

Speed-Aware EBS-EKF for Event-Based Star Tracking

Final Project Presentation

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1. Introduction

Goal

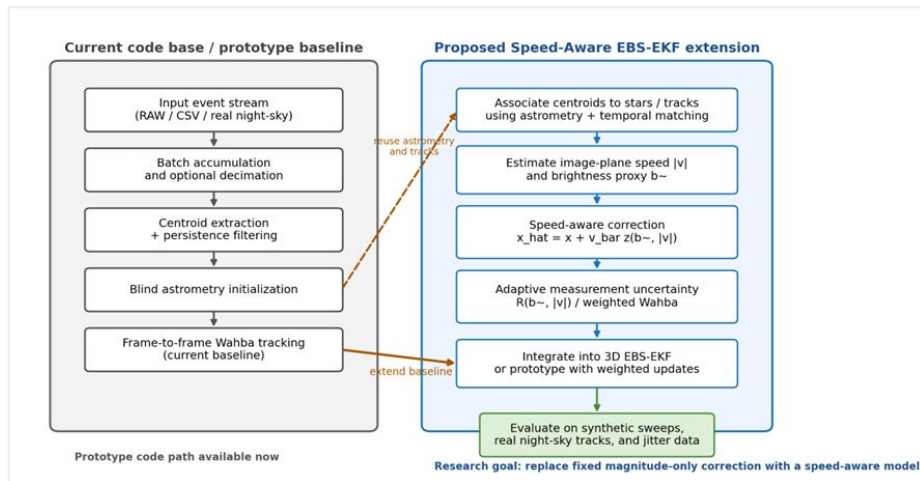
Improve event-based star tracking under low light and high motion

Core Idea

Make EBS-EKF centroid correction speed-aware, not only brightness-aware

Current Status

Prototype implemented; preliminary baseline vs. speed-aware comparison complete



a. Why star tracking matters



Attitude Estimation

Star trackers estimate spacecraft attitude from observed star positions.



Mission Support

Critical for precise pointing in communication, Earth observation, and science.



The Technical Challenge

Conventional APS trackers are limited by exposure time and frame processing rates. This makes rapid motion and high-frequency pointing significantly more difficult to achieve.

b. Why event cameras are promising



High Temporal Resolution

Event cameras output asynchronous brightness-change events at microsecond-scale temporal resolution.



Data Efficiency

For sparse star fields, they naturally produce less data because most pixels stay inactive.



Key Performance Benefits

- Lower latency & power
- Reduced motion blur
- Higher update frequency



The Modeling Challenge

Low-light event measurements are not ideal and require careful, precise modeling for effective performance.

2. Problem

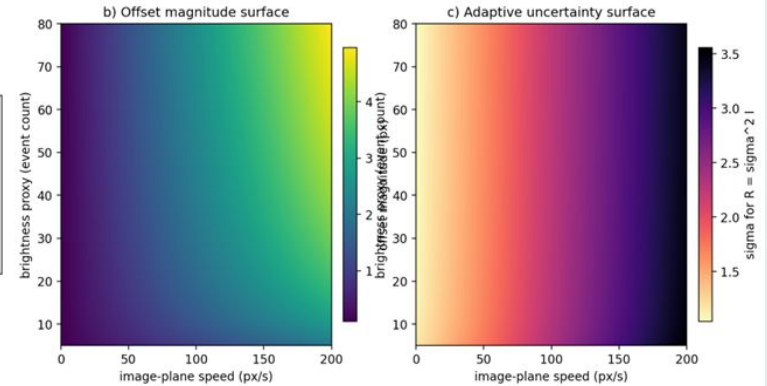
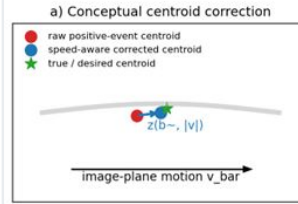
Gap in Current Tracking

EBS-EKF Baseline:

- Low-light event model
- Magnitude-dependent centroid correction
- 3D Extended Kalman Filter

The Critical Problem:

- Offset correction is a **fixed function of brightness only**.
- Theoretically, offset should **vary with star speed**.
- Fast-moving stars remain inaccurately modeled.



Conceptual centroid correction & magnitude/speed surface analysis
Idea: correct the centroid using both brightness proxy and image-plane speed

3. Related Work

2019

Chin et al.

Event images + ICP /
rotation averaging

2020

Bagchi & Chin

Progressive Hough
transforms

2023

Ng et al.

Asynchronous 2D
Kalman filter

2025

Reed et al.

EBS-EKF: low-light
model + 3D EKF

Key supporting literature

- **Low-light DVS modeling:** Graca et al., Jiang & Zhou
- **Calibration / sensing:** Ralph et al.
- **Validation protocol:** Earth-rotation benchmark

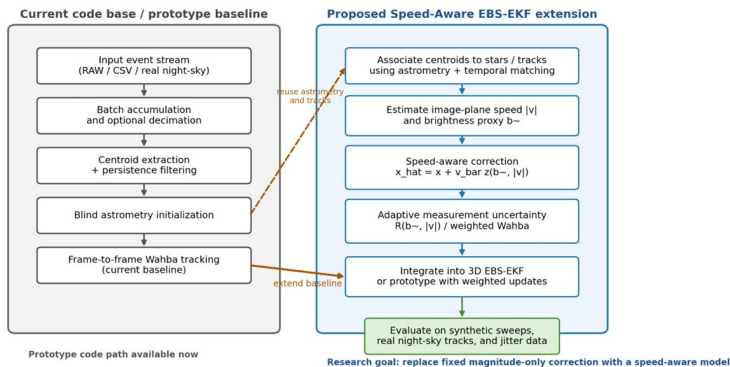
How my project differs

- I am not replacing EBS-EKF.
- I keep its measurement-driven philosophy and 3D filtering target.
- The **novelty** is making centroid correction and measurement uncertainty **speed-aware**.

4. Approach Overview

Prototype Evolution

From current prototype to proposed system



Pipeline

Current baseline:

- Event batching + centroid extraction
- Blind astrometry initialization
- Batchwise weighted-Wahba attitude update

Proposed additions:

- Estimate image-plane speed
- Apply speed-aware centroid correction
- Use adaptive measurement covariance
- Move toward asynchronous 3D EBS-EKF

5. Method Details

Speed-aware correction

$$\hat{x}_i = x_i + \bar{v}_i z(\tilde{b}_i, \|v_i\|),$$

Adaptive uncertainty

$$R_i = \sigma_i^2 I_2, \quad \sigma_i = \sigma_0 \left(1 + \alpha \psi(\|v_i\|) + \gamma \frac{1}{\sqrt{\tilde{b}_i} + \epsilon} \right)$$

Weighted Wahba update

$$R^* = \arg \min_{R \in SO(3)} \sum_i w_i \|u_i - R s_i\|_2^2$$

where $w_i \propto 1/\sigma_i^2$

Interpretation

- The measured centroid is treated as a biased observation.
- The bias grows with motion and with the brightness proxy.
- The covariance is larger when motion is fast or centroid support is weak.
- In the current prototype, corrected centroids are fused batch-by-batch through a weighted Wahba solve.
- That gives a testable bridge before implementing the full asynchronous 3D EBS-EKF.

6. Experimental Setup

Synthetic stage

Use `trade_space_scenarios_v2.csv` to generate controlled synthetic star-motion data.

Run speed sweeps and brightness sweeps first.

Goal:

Calibrate the correction and debug failure modes before large real-data runs.

Real-data stage

Main Benchmark:

Released EBS-EKF real-night-sky dataset.

Validation:

Earth-rotation benchmark for stronger real-sky validation.

Stress-testing:

Public variable-speed slew observations.

Metrics and protocol

Comparisons:

- Baseline
- Original magnitude-only
- Speed-aware prototype

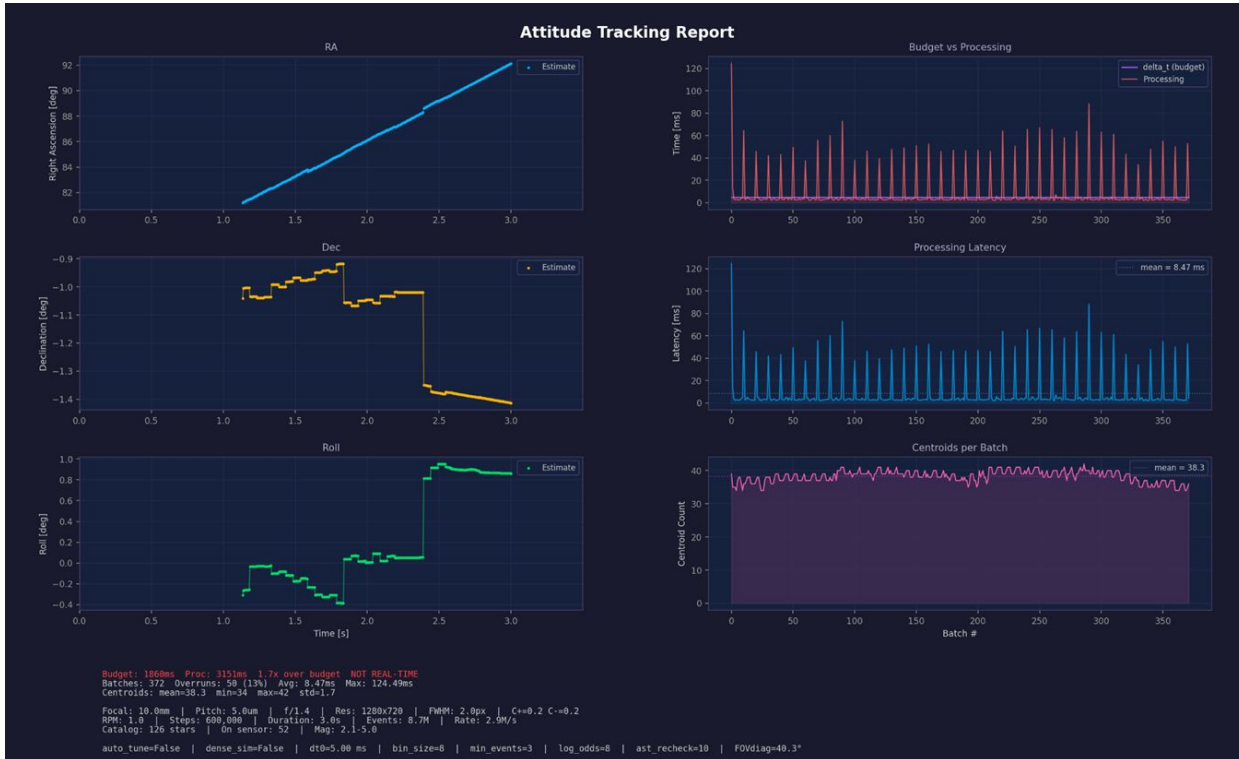
Key Metrics:

Attitude behavior, latency, budget overruns, and centroid statistics.

Use across/about error when trusted reference is available.

7. Preliminary Results

Magnitude-only baseline on one representative track



Baseline summary

3.0 s track

372 batches

8.7M events

Mean 38.3 centroids / batch

Mean latency: 8.47 ms

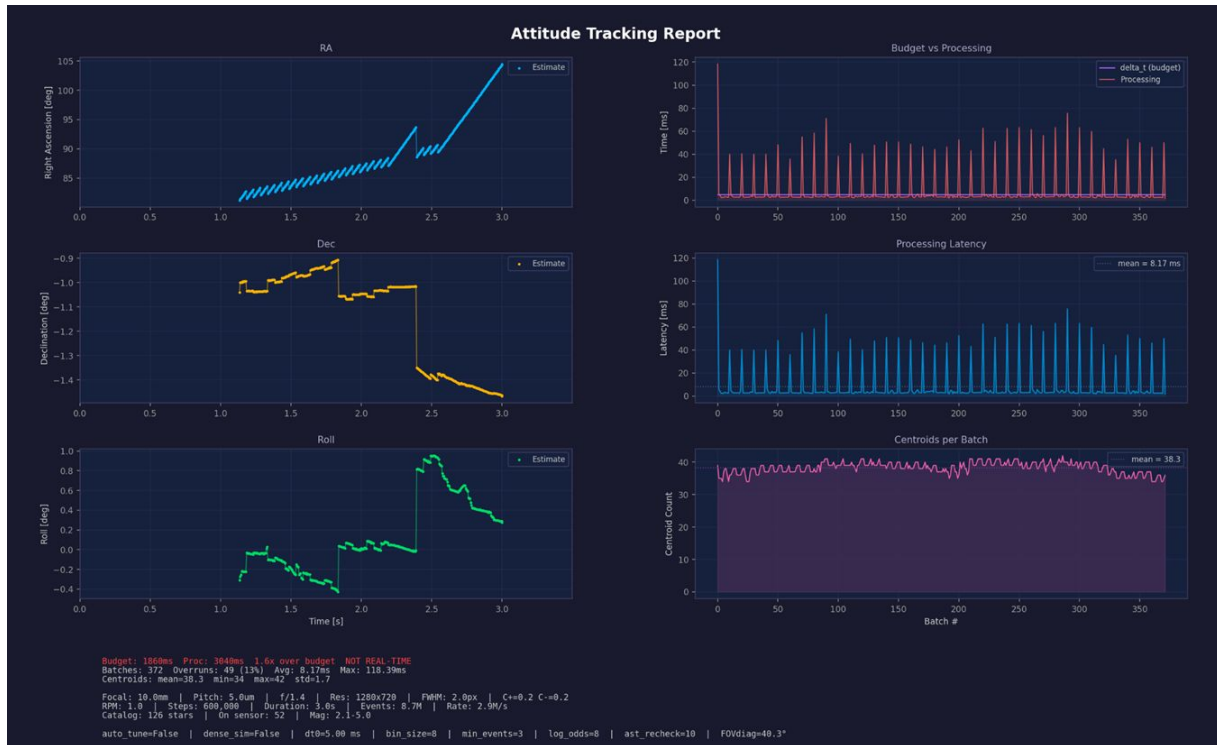
Max latency: 124.49 ms

Budget overruns: 50

Reference behavior before
the speed-aware module

8. Preliminary Results

Speed-aware prototype on the same track



Observed changes

Mean latency: 8.17 ms

Max latency: 118.39 ms

Budget overruns: 49

Interpretation

RA, Dec, and roll trajectories visibly change.

So the speed-aware layer is active end-to-end.

Runtime cost stays essentially the same.

But this is still preliminary: one track is not enough to claim accuracy gains.

9. Conclusion and Future Objectives





Key Takeaways

Limitation: The project targets a real limitation in EBS-EKF where centroid correction should depend on speed, not only brightness.

Prototype: Built a speed-aware prototype with adaptive covariance and a weighted Wahba update.

Status: The module is operational and adjusts final attitude estimates without significant runtime penalty.

Next Steps

-  Run synthetic trade-space sweeps to calibrate the correction.
-  Evaluate on multiple real night-sky tracks instead of one example.
-  Use Earth-rotation and public variable-speed observations for stronger validation.
-  Integrate the measurement model into a fuller asynchronous 3D EBS-EKF pipeline.

Thank you!



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