CHASING ASTEROID OCCULTATIONS – FOR ADVENTURE AND SCIENCE

The San Jose Astronomical Association

Apr 5, 2025

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Through occultations, and with affordable equipment, we can measure the sizes, shapes, and orbits of asteroids better than can the largest telescopes.

And if you’re lucky, discover new moons around asteroids too.

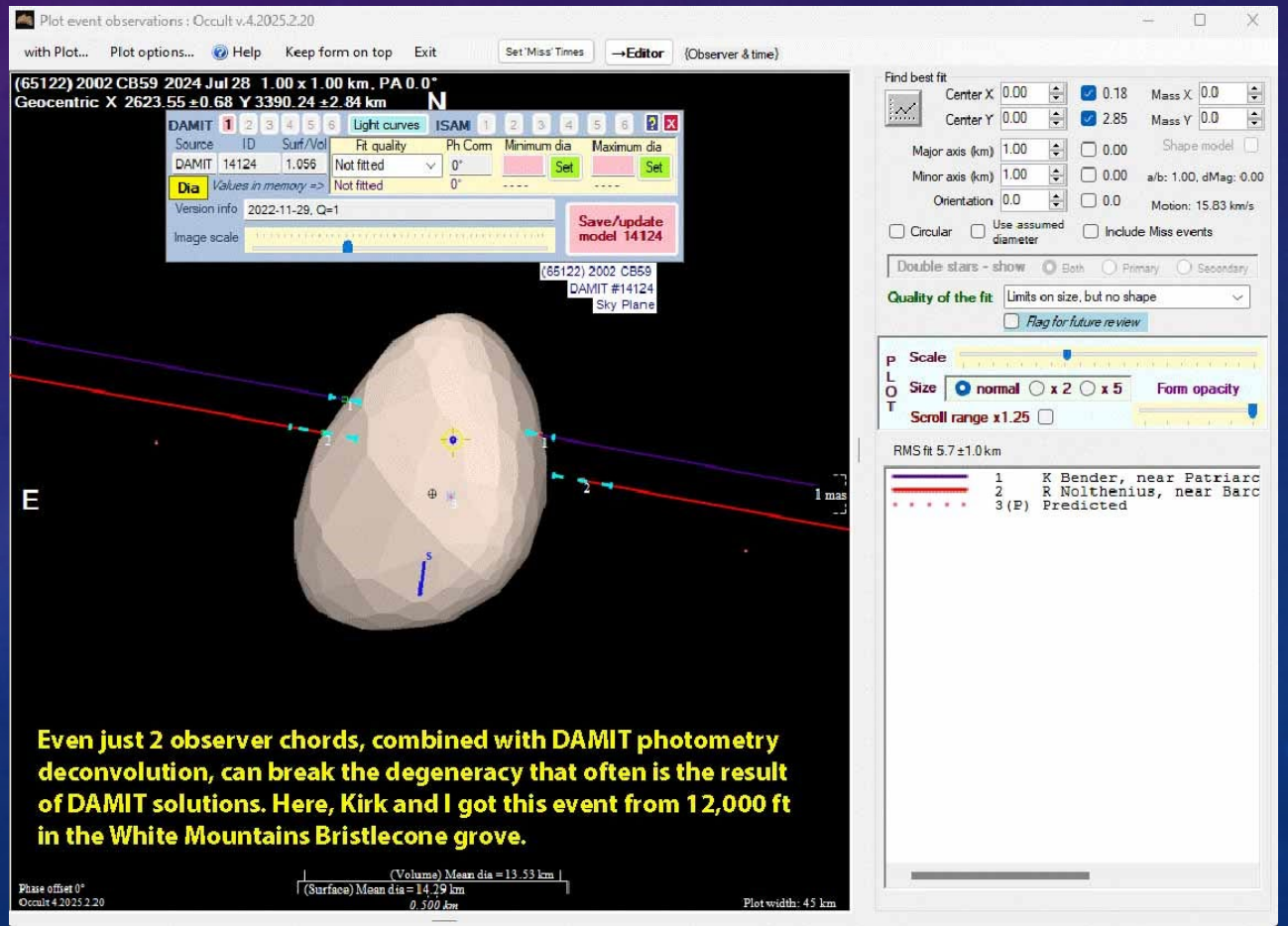
THE KEY IS THIS…

- #1. Asteroids move slowly in their orbits
- #2. And, we can slice time finely and stamp it onto high-speed video frames with GPS gear..
- At right: 9 GPS satellites linked, allowing UT to .0001 sec, stamped onto each 1/60s even/odd field for each interlaced frame, with the IOTA **Video Time Inserter**.

THIS TRANSLATES INTO EXTREMELY HIGH PRECISION ASTROMETRY…

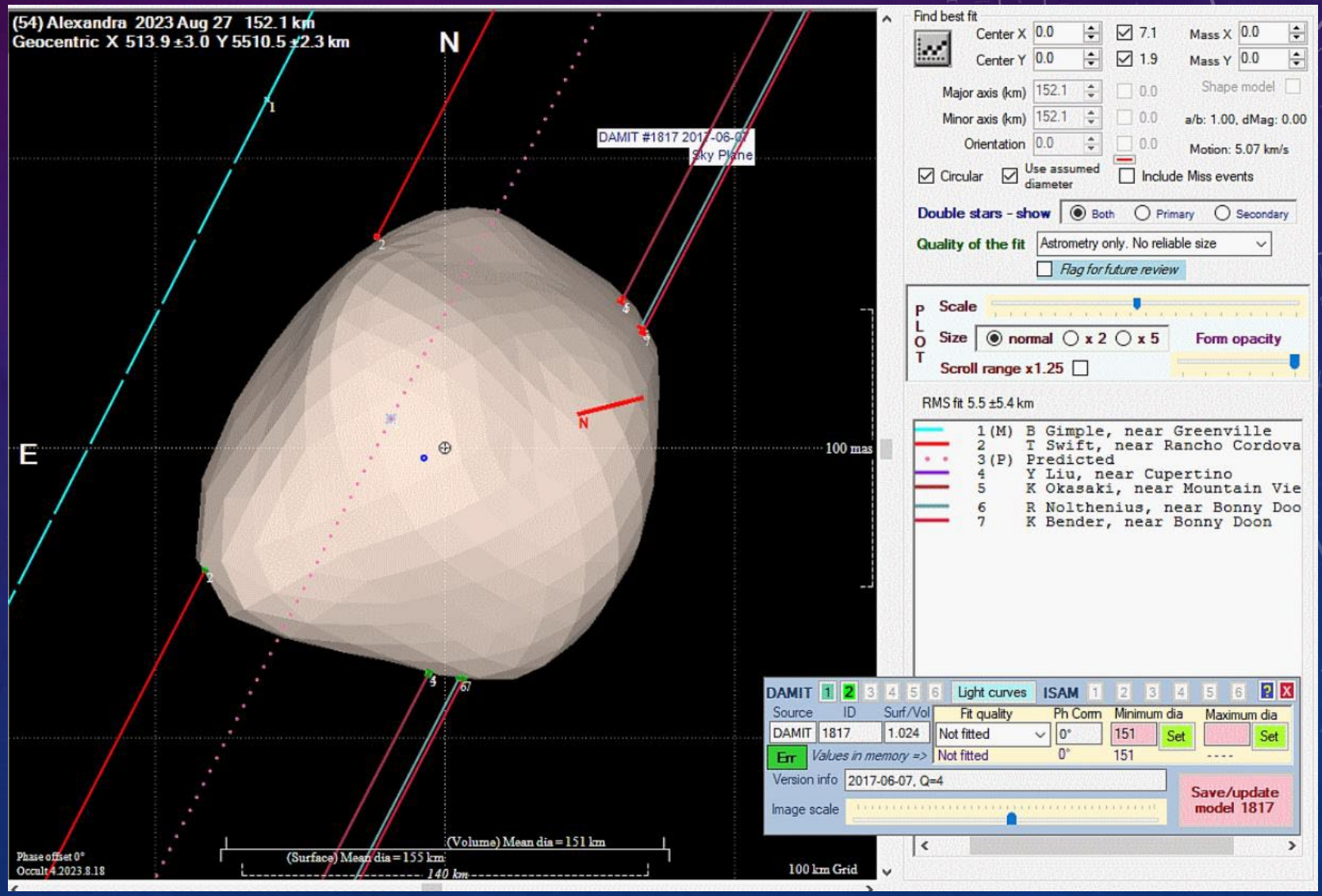
- …of the asteroid edges at the “D” and the “R” moments
- It’s just math, after all, and computers will do that w/o complaint
- Combined with other observers, you can map the sky plane of the asteroid with better precision than even the largest telescopes could do on their own.
- Even monster telescopes will still see almost all asteroids as just pin-points of light.

On an expedition to gather ongoing growth data on bristlecone pines in the White Mtns… this asteroid event!



THANKS TO THE GAIA MISSION AND ITS INCREDIBLE ACCURACY IN MEASURING STAR POSITIONS AND MOTIONS…

- …Volunteer astronomers can now contribute precision measurements of asteroids.
- Combined with photometric DAMIT modelling, can resolve shape, orbit/orientation solutions.



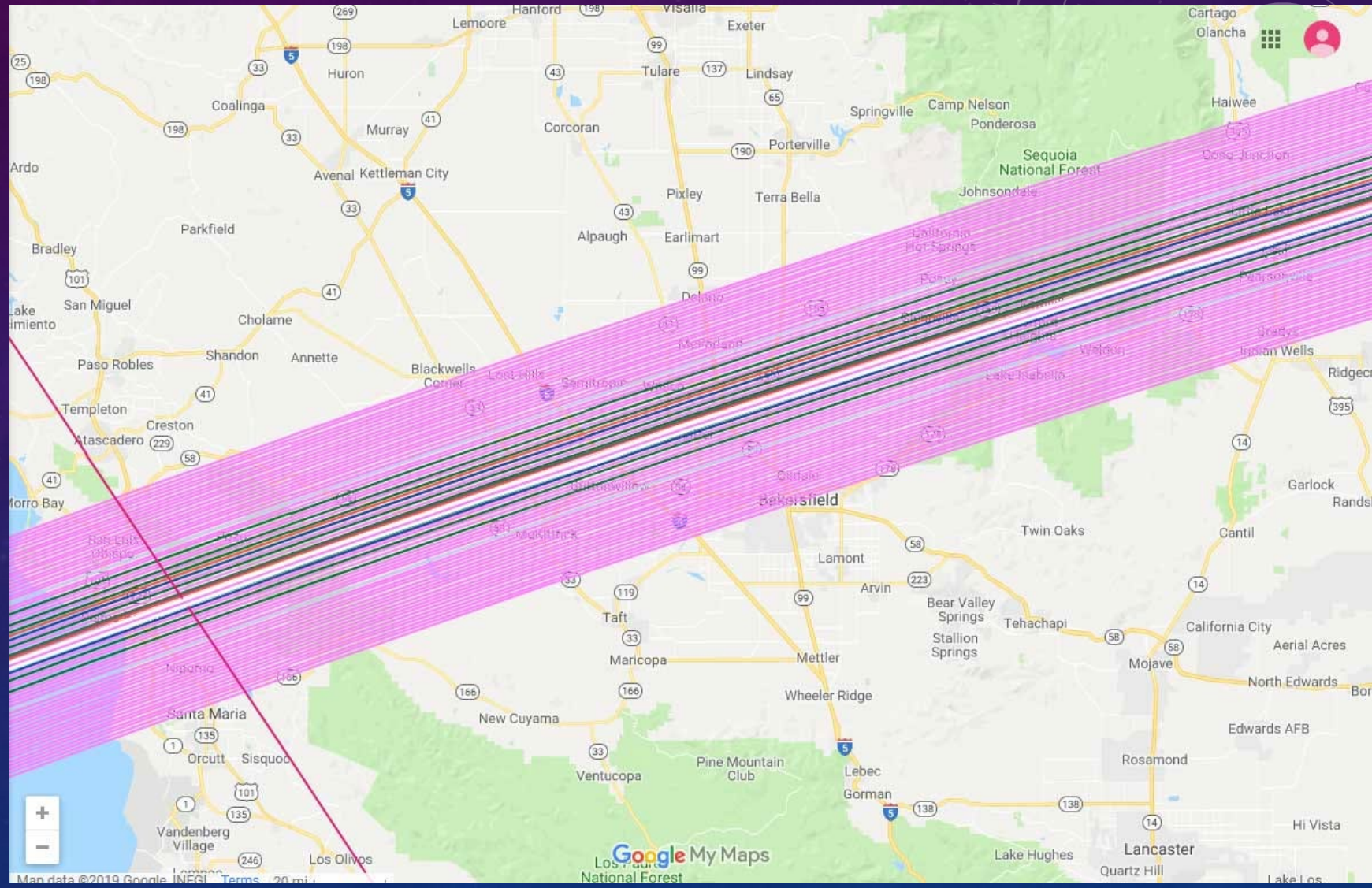
JPL AND NASA SCIENTISTS WILL BEG YOU, EVEN OUTFIT YOU (SOMETIMES) TO GET THIS AFFORDABLE HIGH PRECISION DATA SO THEY CAN BETTER PLAN THEIR RENDEZVOUS MISSIONS

- And the discovery by occultation of a new moon of one of these rendezvouz targets would have big implications for the dangers, and opportunities, for the spacecraft.

I'll now show 6 examples of my team's high adventure / high value occultation successes, in chrono order…

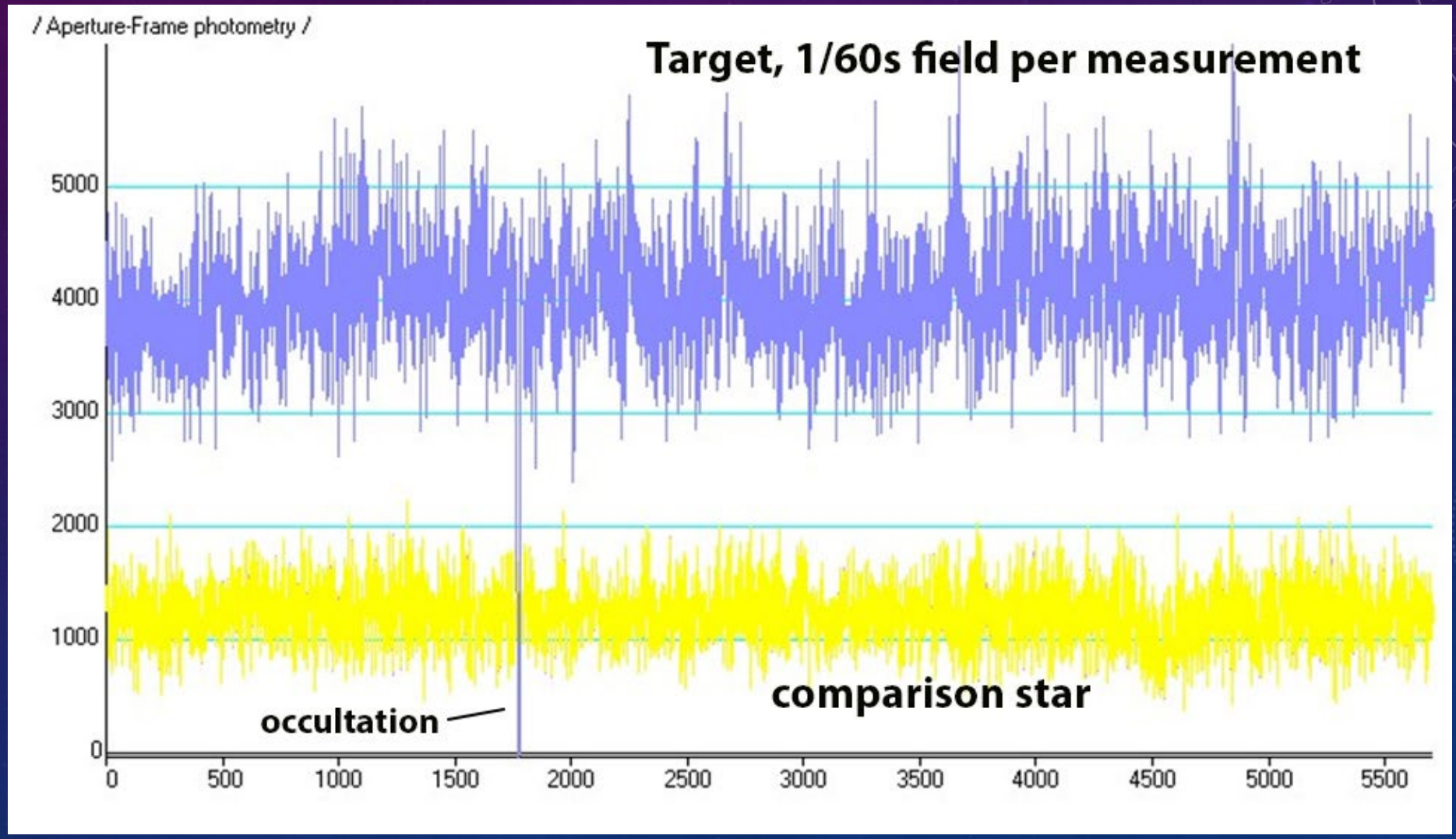
1ST: PHAETHON, PARENT OF THE GEMINIDS, AND IN THE FUTURE; EARTH-DANGEROUS.

High priority! The Phaethon occultation of a bright star on July 29, 2019. IOTA set out a 60 tracks "net" to snare this 7th mag event. Astronomers from around the country converged on California.

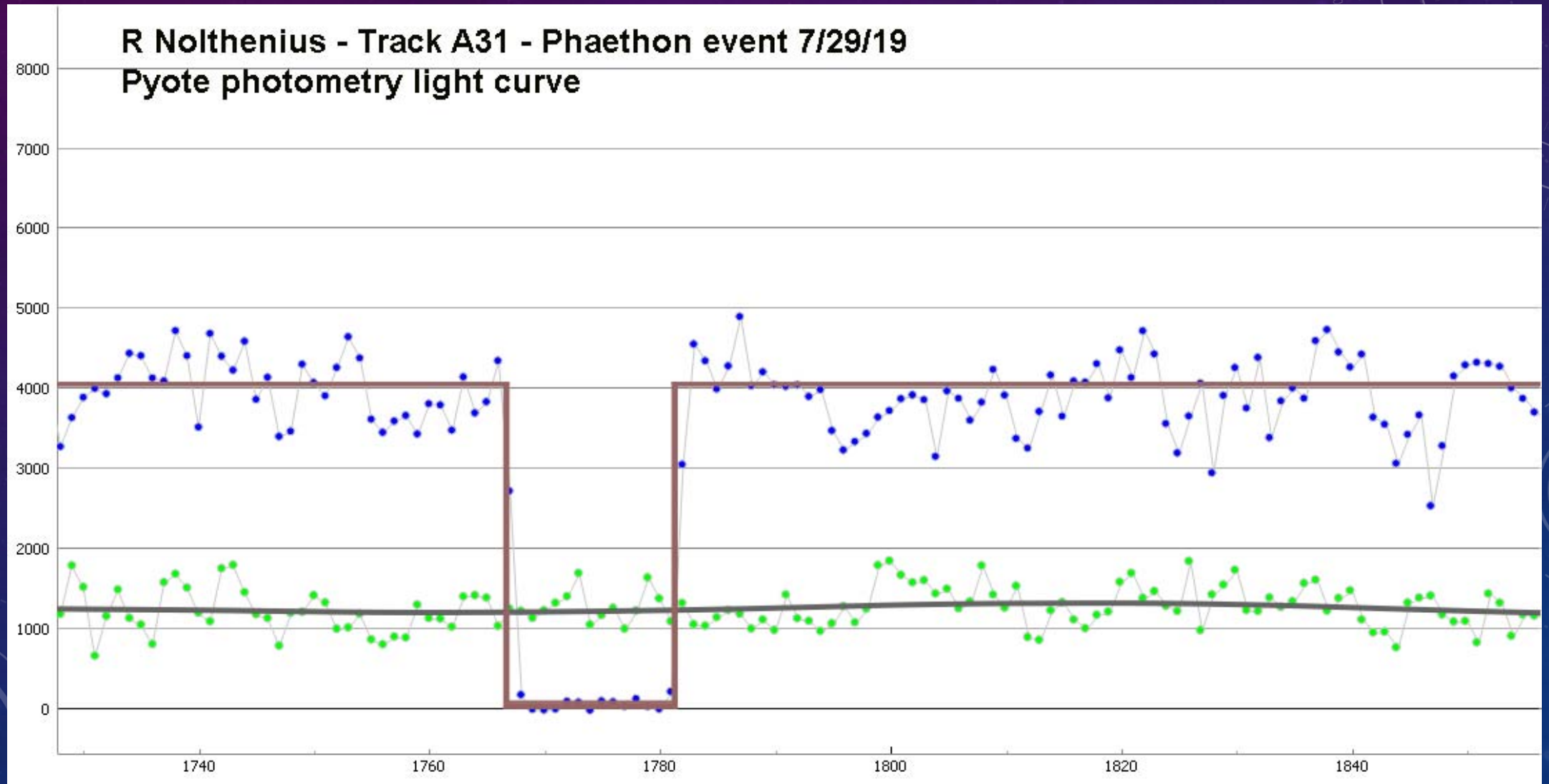


Kirk Bender and I joined the effort, setting up on assigned tracks at Carrizo Plain National Monument (One of my favorite photography and trail running places)

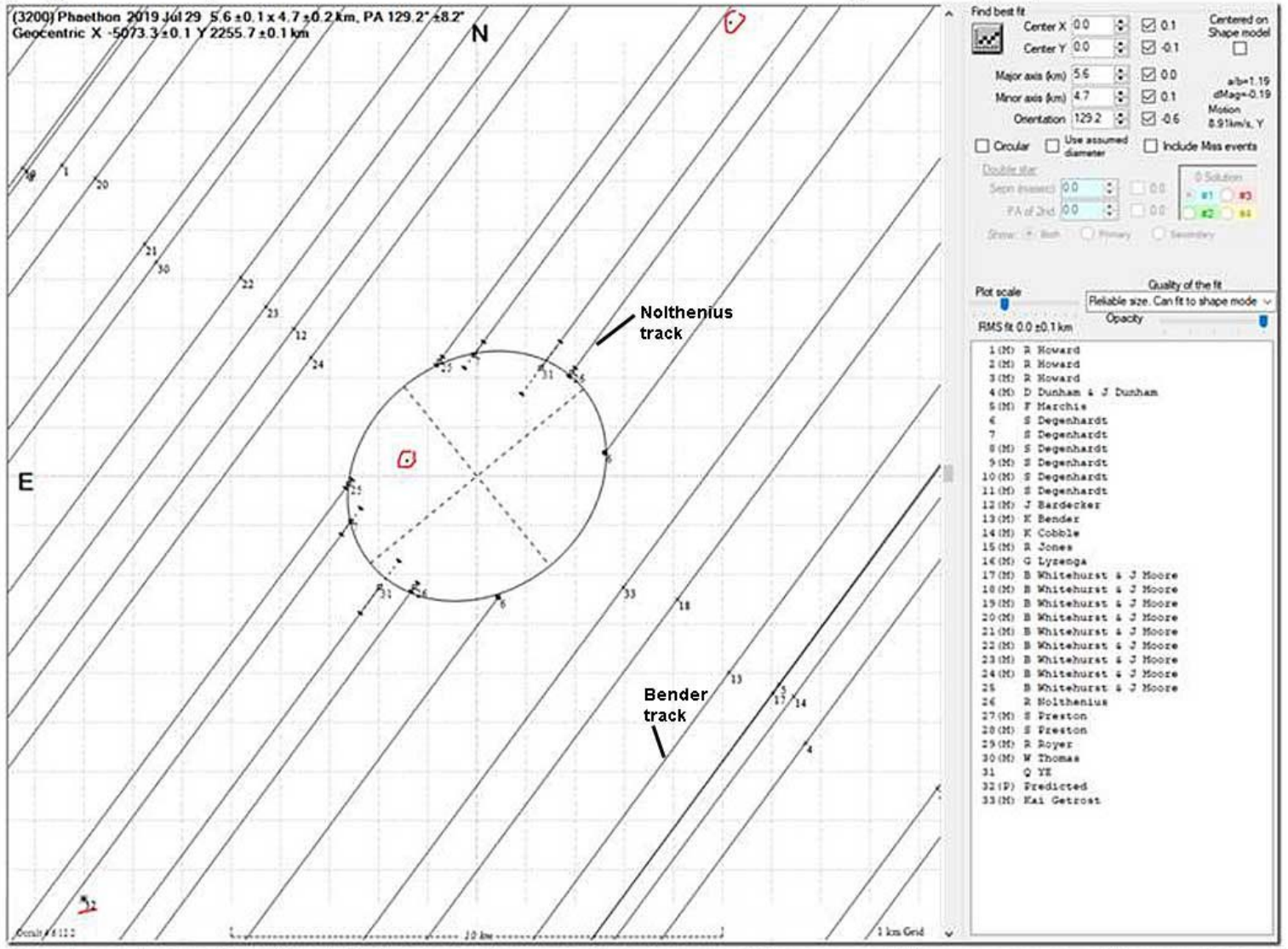
I was assigned a high probability track, and got lucky. The light curve (blue) of the V=7.1 star and Phaethon: Less than ¼ sec long! Success! (24s YouTube video of my occultation)



Zoomed in. A 7.1 magnitude star makes for very high S/N. Very rare to get such a high value event on such a bright star. 11th -13th magnitude stellar targets are more typical. A few per week within ~12 miles.



2019 July 29 Occ'n of 7.3-mag. HIP 24973 by (3200) Phaethon – Preliminary Sky-plane Plot



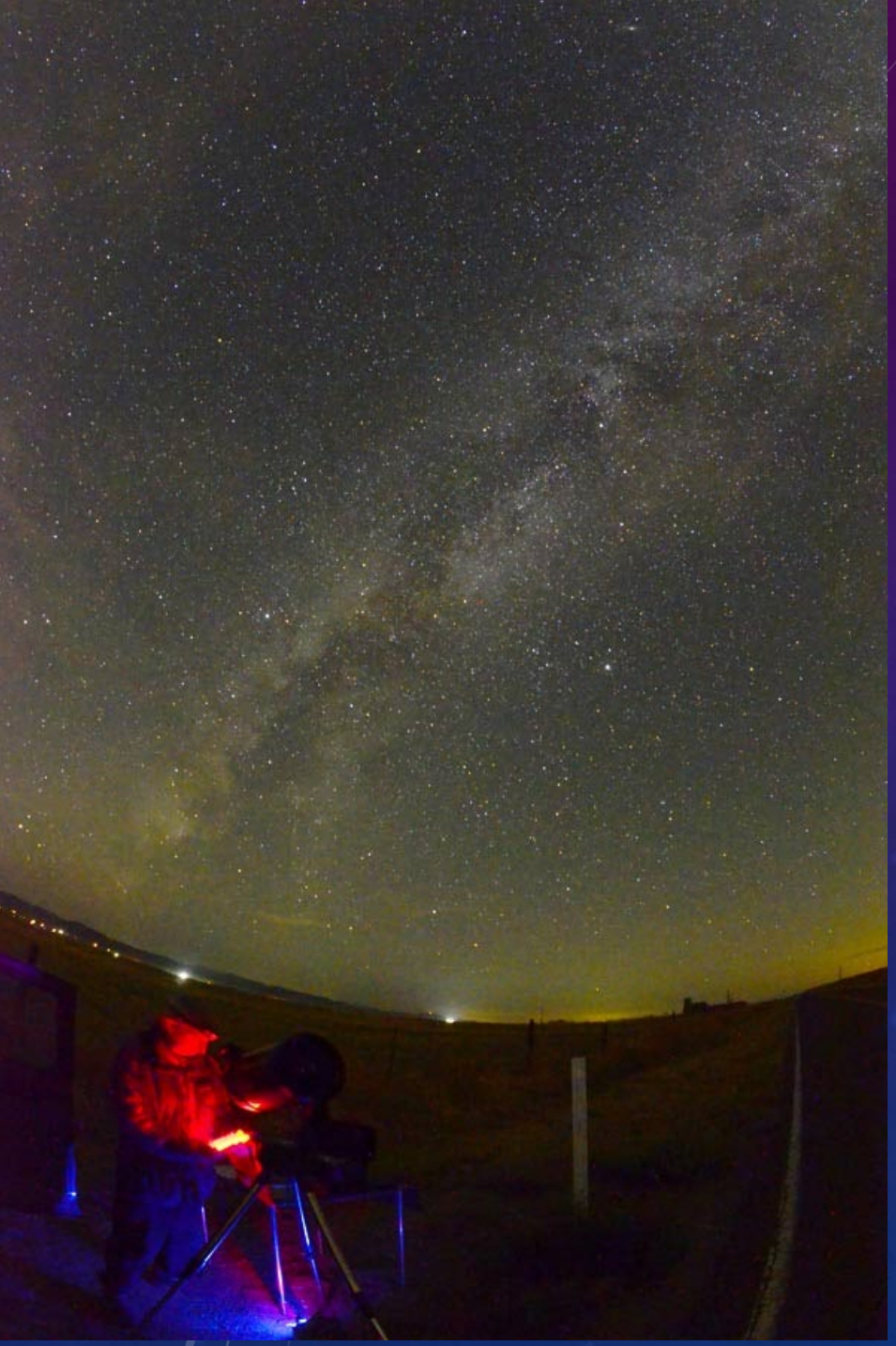
IOTA chords only; SwRI has a bounding negative and 2 more positive chords.

John Moore, Dave Herald, and David Dunham, 2019 August 7

Excellent data.

This asteroid shows significant non-grav forces, and is a threat to Earth.

Orbit changes are vital to monitor. Now, future occultation observers will be placed with far better odds of a success.

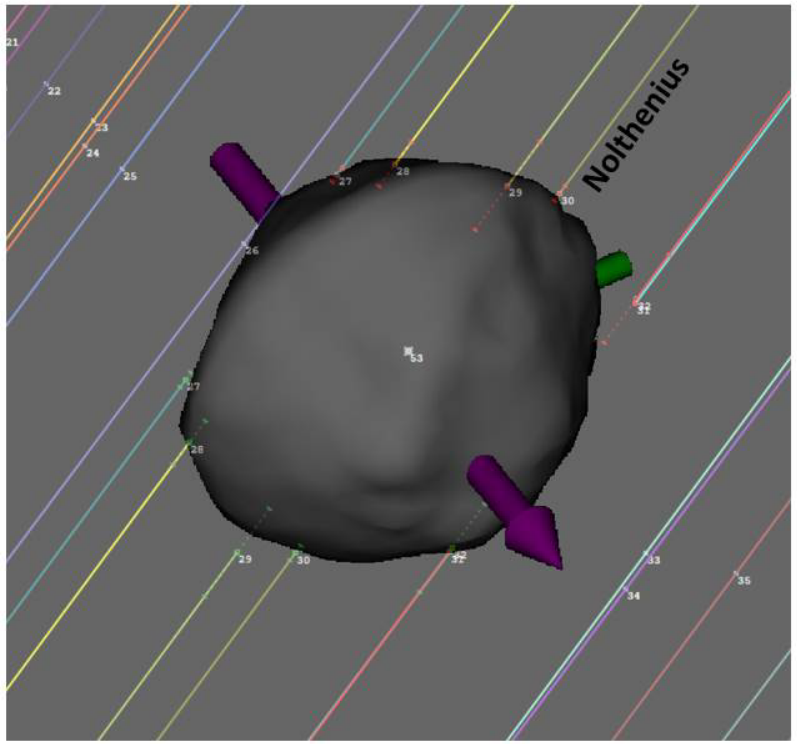


At my Phaethon site… Exciting to be under dark Milky Way skies getting good science. (YouTube; 28min talk on this event in wider context)

Combining our occultation and radar to measure the axis, shape, orientation. valuable to the destiny mission to this unique dead comet / new asteroid transition object

2019 July 29 Phaethon occultation, positive chords

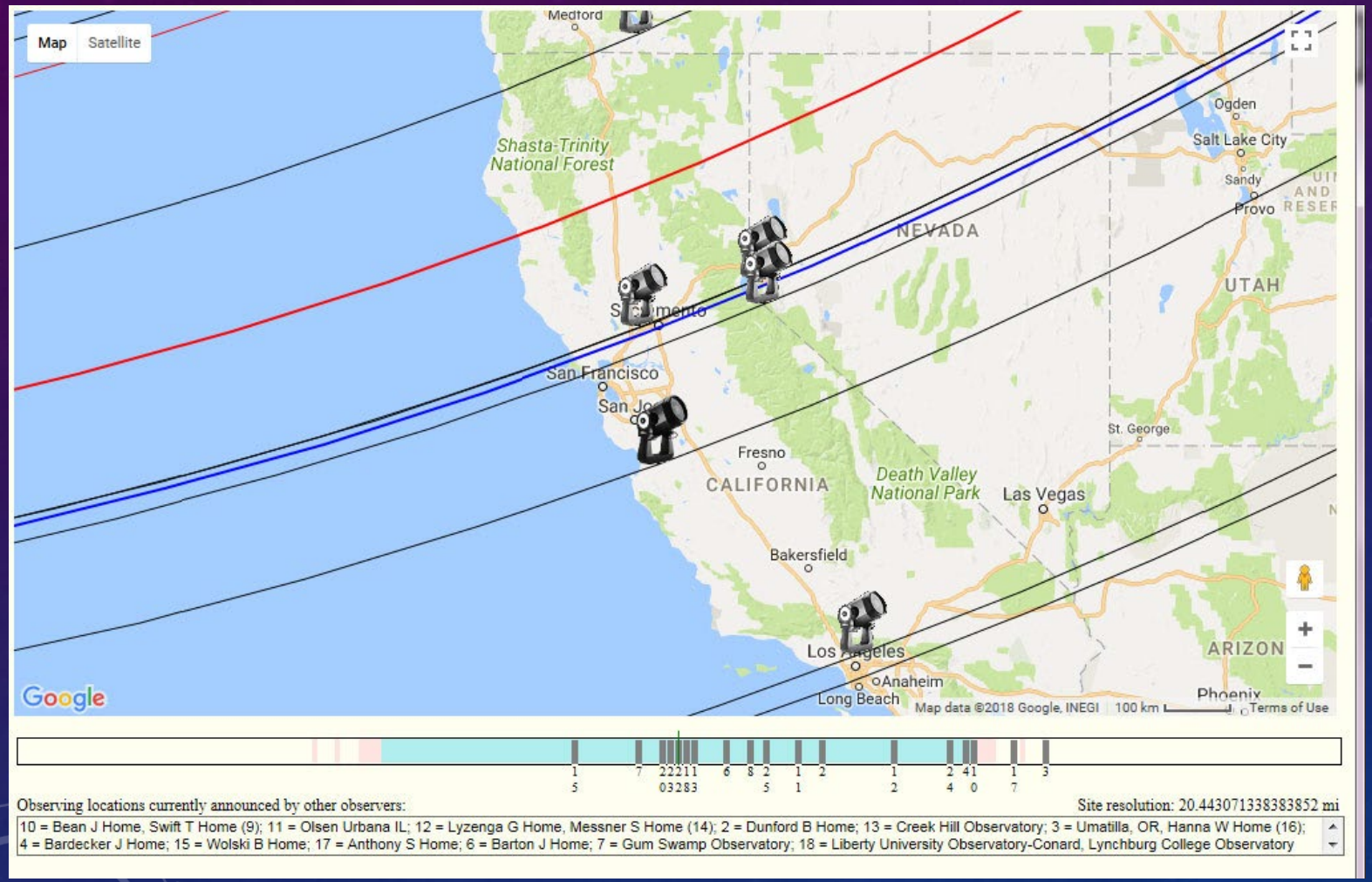
fitted to a shape model determined from 2017 December Arecibo radar observations



by
Dave Herald and
Sean Marshall

The event provided accurate information about Phaethon's size (verifying the radar value), shape, and orbit that will be valuable for DESTINY+'s planning, and will help obtain more data from future occultations that can be better predicted.

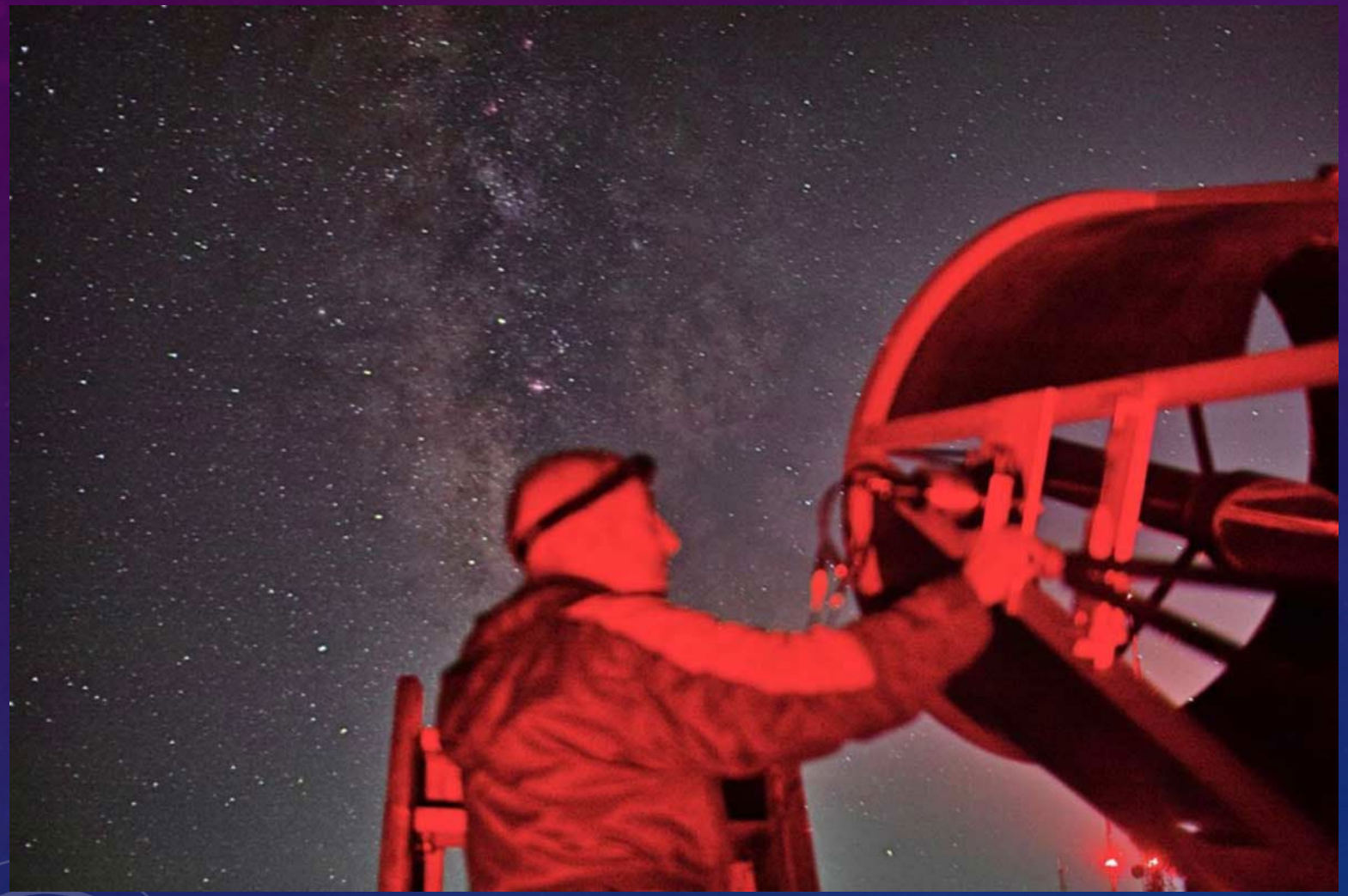
NEXT: the Pluto Occultation of a V=15.2 Star on Aug 15, 2019.



The northern limit crossed Marin county. For us, the resulting extended atmospheric occultation allowed sensitive probing of the temperature and density structure of the now re-freezing nitrogen atmosphere.

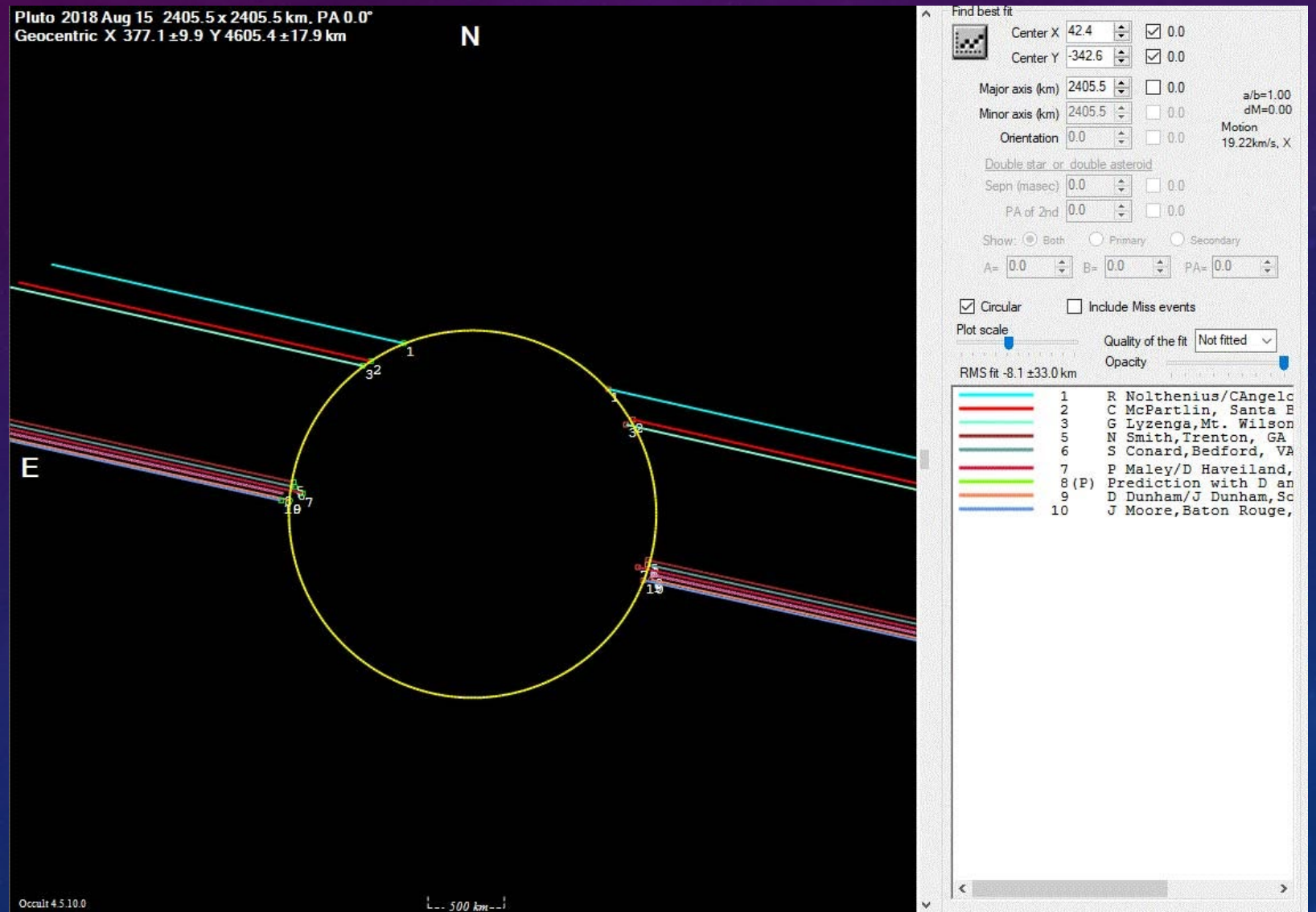
15th magnitude?! Our “Mission Impossible” team: My former student and FPAO member Chris Angelos, me, Kirk Bender, at the 30” at Fremont Peak Observatory

Chris controlled the motors on the the 30”, I did fine guiding, instrument mounting, data monitoring as it came in. Kirk aided both of us.

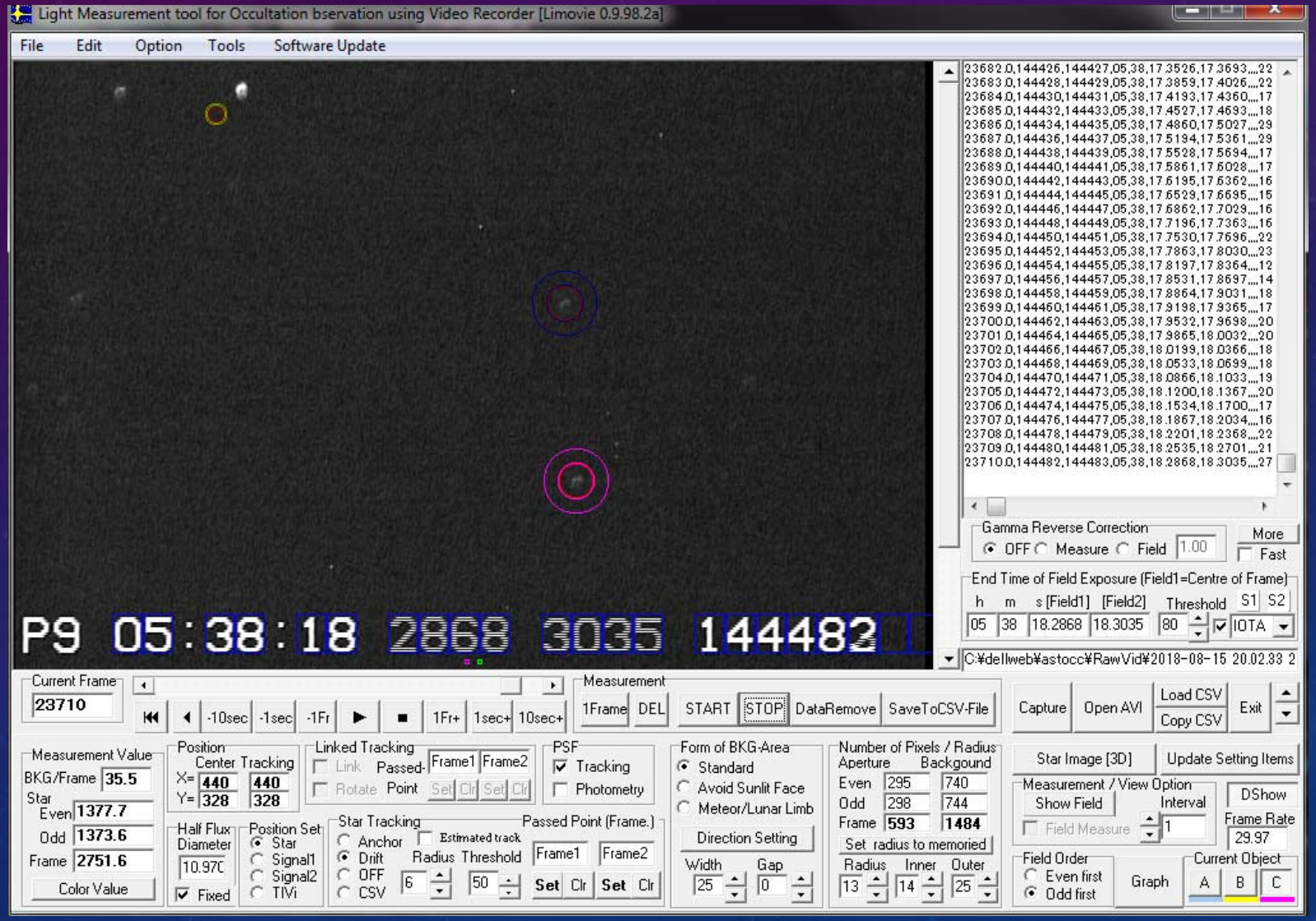


The Watec 910hx video camera is at the Newtonian focus. Pluto’s in the Sagittarius Milky Way – good for more occultations in recent years.

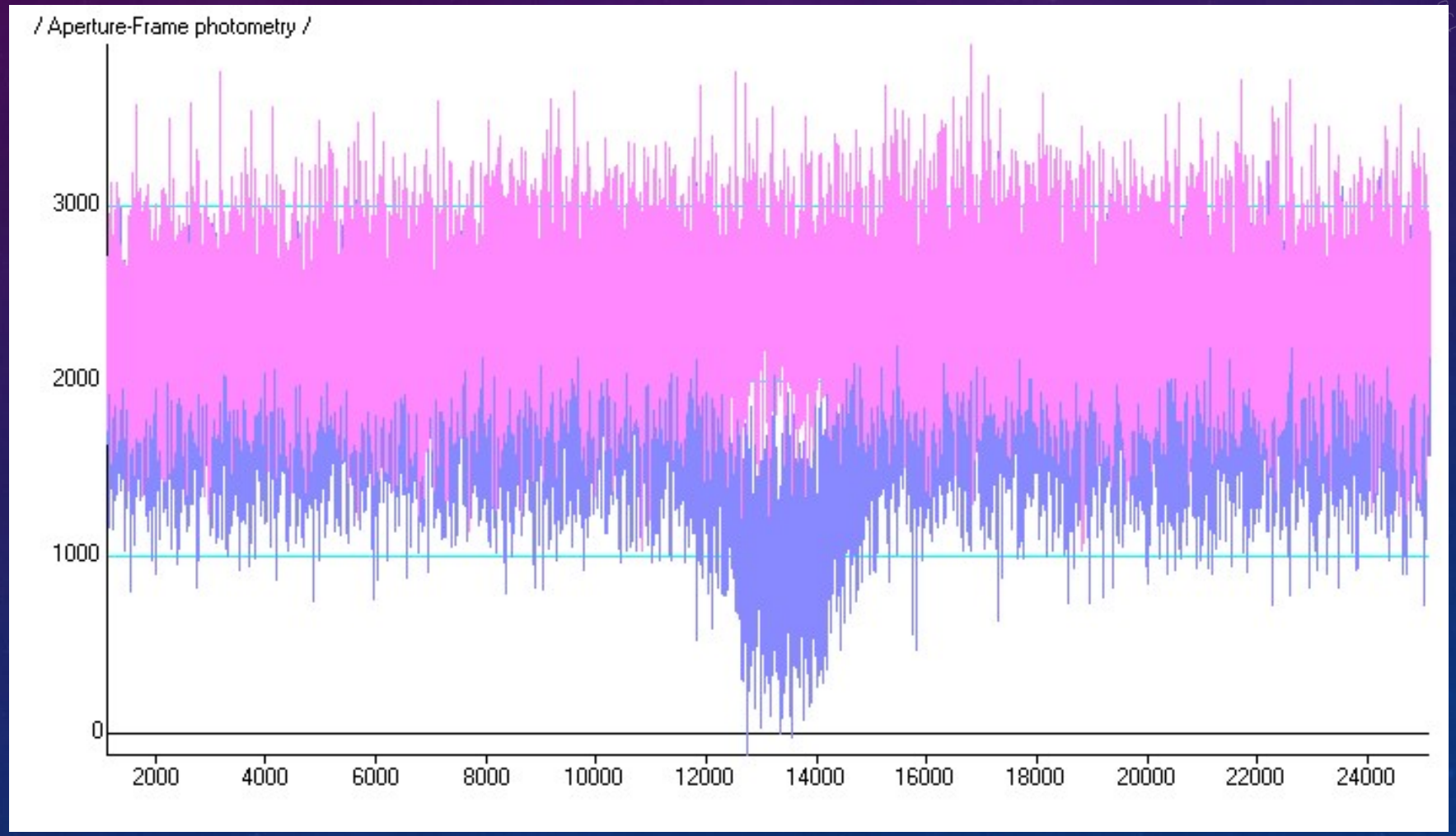
The sky plane plot of the observational timings of the “D” and “R” by the planet (beneath the atmosphere).

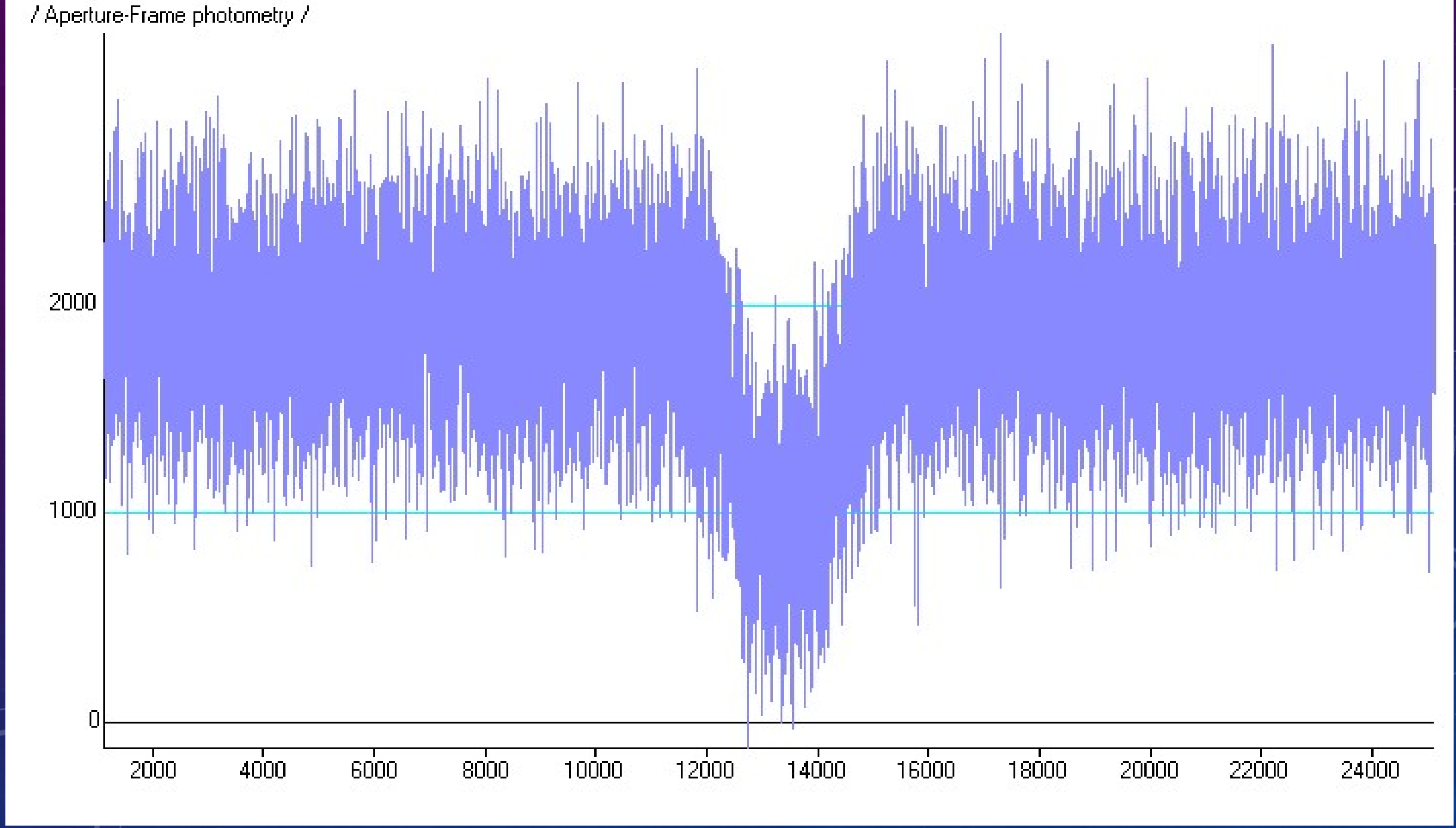


Our 2019 Pluto occultation photometry was done by an ancestor to PyMovie, called LiMovie.



Pluto’s atmosphere – only 13 millionths of Earth’s atmospheric density, but still gave obvious dimming before/after the D and R of the total occultation




/ Aperture-Frame photometry /
2000
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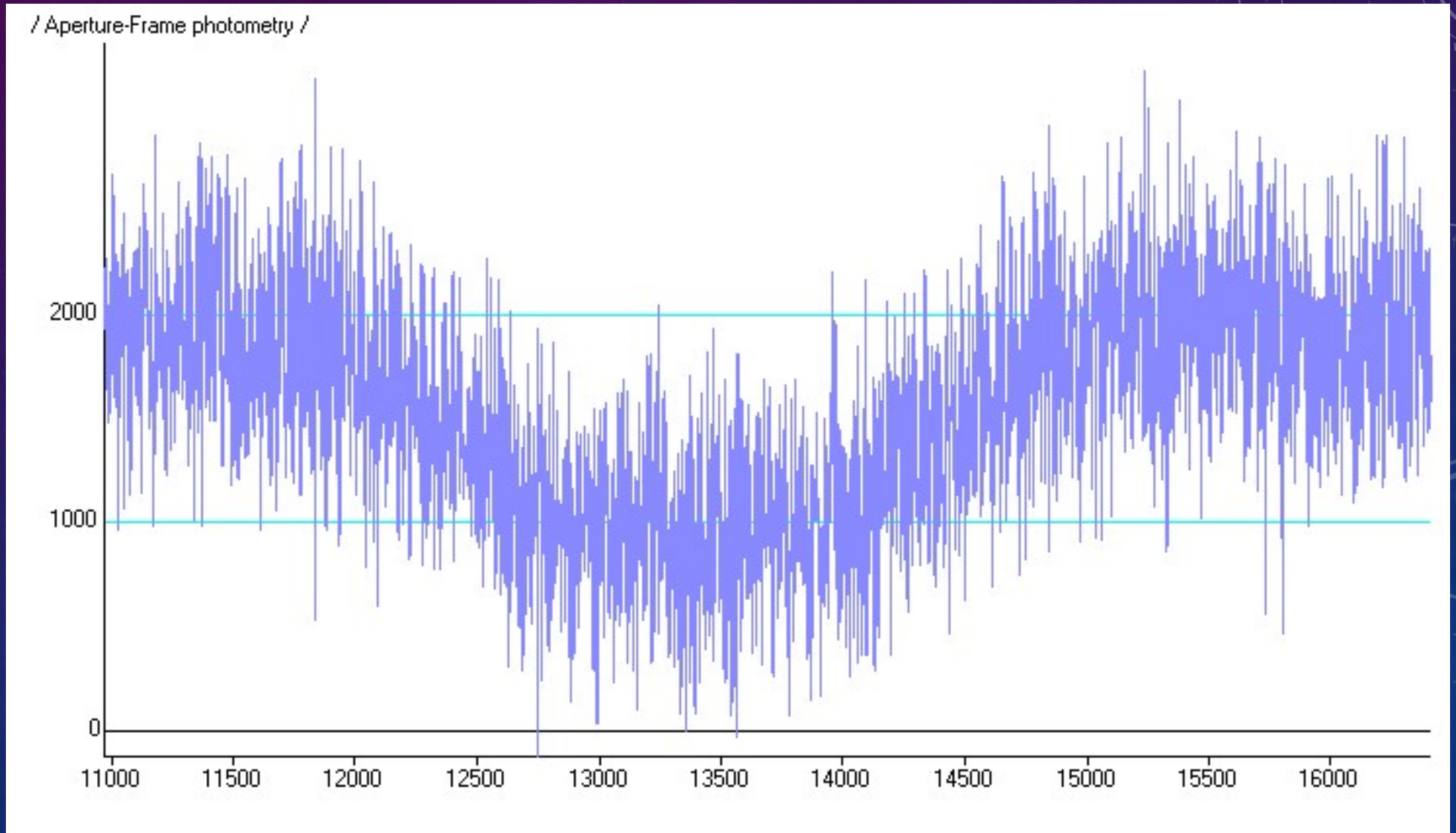
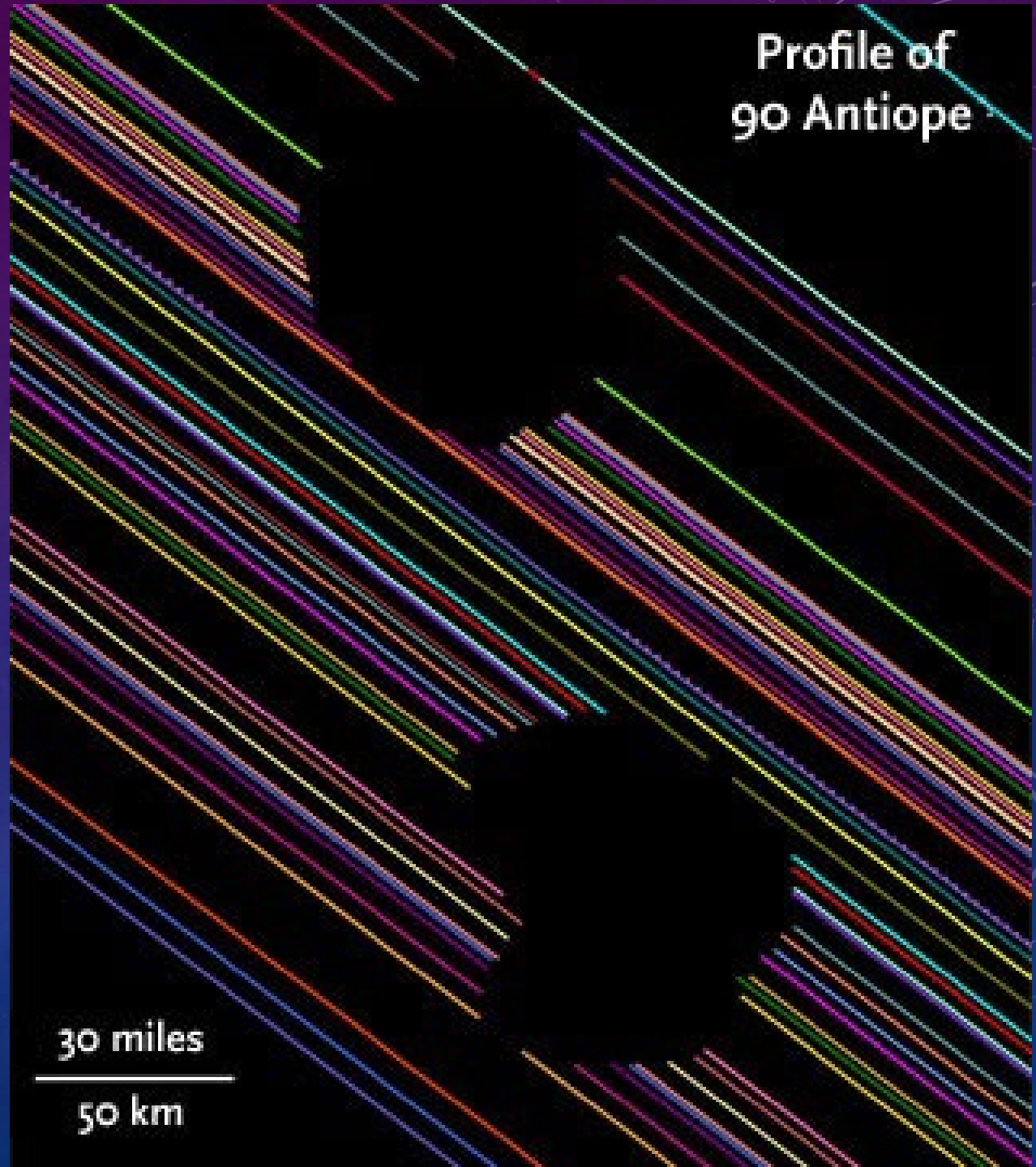
Point-to-point variance is noise, but the spikes which are wider, stronger than the noise level, are real – caused by the layering of density and temperature in the nitrogen / methane Pluto atmosphere

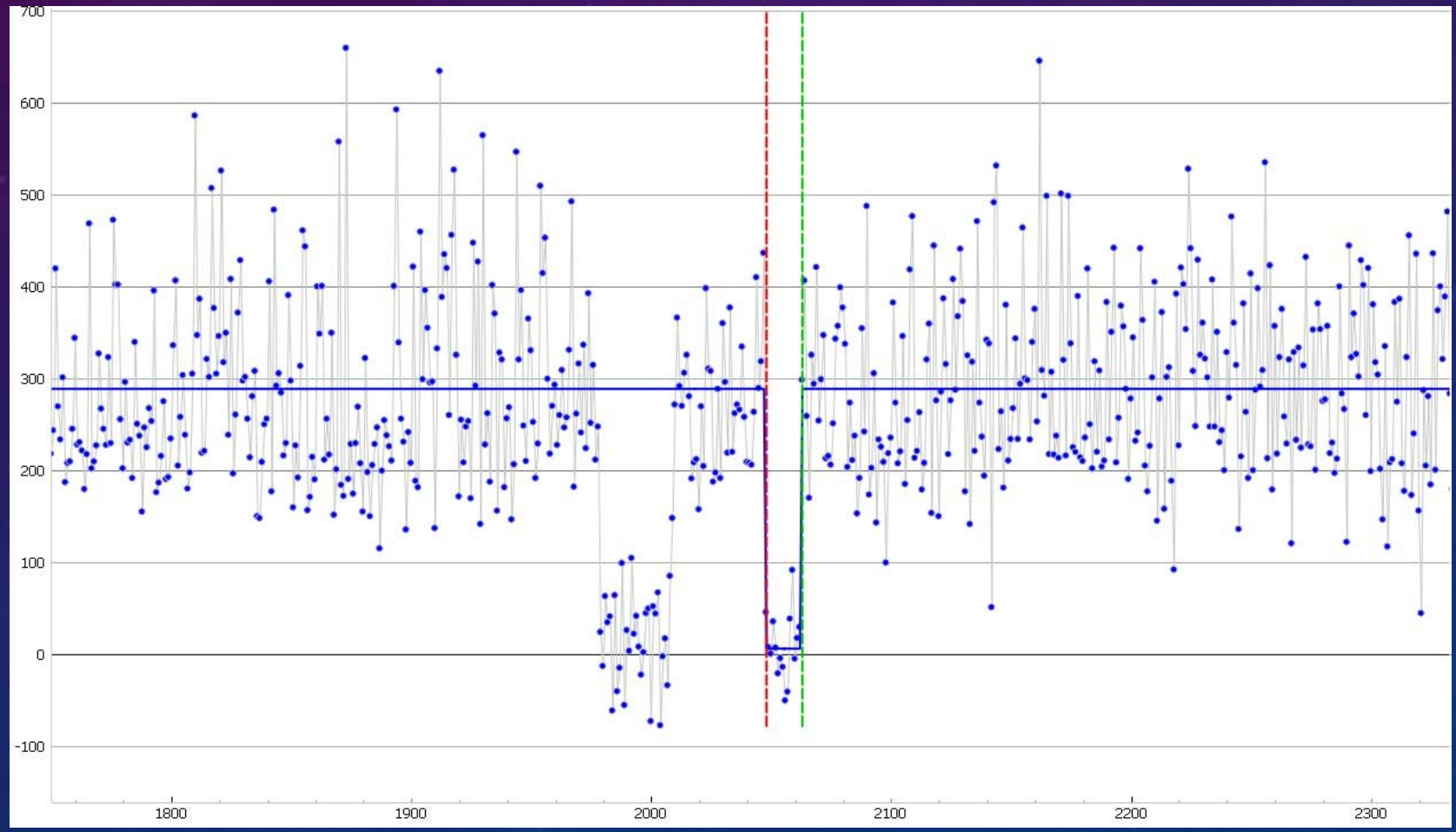


Binary asteroid discoveries… Kirk Bender and I have tackled several events involving ~4 binaries

The most precisely determined orbit for a binary asteroid discovered by occultation, now is Arecibo… That brings us to 2021’s adventures.



May 2021 – Dave Gault and Peter Nosworthy in Australia, recorded high confidence surprise double occultations by **(4337) Arecibo**. David Dunham of IOTA alerted us of another favorable Arecibo occultation across Central California just 3 weeks later. Bender and I jumped into action. Successful confirmation – my light curve below. Kirk's was similar. Peter's 8min video on their discovery.

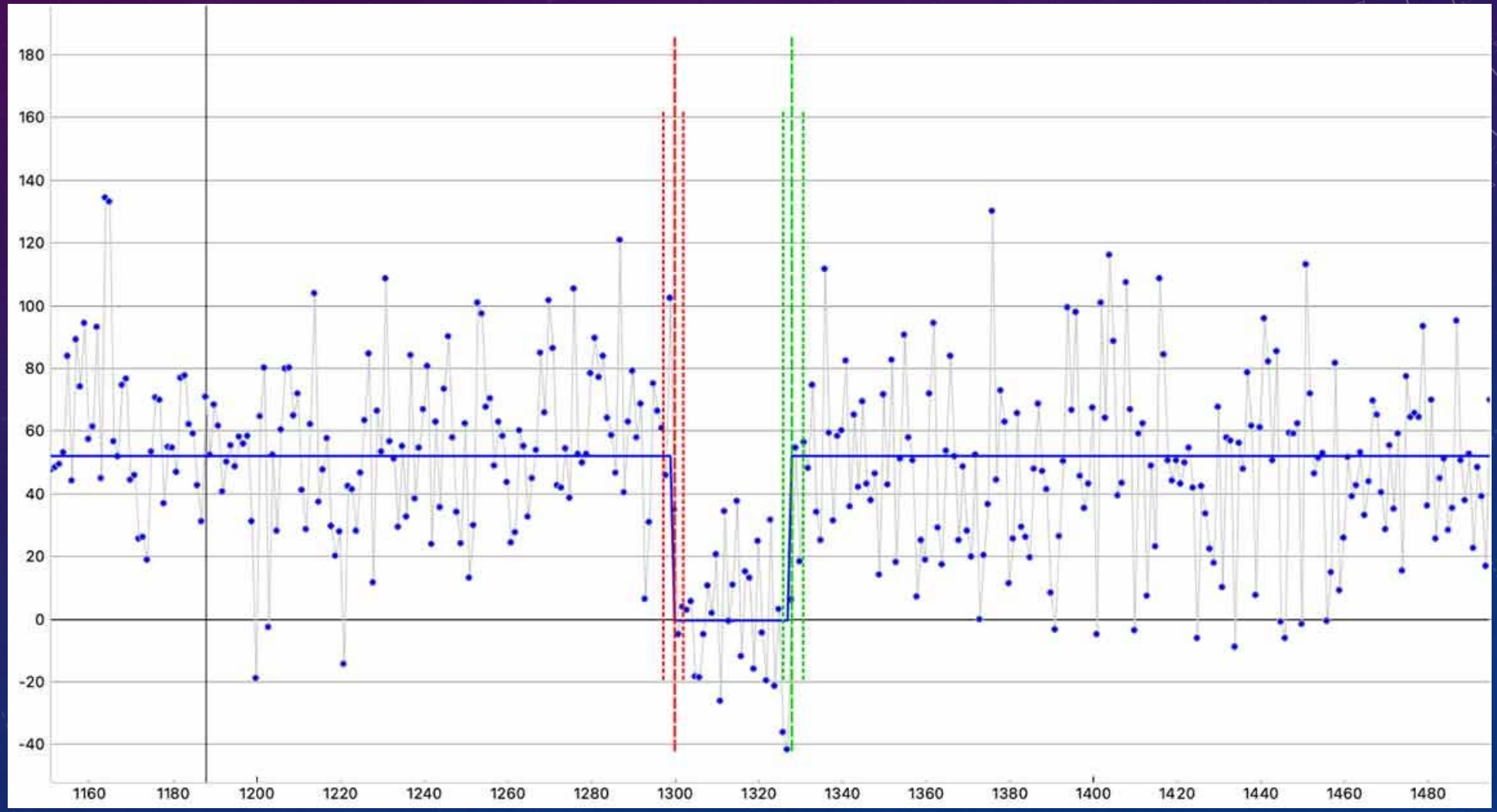


Another 3 weeks later: Kirk Bender, Chris Kitting and I got another Arecibo occultation from the Sacto River Delta area June 30, 2021.

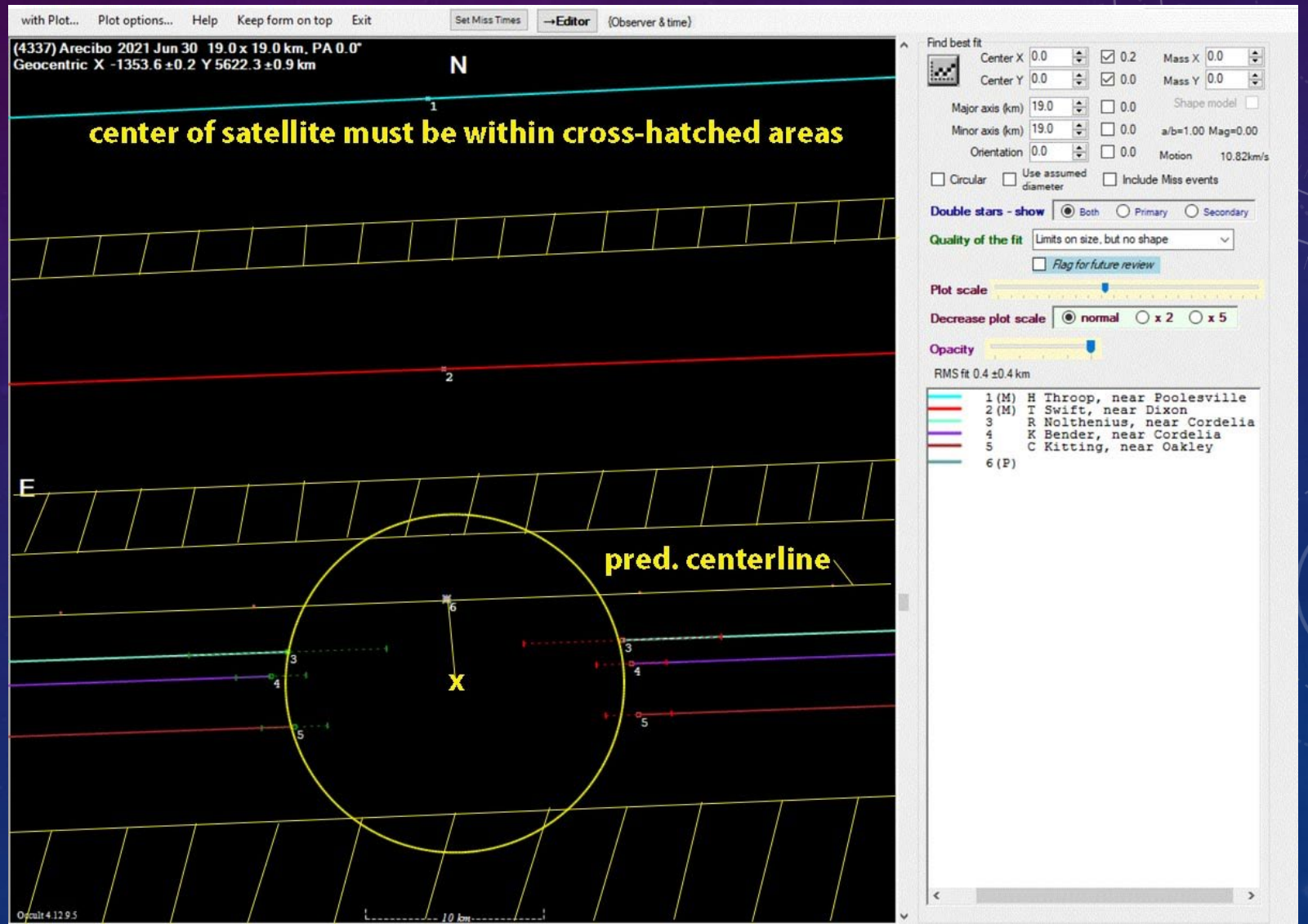
High winds and unlucky placement of the moonlet failed to give a good detection of it.

This impromptu wind shield table lashed to my bike rack blew off right after the occultation, hitting me and scope.

Kirk Bender had the most wind protection and the best data. But, no moonlet occultation seen

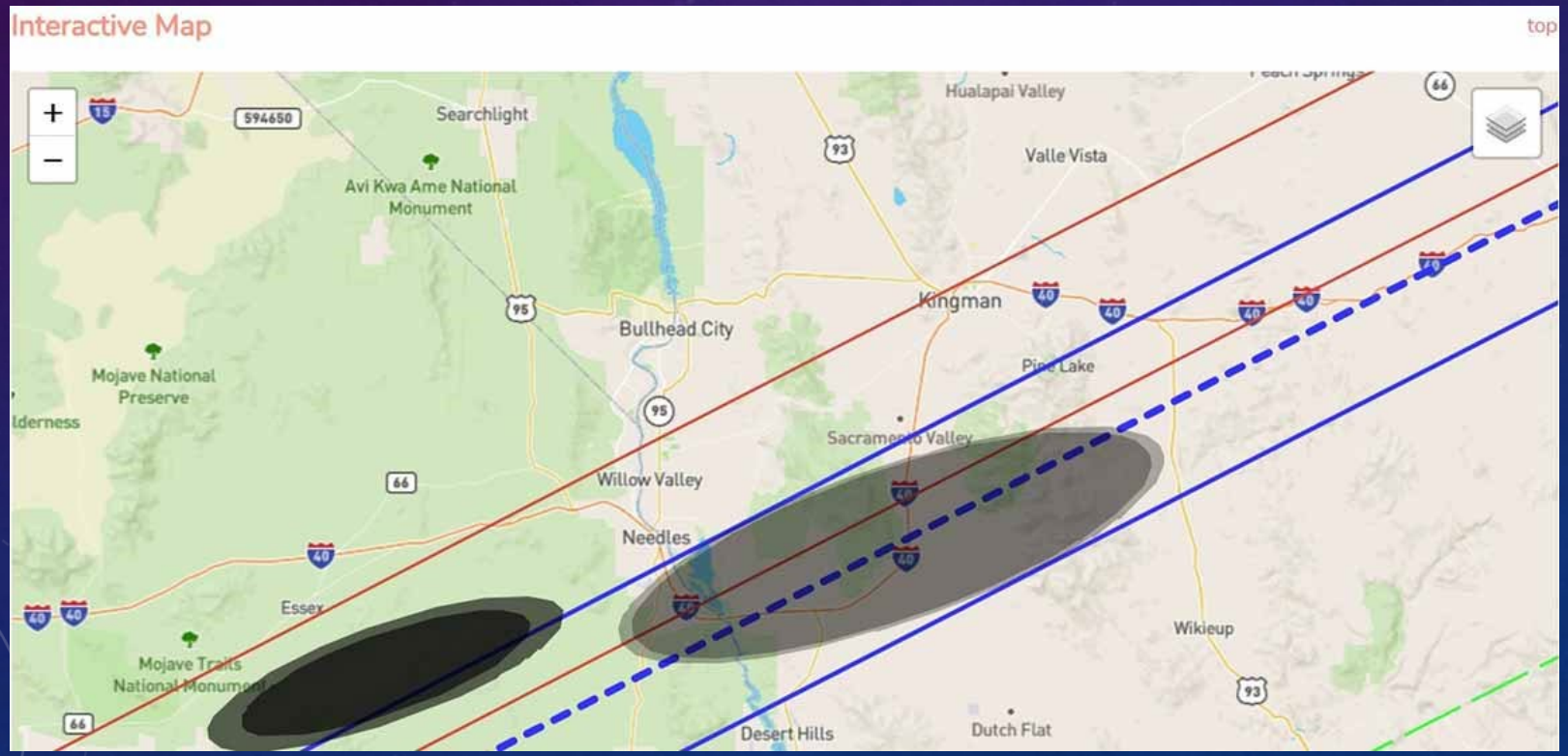


The center of the moonlet, I calculated, must be within the cross-hatched area to have avoided detection, **unless it was directly in front/behind**



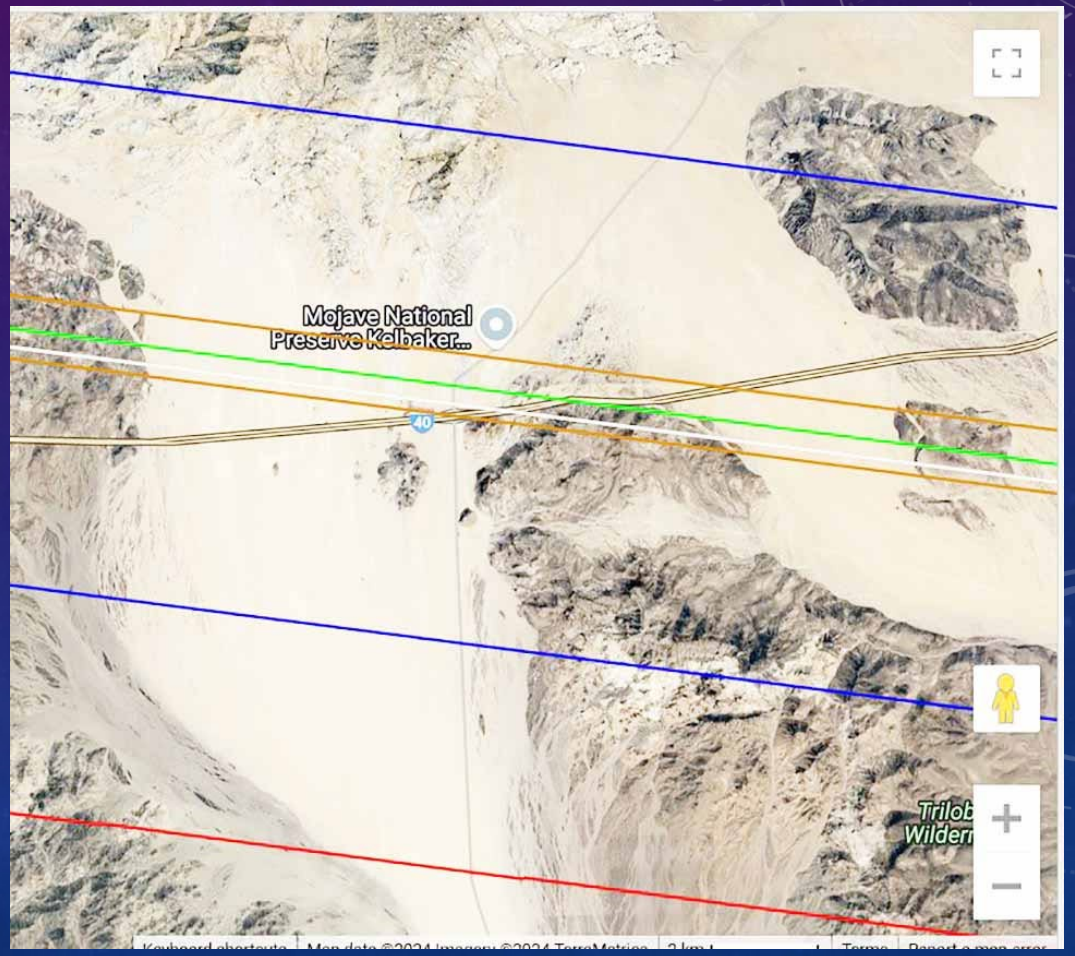
3 years later, we were lucky enough to get another occultation of Arecibo through California; on Saturday Sept 14, 2024

- A success here, with several stations set in CA and Arizona, would allow finally a unique orbit solution.
- With a firm orbit, the masses of the asteroids, their sizes and albedos and hence surface composition hints, and the bulk density of the asteroids, could be determined.



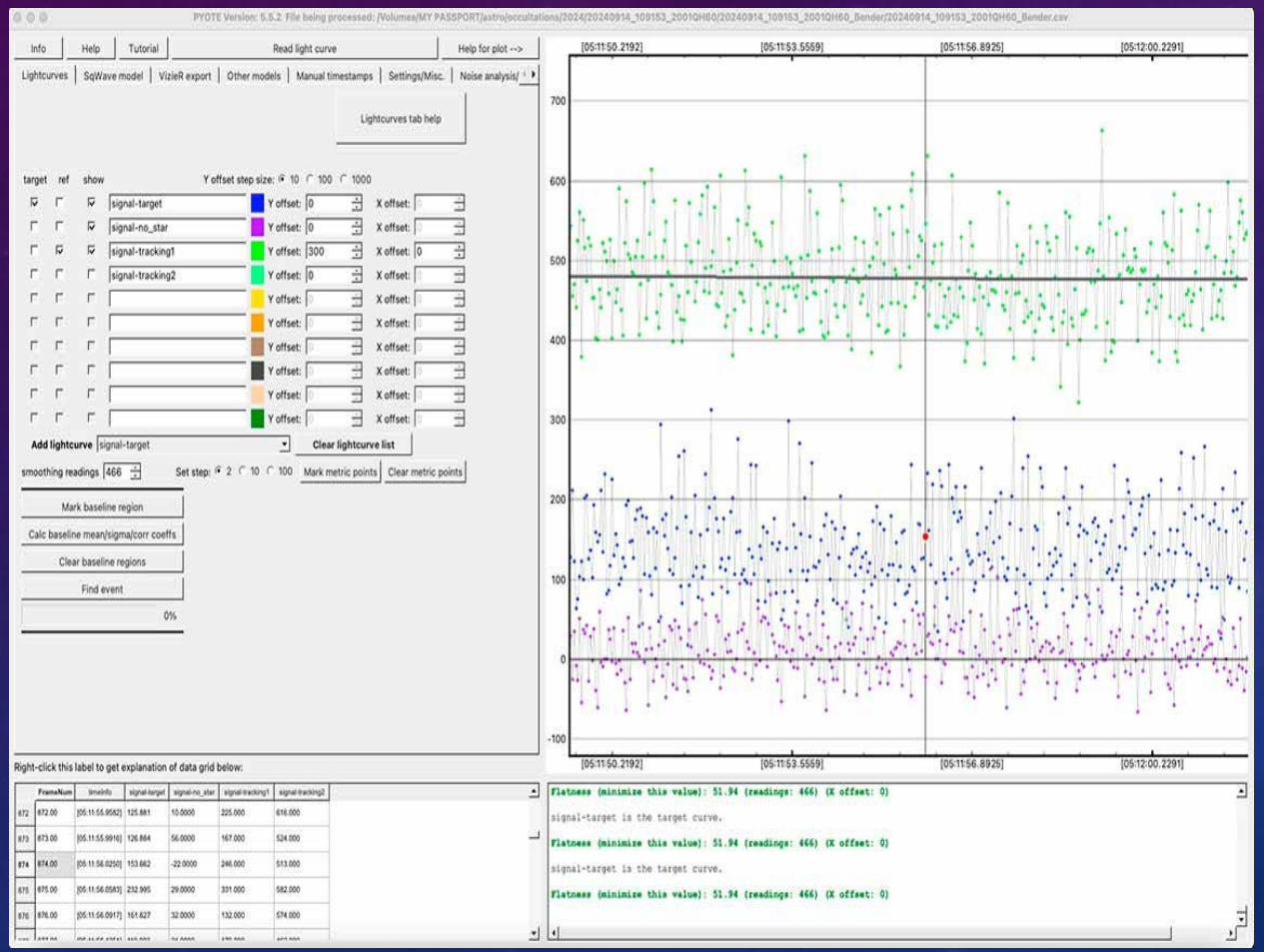
I secured a college van, and with Kirk Bender, set out for Needles, Ca, to get asteroid data

- A 1,000 mile adventure!
- On the long drive through the Mojave Desert, we got two more asteroid events which happened to be conveniently path'd and timed to fit with our drive to Needles. The first was by 2000 CT83, a miss for both of us.
- An hour later, 2001 QH60; is a recently discovered asteroid needing occultations to firm up its orbit.
- It crossed I-40 south of the Mojave National Preserve. Both events were do-able from the same sites!

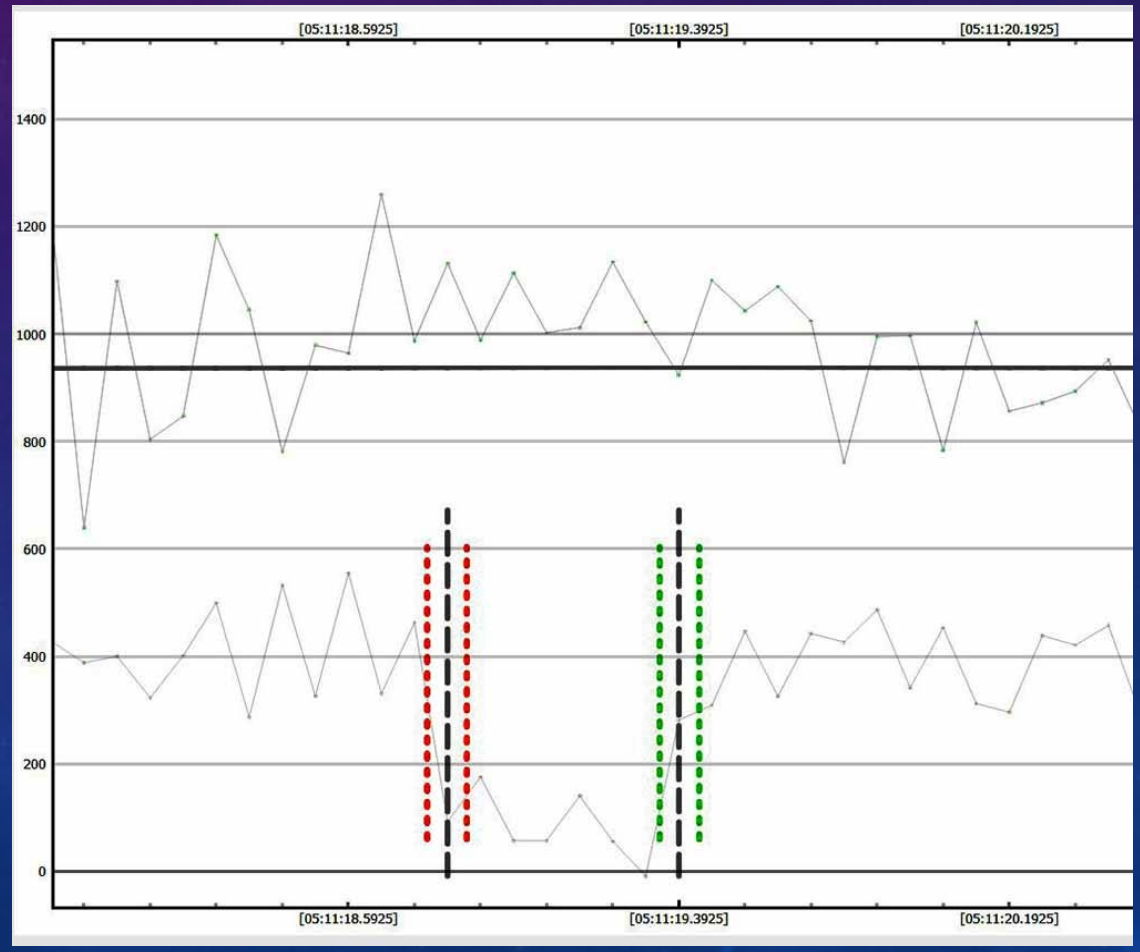


2001 QH60: A south shift; Kirk Bender's site missed the shadow, I got a positive

Kirk's light curve

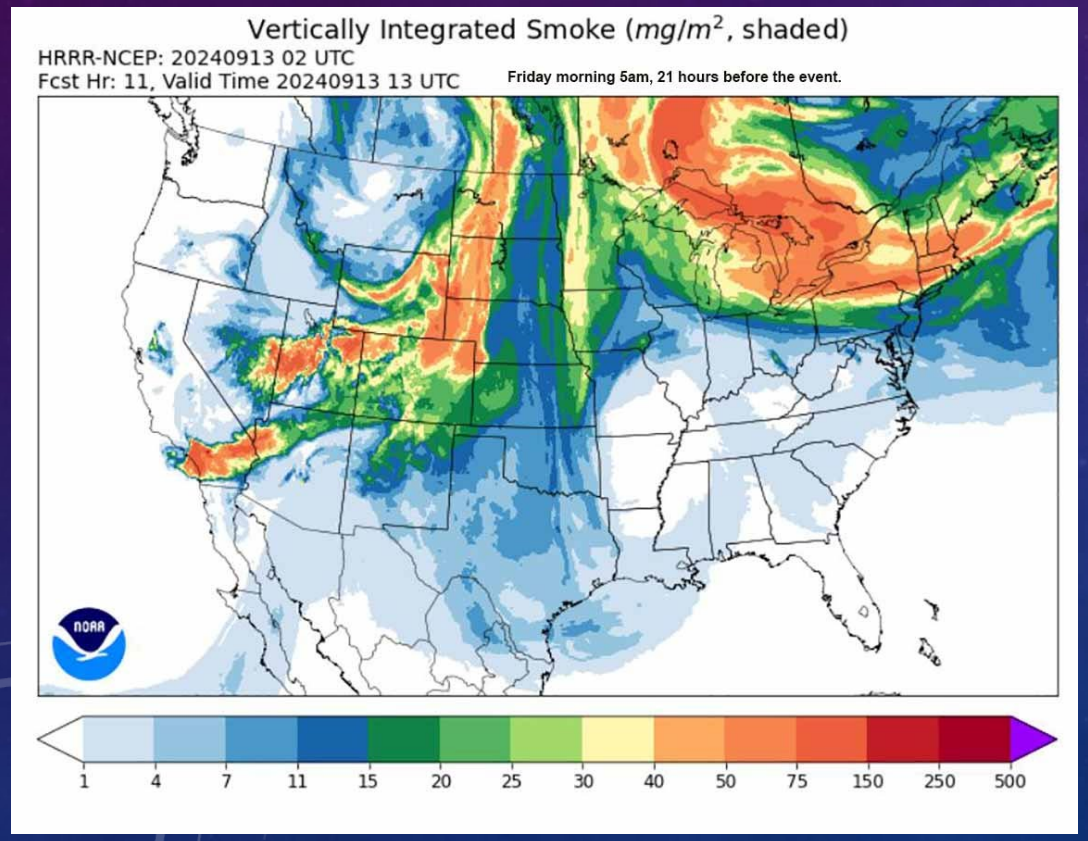


My light curve; a 0.56s event



A new challenge for Arecibo – smoke from wildfires in So.Calif. My site selection was shifting on the fly, with changing smoke predictions… Idyllwild was abandoned for Needles, in the end.

- Smoke prediction! Not good



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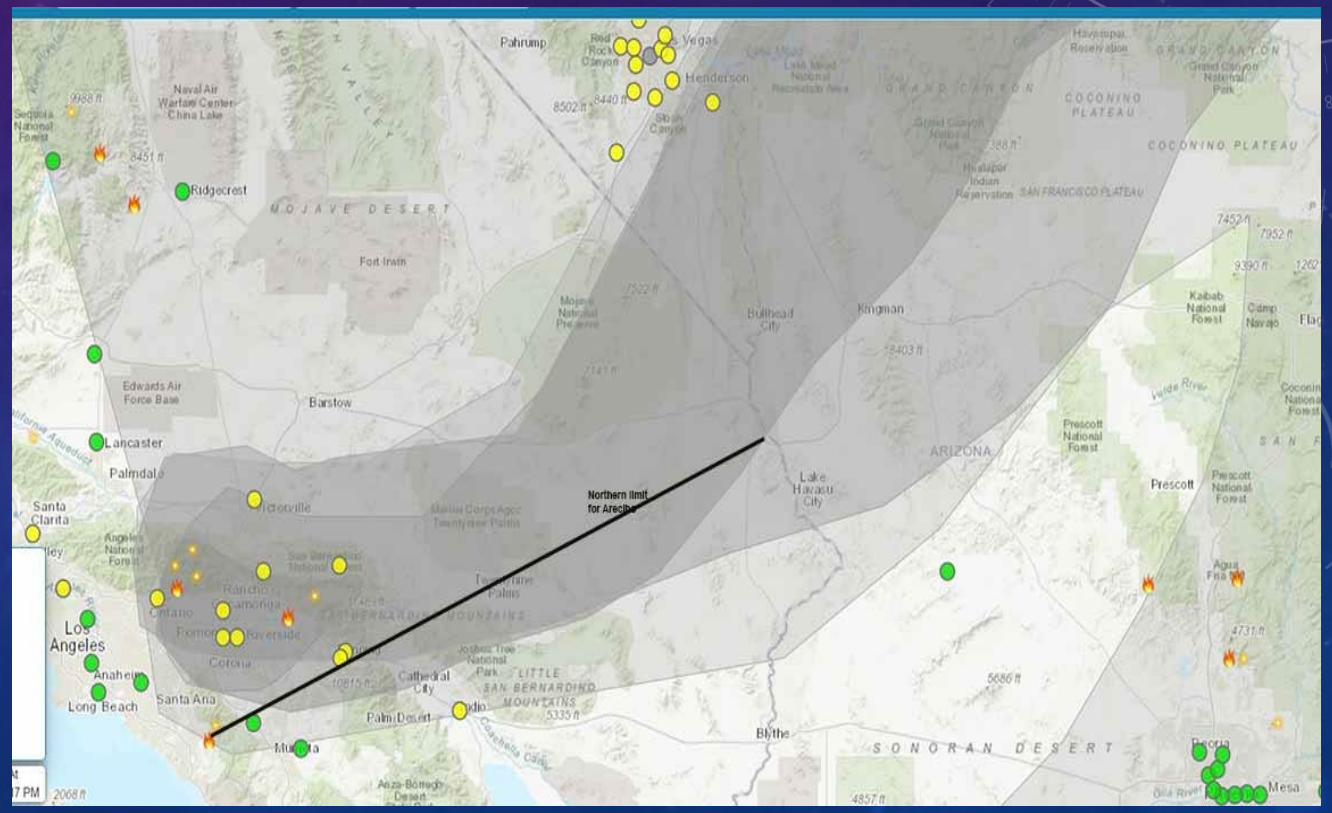
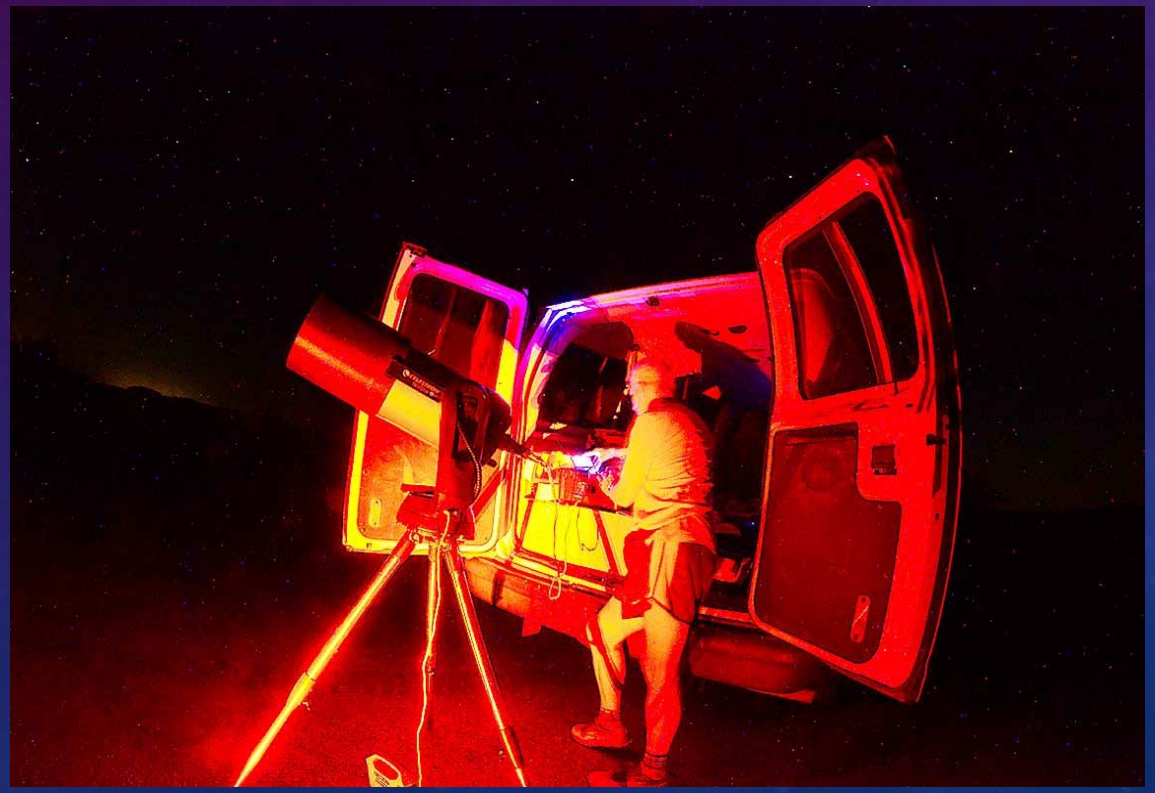
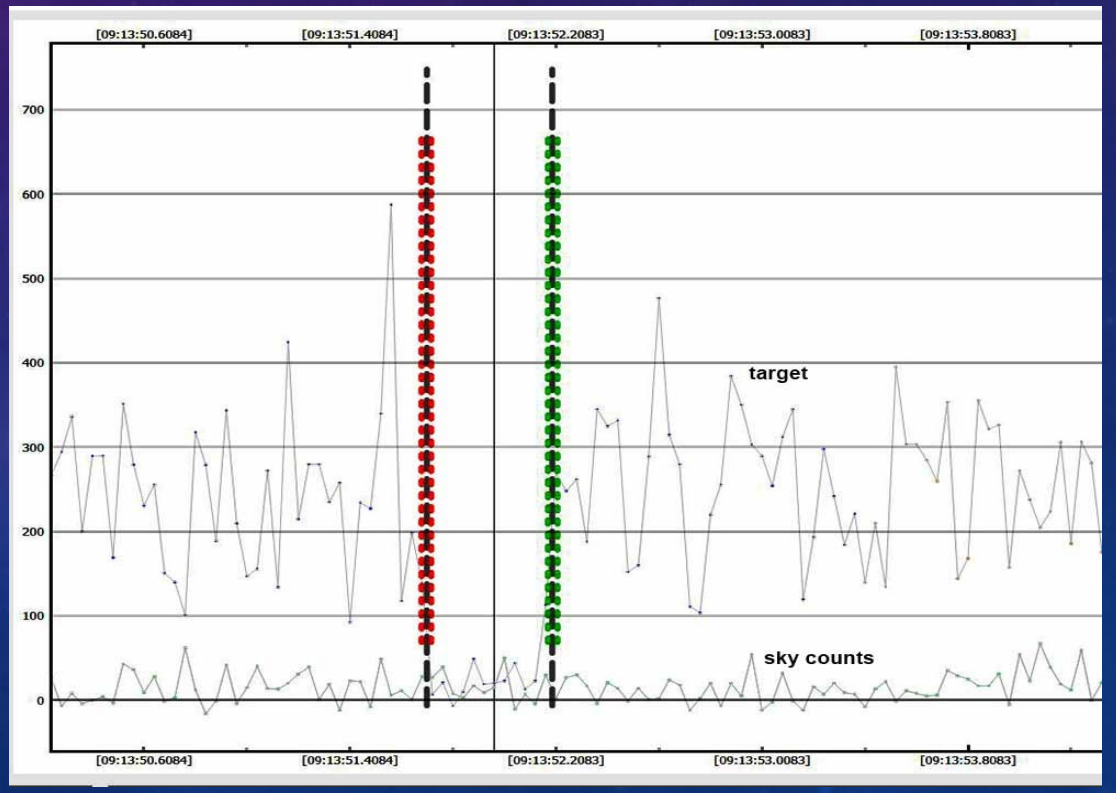


We noted on the road, the smoke plume had drifted west, and we had no trouble farther east in the Mojave. A very successful effort for both Kirk and I.

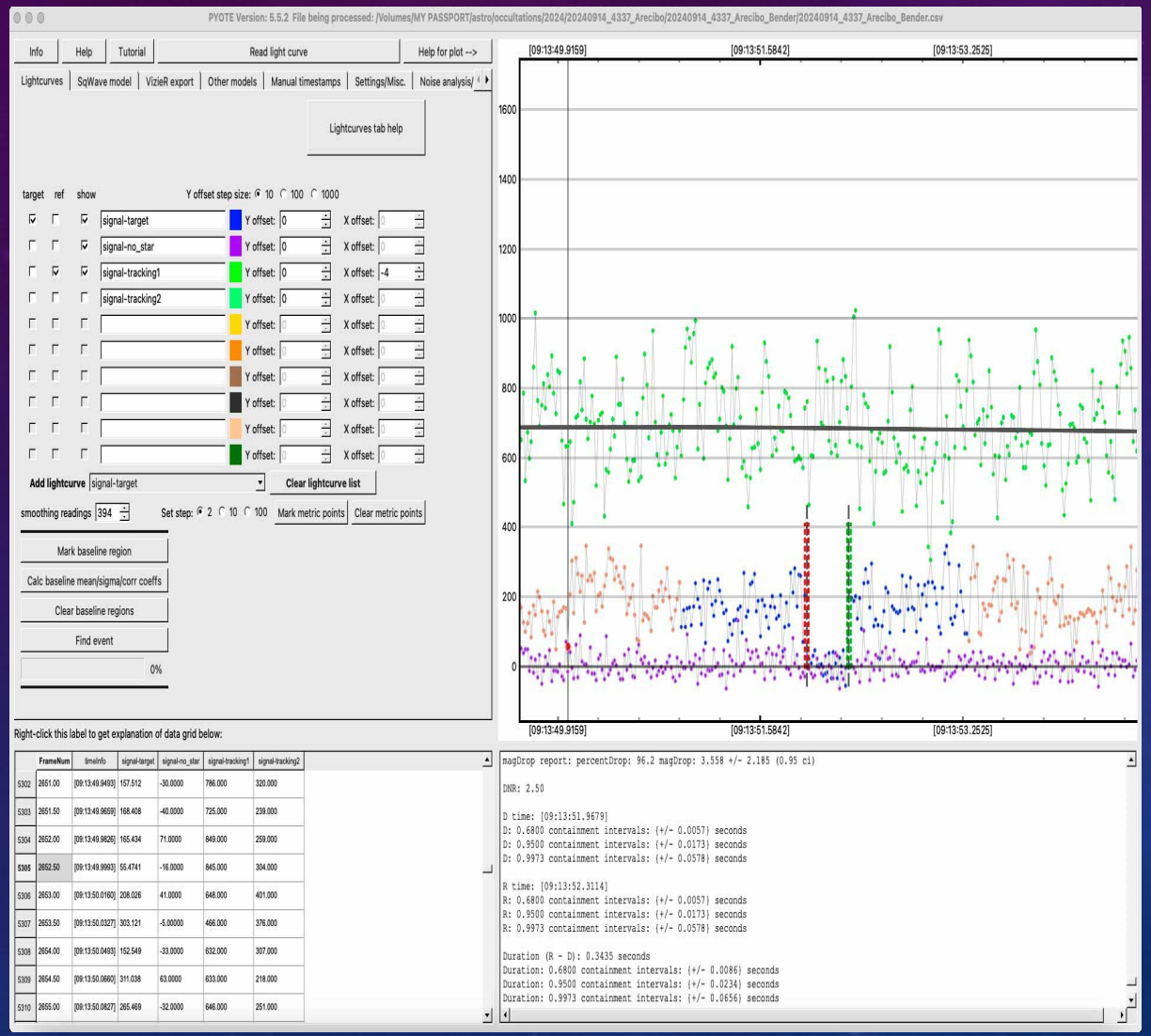
Me, at 2am, still in running shorts at 80F temperatures

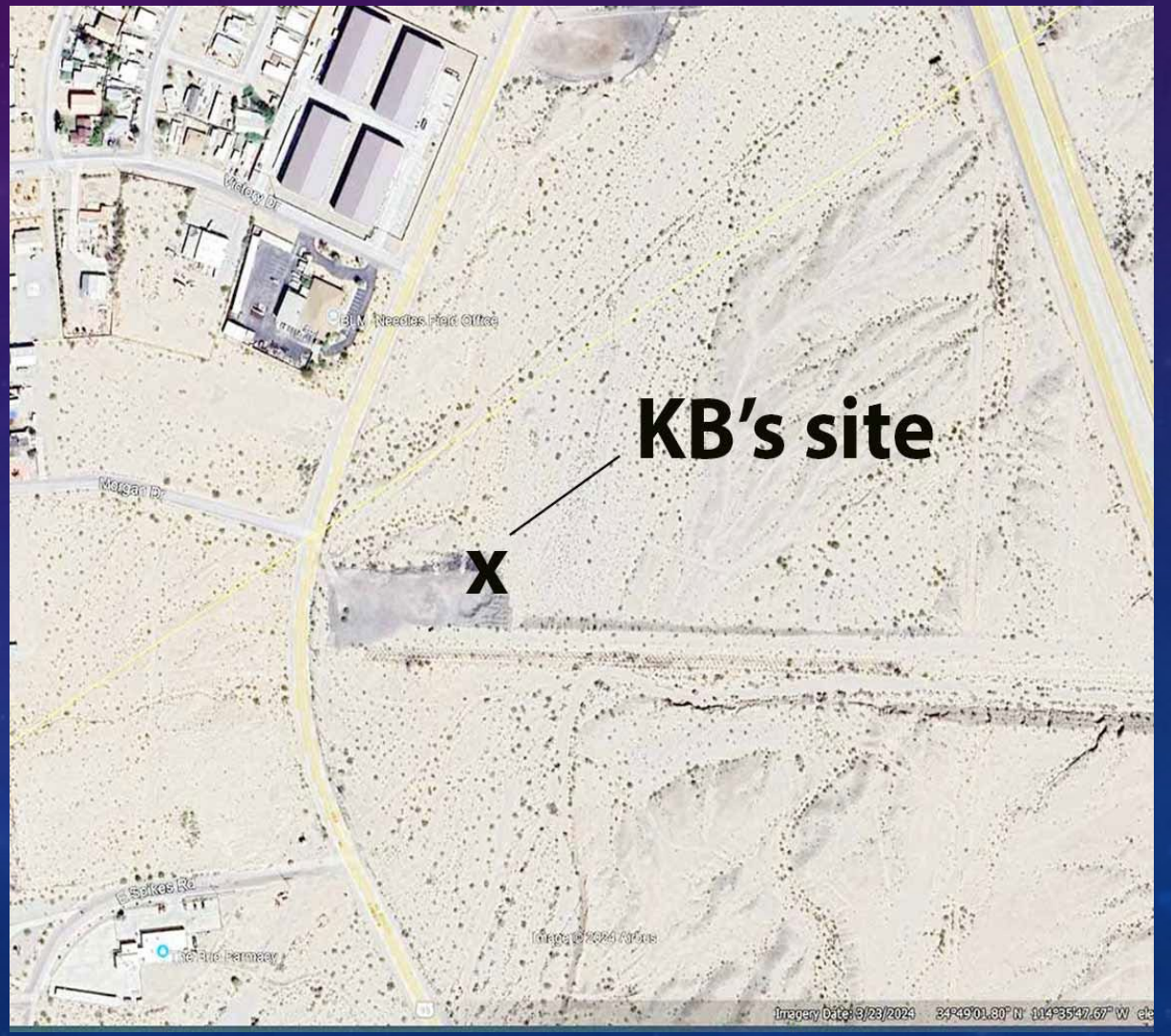


I saw a single occultation



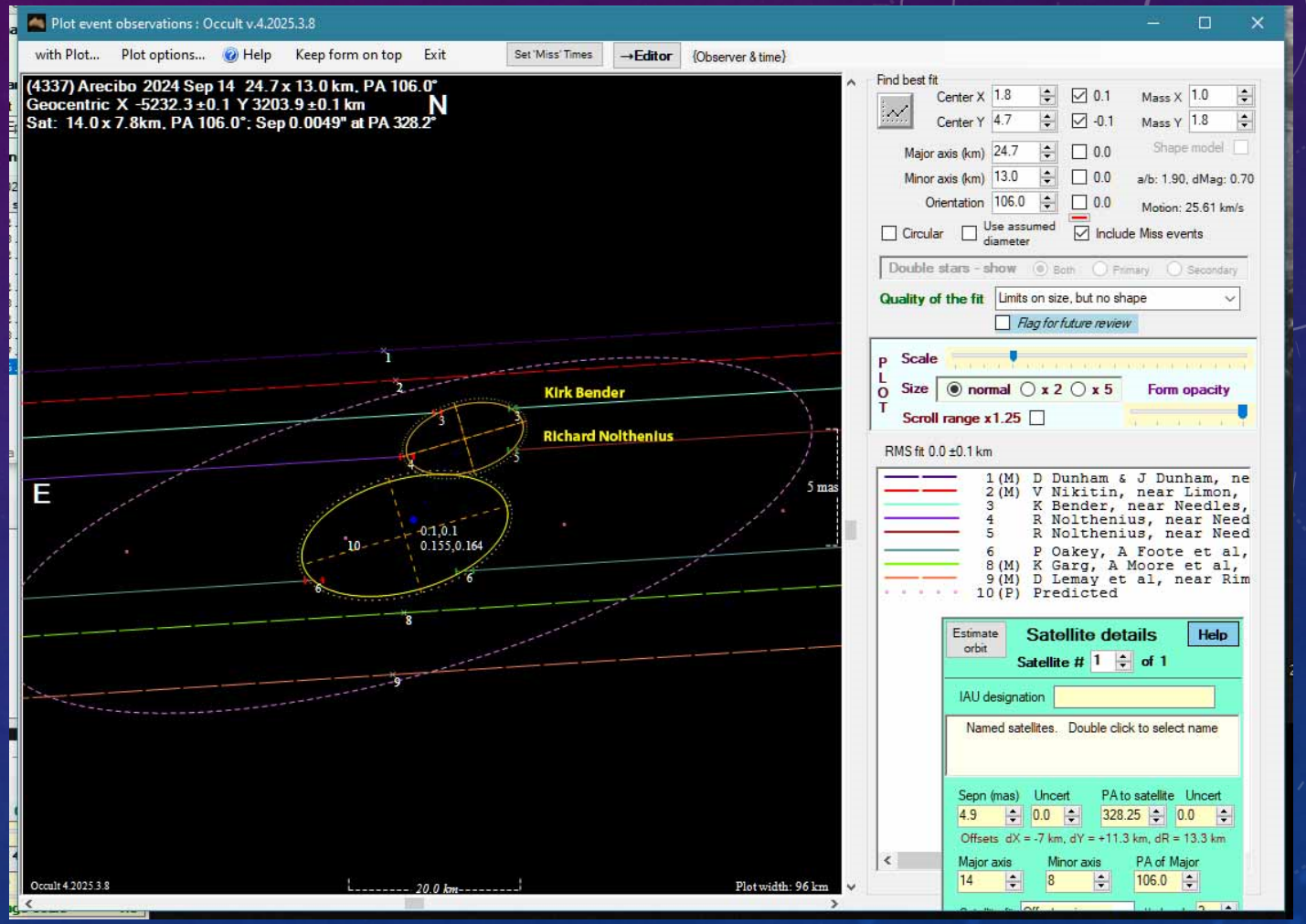
Kirk, too, had a single occultation





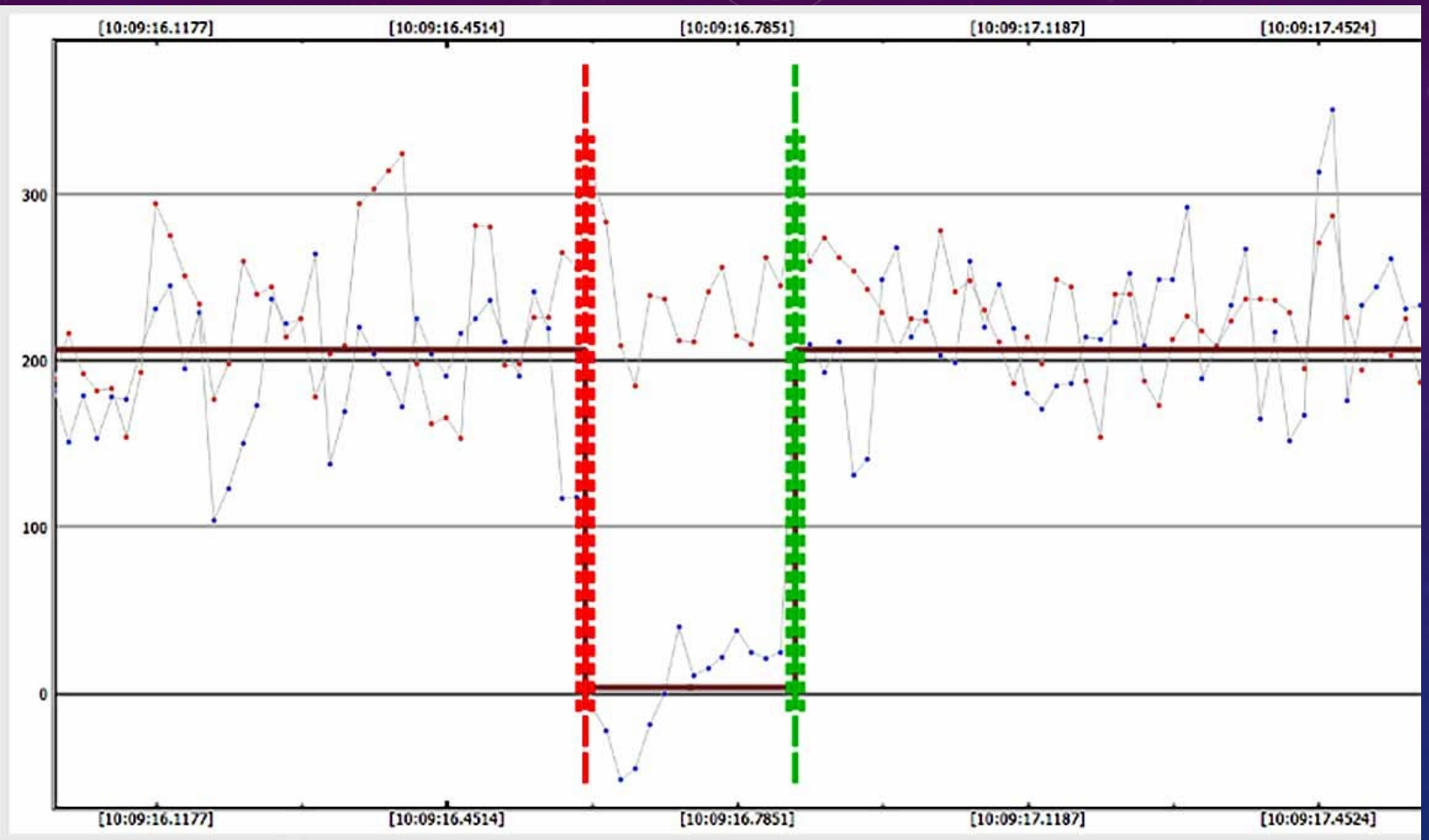
IOTA's Dave Herald and Dave Gault, using their OCCULT4 software, determined the best solution for these objects this night .

For Kirk and I, our events were all on the moonlet.



Next: Nov 12, 2022. The DART mission - NASA tested our asteroid deflection ability by impacting the Didymos / Dimorphos system. After a successful impact, high value per NASA, on getting precision astrometry of the new orbits; that means: <u>occultations</u>

- Didymos and Dimorphos are ~1 km or less! Required high precision timings and placement. An 11th magnitude occultation was predicted to cross SoCal and the Mojave Desert.
- I love the Mojave! Kirk was game. We packed the Cabrillo College van and headed out to Mojave National Preserve, to complement other IOTA occult'rs Robert Jones, Paul Maley, and Norm Carlson. 1,000 mile drive, but fun

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magDrop: 4.384 +/- 4.563 (0.95 ci)

snr: 4.74

D time: [10:09:16.6110]
D: 0.6800 containment intervals: (+/- 0.0033) seconds
D: 0.9500 containment intervals: (+/- 0.0078) seconds
D: 0.9973 containment intervals: (+/- 0.0156) seconds

R time: [10:09:16.8518]
R: 0.6800 containment intervals: (+/- 0.0033) seconds
R: 0.9500 containment intervals: (+/- 0.0078) seconds
R: 0.9973 containment intervals: (+/- 0.0156) seconds

Duration (R - D): 0.2408 seconds
Duration: 0.6800 containment intervals: (+/- 0.0048) seconds
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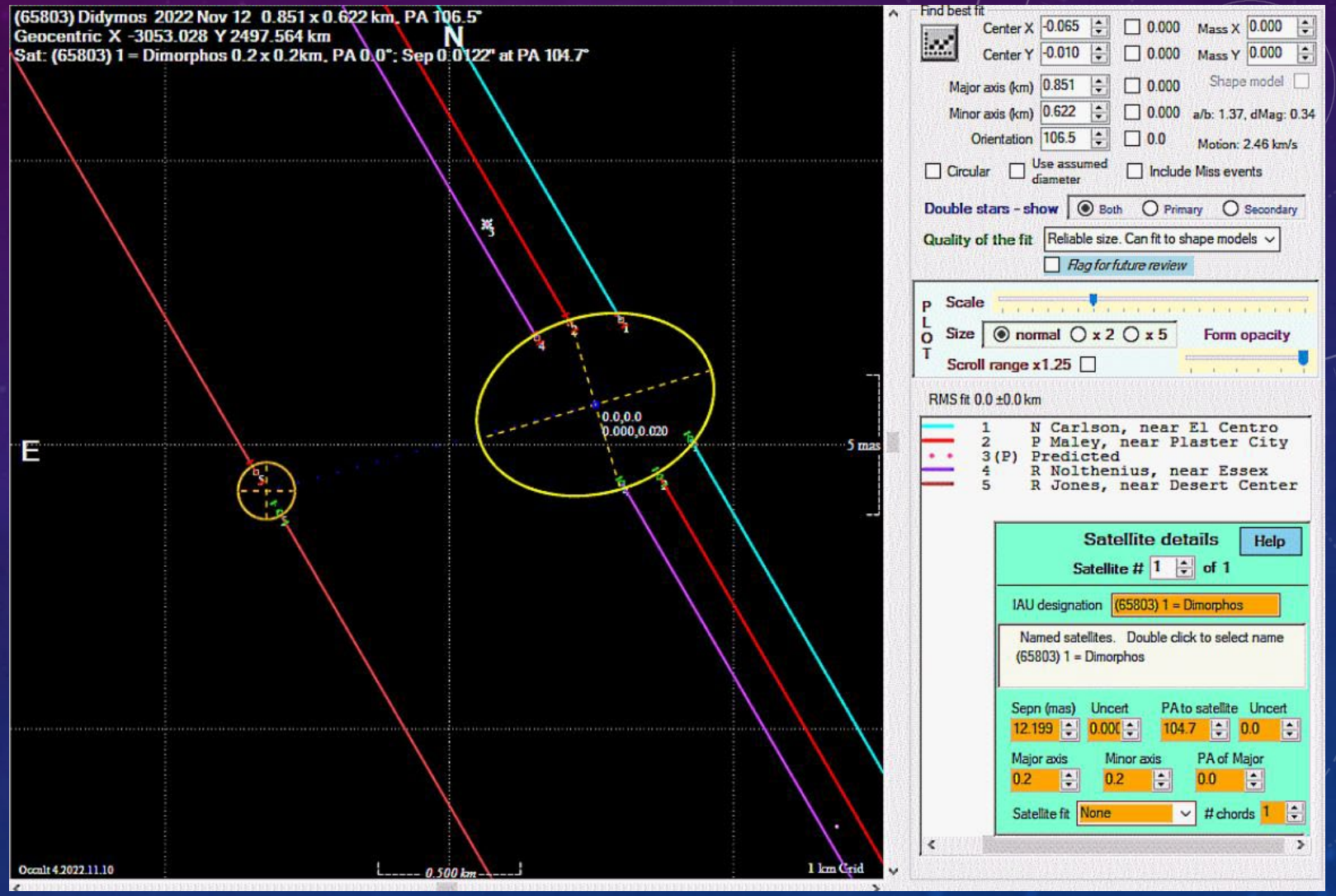
A rock-solid event, at 60 fields per second cadence.

My 0.24 second occultation, with reference star light curve

Together, our team got the first high-precision simultaneous astrometry of the post-DART positions of both primary and moon.

We celebrated with a day of desert photography and explorations.



Afterwards; well earned sleep, and then breakfast of eggs and cowboy toast at our quiet desert campsite – my observing site.

Then, to Mitchell Caverns in the Mojave National Preserve, for photography

Asteroid (4337) Arecibo: Two ice-rich bodies forming a binary

Based on *Gaia* astrometric data

Ziyu Liu[1,*], Daniel Hestroffer[1,*], Josselin Desmars[2,1] and Pedro David[1]

Received: 2 May 2024 | **Accepted:** 18 July 2024

Abstract

Context. Binary asteroids are present in all populations of the Solar System, from near-Earth to trans-Neptunian regions. As is true for the small Solar System bodies (SSSBs), binary asteroids generally offer valuable insights into the formation of the Solar System, as well as its collisions and dynamic evolution. In particular, the binaries provide fundamental quantities and properties of these SSSBs, such as mass, angular momentum, and density, all of which are often hidden. The direct measurement of densities and porosities is of great value in revealing the gravitational aggregates and icy bodies that form the asteroid-comet continuum.

Aims. Several observation techniques from space and ground-based platforms have provided many results in this regard. Here we show the value of the *Gaia* mission and its high-precision astrometry for analysing asteroid binaries and for individually deriving the masses of the components.

Methods. We focus on the binary asteroid (4337) Arecibo, a member of the Themis family. We analysed the astrometry obtained in the *Gaia* FPR catalogue release, and performed orbital fitting for both the heliocentric orbit of the system and the relative orbit of the binary components.

Results. We obtain an estimation of the component masses and their flux ratio, and derive bulk densities $\rho_1 \approx 1.2$ and $\rho_2 \approx 1.6$ for the primary and the secondary, respectively. The results are consistent with an ice-rich body in the outer main belt. They also show a significantly denser secondary or a less closely packed primary. Constraints on these densities and on macroscopic porosities are nevertheless limited by our poor knowledge of the sizes of the components. Observations of future mutual events, and of stellar occultations predicted in 2024–2025, will be essential for improving our knowledge of this system and its formation.

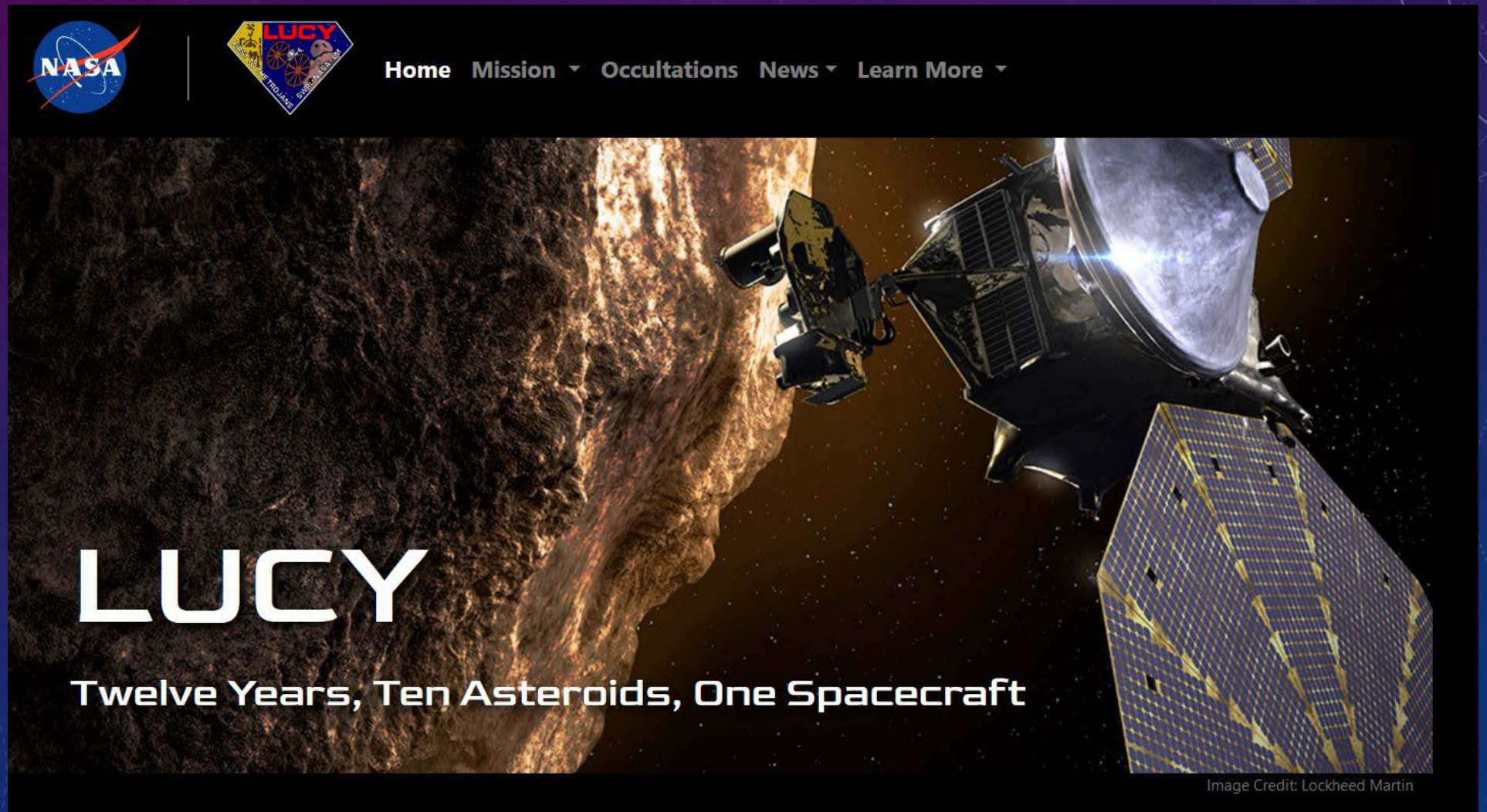
Key words: methods: data analysis / astrometry / minor planets / asteroids: individual: (4337) Arecibo

* Corresponding authors; ziyu.liu@obspm.fr; daniel.hestroffer@obspm.fr.

Liu *et. al.* published a paper in Astronomy and Astrophysics in 2024, on the new binary asteroid Arecibo;

They determined the density of primary and secondary to be 1.6 g/cc and 1.2 g/cc. Hmmm; Different! Interesting!

NEXT, OCT 20, 2021: EURYBATES - The main target of the LUCY Mission – our first spacecraft visit now on its way to the Trojan Asteroids orbiting at the Lagrange Points in Jupiter's orbit



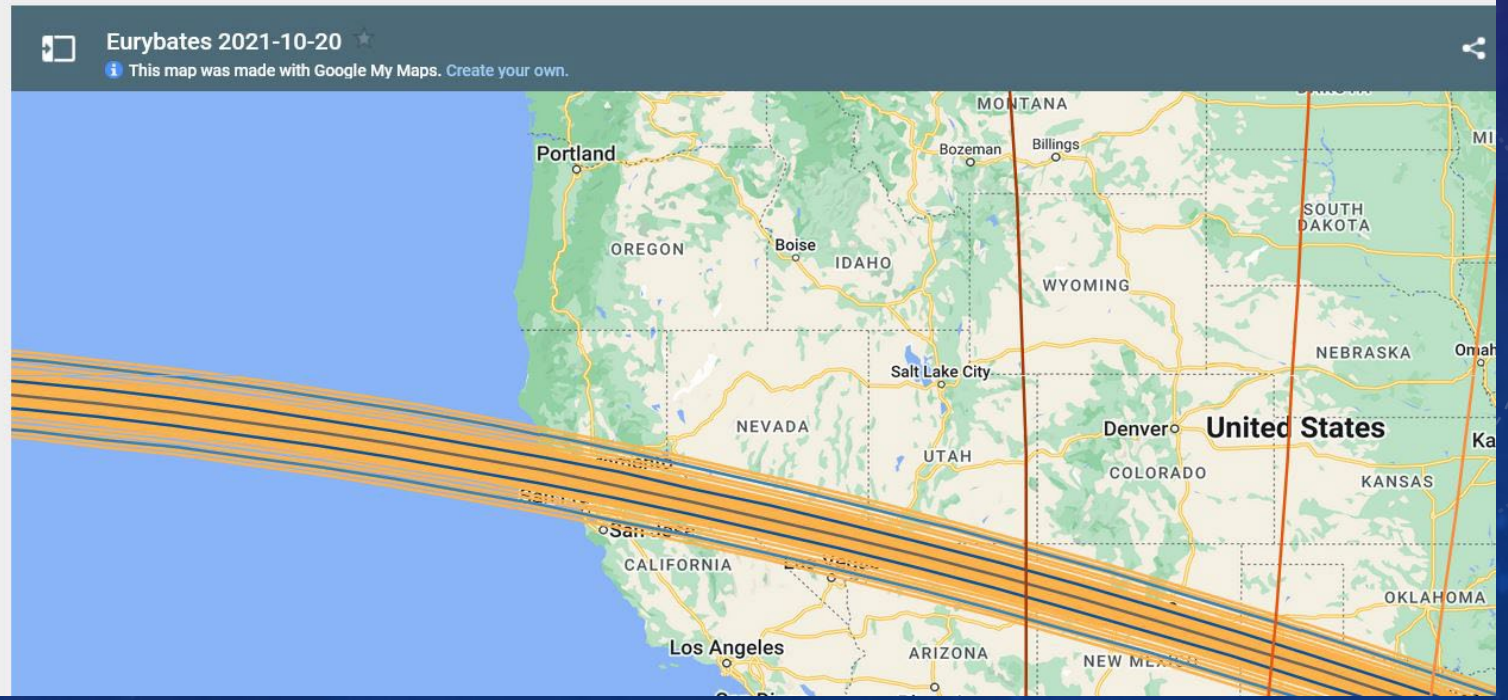
A very high value target, on Oct 20, 2021

- A 13.5 magnitude star in Taurus, shadow path predicted to cross California's Eastern Sierra.
- Tough conditions: Storm system would cloud out everything west of the Sierra, and low altitude and dawn would worsen things farther east.

Eurybates Occultation 2021-10-20 (G* = 12.3)

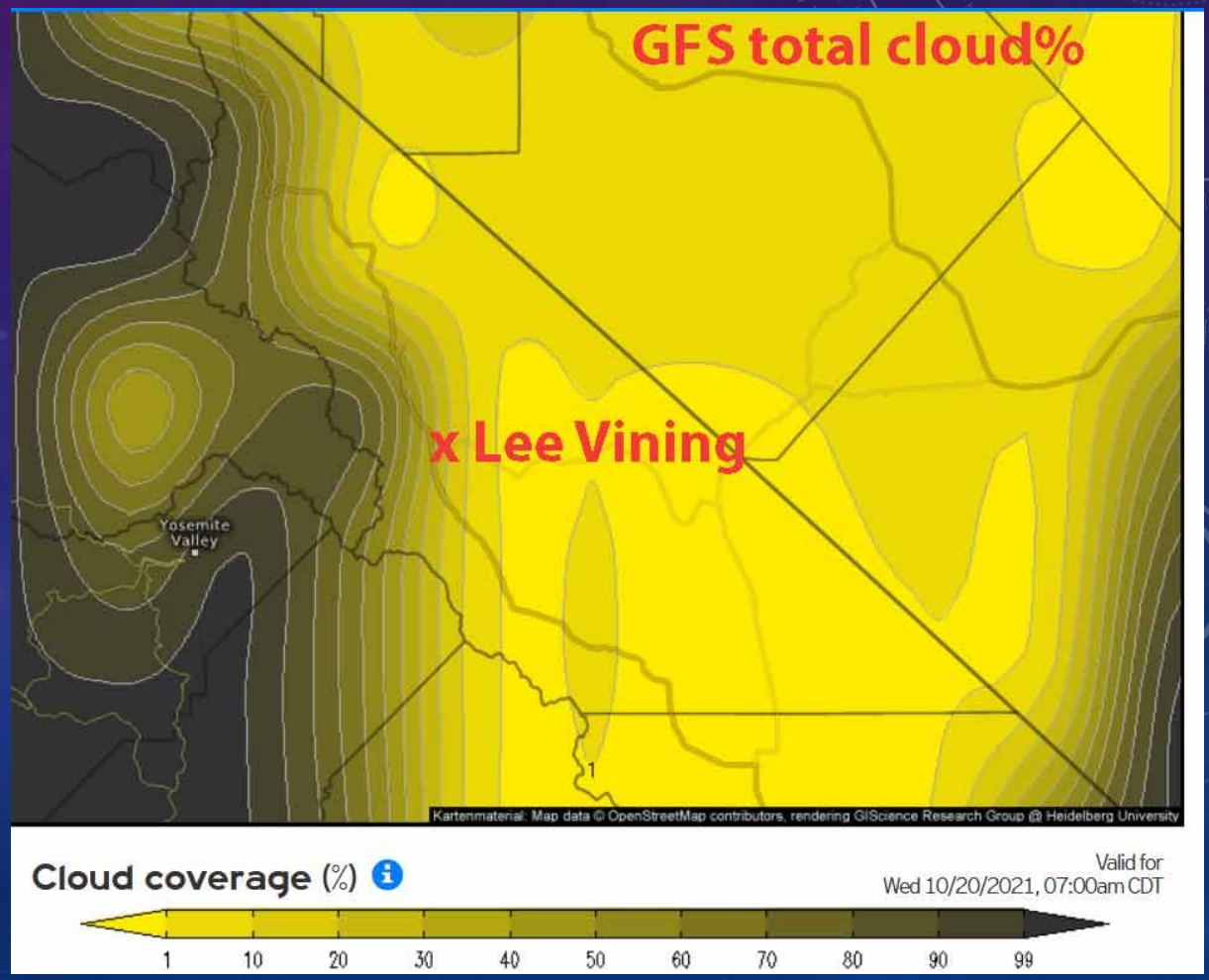
The interactive map below shows our current prediction for the stellar occultation by (3548) Eurybates on 2021 October 20 UT. The predicti
on a Gaia EDR3 position for the star, corrected for parallax and proper motion, and the v20210129201159 orbit estimate for Eurybates, w
1-sigma cross-track uncertainty of 17.7 km.

Geocentric mid-time of the event is 12:03:54 UT. Star position is RA 03:56:45.3, Dec +22:24:10 (J2000), and its magnitude is 13.48. Eurybates is
11 km/s with respect to the star and its diameter is estimated to be 66 km, so central chords are expected to last 6.0 seconds. Eurybates' m
predicted to be 16.5 at event time, so it will be 16 times fainter than the star.

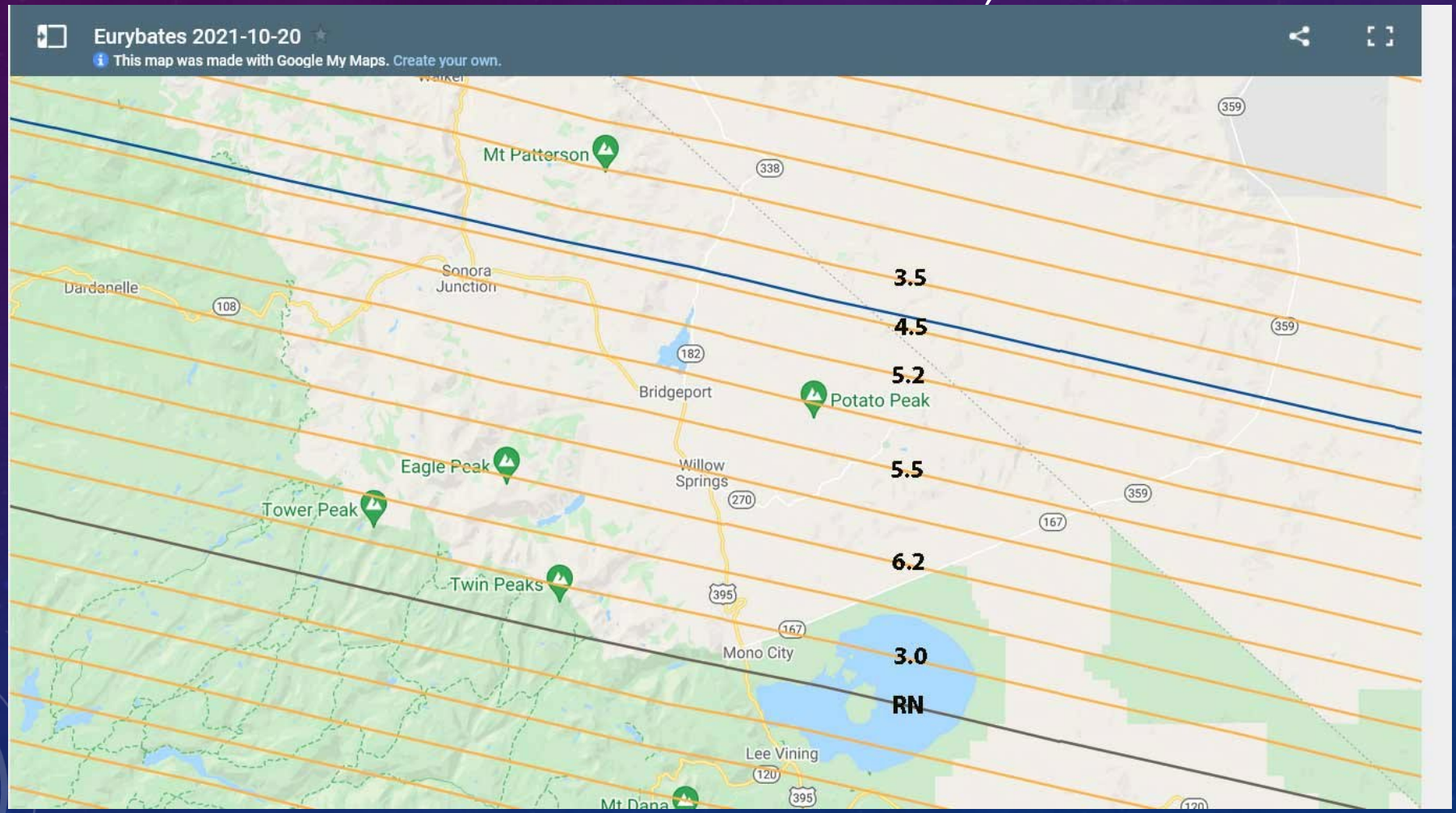


WEATHER WAS A CHALLENGE! FIRST STORM OF THE SEASON, WEST OF THE SIERRAS

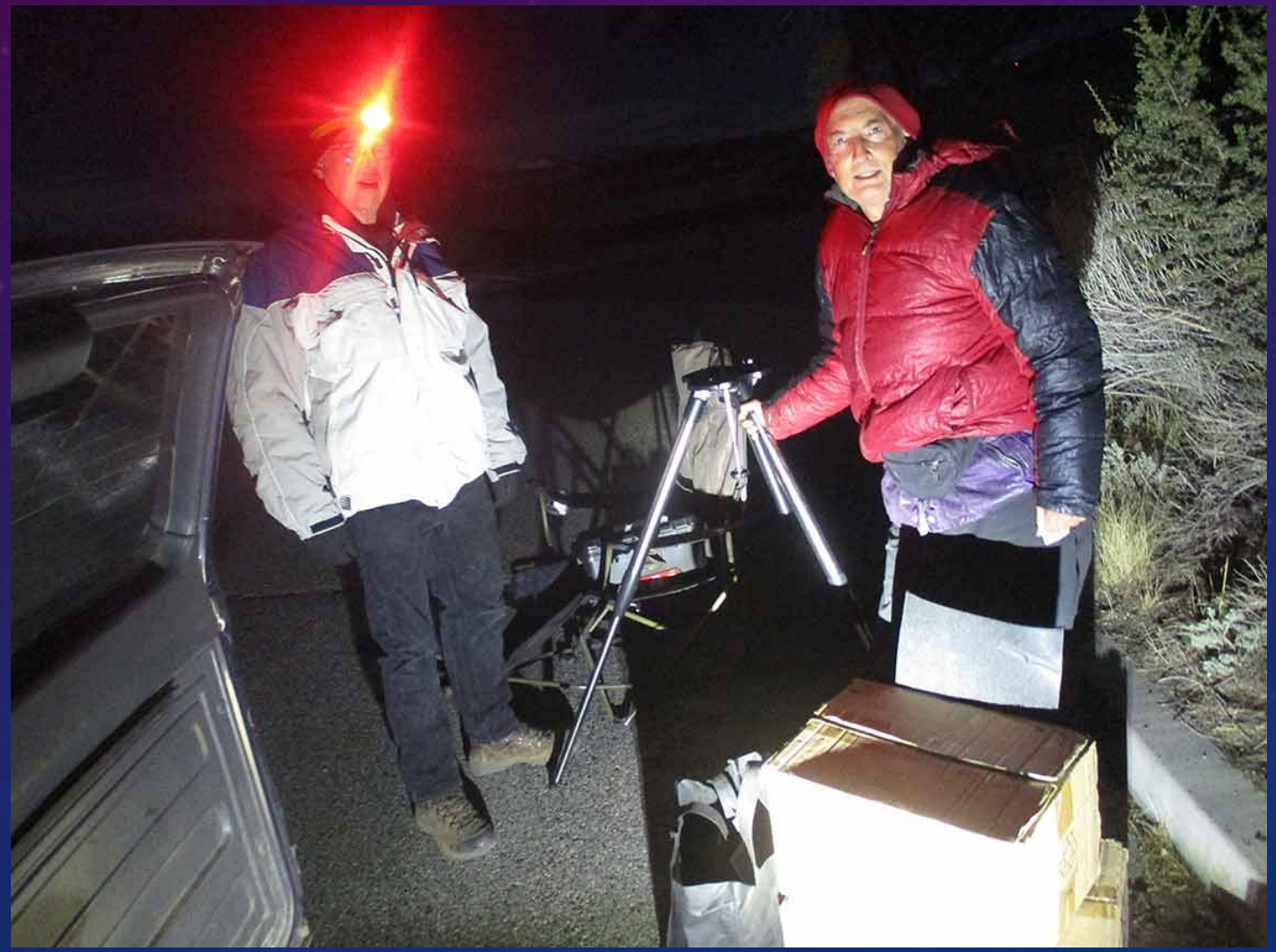
- Much nail-biting, commandeer my Astro 8A class time? Watching latest cloud forecasts come in on Cabrillo College office computer… before I threw caution to winds, called Kirk Bender, told him to meet me at my place, and I'd drive us in my RAV4 to Mono Lake to get clear of the clouds (we hoped).
- Astro Adventure!



SwRI - The Southwest Research Institute, was organizer for this campaign. Regularly spaced tracks were assigned to the "RECON" equipped observers, and Kirk and I ("RN") were to cover what we could. I set Kirk at the Mono Lake Visitor Center, on the track south of mine.



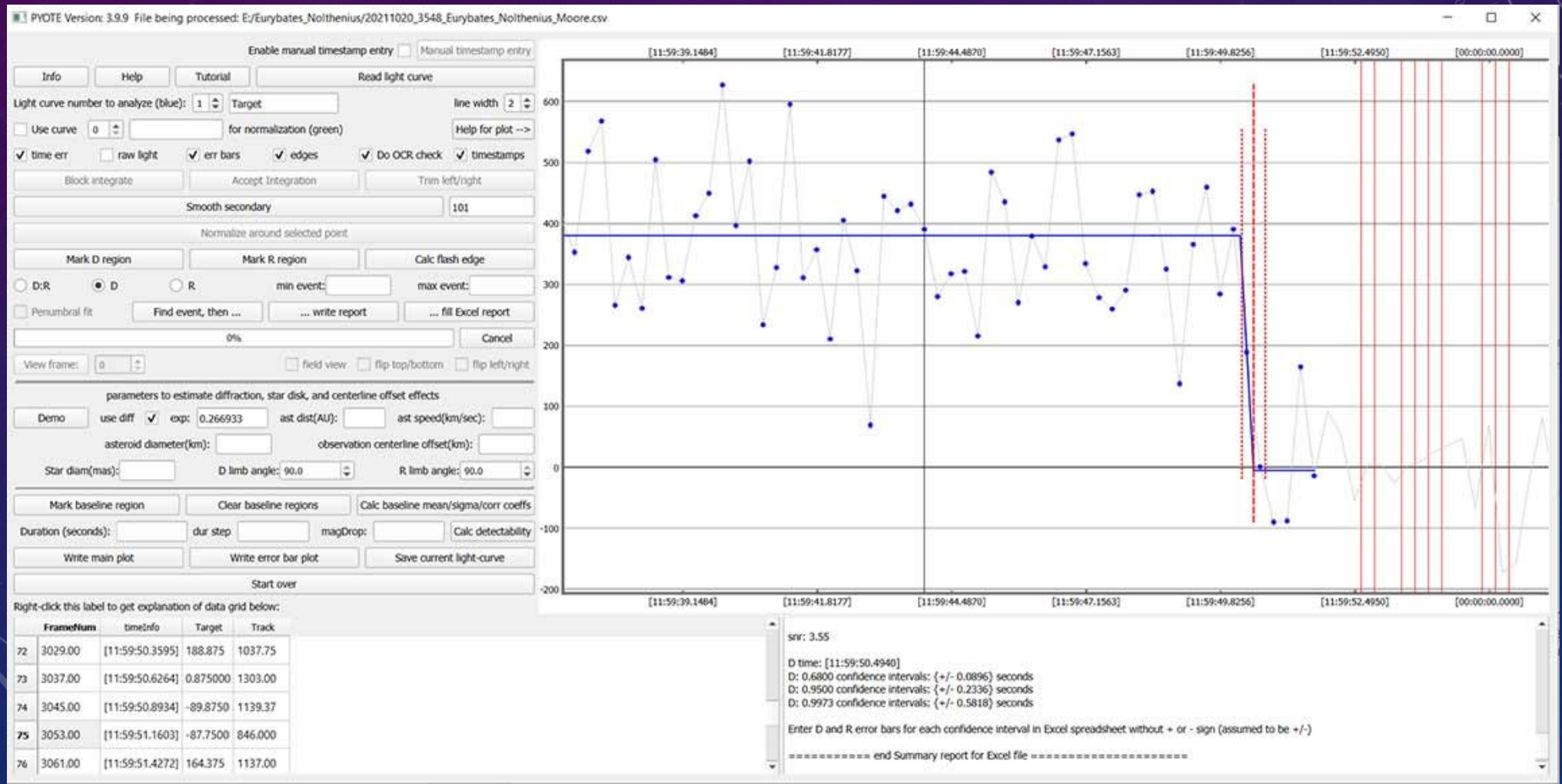
Tioga Pass conquered, we descended to Lee Vining, scouting a site for Kirk. Here I'm helping set up Kirk Bender at the Mono Lake Visitor Center, at 2 am.



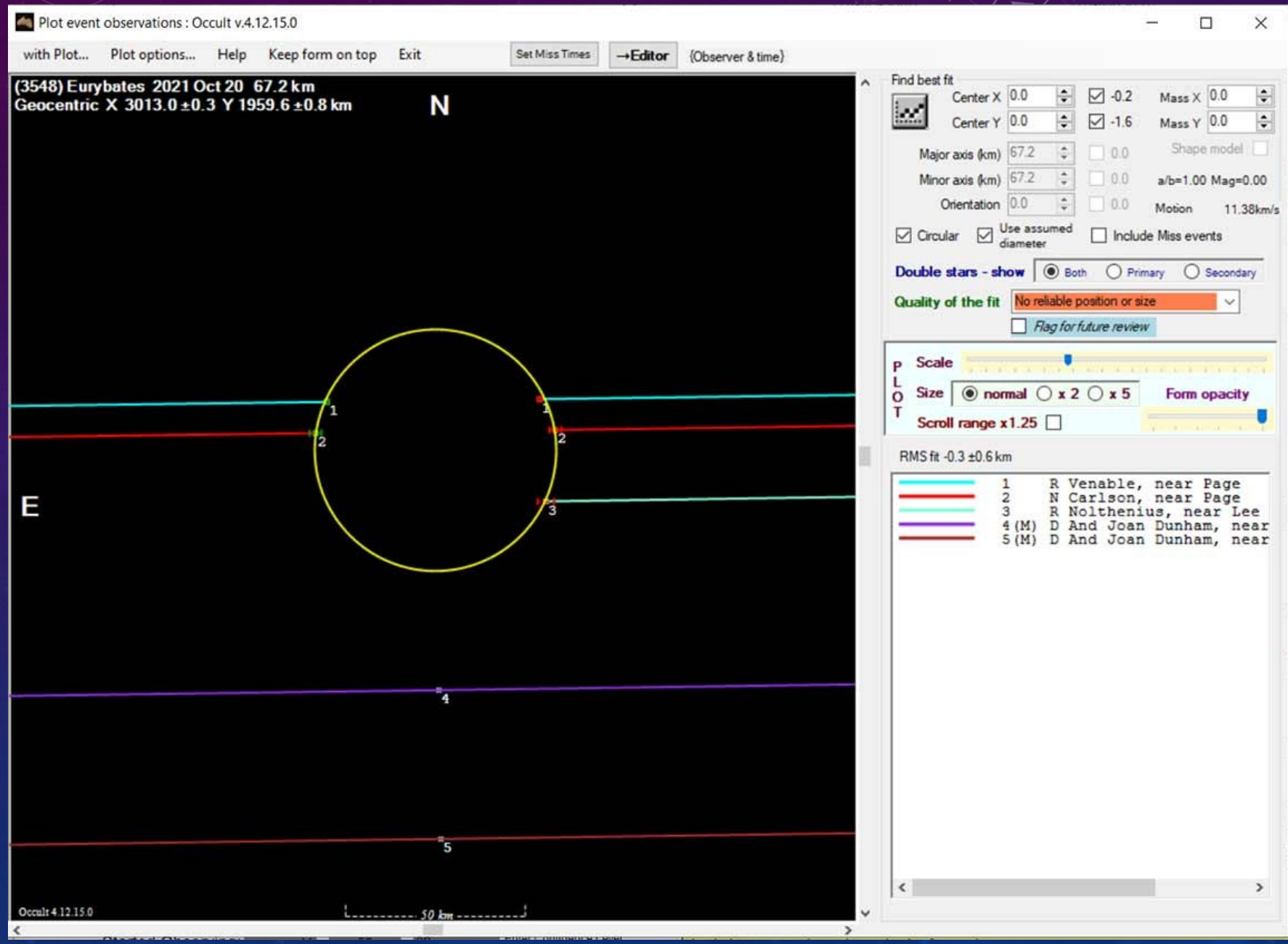
My site, on the central track, at a cemetery dating back to the Old West (I hope it’s not a sign).

Fast-moving clouds made prospects dicey. Would we get data?

MY EURYBATES DATA. Eurybates and a big cloud, raced each other to see who would cover the target star first. Fortunately – Eurybates won, by a nose! (<1 second!)



CLOUDS FOILED MOST, OBSERVERS, ALAS. But a few did get the valuable data needed to pinpoint the orbit of Eurybates and first indications of its shape. My “D” was the only data for IOTA which was south of the center of the star, crucial for accurate centroid astrometry

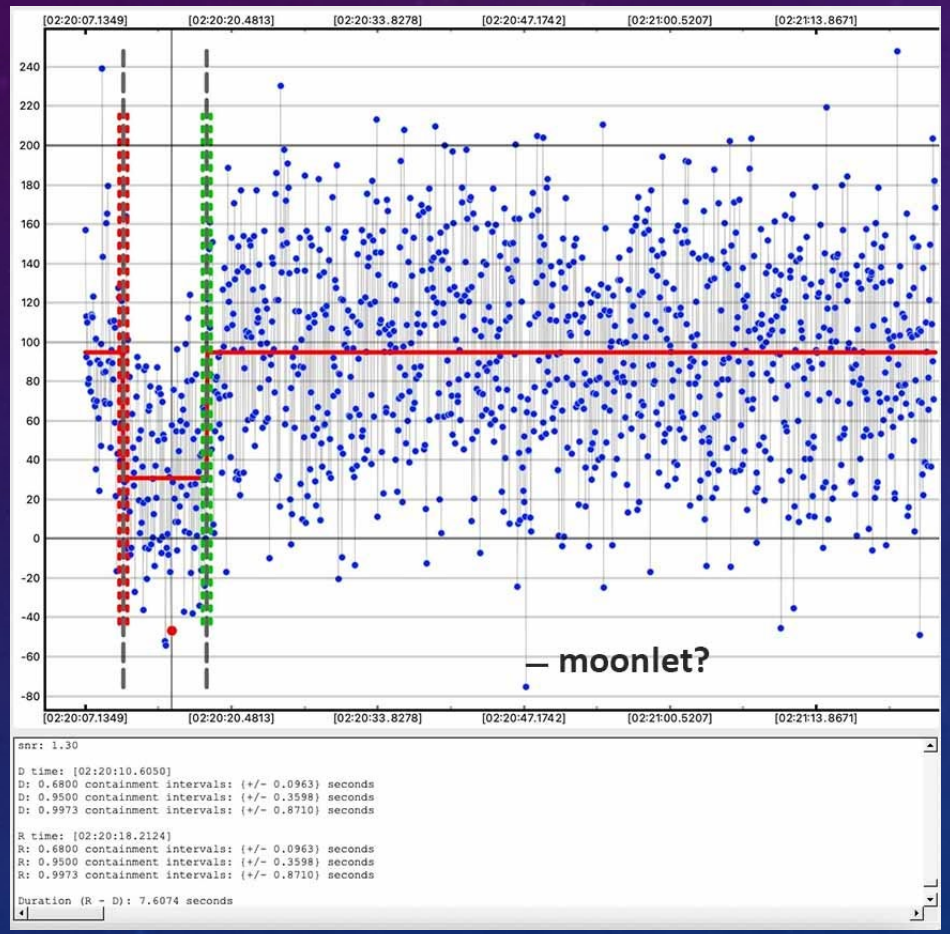


Kirk was clouded out, but we celebrated our team success with some Fall aspen photography, and a beer at a June Lake pub down the road, as we texted the other team members.

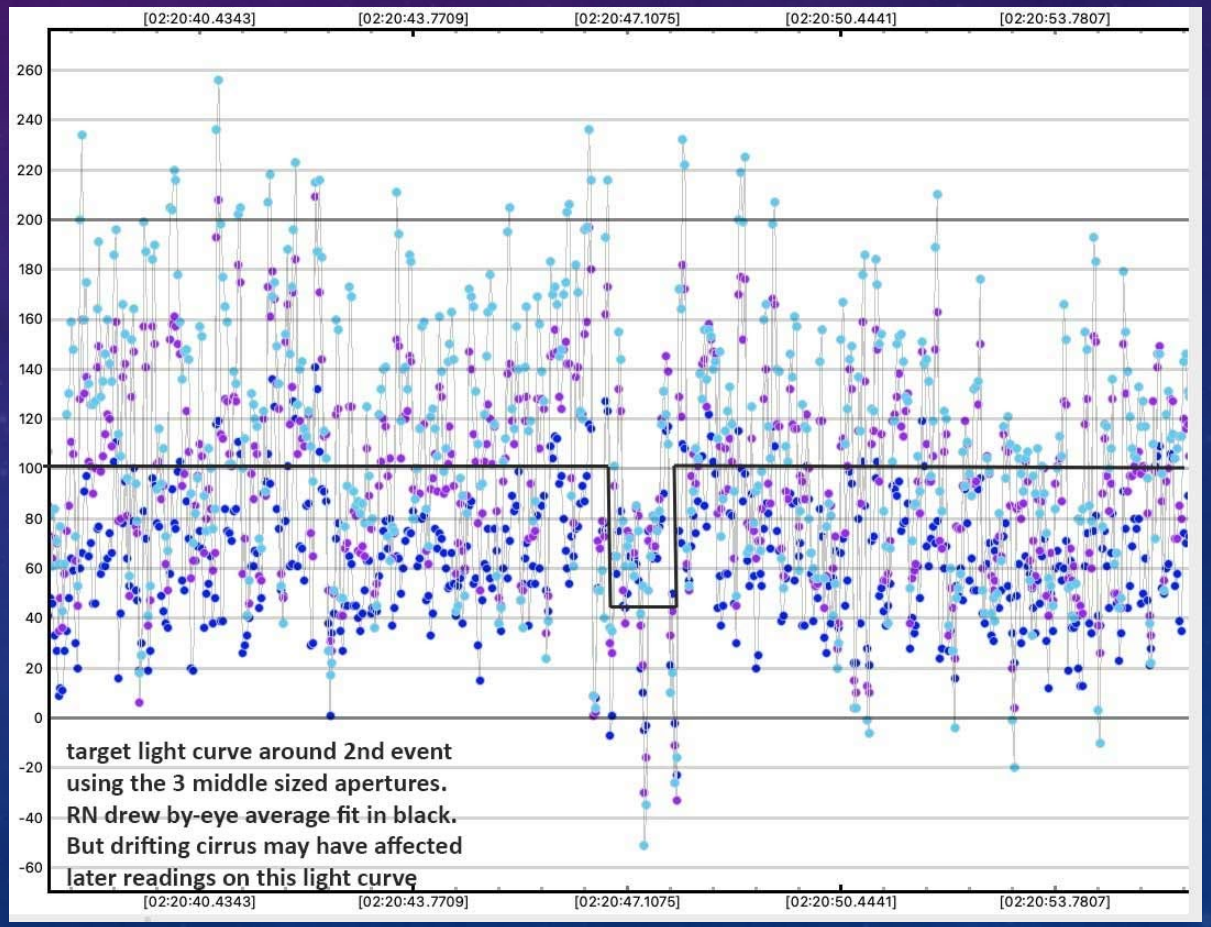
Getting home was more dicey; new snow over Tioga Pass. But, we lived to tell the adventure!

More: Kirk Bender recorded a secondary event during the 1/26/23 occultation by (906) Repsolda. Unconfirmed as yet – but we're on the lookout for more occ's by this asteroid.

The primary occultation



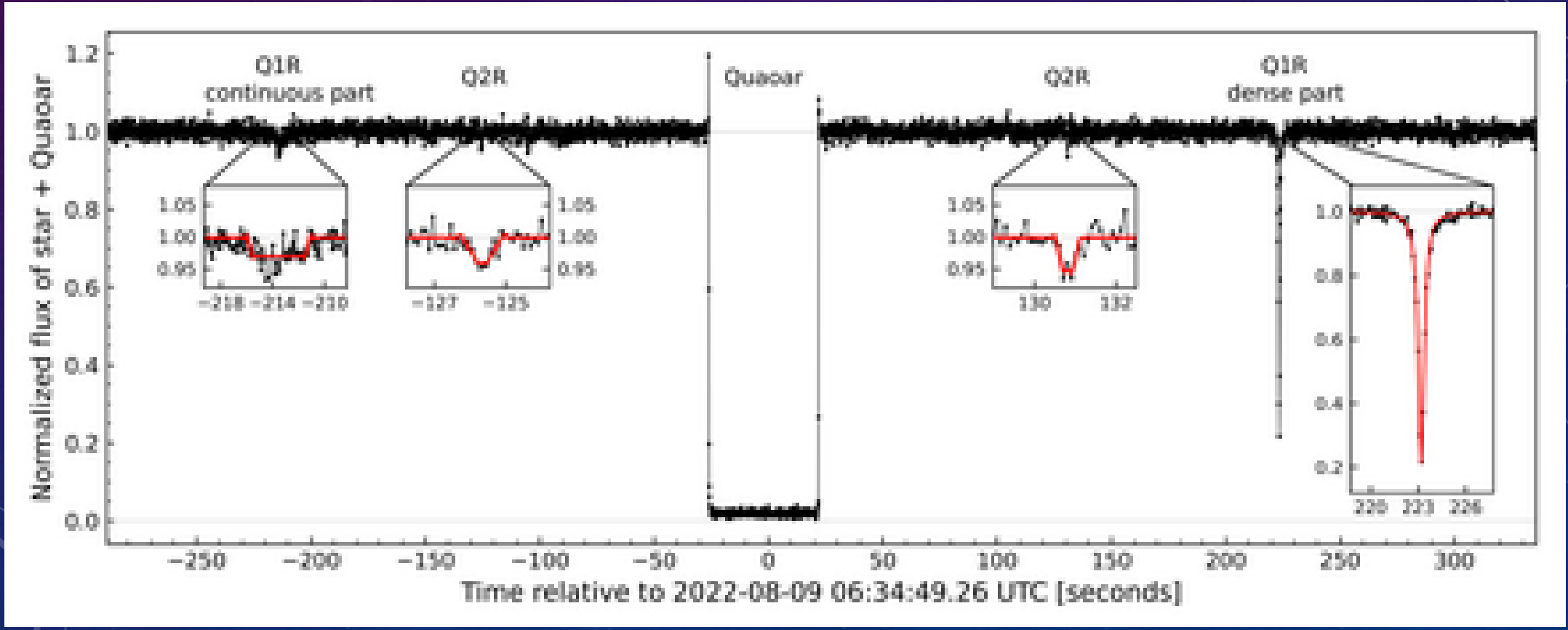
Secondary event: New moonlet?



NEXT: THE FIRST KBO DISCOVERED SINCE PLUTO: QUAOAR

- Through occultations, is now discovered to have two rings around it. And amazingly, both rings are beyond the Roche Limit, the only such known.
- So how did they form?
- How can they be stable, or are they perhaps extremely young and not stable?
- What is their structure? Are they azimuthally uniform in density? Or patchy, like Neptune's rings?
- Quaoar is going through the Scutum Star Cloud now, offering more occultation opportunities…

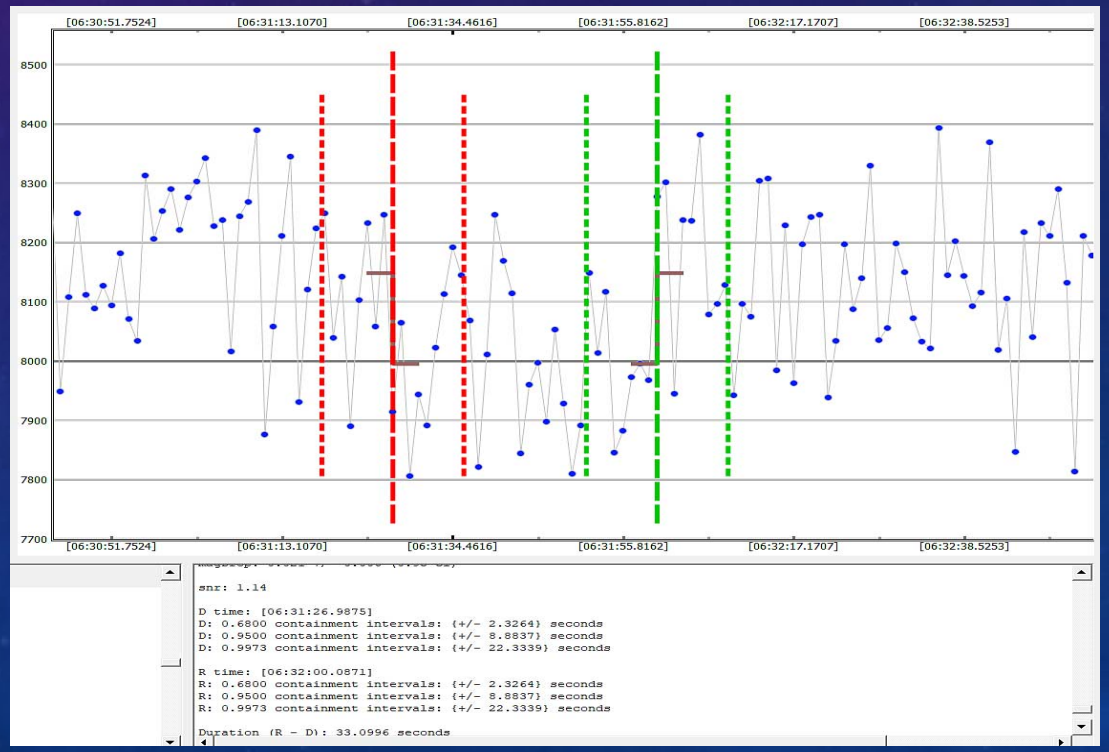
First: the Aug 8, 2022 Event. The CFHT big scope on Mauna Kea discovered the 2nd ring, and the first ring was the denser. Discovery by occultation! Ring?? When you get two occultations on opposite sides of the main body, at perfectly the same space distance from that body, odds are 99.999% you're looking at a ring, not *e.g.* two moons. Note asymmetry!



Insanely difficult on paper: V=15.2 star, only 12 degrees above a gibbous moon in Sagittarius. Could our Cabrillo heroes Rick and Kirk have any hope of success using only 8” Celestrons??

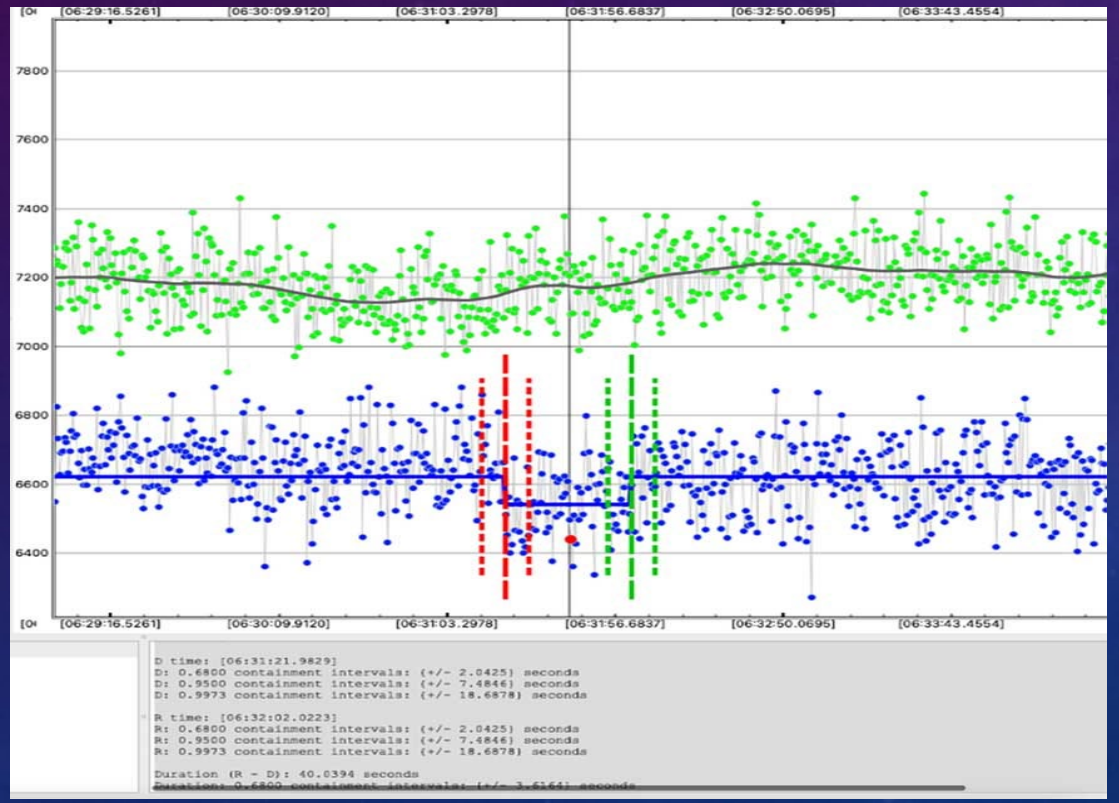
Kirk and I set up separate sites in Bonny Doon

Noisy for sure, but PyOTE dug out timings which beautifully fit with those of bigger scopes in CA and Hawaii. No rings, but helped show ellipsoidal shape of Quaoar.

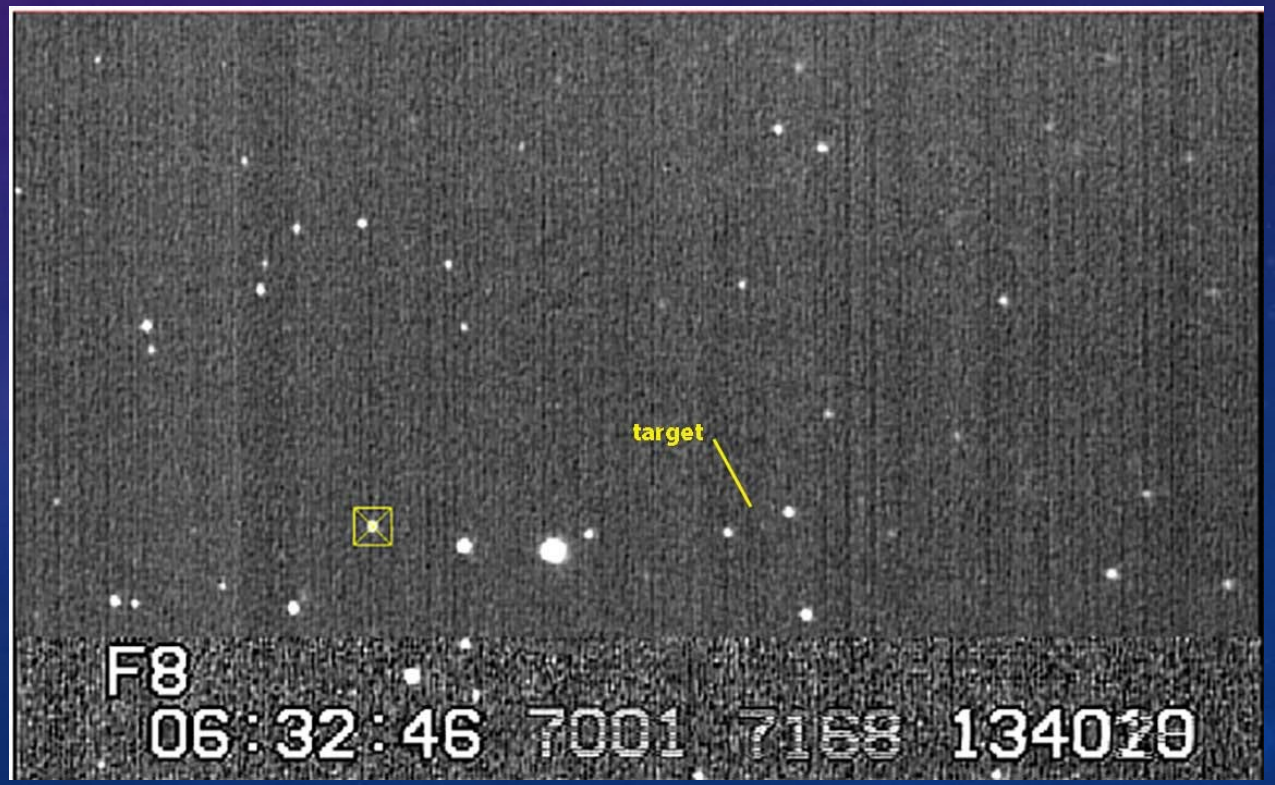


We used in-camera integration of 32 fields per readout, and removed the f/3.3 reducer to lower sky brightness. Can also adjust the camera gain to help with very faint targets. Finally, I did not do sky subtraction, in order to remove uncorrelated subtraction noise too. The result did just “clear the bar” in the S/N reality of the event. This is by far the toughest event I’ve ever tried.

Kirk’s data a bit better than mine, as usual. Timings were consistent.

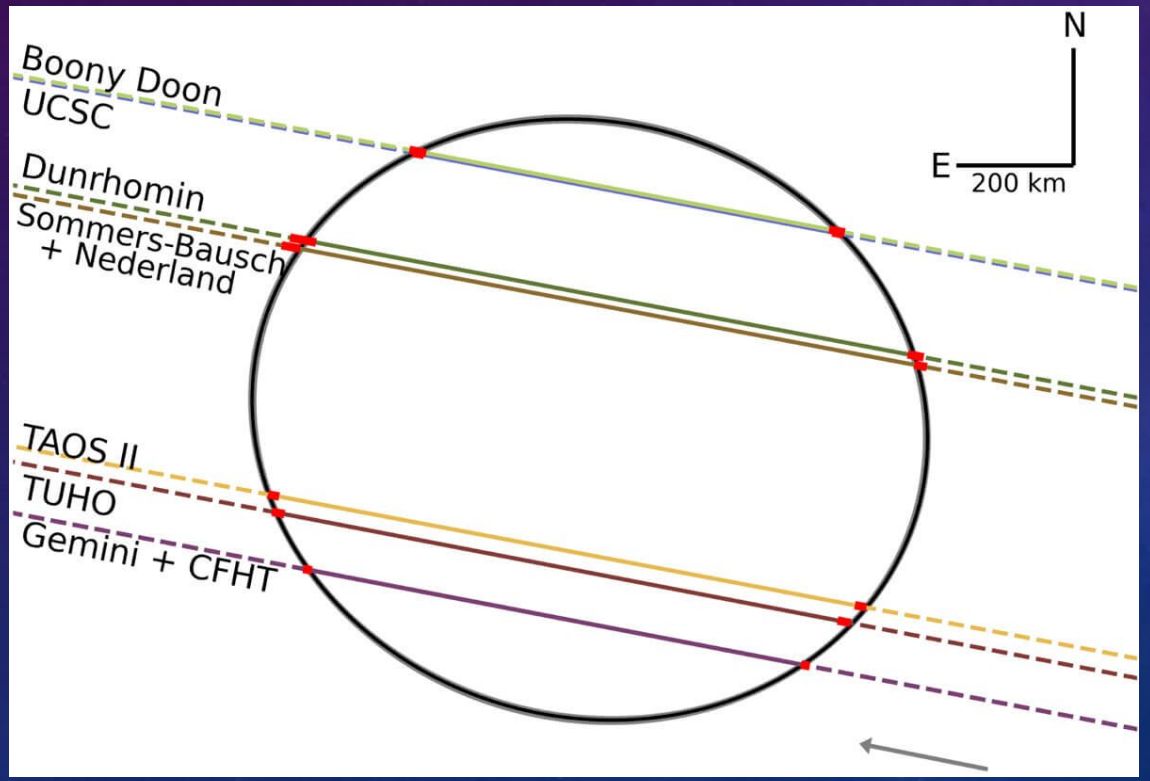


PyMovie “finder” stack of frames, allows better positioning of your tight aperture masks to improve S/N. Target still just barely above “sky”.

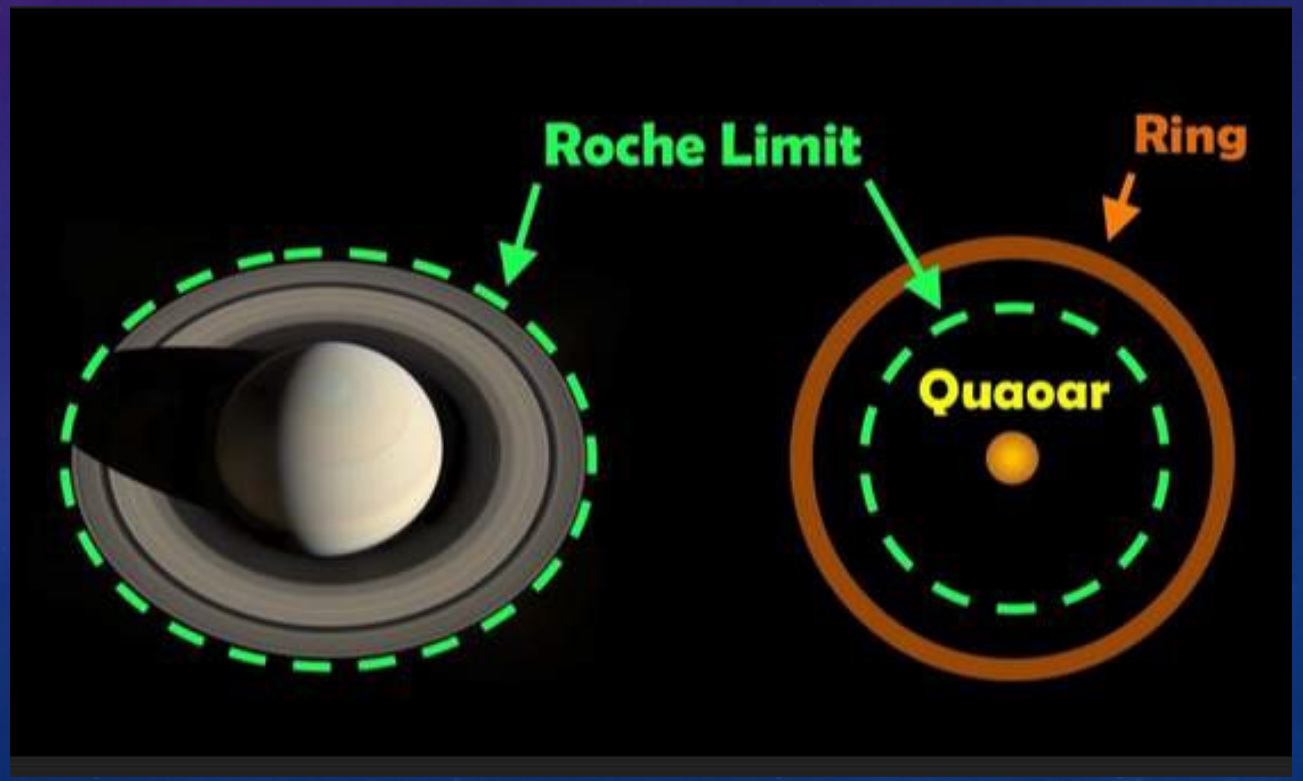


Kirk and I are now co-authors on a paper describing the advances in our knowledge of Quaoar from this event. So, excitement high for the next Quaoar event a year later…

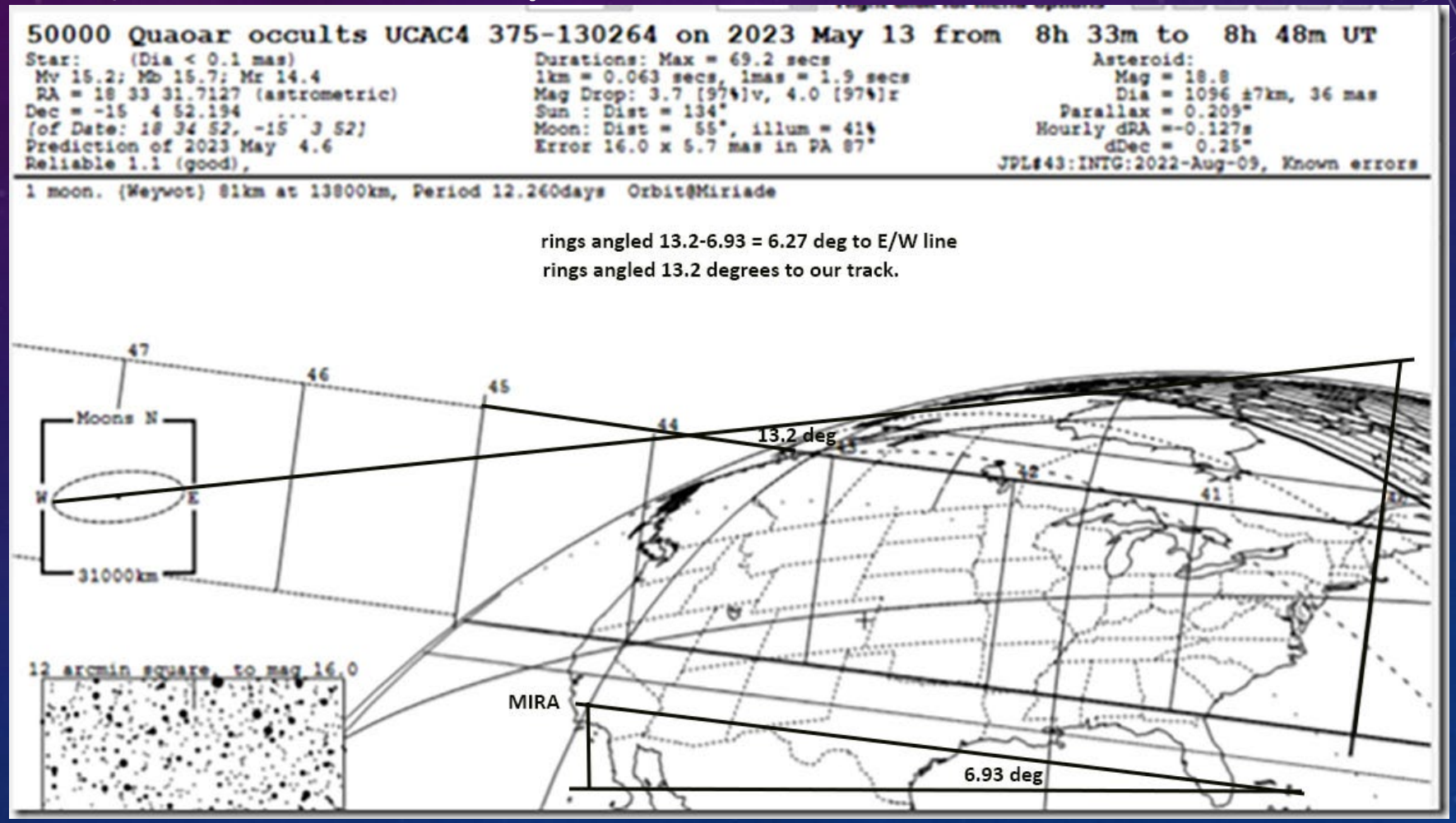
Our timings + Gemini/CFHT, defined e for Quaoar



The rings; now an intense subject of head-scratching study. Stable rings beyond the Roche Limit???

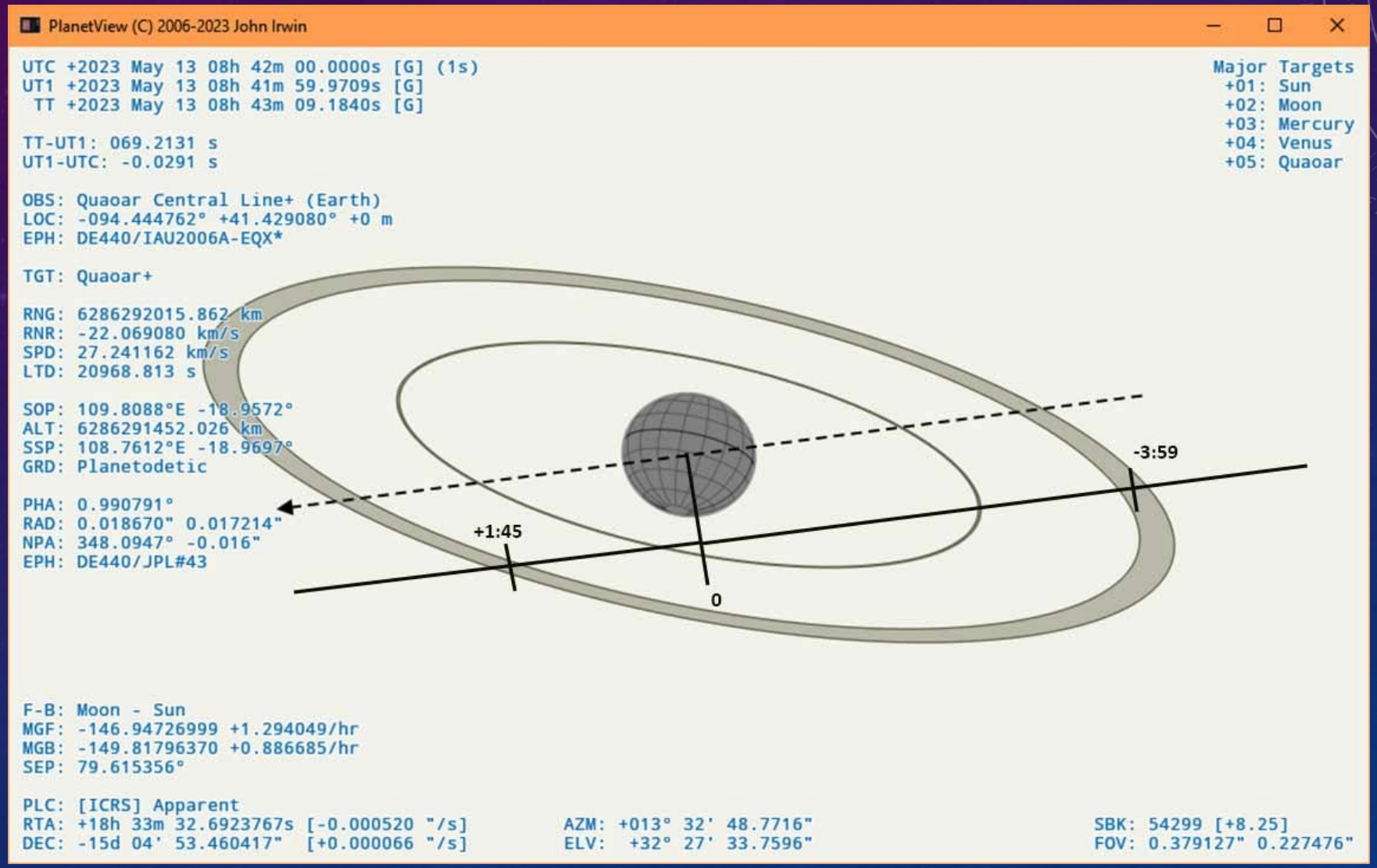


May 13 ‘23, Quaoar occulted a 15.2 mag star. While the main body misses here, Quaoar’s rings would cover the star. But! ***“We need more power, Scotty!”.*** I called up the Monterey Institute for Research in Astronomy: **MIRA, who operates a 36” reflector on Chews Ridge.**

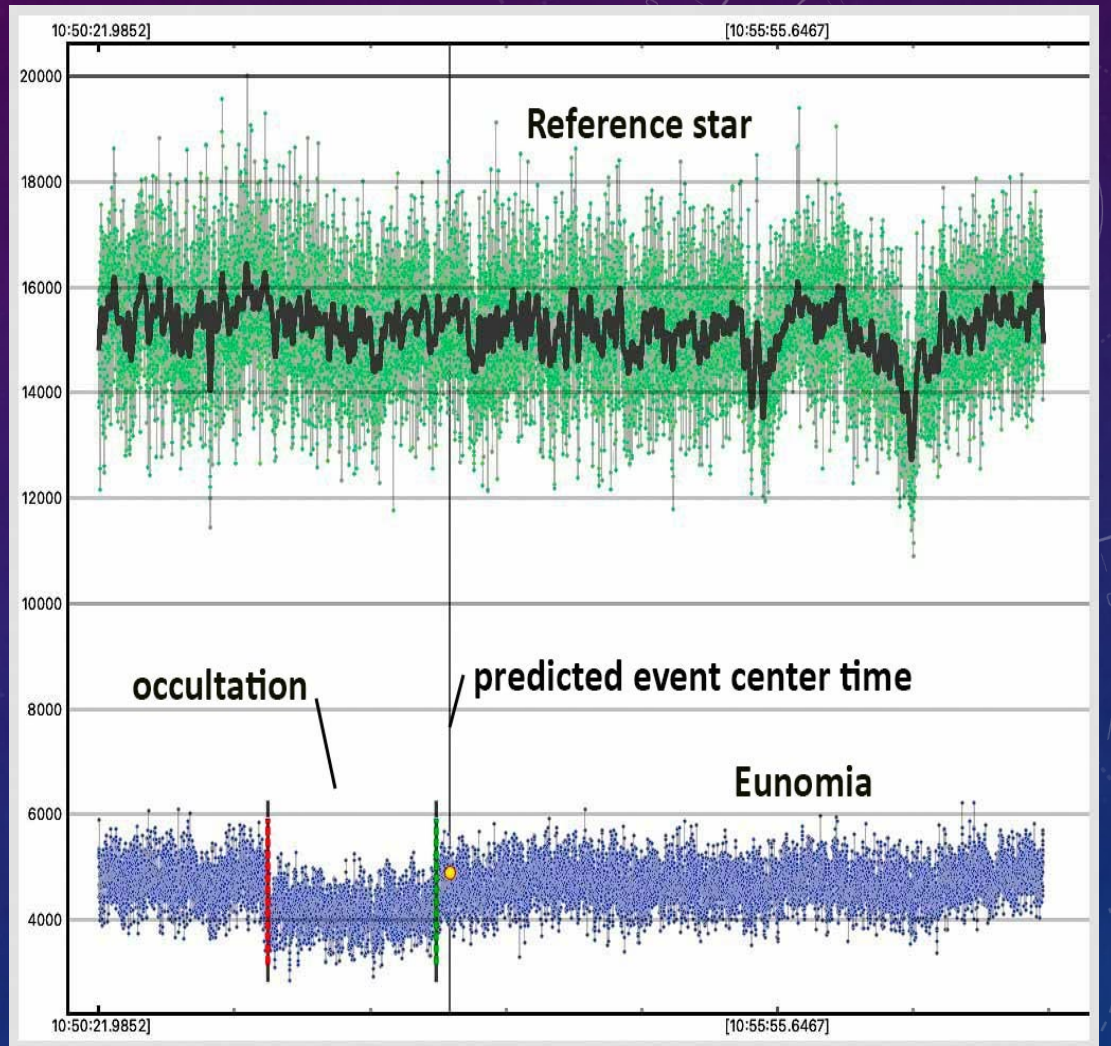


MIRA'S Oliver Observatory Station A 36" highly instrumented Cass in a giant roll-off structure. They loved the idea of expanding their science opportunities into this new area with us. We were given 2 nights on the telescope.

Predictions for the sky track as seen at MIRA's Chews Ridge Observatory. Would we detect the faint rings?



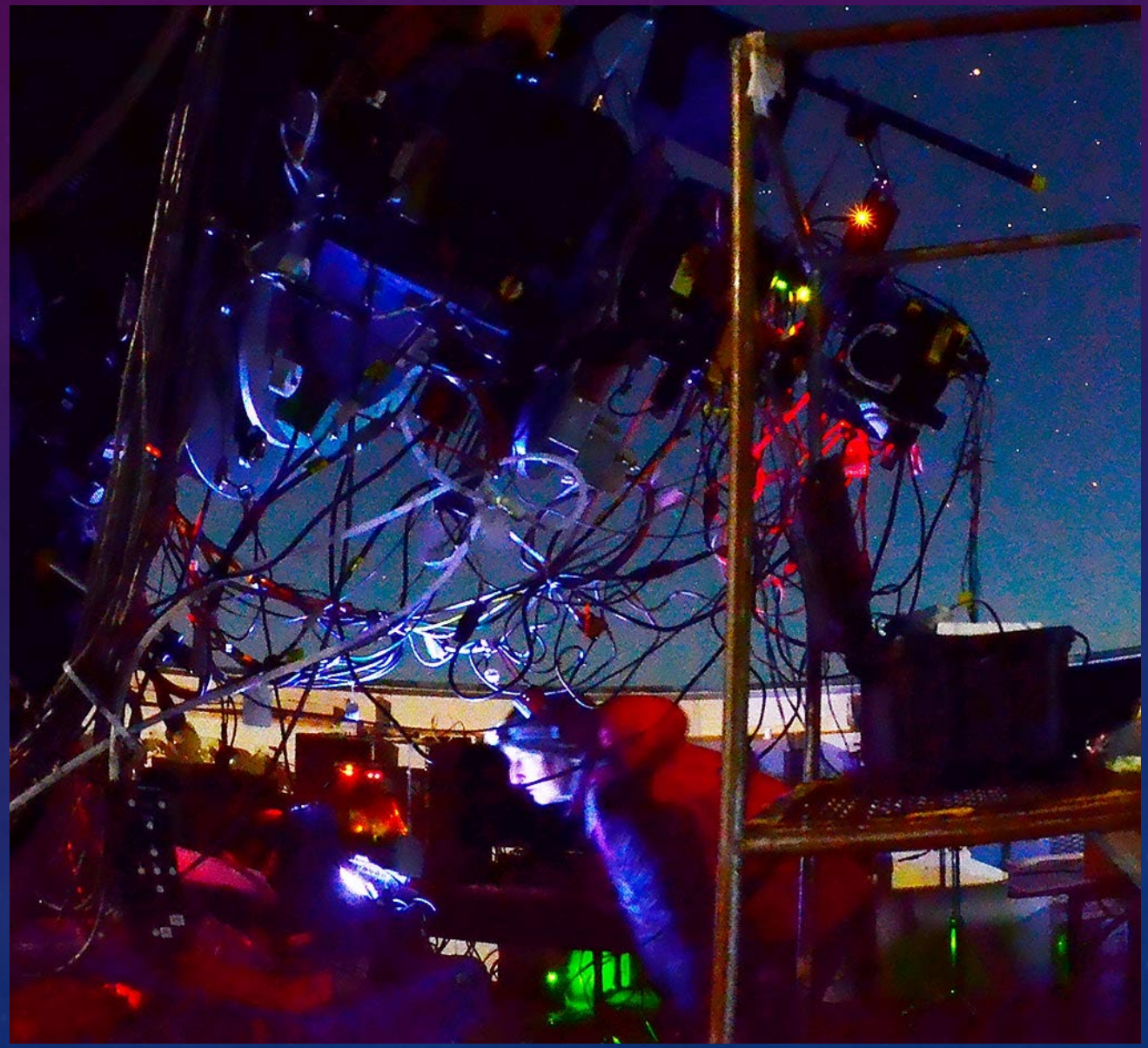
LUCKY AT MIRA – We had another occultation, by Eunomia, on the shake-down night before the main Quaoar 2023 event. Only a 0.09 magnitude predicted drop, but great data none-the-less. Having 36” helps! My data was very clean on the smaller 14” Planewave SCT as well. Note; event was early… interesting, for such a low-number asteroid.



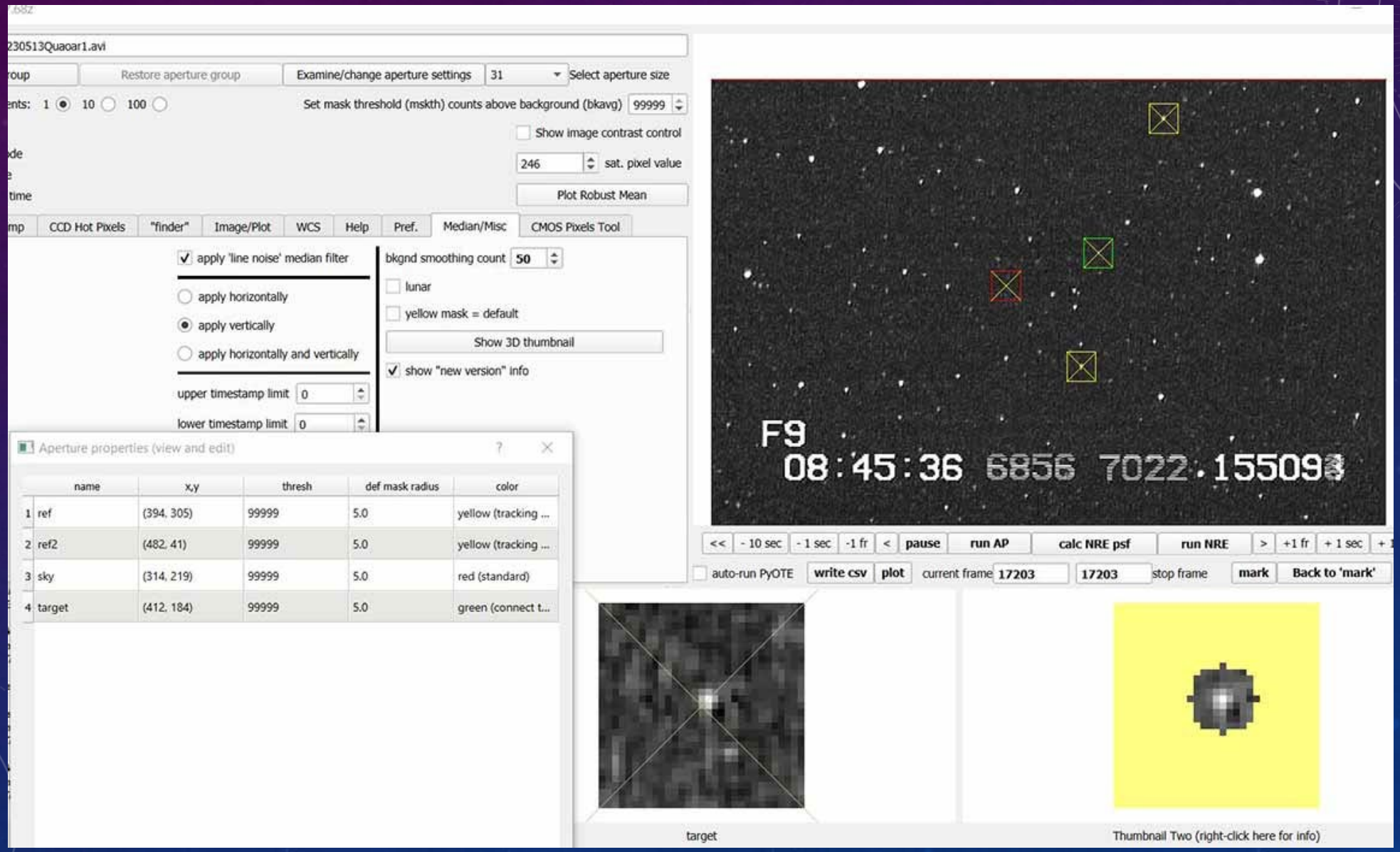

```
snr: 2.19

D time: [10:51:45.1003]
D: 0.6800 containment intervals: (+/- 0.0270) seconds
D: 0.9500 containment intervals: (+/- 0.2380) seconds
D: 0.9973 containment intervals: (+/- 0.6456) seconds

R time: [10:53:07.9151]
R: 0.6800 containment intervals: (+/- 0.0270) seconds
R: 0.9500 containment intervals: (+/- 0.2380) seconds
R: 0.9973 containment intervals: (+/- 0.6456) seconds

Duration (R - D): 82.8148 seconds
```

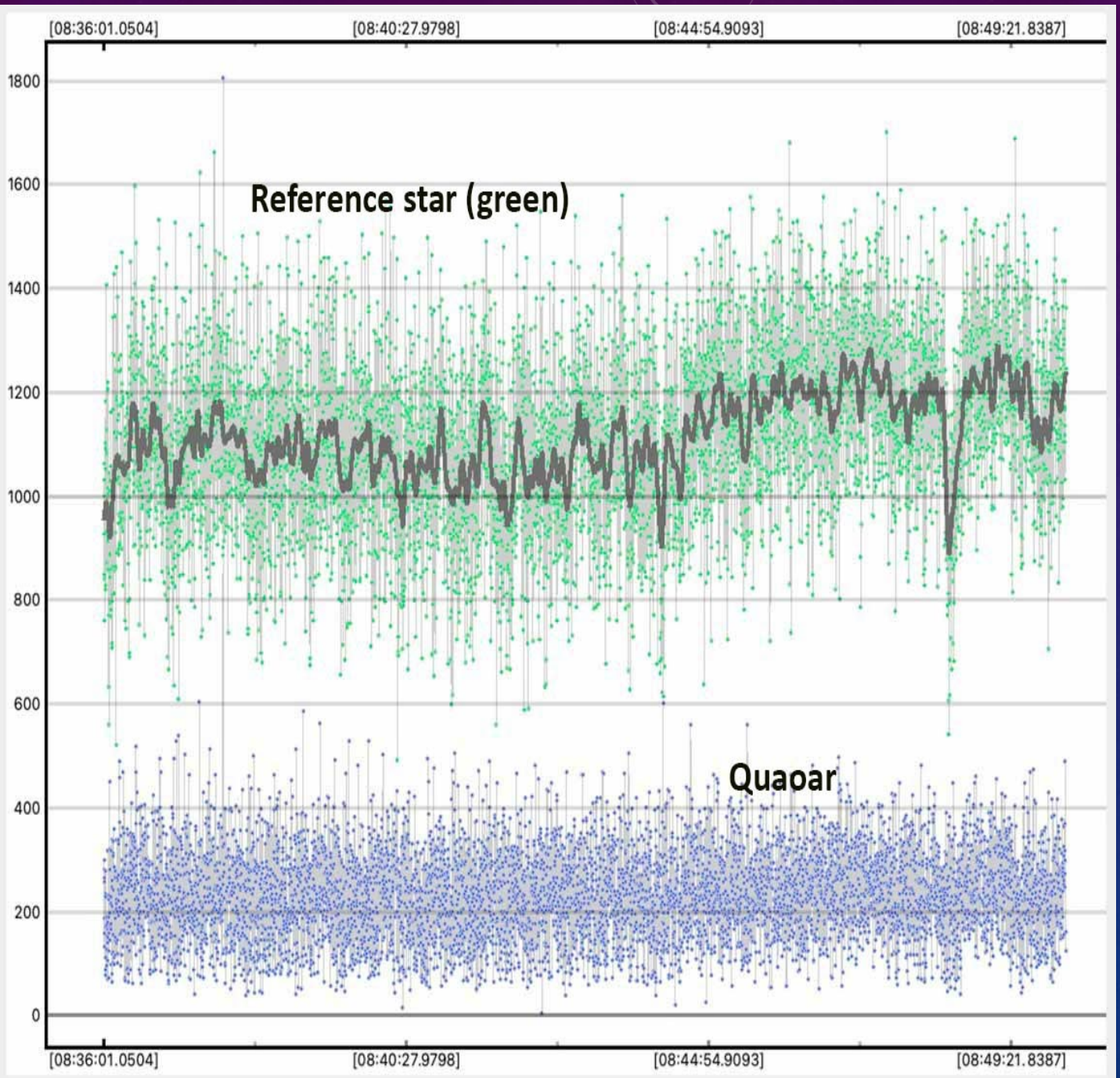
Quaoar Night: Kirk's gear was selected to be on the big scope. The Watec 910hx I loaned him, turns out to be higher S/N than the one I use. I took their new 14" Planewave SCT for parallel data taking.

That’s me… hidden under all the data/power cables



PyMovie – Free Win10 software (by IOTA's crack programmer Bob Anderson) for photometric reduction of raw *.avi* video data





PyOTE: Companion Win10 software for analyzing PyMovie photometric output to determine best-fit occultation timings.

Here, the rings of Quaoar were not dense enough at our position angles to cause detectable drops. But, valuable upper limits obtained.

A&A 673, L4 (2023)
https://doi.org/10.1051/0004-6361/202346365

Astronomy & Astrophysics

LETTER TO THE EDITOR

The two rings of (50000) Quaoar

C. L. Pereira[1,2], B. Sicardy[3], B. E. Morgado[4,1,2], F. Braga-Ribas[5,1,2], E. Fernández-Valenzuela[6,7], D. Souami[3,8,9,10,⋆], B. J. Holler[11], R. C. Boufleur[1,2], G. Margoti[5], M. Assafin[4,2], J. L. Ortiz[7], P. Santos-Sanz[7], B. Epinat[12,13], P. Kervella[3], J. Desmars[14,15], R. Vieira-Martins[1,2], Y. Kilic[16,17], A. R. Gomes Júnior[18,19,2], J. I. B. Camargo[1,2], M. Emilio[20,1,5], M. Vara-Lubiano[7], M. Kretlow[7,21,22], L. Albert[23,24], C. Alcock[25], J. G. Ball[26], K. Bender[27], M. W. Buie[28], K. Butterfield[29], M. Camarca[30], J. H. Castro-Chacón[31], R. Dunford[29], R. S. Fisher[32], D. Gamble[29,33], J. C. Geary[25], C. L. Gnilka[34], K. D. Green[35], Z. D. Hartman[26], C.-K. Huang[36], H. Januszewski[13], J. Johnston[37], M. Kagitani[38], R. Kamin[29], J. J. Kavelaars[39], J. M. Keller[37], K. R. de Kleer[30], M. J. Lehner[36], A. Luken[32], F. Marchis[40,41], T. Marlin[30], K. McGregor[42], V. Nikitin[29,43], R. Nolthenius[27], C. Patrick[29], S. Redfield[42], A. W. Rengstorf[44], M. Reyes-Ruiz[31], T. Seccull[26], M. F. Skrutskie[45], A. B. Smith[26], M. Sproul[46], A. W. Stephens[26], A. Szentgyorgyi[25], S. Sánchez-Sanjuán[31], E. Tatsumi[47,48], A. Verbiscer[45], S.-Y. Wang[36], F. Yoshida[49,50], R. Young[51], and Z.-W. Zhang[36]

(Affiliations can be found after the references)

Received 9 March 2023 / Accepted 17 April 2023

ABSTRACT

Context. Quaoar is a classical trans-Neptunian object (TNO) with an area-equivalent diameter of 1100 km and an orbital semi-major axis of 43.3 astronomical units. Based on stellar occultations observed between 2018 and 2021, an inhomogeneous ring (Q1R, i.e., Quaoar's first ring) has been detected around this body.

Aims. A new stellar occultation by Quaoar was observed on August 9, 2022, with the aim of improving Quaoar's shape models and the physical parameters of Q1R, while searching for additional material around the body.

Methods. The occultation provided nine effective chords across Quaoar, pinning down its size, shape, and astrometric position. Large facilities, such as Gemini North and the Canada-France-Hawaii Telescope (CFHT), were used to obtain high acquisition rates and signal-to-noise ratios. The light curves were also used to characterize the Q1R ring (radial profiles and orbital elements).

Results. Quaoar's elliptical fit to the occultation chords yields the limb with an apparent semi-major axis of 579.5 ± 4.0 km, apparent oblateness of 0.12 ± 0.01, and area-equivalent radius of 543 ± 2 km. Quaoar's limb orientation is consistent with Q1R and Weywot orbiting in Quaoar's equatorial plane. The orbital radius of Q1R is refined to a value of 4057 ± 6 km. The radial opacity profile of the more opaque ring profile follows a Lorentzian shape that extends over 60 km, with a full width at half maximum (FWHM) of ~5 km and a peak normal optical depth of 0.4. Besides the secondary events related to the already reported rings, new secondary events detected during the August 2022 occultation in three different data sets are consistent with another ring around Quaoar with a radius of 2520 ± 20 km, assuming the ring is circular and co-planar with Q1R. This new ring has a typical width of 10 km and a normal optical depth of ~0.004. Just as Q1R, it also lies outside Quaoar's classical Roche limit.

Key words. methods: data analysis – methods: observational – techniques: photometric – Kuiper belt objects: individual: Quaoar – planets and satellites: rings

1. Introduction

In the last decade, three ring systems have been discovered around minor bodies in the outer Solar System: the Centaur Chariklo (Braga-Ribas et al. 2014), the dwarf planet Haumea (Ortiz et al. 2017), and the trans-Neptunian object (TNO) (50000) Quaoar (Morgado et al. 2023). Dense material has also been detected around the Centaur Chiron (Ruprecht et al. 2015; Ortiz et al. 2015; Sickafoose et al. 2020). However, the nature of this material, namely, whether it is a permanent or transient ring or a dust shell, is still a matter of debate.

Quaoar's ring, referred to as Q1R hereafter, was detected during several stellar occultations observed between 2018 and 2021 (Morgado et al. 2023). Q1R has a radius of about 4100 km with significant azimuthal variations in the optical depth, ranging between 0.004 and 0.1–0.7, and in width, ranging from 5 km to 300 km. Like Chariklo's and Haumea's rings, Quaoar's Q1R ring orbits close to the 1/3 spin-orbit resonance (SOR) with the central body, suggesting a link between this resonance and the ring (Salo et al. 2021; Sicardy et al. 2021; Morgado et al. 2023). Meanwhile, a unique property of Q1R is its location, which is far outside Quaoar's classical Roche limit. This limit is estimated to be at 1780 km from the body center, assuming particles with a bulk density of $\rho = 0.4\,\mathrm{g\,cm^{-3}}$. Outside the Roche limit, rings should accrete into satellites over timescales of less than 100 years (Kokubo et al. 2000; Takeda & Ida 2001). However, collisions more elastic than previously considered for Saturn's ring may maintain a ring unaccreted at distances greater than the Roche limit (Morgado et al. 2023). The 6/1

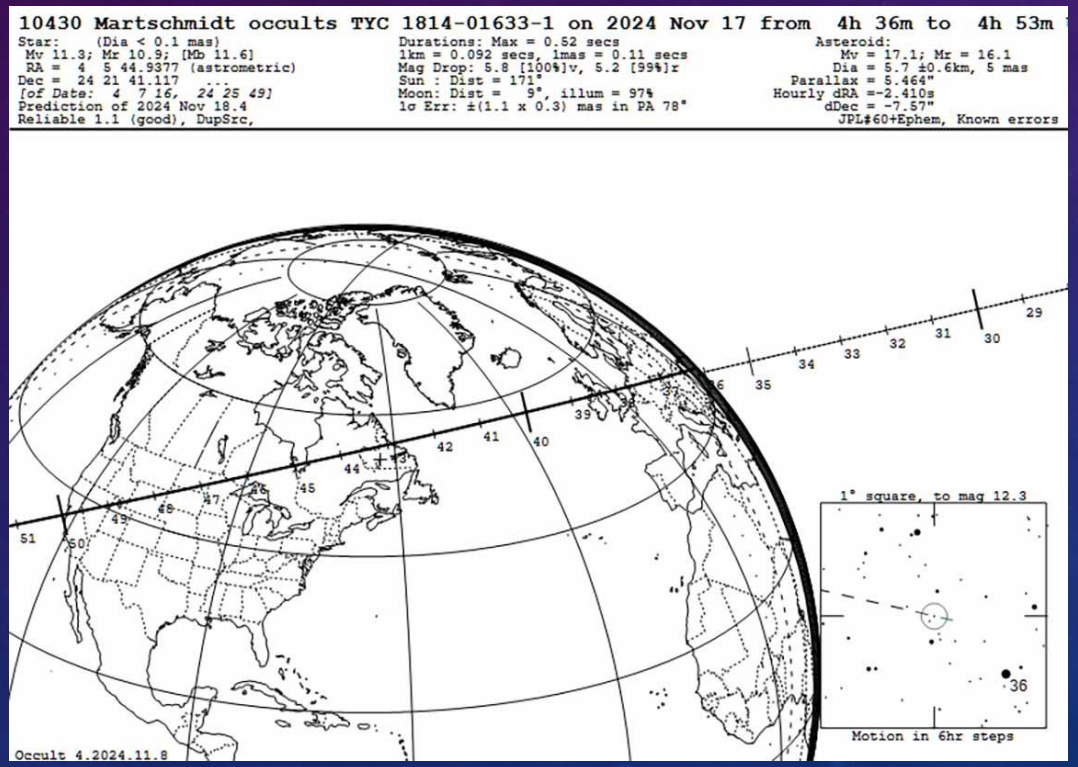
⋆ Fulbright Visiting Scholar (2022–2023) at University of California, Berkeley.

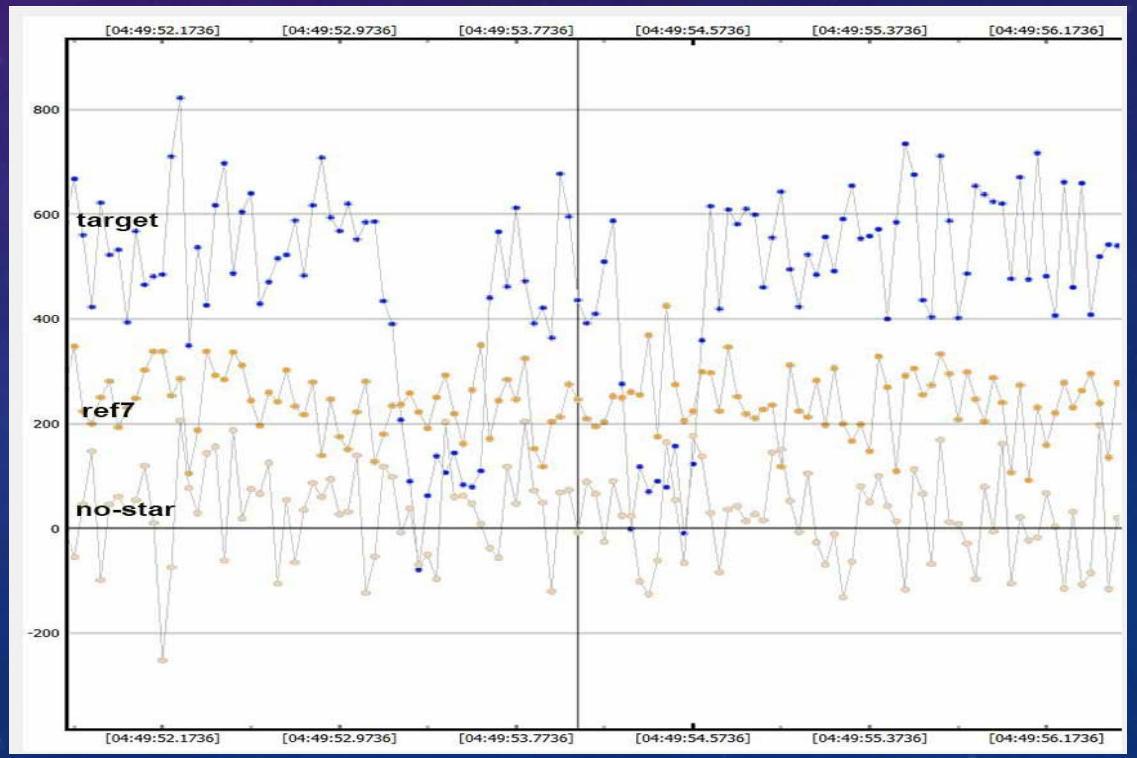
And, at the very similar 2022 Quaoar occultation: Mauna Kea scopes discovered the 2nd ring. Published paper in A&A.

Co-authors Nolthenius & Bender, with our 8SE scopes got data from Bonny Doon; crucial in defining the shape of Quaoar itself and its positioning in the system.

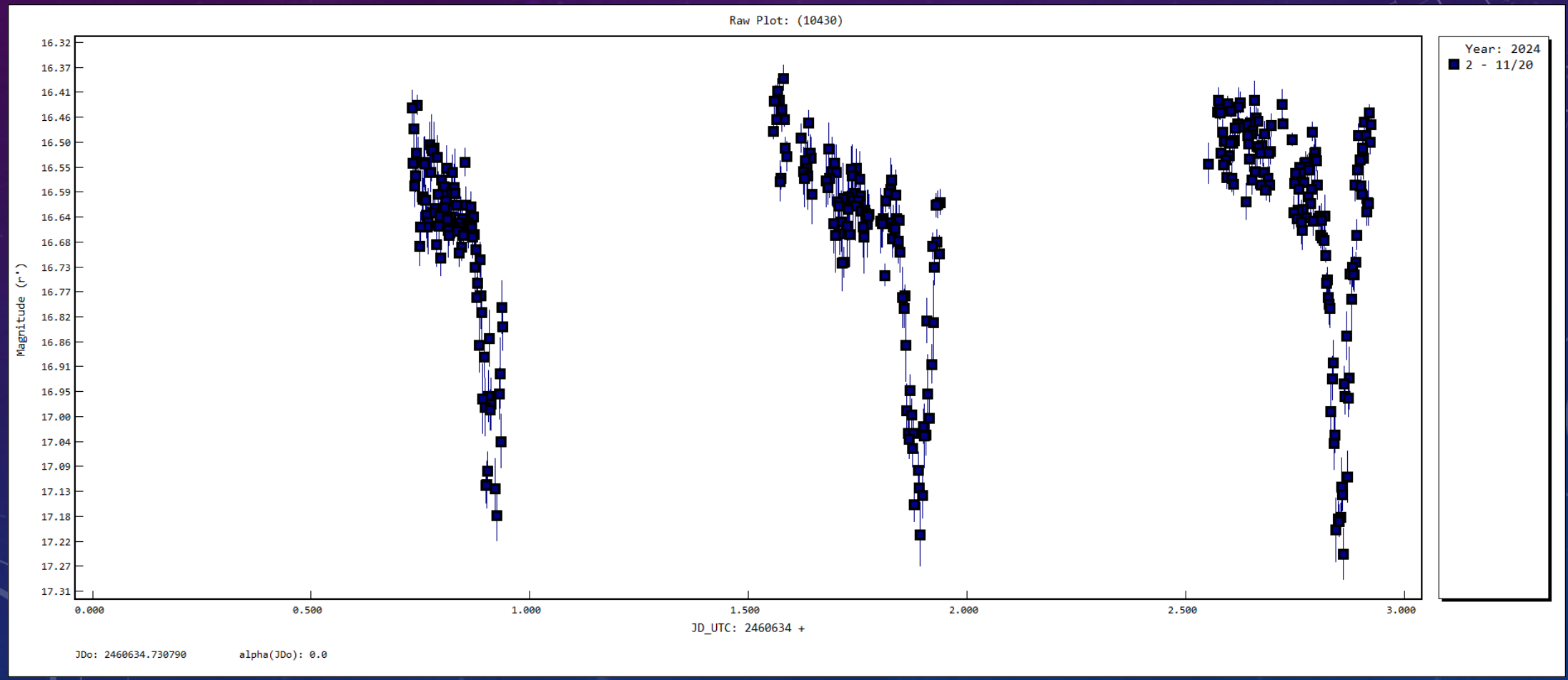
LAST: MY DISCOVERY OF (10430) MARTSCHMIDT AS A NEW BINARY ASTEROID; NOV 16, 2024 AND FEB 23, 2025

Ref7 star is less than half the brightness of the target star, yet both occultations go below it. Proof it was a binary asteroid, not a binary star.

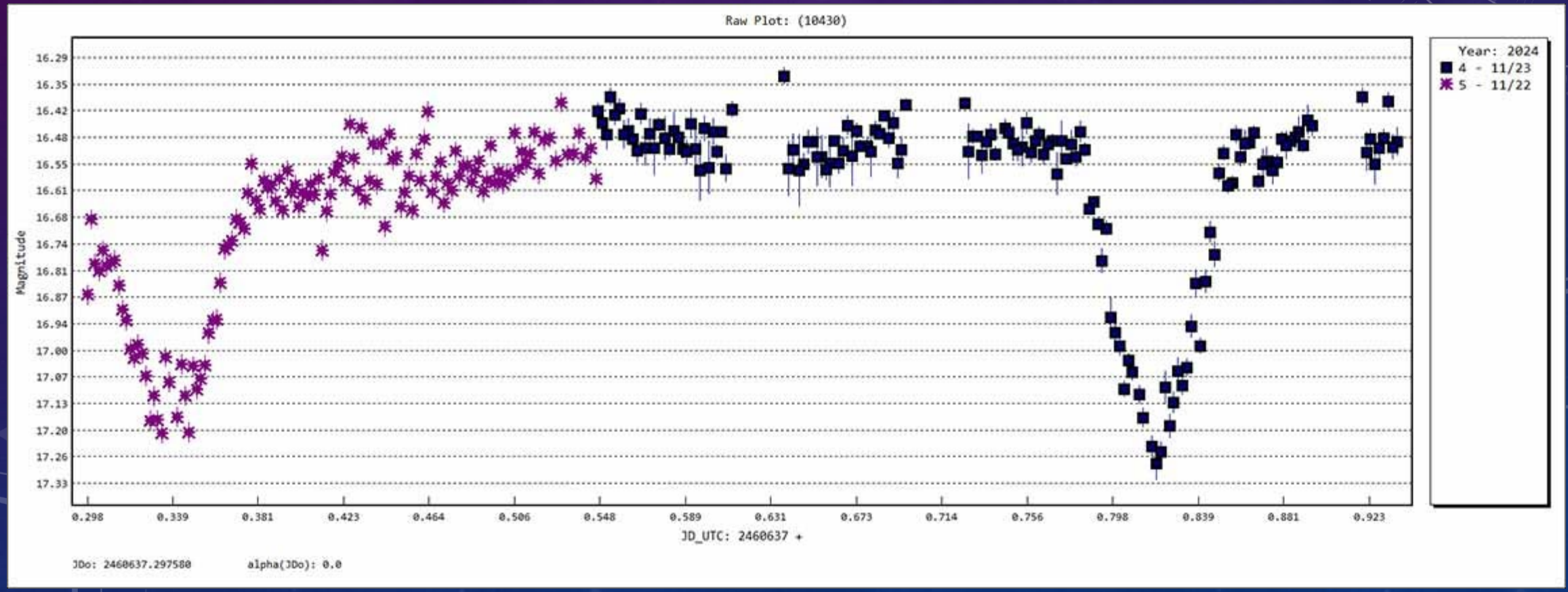




More proof: Jean-Francois Gout and M. Conjat in France, on hearing of my discovery, got on it and did photometry of the faint 17th mag asteroid itself – and wow! mutual eclipses of the two components!



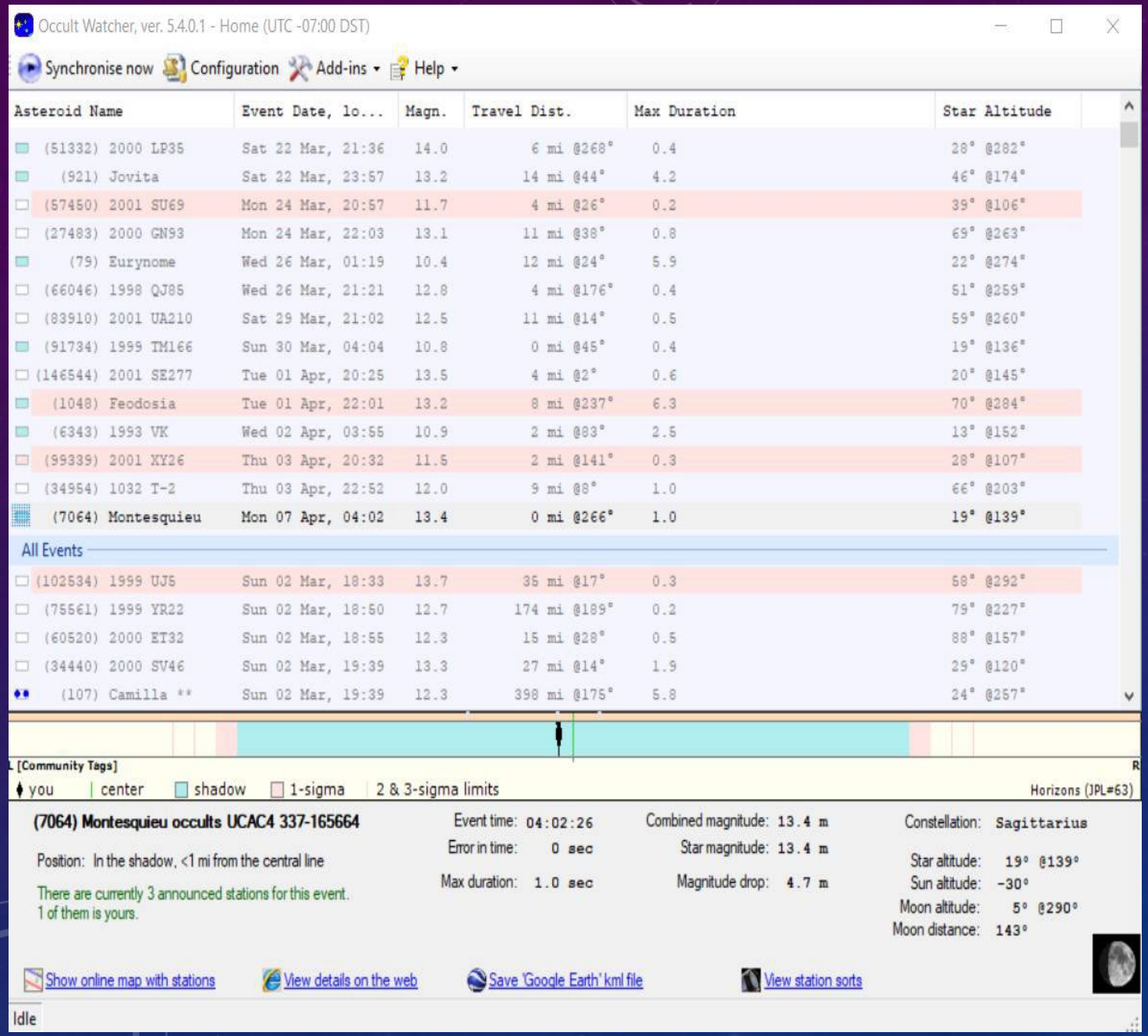
Conjat, at a different longitude, in France, was able to see the secondary eclipse (purple) 11.7 hr before Gout got a primary eclipse! 23.17hr period.



Amazingly, this same asteroid had another occultation just 3 months later, which narrow path went right over Cabrillo College observatory – again! alas, clouds chased us all the way out to the central valley. where my student Bernard nailed a double occultation., and Kirk a single occ

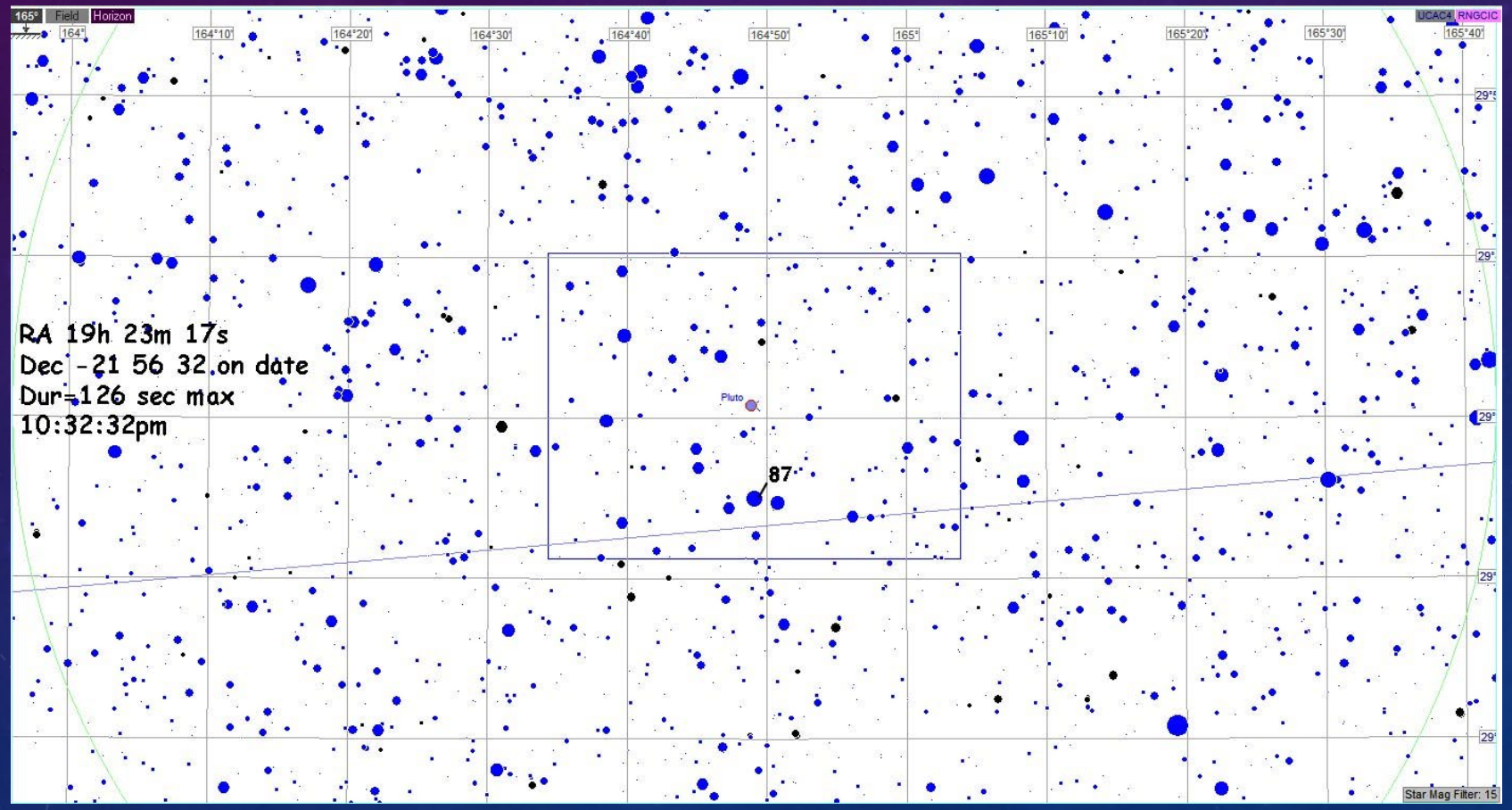
OUR TEAM! SUCCESS AND SMILES

So, how do we get such data as these? What's the process and the gear needed?



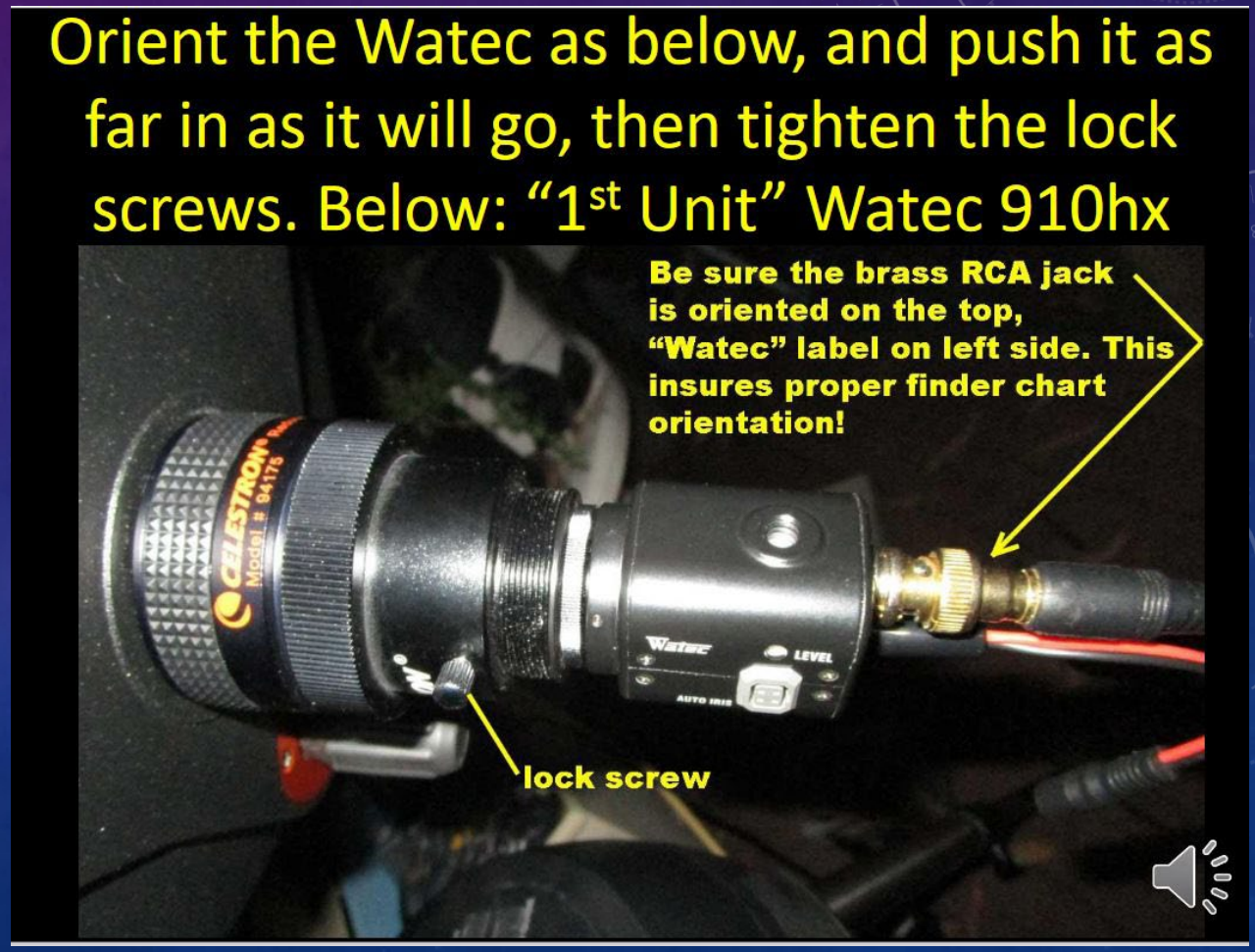
Predictions: Install freeware OWd: OccultWatcher Desktop (OWd) will comb through the master database of global occultations in OccultWatcher Cloud (OWc) and generate a list of all events upcoming that satisfy your filters

If I see one that looks promising and weather is a “go”, I prepare finder charts showing the 32mm Q70 eyepiece view, and Watec’s chip view. OccultWatcher helps make this process fairly easy, by auto-startup of C2A planetarium software at the time and long/lat chosen by you, with eyepiece and camera apertures you set.



EQUIPMENT? I LOVE OUR CELESTRON 8SE SCOPES, AND WATEC 910HX LOW-LIGHT VIDEO CAMERAS

- My gear sets up quickly. From arrival to on-target recording, 20 min if things go smoothly. 8SE's do 2-star align fast and reliably. Has robust electronics (our old Meade scopes? not!), and they're light weight and pack compactly for our many expeditions.
- We use a Celestron f/3.3 reducer to concentrate starlight onto fewer pixels for better S/N. No longer made, but search eBay.



I like deploying out of the back of my RAV4. My home made “Occ Box” houses the DV camcorder, IOTA VTI video time inserter, microphone, battery, data lines to connect to the video camera at the back end of the Celestron 8SE scope

We use mini-DV camcorders to record the time-stamped video out of the IOTA-VTIs. Most IOTA occult'rs these days use laptops and direct-to-disk recording.

But that has its own gotcha's with dropped frames. Personally, I'm not ready to give up on mini-DV tape as my preferred way to go. 91 successes in 2024. 33 so far in '25

The IOTA website – Has links to all the software and instructions you need, as well as publishing sky plane solutions for your occultations submitted to IOTA.

The IOTA message board is excellent to post questions, get answers, and get notifications on new events needing observers.

- Celestron NextStar 8SE SCT telescope..... $1199.00
- Orion Q70 eyepiece..... $ 100.00
- Celestron 2” diagonal..... $ 124.00
- Watec 910hx-RC camera..... $ 700.00
- Canon ZR45mc camcorder (ebay)..... $ 150?
- Meade or Celestron f/3.3 reducer..... $ 100? Will have to find on eBay, not made any longer
- Highpoint 0.5x focal reducer..... $ 26.95
- Astromania 1.25” c-adapter..... $ 16.00
- Short-nose 1.25” c thread for use w/ 0.5x..... $ 12.00
- IOTA VTI video time inserter..... $ 249.00
- 2 Tool boxes (Ace Hardware)..... $ 26.00
- 8ah 12VDC battery ..... $ 35.00
- 2 “LED Innovations” triple sockets..... $ 30.00
- RCA cord, 2 male 2.1mm “N” barrel plugs.....~$ 30.00
- Various fuses, connectors..... $ 38.00
- Total..... ~$2836

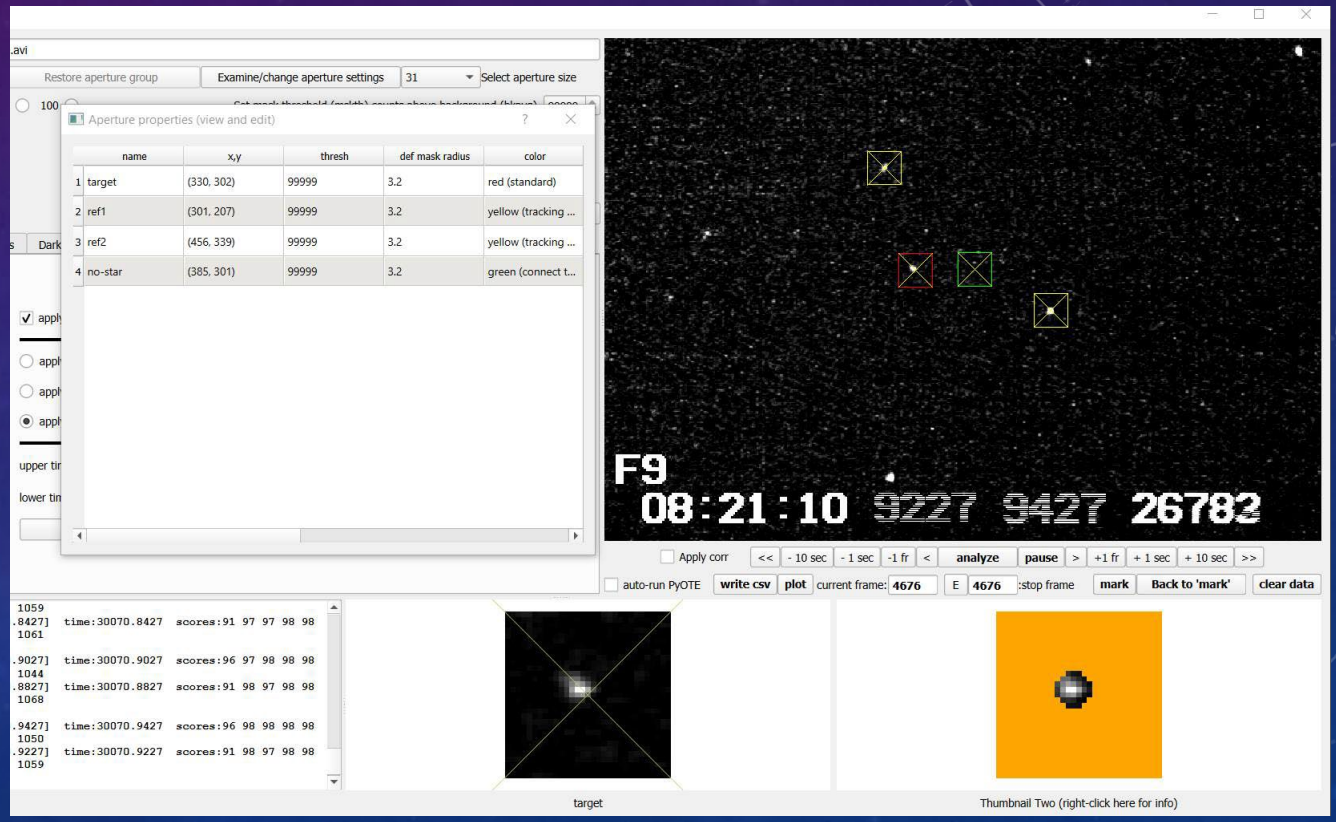
Our classic gear will get 14th magnitude occultations under good conditions. all for under $3k ‘23 prices, alas. Now, more… but given today’s chaotic pricing, I left this slide as is)

IOTA's Mark Simpson has designed a new self contained occultation system: Astrid. ~$600-700

"Astrid is a Raspberry Pi-based, self-contained GPS-equipped astronomy imaging device with features that make it a complete, all-in-one device for recording and accurately timing occultation events. Using a tablet or laptop to connect to Astrid (via its wifi hotspot) the user can plate-solve, pre-point a telescope, control a computerized mount (if desired), schedule a recording, confirm in advance that the exposure and gain chosen are sufficient to record the target star, automatically record an event, and play back the recording (with a helpful identification of the target star)".

Reducing your data (brief summary). PDF for more detail. PyMovie does your photometry

- Your video needs to be raw, no compression. AVI format is what is downloaded off the miniDV camcorders I use, into my Win10 laptop.
- Install the Python programming language onto your Windows machine
- Then install PyMovie. PyMovie lets you place apertures on your target, reference stars, and blank sky.
- Then click “analyze” and in a few minutes you’ll have a .csv file with the photometric values for all selected objects for each frame of your video.



Then Install PyOTE, this uses your PyMovie *.csv* file and plots your light curves and identifies your “D” and “R” times

- Open PyOTE
- Display your light curves, choose a reference star
- Optimize a smoothing length for your reference star (PyOTE will guide you)
- PyOTE will guide you to search for any target brightness drop that may be your occultation.
- Ask PyOTE to find your event, if you suspect one. Or, it may be obvious that you have a “miss”.
- If you have MS Excel installed already, then PyOTE will auto-generate the IOTA report form and fill in your standard answers to many fields, and also your timings and confidence limits.

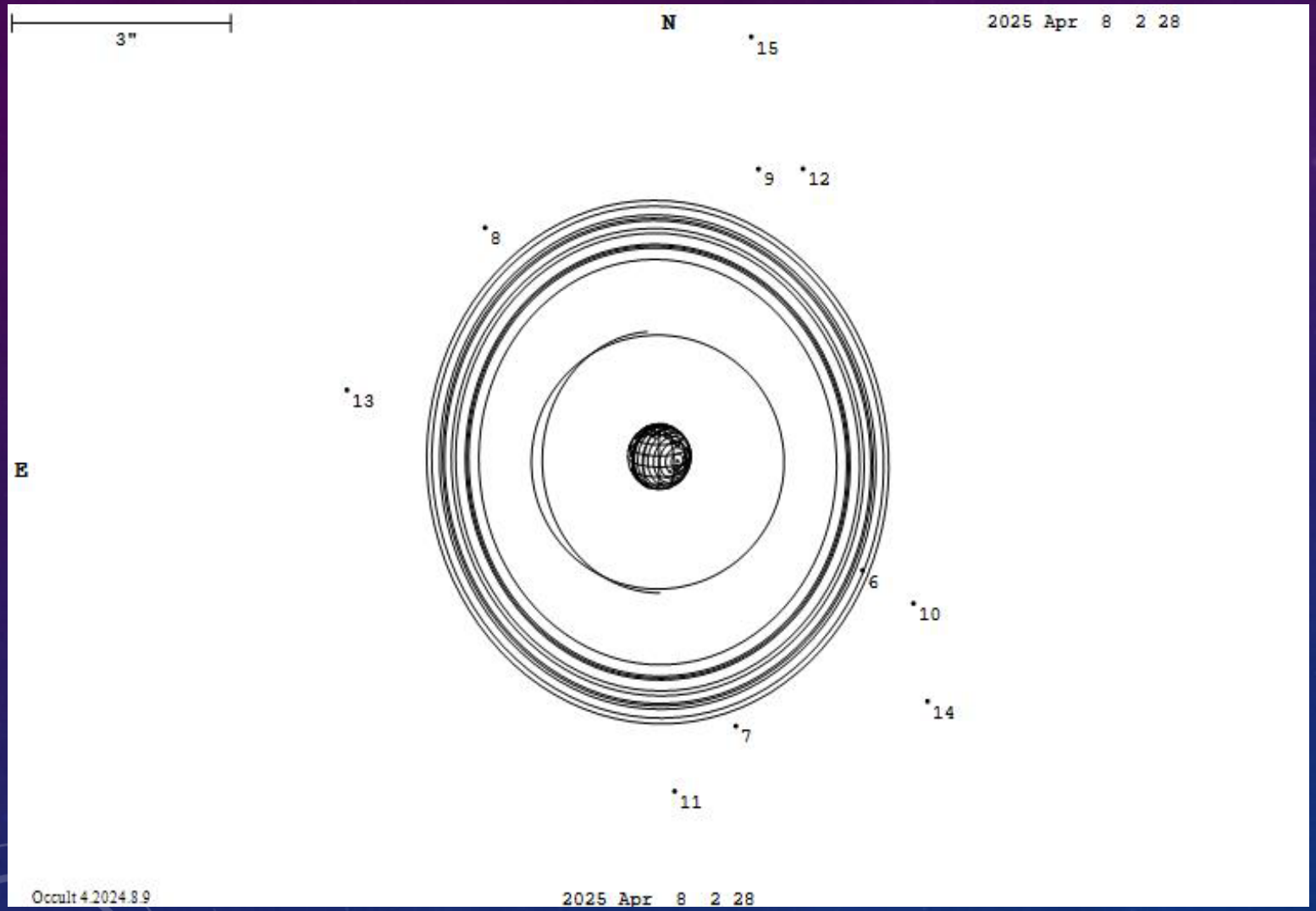
I require my team members to do all this themselves. they then send me images of the relevant light curves and their timings

- I then assemble a web page with the narrative and images of each occultation we try.
- Here's an example; an occultation by Lilaea Jan 30 this year
- It's gotten to be rather time consuming! I'm going to further require my team to send me files that are already properly in my naming convention and size, and a narrative of anything relevant that the IOTA auditors data/checkers may ask as they filter through the data to give it a thumbs up / thumbs down for inclusion into the larger astronomical databases.

Occultations: They're exciting, and they're important real science.

It's an astro adventure, all compressed into a single expedition and a few seconds of climactic data-taking.

A million things can go wrong, but you learn, and the memories of the successes stay with you!



And this coming Monday evening Apr 7, 2025 – Uranus occults a 9th magnitude star, 23 degrees up in the evening sky.

The occultation by the Epsilon Ring might be detectable with long focal length setups and good seeing. But, sun alt= -10 and Uranus is only 23 deg up. And worst – the target star is only 1.5” from Uranus (80x brighter!)

Very tough.

See the IOTA Message Board for details on this and other high value events

MAYBE YOU HAVE SOME QUESTIONS?