LARGE SYNOPTIC SURVEY TELESCOPE

Large Synoptic Survey Telescope (LSST)

Alternate observing strategies

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Contents

Alternate observing strategies

1 Introduction

Here we will present a series of new simulations that were used to test different survey strategies and rolling cadences. All of the runs will be compared to kraken_2026, which will soon be the official replacement for baseline2018a. There is a separate document describing what changes were made to kraken_2026 relative to baseline2018a, and how these changes improve the survey performance. The purpose of this document is give an overall impression of how each new survey strategy compared to kraken_2026 rather than go into the fine details. A list of the surveys is given in Table 1 along with a short summary of how the survey was configured. In this document we will use the following when referring to the various proposal in the surveys: Wide Fast Deep (WFD), Galactic Plane (GP), South Celestial Pole (SCP), North Ecliptic Spur (NES), Deep Drilling Fields (DDFs).

TABLE 1: List simulated alternate observing strategies

`OpSim` Run	Summary	Section
kraken_2026	New Baseline Cadence using dome crawl and 36 second CL delay	
colossus_2665	Minimum and Maximum declination limits of WFD increased by $1.5°$	2.1
pontus_2002	PanSTARRs like survey, WFD and DD only, (X<1.5, DecMin = $-78°$, DecMax = $+18°$)	2.2
colossus_2664	WFD cadence through Galactic plane (GP), GP proposal removed from simulation	2.3
colossus_2667	Single visits per night survey	2.4
pontus_2489	"Many Visits" survey. 20s visits with single snap in g,r,i,z,y, 40s visits with single snap in u	2.5
kraken_2035	9 Deep Drilling Fields (DDFs), 4 already set DDFs + 5 new fields	2.6
mothra_2045	Rolling cadence: 2 dec bands alternating every year. Regular WFD removed	3.2
pontus_2502	Rolling cadence: 2 dec bands alternating every year. Regular WFD at 25% level	3.3
kraken_2036	Rolling cadence: Full WFD during first 2, and last two years, 3 dec bands alternating every year in between	3.4

2 Some Simulated Alternative Observing Strategies

We now describe some alternatives to kraken_2026 that were explored. These `OpSim` databases are all available for further testing with science-based MAF metrics.

2.1 colossus_2665

Minimum and Maximum declination limits of WFD increased by $1.5°$

Motivation and description: The visits in `OpSim` v4 runs are pinned to a fixed tessellation on the sky without any transitional dithering pattern. Using MAF, we are able to apply dithering patterns after the fact in order to smooth out the visit coverage over the sky. This can cause an issue because visits can be pushed out of the main survey footprint, which in turn causes the fO metrics to fall below the SRD requirements. In colossus_2665 we increased the maximum declination limit of the WFD survey to $4.3°$ and decreased the minimum declination limit to $-64°$. The dec limits of the SCP and NES proposal were also adjusted to match the new limits of the WFD area. The motivation for slightly increasing the WFD area was to produce a new baseline simulation that would pass the fO SRD requirements, even when the fields are dithered. .

Expectations: By expanding the WFD declination limits we expect that we can reduce the number of visits that are removed from the main survey footprint after dithering, and therefore still pass the fO SRD requirements. We also expect that this small change will not have a large effect on the overall performance of colossus_2665 relative to kraken_2026.

Analysis and Results: Comparison of colossus_2665 to kraken_2026: In Table 2 we list the fO metrics without (top portion) and with (bottom portion) dithering applied by MAF. As a reminder, the fO metric evaluates the overall efficiency of observing. **foNv**: out of 18000.00 sq degrees, the area receives at least X and a median of Y visits (out of 825, if compared to benchmark). **fOArea**: this many sq deg (out of 18000.00 sq deg if compared to benchmark) receives at least 825 visits. In Figure 1 we plot the total number of visits in all bands using the RandomDitherPerNight schema from MAF.

1. The total number of visits in colossus_2665 is 2.43 million relative to the 2.44 million in kraken_2026.

TABLE 2: Comparison of SRD metrics between kraken_2026 and baseline2018a.

	kraken_2026	colossus_2665
fOArea fO WFD	18040.6	17783.8
fOArea/benchmark fO WFD	1.002	0.988
fONv MedianNvis fO WFD	938	907
fONv MinNvis fO WFD	857	824
fONv/benchmark MedianNvis fO WFD	1.137	1.099
fONv/benchmark MinNvis fO WFD	1.039	0.999
With dithering random dithering per night		
fOArea fO WFD	17422.9	18827.9
fOArea/benchmark fO WFD	0.968	1.046
fONv MedianNvis fO WFD	1123	1078
fONv MinNvis fO WFD	504	1009
fONv/benchmark MedianNvis fO WFD	1.361	1.307
fONv/benchmark MinNvis fO WFD	0.611	1.223

2. The median total number of visits per HealPix in the WFD is slightly reduced in colossus_2665 relative to kraken_2026 (903 vs 938).

3. The median number of visits per night are 803 and 806 for colossus_2665 and kraken_2026, respectively. Both simulations have a median slew time of 4.79 seconds.

4. The median seeing, sky brightness and airmass in the r and i bands are essentially the same between the two runs.

5. The median trigonometric parallax and proper motion errors are essentially the same.

6. There was not a significant change in the faction of total visits used by other proposals (e.g. NES, GP, DDFs, SCP).

Conclusions: By slightly extending the WFD footprint we can generate a simulation that passes the fO SRD requirement when dithering is applied using MAF. This is an improvement over kraken_2026 which fails the fONv MinNvis metric when dithering is applied. The slightly increased WFD footprint did not cause any other major changes to the overall cadence and performance of the survey. colossus_2665 could be considered as a replacement for kraken_2026 in the future.

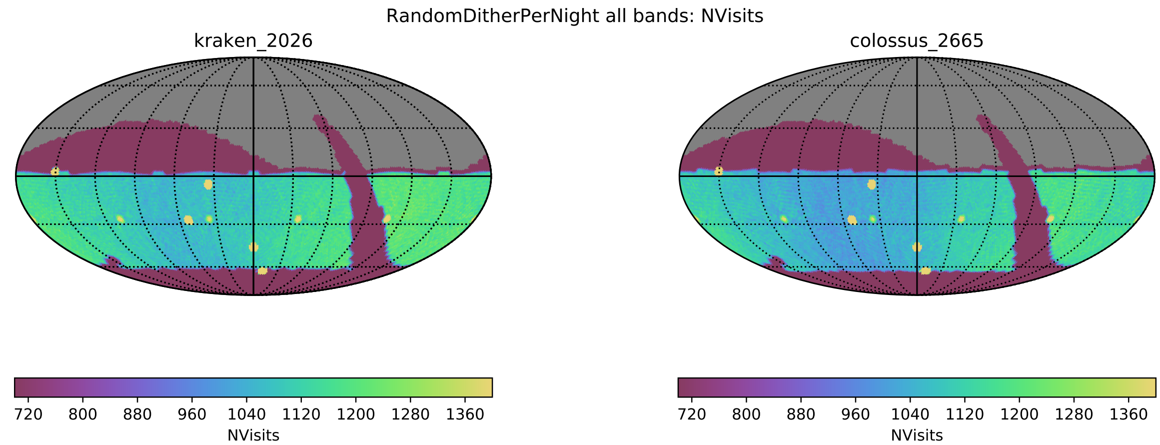

FIGURE 1: Nvisits in all bands for kraken_2026 (left) and colossus_2665 (right).

2.2 pontus_2002

Pan-STARRS-like survey + DDFs

Motivation and description:"Pan-STARRS-like cadence" attempts to apply a uniform cadence strategy throughout the survey region, which is maximized and defined by DecMin = $-78°$, DecMax = $+18°$ deg (about 27,400 deg2). This is similar to the Pan-STARRS 3PI survey which tries to maximize sky area. The maximum acceptable airmass is kept at its default value of 1.5. This simulation utilizes WFD and DDFs, but no other proposals. This survey, like kraken_2026, still required pairs of visits.

Expectations: The total number of visits in pontus_2002 should be approximately the same as kraken_2026, but covering a main survey area over a 42% more sky. Given the larger area, we also expect there to be fewer visits per field.

Analysis and Results: Comparison of pontus_2002 to kraken_2026:

1. The total number of visits in pontus_2002 is 2.43 million relative to the 2.44 million in kraken_2026. See Figure 2 for a comparison of the number of visit maps for each survey. This figure also give a sense of the how the survey footprint is changed in pontus_2002.
2. The median total number of visits per HealPix in the WFD is reduced in pontus_2002 relative to kraken_2026 (696 vs 938).

3. The median number of visits per night is 804 and 806 for colossus_2665 and kraken_2026, respectively. Both simulations have essentially the same slew time.

4. The median trigonometric parallax and proper motion errors show uniform behavior over the entire enlarged area (see Figure 3), with the values similar to those obtained for kraken_2026.

5. The fraction of total visits in the WFD is 0.96 in pontus_2002 and 0.86 in kraken_2026. The fraction of visits in the DDFs remained approximately the same at 0.04.

6. The median coadded depths in pontus_2002 are 0.20, 0.19, 0.18, 0.16, 0.15, 0.16 (u,g,r,i,z,y) magnitudes fainter relative to kraken_2026 in the WFD area.

7. The median airmass in all bands increases by 0.04 in pontus_2002 relative to kraken_2026 in the WFD area.

Conclusions: pontus_2002 increases survey area of the WFD by approximately 40% at the cost of fainter coadded depths in all bands. The loss of depth reduces the galaxy counts at a fixed SNR, but the increase survey area makes up for the loss in depth. The larger median airmass and seeing also reduces the galaxy counts.

2.3 colossus_2664

WFD cadence through GP, GP proposal removed from simulation

Motivation and description: The goal of this simulation was to understand the effect of extending the WFD cadence through the GP. This was configured by removing the GP avoidance region from the WFD and SCP, and removing the GP from the list of available proposals.

Analysis and Results: Comparison of colossus_2664 to kraken_2026:

1. The total number of visits in the two simulations is essentially the same. See Figure 4 for a comparison of the Nvisit maps for each survey.

2. The median total number of visits per HealPix in the WFD is reduced in colossus_2664 relative to kraken_2026 (887 vs 938).

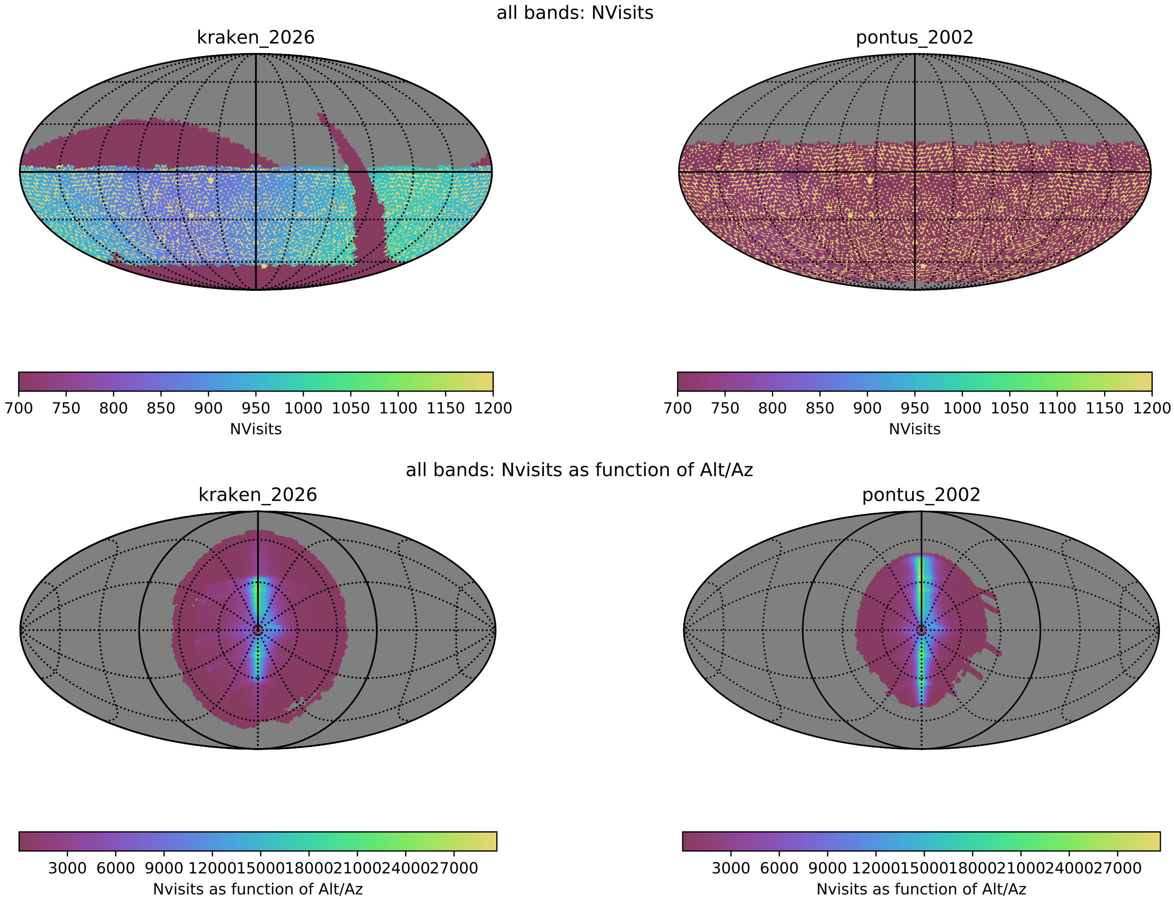

FIGURE 2: Skymaps for the number of visits in all bands. The maps for kraken_2026 are in the left column and the maps for pontus_2002 are in the left column.

3. The total number of visits in the WFD area increases by approximately 2% in colossus_2664 relative to kraken_2026
4. The median coadded depths in colossus_2664 are 0.03, 0.03, 0.02, 0.02, 0.01, 0.03 (u,g,r,i,z,y) magnitudes shallower relative to kraken_2026 in the WFD area.

Conclusions: By extending the WFD cadence through the GP, the WFD makes up approximately 88% of the total number of visits. The increased area of the WFD reduced the median number of visits in the WFD by approximately 5%, which decreases the coadded depth by about 0.03 magnitudes.

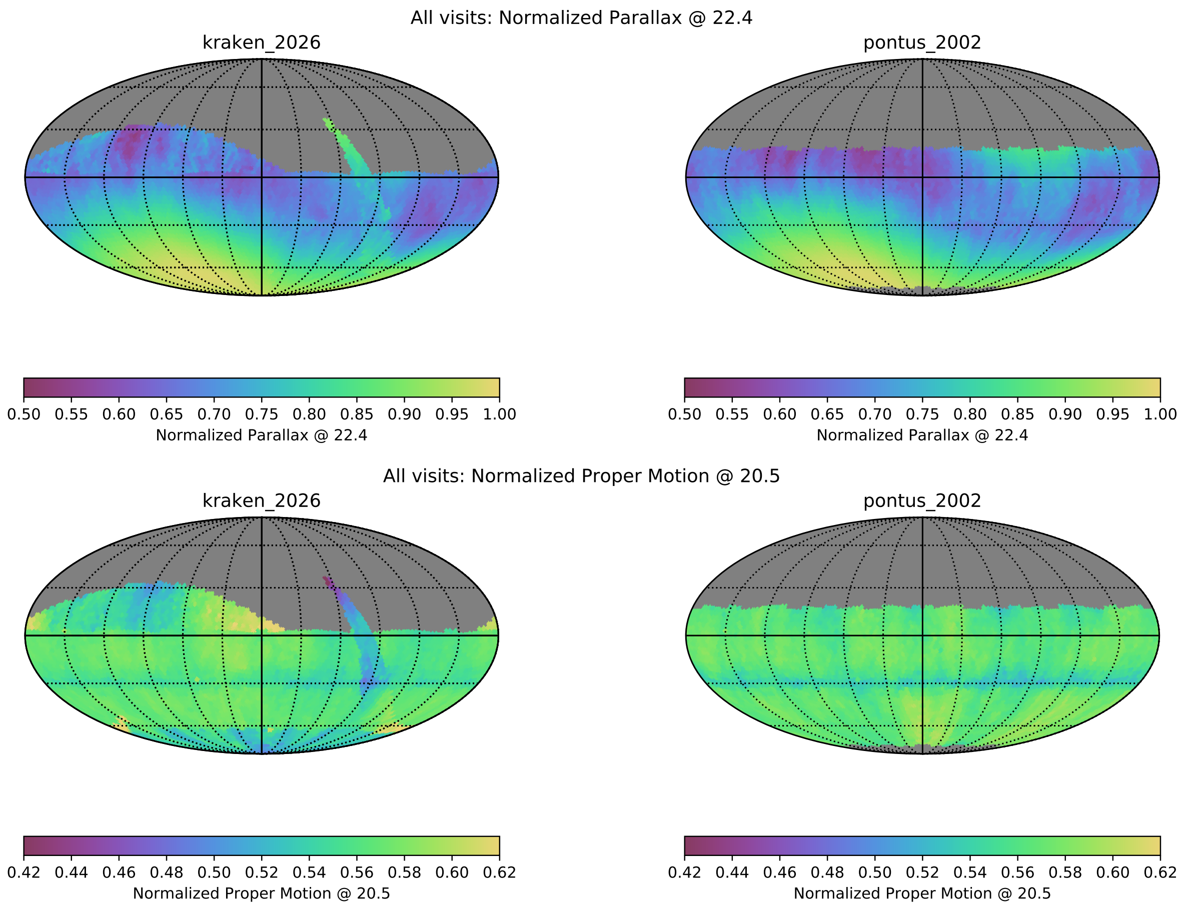

FIGURE 3: Top: Normalized parallax values at 22.4 mags for kraken_2026 and pontus_2002. Bottom: Normalized proper motion values at 20.5 magnitudes for kraken_2026 and pontus_2002.

2.4 colossus_2667

Single visits per night survey

Motivation and description: The goal of this simulation was to determine how requiring visits in a pairs impacts the overall survey efficiency. The only difference between the configuration of colossus_2667 and kraken_2026 is the removal of the visits in pairs requirement.

Analysis and Results: Comparison of colossus_2667 to kraken_2026:

1. The total number of visits in colossus_2667 is 2.5 million, which is a 2.2% increase relative to kraken_2026.

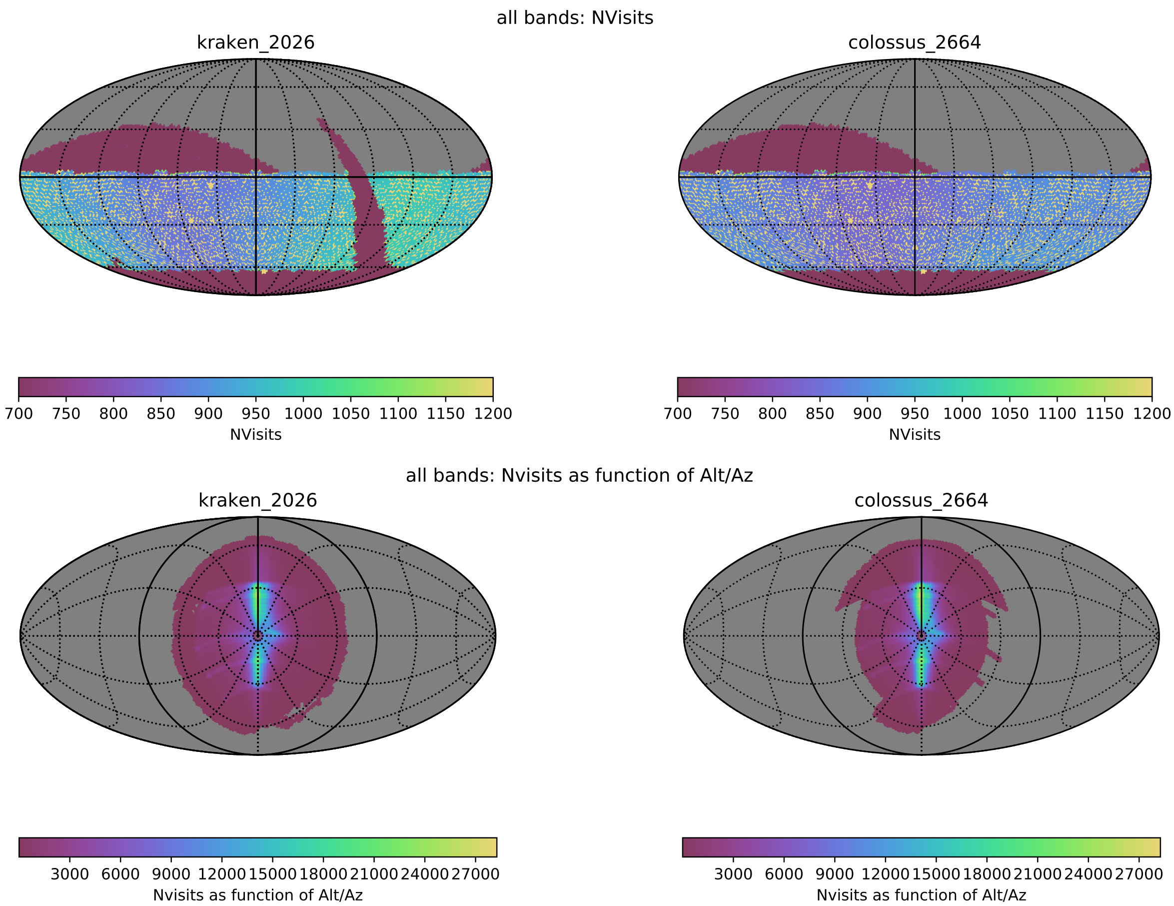

FIGURE 4: Skymaps for the number of visits in all bands. The maps for kraken_2026 are in the left column and the maps for colossus_2664 are in the left column.

2. The mean slew time is 5.8 sec in colossus_2667 compared to 6.8 sec in kraken_2026. See Figure 5 for a comparison of their slew time histograms.

3. The total open shutter fraction increased in colossus_2667 (0.75 vs 0.73).

Conclusions: Only requiring single visits in a night reduced the mean slew time by 1 second and increased the number of visits by 2.2%.

2.5 pontus_2489

Many visits survey

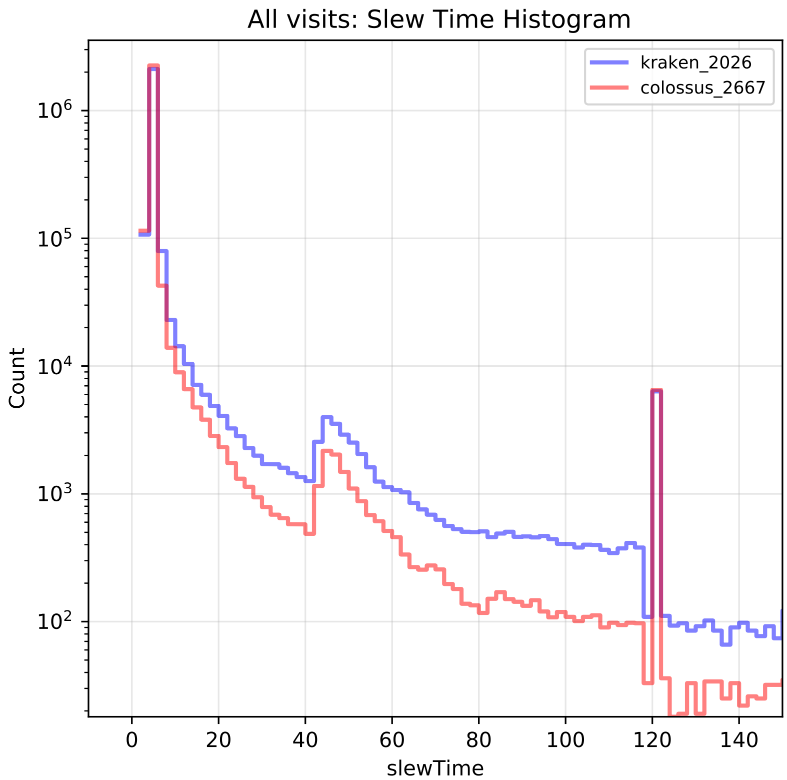

FIGURE 5: Slew time histograms for colossus_2667 and kraken_2026 .

Motivation and description: This survey was designed to use single 20 second snaps in g,r,i,z,y, and single 40 second snaps in u. In kraken_2026, and the rest of the simulations present in this document, a visit is composed of 2 back-to-back 15 second exposures giving the nominal 30 second exposure per visit.

Analysis and Results: Comparison of pontus_2489 to kraken_2026:

1. The total number of visits in pontus_2489 is 3.41 million, which is a 40% increase relative to kraken_2026.
2. The total open shutter fraction of both simulations is essentially the same.
3. The median fraction of visits in pairs in g,r,i increased to 0.90 in pontus_2489 from 0.87 in kraken_2026.
4. The median number of visits in all bands in the WFD increased by 41% relative to kraken_2026.

5. The median u band coadded depth reached 0.44 mags deeper in kraken_2026 (26.09 vs. 25.65).
6. The median g,r,i,y, and z coadded depths are 0.13, 0.08, 0,05, 0.08, 0.07 mags, respectively, shallower than kraken_2026. See Figure 6 and Figure 7 for comparisons of the coadded u band HealPix histograms and sky maps, resepctively.

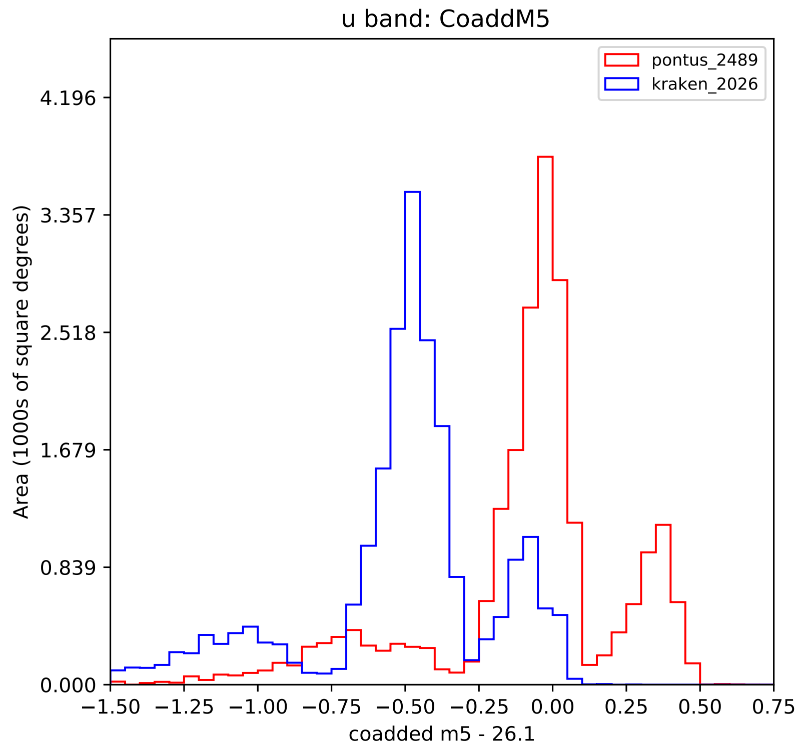

FIGURE 6: Coadded u band magnitude HealPix histograms.

Conclusions: Reducing visits to a single 20 second snap in g,r,i,z,y and 40 second snap in u greatly increased the number visits and reached a much deeper coadded depth in u. The other aspects of the survey remained relatively unchanged relative to kraken_2026.

2.6 kraken_2035

Baseline cadence with 9 Deep Drilling Fields.

Motivation and description: This survey was used to test the effect of adding 5 additional DDFs to the 4 that have been already chosen. The observing cadence in these 5 additional

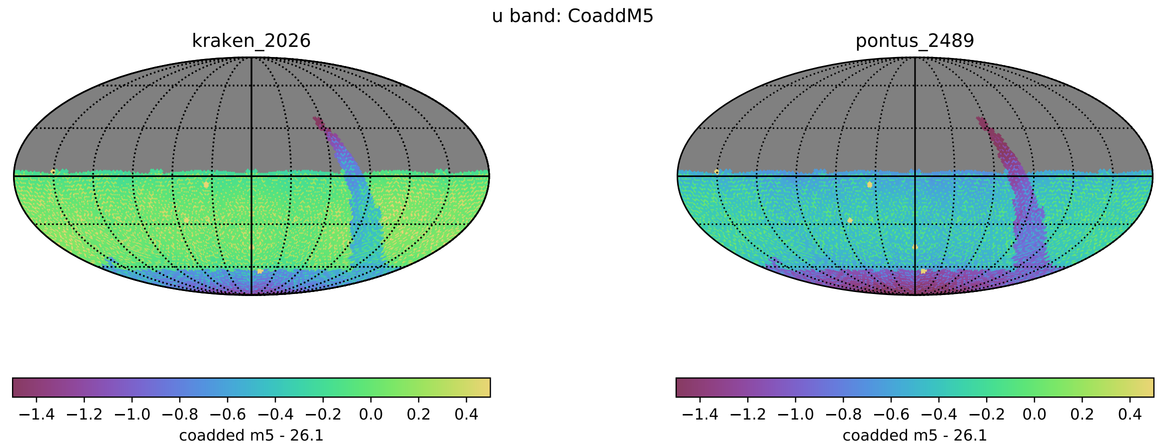

FIGURE 7: Coadded u band magnitude HealPix sky maps.

DDFs was not changed from what was previously used. New fields were not selected with a particular science goal in mind, but an attempt was made to evenly distribute them in Ra, avoid the Galactic center, and be out of the Galactic plane. The WFD is expected to take 85 – 95% of the observing time during the 10 year survey, with the remaining 5 – 15% being used for the other mini-surveys: NES, GP, SCP, and DDFs. By analyzing this simulation, we will be able to see how the increased number of DDFs affects the proposal balance, and the overall survey efficiency. In In Table 3 we list the 9 DDFs used in kraken_2035. They can also be seen on the HealPix Sky map of the coadded r band depth shown in Figure 8.

TABLE 3: List of DDFs used in kraken_2035. The Field IDs with an * are the four already decided fields.

Field ID	Ra (Deg)	Dec (Deg)	Galactic l	Galactic b
290	349.386443	-63.321004	319.34	-50.71
744^*	0.0	-45.524505	328.66	-68.95
820	119.555145	-43.366522	258.34	-7.31
858	187.624779	-42.492805	298.82	20.21
1200	176.62637	-33.146604	287.59	27.78
1427^*	53.009145	-27.438943	222.92	-54.48
2412^*	34.393398	-5.09032	169.72	-59.89
2689	201.854221	0.931384	322.66	62.42
2786^*	150.362355	2.836499	236.32	42.68

Analysis and Results: Comparison of kraken_2035 to kraken_2026:

1. The total number of visits in kraken_2035 is decreased by 1.2$\%$ relative to kraken_2026.

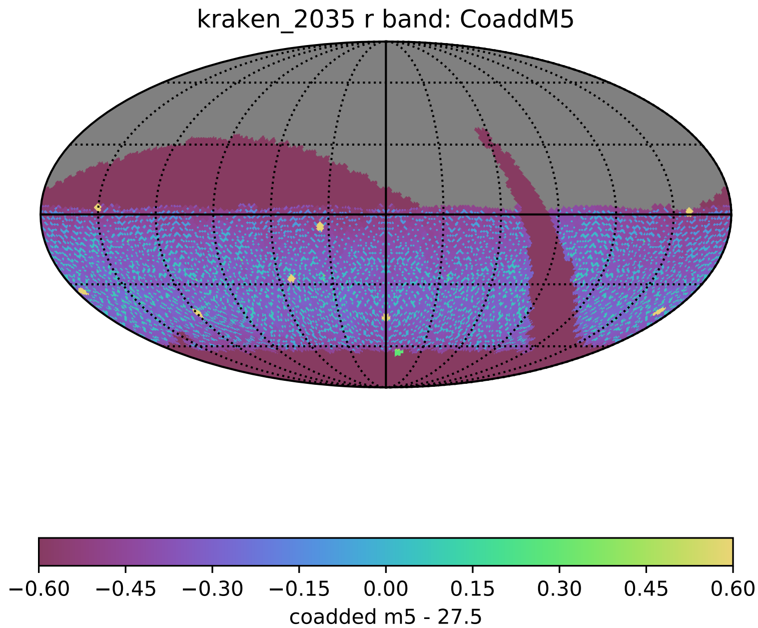

FIGURE 8: Coadded r band magnitude HealPix sky maps.

2. The WFD only makes up 84$\%$ of the total number of visits, compared to 86$\%$ in kraken_2026.
3. The DDFs makes up 7$\%$ of the total number of visits, compared to 5$\%$ in kraken_2026.
4. The rest of the proposal contributions remain approximately the same.
5. The median number of visits in all bands in the WFD decreases by 3$\%$.
6. kraken_2035 still passed the fO SRD metrics.
7. The mean slew time kraken_2035 is longer than kraken_2026 (7.3 vs 6.8 sec). See Figure 9 for the slew time histograms of each run.
8. The total number of filter changes during the whole survey increases by 30$\%$ relative to kraken_2026.
9. The median coadded 5σ depths for the DDFs are (27.7, 28.7, 28.7, 28.2, 27.8, 26.6) in the $ugrizy$ bands, respectively. These values are similar to what was seen in kraken_2026. The coadded HealPix sky maps for all bands in the DDFs are shown in Figure 10.
10. The other major aspects of the survey remain relatively unchanged.

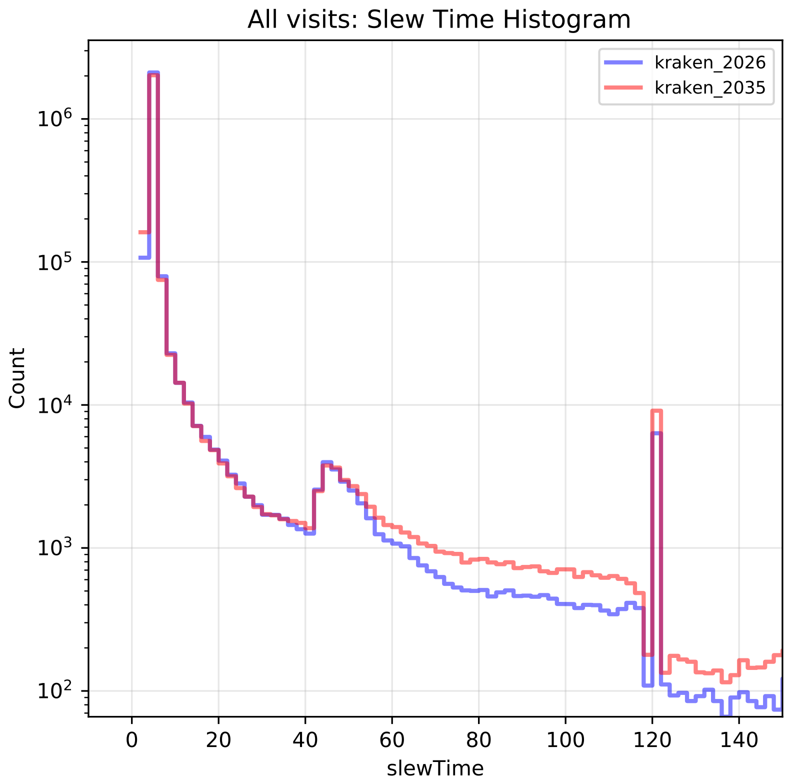

FIGURE 9: Slew time histograms for kraken_2035 and kraken_2026 .

Conclusions: Increasing the number of DDFs shifted the proposal distributions with approximately 2$\%$ of WFD visits going to the DDFs. This shift in visits into the DDFs reduced the WFD fraction just below the nominal limit of 85%. The mean slew time was likely increased in part by the 30$\%$ increase in total filter changes, which in turn reduced the total number of visits. More detailed metrics aimed at DDFs still need to be developed to understand their performance, and how increasing the total number of fields might hurt, or improve, the science goals of the DDFs.

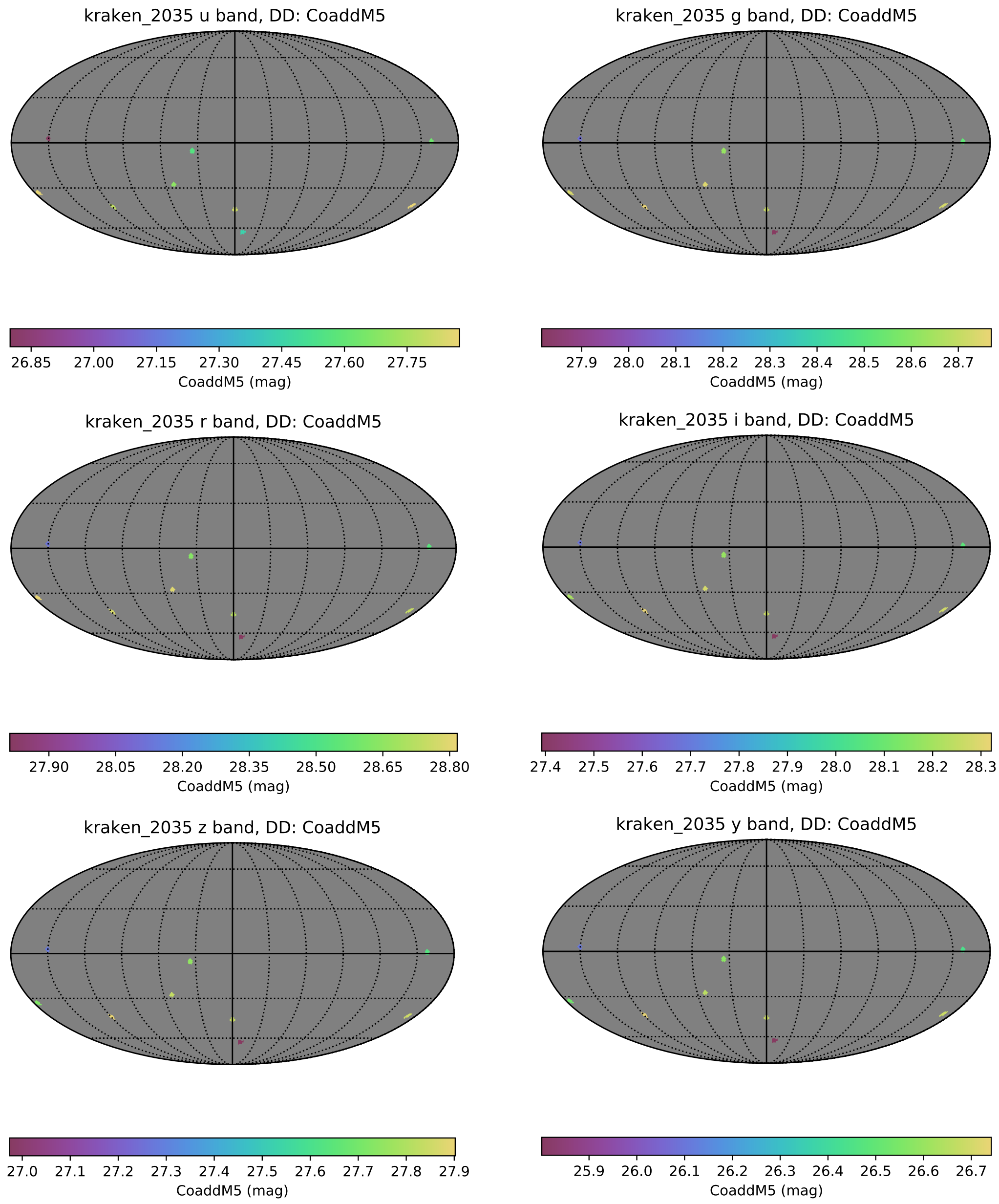

FIGURE 10: Coadded depths in all bands for DDFs in kraken_2035 .

3 Rolling cadence simulations

3.1 Overview

Here we present three simulations that were run with different flavors of a rolling cadence in the WFD survey area. The idea of implementing a rolling cadence is to increase the temporal sampling of fields in the WFD by turning regions of the available sky on/off over the course of a survey. When a single area of the sky is turned on for enhanced sampling, it is called a "roll". In the rolling cadences presented here, we constructed relatively simple rolls defined by bands in declination that alternate each year of the survey. We also explore the effect of leaving some fraction of the non-rolling WFD cadence on in addition to rolling declination bands. It should be noted that these rolling cadence are still very a much a work in progress and should only serve as a starting point for constructing better rolling cadence experiments. In the future we will also develop more complicated rolls that depend on more than just declination. We are also still in the process of developing new metrics for MAF that test the efficiency and benefit of the rolling cadences. It is difficult to make a direct comparison of the rolling cadences to kraken_2026, but we will provide some overall insights in this section. There are many more issues with each of these surveys that can be seen in there total MAF output (`http://astro-lsst-01.astro.washington.edu:8080`), but going into all of the details there is beyond the scope of this document.

3.2 mothra_2045

Two rolling dec bands, no non-rolling WFD included

Motivation and description: This simulations represents one of the simplest implementations of a rolling cadence: two dec bands (northern and southern) that alternate every year for the entire survey. In mothra_2045, the southern dec band extended from from $-62.5°$ to $-24.7°$, and the northern dec extends from $-24.7°$ to $2.8°$. The simulation started with the southern dec band for year 1 and then alternated every year until the end of the survey. In Figure 11 we plot the number of visits over the first four years of the survey to illustrate the locations of the rolls and when they are active.

Analysis and Results: Comparison of mothra_2045 to kraken_2026:

1. The total number of visits in mothra_2045 decreases by 26% relative to kraken_2026.
2. The WFD only makes up 83% of the total number of visits, compared to 86% in kraken_2026. The SCP and NES increased their fraction of the total survey by approximately 2%.
3. The mean slew time kraken_2035 is longer than kraken_2026 (16.19 vs 6.8 sec).
4. The total number of filter changes during the whole survey increases by 144% relative to kraken_2026.
5. The median number of visits per night mothra_2045 lower than kraken_2026 (618 vs 806).
6. The median inter-night gap for all WFD visits in mothra_2045 is shorter than in kraken_2026 by nearly one night (1.01 vs 1.96).

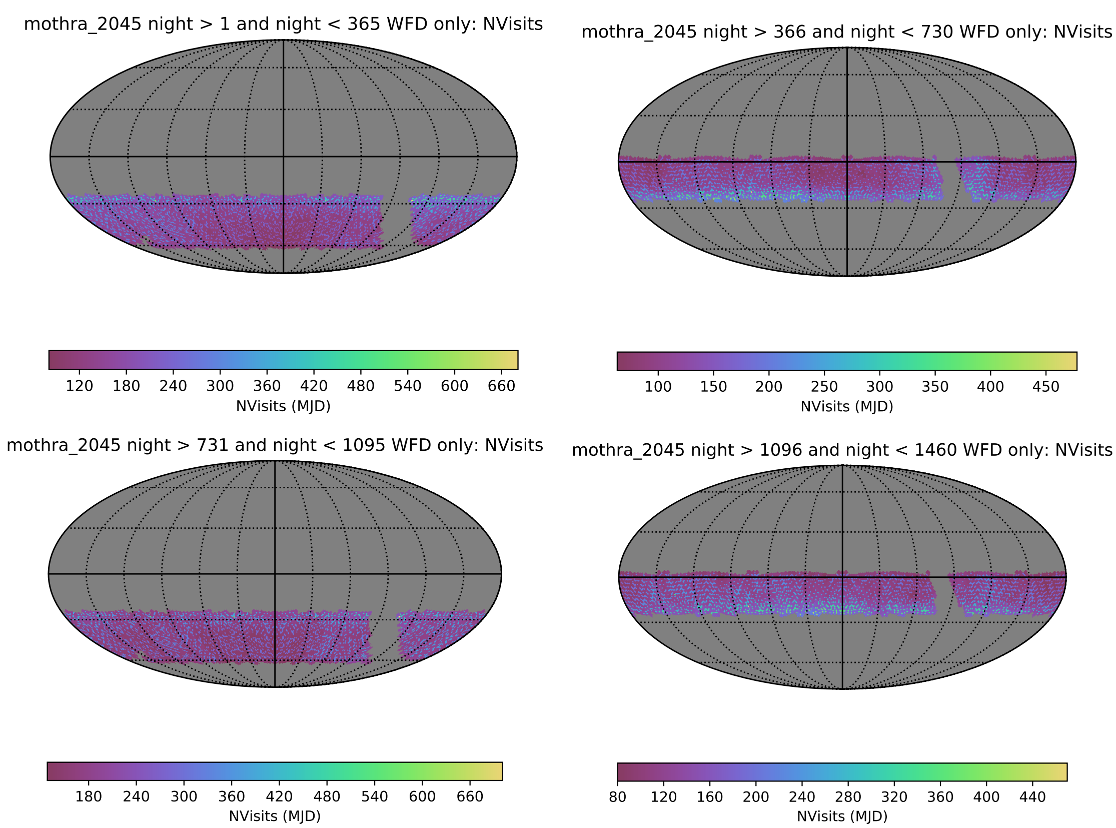

FIGURE 11: First 4 years of rolling WFD observations in mothra_2045.

Conclusions: There are obviously many issues with mothra_2045 that leave room for improvement. The shorter median inter-night gap compared to kraken_2026 shows that the rolling cadence is increasing the temporal sampling in the WFD, but we still need to determine the best way to balance that with the other surveys.

3.3 pontus_2502

Motivation and description: This simulations uses the same two rolling dec bands from mothra_2045, but also has the regular WFD cadence at a 25% level on at all times. To make this configuration, 75% of the total visits needed in the WFD area are requested from the rolling dec bands, and the remaining 25% from the non-rolling WFD cadence. The configuration was done so that the rolling and non-rolling WFD proposals could not co-add their weights when selecting the next target in the simulation. In Figure 12 we plot the number of visits over the first four years of the survey to illustrate the locations of the rolls and when they are active. By comparing Figure 12 to Figure 11 you can get a sense for how pontus_2502 differs from mothra_2045.

Analysis and Results: Comparison of pontus_2502 to kraken_2026:

1. The total number of visits in pontus_2502 decreases by 17$\%$ relative to kraken_2026.
2. The total WFD area makes up 89$\%$ of the total number of visits, compared to 86$\%$ in kraken_2026. 59$\%$ percent of the visits were from the rolling dec bands, and 31$\%$ were from the non-rolling WFD proposal.
3. The DDFs only made up 0.3$\%$ of all visits suggesting that the proposals need better balancing.
4. The mean slew time in pontus_2502 is longer than kraken_2026 (7.86 vs 6.8 sec).
5. The total number of filter changes during the whole survey increased by 18$\%$ relative to kraken_2026.
6. The median number of visits per night in pontus_2502 is lower than kraken_2026 (721 vs 806).
7. The median inter-night gap for all WFD visits in pontus_2502 is basically the same as kraken_2026 (1.88 vs 1.96).

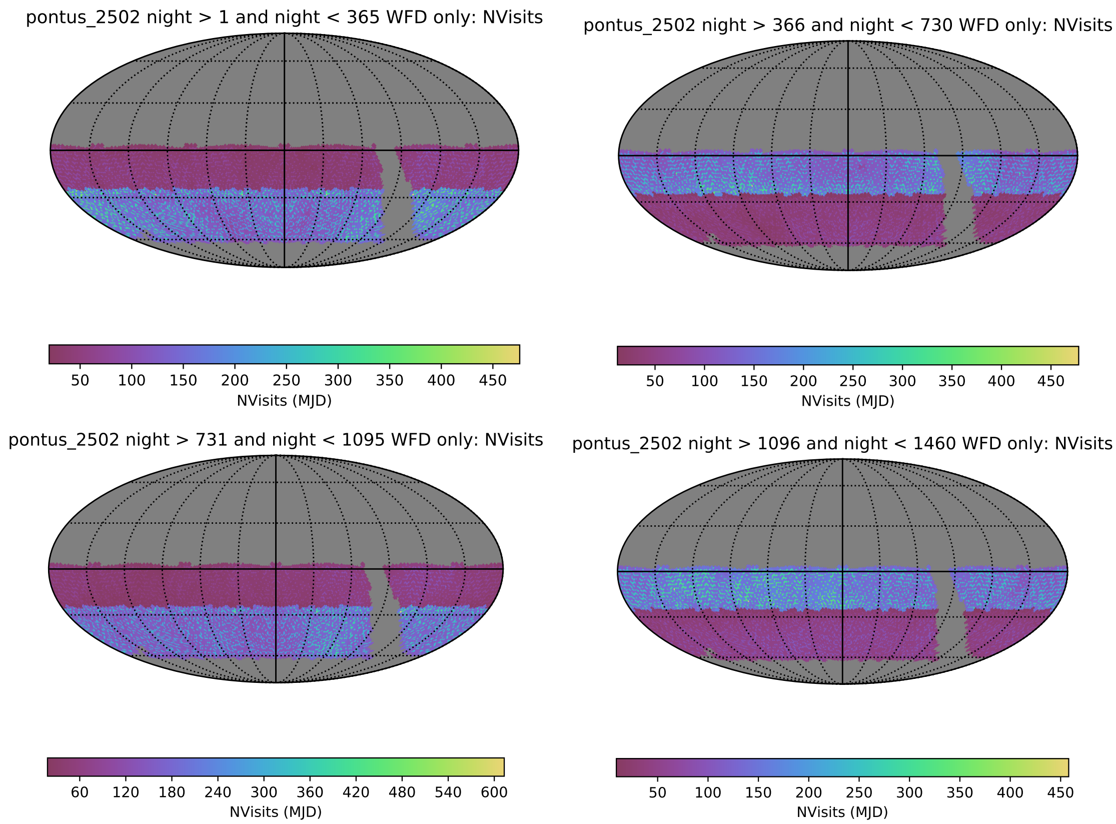

FIGURE 12: First 4 years of rolling WFD observations in pontus_2502.

Conclusions: Including the non-rolling WFD cadence at 25% improved some aspects of the survey relative to mothra_2045, which had the non-rolling WFD completely turned off. We saw an increase in the number of visits, and decreases in the number of filter changes and mean slew times. This run did have the major issue that the DDFs only make up a fraction of a percent of the total number visits. There was also not a large improvement in the median-inter night gap relative to kraken_2026, which is one of the main goals of using a rolling cadence.

3.4 kraken_2036

Three rolling dec bands

Motivation and description: In this simulation we take a different approach approach to the rolling cadence. During the first and last to years of the survey, the full area of the WFD is available for observations ($-62.5°$ to $2.8°$), so essentially operating at the usual WFD cadence. For the remaining six years, the WFD region is broken up into three dec bands that alternate every year, so each of the three dec bands is turned on twice during the 10 year survey. In Figure 13 we plot the number of visits over the first five years of the survey to illustrate the locations of the rolls and when they are active. Note that the upper left panel in Figure 13 covers two years of the survey.

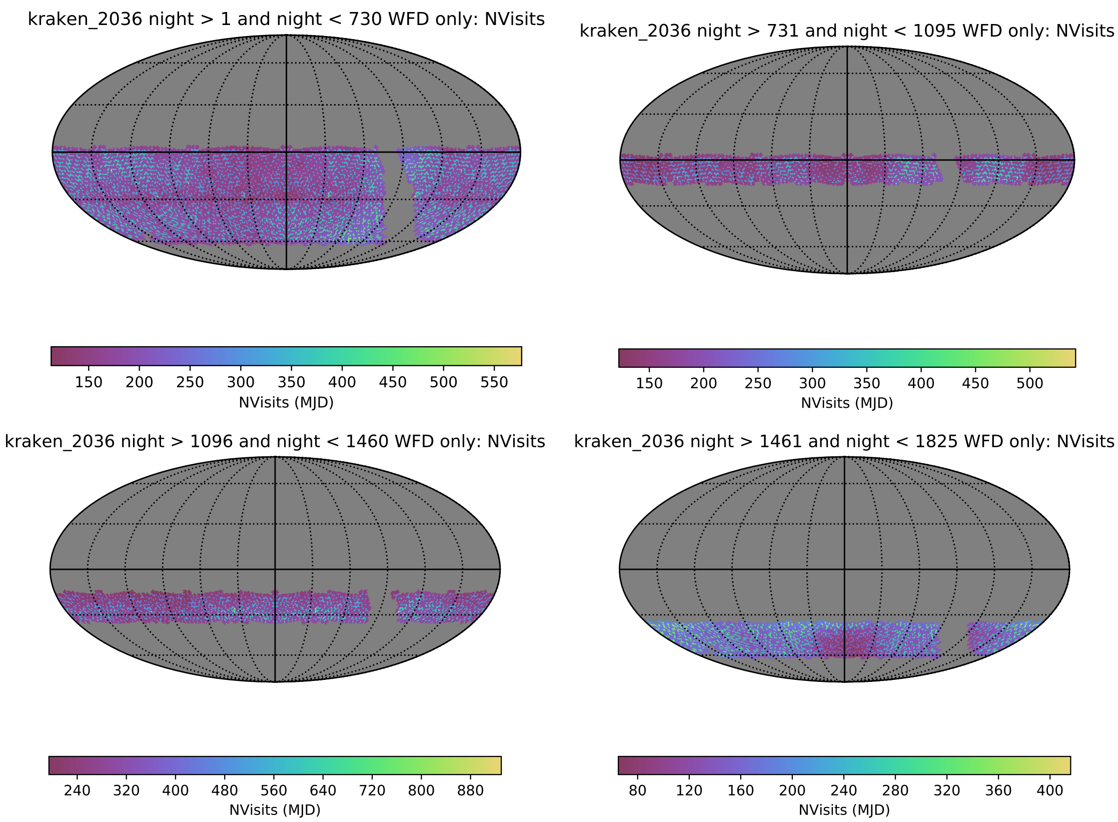

FIGURE 13: First 5 years of rolling WFD observations in kraken_2036.

Analysis and Results: Comparison of kraken_2036 to kraken_2026:

1. The total number of visits in kraken_203 decreases by 15% relative to kraken_2026. This is the best performance of the rolling cadences presented here.
2. The total WFD area makes up 85% of the total number of visits, compared to 86% in kraken_2026.
3. The remaining proposal fractions are similar to what is seen in kraken_2026.
4. The mean slew time kraken_2036 is longer than kraken_2026 (12.61 vs 6.8 sec). The slew time and slew distance histograms are shown in Figure 14. From these histograms we

can see that kraken_2036 is making longer slews in distance and time, which is likely due to jumping between the dec bands and area proposals.

5. The total number of filter changes during the whole survey increases by 70% relative to kraken_2026.

6. The median number of visits per night kraken_2036 lower than kraken_2026 (721 vs 806).

7. The median inter-night gap for all WFD visits in kraken_2036 is shorter than in kraken_2026 by nearly one night (1.01 vs 1.96).

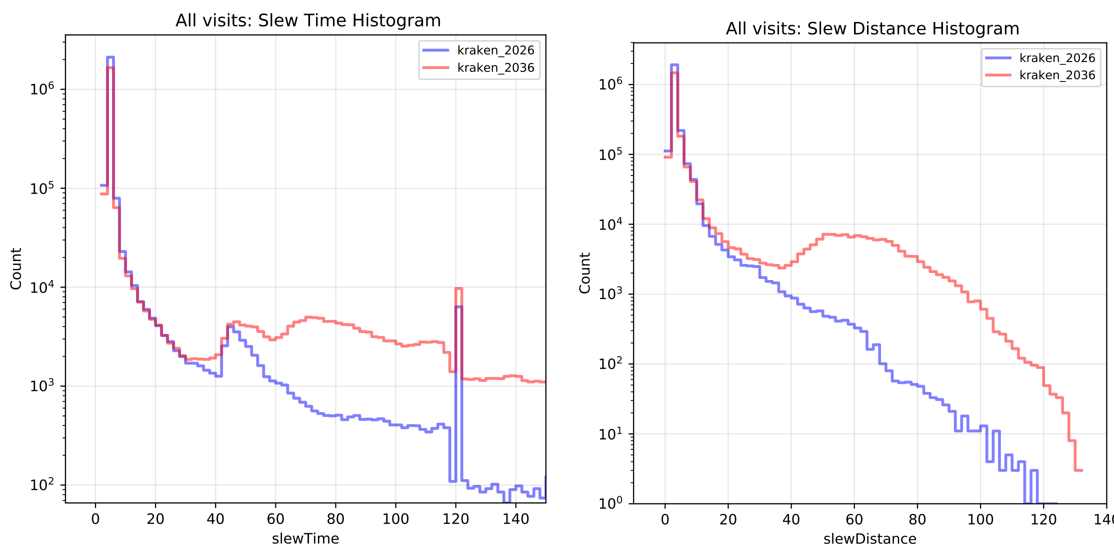

FIGURE 14: Slew time and distance histograms for kraken_2036 and kraken_2026.

Conclusions: This simulation performed the best out of the three rolling cadence experiments shown here. We saw the largest number of visits without drastically changing the distribution of visits among the various proposals, and a significant decrease in the median inter-night gap relative to the non-rolling baseline. Like the other rolling cadences, however, there is still room a lot for improvement in how cadences such as this are implemented.