THE JUNE 29/30, 2021 OCCULTATION BY THE BINARY ASTEROID (4337) ARECIBO. CAN WE CONSTRAIN THE SATELLITE ORBITAL PARAMETERS?

IOTA ANNUAL MEETING JULY 17, 2021

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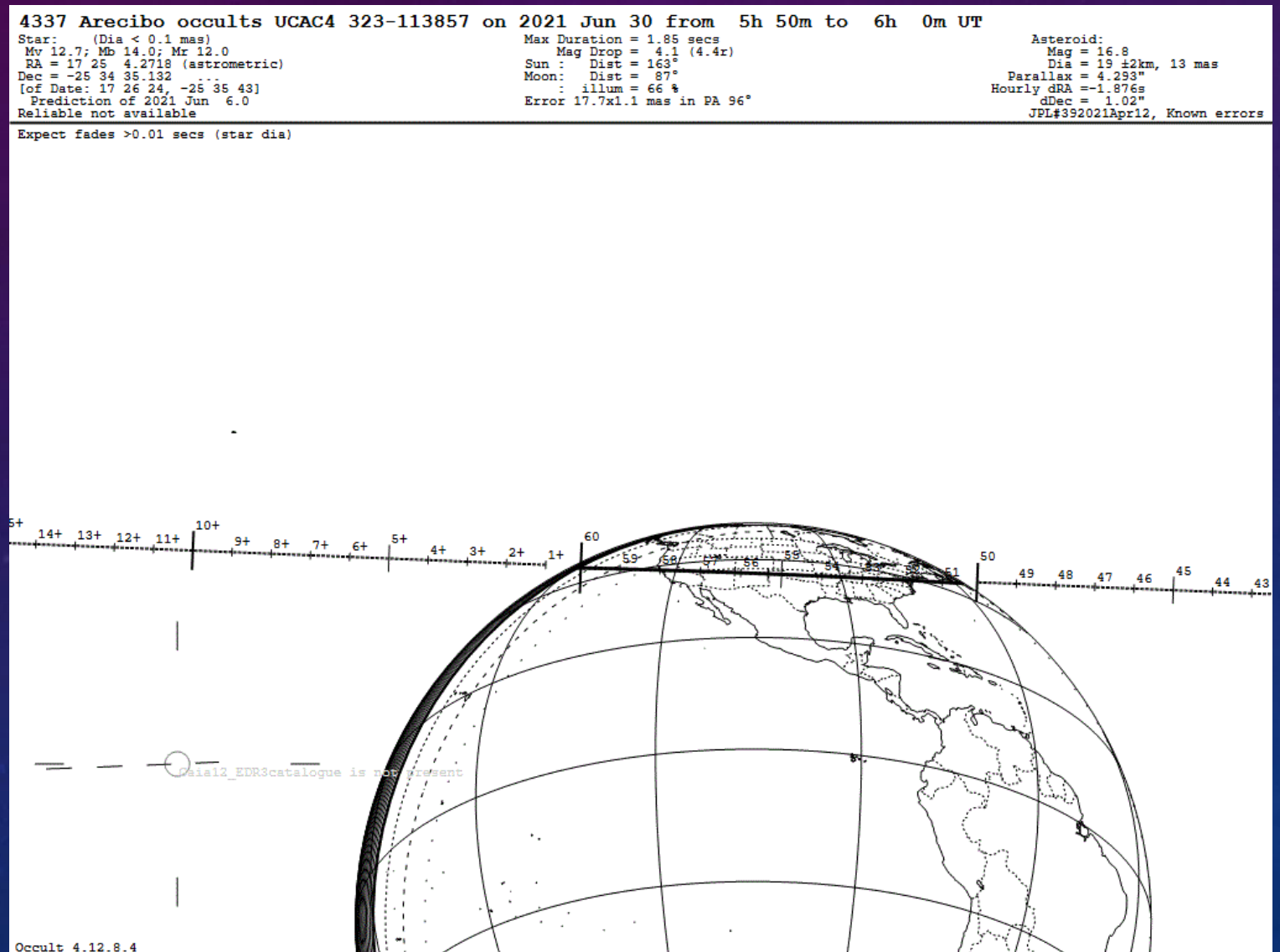
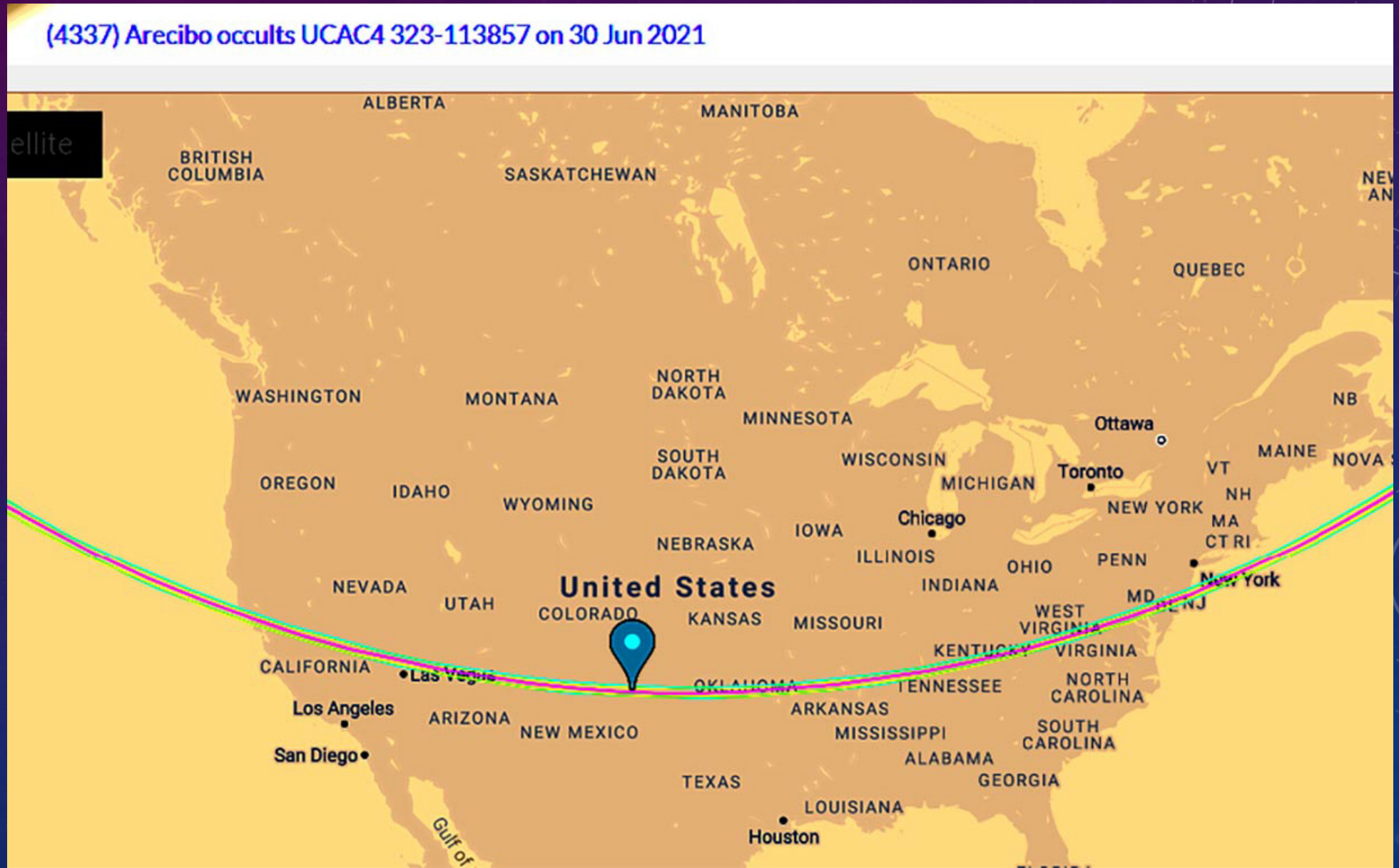
CHAIR, DEPT OF ASTRONOMY

CABRILLO COLLEGE, SANTA CRUZ, CA

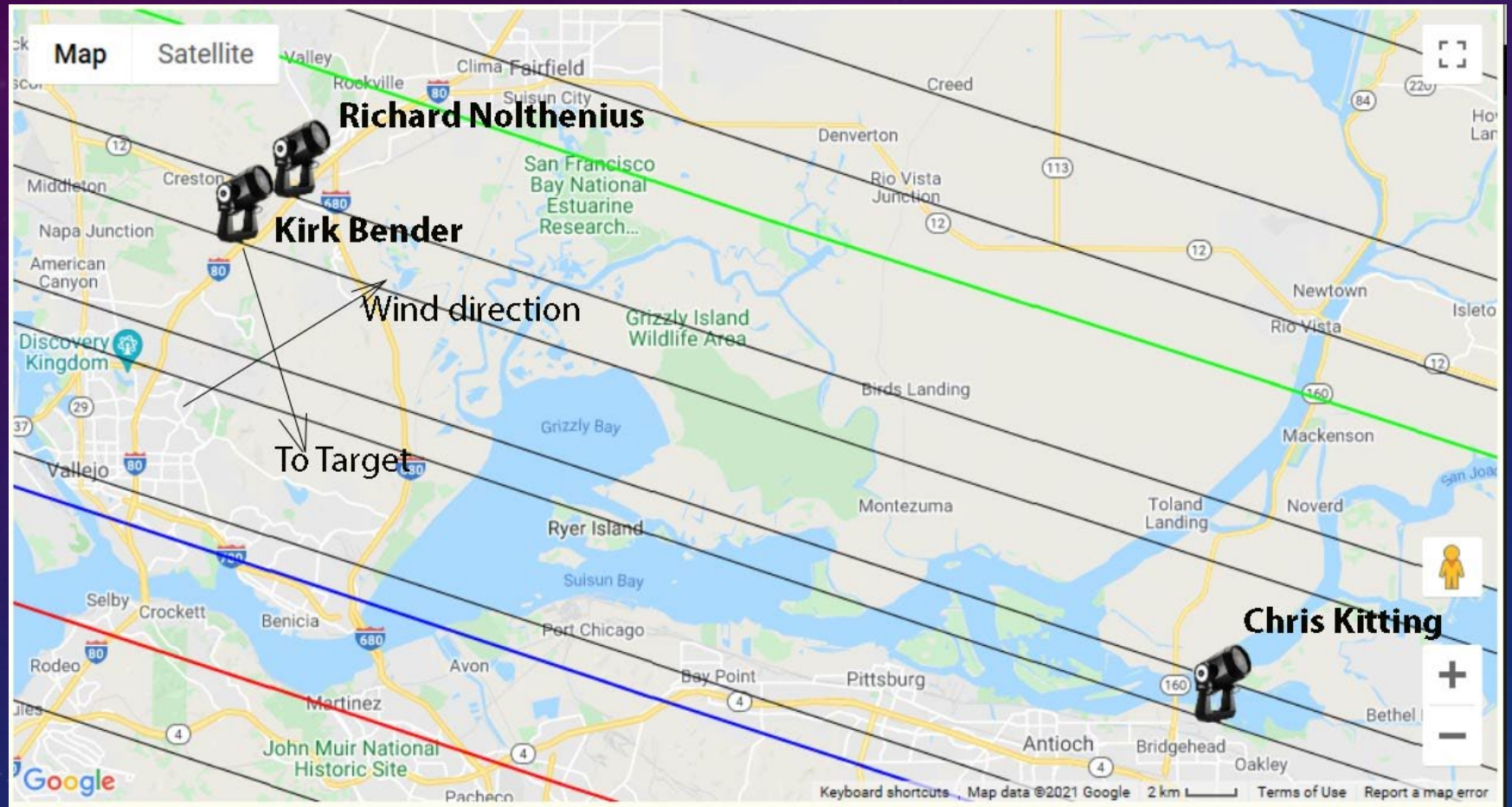
THE PERFECT PATH? CROSSING THE U.S. COAST TO COAST, PROMISING A LARGE TURNOUT OF OBSERVERS. 12.7 MAGNITUDE STAR 25 DEGREES UP IN THE SOUTHERN MILKY WAY



CROSSING THE BAY AREA, ARIZONA, OK, AND MARYLAND – ALL HOT BEDS OF ASTEROID OCCULTATION ENTHUSIASM!



MY 3-MAN TEAM WAS ALL SOUTH OF THE CENTERLINE, AND THE WIND DIRECTION WAS ~PERPENDICULAR TO THE EVENT AZIMUTH, ALLOWING THE POSSIBILITY OF WIND PROTECTION

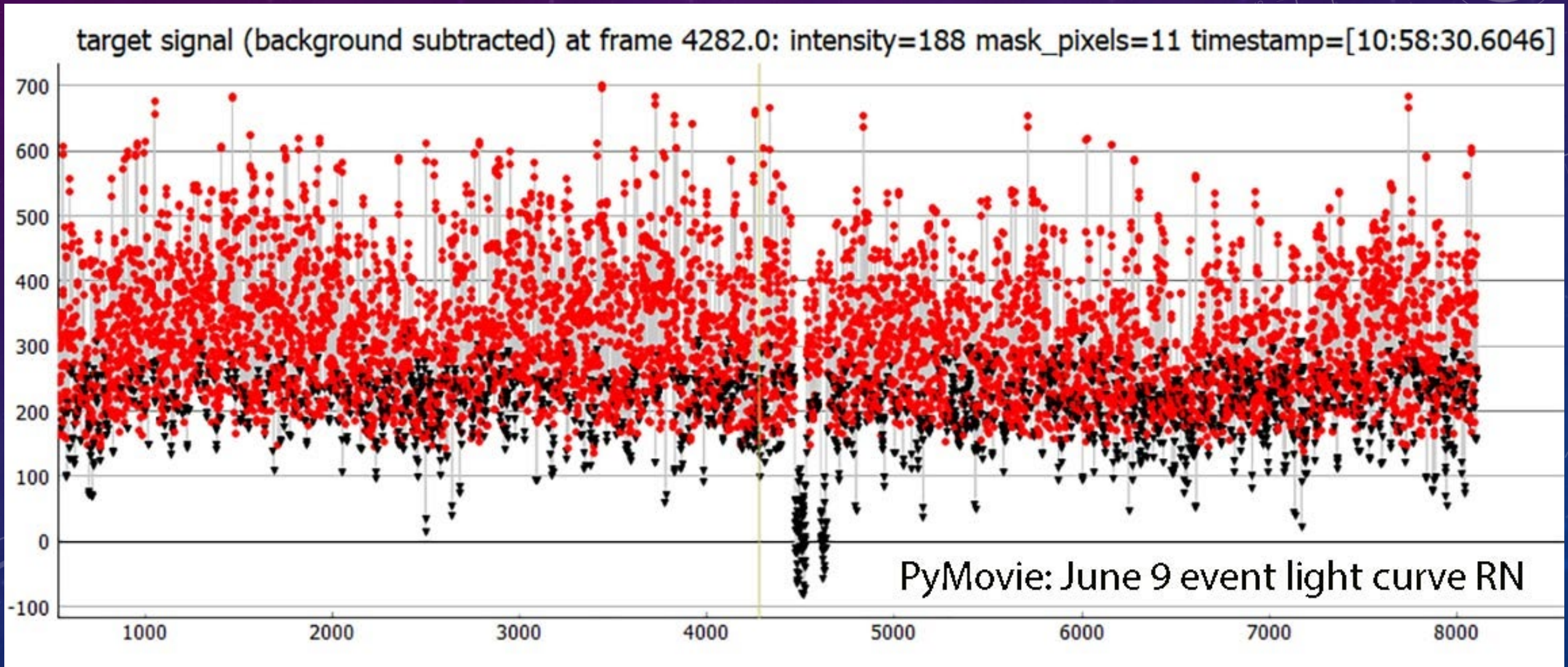


Observing locations currently announced by other observers:

Site resolution: 0.186410984848485 mi

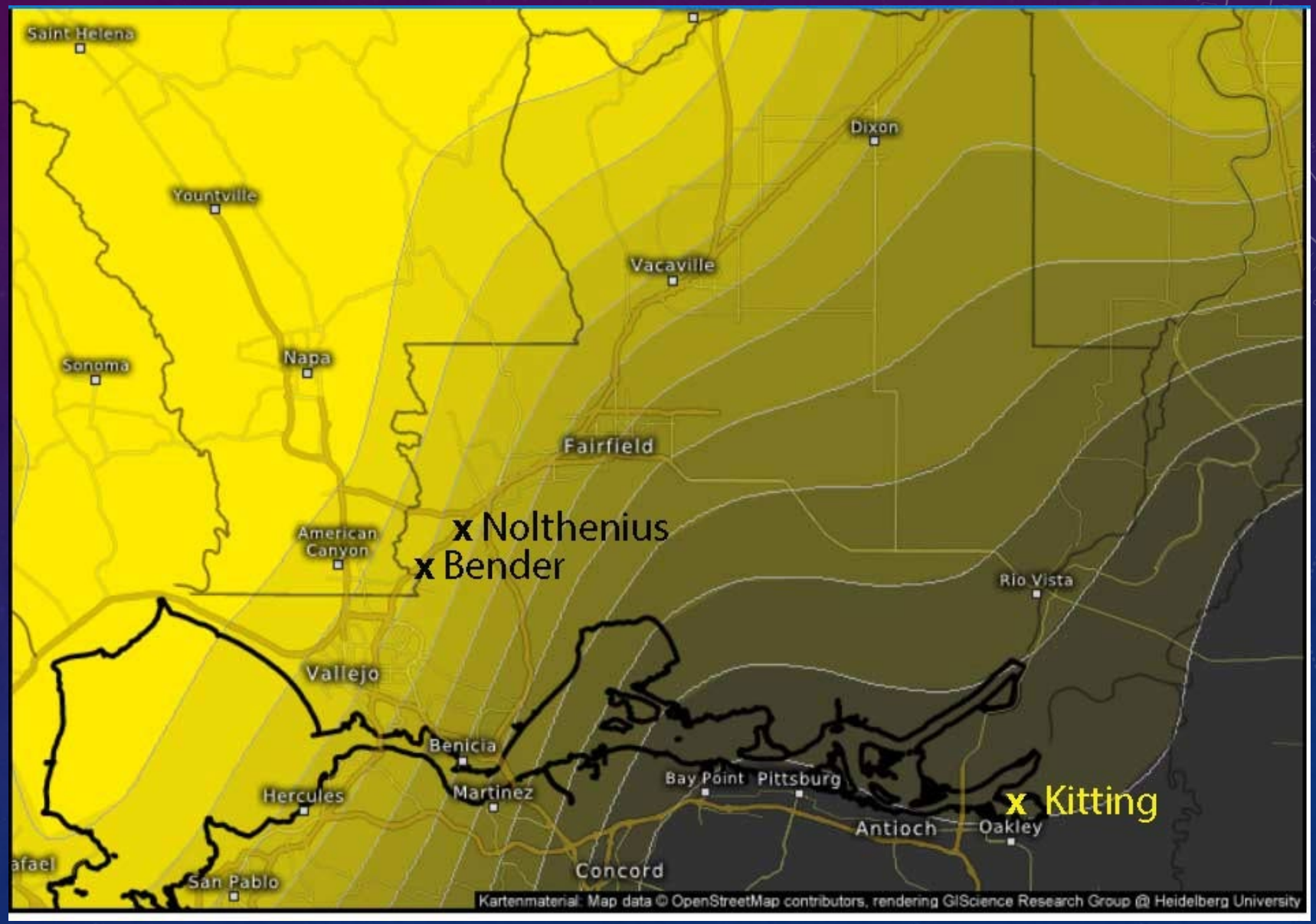
16 = Nolthenius R Mobile; 6 = Swift T Home; 15 = Kirk Bender - mobile; 13 = Kitting, mobile; 7 = Swift Mobile Dixon; 3 = Hawthorne MD #3 mobile; 10 = Heller J Mobile; 4 = Carlson N- Prelim Mobile; 14 = Ast. Soc. Greenbelt Obs.; 1 = Westphalia MD remote1; 2 = Cheltenham MD remote2; 17 = K. Getrost (mobile)

JUNE 9 EVENT: GOOD SEEING, 2X BRIGHTER STAR (V=12.0), NO WIND, ALLOWED GOOD S/N. BELOW IS THE PYMOVIE LIGHT CURVE FOR NOLTHENIUS. CONTRAST THIS WITH TOUGHER JUNE 29 EVENT…



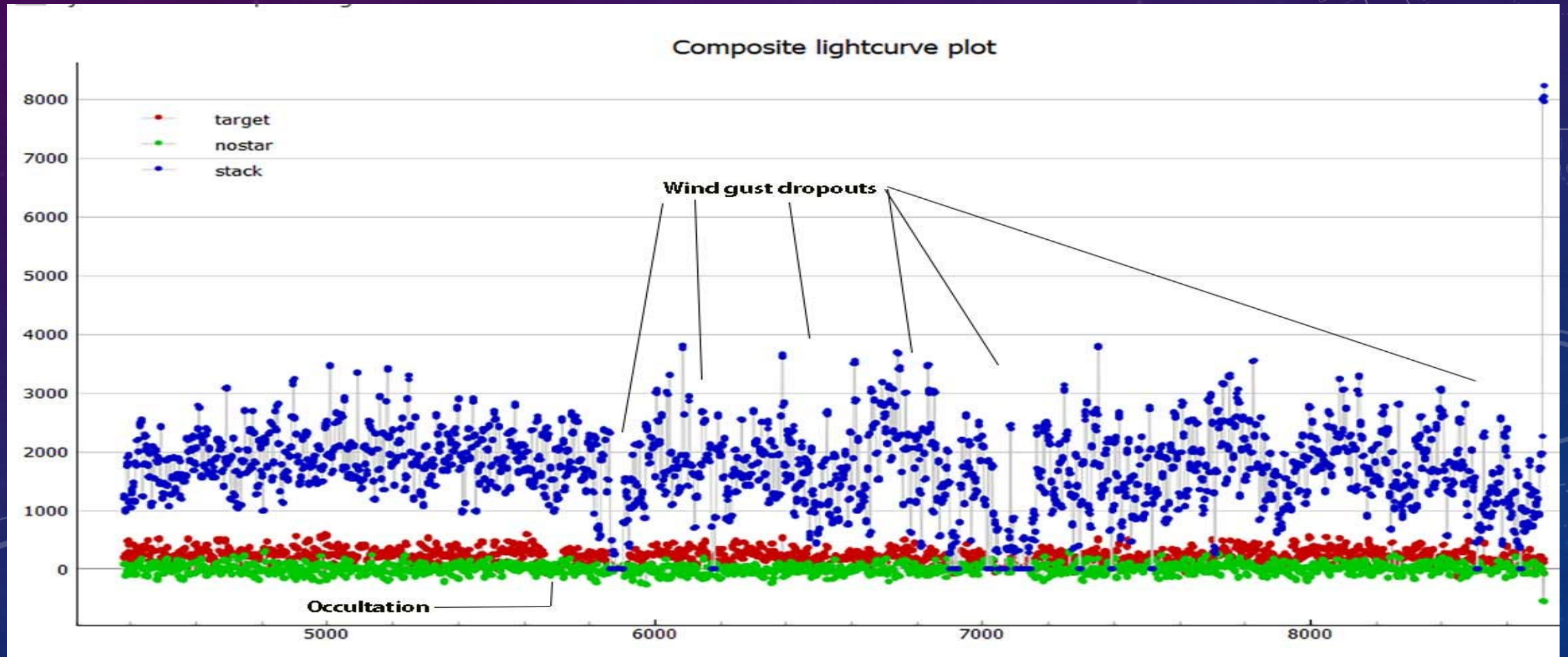
35 KNOT WINDS, POOR SEEING, BRIGHTER SKIES, 25 DEGREES ALTITUDE, AND A STAR AT ½ THE BRIGHTNESS OF THE JUNE 9 EVENT. SO, IT WAS A CHALLENGE….

WE ALSO HAD TO WORRY ABOUT POSITIONING TO AVOID CLOUDS… WHICH ACTUALLY NEVER SHOWED UP. CLEAN SKIES FOR ALL.

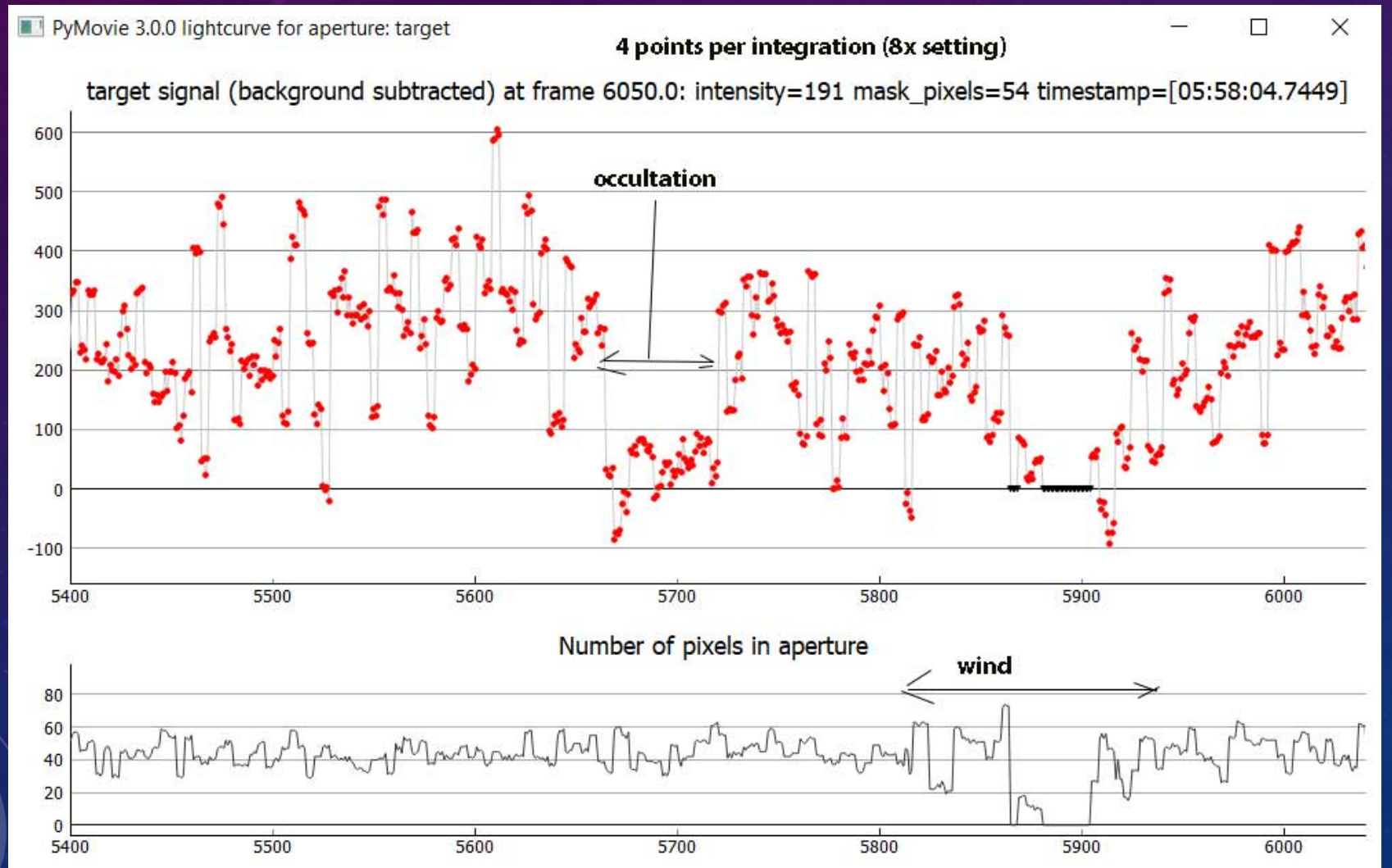


WIND WORSENED. I MOUNTED A TABLE ON CAR ROOF, LASHED LEGS TO BIKE CARRIER. THAT HELD THROUGH THE EVENT, BUT SHORTLY AFTER, IT WORKED LOOSE AND FLEW OVER THE TELESCOPE, KNOCKING ME OVER AS I STOOD ON THE NEAR SIDE OF THIS PICTURE AT THAT TIME. *RISKING LIFE/LIMB FOR SCIENCE!*

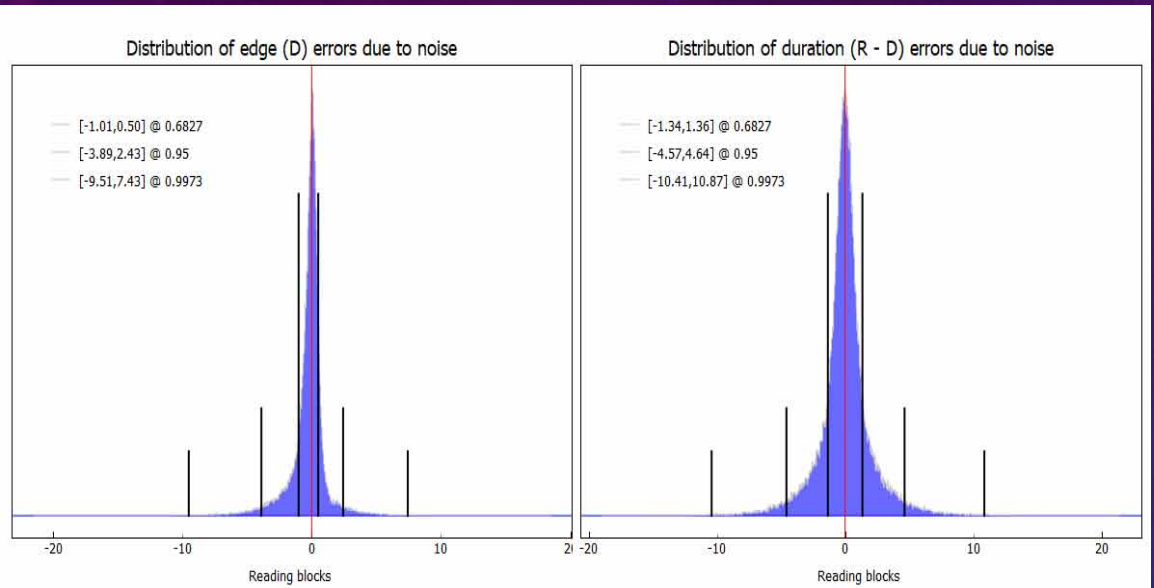
NOLTHENIUS DATA: TARGET STAR IN RED. WORST WIND GUSTS STARTED JUST ~5 SEC AFTER THE EVENT. PYMOVIE LOST ACQUISITION OF EVEN THE BRIGHT TRACKING STAR AT THESE TIMES. NO EVIDENCE OF SATELLITE OCCULTATION. BENDER, NEARBY, BETTER CONFIRMS.

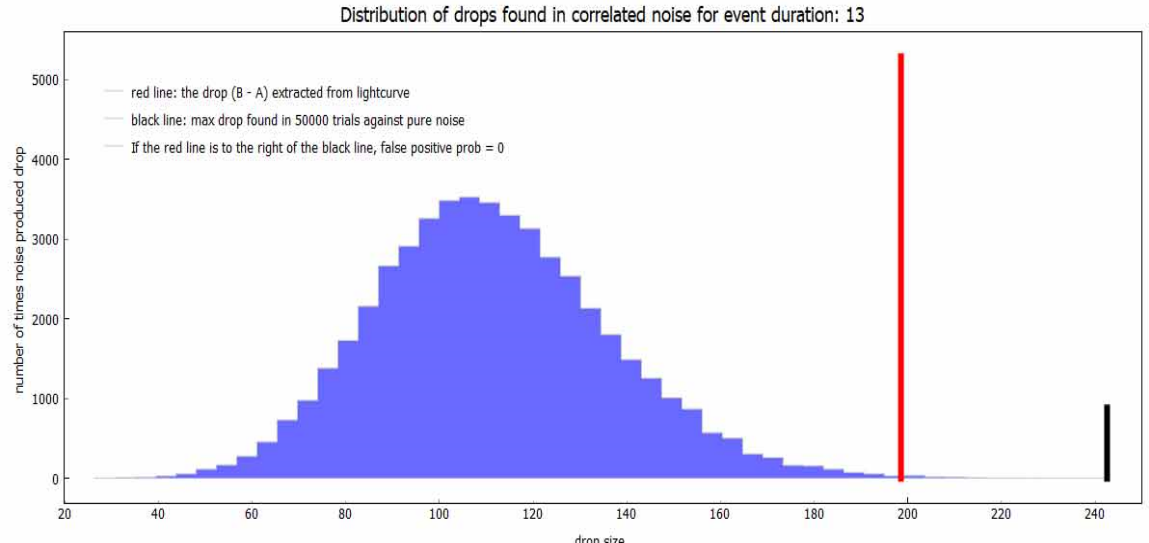


ZOOMED IN ON OCCULTATION MOMENT. 8X INTEGRATION ON WATEC 910HX, 8” CELESTRON 8SE WITH F/3.3 REDUCER. NOLTHENIUS RAW LIGHT CURVE FROM PYMOVIE



FORMAL FALSE-POSITIVE ERROR HISTOGRAM FROM PYOTE ON NOLTHENIUS DATA. FALSE POSITIVE PROBABILITY TINY, BUT NON-ZERO



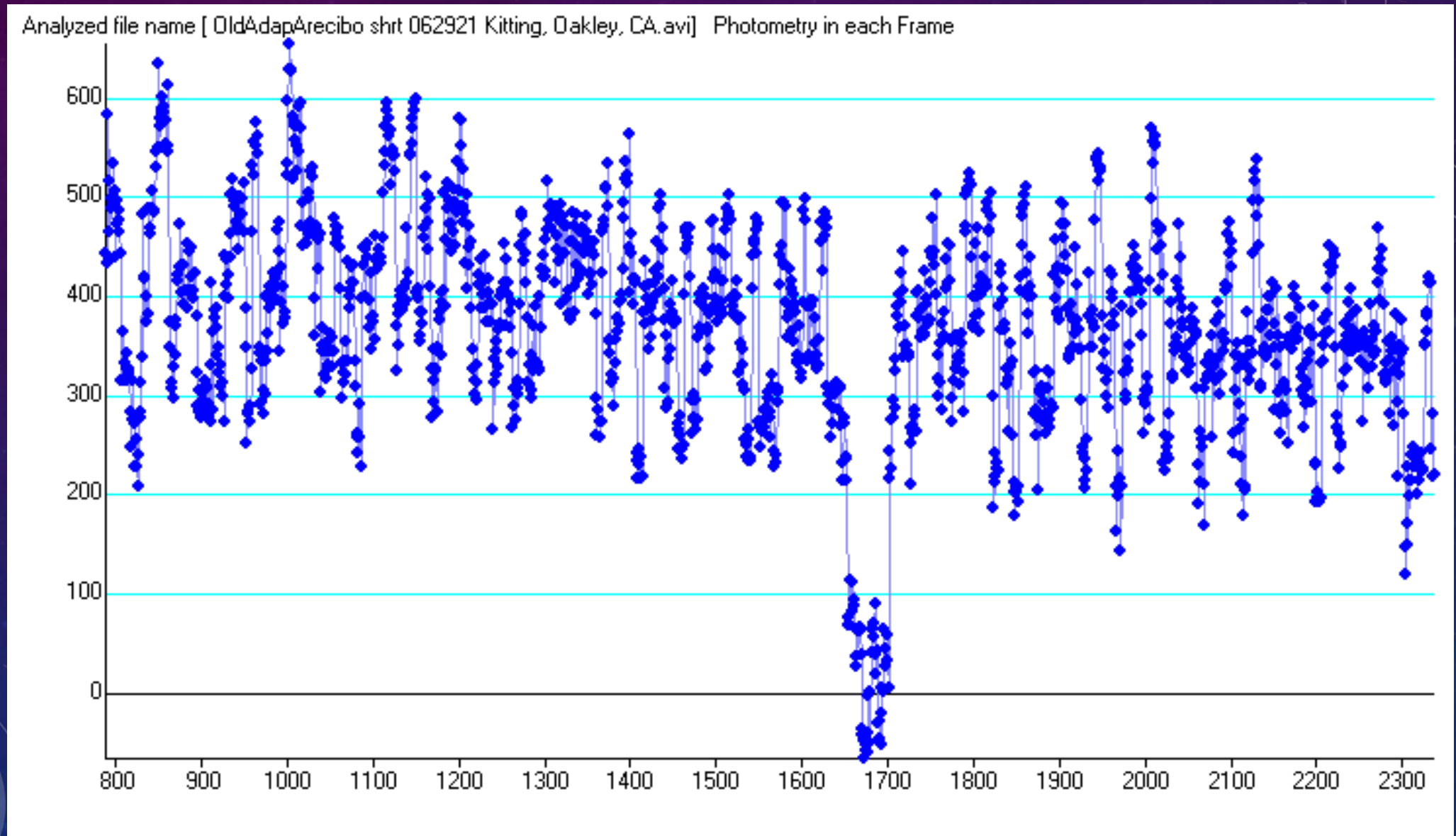


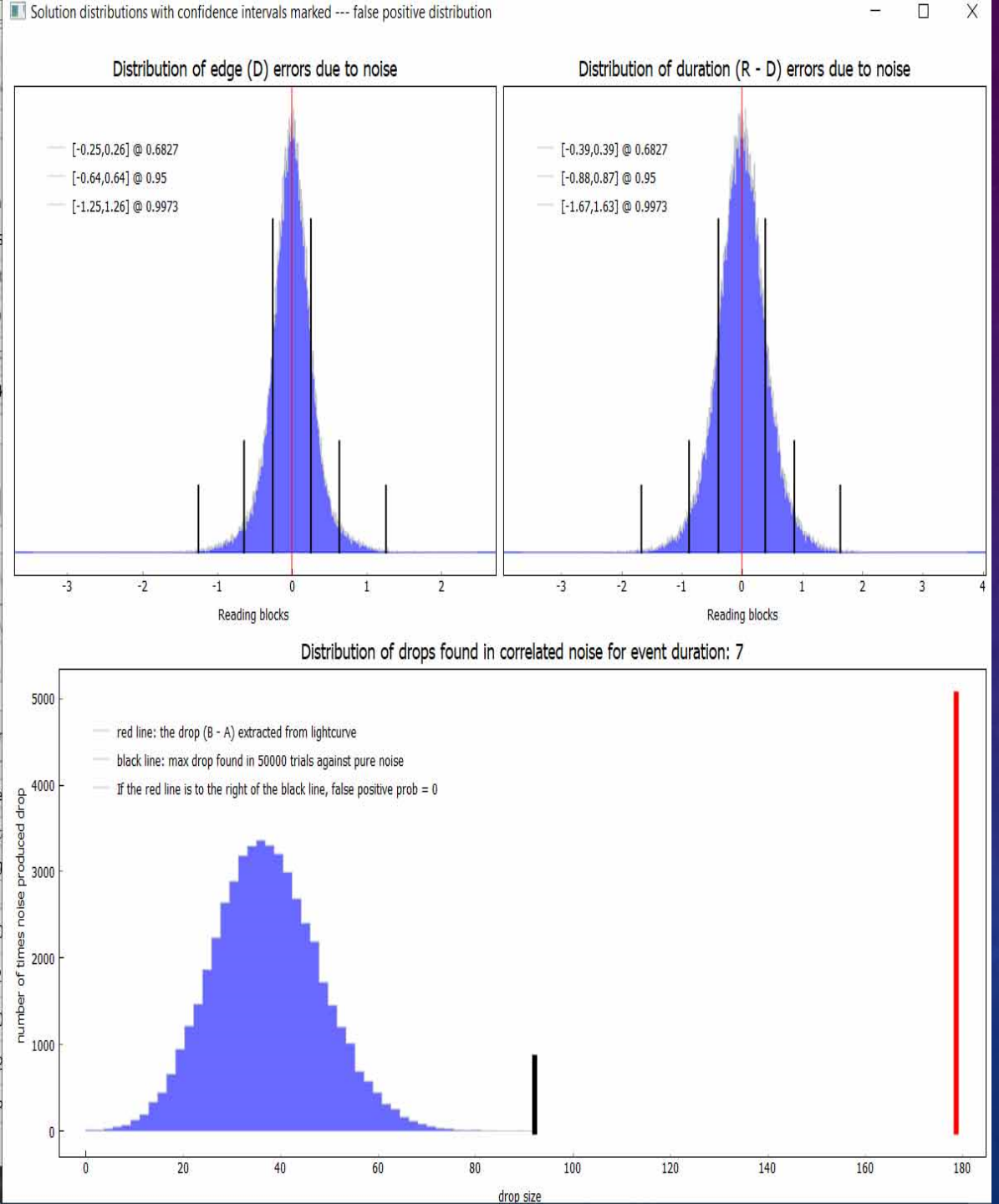
- Wind shake events left in the .csv data analyzed by PyOTE
- These are clearly wind-shake: <u>All</u> stars shook and lost acquisition!
- Current coding does not permit using the calm periods data if it is not contiguous with the event,
- This pushes the PyOTE decided false-positive probability higher than necessary (99.995% certain of a positive, is this the criterion??)

IN ADDITION TO KIRK BENDER AND WE ADDITIONALLY HAD CHRIS KITTING…

- Chris is a professor of marine biology at CSU East Bay, and was going to be inside the occultation path doing marine research in the Delta region he set up at, near Oakley, and brought his astro equipment along, and took time out to get the occultation .
- He’s occasionally done other high-value occultation attempts in the past, and his 10” Newtonian had good light gathering for this difficult event.
- Getting the data from his Sony DV camcorder to his Mac computer and then analyzed into a CSV file was a challenge, due to driver errors and the general trouble we’ve had in transfers into computers… but ultimately successful.
- He spent much time away from his research to contribute to this campaign and deserves our thanks.

KITTING'S LIGHT CURVE, ZOOMED IN ON EVENT (OTHER DATA IN WINGS NOT SHOWN). NO EVIDENCE OF THE SATELLITE.

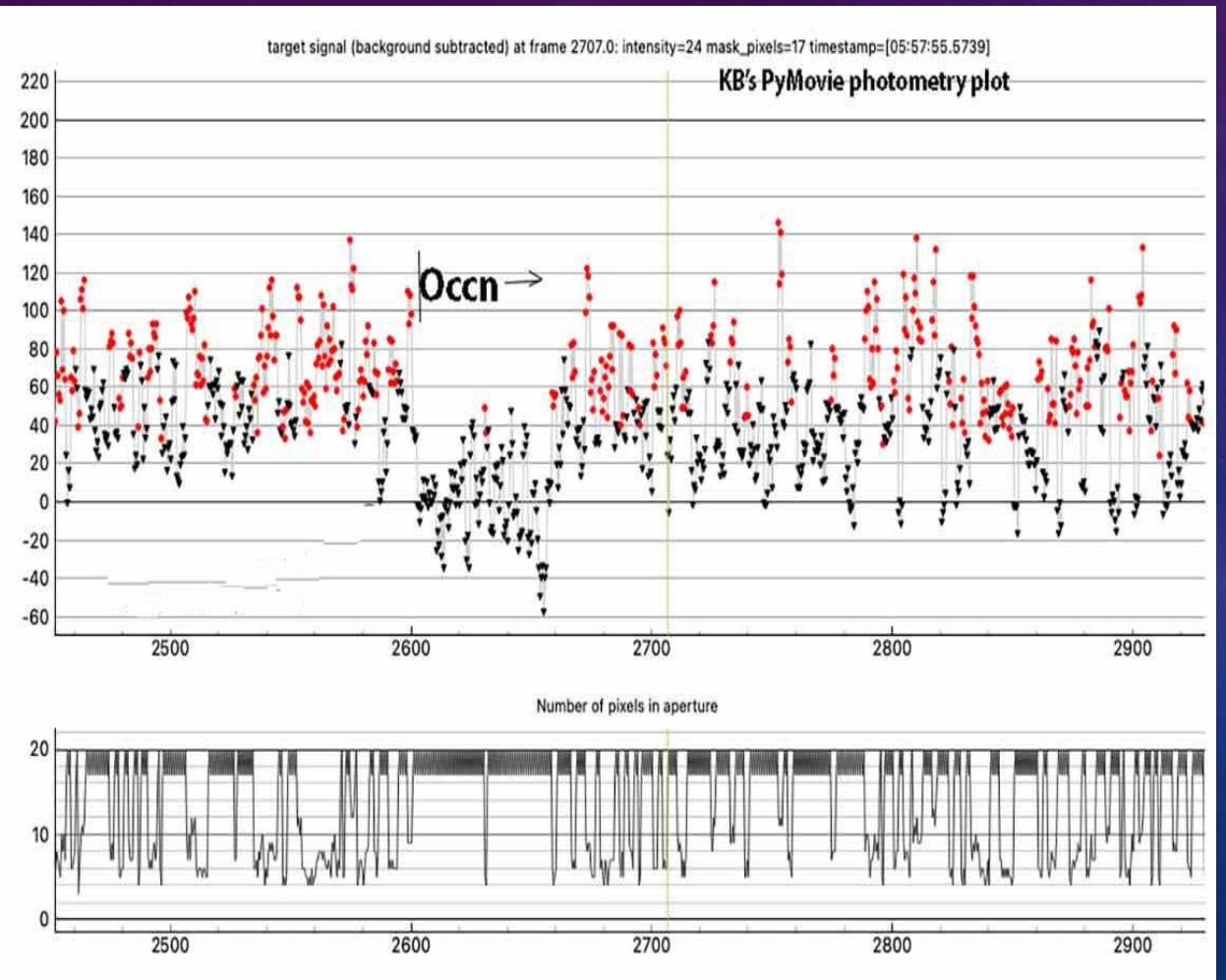


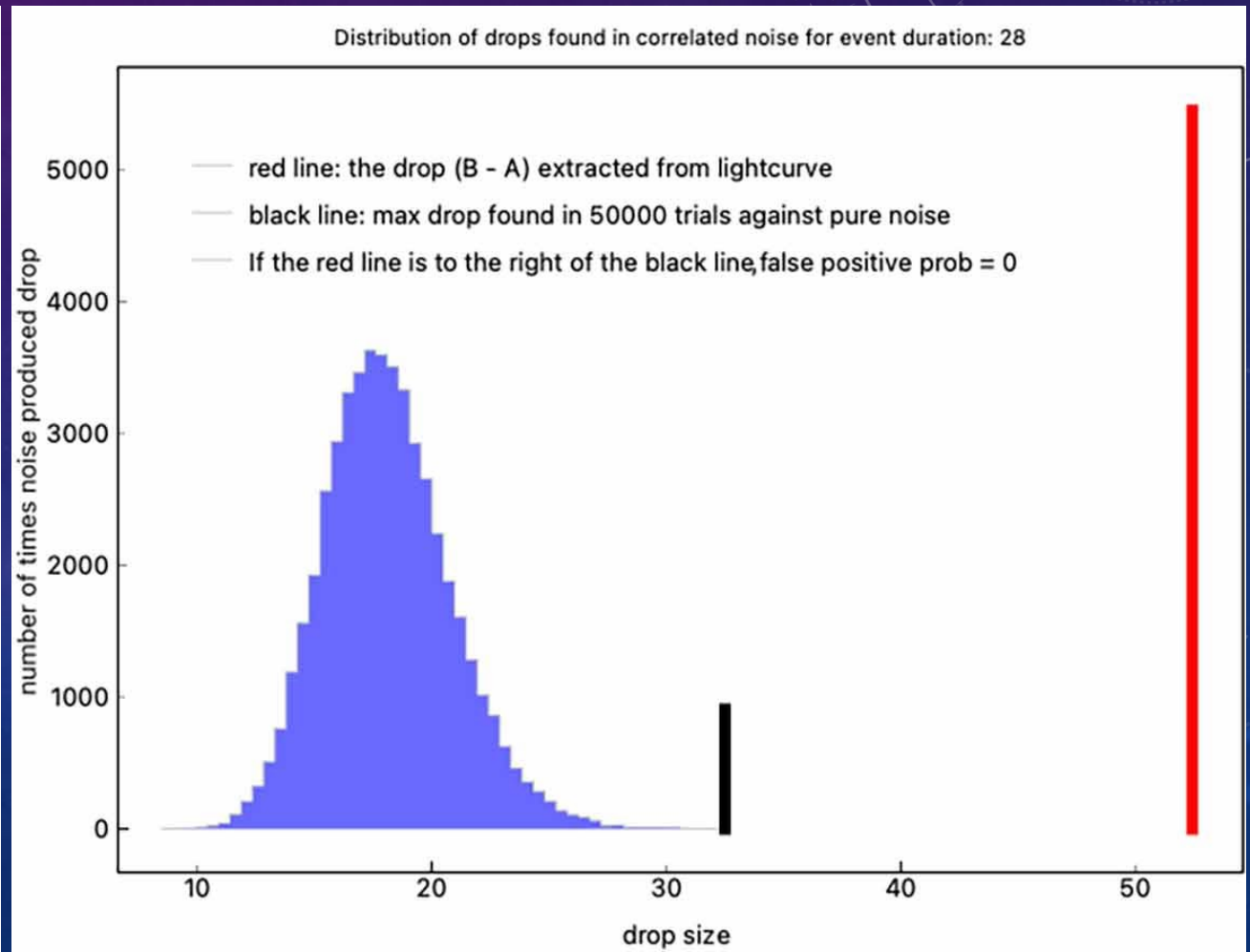


KITTING'S FALSE-POSITIVE HISTOGRAM. SOLID!

- 10" f/4.5 Newtonian, Watec 910hx with IOTA VTI. Sony video-cam for recording MiniDV.
- Clear, slight breeze but did not interfere with stability.
- Left on 16x in the rush; could have done 8x or even 4x.

KIRK BENDER'S PYMOVIE LIGHT CURVE OF TARGET. MUCH LESS WIND TROUBLE. 4X SETTING, IDENTICAL EQUIPMENT AS NOLTHENIUS. NO EVIDENCE OF SATELLITE, 3 MINUTE TOTAL RECORDING DURATION.

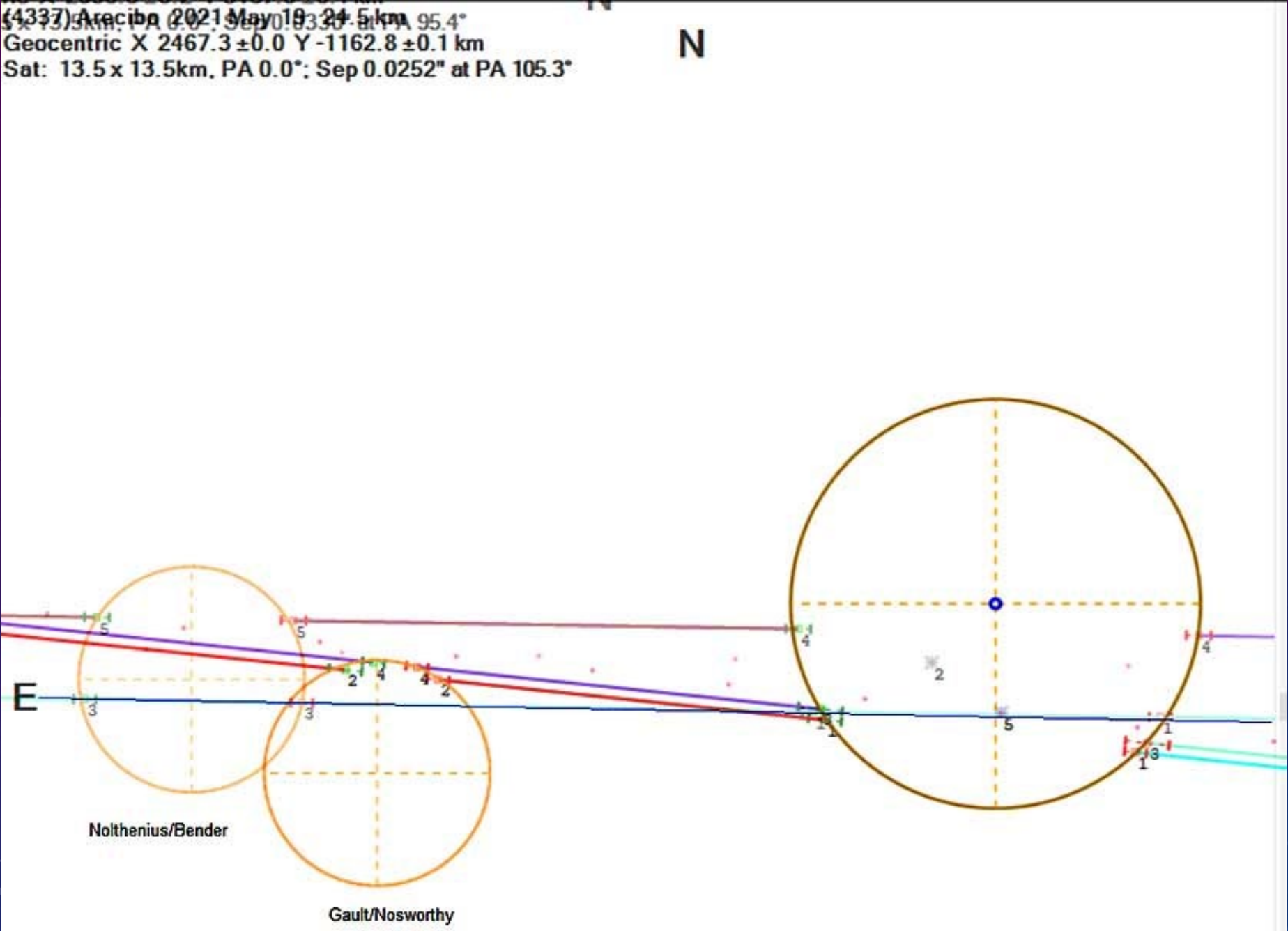




I'M EXTREMELY IMPRESSED WITH PYMOVIE'S ABILITY TO GET SIGNIFICANTLY HIGHER SIGNAL OUT OF ATMOSPHERICALLY CHALLENGED DATA, VS. LIMOVIE.

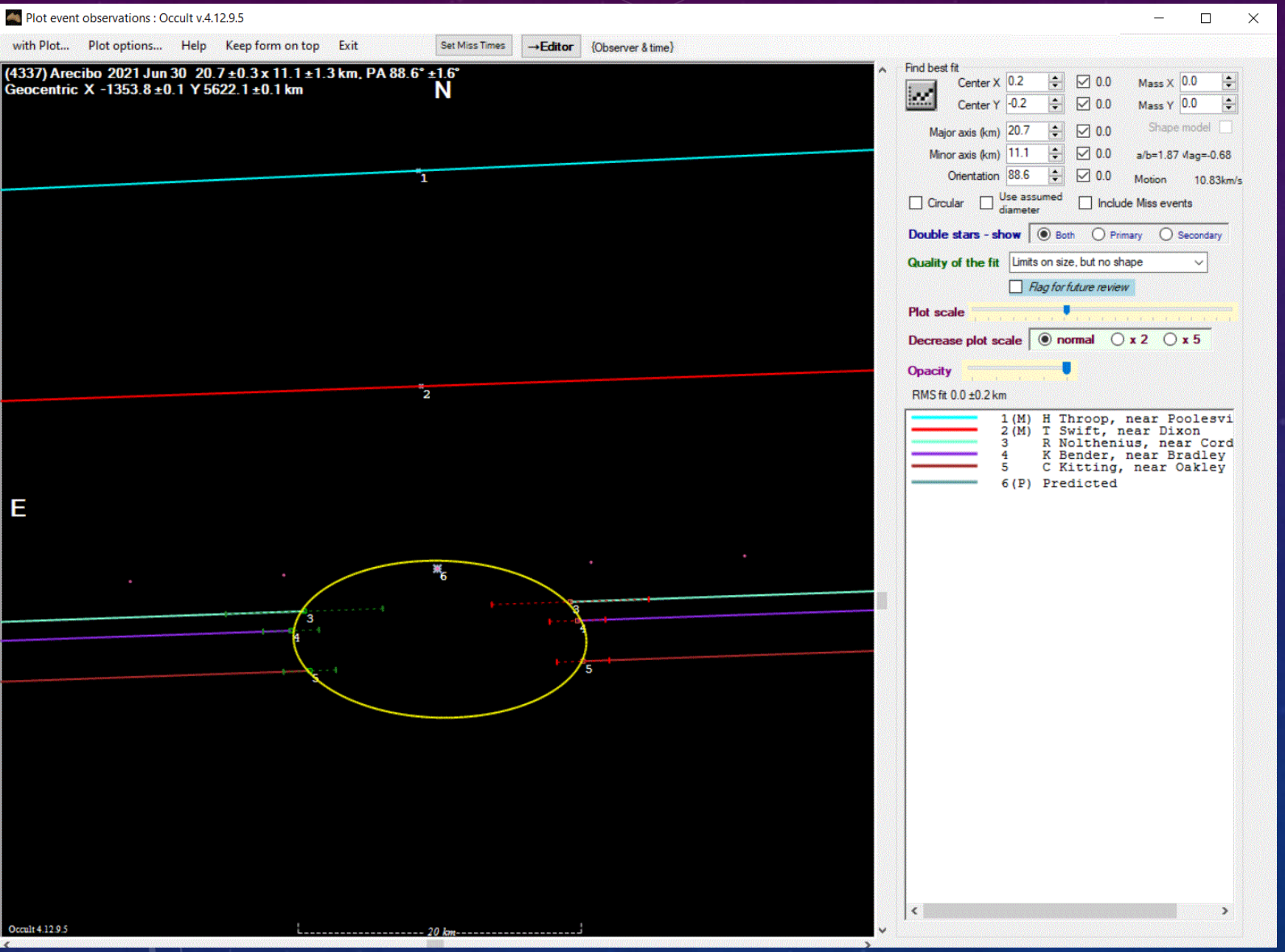
- I was skeptical at first, but have become a convert of its remarkable adaptive skills in allowing maximum extraction of data from our recordings. Occultationists should be using PyMovie
- **But I do have suggestions for PyMovie, PyOTE…**
- **1.** Allow observer to surgically delete brief periods of wind shake (or tripod-tripping, etc.) out of CSV record. Modify "trim" feature in PyMovie to allow this
- **2.** When selecting the D and R regions for PyOTE to search, allow the bottom of the occultation to be used for both the D region and the R region. Currently, it forbids this. A good sampling of occulted vs unocculted can only help better determine the D and R moments.
- **3.** In PyOTE, allow the observer to select an arbitrary smoothing length for using the comparison star in the light curve of the target. Why? Because long integration times and fast moving clouds can require the smoothing time to be much less than 30 data points, which is the current lower limit.

USING THE SKY SAFARI APP ON KIRK'S IPHONE – SHOWS THE ASTEROID AND HORIZON AT USER-SPECIFIED TIME, ALLOWING CONFIDENCE OF A CLEAR VIEW AT EVENT TIME



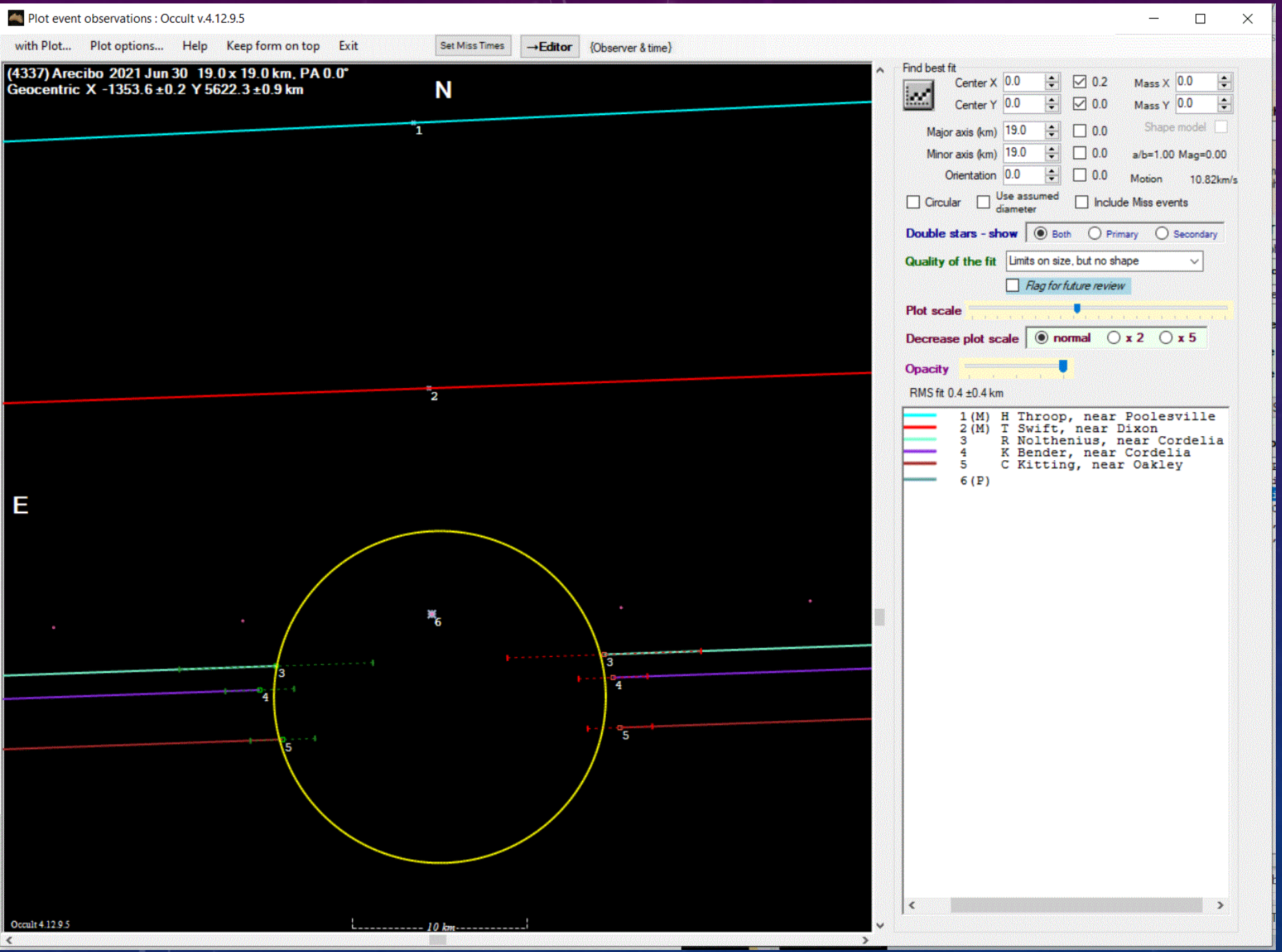
THE SATELLITE POSITION WAS SIMILAR FOR BOTH THE MAY 19/20 DISCOVERY AND THE JUNE 9 EVENT 20.708 DAYS LATER.

ANOTHER 20.788 DAYS LATER, WE HAVE THE MOMENT OF OUR 3RD EVENT: JUNE 29. WOULD THE SATELLITE BE IN A SIMILAR POSITION AGAIN?



TAKING OUR FORMAL JUNE 29/30 EVENT TIMINGS GIVES A PRETTY ELONGATED MAIN BODY… BUT THE TIMING ACCURACIES ON THIS BRIEF 1.9 SEC DIFFICULT EVENT EASILY ALLOW A MORE LIKELY FIT:

A CIRCLE WORKS FINE… (NEXT SLIDE)



THE SKY PLANE PLOTTED RESULT:

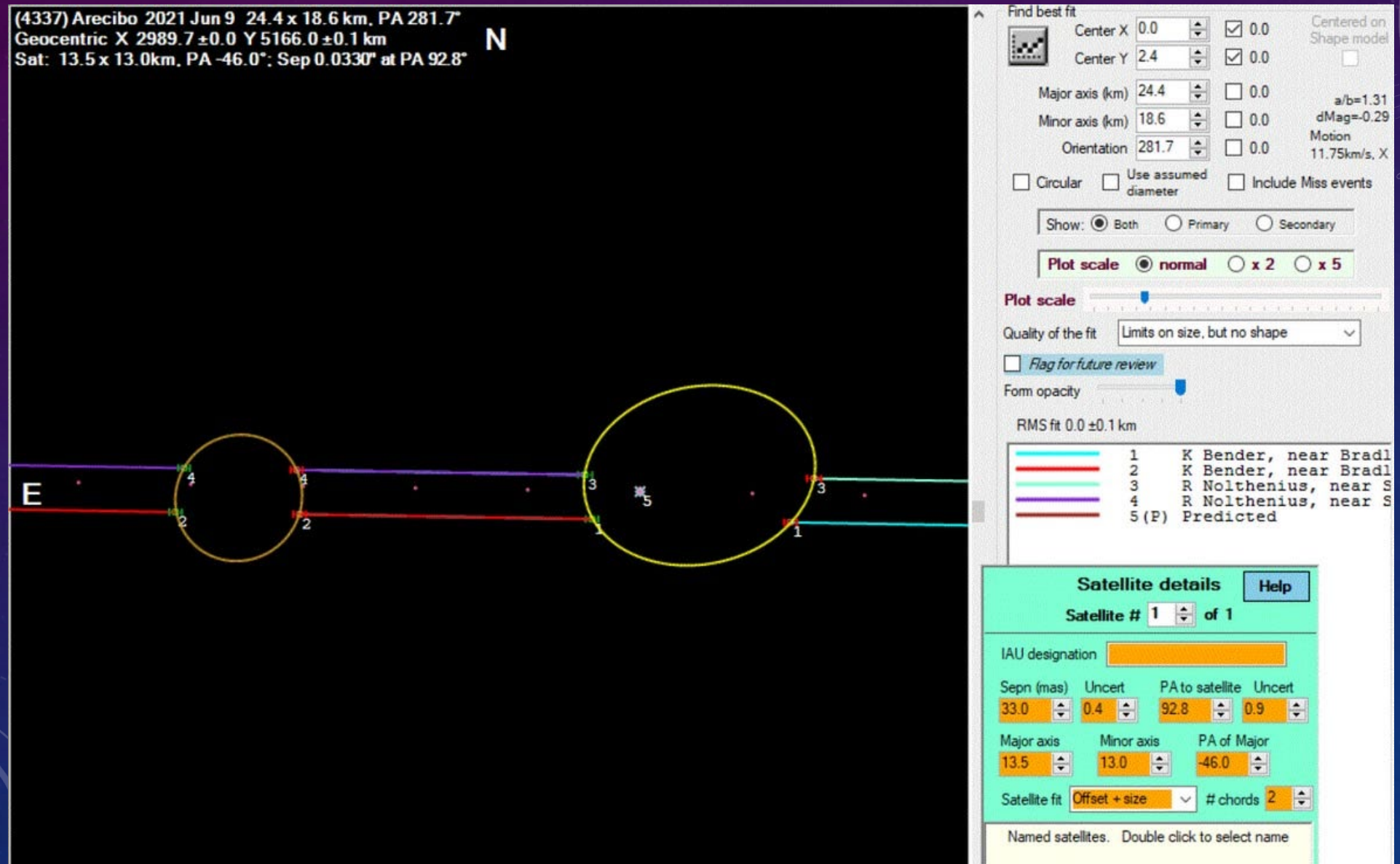
TED SWIFT NEAR DIXON, AND H. THROOP FARTHER EAST, SAW MISSES.

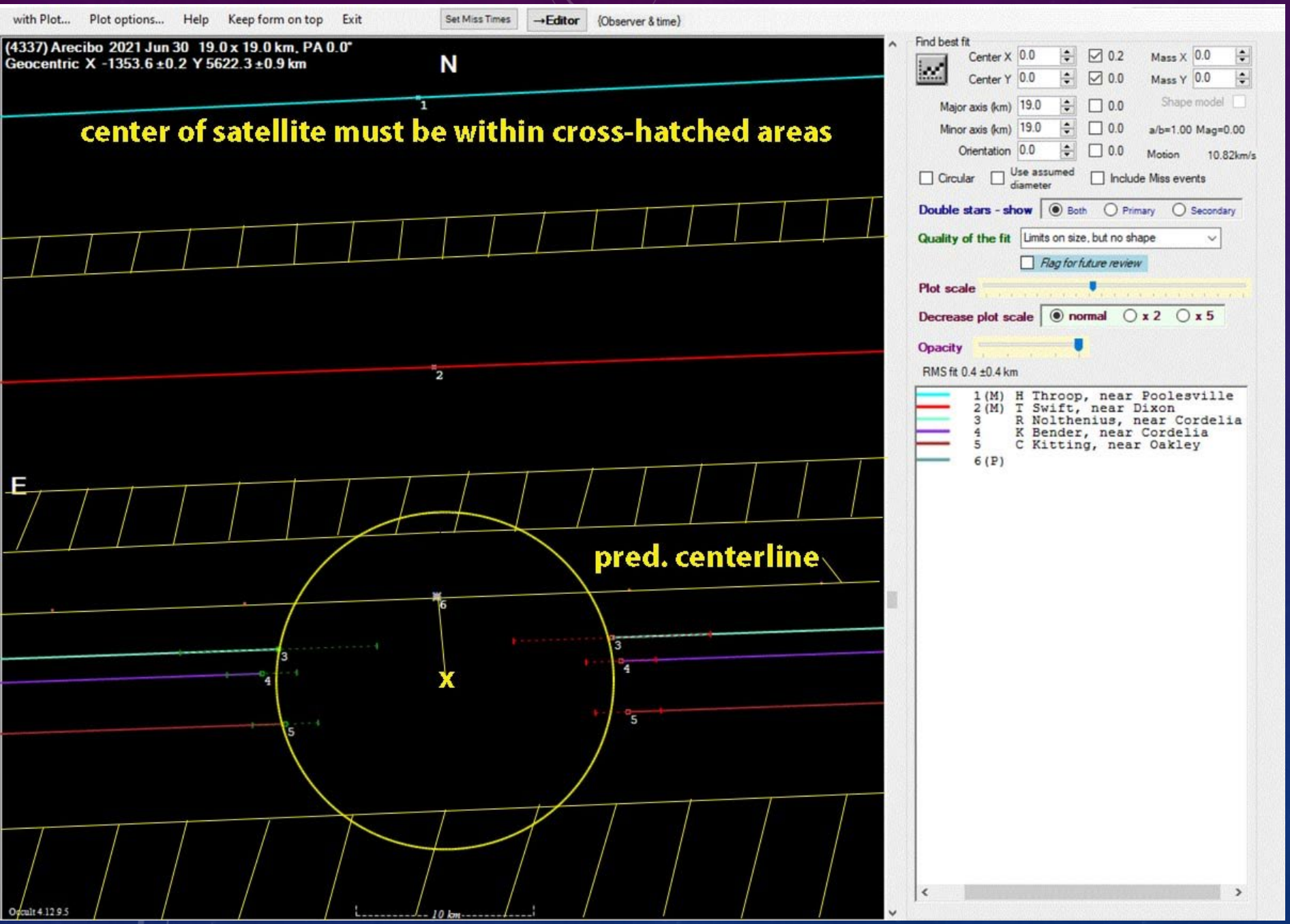
ALAS, NO SATELLITE HIT

OUR D, R TIMES NOT ACCURATE ENOUGH TO SAY MUCH ABOUT THE POSSIBILITY WE SAW A BLENDED IMAGE OF ARECIBO + MOON.

- However, if not a blended image, then the small formal errors on the Arecibo main body path suggest…
- … the moon would likely be **north** of the main body, since our best fit shows the main body centered significantly south of the centerline, unlike at the prior two events where main body was significantly closer to the centerline
- But if the satellite were as close in the north/south direction as for the May 19 Gault/Nosworthy discovery and the June 9 Nolthenius/Bender confirmation, then there's precious little space for that satellite to have escaped our June 29/30 net…

THE WELL MEASURED DIAMETER AT THE JUNE 9 EVENT SAYS THE SATELLITE WAS 13.2 KM IN DIAMETER AND NEARLY CIRCULAR. THEREFORE…





THIS REQUIRES THE CENTER OF THE SATELLITE TO BE WITHIN THE CROSS-HATCHED AREAS ON JUNE 29/30 EVENT…. NOT IMPOSSIBLE, BUT UNLUCKY FOR SURE.

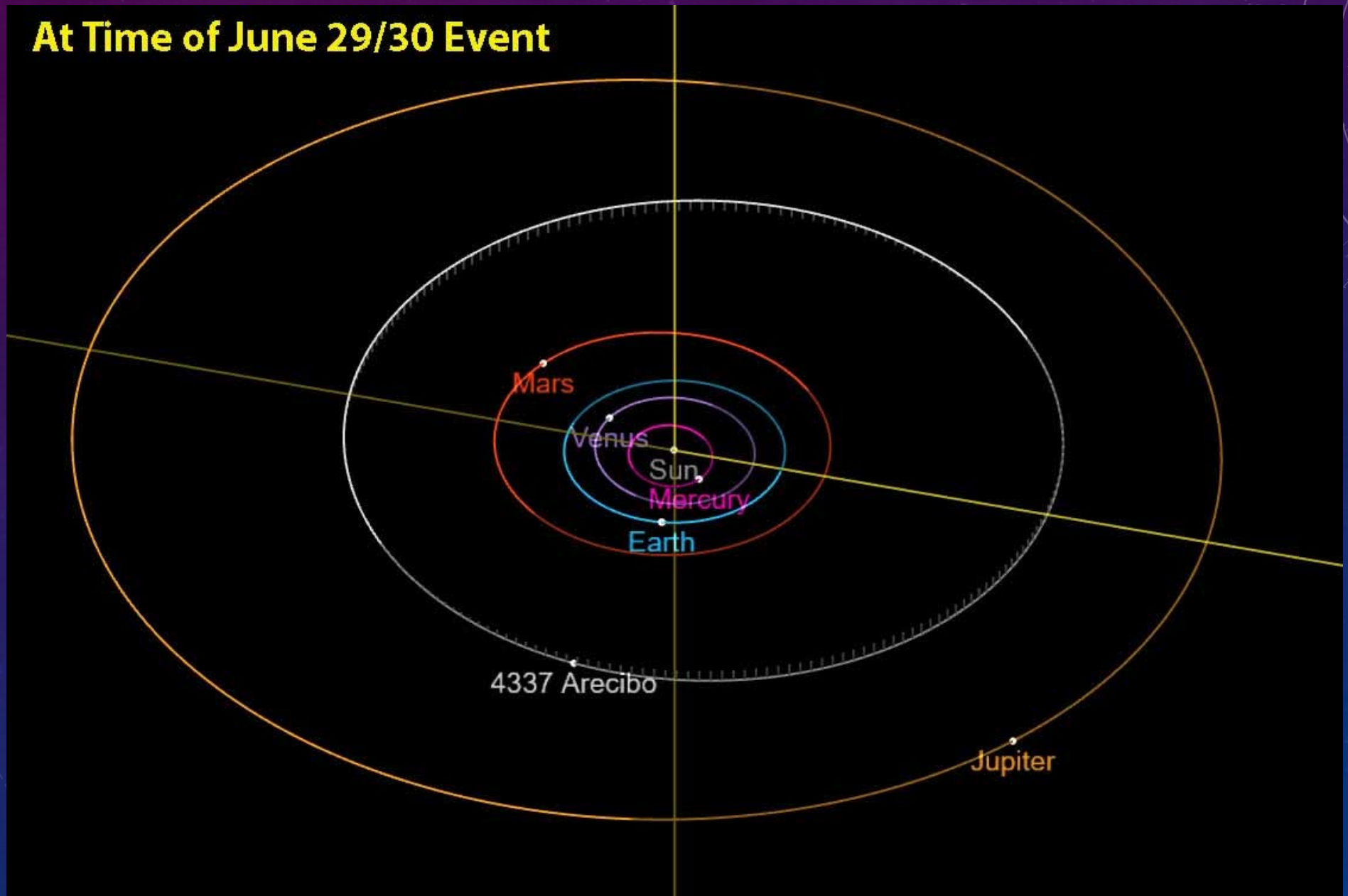
BUT HOW SMALL MUST THE SATELLITE SEMI-MAJOR AXIS BE?

THE NOLTHENIUS/BENDER JUNE 9 TRACKS WERE SELECTED TO GET THE MAIN BODY. THE GALT/NOSWORTHY MAY 19 (FIXED SITES) ENDED UP MIMICING THIS TOO, SO THE FACT THE SATELLITE WAS CLOSE TO THE MAIN BODY FOR BOTH OF THESE EVENTS DOESN'T NECESSARILY IMPLY THE SATELLITE IS IN A CLOSE ORBIT… THEY'RE NOT RANDOM TRACKS

SO, HOW FAR AWAY COULD THAT MOON BE?

- The absolute limit is the distance such that the satellite's pull towards (4337) Arecibo is the same as its pull towards Jupiter – the strongest competition.
- This is an outer main belt asteroid, and given the near circular orbit (e=.09) and Jupiter being only 0.86 AU further, at conjunctions, I hoped would provide a tight constraint… but when I did the calculation, it's not very tight.
- Assuming an outer belt representative density of ~1.9 g/cm^3, then Jupiter's gravity would tidally unbind the satellite if its (assumed circular) orbiting distance were larger than 292 km (that's 28.5 sec either side of the June 29 event time, so all of our data easily includes the possible satellite positions).
- If the satellite orbit is elliptical, then the limit could be smaller, since it's the farthest point that controls here, not *a* itself.

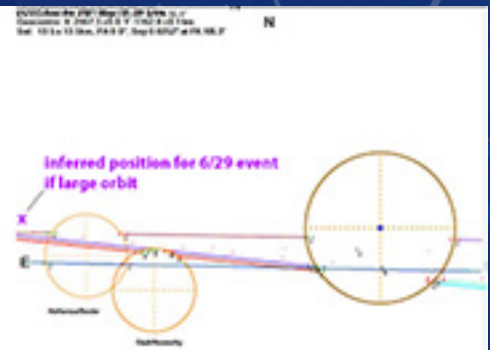
ARECIBO AND JUPITER GET LESS THAN 1 AU APART

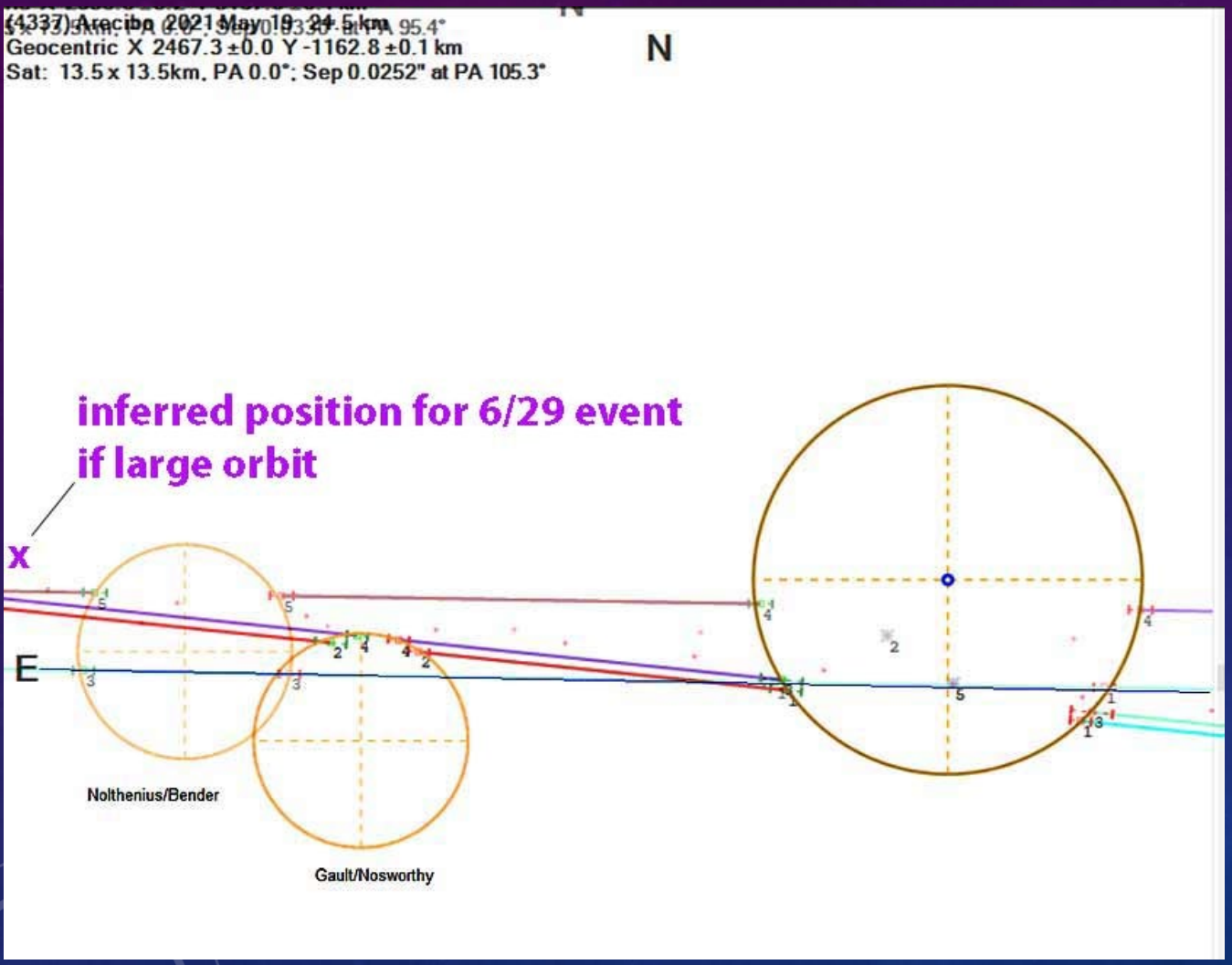


TIDAL SEPARATION BY JUPITER CONSTRAINT

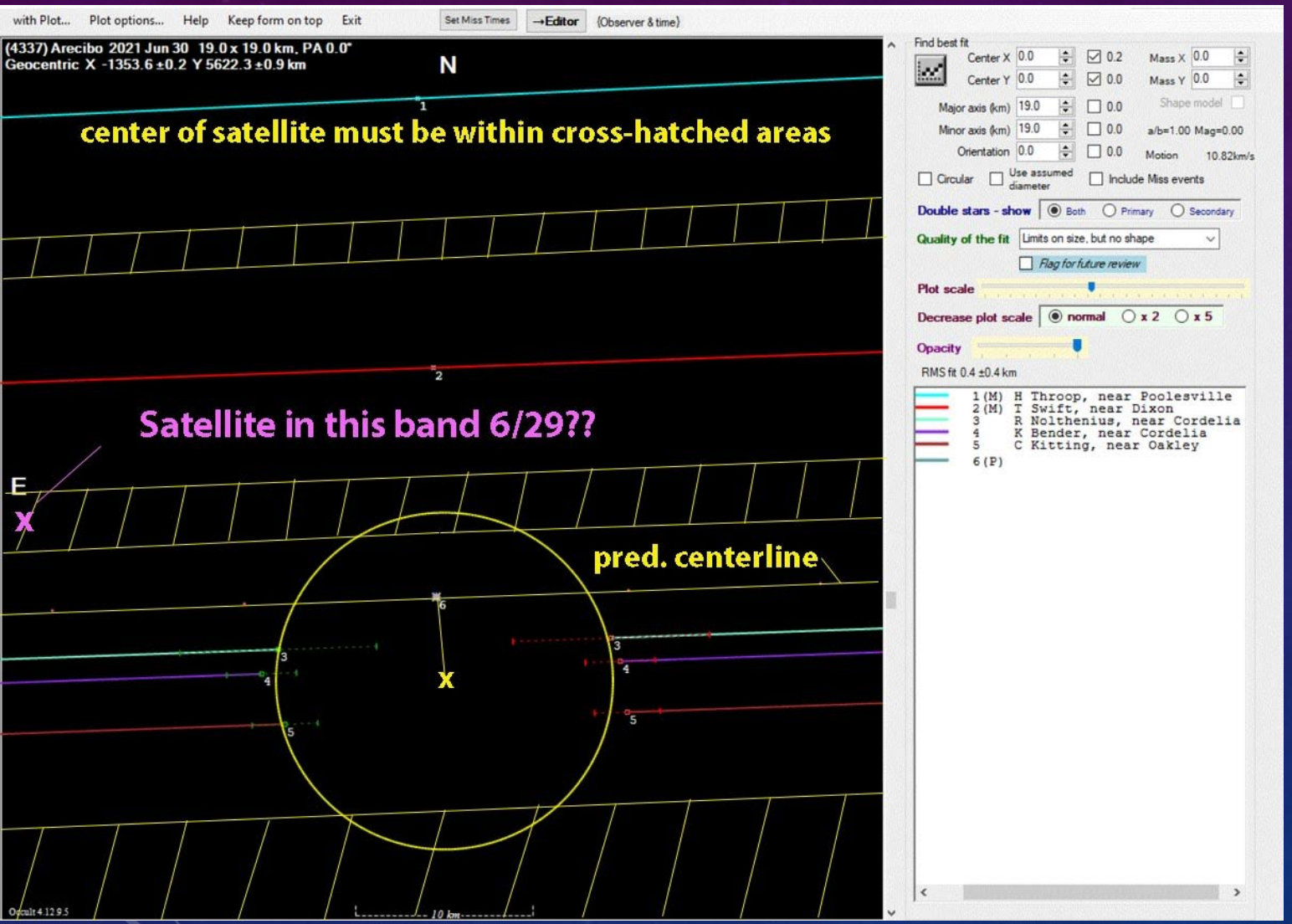
- This is an outer main belt asteroid, if you assume a typical (rough) density of 1.9 g/cc, then the occultation determined main body size infers a mass of 9.6 x 10^{18} g.
- Gravitational force on satellite from main body (subscript a = Arecibo) matches that for Jupiter (J) at a separation of…
- $R = (a_J - a_a)\ \mathrm{sqrt}(M_a/M_J)$ where a is the semi-major axis

Tidal unbinding by Jupiter beyond 290 km, for typical density





IF THE ORBIT IS REASONABLY LARGER THAN THE SEPARATIONS HERE, THEN THE VERY CLOSE MATCH IN TIME INTERVALS FROM THE MAY 19->JUNE 9 -> JUNE 29 EVENTS (20.708 DAYS *VS.* 20.788 DAYS) ARGUES A SIMPLE EXTRAPOLATION PUTS THE SATELLITE AT THE PURPLE POSITION FOR OUR JUNE 29 EVENT.



THAT WOULD INFER THE SATELLITE CENTROID WAS INSIDE THE PERMITTED HATCHED AREA HERE.

TEMPTING TO INFER P=20.0 DAYS, BUT THAT WON'T WORK… THAT GIVES *a*=392 KM, WELL BEYOND THE JUPITER TIDAL LIMIT

ASSUME TYPICAL DENSITY OF 1.9 G/CM^3, GIVES MASS OF SYSTEM = 11.9 X 10^{18} G

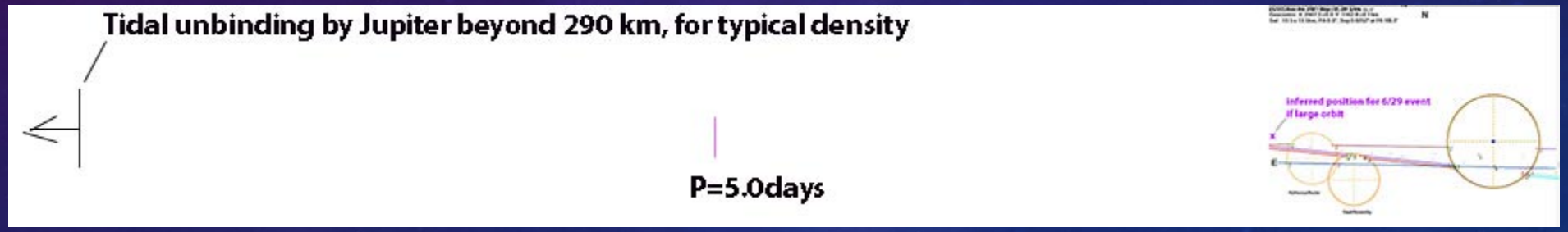
- Assume orbital semi-major axis of a=100 km =~2x the Gault/Nosworthy position, projected onto sky.
- Then Kepler's 3rd Law gives…
- orbital period of only ~2.58 days
- But poorly constrained… P proportional to $a^{1.5}$

THERE'S A GOOD 50% CHANCE THE SATELLITE WAS ON THE SAME SIDE OF THE SKY PLANE AT BOTH OBSERVED EVENTS. (AND A 50% CHANCE IT WASN'T).

- If on the same side, then it argues the orbital period is a sub-multiple of 20 days. (Remember – 20 days itself is impossible – it violated the Jupiter tidal limit)
- So; 10, 6.667, 5, 4, 3.333, 2.857, 2.5, 2.222 days are possible.
- Unlikely less than that as it constrains the position at the June 9 event.

P=10.0 DAYS COULD WORK

- That gives a=247 km, but that's uncomfortably close to the Jupiter tidal limit of 292 km
- So perhaps P=5.0 days, then get a= 156 km



- We're not well constrained here… but there's a better way to answer the orbital period…

THE BEST WAY?… FIND THE PHOTOMETRIC PERIOD OF (4337) ARECIBO.

- Tidal locking is likely, so that any ellipticity or varying albedo should produce a photometric period = orbital period of satellite.
- The **Johnston data base** gives the most up to date information I can find **on (4337) Arecibo**.
- No photometric period is given.
- But the PANSTARRs database should have many observations of this asteroid.
- And the SuperWASP database was used to help classify variable stars from their periodograms, and may also have solar system objects (with their varying positions) also available. Not all data is publicly available. A quick look did not show me how to get asteroid photometry data.

2ND BEST WAY – GET ONE MORE OCCULTATION

- While it's true the mass of the objects is not a given and therefore we really need 4 observations to fix an orbit, still – it's reasonable to guess a typical density, hence mass, and then have a good set of guesses for the position at future occultations, for placing observers.
- The period P only varies with the square root of the system mass M, and so is not very sensitive to the assumed density – this is good.
- But it also means for the interesting science, we need a very well-determined orbit. But, for the near term, our goal is to optimally guess how to place observers at future events.

ANOTHER WAY: GET THE VELOCITY OF THE SATELLITE WITH JUST ONE MORE OCCULTATION

- For a Period of 2.5 days, the satellite moves its own 13km diameter every ~48 minutes
- With another cross country or intercontinental path, we could, with good timings, get a handle on the velocity of the satellite. This would rule out may of the sub-multiple periods
- For this, I suggest a good strategy would be for at least two of the widely spaced observers to be on the same track, to minimize topographic variation-caused time differences, and isolate the velocity.

(4337) ARECIBO WILL REMAIN IN THE MILKY WAY FOR SEVERAL MORE MONTHS – HRISTO'S NEW OCCULT-WATCHER CLOUD SITE HAS MANY MORE PREDICTIONS. NOTE: CABRILLO COLLEGE OBSERVATORY HAS A 12.5" SCT (FIXED, ALAS) WITH WATEC 910HX CAPABILITY.

LAST SLIDE: SCIENTIFIC VALUE

- There are currently only 201 main belt asteroids with known satellites.
- With firm periods and orbital sizes, you can calculate the mass of the objects.
- Mass and size give density, and thus a giant step towards likely composition
- Multi- $Million pick-up-surface-and-bring-home missions, like Hayabusa, only get what's on the surface, which could be detritus from environment and not represent the bulk of the asteroid.
- **Are they made of mostly ice? Mostly light rock? Dense rock? Carbon? (carbon rich asteroid surfaces in the outer Main Belt), puff balls of dust with empty space… pixy dust??**