D3.3.2: TiDES Cadence Note

WP3.3 Spectroscopic classification of transients

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1 Executive Summary

The Legacy Survey of Space and Time (LSST) at the Rubin Observatory will revolutionise our understanding of the Universe by creating a decade long movie of the time-domain sky. Repeated and cadenced imaging alone, however, does not provide a complete picture of transient phenomena. This is where the 4MOST Time-Domain Extragalactic Legacy Survey (TiDES) adds crucial scientific value to LSST:UK investment in transient science. TiDES will follow-up LSST discovered transients to obtain spectroscopic measurements for tens-of-thousands of supernovae, galaxies, and active-galactic nuclei (AGN). This additional data will allow us to map the astrophysical diversity of cosmic explosions, measure the equation of state parameter for dark energy to unprecedented precision, and perform a comprehensive AGN reverberation mapping experiment.

The survey strategies for both LSST and TiDES are being finalised. The success of TiDES will be determined, in part, by the survey design choices of LSST. Motivated by this, as part of LSST:UK WP3.3 we have authored a short document in response to an LSST request for a 'Cadence Note' from participating scientific communities. LSST provided us with several survey strategies from which we were able to build a simulation framework compatible with 4MOST's own survey simulations.

This TiDES cadence note answers seven key questions presented by the LSST Survey Cadence Optimization Committee (SCOC). In addressing each question, we consider several combinations of the LSST survey simulations and TiDES simulations to find the best performing solution for the TiDES science goals. As a result of this investigation we were able to produce recommendations to the SCOC for their consideration when finalising the LSST survey design.

2 Introduction

Work Package 3.3 focuses on the spectroscopic classification of transient events from LSST using the 4MOST/TiDES facility. These transients will be predominantly supernovae (SNe) but, given the industrial scale at which TiDES will operate, more exotic phenomena such as tidal-disruption events and binary neutron star collisions may be observed. The success of both LSST and TiDES will rely on an inter-play of strategies between the two surveys. As our targets will be discovered by LSST, we aim to influence LSST's strategy to maximise sample size and data quality to ensure that TiDES will have a rich pool of transients and host galaxies to draw from.

Our report is presented as follows: in Section 3 we summarise the simulation data used within the cadence note. Finally, in Section 4 we present our submitted cadence note.

2.1 LSST call for Cadence Notes

The SCOC solicitation for Cadence Notes was announced in December 2020[1]. Previous investigations into survey optimisation only evaluated performance based on a set of predetermined metrics. The most recent round of community Cadence Notes were an opportunity to fill gaps where community requirements could not be addressed with the current metrics. As part of WP3.3 we developed the simulation infrastructure to assess the proposed LSST strategies and interface this with the 4MOST survey simulations. Our Cadence Note was presented to the LSST SCOC on 15$^{\text{th}}$ April 2021.

[1] https://www.lsst.org/content/charge-survey-cadence-optimization-committee-scoc

2.2 Glossary of Acronyms

4MOST	4m **M**ulti-**O**bject **S**pectroscopic **T**elescope
DESC	**D**ark **E**nergy**S**cience **C**ollaboration
LSST	**L**egacy **S**urvey of **S**pace and **T**ime
SCOC	**S**urvey **C**adence **O**ptimization **C**ommittee
TiDES	**Ti**me-**D**omain **E**xtragalactic **S**urvey

3 Simulation Data

Our LSST simulation framework uses the public release of the Operation Simulations (OpSim) of the survey strategy[2]. We used version 1.7 of the simulations. In collaboration with the Dark Energy Science Collaboration (DESC), we chose seven LSST strategies to analyse in our work. Each of these strategies are described on the LSST community public forum[3]. Most strategies tweak various observational parameters such as the survey footprint, filter pairings, and rolling cadences with the aim of creating a final optimised strategy that meets the LSST science requirements.

Our simulation pipeline uses the `SNANA` package[1] to generate light curves as observed under the conditions presented in each LSST strategy. The LSST OpSim files are converted to an SNANA-compatible file by the `OpSimSummary`[2] package. SNANA is hosted on the Cori supercomputer under the DESC project affiliation and we process the files under their standard prescription described in [3]. The output from SNANA is stored in an SQL database which forms the basis of our data analysis framework. The software and metrics description for this is presented in our LSST:UK deliverable D3.3.1[4].

The second branch of the simulation requires a 4MOST survey strategy to perform mock spectroscopic follow-up of the LSST transients. These strategies are privately hosted within the 4MOST collaboration. The current 4MOST simulations contain simple solutions to tile the sky with the 4MOST instrument, providing information such as the sky coordinates and epoch of each pointing over the 5-year survey. An algorithmic breakdown of the tiling solution is presented in [5]. Again, a description of how we process these files is contained within D3.3.1[4].

Our LSST simulations contain the light curve information for the set of transients for this survey. The 4MOST simulations tell us on which nights certain regions of the sky will have spectroscopic coverage. Hence, a cross-match of these data will produce a set of transients for which we will obtain spectra. In the following section our Cadence Note presents how the population and properties of our spectroscopically observed population changes under different LSST strategies.

4 The Cadence Note

In this Section we append the TiDES Cadence Note to the document. The submitted version to LSST is publicly available from their Cadence Note repository along with all the other community submissions[4].

[2] http://astro-lsst-01.astro.washington.edu:8081
[3] https://community.lsst.org/t/survey-simulations-v1-7-release-january-2021/4660
[4] https://www.lsst.org/content/survey-cadence-notes-2021

References

[1] Richard Kessler et al. 2009,"Enabling Catalog Simulations of Transient and Variable Sources Based on LSST Cadence Strategies" DOI 10.3847/1538-4365/ab72f2.

[2] Rahul Biswas et al. 2020, "SNANA: A Public Software Package for Supernova Analysis" DOI 10.1086/605984.

[3] Richard Kessler et al. 2019, "Models and Simulations for the Photometric LSST Astronomical Time Series Classification Challenge (PLAsTiCC)" DOI 10.1088/1538-3873/ab26f1.

[4] LSST/TiDES Metrics Software, Project Deliverable D3.3.1.

[5] Elmo Tempel et al. 2020, "An optimized tiling pattern for multiobject spectroscopic surveys: application to the 4MOST survey" DOI 10.1093/mnras/staa2285.

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The Time-Domain Extragalactic Survey Cadence Note

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ABSTRACT

The 4m Multi-Object Spectroscopic Telescope (4MOST) Time-Domain Extragalactic Survey (TiDES) is primed for the spectroscopic follow-up of LSST transients at an industrial scale. TiDES will use its 250,000 fibre-hours to conduct a comprehensive census of the time-domain sky with a focus on 3 key science areas: (i) spectroscopic observations of live transients, (ii) redshift measurements of host-galaxies for supernova photometric classification and cosmological measurements, (iii) cadenced spectra to enable the reverberation mapping of Active Galactic Nuclei out to z=2.5.
In this note we explore the effect of several LSST cadence simulations on the TiDES transient and AGN samples. This document is submitted in response to the solicitation for Cadence Notes[a)]

QUESTION 1: FOOTPRINT

The current 4MOST observing strategy (Tempel et al. 2020) covers the entire southern sky between $-80 <$ decl. $< +5$ with at least 2 observations over the 5-year survey lifetime. Extending the LSST footprint to higher declinations will result in the discovery of additional transients that TiDES will not observe. While extending to more southerly declinations — where 4MOST does observe — will certainly mitigate this, the extra area will come at the expense of fewer total visits and shallower integrated depths. In Figure 1 we show the 4MOST footprint visit-density and overlap the boundaries of two LSST cadence footprints. The `baseline_nexp2_v1.7_10yrs.db` cadence file sufficiently envelopes all observations from the 4MOST survey and would, therefore, provide better sampled light curves.

QUESTION 2: ADDITIONAL TIME ALLOCATION

The DDFs will be visited by 4MOST at least every 14 days for the TiDES AGN reverberation mapping project. This will also produce increased opportunities for the rapid spectroscopic classification of transient objects with improved light curves compared to the WFD fields. Furthermore, with repeat visits, TiDES is able to stack spectra of SN host galaxies for observations of more distant targets. The DDFs will provide a sample of transients in these higher redshift galaxies compared to WFD, this is crucial for improving the constraints on cosmological parameters. Furthermore, TiDES AGN RM will use LSST multi-band light curves to recover the intrinsic accretion disk variations that drive the broad line variations. For this, a cadence at least twice as high as the spectroscopic observations are required

a) https://docushare.lsst.org/docushare/dsweb/Get/Document-36755

($\lesssim$7 days) in at least g or r band. LSST single epoch depths in the DDFs are several magnitudes deeper than the limiting magnitude for 4MOST. Therefore, we prefer an observing strategy that maximises observing season in the DDFs over one that maximises single epoch depth. TiDES would advocate for any additional observing time be spent on the DDFs to improve both the SN and AGN light curve sampling, resulting in reduced systematics in the final cosmological parameters. The conclusions we draw from our analysis are the same as those presented in the DESC cadence note.

QUESTION 3: U-BAND EXPOSURE TIMES

Spectroscopic follow-up prioritisation for the the TiDES SN Ia sample is not governed by observations in the u-band because it is unlikely many supernovae would be detected to high significance in this filter. We analysed the `u_long_ms_50_v1.7_10yrs.db` cadence file and compared this to the `baseline_nexp2_v1.7_10yrs.db` in Figure 2 (along with several other cadence assumptions). As can be seen, the u-long 50s cadence shows little effect on several of our metrics.

Observations in the u-band, however, are useful for the early identification of fast-transients, such as kilonovae (KNe) or fast-blue-optical transients (FBOTs), and may help identify contaminants in SNe Ia photometric cosmology samples. 4MOST/TiDES is not the ideal survey for rapid, targeted classification of unusual transients, however, chance-encounters are likely. Additional data beyond *griz* may well help TiDES map the diversity of the transient phase-space and train machine learning algorithms for photometric classification. Though overall, the TiDES primary science goals appear unaffected in a comparison between `baseline_nexp2_v1.7_10yrs.db` and `u_long_ms_50_v1.7_10yrs.db`, we therefore take a neutral position on the u-band exposure time discussion.

QUESTION 4: FILTER DISTRIBUTIONS

The TiDES metrics perform well with the `baseline_nexp2_v1.7_10yrs.db` cadence and we see no strong case to significantly depart from this to bias towards bluer or redder filters.

QUESTION 5: VISIT PAIRS

Intra-night visit pairing in the same filter has a strong detrimental effect on transient science from TiDES. To test this we analysed a TiDES-cosmology sample using the `baseline_samefilt_v1.5_10yrs.db` cadence simulation. This is by-far the worst performing cadence of our simulation set. The performance of `baseline_samefilt_v1.5_10yrs.db` is shown in Figure 2 where there is an almost 10% increase in the uncertainty on the distance modulus to the SN Ia sample — which is crucial for cosmology — and on the date of maximum brightness. We, therefore, strongly endorse observing strategies that make intra-night observations in different filters. Our case for different intra-night filters is strongly supported by the findings in the DESC cadence note.

TiDES will also use its vast spectroscopic sample to train machine-learning algorithms for photometric classification of transients (Carrick et al. 2020). Colour information on a single epoch can help the rapid and early photometric classification of transients.

Two randomly chosen SNe Ia are shown in Figure 3, with observed light curves generated under several cadence assumptions. The light curves observed under the `baseline_samefilt_v1.5_10yrs.db` cadence file are clearly inferior to other strategies; they lack multi-band observations that are critical for constraining colour evolution. No significant temporal evolution is expected between the same-filter-same-night re-visits, with little new information gained about the transient other than an improved signal-to-noise. This is further supported by Figure 2 where we count the unique epochs and filters as single pre- and post-peak detections to show that there are 30% fewer light curve points from `baseline_samefilt_v1.5_10yrs.db` compared to `baseline_nexp2_v1.7_10yrs.db`.

QUESTION 6: ROLLING CADENCE

In principle, rolling cadence strategies should have a clear benefit to transient science, chiefly, that light curves are better sampled. Not only would this allow for better studies of individual objects, but would also improve the photometric classification of transients and hence the purity of any resulting SN Ia cosmology samples. We do not, however, see this improvement in any of our metrics presented in Figure 2. It may seem surprising that our simulations using the `rolling_scale0.2_nslice2_v1.7_10yrs.db` and `rolling_scale1.0_nslice2_v1.7_10yrs.db` cadence files do not show a substantial improvement over `baseline_nexp2_v1.7_10yrs.db` — with only a small percentage increase in the number of pre- and post-peak detections in Figure 2 — but we believe this is due to a rolling cadence being

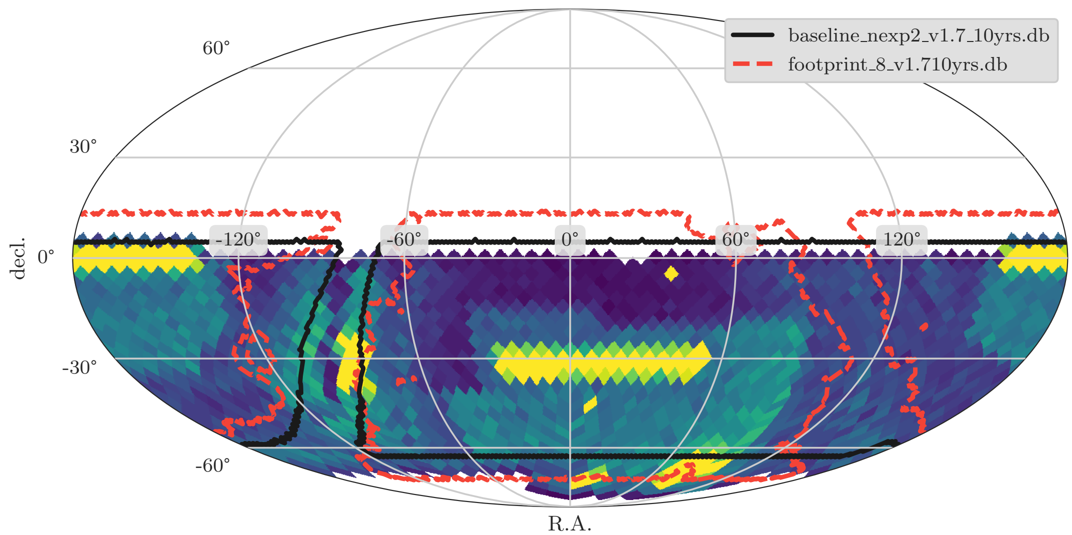

Figure 1. The 4MOST sky coverage is show by the heatmap with the scale determined by the number of repeat visits. The 4MOST footprint will be observed at least twice (purple on the colorscale) with the LSST DDFs more frequently observed (at least every 14 days; yellow on the colorscale). Other areas of the sky, such as the WAVES fields (Driver et al. 2019) or LMC/SMC observations (Cioni et al. 2019), are observed more frequently to meet the science requirements of the other 4MOST consortium surveys. The red dashed line shows the boundary of the `footprint_8_v1.710yrs.db` cadence simulation and the solid black line represents the `baseline_nexp2_v1.7_10yrs.db` boundary.

difficult to simulate within the LSST scheduler. Balancing the needs of other science cases that require uniform sky coverage or increased season length is especially challenging for a rolling cadence. TiDES would advocate for continual efforts in producing simulations of rolling cadence strategies in line with the requests of the DESC cadence note. If such a cadence proved successful, TiDES would have a powerful case for 4MOST to adopt a rolling strategy that followed LSST. This would certainly increase the number of young transients that TiDES could classify, allowing the community to follow-up the most interesting candidates.

For TiDES RM, we require continuous light curves in each available observing season of the DDFs. Therefore, for reverberation mapping, a non-rolling cadence of the DDFs is strongly preferred for at least the first 5 years of LSST.

QUESTION 7: DITHERING

Dithering is an essential part of survey operations to mitigate the effects of non-uniform response over the image plane. For 4MOST follow-up, TiDES would strongly argue for a dither strategy that retains an overlap of the central 4.2 deg^2 (the 4MOST field-of-view) of the LSST field for each visit to the DDFs. The TiDES requirements for dithering are shared with DESC and we refer to the findings in their cadence note.

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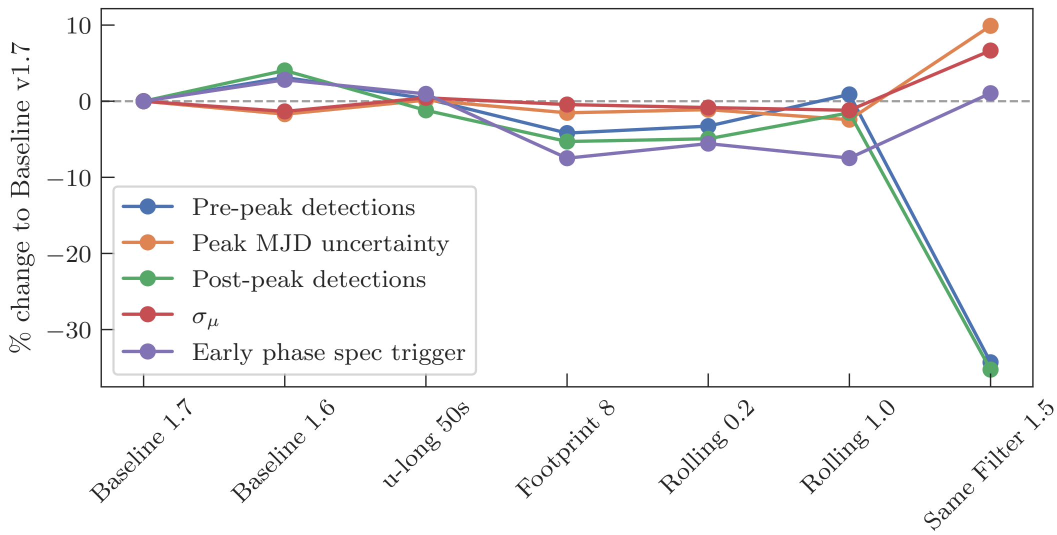
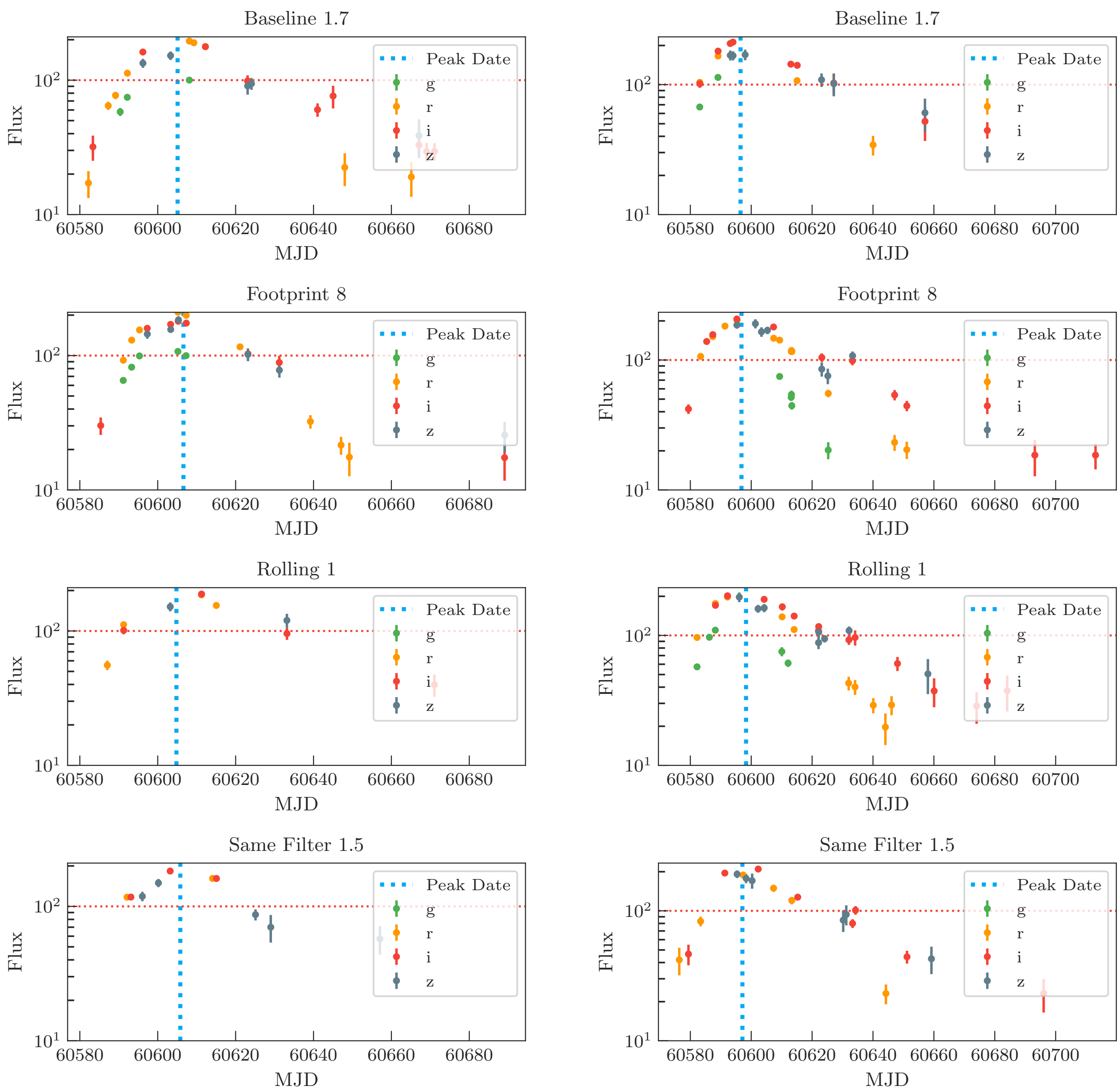


Figure 2. A comparison of several metrics that contribute to the success of the 4MOST/TiDES survey. The metrics shown are evaluated just for the type Ia supernova sample, however, the performance for other SN sub-types is considered in the arguments presented in this document. We show the percentage change from the `baseline_nexp2_v1.7_10yrs.db` cadence simulation. The number of pre-peak detections ($> 5\sigma$ in any filter) is represented by the blue circles. Here, peak is defined as the date of maximum brightness in the B-band. The number of post-peak detections is shown by the green points. We fit the SALT2 model to the light curve to determine the uncertainty on our date of peak. Equivalently, we use the SALT2 model to compute the distance modulus, μ, for each SN Ia and present the uncertainty on this with the red circles. Finally, the light curve phase we trigger the object into the 4MOST queue is shown by the purple points (positive values indicate earlier triggering).



(a) (b)

Figure 3. Two different type Ia supernovae are observed in our simulations under different cadence assumptions. Each 5σ observation in the `griz` filters is shown and the date of maximum brightness is marked by the blue dashed line. The horizontal orange dotted line shows the typical limiting depth of a 1 hour spectrum taken by 4MOST. Early light curve triggering allows a greater opportunity for a live classification spectrum to be taken at phases above this flux limit. Once a supernova has faded below this, the host-galaxy will be targeted to measure the redshift of the target. We will be able to reach greater depths as multiple epochs of galaxy spectra can be stacked to improve signal-to-noise .