Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) Solar System Science Collaboration (SSSC) Cadence Note

Meg Schwamb[1], Michele Bannister, Bryce T. Bolin, Rosemary Dorsey, Henry Hsieh, Lynne Jones, Laura Inno, Tim Lister, Colin Snodgrass, Sarah Greenstreet, Cyrielle Opitom, Kat Volk, Siegfried Eggl, Michael S. P. Kelley, Steve Chesley, Wes Fraser, Alan Fitzsimmons, Mario Jurić, William J. Oldroyd, Robert Seaman, and Michael Solontoi

For the LSST SSSC

[1] Corresponding author: mschwamb.astro@gmail.com

1. SSSC Evaluation Workflow

The SSSC chose a unified approach, equally considering the impact to NEOs (Near Earth Objects), interstellar objects, Trans-Neptunian Objects (TNOs), Main Belt Asteroids (MBAs), and comets/active objects. Secondary consideration was given to the giant planet Trojans. Using the SSSC Science Roadmap ([Schwamb et al. 2018](#)), we evaluate in priority order the impact on 1) discovery/orbital characterization, 2) color measurements, and 3) rotational light curves. Comparing to the relevant baseline cadence or within a simulation family, reductions in relevant metrics[2] larger than ~5% were deemed unsuitable. This threshold enables our key goals, which are derived from increasing sample sizes by an order of magnitude, while buffering against any future unexpected small observing time losses. We label each simulation as: '**silver**' ('preferred'), '**green**' (acceptable), '**red**' (not acceptable), or '**blue**' (requires testing during commissioning). These assessments are also captured in this spreadsheet. We note that scenarios currently labeled 'green' or 'silver', may become 'red' when combined with other scenarios in future simulations. We also stress that we have only compared the relative performance of the version 1.5, 1.6, and 1.7 simulations; we have not verified if they perform favorably relative to previous simulations older than version 1.5.

2. Question 1 - Wide Fast Deep Footprint (WFD)

Are there any science drivers that would strongly argue for, or against, increasing the WFD (Wide Fast Deep) footprint from 18,000 sq. deg. to 20,000 sq.deg.?

We favor expanding the WFD footprint with part of the additional sky coverage in the Northern Ecliptic Spur (NES). The original WFD footprint includes half of the ecliptic plane. The NES is ~5800 deg^2 from 0° declination northward up to +10° ecliptic latitude. **Observing the NES as part of the WFD and/or mini-survey is our highest priority request.** Surveying the NES provides significant gains for TNOs, interstellar objects, and active objects. It provides unique science opportunities with Neptune Trojans, active asteroids, Inner Oort Cloud objects, and resonant TNOs (see Schwamb et al. 2018). For footprint, we classify **barebones_v1.6_10yrs, barebones_nexp2_v1.6_10yrs,** and **filterdist_indx2** (only for footprint considerations), as red; they include no NES pointings, resulting in a 30% loss in TNOs. **footprint_big_sky_nouiyv1.5_10yrs** includes the NES, but we consider it red due to the drop in TNO discoveries (which are more easily detected in r and i filters) and the loss of i-band for color estimates. Simulations **wfd_depth_*, baseline_nexp2_v1.7_10yrs.5_10yrs**, and **footprint_[0,1,2,3,4,5,6]_v1.710yrs** are green as they do well for our key metrics. We label **footprint_newAv1.5_10yrs, bulges_cadence_bs_v1.5_10yrs**, and **footprint_[7,8]_v1.710yrs** red due to the impact on small NEOs/Jupiter Trojans rotational light curves. The remaining **bulges*_v1.5_10yrs** simulations and **footprint_newBv1.5_10yrs** are silver due to the increased detections. The **baseline_v1.5_10yrs** and remaining **footprint*v1.5_10yrs** simulations are green.

3. Question 2 - Mini-Survey and Deep Drilling Field (DDF) Observing

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. What is the best scientific use of this time?

Snaps: If possible, we favor 1x30s (**baseline_v1.5_10yrs, baseline_nexp1_v1.6_10yrs,** and

[2] The completeness at a given absolute magnitude (H) with the DiscoveryMetric, the number of gri nightly pairs suitable for moving object detection using the PairMetric, and the fraction of objects at a given H with suitable observations for light curve inversion with the LightcurveInversionMetric. Plots showing the variations of these metrics compared to a relevant baseline can be found here and also generated with this notebook.

baseline_nexp1_v1.7_10yrs) over 2x15s snaps (**baseline_2snaps_v1.5_10yrs, baseline_nexp2_v1.6_10yrs, baseline_nexp2_v1.7_10yrs**) because of the increased observing time. Variable snaps (**var_expt_v1.5_10yrs**) will change which populations are streaked; commissioning tests are needed to assess the impact.

NES & WFD Depth: Our Question 1 response also applies here. **We ask that the portion of the NES not included in the WFD be observed in a mini-survey** (see Schwamb et al. 2018). All simulations covering the NES have >~700 griz visits per NES field; this is suitable for our needs. Therefore we classify the **wfd_depth_scale[0.65-0.90]***, **mw_heavy***, and **combo_dust_*,** and **wfd_depth_scale0.95_noddf_v1.5_10yrs**, simulations are green. We also classify **wfd_depth_scale0.99***, **wfd_depth_scale0.95_noddf_v1.5_10yrs**, and **wfd_depth_scale0.95_v1.5_10yrs** cadences red due to the impact on lightcurve inversion for faint MBAs. The **dm_heavy*** and **ddf_heavy*** simulations are red because they generate significant losses (> 20% drop) for Jupiter Trojans.

Twilight Solar System Mini-Survey: We propose a modification to this mini-survey that achieves our science goals while saving more time for WFD observations. We propose a 4 nights on, 4 nights off cadence, observing solar elongations (SE)≲60° using 50% of the twilight time during the 'on' period. **Observing the low SE sky during evening and morning twilight is the only time when viewing Solar System objects (SSOs) inward to Earth is possible**. This would make LSST uniquely sensitive to inner-Earth objects (IEOs; NEOs on orbits interior to Earth's orbit), Earth Trojans, and sun-grazing comets (see Seaman et al 2018). Recent observational evidence suggests a larger abundance of IEOs compared to asteroid models (Ip et al. submitted); an LSST SSO twilight survey would be able to test this. The **twi_neo_pattern5_v1.7_10yrs** (4 nights on, 4 nights off, SE≲60°using 100% of twilight time) simulation significantly boosts overall NEO discovery and finds IEOs (which are completely missed in the WFD survey). The sequential 4 nights on would enable LSST to self-recover discoveries made during the 4-night-on session. Dropping to 50% of twilight time (as opposed to all of twilight time as simulated) with 3 observations per field per night during each 4-night-on session would suffice for IEO discovery/recovery and allow the other 50% of twilight time to be used for other observing. The 4-on-4-off cadence can be a bit flexible as needed to allow for things such as Moon avoidance.

DCR, good seeing, short exposure mini-surveys & DDFs: The differential chromatic refraction (DCR) mini-survey, with extra high airmass exposures, has no significant benefit for our science. We find **dcr_nham[1,2]_ug_v1.5_10yrs** and **dcr_nham1_ugri_v1.5_10yrs** are green. **dcr_nham2_ugri_v1.5_10yrs** is red due to the impact on MBA discoveries. **dcr_nham[1,2]_ugr_v1.5_10yrs.5_10yrs** are red due to the impact on NEO light curves. Our metric thresholds are met for the the short exposure (**short_exp***) and the **goodseeing*** (prioritizing a good seeing image per year in certain filters) mini-surveys; we classify those scenarios green. Solar System science is not a driver for the planned DDF fields, but we have a preference for the **baseline_v1.5_10yrs, descddf_v1.5_10yrs.5_10yrs,** and **agnddf_v1.5_10yrs** DDF cadences because **daily_ddf_v1.5_10yrs** is labeled red due to the impact on the rotational light curves of small NEOs.

4. Question 3 - u-band exposure times

Are there any science drivers for, or against, changing the u band exposure from 2x15 s to 1x50 sec?

We classify **u_long_ms_[30,40,50]_v1.7_10yrs** as green. Longer (1x40s or 1x50s) u-band exposures are advantageous for the detection of faint gas activity levels on SSOs. However, the **u_long** simulations with exposures time > 50s (and especially the **u_long_ms_60_v1.7_10yrs** which we classify as red), should be avoided as they decrease significantly the number of detections of faint NEOs and trojans and the number of SSOs for which lightcurve inversion can be performed. This derives from the lower number of observations performed in other filters.

5. Question 4 - Observing Time Allocation Per Band/Filter Distribution

Are there any science drivers for, or against, further changes in observing time allocation per band?

We find that the **filterdist_indx2** (baseline-like; ranked silver) and **filterdist_indx6** (i-heavy; ranked green) simulations produce the best discovery rates for most SSO populations and are our preferred filter allocations for SSO science. While most other filter distributions incur an acceptable <5% variation in discovery rates, **filterdist_indx1** (uniform) and **filterdist_indx4** (u-heavy) incur a significant decrease (>5%) since SSOs tend to be much fainter in u-band (e.g., Volk et al. 2018), therefore arguing against the use of blue-heavy cadences. Meanwhile, we find that the **filterdist_indx2** and **filterdist_indx6** simulations produce much better light curve inversion coverage (increases of 70-150% for faint PHAs and NEOs) than heavily red- or blue-skewed filter distributions. For example, the **filterdist_indx1**, **filterdist_indx4**, and **filterdist_indx5** (z- and y-heavy) simulations show large decreases (50-90%) in light curve inversion rates for faint MBAs and Trojans. Additional science drivers (e.g. compositional characterization of asteroids and comets, detection and characterization of their gas production) benefit from additional u and g-band photometry. These drivers therefore also argue against the use of heavily blue- or red-skewed filter distributions (such as **filterdist_indx1**, **filterdist_indx4**, and **filterdist_indx5**). We find that the **filterdist_indx3**, **filterdist_indx7**, and **filterdist_indx8** simulations provide acceptable discovery rates but a ~20% decrease in the light curve inversion metric for MBAs; thus we classify them red.

6. Question 5 - Filter Distribution for Nightly Visits and Nightly Pair Separation

Are there any science drivers 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?

Section 6.1 Nightly Filter Distribution and Triplet Visits: For our discovery metric, there is no significant difference between same-filter (**baseline_samefilt_v1.5_10yrs**) and mixed-filter (**baseline_v1.5_10yrs**) pairs (same-filter pairs boost faint discoveries by a few percent). Both are classified green. This is because the mixed-filter pairs simulation contains g-r and r-i pairs, and visits in gri are the most helpful for detecting SSOs, with r-i pairs better for the reddest objects like TNOs; see, e.g., Schwamb et al. (2019). None of the cadence simulations tested r-r pairs near opposition visits to try to maximize SSO discoveries (proposed in Volk et al. 2018); if the desired filter combinations for other science cases differ from those already simulated and negatively impact Solar System metrics, we suggest simulations that add r-r pairs. There is no significant impact from the simulated third visits (in mixed griz filters) on discovery or lightcurve metrics, but fewer small NEOs are found as the third visit fraction increases. Thus, we classify all **third_obs*** simulations as green. The cadence_drive_gl family investigates adding "fill-in" g-band visits to the filter cadence. Most of these (**cadence_drive_gl[30,100]***) are green for our metrics, however the two simulations with the most time devoted to these visits (**cadence_drive_gl200***) are red because they significantly reduce (50-80% compared to baseline) the number of faint SSOs with lightcurve inversions.

Section 6.2 Nightly Pair Separation: The time separation between nightly pair visits determines the maximum heliocentric distance at which the Rubin Observatory's Solar System Processing (SSP) pipelines[3] can discover new SSOs. 11 minute separations enable discoveries

[3] SSP requires motion to be detected between nightly pairs in order to discover new SSOs.

out to 50 au. The classical Kuiper belt would be detected, but the scientifically interesting detached high-perihelion TNO population (75-100 au) would be missed. Being able to detect motion out to at least 75 au is important for the SSSC, which requires pair separations of greater than ~18 minutes. Separations longer than ~40 minutes push the detection distance outward, but negatively affects total detections due to more incomplete pairs within a night; longer separations can also negatively impact linking of fast-moving NEOs. Therefore **pair_times_[11, 44, and 55]_v1.7_10yrs** are all labeled red. Pairs at 33 minutes is a good compromise for all SSO populations which is why we classify **pair_times_33_v1.7_10yrs** as silver and **pair_times_22_v1.7_10yrs** as green.

7. Question 6 - Rolling Cadence and AltScheduler North/South Nightly Patterns

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?

Given that the majority of SSOs, other than NEOs and comets, will be discovered during the early survey before rolling cadence (RC) starts, we find little impact on the metrics from the use of the RC. The higher strength RCs (v1.7 simulations ***_scale[0.8,0.9,1.0]_*** either with or without modulation, and for all stripe patterns) and the v1.7.1 simulations **full_disk_*, rolling_nm_scale0.90***, and **six_stripe*** are labelled red as they cause a large drop-off in both discovery and light curve inversion metrics for MBAs and Jupiter Trojans. Overall, **RC versions with scale < 0.8 and bulge_roll*** cadences have little impact over baseline for most SSO science. The main negatives are on the cadence for characterizing comet activity, where baseline gives a more consistent <1 week gap, and on the discovery and light curve metrics for the Trojans, likely due to the Trojan clouds being out of the surveyed area in ‘off’ years. In general, RC gives a slight advantage in discovery metrics, but in ‘off’ years there could be significant areas of the sky where no new detections are possible at all, **a potential concern** for rare discoveries like interstellar objects. Strong winds frequently come from the North in Chile, which may prevent observations in that part of the sky, potentially having a large impact on the north-pointing nights with the AltSched N/S modulated RC. Wind direction and strength are not included in the cadence simulations; **this may merit further study**.

8. Question 7 - Dither Patterns and Camera Rotations

Are there any science drivers pushing for or against particular dithering patterns (either rotational dithers or translational dithers?)

Dither patterns which are favorable for high-quality image differencing are preferred, given SSP’s dependence on image differencing. We have no science drivers affecting the selection of dither patterns. All **euclid_dither***, **ddf_dither***, and **spiders*** simulations are classified green.

References

Ip, W. H., et al. submitted, arXiv:2009.04125.

Schwamb et al. 2018. “A Northern Ecliptic Survey for Solar System Science”. LSST Cadence Optimization White Paper, arXiv:1812.01149

Schwamb et al. 2019. “Col-OSSOS: The Colors of the Outer Solar System Origins Survey”. ApJS, Volume 243, Issue 1, article id. 12

Seaman et al. 2018. “A near-Sun Solar System Twilight Survey with LSST”. LSST Cadence Optimization White Paper, arXiv:1812.00466

Volk et al. 2018. “The Effects of Filter Choice on Outer Solar System Science with LSST”. LSST Cadence Optimization White Paper, arXiv:1812.00937