields; and maximizing the season length to provide sampling on many month timescales. For efficiency these additional observations might only use a subset of the available filters. Reserving a few percent of observing time for a series of such experiments (“**micro-surveys**”) throughout the survey might yield outsized scientific returns. **Exploration alone is unlikely to provide sufficient justification for this investment of resources. Additional metrics (e.g., Andreoni et al. 2021a, Bonito et al. 2021, Raiteri et al. in prep.) will be needed to show that specialized observing modes are needed to enable discovery of specific classes of astrophysical objects—for instance, that only a densely-sampled LSST lightcurve enables secure classification of a rare transient or variable among many contaminants.** Nevertheless, our temporal gaps metric provides a straightforward and useful means of thinking about how to allocate the temporal “budget” of the survey. Cadence optimizers can then weigh the value of balanced exploration against specific scientific goals.

The Vera C. Rubin Observatory’s Legacy Survey of Space and Time will transform time-domain astronomy over the next decade. Fulfilling its discovery potential across a wide range of science requires challenging cadence optimization. In particular, efficient asteroid discovery requires closely-spaced visit pairs early in the survey. The moderate number of available visits per year ( $\sim 80$ , on average) to a given sky position and the need for effective sampling of supernovae on timescales of months further limit the ease with which LSST can observe short variability timescales. Nevertheless, we

argue that LSST should consider creative opportunities to enable exploration of the widest range of time-domain astrophysics.

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*Software:* LSST Metrics Analysis Framework (MAF; Jones et al. 2014), **Astropy** (Astropy Collaboration et al. 2013, 2018), **Numpy** (Van Der Walt et al. 2011; Harris et al. 2020), **Matplotlib** (Hunter 2007), **healpy** (Górski et al. 2005; Zonca et al. 2019).

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