



OPTICAL TRIANGULATION FOR THE DETECTION OF TRANSIENT IONOSPHERIC EVENTS

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The Stakes

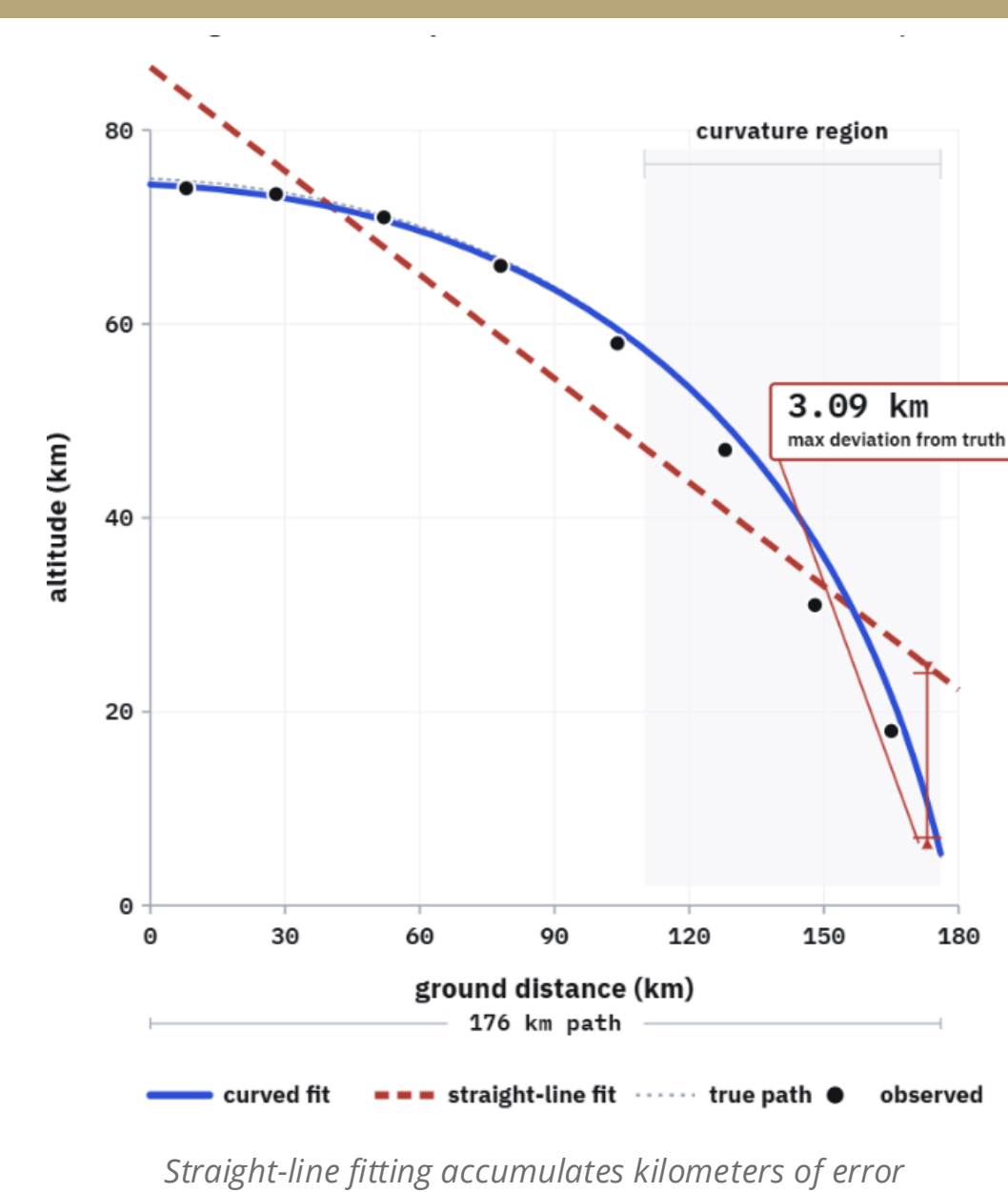
Every day, ~44 tons of rock strike our atmosphere [1]: Almost all of it burns harmlessly at altitude — *the difference is size*. When a body is large enough, that energy doesn't dissipate: in 2013, a ~20 m asteroid detonated over Chelyabinsk with the force of ~500 kilotons of TNT, damaging 7,200+ buildings and injuring ~1,500 people [2]. *Knowing which is which means reading the path.* A meteor's trajectory curvature encodes its mass and density; the timing of its fragments reveals material strength. Recovering that demands reconstructing the path accurately — not just detecting the flash.



Chelyabinsk Impact

The Gap We Close

Today's meteor networks — the Global Meteor Network, CAMS, and the Desert Fireball Network, collectively operating hundreds of cameras across dozens of countries [3] — reconstruct trajectories with **straight-line fits**. That assumption throws away the very curvature that encodes a meteor's mass and density. Over a 176 km path, DFN measured a straight-line deviation of **3.09 km** [4]; enough to corrupt the kinematics on which science depends.



Straight-line fitting accumulates kilometers of error

Our approach resolves the curved path, which demands higher angular resolution, greater light-gathering, and sub-millisecond timing than current systems provide.

Design Target Specifications

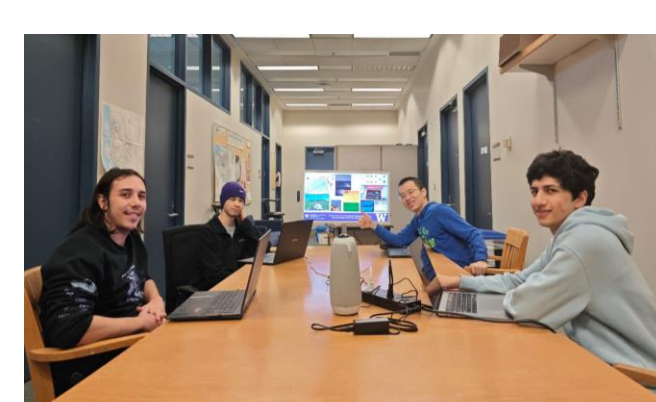
The platform is built to meet five measurable targets:

Requirement	Target
3D position accuracy	≤ 5 km at 100 km alt (40 km baseline)
Cross-station timing	± 0.5 ms
Detection sensitivity	meteors to apparent magnitude +6
Detection recall / precision	≥ 95% / ≥ 80%
Velocity uncertainty	< 5% (events ≥ 2 s)

A historical moment



Movie: Contact (1997)
"That's the moment where contact becomes possible. The very large array in New Mexico is the key to our chance for success. With its 27 linked radio telescopes, we can search more accurately than at any other conventional facility."



Triangulation Team (2026)
"That's the moment where direct probing of the ionosphere becomes possible. The Triangulation autonomous node is the key to our chance for success. With several linked receivers and controllable ionospheric disturbances, we can gain a greater understanding of ionosphere physics and our ability to control its parameters than any conventional system."

The Station

Each station pairs a **ZWO ASI585MM** monochrome camera (Sony IMX585, 4K, 2.9 μm pixels, ~80%+ peak QE) with an edge-compute unit and a GPS-disciplined clock, housed in an **IP65 enclosure** with a quartz dome and heated anti-fog window for year-round outdoor operation. Monochrome doubles effective sensitivity — no Bayer filter absorbing half the photons — and sharpens the point-spread function for sub-pixel centroiding.

Each unit captures **4K at 30 fps across a ~110° field of view**, GPS-timestamped to ±0.5 ms so frames from three stations fuse into a single trajectory.



The station design — Sky Camera Nodes

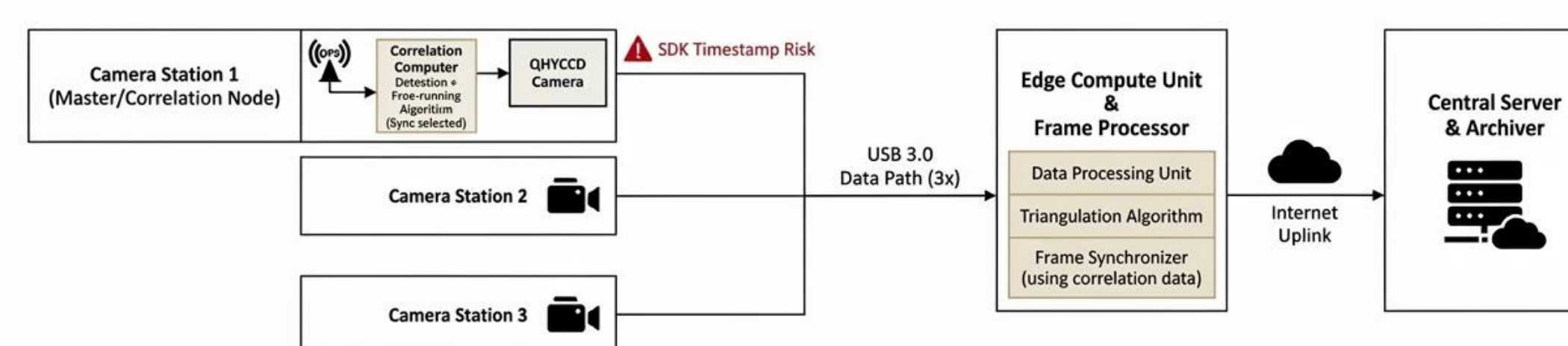
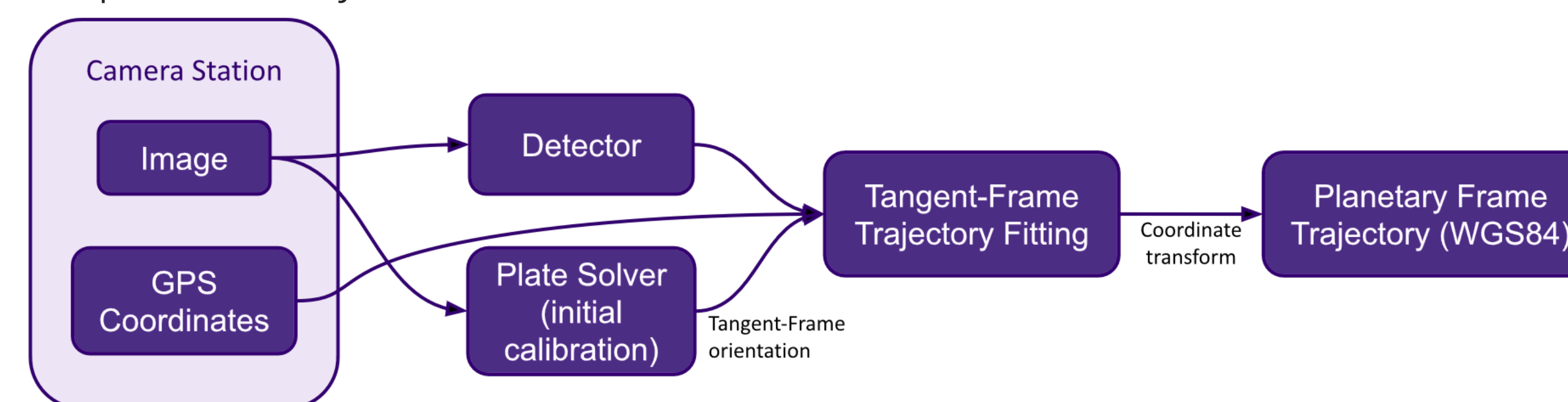
The station design — Capturing Operator Panel

Approach & Key Design Decisions

Detection runs live on every frame — frame differencing, blob detection, and tracking — while plate-solving and a nonlinear-optimization fit reconstruct the 3D trajectory offline.

A **continuous ring buffer** retains the frames *before* each trigger, so the complete event — including the atmospheric-entry phase where deceleration and fragmentation occur — is captured, not just the bright tail.

Our **operator software runs the full live pipeline today**: real-time 4K preview, detection overlay, and capture telemetry.



System design and data flow

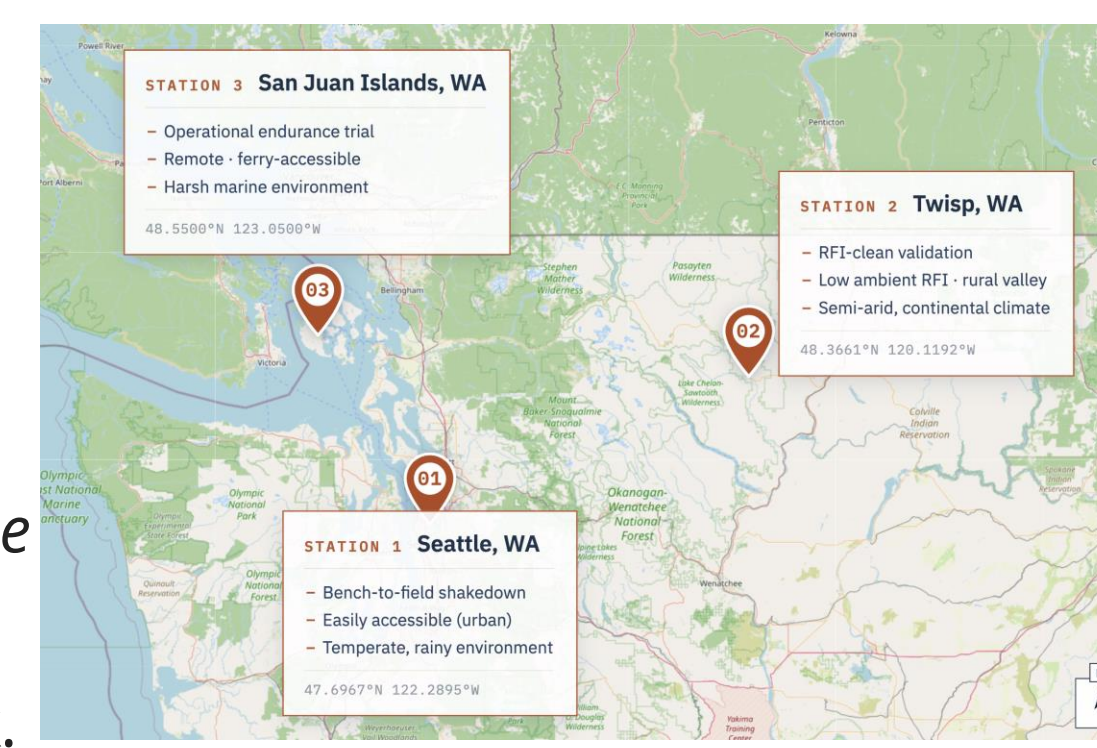
Future Work

The system is **built and ready to deploy**. Three milestones follow:

First light: the first real multi-station capture and curved-path reconstruction.

Multimodal ground truth: optical trajectories give known position and timing, providing the labeled ground truth an autonomous RF ionospheric-sensing system is trained and validated against. (*Optical is designed to feed the RF system; that integration is the next phase.*)

Scale: a validated station design replicated into a statewide sensing network.



Field Deployment Plan

Results

Plate-solving — validated: On third-party sky footage, our pipeline solves pixel-to-celestial coordinates and flags the wide-angle lens distortion that must be corrected before accurate astrometry.

Detection — demonstrated: Frame differencing and blob detection isolate and label transient events on real test video.

Denoising — demonstrated: On-camera and pipeline denoising recover faint tracks from noisy frames.

Triangulation — validated in simulation: The nonlinear-optimization solver recovers a known 3D trajectory from synthetic three-station detections, handling non-simultaneous frames.

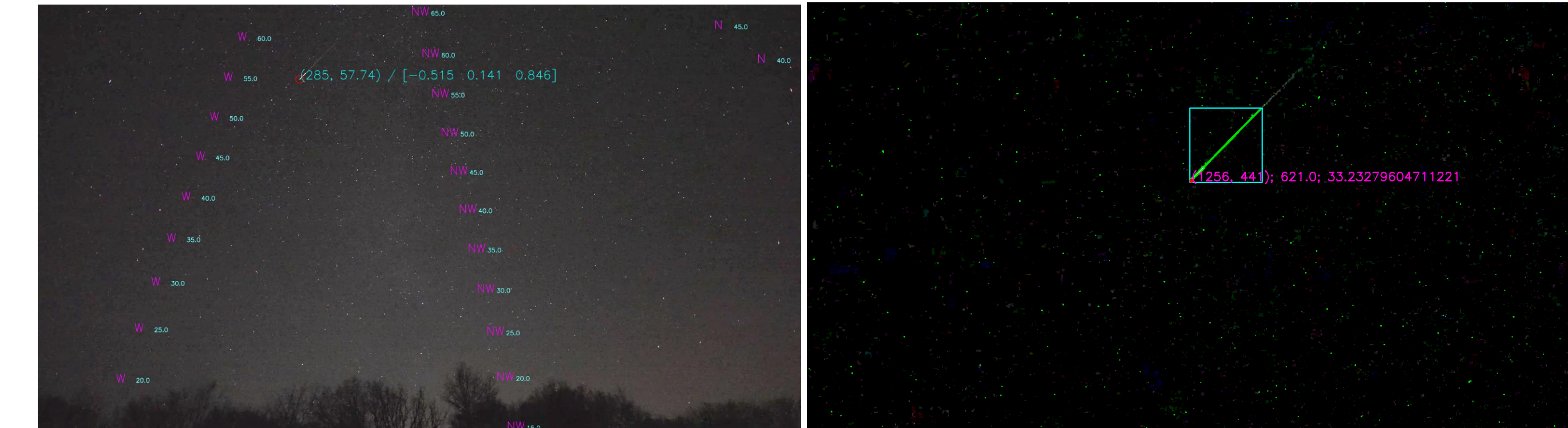
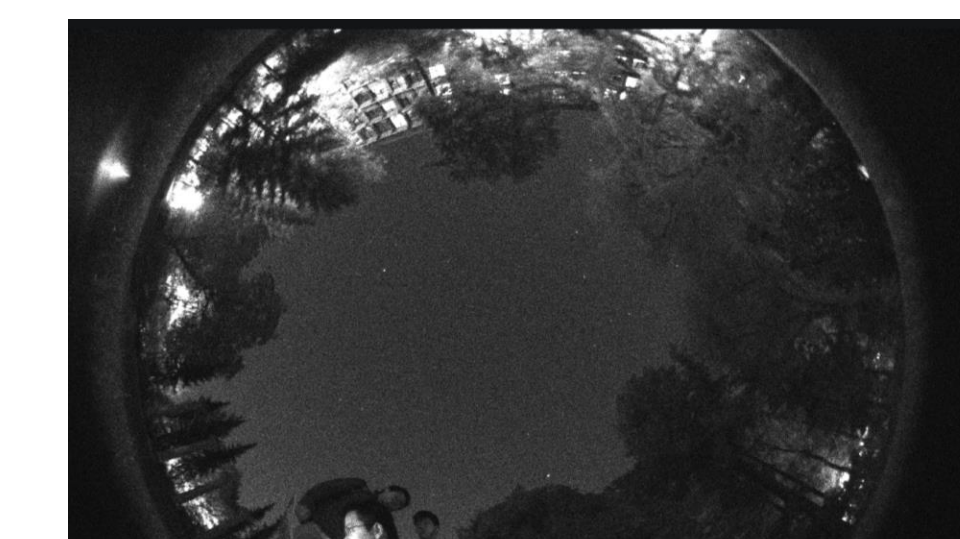


Plate-solving — WCS grid on test footage

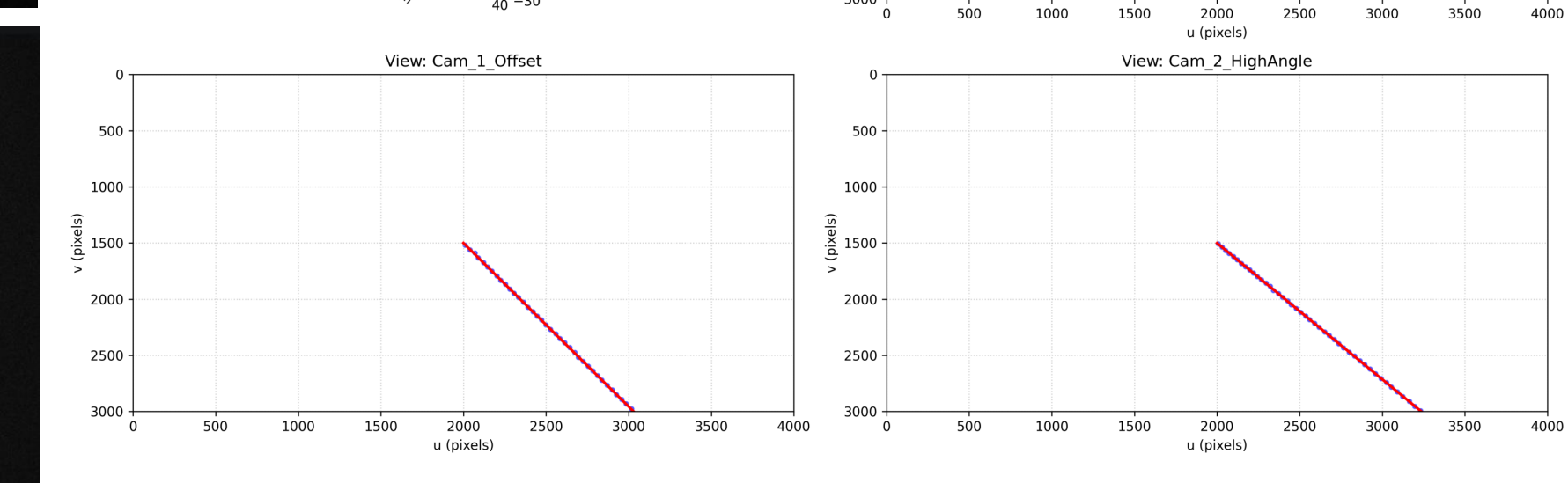
Detection — labeled meteor on real video



Meteor Trajectory Reconstruction: 3D Path and Camera Views



Denoising — before/after

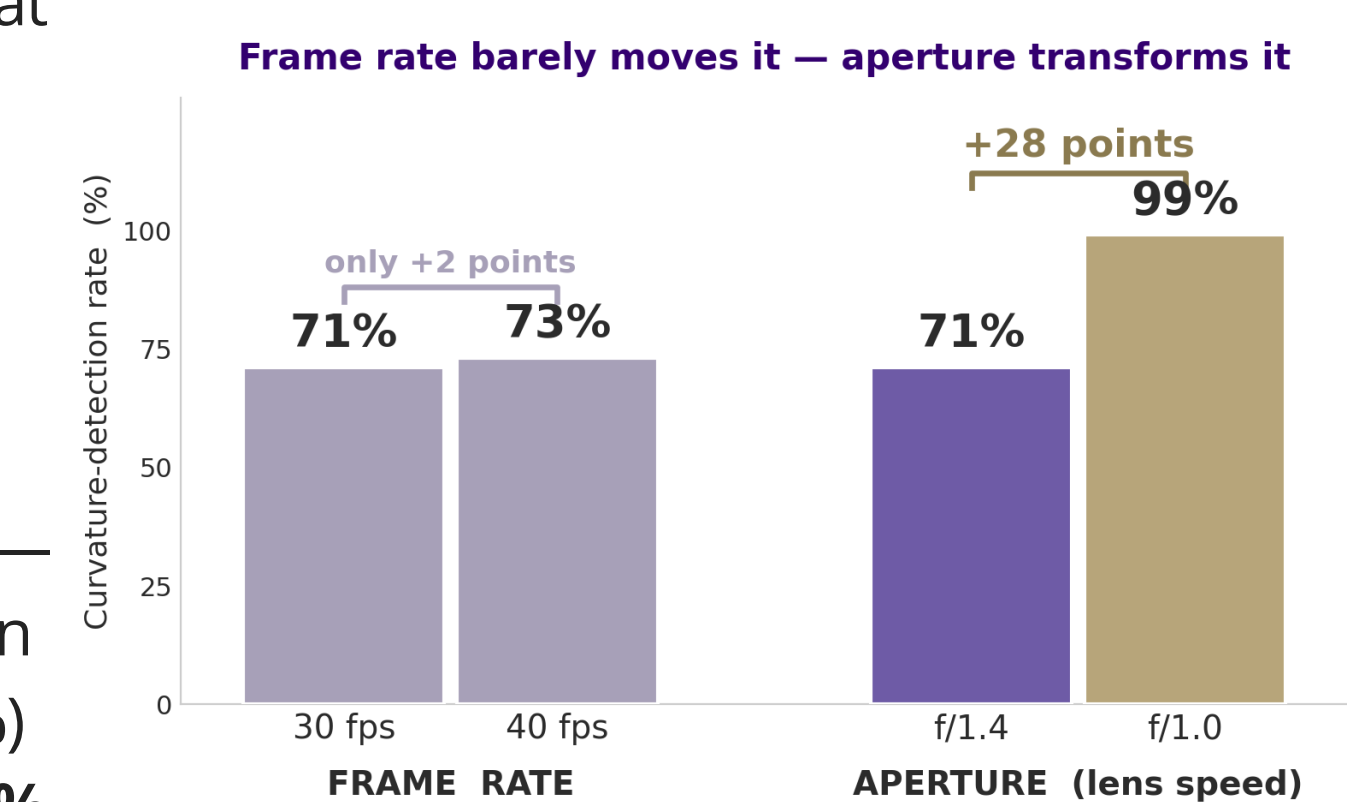


Triangulation — 3D reconstruction (synthetic)

Conclusion & Key Takeaway

We built an optical triangulation platform that resolves the meteor curvature straight-line networks discard — and engineered it to anchor ground truth for autonomous RF ionospheric sensing. The instrument is complete; first light is next.

Key finding: for curvature science, the lens — not the frame rate — sets the limit. Detection barely moves from 30 to 40 fps (**71% → 73%**) but climbs sharply with aperture (**71% → 99%**, f/1.4 → f/1.0). (*Model estimate.*)



References

- [1] NASA, "Meteors & meteorites: Facts," <https://science.nasa.gov/solar-system/meteors-meteorites/facts/>
- [2] D. Lang, D. W. Hogg, K. Mierle, M. Blanton, and S. Rowels, "Astrometry.net: Blind astrometric calibration of arbitrary astronomical images," *AJ*, vol. 137, pp. 1782–2800, 2010, arXiv:0910.2233.
- [3] D. Segon et al., "The Global Meteor Network — Methodology and first results," 2021.
- [4] E. K. Sansom et al., "3D meteoroid trajectories," *Icarus*, vol. 321, pp. 388–406, 2019, doi: 10.1016/j.icarus.2018.09.026.