Autonomous Observations of Starlink Satellites with the Pomenis Observatory

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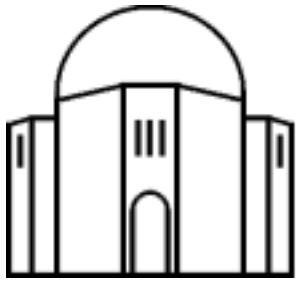


STEWARD OBSERVATORY

Pomenis

- Wide-field astrograph for satellite tracking and survey style observations
- Takashi Epsilon 180mm f/2.8
- Apogee Alta F9000 (3056 x 3056)
- 4.2° x 4.2° FOV @ 4.9 arcsec/pixel
- 7-color filter wheel
- Paramount MyT mount

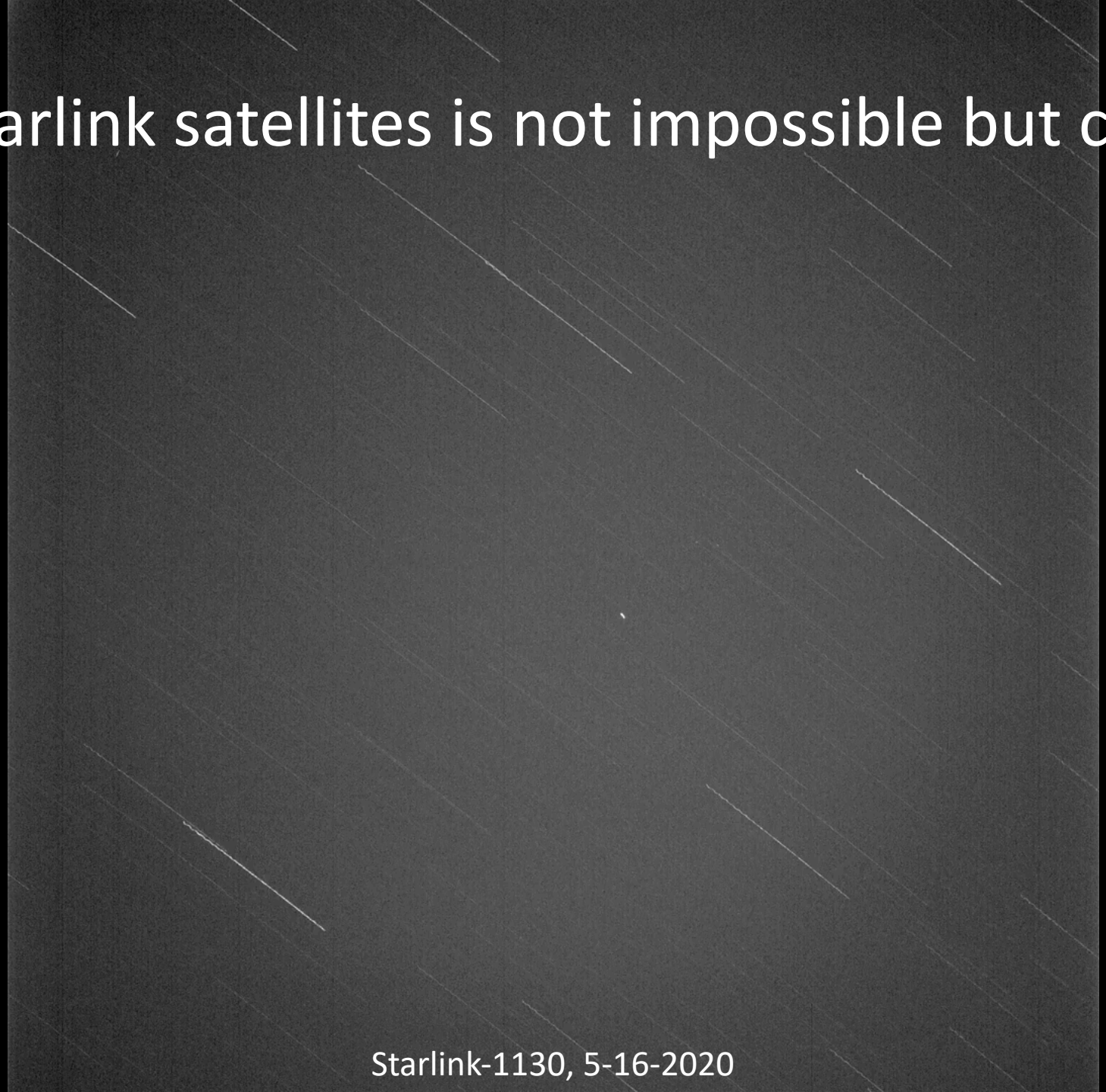
The Dog House

- Trailer-based mobile enclosure
- Remote and autonomous operation
- ACP Observatory Control Software
- Flat-field panel, sky brightness sensors, weather monitoring, CCTV
- Most frequently located at Mt. Lemmon, Tucson AZ

How to Observe Starlink Satellites

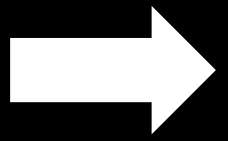
- Narrow window of time after sunset and before sunrise
- Fast moving; ~1° per second
- Need precise prediction, timing, and telescope control
- Tracking
  - Record the entire flyover pass and sample variety of angles
  - Capture flares or other events
  - Deadtime between images
- Wait and Catch
  - Narrow window of opportunity
  - Observe more satellites in one night

Tracking Starlink satellites is not impossible but challenging



Starlink-1130, 5-16-2020

Employing a Wait and Catch technique is much easier and yields better measurements



Starlink-1214, 5-23-2020

Wait and Catch Technique

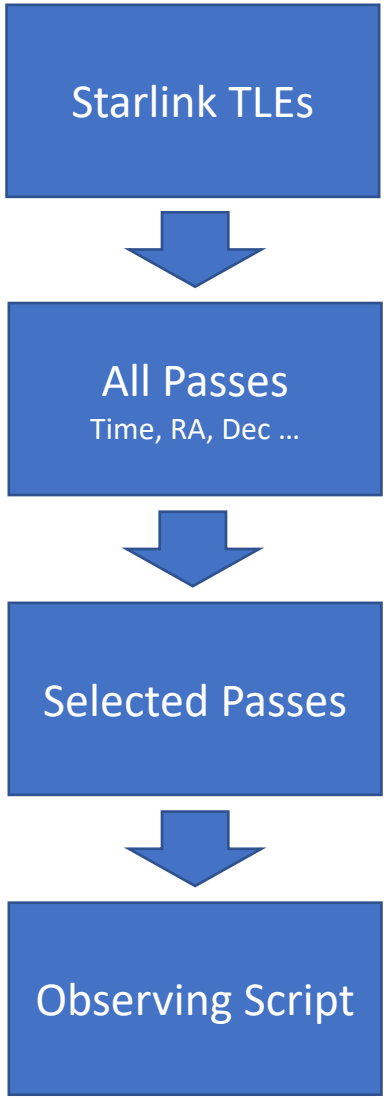
- Calculate RA and Dec of satellite at specific time
- Slew telescope to RA and Dec beforehand
  - Track at sidereal rate
- Trigger camera to image satellite as it passes through the FOV
  - Satellite is streaked but background stars are not
  - Capture full streak for unambiguous exposure time

Pomenis Autonomous Starlink Observing

- Observatory is fully robotic
- Software does everything autonomously
  - Predict Starlink flyover passes
  - Select satellites for observation and generate observing script
  - Observe each satellite with Wait and Catch technique
  - Process images and produce photometric measurements

Starlink Pass Predictor

- Custom Python software
- Download latest TLEs from *Celestrak*
  - Supplemental TLEs generated from SpaceX telemetry
- Determine all visible passes for given date and location
  - Passes filtered on user criteria
- Calculate ephemerides with *SkyField* code library
  - Uses proper SGP4 algorithms for better accuracy
  - RA, Dec, velocity, range, altitude, and more



ACP Telescope Control and Imaging Process

- Software generates ACP observing script
  - Include overhead time for slewing, image download etc.
  - Two scripts: evening and morning
- For each satellite
  - Telescope slews to RA and Dec prior to satellite pass
  - Captures an image of the background stars
  - Waits and continues to track sidereally
  - At scheduled time, captures image of satellite moving through FOV

Image Processing

- Custom Python software
  - Utilizes many *Astropy* tools
- Simple image calibration
  - Bias, flat-field, background
- Source detection
  - *Image Segmentation* algorithm detects sources of any shape
- Sum flux in corresponding pixels

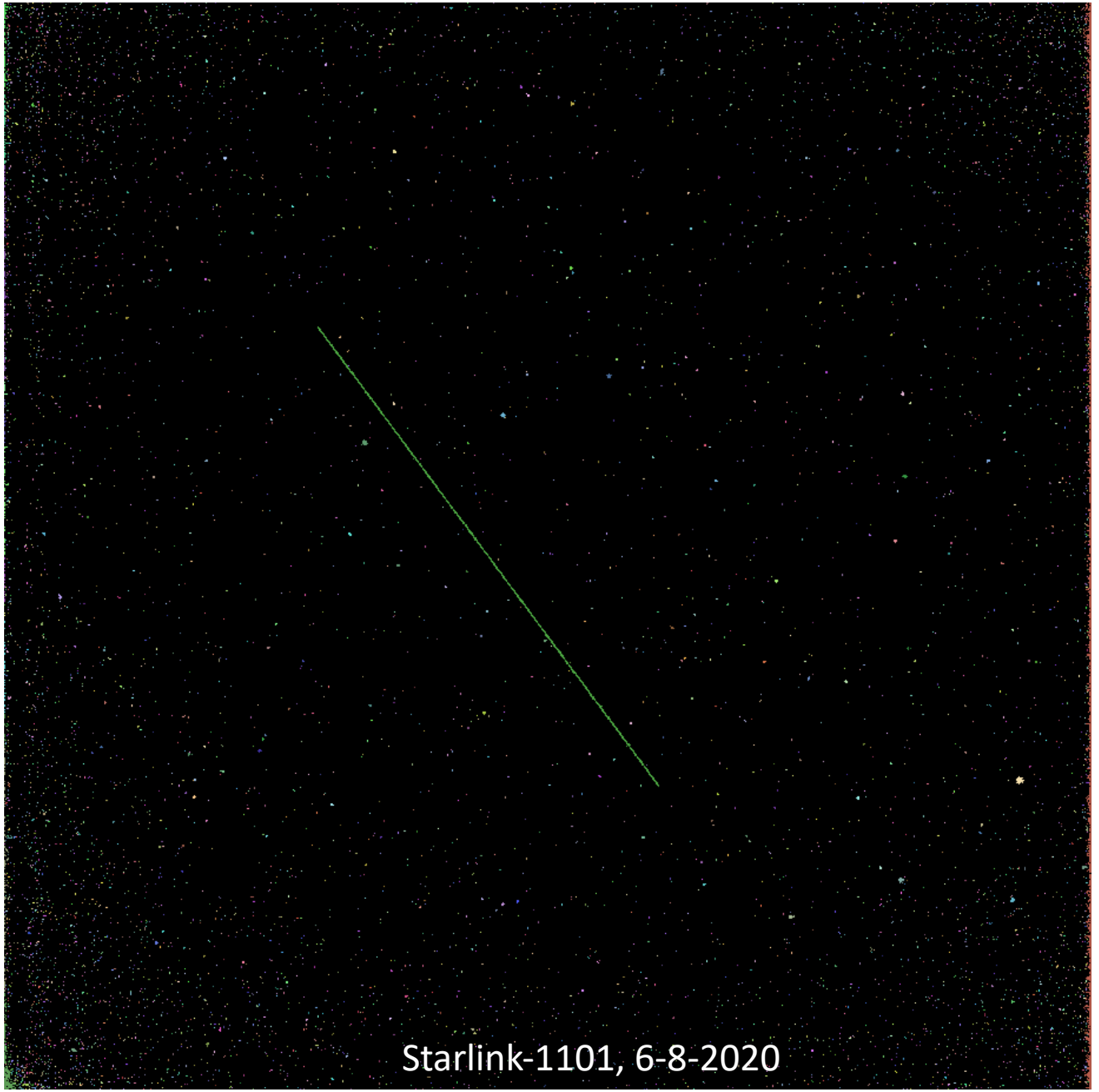


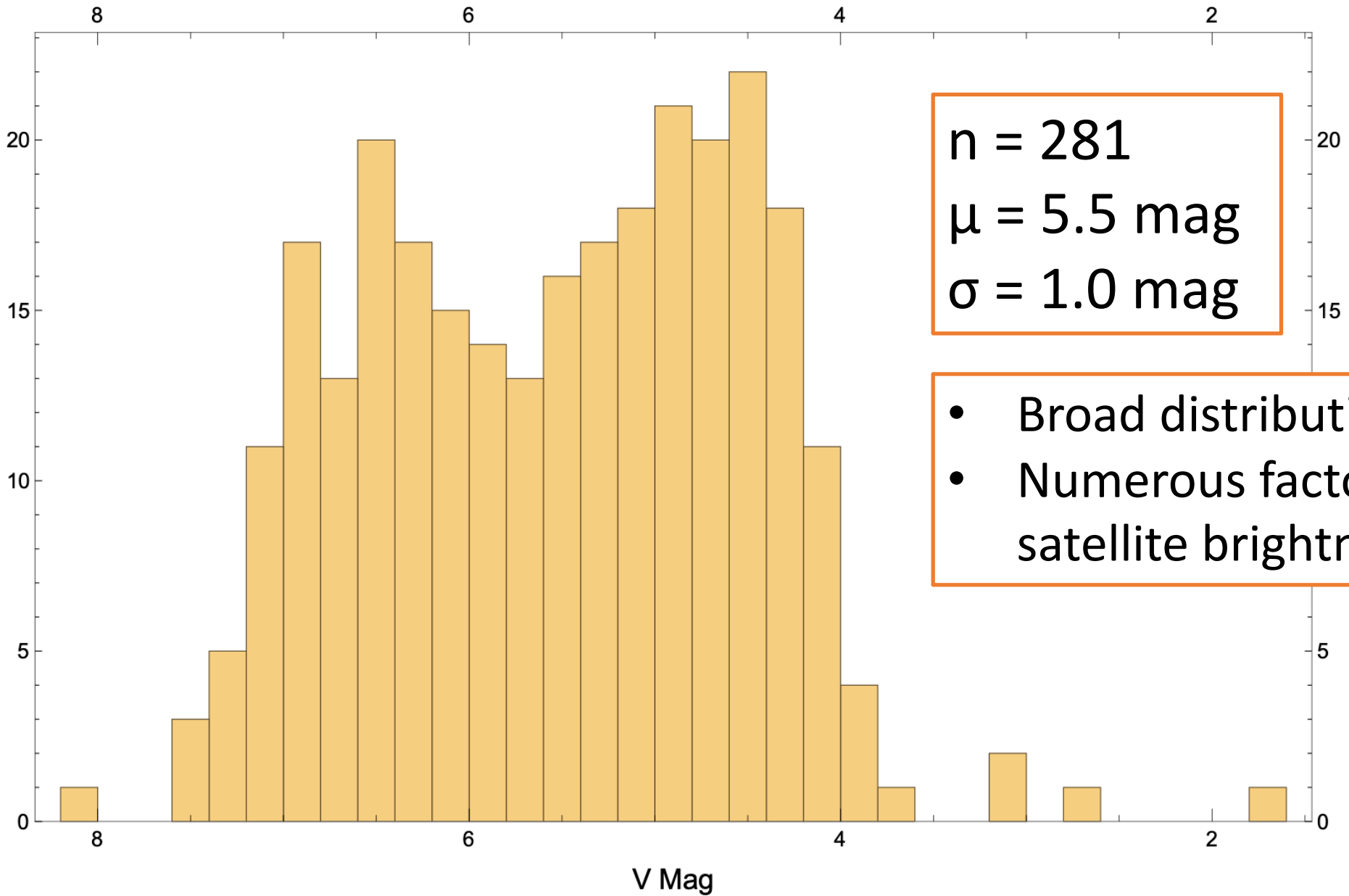
Image Processing: Photometry

- Software makes a conservative guess to which source is the satellite
  - If unsure, rejects the image and does not process it
- Submits brightest stars to *astrometry.net* for plate solution
- Submits brightest stars to SIMBAD for reference magnitudes
- Guesses the correct zero-magnitude flux using modal statistics
- Calculate the magnitude of satellite with relative photometry

Opportunities for Improvement

- Observation planning
  - Minimize dead time and maximize number of observations
  - Select satellites for observation with priority weighting scheme
  - Image satellites at different angles to better sample geometry
- Better source detection
  - Background star subtraction
  - Intelligently differentiate target satellite from incidental satellites
  - Fainter target detection
- Better photometric calculations
  - Reference star magnitudes
  - Error estimations

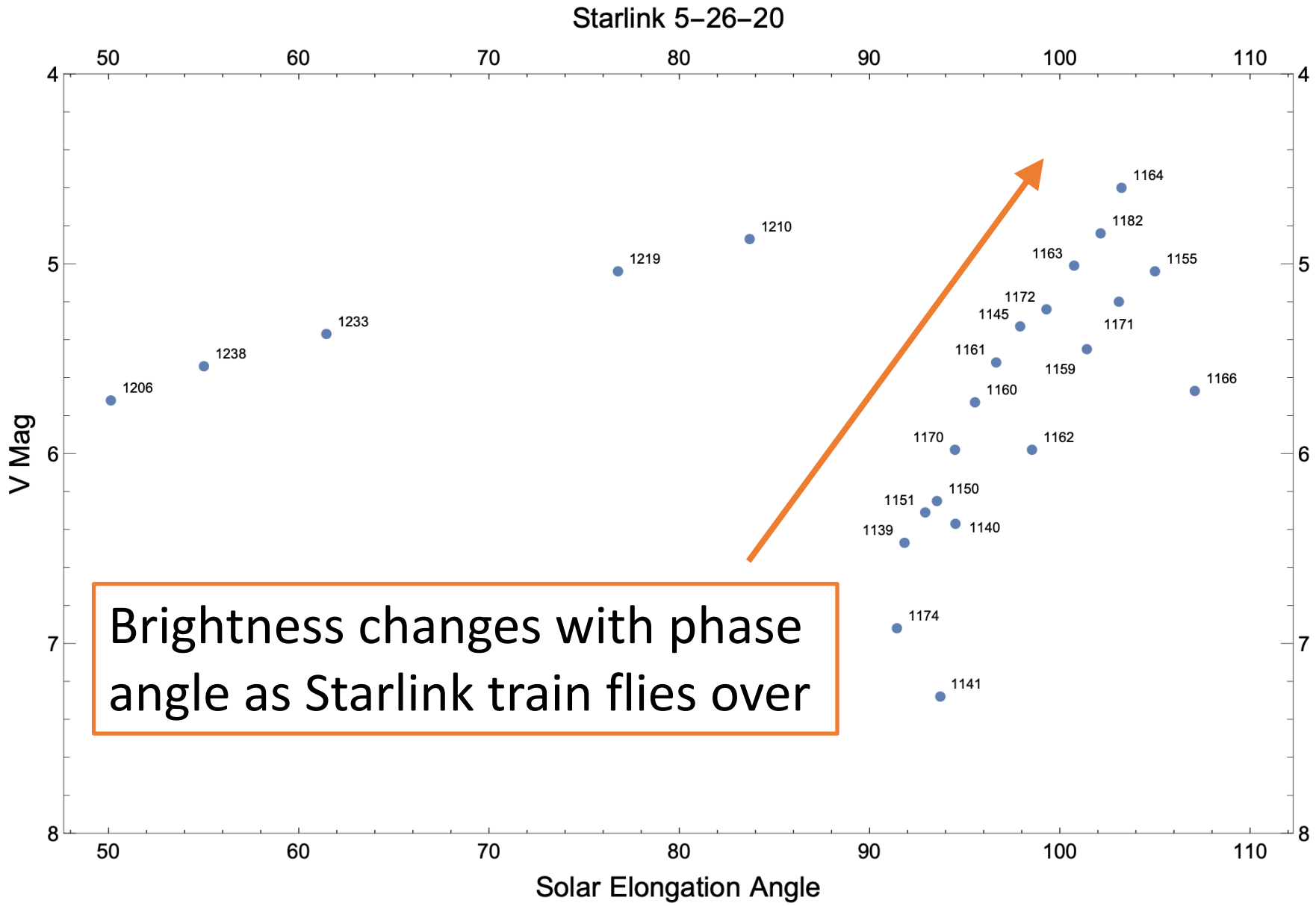
Results → 281 measurements in <2 weeks



n = 281
μ = 5.5 mag
σ = 1.0 mag

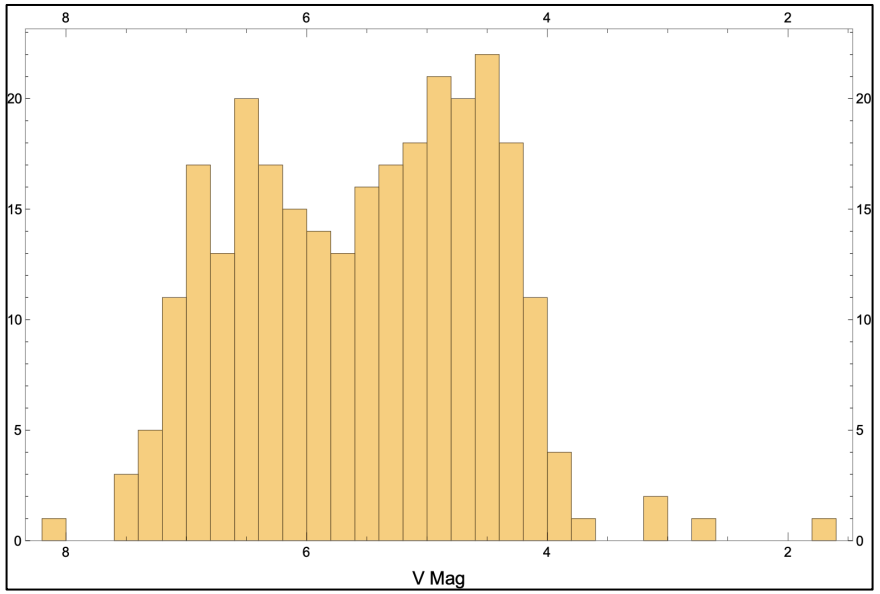
- Broad distribution
- Numerous factors determine satellite brightness

Easily Plot Measurements Against Any Parameter



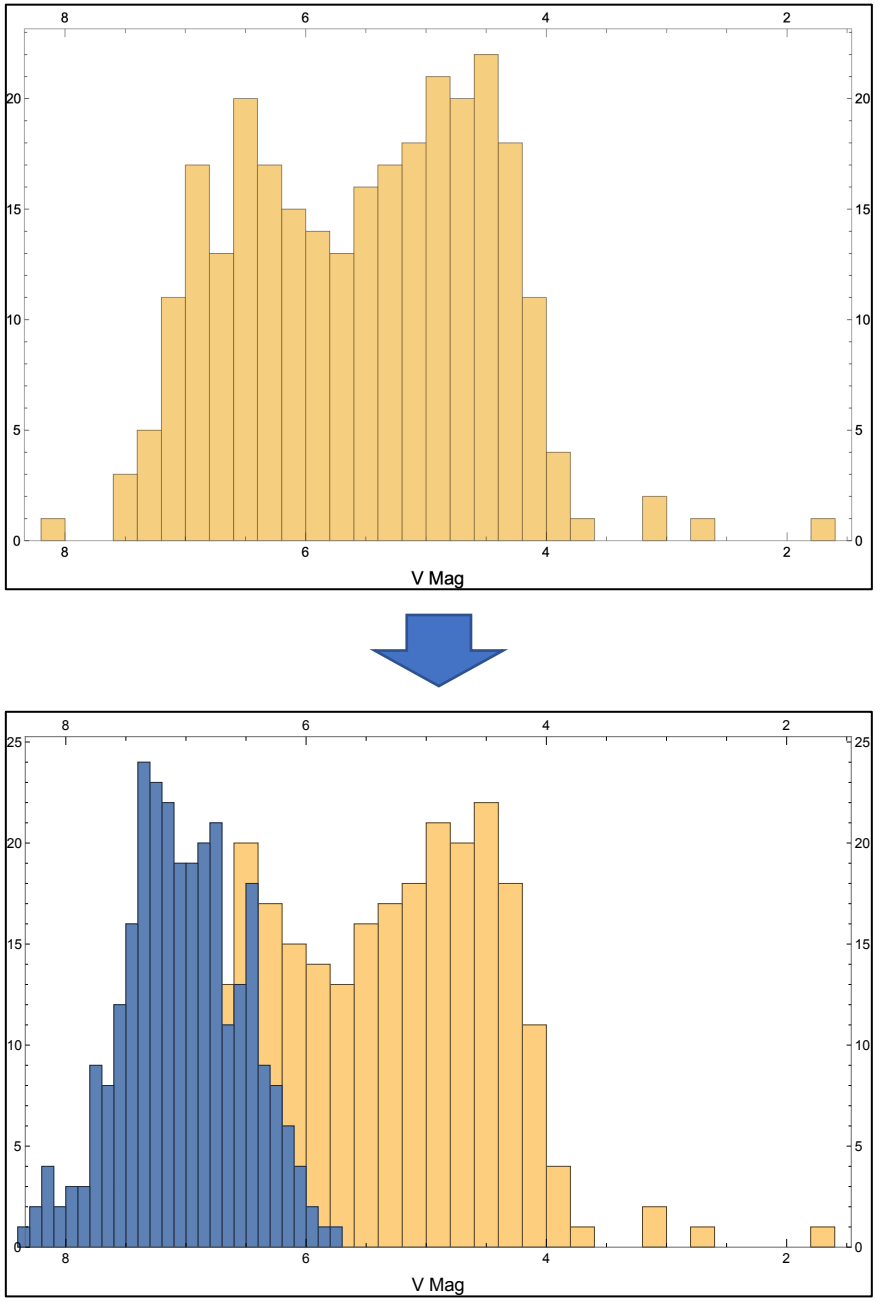
What do these measurements mean?

- A given Starlink satellite will be between 4th and 8th magnitude
  - Cannot characterize a satellite with a single measurement
  - Cannot test mitigation efforts (e.g. DarkSat, VisorSat) with a single measurement
- Numerous factors determine brightness
  - Phase angle, range, orientation, specularity etc.
  - Difficult to model accurately
- With more analysis we can untangle the factors
  - Requires many measurements with a variety of geometries



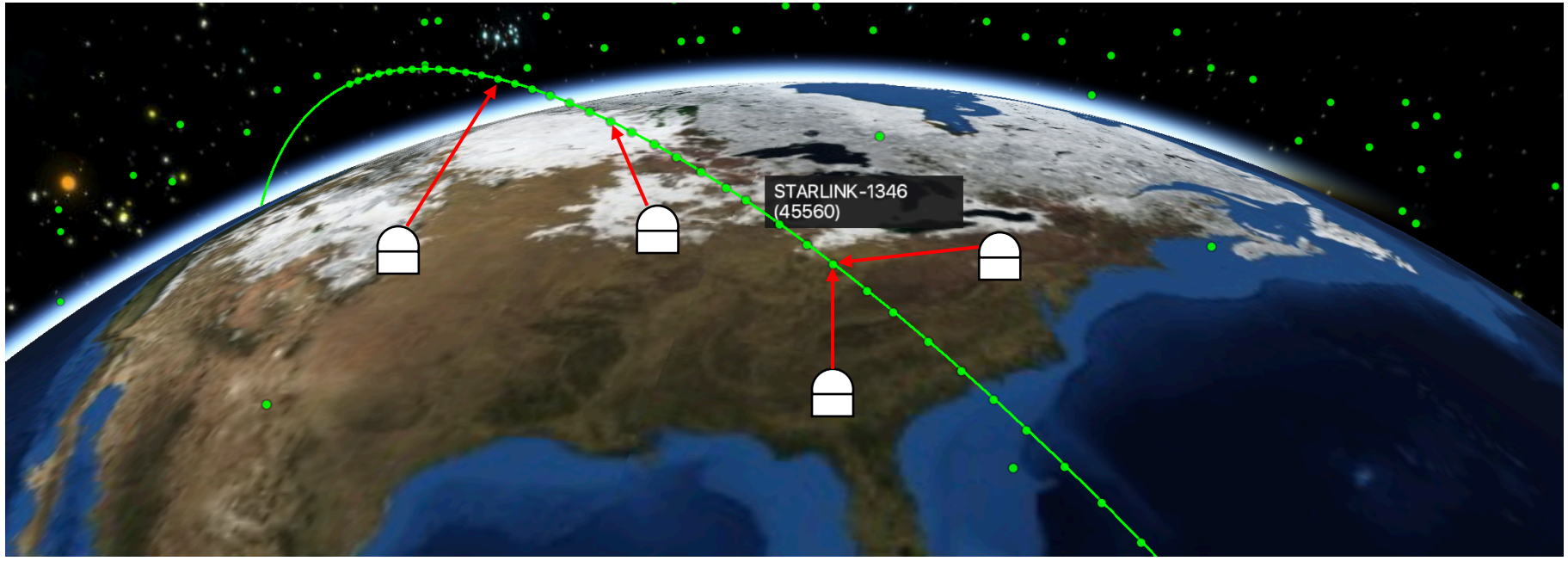
Build a Statistical Picture

- Make many measurements
- Measure satellite brightness in all geometries
  - Untangle the effects of phase angle, orientation…
  - Particularly important for VisorSat
- Test mitigation efforts by comparing distributions of brightness
- One telescope is insufficient
  - Sampling bias due to location
  - Specific satellites infrequently observable
  - Difficult to test mitigation efforts with only one observatory



Utilize a Network of Telescopes

- Apply same observing scheme to many telescopes
- Many geographically separated observers leads to better overall characterization of satellite brightness
- Measure specific satellites (e.g. DarkSat) more frequently
- Follow new satellites during short orbit-raising period



Vision of a LEO-Sat Observers Network

- Website for observers
  - Web tools for predicting satellite passes and generating observing scripts
  - Upload image data for processing
- Centralized SQL-like database of measurements
  - Couple photometric measurements with detailed orbital parameters
  - Easily query database by any criteria
  - Rich opportunities for data mining, machine learning, statistics etc.
- Involve professional observatories and amateurs

Citizen Scientists

- Advanced amateurs already have equipment capable of imaging LEO satellites
  - Pomenis serves as an example and model
- Astrophotographers share concerns about LEO satellite impacts
- Amateur satellite tracking community
- More observers doing more measurements from more locations
  - Potentially 100+ participants

Operation Moonwatch *(est. 1956): F.L. Whipple organized amateurs to track the first satellites before optical imaging stations were created*

Summary

- Pomenis Observatory is highly capable of observing Starlink satellites
- Characterizing satellites constellations and testing mitigation efforts will require many measurements at a variety of geometries
- A network of many telescopes will best fill in the statistical picture
  - One observatory is not sufficient due to limitations
- Great opportunity to involve Citizen Scientists to make measurements

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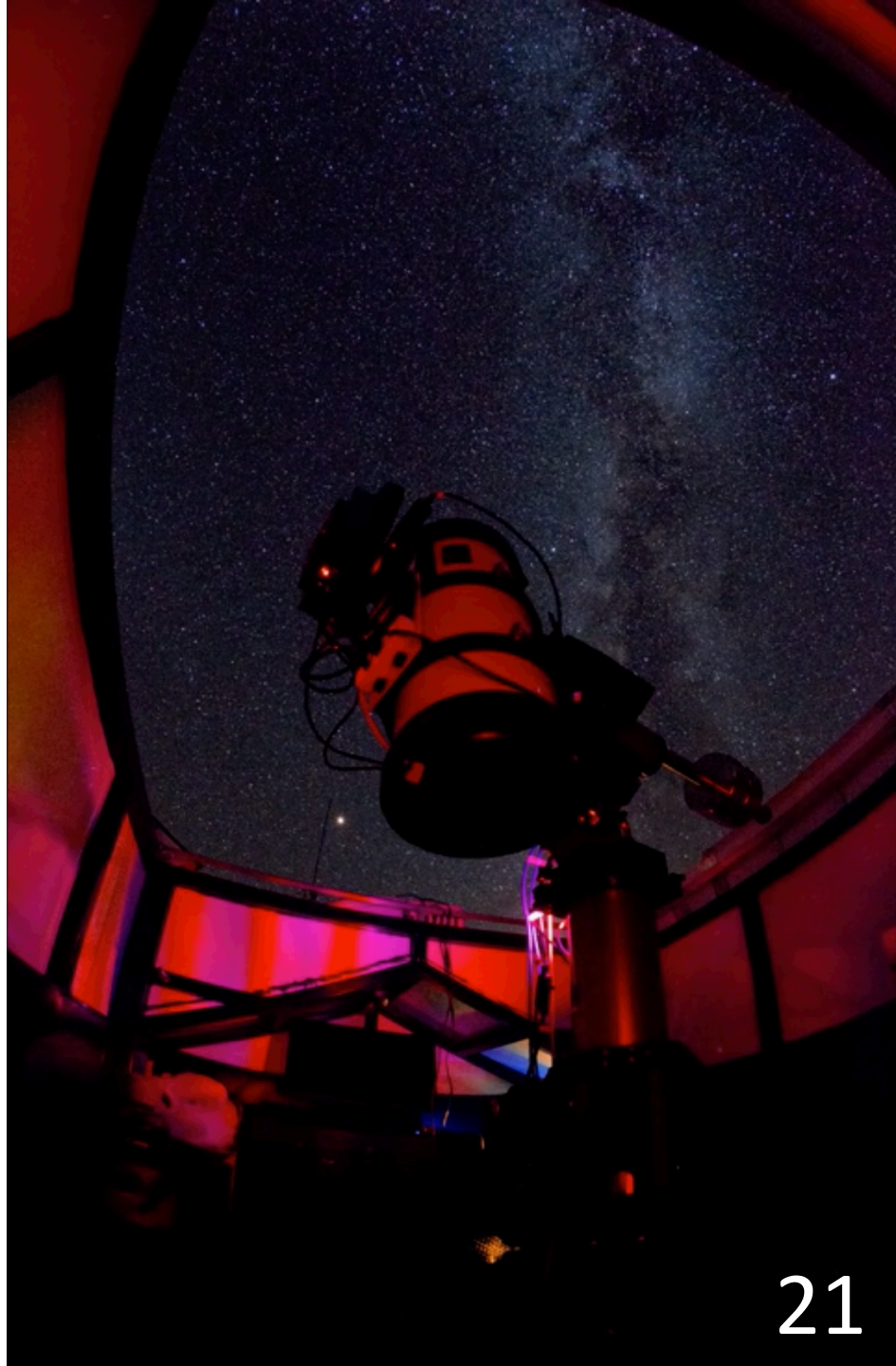

Submit Questions to Q&A

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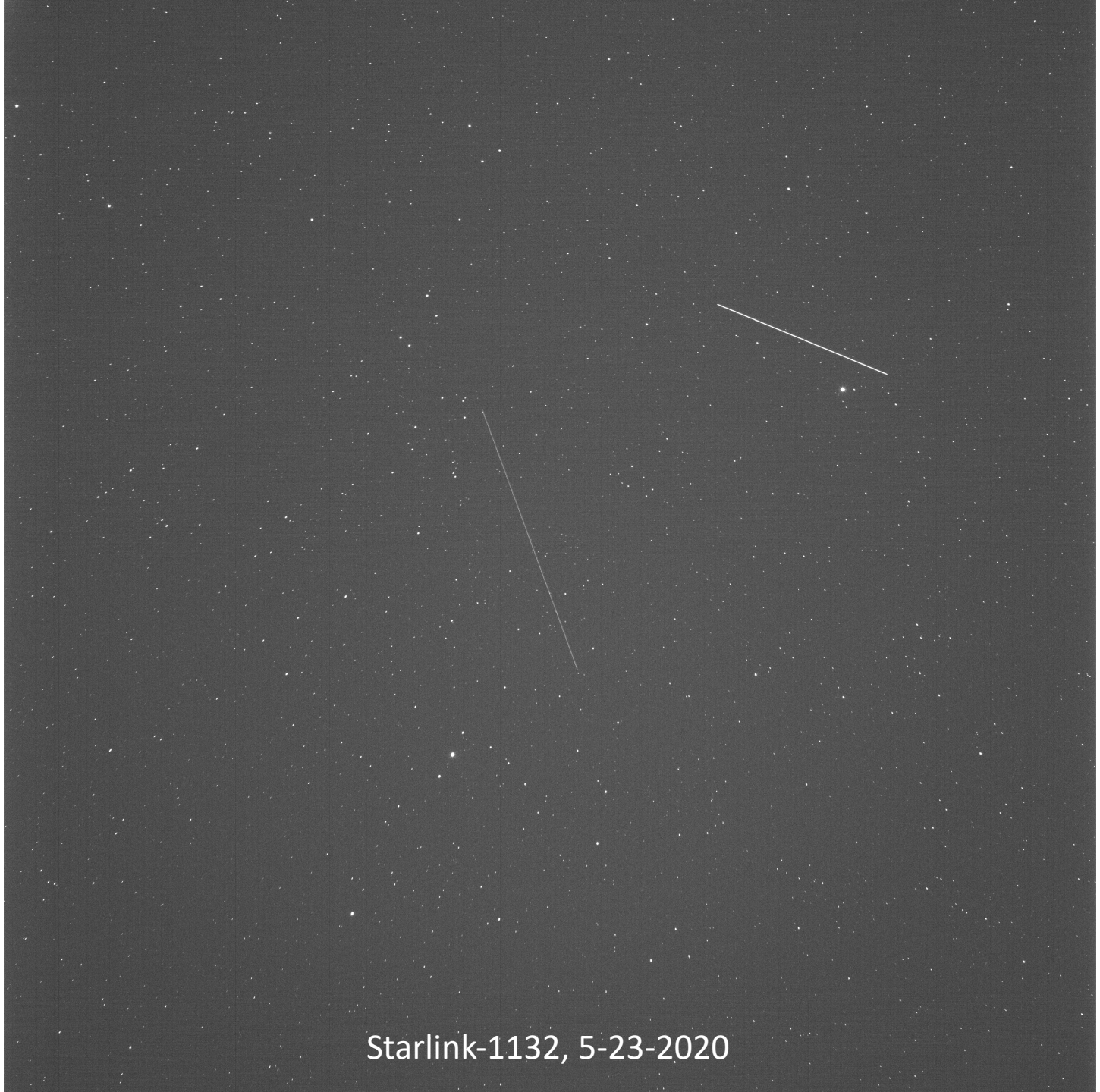
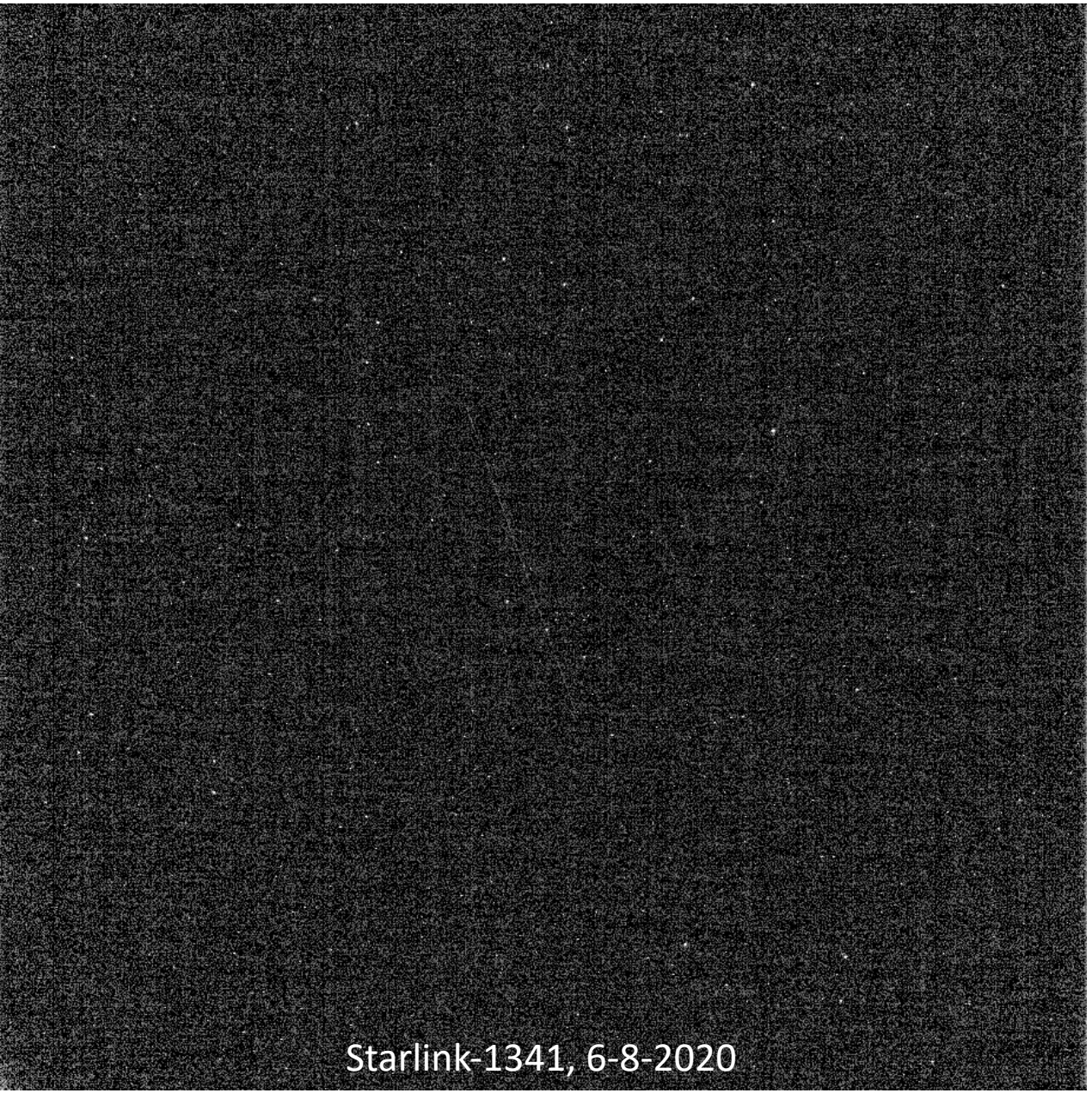
Backup Slides

Starlink-1352, 6-7-2020



Starlink-1132, 5-23-2020


Starlink-1341, 6-8-2020