Unveiling the Rich and Diverse Universe of Subsecond Astrophysics through LSST Star Trails

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Abstract

We present a unique method that allows the LSST to scan the sky for subsecond stellar variability. The method has operational and image processing components. The operational component is to take star trail images, which facilitate subexposure photometry. The image processing component is to use deep learning to sift for transient events on timescales down to 10 ms. We advocate for coupling this capability with the LSST's unrivaled 319.5 m^2deg^2 etendue to produce the first optical survey of the universe on these timescales. We explain how this data will advance both planned lines of investigation and enable new research in the areas of stellar flares, cataclysmic variables, active galactic nuclei, Kuiper Belt objects, gamma-ray bursts, and fast radio bursts.

1 White Paper Information

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1. **Science Category:** We introduce a mechanism that enables the LSST to provide new data with higher time resolution that not only enhances existing investigations, but allows LSST to contribute to new science use cases that generally lie within the categories: *Exploring the Transient Optical Sky*, *Mapping the Milky Way*, and *Taking an Inventory of the Solar System*.

2. **Survey Type Category:** We propose inserting occasional star trail images into the main *Wide-Fast-Deep* survey.

3. **Observing Strategy Category:** While different fields are conducive to different aspects of our method - for example, searching open clusters for flare stars - it is largely agnostic of where the telescope is pointed. Furthermore, our proposal can be trivially interleaved with the main LSST survey.

2 Scientific Motivation

Describe the scientific justification for this white paper in the context of your field, as well as the importance to the general program of astronomy, including the relevance over the next decade. Describe other relevant data, and justify why LSST is the best facility for these observations. (Limit: 2 pages + 1 page for figures.)

A wide range of astrophysical phenomena ranging from local Kuiper Belt object occultations to cosmic gamma-ray bursts manifest on subsecond time scales. Conventional optical telescopes rely on charge-coupled devices (CCDs) which typically take around ten seconds to read out. This readout time limits the time resolution they can achieve and precludes them from participating in high time resolution investigations. Furthermore, the special instruments that can image optical bands at high speeds have fields of view that are typically a few arcminutes, or less than 1/1000th of the LSST field of view. We present a mechanism that allows the LSST to explore the subsecond universe and describe how this unique data will (i) enhance planned LSST investigations of active galactic nuclei (AGN), stellar flares, and exoplanets and (ii) enable new LSST science with Kuiper Belt objects, fast radio bursts (FRBs), gamma-ray bursts (GRBs), and cataclysmic variables.

This proposal relies on a key insight originally from Howell & Jacoby (1986) and further developed in Thomas & Kahn (2018): star trail images are a conduit to achieving subsecond photometry of stellar sources. In star trail images, the tracking is turned off so the telescope rotates with the Earth during the exposure. Stellar sources are stretched into coherent linear trails, which show how the flux of the sources changes throughout the exposure. Figure 1 shows a simulated LSST star trail image with a one second exposure time. This choice of exposure time is elaborated on in Section 3. We then train a deep neural network to scan these large, unorthodox images and detect variability.

The input to the network is a 80x80 pixel crop of an LSST star trail image, the output is a binary classification which determines whether the sample are worthy of more detailed, science specific examination. As in many deep learning applications, high quality data and training feedback are essential. We use a suite of LSST simulation tools to produce realistic images. We sample visits from the *minion_1016* OpSim observing run, then we use CatSim to procure catalogs for each visit, then we use PhoSim to produce high fidelity simulated images of the catalogs (Delgado et al., 2014; Connolly et al., 2014; Peterson et al., 2015). We add a new interface into the PhoSim code to simulate *bursts* - a tophat change in flux added to an otherwise flat and static light curve of a source - parameterized by the magnitude change and duration. We train the network over 5 epochs of 80,000 sample 80x80 pixel crops, half of which contain a burst. We train the network to both predict whether the burst exists and to predict the exact photons resulting from the change in flux. Figure 2 highlights this process.

We assess the performance of our technique on visits and corresponding images that the network was not trained on. Figure 3 shows the results. These results are competitive with the state of the art (Dhillon et al., 2016).

Science Sections (AGN/Blazars, Stellar Flares, Exoplanets, Gamma-Ray Bursts, Kuiper Belt Objects, Fast Radio Bursts, Cataclysmic Variables)

Conclusion.

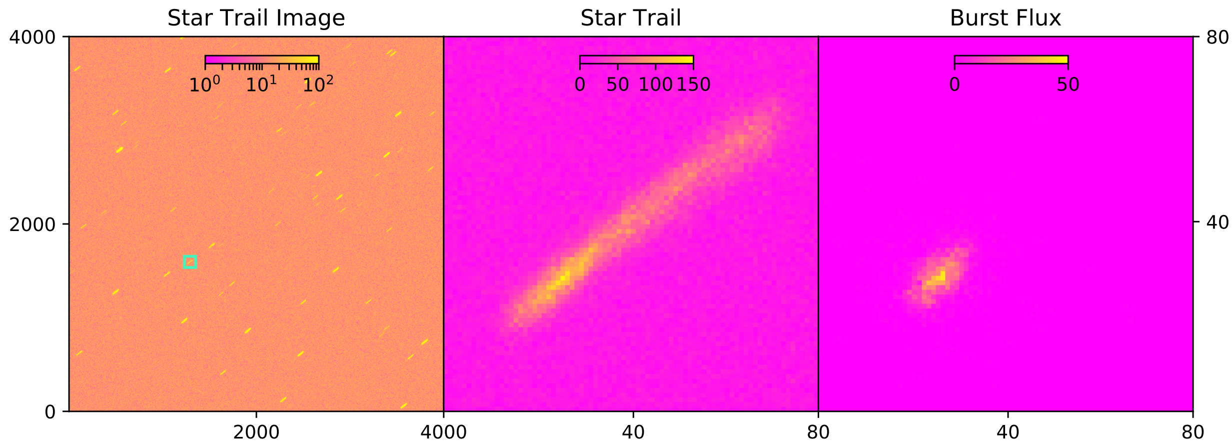

Figure 1: *Left:* a star trail image corresponding to a 1 second exposure on a single LSST CCD in the 'r' filter. *Middle:* zoom-in of a single star trail that is in the green box region in the full image. *Right:* zoom-in of the extra flux due to the burst.

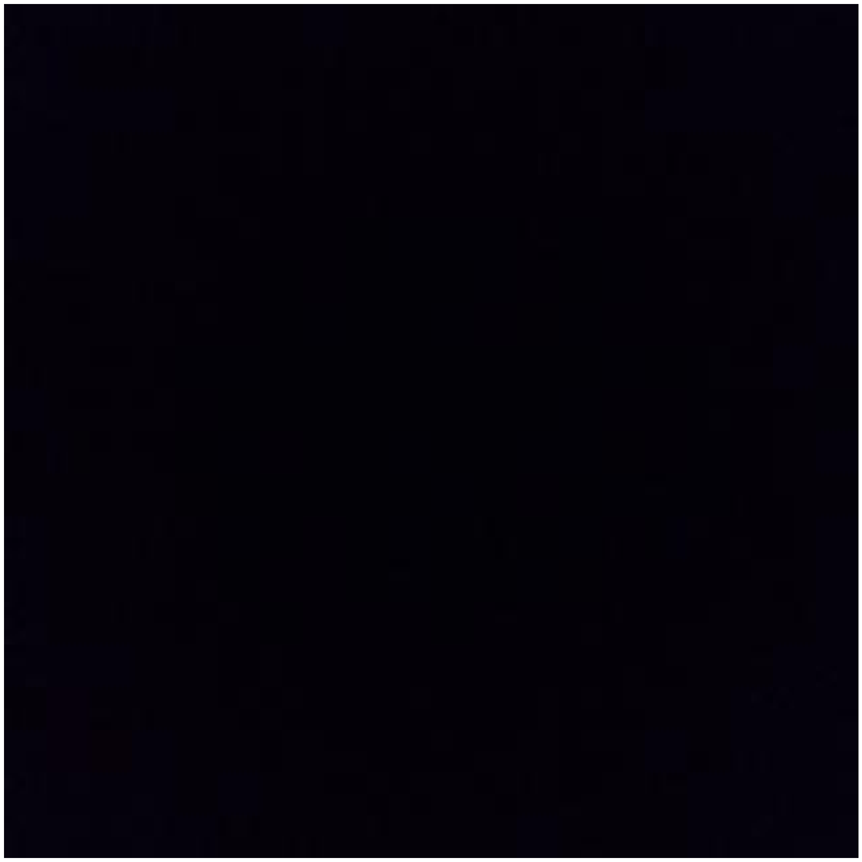

Figure 2: Image processing pipeline.

3 Technical Description

Describe your survey strategy modifications or proposed observations. Please comment on each observing constraint below, including the technical motivation behind any constraints. Where relevant, indicate if the constraint applies to all requested observations or a specific subset. Please note which constraints are not relevant or important for your science goals.

3.1 Taking Star Trail Images

The key element of our proposal is taking star trail exposures with the telescope tracking turned off. The rotation of the Earth during the exposure with respect to the field produces trails. The trails allow us to see how sources change throughout an exposure.

Star trail images require new signal analysis to optimize exposure times. Consider the simple scenario of the signal to noise ratio for a single pixel that a source trails over. Let A be the 100 μm^2 area of the pixel; N be the flux from the source deposited in the pixel; S be the the flux from the sky background; R be the readout noise; t_{pixel} be the 14 ms time the source spends over a single pixel; t_{exp} be the exposure time. Then the signal to noise ratio

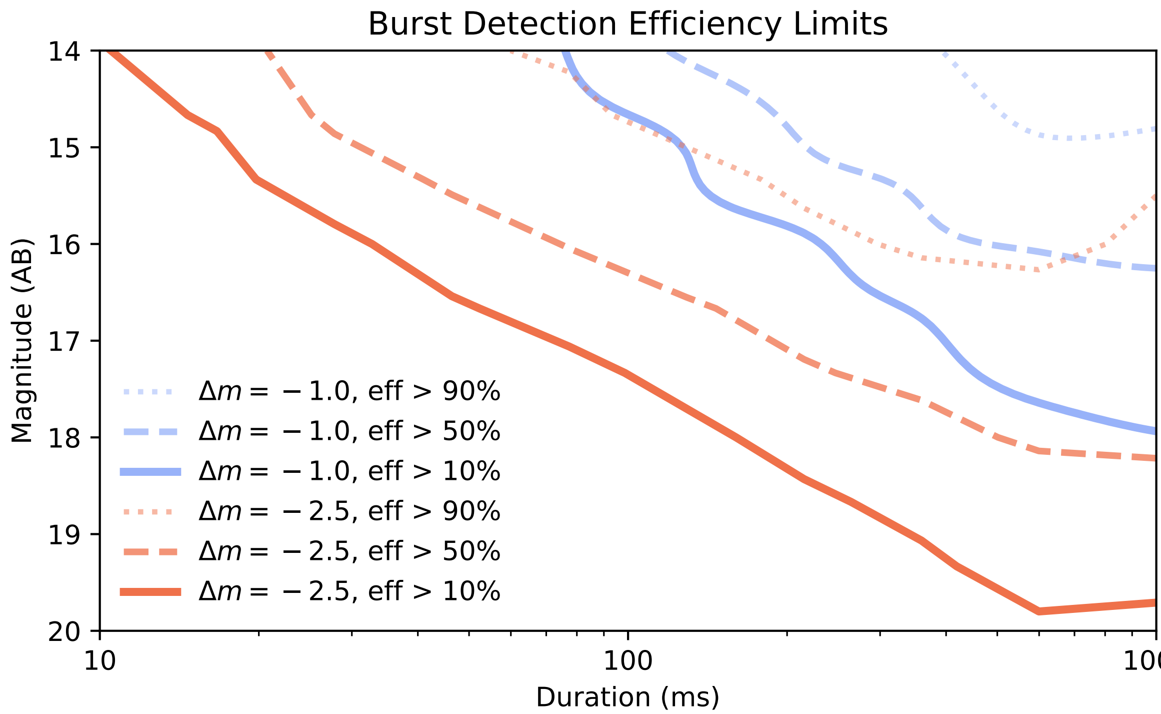

Figure 3: Detection accuracy and performance limits for 15s star trails. We expect to have updated performance curves for 1s star trails shortly.

for resolving a trail amongst the background is:

$$SNR_{trail} = \frac{N \cdot t_{pixel}}{\sqrt{N \cdot t_{pixel} + S \cdot A \cdot t_{exp} + R^2 \cdot A}}$$

There are additional signal to noise analyses that depend on the signature we are sifting for: bursts, occultations, or gradual changes in flux. These all share the $t_{exp}^{-1/2}$ dependence, which shows that shorter exposures provide stronger signal. The operation of the shutter provides a physical lower bound that constrains the minimal exposure time.

The shutter consists of two sets of flat, sliding plates on opposite sides of the focal plane. During each exposure the plates on one side are drawn back to initiate the exposure and the plates on the other side are pulled over to end the exposure. This double act ensures exposure time uniformity across the focal plane. The minimal exposure time is attained by immediately closing the shutter after the opposite plates finish opening. The exposure time is one second, but the total shutter operation time is two seconds. Two more seconds are required to read out the CCDs and complete the cycle. The total cycle is four seconds with a 25% duty cycle. Many applications are better served by a higher duty cycle at the expense of some signal. We present three modes of operation:

- **Short Trail:** Taking one second exposures to optimize for signal power and time resolution.

- **Long Trail:** Taking 15 second exposures to optimize for duty cycle.
- **Strategic Anti-Tracking:** In theory tracking can not only be turned off, but strategically controlled to extend trails further and achieve even higher time resolution.

We have simulated both short and long trails with high fidelity simulations. In each case, we trained deep neural networks to detect bursts in a range of conditions. The detection efficiency for the short trails is shown in Figure **??** and for the long trails in Figure **??**.

3.2 Constraints

- **Footprint.** The length of a star trails depends on the declination through the formula $l = 3.75 \cdot \cos(\delta)$ arcminutes or $1071 \cdot \cos(\delta)$ LSST pixels. We have a slight preference for pointings closer to the equatorial plane. We plan to continue evaluating specific science use cases and to provide more comprehensive footprint guidance by Summer 2019. Section 6 describes this future work in more detail.
- **Image Quality.** In theory, a worse seeing will weaken the signal power of a trail against the background by spreading out its flux in the transverse direction. In practice, the performance of the networks we have developed to process star trail images is fairly uncorrelated with seeing. This may change as we continue to refine these methods.
- **Sky Brightness.** The SNR for resolving trails is proportional to $S^{-1/2}$, where S is sky brightness (described in Section 3.1). A 4 times brighter sky background reduces the SNR by a factor of 2, which can dramatically alter the number of trails that can be resolved. Star trail imaging is very sensitive to sky brightness.
- **Total Number of Visits.** Star trail science consists of searching large expanses of sky for rare events. The number of detected events grows linearly with time. Hence the total number of star trail images, or time on the sky, is important.
- **Distribution of Visits Over Time and Within a Night.** Currently, there are no constraints on the distribution generally, nor on the number of visits within a night.
- **Filter Choice.** We use the 'r' filter in our experiments because it gives the most sources. This filter has a high transmission efficiency and good intersection with many stellar SEDs.
- **Exposure Constraints.** The shutters prevent exposures below 1 second while longer exposures have weaker signal. We discuss this further in Section 3.1.

Properties	Importance
Image quality	2
Sky brightness	1
Individual image depth	3
Co-added image depth	3
Number of exposures in a visit	3
Number of visits (in a night)	3
Total number of visits	1
Time between visits (in a night)	3
Time between visits (between nights)	3
Long-term gaps between visits	3

Table 1: Summary of the relative importance of various survey strategy constraints. Each constraint is ranked (1) very important, (2) somewhat important, or (3) not important.

4 Performance Evaluation

Please describe how to evaluate the performance of a given survey in achieving your desired science goals, ideally as a heuristic tied directly to the observing strategy (e.g. number of visits obtained within a window of time with a specified set of filters) with a clear link to the resulting effect on science. More complex metrics which more directly evaluate science output (e.g. number of eclipsing binaries successfully identified as a result of a given survey) are also encouraged, preferably as a secondary metric. If possible, provide threshold values for these metrics at which point your proposed science would be unsuccessful and where it reaches an ideal goal, or explain why this is not possible to quantify. While not necessary, if you have already transformed this into a MAF metric, please add a link to the code (or a PR to sims_maf_contrib) in addition to the text description. (Limit: 2 pages).

Total time imaging is the most important factor. We can also inject simulated bursts into images to validate the predicted constraining power.

5 Special Data Processing

Describe any data processing requirements beyond the standard LSST Data Management pipelines and how these will be achieved.

In order to perform a star trail survey, new LSST telescope control commands will need to be exposed for regular and autonomous toggling of the telescope tracking. As we continue to validate star trail imaging and do small surveys with other facilities, we will be implementing similar commands.

Mention locality. Securing a small GPU cluster at NCSA ...

6 Future Work

The primary goal of this white paper is to bring star trail imaging and its potential to the attention of the LSST Science Advisory Committee and broader LSST community. Star trail imaging offers a bold new opportunity that the LSST, with its enormous etendue, is uniquely positioned to capture. We are building a community of astronomers excited for star trails to help the LSST realize this potential.

Our community is planning more specific investigations of the individual science cases mentioned here. These involve calculating the observational signature of the phenomena of interest, generating simulated images, and assessing the data's ability to constrain theoretical models. We plan to have a session dedicated to this technique at the 2019 LSST Project and Community Workshop where community members can present their results.

We have already submitted a proposal for imaging four Kepler K2 fields with star trails with the Dark Energy Camera. We will measure how various stellar variability detection methods translate to real data. It will also give us experience programmatically operating telescopes in this manner. Through private communication with Steven Kahn and Chuck Claver we have also discovered that star trail images will be taken during the LSST commissioning.

References

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