AURORAS: Orbit Determination with Just One Look

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ABSTRACT

The AURORAS technique achieves orbit determination an order of magnitude faster than conventional angles-only techniques using a single passive optical sensor. AURORAS is a new approach to orbit determination utilizing a differential estimate of motion at one point in time rather than integration of motion over a long arc of the orbital path. This approach relies on high cadence event-type data produced by event-based cameras that record the position and time of change-detection events or from processed image stacks produced by fast framing global shutter CMOS cameras.

While conventional angles-only techniques require multiple observations separated in time, AURORAS requires only one continuous observation over a short time, just one look, to simultaneously measure angular position, velocity, and acceleration. Utilizing high-cadence detections (i.e., temporally dense angles-only observations) the AURORAS technique discerns subtle curvature in motion and calculates a state estimate without the lengthy observation time required by conventional techniques.

Using simultaneous collections from two side-by-side sensors we compare AURORAS with a conventional angles-only technique and determine the shelf-life of the produced element set (elset) as if used to task another sensor. To reach the same level of accuracy produced by AURORAS, the conventional angles-only technique required significantly longer observing time. By reducing the necessary observation time, AURORAS poses to significantly improve the timeliness of vital Space Domain Awareness information to support decision making in the increasingly congested space environment.

The AURORAS technique for orbit determination is protected by patent US12080000.

1. INTRODUCTION

The Advanced Uni-sensor Rapid Orbit Reconstruction Analysis and Sensing (AURORAS) technique is a new approach to orbit determination (OD) of Earth-orbiting objects using ground-based or space-based passive optical sensors. AURORAS is a combination of new algorithms for OD combined with new optical sensors including event -based cameras (EBCs), photon counting imagers, and high-speed CMOS framing cameras.

Conventional angles-only OD techniques require at least three discrete observations of the object's angular position over an extended time period (lefthand panel of Figure 1). These three observations yield six independent numbers (two per observation, i.e., azimuth and elevation angles) used to fully constrain the OD. The duration of time between measurements must be long enough to see a difference in position and discern the arc of motion along the orbital path. Customary guidance for a single sensor system prescribes the total observation time span cover at least 1/8th of the object's orbit period to produce an accurate OD. For an object in geosynchronous Earth orbit (GEO) with a 24-hour period, this guidance suggests observations spanning multiple hours are necessary.

In contrast, AURORAS requires only one continuous observation over a short time (see righthand panel of Figure 1) to simultaneously measure angular position, angular velocity, and angular acceleration providing six independent numbers for OD (see Figure 2). AURORAS is a differential approach, rather than integral approach, to calculating a state vector using a modified version of Laplace's equations for OD. Utilizing high-cadence detections (i.e., temporally dense angles-only observations) the AURORAS technique discerns subtle curvature in motion without the lengthy time required by conventional techniques. Initial simulations indicated that AURORAS could achieve an order of magnitude improvement compared to conventional single-sensor techniques [1] and subsequent real-world experiments confirmed this with AURORAS producing accurate ODs with observation duration less than 1/100th of the orbit period [2]. The AURORAS technique works for both ground-based and space-based sensors.

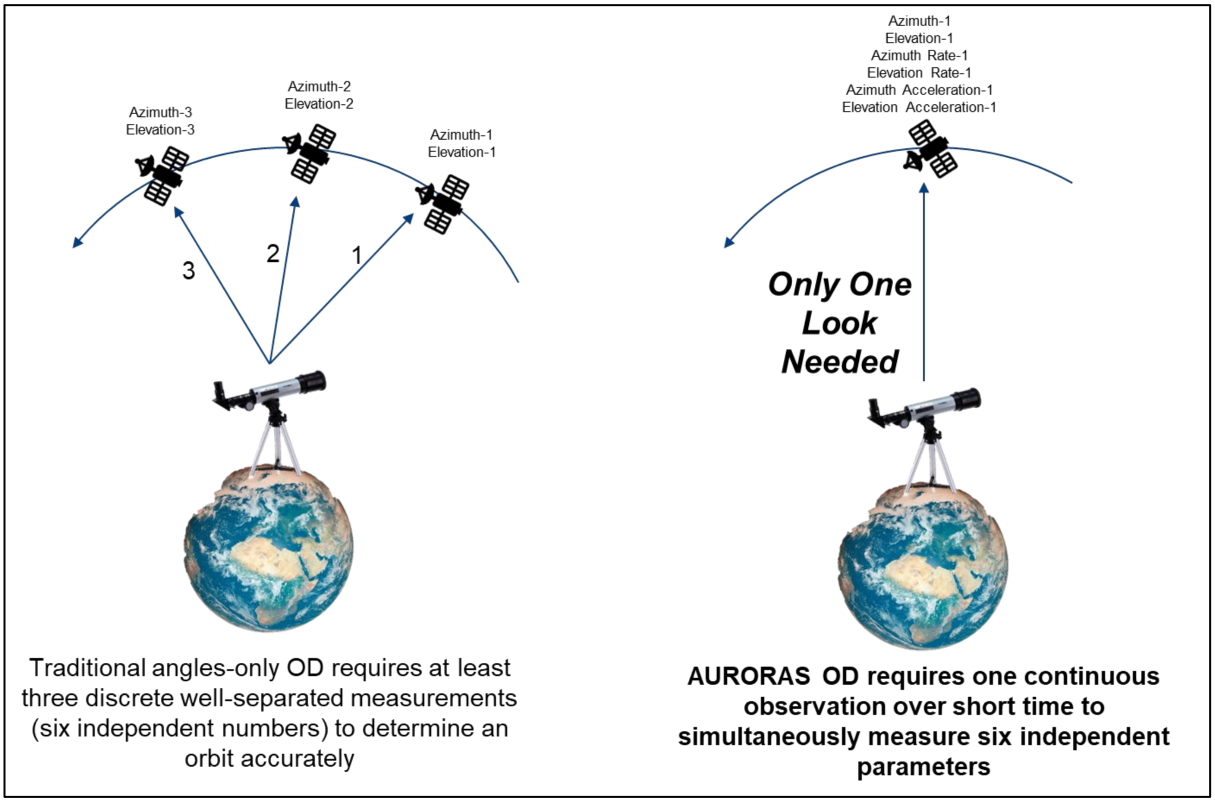

Figure 1. While conventional angles-only orbit determination techniques require multiple discrete observations over time, AURORAS uses one continuous observation over a short time.

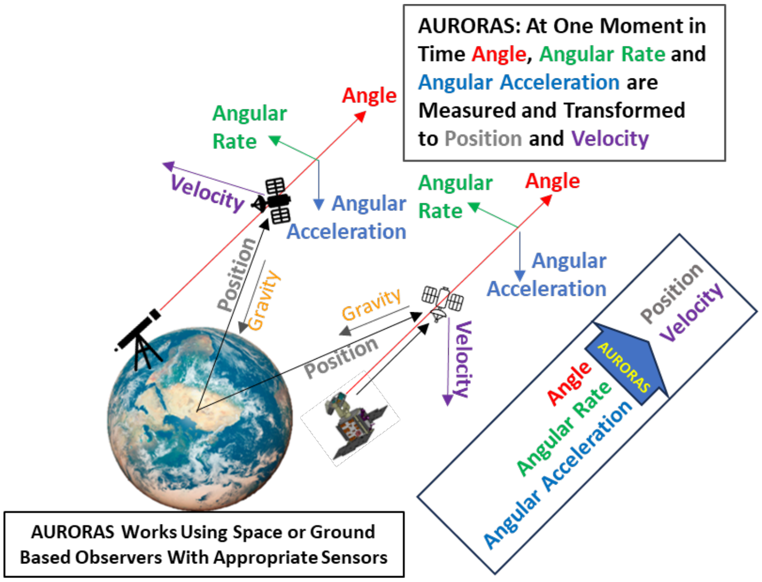

Figure 2. AURORAS measures the space object's angular position, angular velocity, and angular acceleration to determine the object's state vector and orbit.

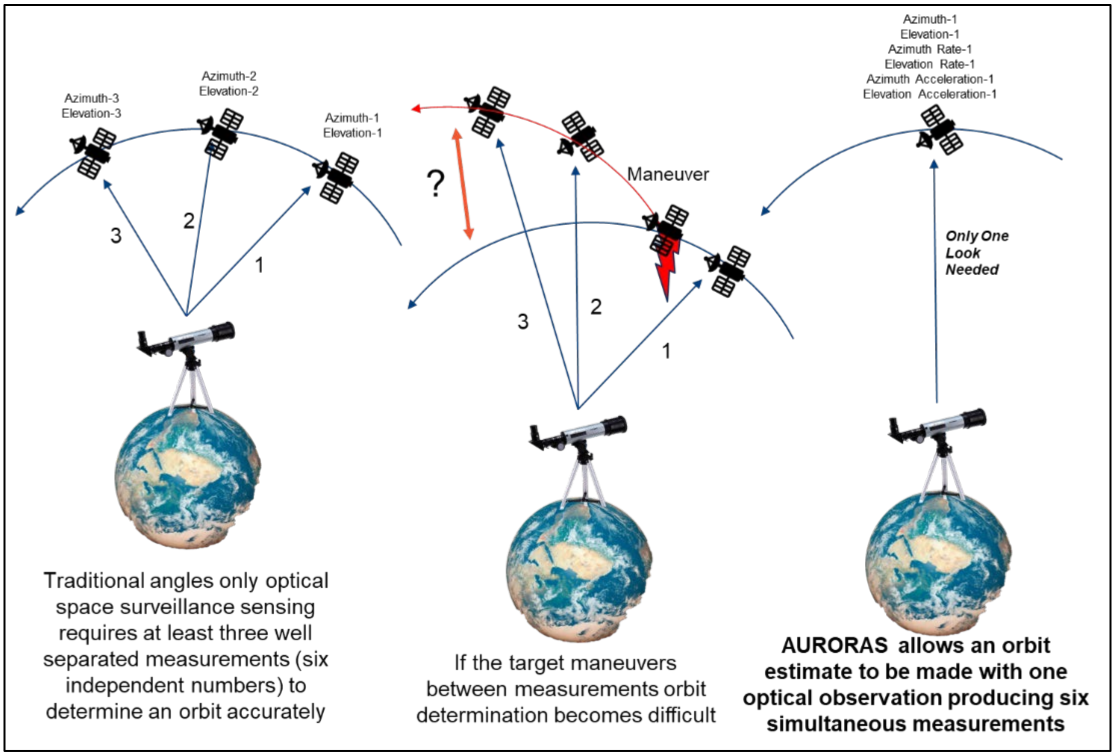

Figure 3. AURORAS produces near-immediate OD updates for a rapidly maneuvering object that would otherwise be lost by conventional OD techniques that require multiple observations.

By significantly reducing the time needed to produce a state estimate and OD, AURORAS overcomes challenges experienced by conventional angles-only techniques. Specifically in the scenario of a maneuvering object, conventional techniques requiring a long observation time span will fail to produce an accurate OD (or any at all) if the observed object maneuvers during the observing sequence resulting in inconsistent measurements or loss of the object and an incomplete dataset (see Figure 3). Failure to produce a timely OD inhibits the potential for other sensors to pick up the same object via handoff and cueing. In the same scenario, an AURORAS sensor may produce a rapid OD with just one look at the object. The timely OD produced by AURORAS enables a downstream sensor to track the object and maintain custody.

To assess AURORAS performance in this scenario we completed an experiment to determine the shelf-life of the AURORAS OD and compare it to one from a conventional angles-only OD.

2. EXPERIMENT

For this experiment we utilized our telescope system located in western New Mexico. This system shown in Figure 4 features dual Celestron RASA f/2.2 36 cm telescopes on a PlaneWave mount. One telescope is equipped with a CMOS framing camera, and the second telescope is equipped with an event-based camera (EBC). The telescopes are aligned to view the same patch of sky and produce simultaneous side-by-side recordings. The two sensors, although based on different sensing methodologies, feature similar resolutions and pixel sizes to produce comparable datasets. For this experiment the EBC served as the AURORAS sensor and the CMOS a conventional angles-only sensor. The CMOS camera can support AURORAS when run in high-speed mode.

We recorded data with both sensors simultaneously while tracking the object. With the EBC we recorded up to 20 min of continuous data. With the CMOS camera we recorded up to 60 min of data at 1 frame per second with 40 msec integration for each image. This integration is long enough to detect the target and many background stars but with negligible trailing that would impact the astrometry. Both sensors are synchronized with a GPS time server for accurate timestamping.

Due to the limited scope and time for this experiment we could not complete a sufficient number of collections and analyses to compile meaningful statistics. We include one example here as a demonstrable showcase of AURORAS performance. Table 1 lists the object and observations made.

Table 1. Side-by-side simultaneous datasets collected for this experiment.

Observation Start Time (UTC)	**Object**	**Orbit**	**EBC Recording**	**CMOS Recording**
2025-06-22 03:30	GOES 16 (41866)	GEO	~20 min	~60 min, ~1 fps, 3583 images

Figure 4. The AURORAS testbed system features dual Celestron RASA 36 cm telescopes equipped with an event-based camera and a CMOS sensor to enable simultaneous side-by-side observations with both sensor types.

Table 2. The AURORAS telescope sensor specifications.

	Event-Based Camera	**CMOS Framing Camera**
Sensor	Prophesee EVK4	QHY 174M
Resolution	1280 x 720	1920 x 1200
Pixel Size	4.86 μm	5.86 μm
FOV	0.45° x 0.25°	0.82° x 0.51°
Pixel Scale	1.27”	1.53”

3. AURORAS PROCESSING

The AURORAS software processes raw data through a series of modules to produce calibrated data, detect the resident space object(s) of interest, and calculate state vector(s) and SGP4 element set(s).

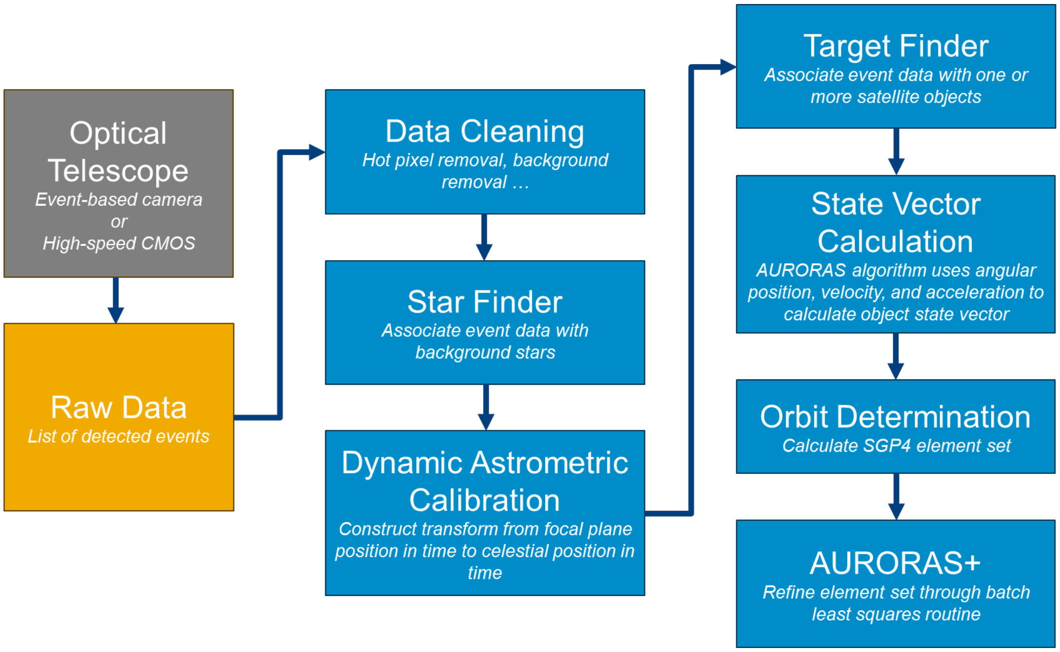

Figure 5. The current AURORAS processing pipeline follows a linear series of modules and processes.

The first processing step is Data Cleaning which involves removing unwanted data and noise reduction (see Figure 6). For EBC data, we remove negative events since the current generation of EBCs produce negative events with significantly higher latency than allowable for AURORAS. For noise reduction, we run a hot pixel removal process and a background removal process. These processes are analogous to conventional image processing techniques, however conventional image processing algorithms do not work with event data thus we created new algorithms.

Next is the Star Finder module. This module estimates the background star motion and utilizes a shifting algorithm to create a virtual image where the stars appear as static dots. Through a source detection routine and astrometric plate solution we determine where in the sky the telescope was looking and match detected stars (see Figure 7) with known stars in the GAIA catalog.

The matched catalog stars form the basis for Dynamic Astrometric Calibration. In a conventional static image, determining the astrometric position of any object in the field is common practice using a well-known mathematical transform from (X,Y) pixel position to (RA,Dec) celestial position. The parameters for the transform are optimized with the positions of known reference stars in the field (see Figure 8). For AURORAS the process is similar but with the added third dimension of time, thus the parameters in the transform are not static but time dependent. We created a new algorithm that encodes a dynamic model that transforms (X,Y,Time) positions to (RA,Dec,Time) for each event in the data set. The residuals, i.e., the difference between the catalog (RA,Dec) star coordinates and the observed coordinates computed by the transformation, yield a measure of the quality of fit. Ideally the residual values should be zero. After fitting, we apply a jitter correction that removes any remaining time dependent jitter in the transform from (X,Y,Time) to (RA,Dec,Time) (see Figure 9). These bumps and wiggles are often the product of wind shake or other erratic motion in the telescope or telescope mount.

An exquisite astrometric calibration is vital for AURORAS to produce an accurate OD as even small inaccuracies in the astrometrics can yield notable error on the measured space object's motion and resultant OD. Our strategy for dynamic astrometric calibration allows us to take full advantage of the temporally dense event data and produce the highest fidelity measurements of the space object's angular position, velocity, and acceleration.

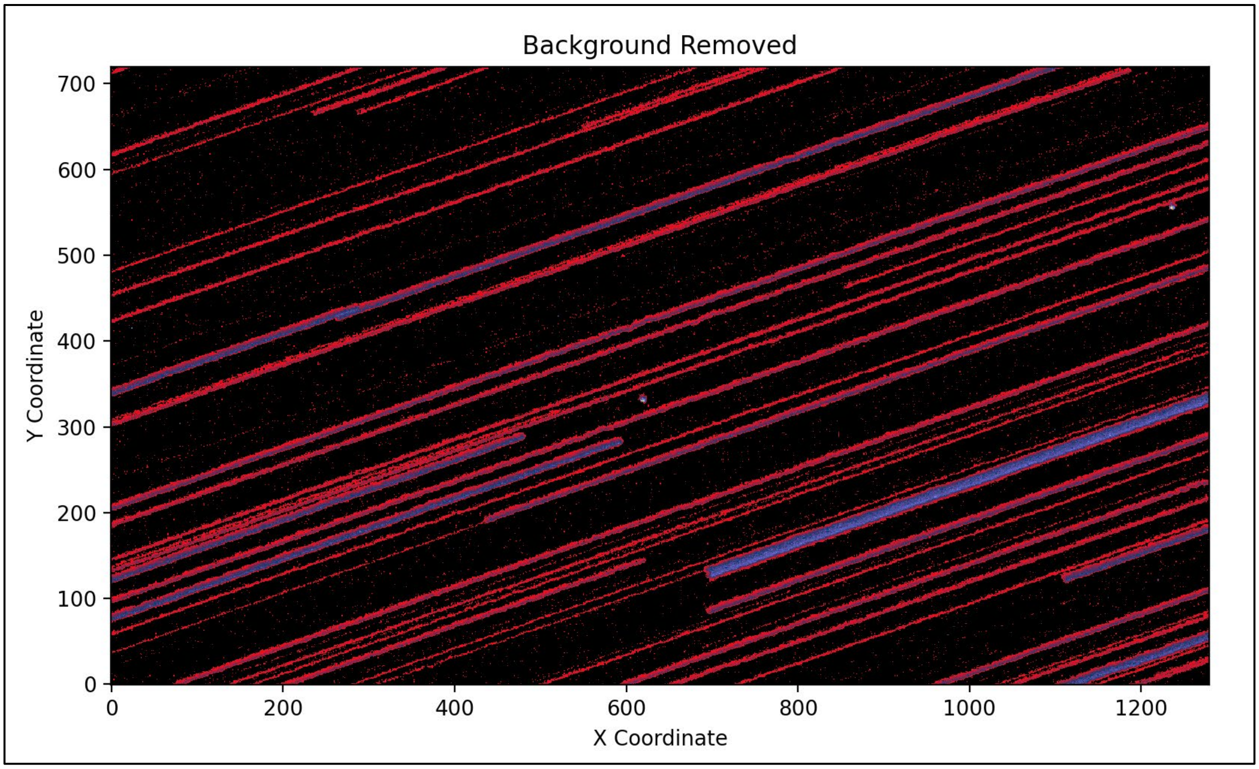

Figure 6. Compiling event data into a virtual image produces a view analogous to a long-exposure image produced by a conventional imaging detector. In this example the resident space object is visible in the center and the background stars as parallel trails across the virtual image.

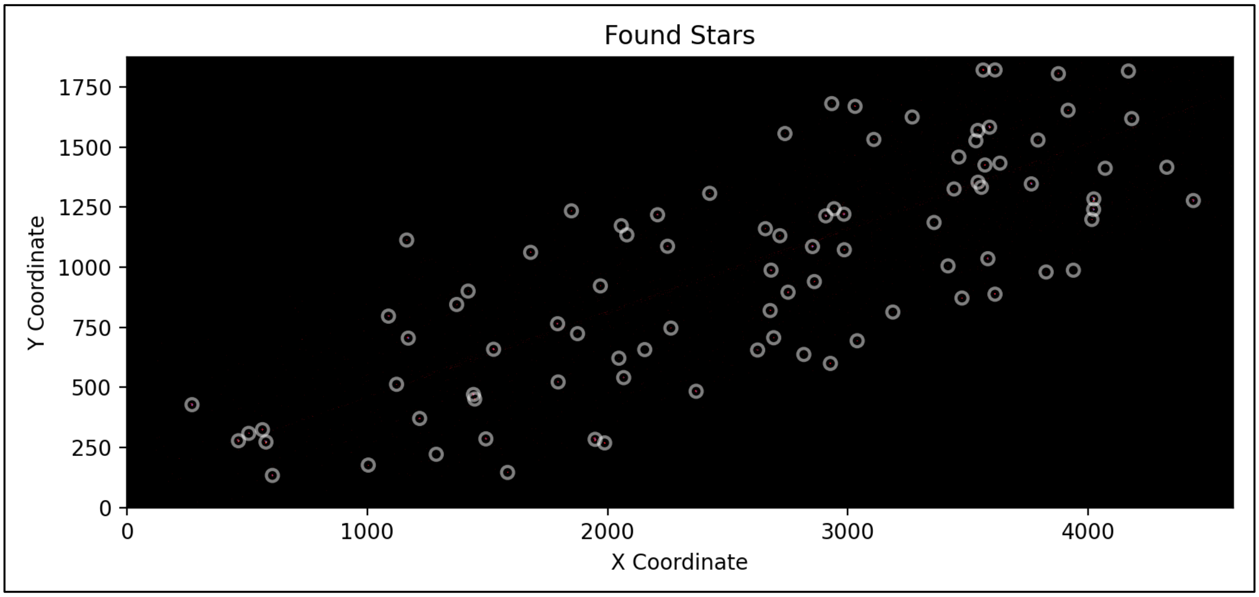

Figure 7. After shifting events in (X,Y,Time) space to match the background star motion, the virtual image shows the stars as static points and the tracked object as a trail. Detected stars are marked with circles.

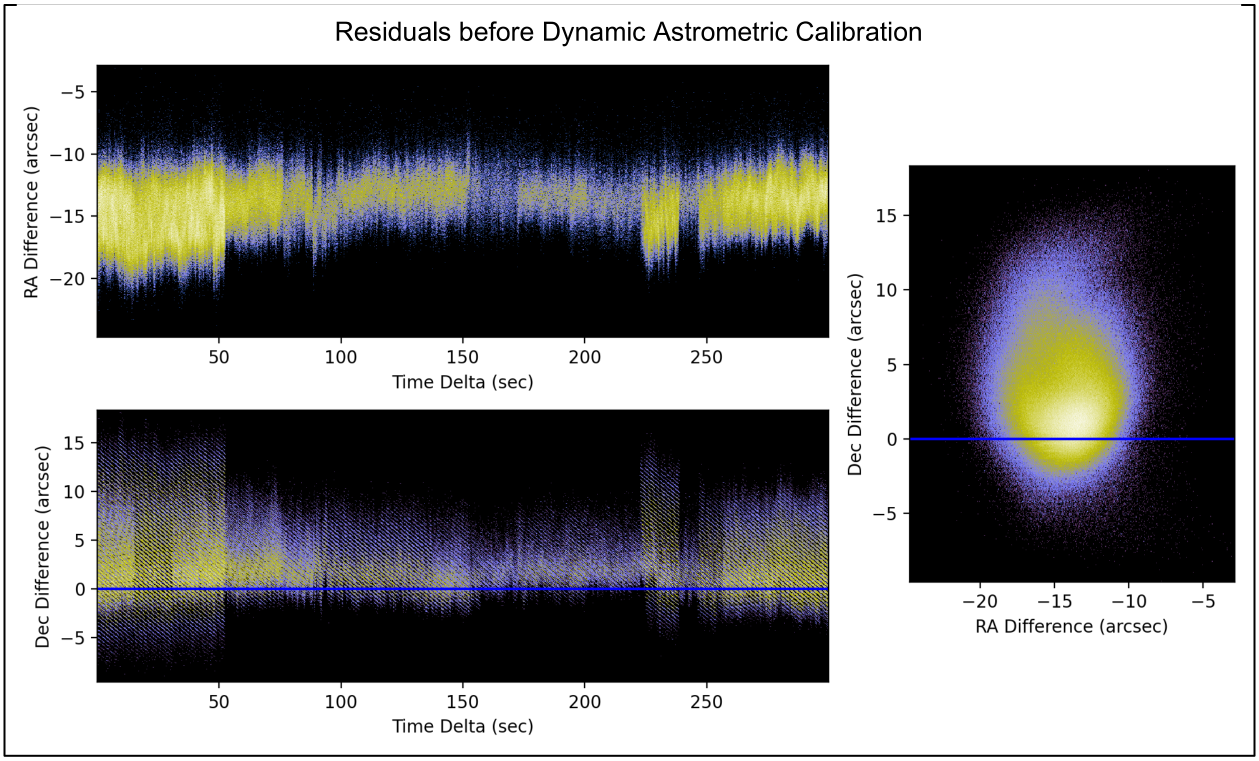

Figure 8. The star position residuals before the Dynamic Astrometric Calibration show offsets from zero as well as curvature indicative of the moving tangent plane.

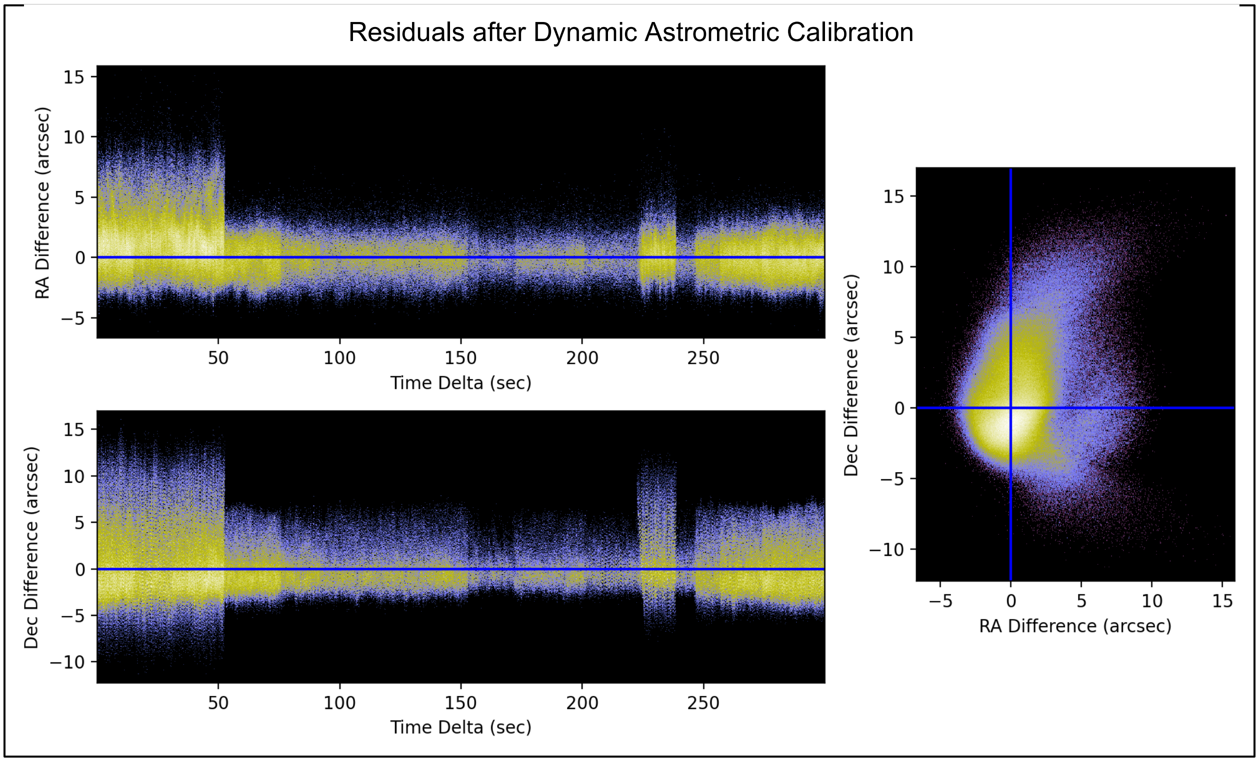

Figure 9. After the Dynamic Astrometric Calibration routine, the star position residuals are now centered on zero and do not show any significant curvature or deviation. The oddly shaped virtual PSF in the right-hand panel is an effect of the event-generation in the camera which yields a bow-shaped appearance as stars move across the focal plane.

After the Star Finder and Dynamic Astrometric Calibration routines, all events now have a calibrated (RA, Dec) position and events associated with background stars are tagged as such. The only events untagged are those associated with non-stellar objects or remaining noise. The next step in the process is the Target Finder that estimates the object(s) motion and shifts events in (X,Y,Time) space, similar to the Star Finder, to produce a virtual image where the space object appears as a static point (see Figure 10). The AURORAS software automatically detects and differentiates multiple objects in the same field even if they have different motion. The algorithms work whether the object is static in the field, i.e., being tracked during observation, or moves through the field if not being tracked.

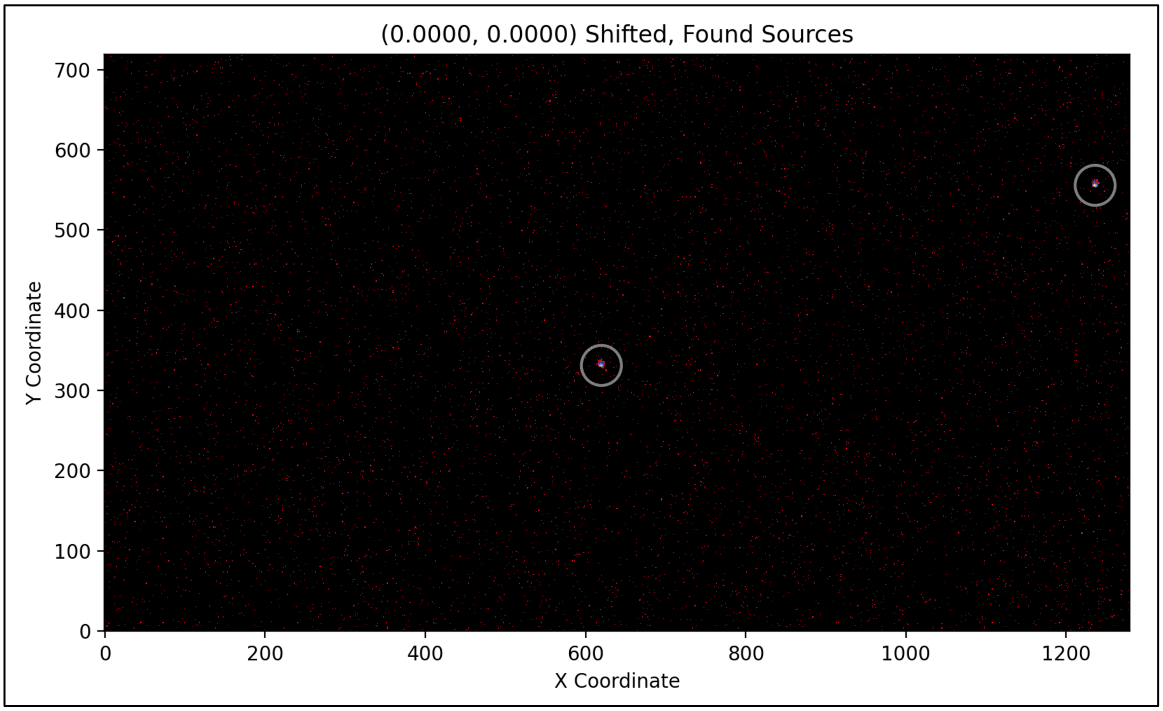

Figure 10. After shifting events in (X,Y,Time) space to match the space object motion, the virtual image shows two objects with similar motion. In this case the object of interest is the one in the center, though the AURORAS software automatically detects and computes an OD for both objects.

Now that events are associated with the space object, we begin the process of State Vector estimation and OD. The software fits polynomial functions to the angular motion of the object (see Figure 11). The polynomials yield the angular position, and the first and second derivatives yield the angular velocity and angular acceleration of the object at a chosen epoch time (typically the midpoint time of the dataset) which is then input into the AURORAS equations to calculate a range and range rate state vector. From the state vector we calculate the orbital elements for the SGP4 orbital model. We estimate covariance through a Monte Carlo routine where the angular position, velocity, and acceleration values at epoch time are recalculated based on the covariance of the polynomial fit, and then the state vector and orbital elements recalculated from these.

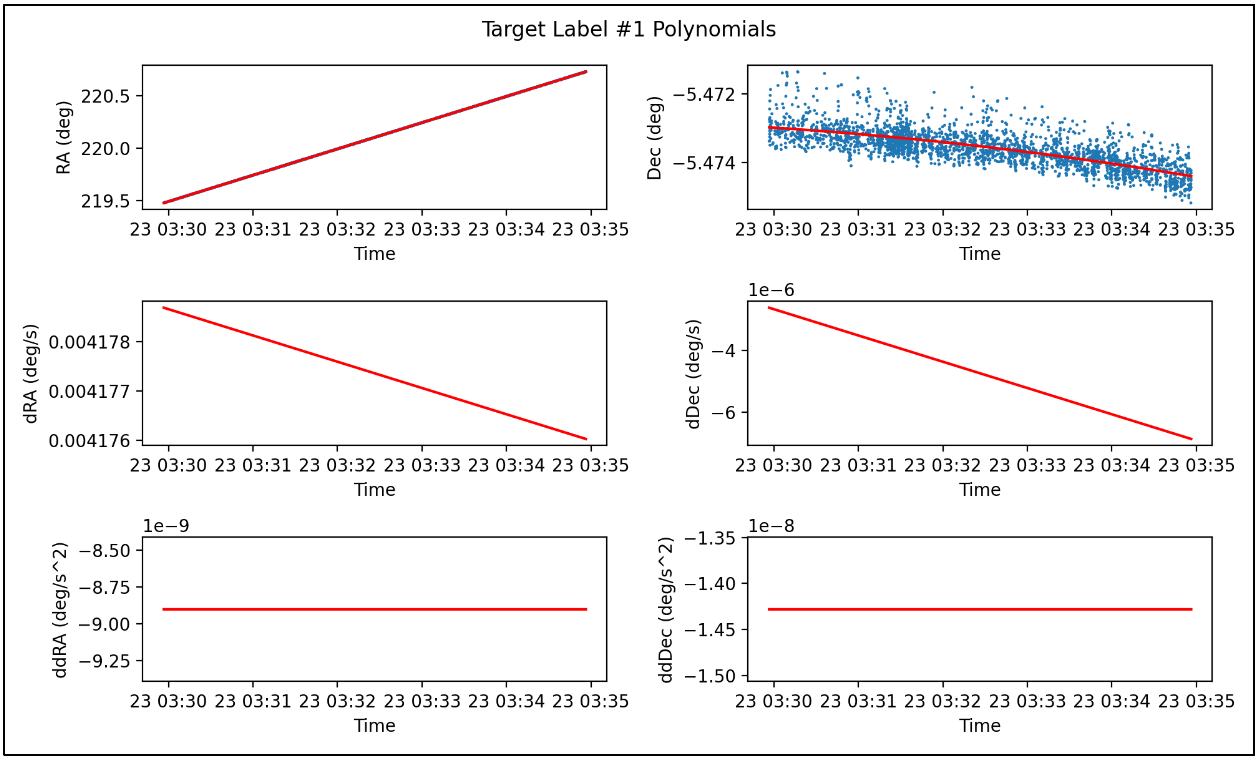

Figure 11. The processing software fits polynomial functions to the calibrated RA and Dec coordinates of all events associated with the target. The polynomials and their first and second derivatives describe the angular position, velocity, and acceleration of the object over the course of the observation.

4. CONVENTIONAL ORBIT DETERMINATION PROCESSING

Conventional angles-only OD techniques utilize a series of images from which the object's position in RA & Dec coordinates are measured. Then using the measure angular positions, an algorithm determines the best fit orbit parameters that match the observations.

For this experiment, we recorded a series of images with the CMOS sensor over an hour of time at a rate of one image per second (see Figure 12). We plate solved each image with Astrometry.net which produced a World Coordinate System (WCS) transform that enables us to calculate the calibrated RA & Dec coordinates for any pixel location in the image. Next, we determined the flux-weighted centroid of the object in pixel coordinates and using the WCS calculate the RA & Dec position of the object for that image. We timestamped each position measurement with the midpoint time of the image exposure. This process yielded a list of RA & Dec angle measurements that we use to estimate the OD via the technique of Gooding.

Initially the OD is calculated from just three observations: the first, middle, and last from the entire series. As a second step, we utilized a batch least squares fitting routine to consider all the observations in a differential correction of the orbital elements using the initial OD as the seed for the fitting routine.

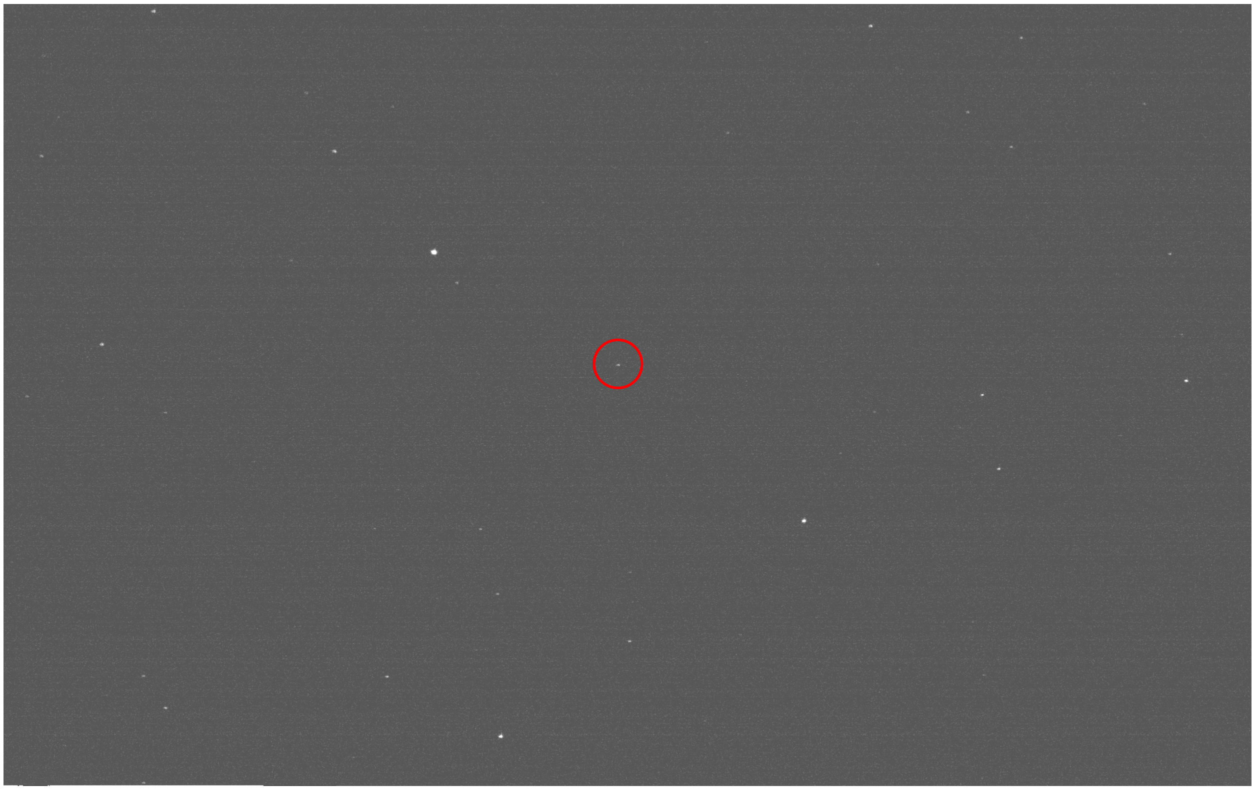

Figure 12. A single 12-bit image from the CMOS camera showing the satellite near the center. With a 40 msec exposure duration many stars are detected for calibration but with negligible trailing.

5. SHELF-LIFE COMPARISON

To determine the accuracy of each OD in the scenario of a handoff to a second sensor we calculated the predicted on-sky position of the satellite as if viewed from Maui (the second sensor) and measured the angular separation between our OD estimates and the “true” position determined from the catalog TLE retrieved from Space-track.org. If the angular separation is larger than half the FOV of the second sensor, then the object will not be seen. For our comparison we set our threshold for successful handoff at 1 deg of separation (representative of a large FOV sensor).

We repeated this calculation at increasing times starting from the original observation to produce plots like Figure 13 that show how the angular separation increases with time and eventually passes the 1 deg threshold after which the handoff would not be successful. We define the shelf-life time as how long the object would stay in the FOV, or in other words, how much time the receiving sensor has to pick up the object before the original element set (elset) will not yield a successful handoff.

Figure 13 shows the shelf-life of the elsets produced by AURORAS and the conventional angles-only technique from just 10 min of observation time. While both techniques could result in a successful handoff, the AURORAS elset yields a significantly lower angular separation and the object would appear near the center of the FOV, whereas the conventional technique elset only barely makes it under the 1 deg threshold. The AURORAS elset shelf-life is over 4 hours while the conventional technique elset shelf-life is a little over 2 hours, roughly half as much time.

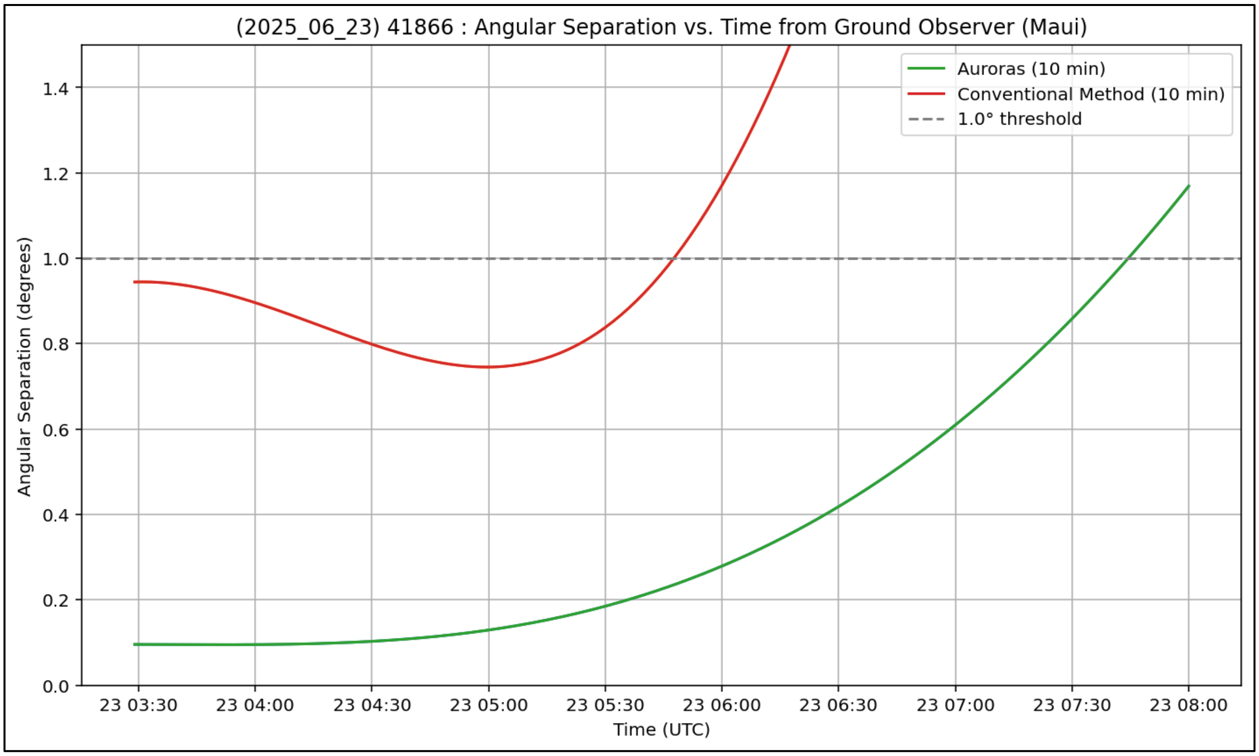

Figure 13. Given just 10 min of observation time, the AURORAS OD will yield a successful handoff with the object appearing near the center of the FOV and staying in the FOV for over 4 hours. In contrast, the conventional angles-only OD would only barely be in the FOV and would drift out after only 2 hours.

AURORAS needs less observing time than conventional angles-only techniques to produce the same level of accuracy. To show this we produced the plot in Figure 14. This plot shows the shelf-life for the 1 deg threshold as a function of the observation duration. Even at short observation times of less than 5 min, the AURORAS elsets could yield a successful handoff. Increasing the observation time for AURORAS to 10 min or more produces elsets with shelf-life times as long as 10 hours.

The AURORAS example from June 2025 collected for this experiment was limited by low detection SNR with the EBC during data collection. Figure 14 also includes a prior data collection on the same object from March 2025 that yields an AURORAS result in line with our typical expectations, that is an accurate elset in 5 to 10 min.

The conventional angles-only technique began producing elsets that could yield a successful handoff with 10 min of data but only with short shelf-life times. To match the shelf life of AURORAS, the conventional technique required 30 to 60 min of observation time.

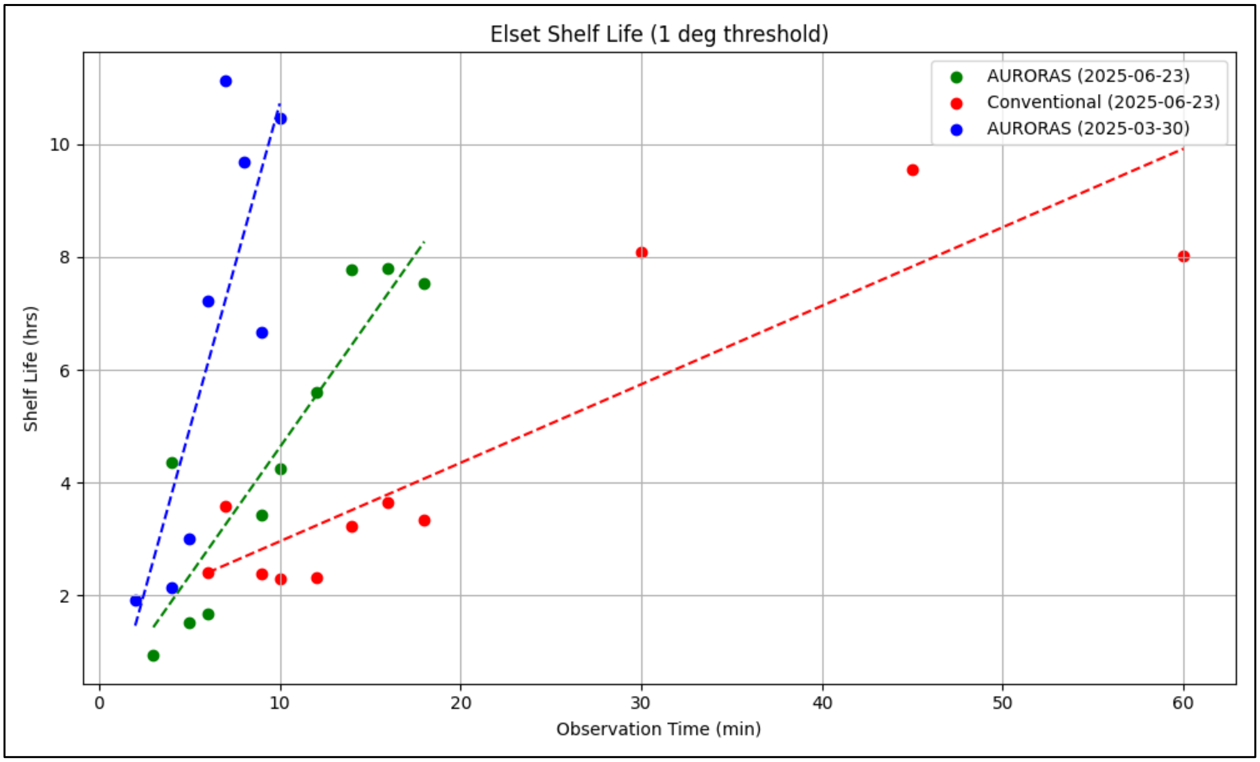

Figure 14. The AURORAS produced elsets yield longer shelf-life times than the conventional angles-only technique when using the same amount of observation time. The conventional angles-only technique required about 20 to 60 min of observation time to yield the same shelf life as an AURORAS result from 10 min of observation time.

6. CONCLUSIONS

AURORAS is a new technique for orbit determination utilizing event-based optical sensors and new algorithms to measure an object's angular position, angular velocity, and angular acceleration. By discerning subtle curvature in motion, AURORAS can produce an accurate OD significantly faster than conventional angles-only optical techniques while also providing additional benefits to overall network design and resilience.

In our experiment, the AURORAS-produced elsets would yield a successful handoff with short observation times of less than 10 min. To match the handoff shelf life of AURORAS with 10 min of observation time, the conventional angles-only technique would need much more observation time, at least 30 to 60 min, to match AURORAS.

Acknowledgements

Applied Research Associates, Inc. owns the patent (United States Patent No. 12,080,000, issued to Applied Research Associates, Inc. on September 3, 2024) for the Advanced Uni-sensor Rapid Orbit Reconstruction Algorithm and Sensing (AURORAS) technique which covers the technology, software instantiation, and derived data products from AURORAS. For information on permitted use, licensing and limited government purpose rights, please contact ARA at auroras@ara.com.

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