NOAO Observing Proposal   *Standard proposal*   **Panel:**   *For office use.*
Date: September 28, 2018   **Category:** Galactic - Other

Probing Short Duration Stellar Variability with Star Trail Images of K2 Fields

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**
Thomas & Kahn (2018) demonstrated, using high fidelity ray-tracing simulations, that star trail images enable wide-field ground-based telescopes to resolve stellar variability down to a time scale of 10 milliseconds. We request half a night with the Dark Energy Camera on the Blanco 4-m telescope to take star trail images of four K2 fields to validate this method, characterize its performance, and detect new sources of stellar variability and events. The 270 square degree survey will be the first of its kind and will add a new dimension to our understanding of over 10,000 sources.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	DECam	0.5	bright	Feb - July	Feb - July
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to six lines).*

We have no scheduling constraints.

Investigators   *List the name, status, and current affiliation for all investigators. The status code of "P" should be used for all investigators with a Ph.D. or equivalent degree. For graduate students, use "T" if this proposal is a significant part of their thesis project, otherwise use "G".*

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CoI: Steven M. Kahn   **Status:** P **Affil.:** Stanford University
CoI: Krista Lynne Smith   **Status:** P **Affil.:** Stanford University
CoI: Robert Blum   **Status:** P **Affil.:** National Optical Astronomy Observatory
CoI: Zeljko Ivezic   **Status:** P **Affil.:** University of Washington
CoI: Colin Burke   **Status:** G **Affil.:** University of Illinois Urbana-Champaign

Probing Short Duration Stellar Variability with Star Trails

Charge-Coupled Devices (CCDs), the detector of choice for optical astronomy, take around 10 seconds to read out. This limits the time resolution of conventional telescopes. Dedicated instruments using special frame transfer and electron multiplying CCDs have achieved time resolution in tens of milliseconds on a 5 arcsecond field of view (Dhillon et al. 2007, 2014, 2016; Harding et al. 2016). While these instruments are sufficient for studying individual sources of variability, they are not well-suited for large surveys or searching for new sources of variability. In Thomas & Kahn (2018), we present a technique that allows existing wide-field telescopes to achieve comparable time resolution. We propose using the Dark Energy Camera (DECam) on the Blanco 4-m telescope to validate this method and to provide sub-second photometry for four strategically chosen K2 fields.

The method is comprised of operational and image processing components. The operational component is to take star trail images. Howell and Jacoby realized that each trail serves as a light curve for its corresponding source and facilitates high time resolution photometry (Howell & Jacoby 1986). We process the noisy star trail images by training a deep neural network to identify stellar variability in simulated star trail images from the Large Synoptics Survey Telescope. The network detection efficiency on tophat-like flares is shown in Figure 2.

The Dark Energy Camera on the Blanco 4-m telescope is the best instrument to validate our method on because it has a wide field of view and superb resolution. The 2.2 degree field of view captures many sources simultaneously and allows us to survey the sky around 700 times faster than existing high time resolution instruments. The wide field is complemented by a 570 Megapixel camera and 0.26 arcsecond pixel scale which mean that a trailing source will spend approximately $17/\cos(\delta)$ milliseconds over each pixel, fostering excellent time resolution. After validating and further refining our method on DECam we hope to employ it during the commissioning of the Large Synoptic Survey Telescope.

The proposed survey is the first of its kind and will add a new dimension to our knowledge of the four chosen K2 fields. The analysis we will pursue is contingent on what we uncover. Detections of M-dwarf flares in open clusters would allow us to constrain their frequency, correlate them with cluster properties, and compare high time resolution photometry of the flare up with numerical simulations. Occultations from Trans-Neptunian Objects would allow us to detect new structures in the solar system. The small Kuiper Belt Objects that are of particular theoretical interest, would produce occultations lasting for tens of milliseconds. Finally, perhaps the most intriguing possibility is that we will discover new sources of variability.

Figure 1: Example DECam star trail image.

Burst Detection Efficiency Limits

- $\Delta m = -1.0$, eff > 90%
- $\Delta m = -1.0$, eff > 50%
- $\Delta m = -1.0$, eff > 10%
- $\Delta m = -2.5$, eff > 90%
- $\Delta m = -2.5$, eff > 50%
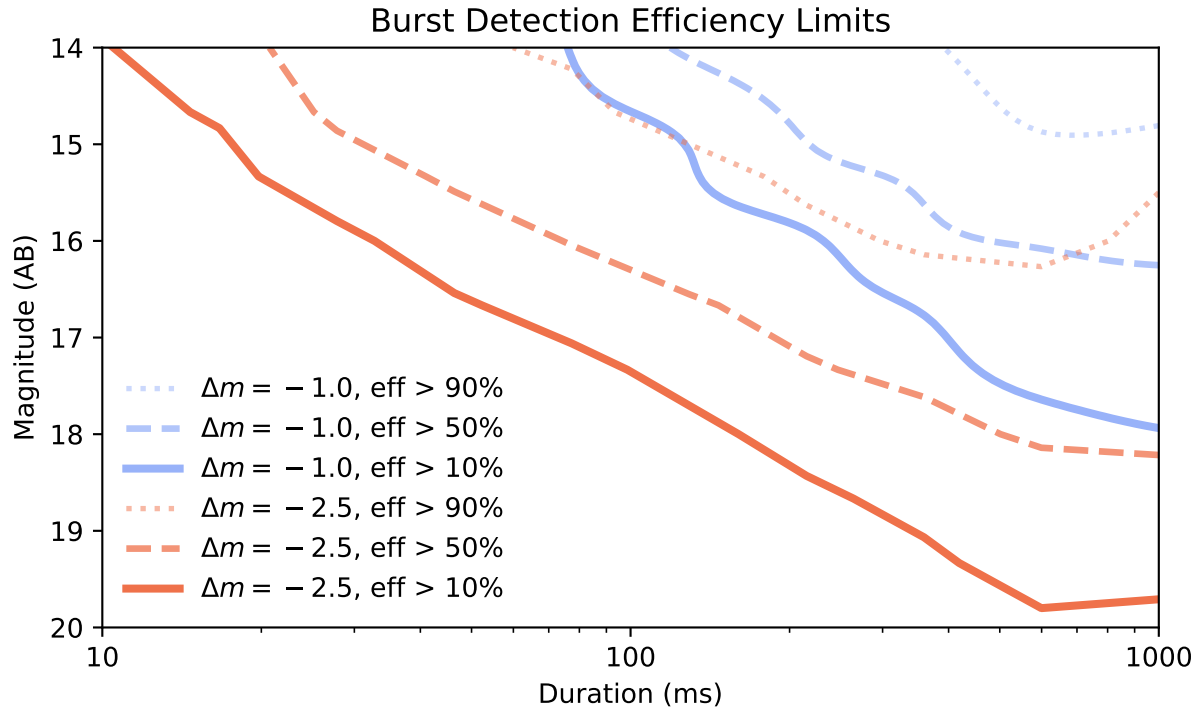- $\Delta m = -2.5$, eff > 10%

Figure 2: The contours show the probability the combined network will detect a burst with the given source magnitude and burst duration. The blue and red contours correspond to burst magnitude changes of -1.0 and -2.5 respectively. The dotted, dashed, and solid lines correspond to 90%, 50% and 10% detection efficiencies respectively.
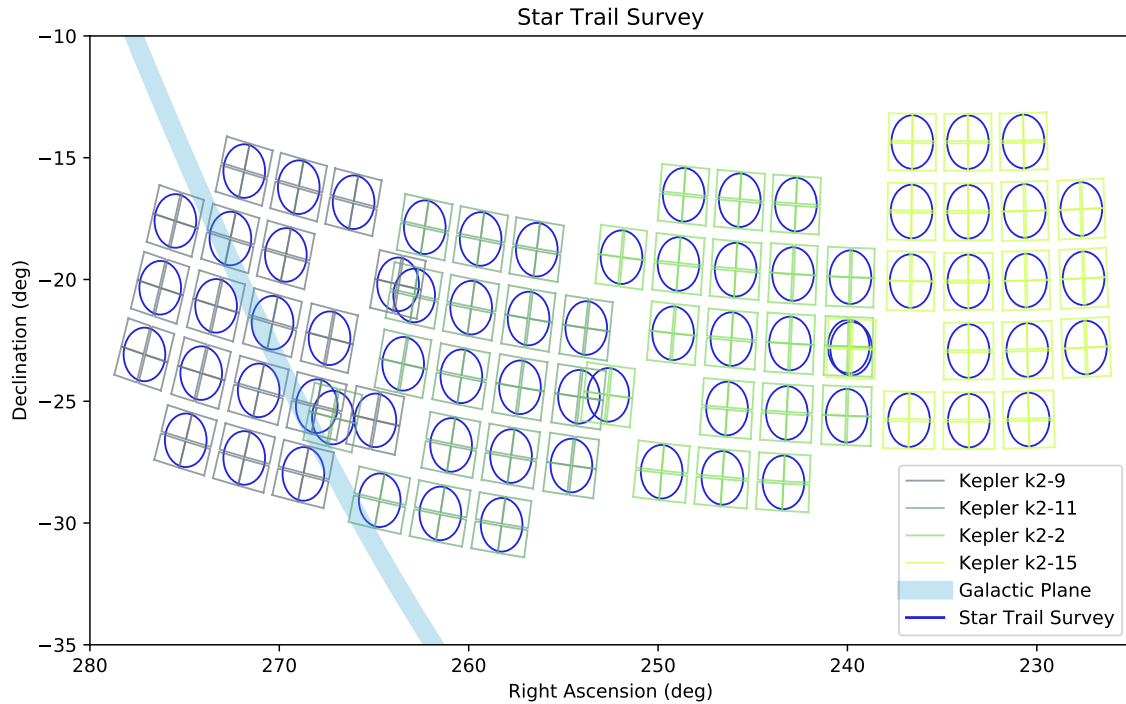

Figure 3: The planned survey.

Experimental Design   *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

Observing Four Adjacent K2 Campaigns: 2,9,11,15

The Kepler K2 mission is a sequence of 80-day continuous observing campaigns of fields distributed around the ecliptic plane. For each field, K2 provides state of the art photometry for thousands of targets. This rich data has compelled astronomers to image these fields extensively, including in the near infrared and x-ray regimes. The constituents of these fields are well known, making them excellent targets to validate our method on. Furthermore, the analysis of any rare events we uncover will benefit from the wealth of existing data.

The survey we propose covers four K2 fields: 2,9,11,15. These adjacent fields extend from the galactic plane to 35 degrees above it, providing a wide range of source densities for our method. The fields in this suite also share good observing periods. The DECam field of view almost perfectly inscribes a single Kepler Module of four CCDs. This allows us to efficiently cover the K2 fields by visiting the center locations of the modules. We tile each field 3 times in the 'r' band. The first is a static exposure for reference. The following two visits take 15 second star trail exposures. We discuss these choices further in the technical description.

Image Processing and Analysis

The image processing and analysis has three stages. First we generate simulated data and train the algorithm on it. We will use the Sherlock 2.0 high performance computing cluster at Stanford University to produce a suite of simulated DECam star trail images. CatSim will be used to seed realistic catalogs; PhoSim, which has already been used to study DECam, will be used for the image simulations. Then we will train networks to detect three variable signatures: bursts, occultations, and smooth trends on timescales of tens of milliseconds to minutes.

In the second stage we calibrate the performance of the algorithm. We will insert simulated variable star trails in the real DECam images and examine the algorithm's ability to uncover them. If we discover effects in the DECam images that are not captured in the simulations, then we can set aside a partition of the real data to use in the training, which will push the network to generalize. At the end of this stage we will have established consistent performance on simulated and real images and have measured the algorithm's performance limits on the signatures of interest.

The third stage will be scanning the real DECam data and communicating the results. The variable events we find will collectively support global statistical analysis and individually be candidates for custom, detailed follow-up analysis. We will combine the variable events with the performance limits to constrain the frequency of specific short duration phenomena in our galaxy.

Proprietary Period: 18 months

| **Use of Other Facilities or Resources** | *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

This is LSST pathfinder. We work on LSST commissioning. We have computing resources.

| **Previous Use of NOAO Facilities** | *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

This will be the first time David Thomas uses NOAO facilities. He is supported by a team with ample observing and NOAO experience.

Observing Run Details for Run 1: CT-4m/DECam

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

- We used JSkyCalc to confirm there are good dates between May-July where all fields can be observed through a reasonable airmass.

- Confirmed survey is within Blanco 4-m horizon limits.

- Survey should take 3 hours and 8 minutes in theory, which leaves a buffer of approximately 2 hours.

- We used DECam zero-magnitude and filter throughput data to model the signal to noise ratio. The choice of 15 second exposures is guided by 3 effects: background noise increases while signal is constant after source trails through so after a few 100 milliseconds SNR $\sim 1/\sqrt{(t_{exp})}$, we don't want trails to be significant portion of CCD, and we want a reasonable duty cycle given almost 20 second readout time.

Instrument Configuration

Filters: r
Grating/grism: -
Order: -
Cross disperser: -

Slit: -
Multislit: -
λ_{start}: -
λ_{end}:   -

Fiber cable: -
Corrector: -
Collimator: -
Atmos. disp. corr.: -

RA (deg)	Dec (deg)	Filter	Tracking	Exposure Time (sec)	Comment
263.72779	-20.201175	r	on	15	K2 Campaign-9, Module-1
264.9247	-25.784213	r	on	15	K2 Campaign-9, Module-3
266.07655	-16.82745	r	on	15	K2 Campaign-9, Module-4
267.34745	-22.412586	r	on	15	K2 Campaign-9, Module-6
268.0217	-25.201351	r	on	15	K2 Campaign-9, Module-7
268.72661	-27.984544	r	on	15	K2 Campaign-9, Module-8
268.97252	-16.209388	r	on	15	K2 Campaign-9, Module-9
269.65253	-18.992061	r	on	15	K2 Campaign-9, Module-10
270.35534	-21.774739	r	on	15	K2 Campaign-9, Module-11
271.08764	-24.552602	r	on	15	K2 Campaign-9, Module-12
271.85166	-27.328437	r	on	15	K2 Campaign-9, Module-13
271.8502	-15.549016	r	on	15	K2 Campaign-9, Module-14
272.58167	-18.316964	r	on	15	K2 Campaign-9, Module-15
273.33749	-21.082731	r	on	15	K2 Campaign-9, Module-16
274.12191	-23.844644	r	on	15	K2 Campaign-9, Module-17
274.93987	-26.602962	r	on	15	K2 Campaign-9, Module-18
275.48614	-17.597012	r	on	15	K2 Campaign-9, Module-19
276.2882	-20.33974	r	on	15	K2 Campaign-9, Module-20
277.12054	-23.077546	r	on	15	K2 Campaign-9, Module-21
263.72779	-20.201175	r	off	15	K2 Campaign-9, Module-1
264.9247	-25.784213	r	off	15	K2 Campaign-9, Module-3
266.07655	-16.82745	r	off	15	K2 Campaign-9, Module-4
267.34745	-22.412586	r	off	15	K2 Campaign-9, Module-6
268.0217	-25.201351	r	off	15	K2 Campaign-9, Module-7
268.72661	-27.984544	r	off	15	K2 Campaign-9, Module-8
268.97252	-16.209388	r	off	15	K2 Campaign-9, Module-9
269.65253	-18.992061	r	off	15	K2 Campaign-9, Module-10
270.35534	-21.774739	r	off	15	K2 Campaign-9, Module-11
271.08764	-24.552602	r	off	15	K2 Campaign-9, Module-12
271.85166	-27.328437	r	off	15	K2 Campaign-9, Module-13
271.8502	-15.549016	r	off	15	K2 Campaign-9, Module-14
272.58167	-18.316964	r	off	15	K2 Campaign-9, Module-15
273.33749	-21.082731	r	off	15	K2 Campaign-9, Module-16
274.12191	-23.844644	r	off	15	K2 Campaign-9, Module-17
274.93987	-26.602962	r	off	15	K2 Campaign-9, Module-18
275.48614	-17.597012	r	off	15	K2 Campaign-9, Module-19
276.2882	-20.33974	r	off	15	K2 Campaign-9, Module-20
277.12054	-23.077546	r	off	15	K2 Campaign-9, Module-21
263.72779	-20.201175	r	off	15	K2 Campaign-9, Module-1
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267.34745	-22.412586	r	off	15	K2 Campaign-9, Module-6
268.0217	-25.201351	r	off	15	K2 Campaign-9, Module-7
268.72661	-27.984544	r	off	15	K2 Campaign-9, Module-8
268.97252	-16.209388	r	off	15	K2 Campaign-9, Module-9
269.65253	-18.992061	r	off	15	K2 Campaign-9, Module-10
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271.08764	-24.552602	r	off	15	K2 Campaign-9, Module-12
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271.8502	-15.549016	r	off	15	K2 Campaign-9, Module-14
272.58167	-18.316964	r	off	15	K2 Campaign-9, Module-15
273.33749	-21.082731	r	off	15	K2 Campaign-9, Module-16
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274.93987	-26.602962	r	off	15	K2 Campaign-9, Module-18
275.48614	-17.597012	r	off	15	K2 Campaign-9, Module-19
276.2882	-20.33974	r	off	15	K2 Campaign-9, Module-20
277.12054	-23.077546	r	off	15	K2 Campaign-9, Module-21
267.17021	-25.669376	r	on	15	K2 Campaign-11, Module-1
264.69931	-29.064482	r	on	15	K2 Campaign-11, Module-4
263.45917	-23.462254	r	on	15	K2 Campaign-11, Module-6
262.87765	-20.656998	r	on	15	K2 Campaign-11, Module-7
262.31833	-17.852577	r	on	15	K2 Campaign-11, Module-8
261.49601	-29.605946	r	on	15	K2 Campaign-11, Module-9
260.92737	-26.79314	r	on	15	K2 Campaign-11, Module-10
260.38681	-23.975597	r	on	15	K2 Campaign-11, Module-11
259.86765	-21.157819	r	on	15	K2 Campaign-11, Module-12
259.36942	-18.336932	r	on	15	K2 Campaign-11, Module-13
258.25987	-30.072995	r	on	15	K2 Campaign-11, Module-14
257.76264	-27.251584	r	on	15	K2 Campaign-11, Module-15
257.28983	-24.428065	r	on	15	K2 Campaign-11, Module-16
256.83751	-21.60315	r	on	15	K2 Campaign-11, Module-17
256.40292	-18.776225	r	on	15	K2 Campaign-11, Module-18
254.57518	-27.639373	r	on	15	K2 Campaign-11, Module-19
254.17478	-24.816517	r	on	15	K2 Campaign-11, Module-20
253.79079	-21.993558	r	on	15	K2 Campaign-11, Module-21
267.17021	-25.669376	r	off	15	K2 Campaign-11, Module-1
264.69931	-29.064482	r	off	15	K2 Campaign-11, Module-4
263.45917	-23.462254	r	off	15	K2 Campaign-11, Module-6
262.87765	-20.656998	r	off	15	K2 Campaign-11, Module-7
262.31833	-17.852577	r	off	15	K2 Campaign-11, Module-8
261.49601	-29.605946	r	off	15	K2 Campaign-11, Module-9
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259.36942	-18.336932	r	off	15	K2 Campaign-11, Module-13
258.25987	-30.072995	r	off	15	K2 Campaign-11, Module-14
257.76264	-27.251584	r	off	15	K2 Campaign-11, Module-15
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256.83751	-21.60315	r	off	15	K2 Campaign-11, Module-17
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261.49601	-29.605946	r	off	15	K2 Campaign-11, Module-9
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260.38681	-23.975597	r	off	15	K2 Campaign-11, Module-11
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259.36942	-18.336932	r	off	15	K2 Campaign-11, Module-13
258.25987	-30.072995	r	off	15	K2 Campaign-11, Module-14
257.76264	-27.251584	r	off	15	K2 Campaign-11, Module-15
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252.62898	-24.737815	r	on	15	K2 Campaign-2, Module-1
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249.8097	-27.893175	r	on	15	K2 Campaign-2, Module-4
249.20516	-22.208053	r	on	15	K2 Campaign-2, Module-6
248.92019	-19.36398	r	on	15	K2 Campaign-2, Module-7
248.64576	-16.522263	r	on	15	K2 Campaign-2, Module-8
246.60037	-28.147494	r	on	15	K2 Campaign-2, Module-9
246.35669	-25.298709	r	on	15	K2 Campaign-2, Module-10
246.125	-22.447025	r	on	15	K2 Campaign-2, Module-11
245.90076	-19.596442	r	on	15	K2 Campaign-2, Module-12
245.68598	-16.744145	r	on	15	K2 Campaign-2, Module-13
243.37691	-28.329937	r	on	15	K2 Campaign-2, Module-14
243.20141	-25.47929	r	on	15	K2 Campaign-2, Module-15
243.03384	-22.627974	r	on	15	K2 Campaign-2, Module-16
242.8729	-19.7765	r	on	15	K2 Campaign-2, Module-17
242.71813	-16.924105	r	on	15	K2 Campaign-2, Module-18
240.03962	-25.593367	r	on	15	K2 Campaign-2, Module-19
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239.84013	-19.90586	r	on	15	K2 Campaign-2, Module-21
252.62898	-24.737815	r	off	15	K2 Campaign-2, Module-1
251.92999	-19.084268	r	off	15	K2 Campaign-2, Module-3
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239.84013	-19.90586	r	off	15	K2 Campaign-2, Module-21
239.80112	-22.842778	r	on	15	K2 Campaign-15, Module-1
236.74854	-25.77599	r	on	15	K2 Campaign-15, Module-4
236.66006	-20.065128	r	on	15	K2 Campaign-15, Module-6
236.61699	-17.208912	r	on	15	K2 Campaign-15, Module-7
236.57571	-14.355501	r	on	15	K2 Campaign-15, Module-8
233.58956	-25.795758	r	on	15	K2 Campaign-15, Module-9
233.60258	-22.938687	r	on	15	K2 Campaign-15, Module-10
233.61604	-20.079162	r	on	15	K2 Campaign-15, Module-11
233.62703	-17.220917	r	on	15	K2 Campaign-15, Module-12
233.63942	-14.361349	r	on	15	K2 Campaign-15, Module-13
230.42998	-25.750422	r	on	15	K2 Campaign-15, Module-14
230.50193	-22.89622	r	on	15	K2 Campaign-15, Module-15
230.57069	-20.041484	r	on	15	K2 Campaign-15, Module-16
230.63687	-17.186745	r	on	15	K2 Campaign-15, Module-17
230.70161	-14.331263	r	on	15	K2 Campaign-15, Module-18
227.40562	-22.794871	r	on	15	K2 Campaign-15, Module-19
227.53054	-19.951623	r	on	15	K2 Campaign-15, Module-20
227.64949	-17.108981	r	on	15	K2 Campaign-15, Module-21
239.80112	-22.842778	r	off	15	K2 Campaign-15, Module-1
236.74854	-25.77599	r	off	15	K2 Campaign-15, Module-4
236.66006	-20.065128	r	off	15	K2 Campaign-15, Module-6
236.61699	-17.208912	r	off	15	K2 Campaign-15, Module-7
236.57571	-14.355501	r	off	15	K2 Campaign-15, Module-8

233.58956	-25.795758	r	off	15	K2 Campaign-15, Module-9
233.60258	-22.938687	r	off	15	K2 Campaign-15, Module-10
233.61604	-20.079162	r	off	15	K2 Campaign-15, Module-11
233.62703	-17.220917	r	off	15	K2 Campaign-15, Module-12
233.63942	-14.361349	r	off	15	K2 Campaign-15, Module-13
230.42998	-25.750422	r	off	15	K2 Campaign-15, Module-14
230.50193	-22.89622	r	off	15	K2 Campaign-15, Module-15
230.57069	-20.041484	r	off	15	K2 Campaign-15, Module-16
230.63687	-17.186745	r	off	15	K2 Campaign-15, Module-17
230.70161	-14.331263	r	off	15	K2 Campaign-15, Module-18
227.40562	-22.794871	r	off	15	K2 Campaign-15, Module-19
227.53054	-19.951623	r	off	15	K2 Campaign-15, Module-20
227.64949	-17.108981	r	off	15	K2 Campasdign-15, Module-21
239.80112	-22.842778	r	off	15	K2 Campaign-15, Module-1
236.74854	-25.77599	r	off	15	K2 Campaign-15, Module-4
236.66006	-20.065128	r	off	15	K2 Campaign-15, Module-6
236.61699	-17.208912	r	off	15	K2 Campaign-15, Module-7
236.57571	-14.355501	r	off	15	K2 Campaign-15, Module-8
233.58956	-25.795758	r	off	15	K2 Campaign-15, Module-9
233.60258	-22.938687	r	off	15	K2 Campaign-15, Module-10
233.61604	-20.079162	r	off	15	K2 Campaign-15, Module-11
233.62703	-17.220917	r	off	15	K2 Campaign-15, Module-12
233.63942	-14.361349	r	off	15	K2 Campaign-15, Module-13
230.42998	-25.750422	r	off	15	K2 Campaign-15, Module-14
230.50193	-22.89622	r	off	15	K2 Campaign-15, Module-15
230.57069	-20.041484	r	off	15	K2 Campaign-15, Module-16
230.63687	-17.186745	r	off	15	K2 Campaign-15, Module-17
230.70161	-14.331263	r	off	15	K2 Campaign-15, Module-18
227.40562	-22.794871	r	off	15	K2 Campaign-15, Module-19
227.53054	-19.951623	r	off	15	K2 Campaign-15, Module-20
227.64949	-17.108981	r	off	15	K2 Campaign-15, Module-21

R.A. range of principal targets (hours): X hours

Dec. range of principal targets (degrees): Y degrees

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

We need to review the DECam community pipeline and specify which stages we need (or need to remove) for star trail images.