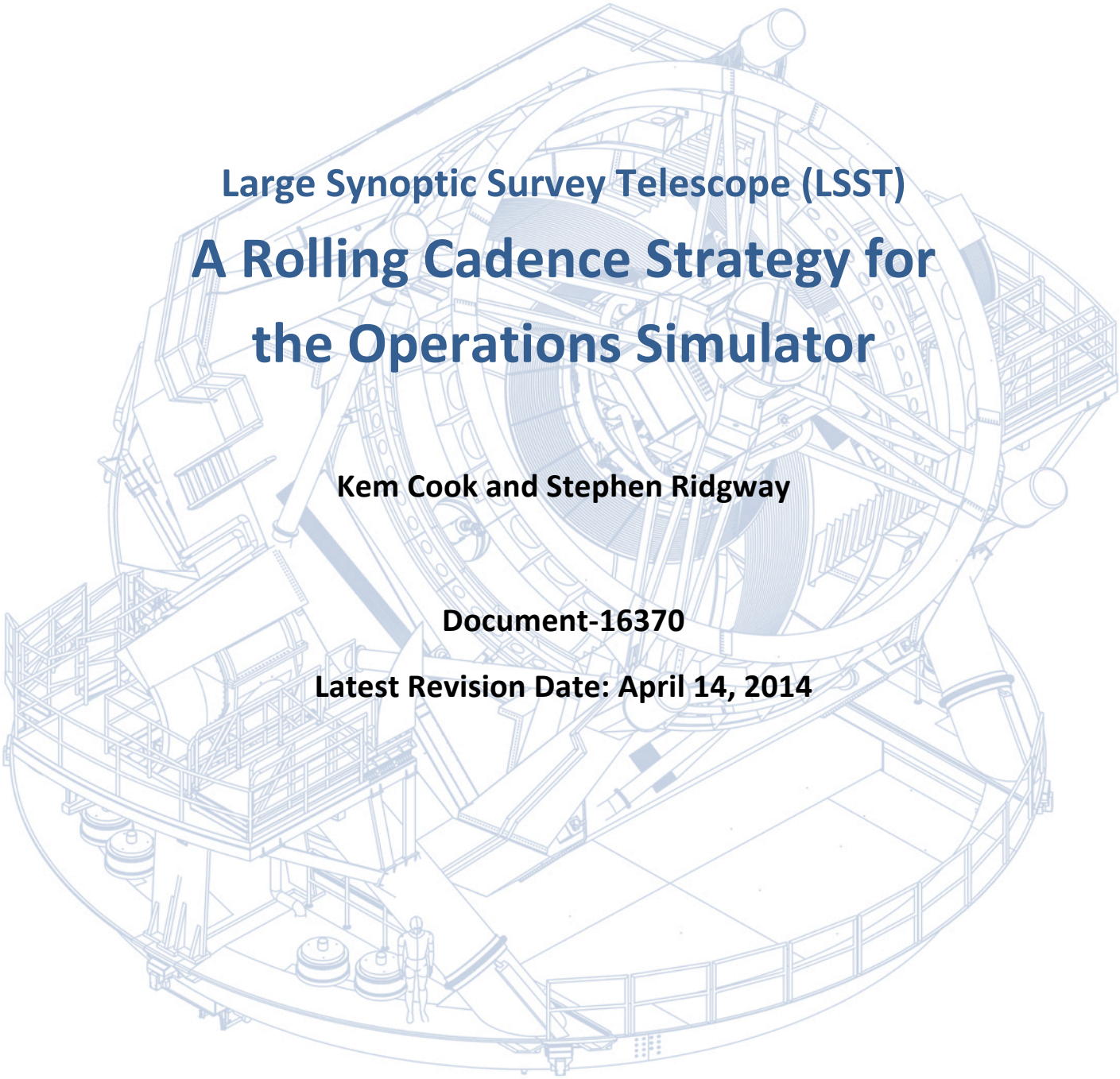
LARGE SYNOPTIC SURVEY TELESCOPE



Large Synoptic Survey Telescope (LSST)

A Rolling Cadence Strategy for the Operations Simulator

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1.0	2013-12-17	First draft for discussion	Ridgway
1.1	2014-01-15	Added 3-year cycle, per Eric	Ridgway
1.3	2014-04-07	Added objectives for first rolling cadence experiments	Ridgway

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A Rolling Cadence Strategy for the Operations Simulator

Summary

The conceptual observing strategy for the LSST is a *universal cadence*, in which all parts of the sky in the wide-fast-deep survey are observed similarly – most simply in a pattern that is uniform through the full 10 years of the survey. For a number of reasons, it is timely to consider extensions of the universal cadence concept for which each region of the sky would be visited for a fraction of the survey with a cadence that differs from the average or uniform cadence. The class of patterns that provides such a cadence, with the focus region shifting from time to time, is termed a *rolling cadence.* This report describes a number of basic considerations for the design and implementation of a rolling cadence in the operations simulator.

Definitions of Terms

Dithering - Adjusting the pointing on revisits, typically by less than the field half-width, to improve the uniformity of the stacked image and reduce the signature of field shape and visit pattern.

Field – the standard tiling of the sky in hexagonal units approximately equal in size to the LSST field of view

OpSim – the operations simulator

Rolling cadence – a visit sequence that is applied to each part of the sky, but for only part of the survey

Rolling cadence cycle – the length in time of the basic rolling cadence program, which may repeat

Rolling cadence units – regions on the sky selected for a rolling cadence

Simulation – a simulated LSST observing schedule, produced by a run of the operations simulator

Visit – a single pointing to a single field, with a data acquisition cycle consisting of recording of two images which are merged into a single image product

Reference Documents

TBD

A Rolling Cadence Strategy for the Operations Simulator

1 Overview

The LSST 10-yr survey will visit each part of the main survey sky in the r or i filter approximately 824 times (design specification). These visits will be almost entirely scheduled as visit pairs, with a spacing of ~30 minutes. For most science, the 30-minute pairs are effectively a single visit epoch. If distributed uniformly, this corresponds to 41 visit epochs per year. Assuming an observing season of 6 months, it then corresponds to an interval between epochs of 4 days during the observing season.

For some targets, it may be more important to have a visit series in a single filter. For the most frequently used filters, r and i, the typical interval between epochs in each would be ~20 days.

Many science programs would benefit from more frequent visits. This cannot be supported for all the sky all the time by a universal cadence. However, it could be supported over part of the sky part of the time by a cadence that increased the visit rate in part of the sky for a limited interval. By rotating the region selected for temporarily higher cadence, substantial parts of the sky could be covered in this way. The class of cadences that provides such rotating intervals of enhanced visits, with the focus region shifting from time to time, is termed here a rolling cadence. In one interesting limiting case, the entire wide-fast-deep survey could be subjected to a rolling cadence, preserving some elements of the universal cadence concept. This report describes a number of basic considerations for the design and implementation of a rolling cadence in the operations simulator.

The following discussion reveals a number of major considerations for rolling cadences.

- There are several possible general approaches to a rolling cadence.
- A large investment of visits in increased sampling in rolling cadence(s) imposes a substantial reduction in the sampling rate for the rest of the survey.
- In order to provide good sampling over a range of time scales 1-30 days, several rolling cadences might be required.
- An essential design choice for a rolling cadence is the choice of filters.
- Dithering reduces the efficacy of a rolling cadence.

2 Customers for Enhanced Sampling

Interest in a rolling cadence has not been systematically surveyed, but the science collaborations have expressed interest in the following benefits.

- Improved sampling for SN studies in the main survey
- Improved cadence for the determination of time lag in strong lensed galaxies (for the case of short lag)
- Early increased sampling of a subset of fields as a way of jump-starting science programs faster than might be possible with a uniform survey
    - for identification of particular types of galactic variables early in the survey

- to reach greater depth over part of the sky early in the survey

Among these, several groups are carrying out studies to determine the degree of benefit delivered by various possible cadences. At present they are limited to estimating possible cadences without support from OpSim, which has not yet been employed for cadence experiments.

3 High Level Questions

This document is only a first pass at systematizing the discussion of rolling cadences, and we can't expect it to uncover all the issues or reach definitive conclusions. Here is a list of questions that we can hope to answer provisionally to let us move ahead with OpSim experiments.

- What range of enhanced cadence is possible at what approximate cost?
- Do we want to initially focus on a single simulation experiment, or try to implement a very general capability?
- Do we want to lock the filter mix at the standard ratios, or define a new mix for the (each) rolling cadence?
- Do we want to automate the tiling of the sky into rolling units from parameters, or provide it by other means?

A major consideration in reading this report is in identifying what has been overlooked.

4 Enhanced Sampling

The objective of the rolling cadences considered here is to provide more frequent sampling of each part of the sky during a fraction of the survey. One cost of this enhanced sampling for each region is a reduced sampling rate for the same regions during other parts of the survey (when other regions are receiving enhanced sampling).

A simple way of looking at the cost/benefit in cadence terms is to consider a single field that would normally have a total number of visits Ntot, spread "uniformly" over 10 years. As a simple conceptual example, we assume that the visits are redistributed so that a fraction f1 of the total visits is subtracted from the standard cadence, and redistributed over a fraction f2 of the full survey. This is illustrated in Figure 1.

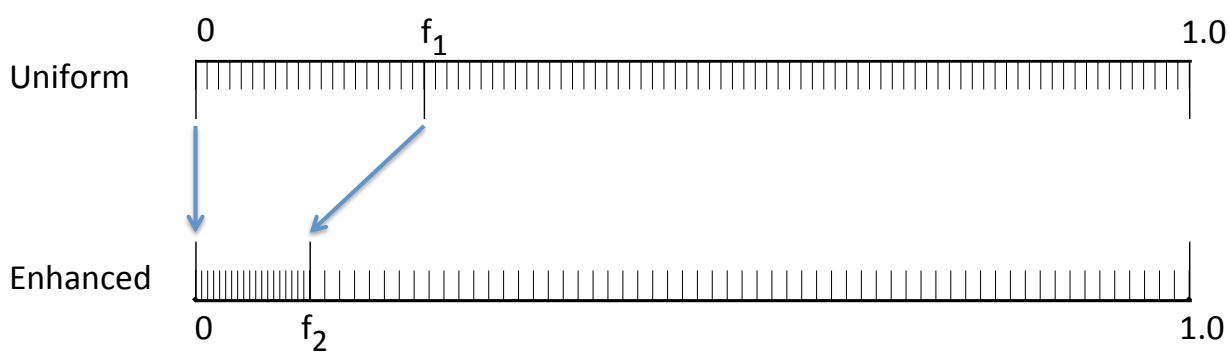

Figure 1. The horizontal scale represents time and is labelled by the fraction of the survey. The fine tics represent visits, here assumed uniformly distributed in the "uniform" survey. For an enhanced cadence, fraction f1 of the visits are achieved in fraction f2 of the survey time. In this example, the enhanced interval achieves a 2X average visit rate, and the balance of the survey has distinctly reduced visit rate.

In this model, the sampling rate *enhancement* during the high cadence interval would be f1/f2, and the sampling rate *reduction* during the rest of the survey would be (1-f1)/(1-f2). This lets us consider some typical numbers for example science objectives.

The parameter f1 most strongly determines how large is the impact on the non-enhanced survey. Whereas values of f1 in the vicinity of 0.1 to 0.2 produce fractional reductions in the visit rate during the balance of the survey, and may be relatively benign, values of f1 ~ 0.5 produce substantial (2X) impact.

The ratio f1/f2 determines how significant the enhancement of sampling will be. Imposing the complications of a rolling cadence might not be justified by a small fractional enhancement, but a visit rate increased by 2-10X could have a significant value.

These rough arguments lead us to expect interest in cadences that utilize 1-2 years of standard-rate visits to enable periods of enhanced cadence. Taking into account the limited observing season, this suggests redeploying 1 – 2 years of visits over 0.5 – 6 months.

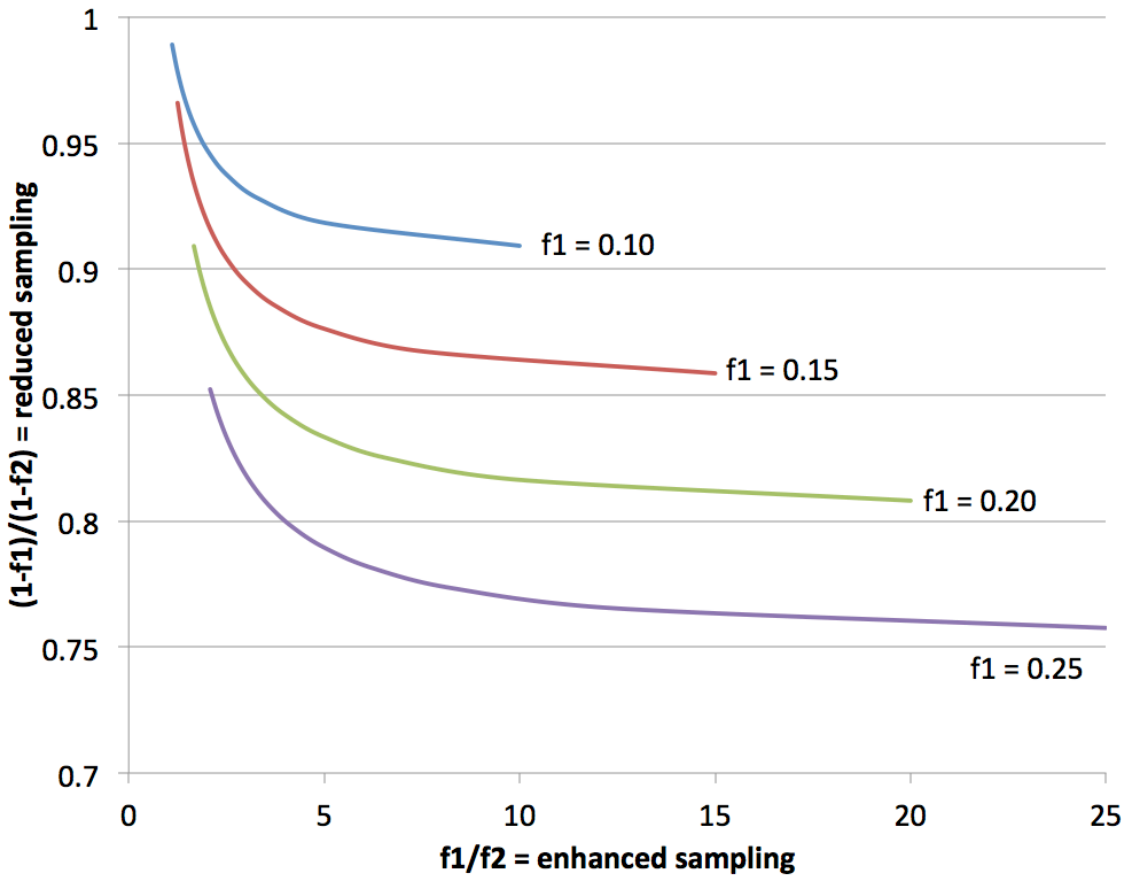

Figure 2. For values of f1 in a range likely to be of interest, this chart shows the price paid in reduced sampling during the rest of the survey as a function of the accessible enhancement of sampling available. When interpreting this figure, it is important to recall that a typical field is conveniently accessible for approximately 6 months per year, and most of the year's visits to the field will take place within 6 months. Therefore, the typical cadence of the standard survey corresponds approximately to F1/F2 = 2. Furthermore, this figure is based on the assumption that all rolling cadence visits are acquired as visit pairs, the same as the main survey. This is probably not a good assumption and the figure should be recalculated for single visits instead of pairs.

A way of visualizing the trade is shown in Figure 2. Quite large enhancements are possible with modest corresponding reductions in the rest of the survey. However, it is important to remember that we are discussing quite small epoch counts per field – in the r or i filter, f1 = 0.1 – 0.2 corresponds to only 9 – 18 visit-pairs.

4.1 Some Complications

- The actual cadence rates depend on the length of the observing season, which could vary due to declination (different duration of accessibility) or intentionally (e.g., shortened to enhance the cadence, or lengthened to minimize the annual inter-season gap.

- Rapid sampling in a single filter could provide one type of information, and rapid acquisition of multicolour information could provide another type of information.
- Filter swaps needed to best utilize dark sky time will limit the availability of certain filters at certain times during the month.
- The requirement for visits to be obtained as visit pairs may be eased as visits become much more frequent.

5 Some Possible Cadence Strategies

A completely general rolling cadence can be arbitrarily complicated, so we just give two examples that have been discussed.

5.1 Ten-year Simple Cycle

The simplest pattern requires the division of the observed sky into 10 equal units, with each observed at an enhanced rate during 1 year. The cadence enhancement can be selected, as in Figure 2, with for example a small enhancement over a number of months, or a larger enhancement over a month or less.

5.2 Three-year Closure

A disadvantage of the 10-year simple cycle is that the stacked depth is inhomogeneous by design until the end of the survey, and is worst early (largest contrast in depth across the catalog). The closure to uniformity could be accelerated by subdividing the rolling cadence visits into 3 independent cycles. For example the sky could be divided into 9 units, with enhanced sampling of 3 units each year. Thus after a cycle duration of 3 years, the entire sky would have undergone enhanced cadence during one session, and at that time the total survey could have converged to uniform depth. Additional cycles could reach uniformity after 6 and 9 years.

5.3 Other Cadence Options

Rather than try to exhaustively illustrate possible rolling cadences, we note that a fairly general approach is to think in terms of a basic cycle length, with an associated number of sky units, and a cadence rate enhancement factor (essentially the f1 and f2 parameters above). More complex cadences may best be described as independent proposals, which can have auto-generated or prescribed patterns, arbitrary field lists and start-stop dates. This could be facilitated by providing a standard set of rolling cadence unit definitions.

5.4 Comparing Cadence Options

Metrics closely tied to science objectives are essential for evaluating the performance of different cadences.

6 Enhanced Sampling in One Filter

To simplify the introduction to rolling cadences, we will start with the case of enhanced sampling in just

one filter, and later consider the additional complications of multiple filters.

6.1 Some Example Rolling Cadences

6.1.1 Slow Transients – SNe

While we do not have firm recommendations from the community, we have been advised by the DESC SN working group that an enhancement of the sampling by 2X would be valuable. Since the typical event length is ~30 days, and to make efficient use of time (in the sense of minimizing truncated series) the enhanced cadence duration should be several months. Let's adopt an interval of 4 months, and assume that 4 months is also the standard observing season. Then increasing the cadence by 2X requires adopting f1=0.2 and f2=0.1, which gives the 2X doubling, and the cost is reducing the cadence for the rest of the survey to 0.89 of original. This sampling could be applied to all or any subset of filters.

There is also a multi-filter requirement for SNe, which is discussed in the multi-filter section below.

6.1.2 Medium-fast Transients – 1 Day Sampling

No sampling pattern covers all event durations. One simple model is a sampling pattern that provides daily visits. Daily visits in r for 20 days would require a maximum of f1 = 0.2. Allowing for the frequent sampling, half of these might be single visits instead of visit pairs, reducing f1 to 0.15.

6.1.3 Medium-fast Transients – Fractional Day Sampling

The next step after daily sampling would be twice daily sampling. Selecting a duration of 10 days with twice daily sampling in r would again require a maximum of f1=0.2, but allowing for the frequent sampling, ¾ of these might be single visits instead of pairs, reducing f1 to 0.125.

6.1.4 Applying Multiple Rolling Cadences

The above patterns can be combined. In dealing with multiple cadences, the f notation must be extended, as in f1(a) where *a* is a cadence algorithm.

From the above, one could apply 3 rolling cadences, achieving double cadence for 4 months, daily sampling for 20 days and twice daily sampling for 10 days. Correcting as described for the possibility of single-visit epochs, the sum of the f1(c) is 0.475. Allowing another small correction for sharing of visits between the three patterns (assuming that they could be contemporaneous) could bring the sum of f1 down to ~0.37, which would reduce the frequency in the rest of the survey to ~ 0.58 [estimate, needs more careful calc]. This shows that attempting to use rolling cadences to cover multiple characteristic time scales can add up to a high impact (2X) on the balance of the survey.

6.2 Ultra-fast Cadences

The fastest possible LSST cadences are already planned for the Deep Drilling fields, giving an interval between epochs as small as a few minutes. The amount of time dedicated to these is expected to be f1 = 0.05 – 0.10. Deep drilling should not be considered a rolling cadence because it more naturally fits the model of a set of mini-surveys with special sequences.

7 Rolling Cadences in Multiple Filters

The discussion above dealt with a single filter. For ease of analysis, a time series in a single filter can be far more easily processed than a series in varying filters. However, for interpretation, measurements in multiple colors will more often than not be essential. Ideally these would be recorded in coeval sets, but in general this will not be the case with LSST, owing to the price in time and reliability of frequent filter changes. As long as images in different filters are obtained in different numbers and at different visits (often on different days) the multi-filter implementation of a rolling cadence offers many options. The most natural would perhaps be to reflect the standard visit ratio in the rolling cadence, but enhancement or suppression of filters would also be possible.

Multiple filters may impact a rolling cadence in various ways. For example, if r and i deliver generally the same information for some purposes, the visits available to both might be merged to enhance the visits in just one. It is possible to foresee interesting discussions ahead.

We note two quite different approaches to defining cadences:

- Flexible Generation of Rolling Cadences - Each cadence in each filter could constitute an independent cadence. In this description, the f notation might become, e.g., f1(a,c), where a is the cadence algorithm and c the color. In addition, a mechanism would be needed to ensure that multiple filter cadences were coordinated to deliver the full package of required observations.
- One-off Definition of Each Rolling Cadence - At the other extreme, one or a few cadences could be generated in considerable detail, each with rules for the numbers and spacing of visits in filters.

8 Problematics

While it may appear that the rolling cadence can be implemented at “no cost”, in fact there are a variety of factors that that may impose potential penalties, which though possibly small should be considered.

- Uniformity of observing conditions – if a large fraction of the observations of a field are in one season, they may be biased by unusually poor or favourable conditions of, e.g., image quality, whether as result of atmosphere or telescope function.
- Proper motions – if a large fraction of the visits are obtained in a short period of time, the effective time base for measuring proper motions will be somewhat degraded.

8.1 Some Areas that will Need Special Attention

- The total number of visits should not be significantly reduced
- The stacked depth should not be significantly reduced
- Sampling of periodic variables of random period should not be compromised
- The timing of rolling cadence units should be selected to not negatively impact parallax determination, and could be selected to enhance parallax by setting the rolling unit visits near maximum parallax factor

- While visits are specified in the SRD to be acquired in pairs, to support solar system science, if visits are greatly accelerated by rolling cadence, this condition may deserve reconsideration.

8.2 The cost of Dithering During Enhanced Cadence

It is widely expected that dithering will be adopted for the survey, offsetting the field of view on successive visits to a field. Dithering by a substantial fraction of the field diameter will impose an efficiency price on the rolling cadence itself, since parts of the cadence unit will not receive the full visit count during the enhanced sampling interval. (Of course the visits will not be wasted as they will contribute to the full survey.)

This can be illustrated with examples. Let's assume the Three-year Closure cadence described above. This corresponds to 600 square degrees per rolling unit. There are several options for defining the units:

- Declination strips – For convenience in accessing a cadence unit over an extended season, equal declination strips would be a natural choice. The strips would have approximate dimensions of a tall trapezoid 70 degrees in height with a width of ~3 degrees in right ascension in the south and ~8 degrees wide in the north. With half-field dithering in the RA direction, a significant fraction of the unit, approaching 25%, would not receive the full visit count. However, if the dithering were entirely in the North-South direction, the loss of coverage might be as small as ~3%.
- Minimum-Circumference Units – this would correspond to approximate squares 25 degrees on a side. For half-field dithering, the incompletely visited area would be ~20% for 2-d dithering and ~10% for 1-d dithering.
- Right Ascension Strips – Cadence units consisting of RA strips could in principle be used. If no more than one epoch is needed per night, the strips could be long, eg 100 degrees in RA by 6 degrees in Dec. With dithering in RA, half-field dithering would result in ~3% incomplete overlap. Such long strips would probably rule out two epochs per night. For shorter, wider strips, the 1-d dithering loss would be proportionally higher.

The conclusion from these examples is that more compact rolling cadence units, smaller dithering amplitude, and 1-d instead of 2-d dithering, all can be traded in reducing the loss of visits to a rolling cadence, but for large amplitude dithering, losses of 3-10% will be the best achievable. It also shows that dithering of non-contiguous fields can carry a high price in overlap efficiency, and dithering of deep drilling fields would be particularly costly.

9 Suggested Requirements for Implementing a Rolling Cadence in OpSim

- **Level 1** – Define an algorithm for the determination of the spatial parsing of the sky into individual rolling cadence units. One configuration parameter is the rolling cadence time devoted to each unit, and a second is the fraction of total visits devoted to each such unit. Automatically generate the unit field list. Another configuration is the list of filters to be observed. Activate the enhanced cadence for each unit according to a prescribed pattern such

as "start cadence on sky unit which is next rising at sunset and which has not yet been observed in rolling cadence".

- **Level 2** – Allow for several definitions of rolling units, with different configurations, and executed "simultaneously". Problem – how to coordinate to optimize shared visits?
- **Level 3 –** Develop rules for the visit-pair requirement to avoid unnecessary extra visits during periods of frequent visits.
- **Level 4** – Allow more flexible definition of rolling cadence units so that the total sky coverage of each rolling cadence is independently determined, allowing different cadences, at least as a function of declination.
- **Level 5** – Allow rolling cadences for non-WFD sky areas, especially Galactic plane and Magellanic Clouds.

10 Rolling Cadence Simulation Objectives

The rolling cadence concept is just beginning development, and it is premature to predict what level of simulation experimentation will be required to evaluate rolling cade over the simulator and scheduler developmetn

10.1 Experiments in early 2014

The following is a proposal, subject to review and updates as additional experience and input becomes available.

The rolling cadence can be applied to any part of the survey, but for initial experiments it should be applied to the WFD main survey only. During the enhanced cadence intervals, the standard survey cadence will continue, with visits in pairs for detection of moving objects. The additional visits provided with the rolling cadence will not be in pairs.

The intention is to distribute the new visits provided by the rolling cadence uniformly through the enhancement intervals.

The initial objective is to produce two sample rolling cadence simulations, one using a 10-year closure cycle, and one using a 3-year closure cycle.

- 10-year closure. For the first experiment, the goal will be to quadruple the cadence over standard. It should be possible to achieve this for approximately 3 consecutive months on each field. The sky will be divided into 40 regions, which are sorted into 10 groups. Each group will consist of 4 regions distributed uniformly in RA, so that the impact of the rolling cadence on the regular cadence is uniform through the year. Each group will be subject to enhanced cadence once during the 10-year survey. This should be done at the rate of one group per year, in order to limit the impact on the regular survey visits underway in parallel. This will require taking 0.075 of the visits from the regular cadence and redeploying them in the rolling cadence, thus leaving the regular cadence active at 0.925 of the standard level.
- 3-year closure. For the first experiment, the goal will be to double the cadence over standard. It should be possible to achieve this for approximately 3 consecutive months on each field 3

times during the 10-year survey. The sky will be divided into 12 regions, which are sorted into 3 groups. Each group will consist of 4 regions distributed uniformly in RA, so that the impact of the rolling cadence on the regular cadence is uniform through the year. Each of the groups will be subject to enhanced cadence once during years 1-3 of the survey, again during years 4-6, and again during years 7-9. This should be done at the rate of one group per year, in order to limit the impact on the regular survey visits underway in parallel. This will require taking 0.075 of the visits from the regular cadence and redeploying them in the rolling cadence, thus leaving the regular cadence active at 0.925 of the standard level.