Two-drop light curves
is it a

Double star ?
Graze ? or
Satellite ?

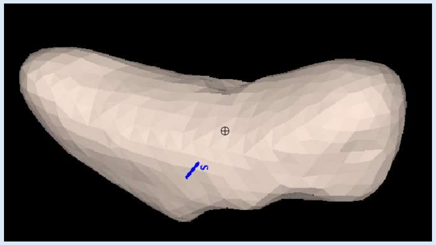
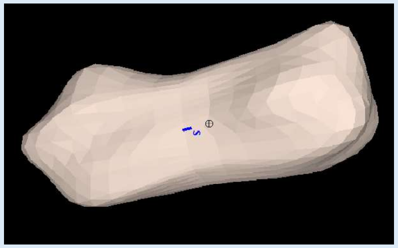
The issue

- Multi-drop light curves can be a challenge
- The excitement of a possible satellite discover can bias their thinking
- Satellite discoveries can range from being ‘obvious’, to being very complicated
- There is no single test that can be applied to explain a light curve as being caused by a satellite
- The process is one of elimination. To be confident that you have discovered an asteroidal satellite, you must be able to reasonably exclude all other plausible explanations

Possible explanations

A double-drop light curve can be caused by:

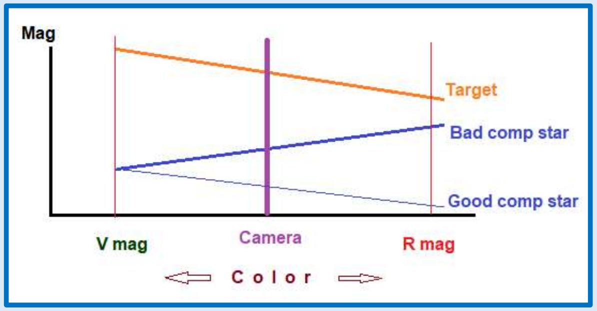
- A **double star**, with the components being occulted separately
- A **grazing occultation**, where the asteroid is elongate and occultations occur at both ends. Think of

Eros  and Kleopatra 

- A **satellite**, where each component of the asteroid occults a single star
- Significantly, a double star event and a satellite event have one thing in common. The interaction between a single object and a double object

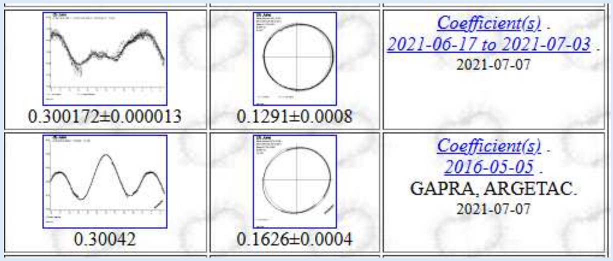
Double star considerations

- The mag drops will *generally* be different, although they can be the same
- Both drops will be less than the predicted full drop
- The sum of the two drops will equal the expected drop if the star was a single star
- Our light curves are generally uncalibrated. You cannot assume the zero level after background subtraction is actually at the true zero light level. **To measure light drops, comparison stars *must* be used**
- Light drops should be color independent. Asteroid color generally not known. Cameras are broad band response. To get reliable mag drops, comparison stars should be of similar color to the target star. That is, the mag differences (B-V) or (V-R) should be similar for the target and comparison stars.



Double star considerations #2

- The light from the asteroid must be included in any light drop calculations.
- For small mag drops – allowance for rotational variations in the asteroid's magnitude must be considered likely, and allowed for.
- Availability of ephemeris? Unknown…
  - ➢Rotational light curve data. Mag drops <0.5
  - ➢Asteroid Light Curve data
  - ➢Web site of Raoul Behrend [Geneva Obs]



- For asteroid light variation ±0.2 mag

$M_{asteroid} - M_{star}$	-1.0	-0.5	0	+0.5	+1.0	+1.5	+2.0
Flux drop range	67%-75%	57%-67%	45%-55%	34%-43%	25%-32%	18%-23%	11%-16%

Double star considerations #3

- Combination double star + double asteroid. Could get occultations involving either 1one or both components of the two systems. Light drops could be the same or different. We have had this situation once, with a known binary system (Antiope, 2015 Apr 12, with the star being discovered to be double). As far as we know, we have never had this situation with an unknown asteroidal satellite. Who knows how such an event will be worked through.
- If an asteroidal satellite is small, Fresnel diffraction will reduce the light drop for the satellite, giving the *appearance* of un-equal drops - thereby suggesting a double star.
- Even worse: if both components are small enough, Fresnel diffraction will reduce the light drop of both components, making a double star explanation seem plausible

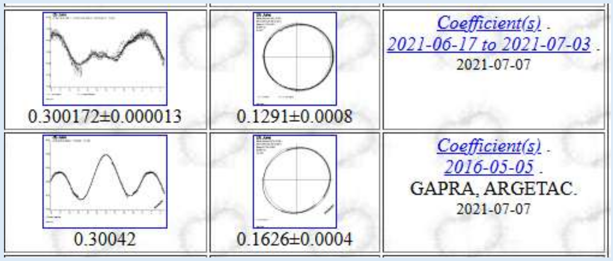
Graze considerations #1

- It requires an elongate asteroid
- The elongation can be large, with lumps at each end – Eros & Kleopatra
- If the shape model has a long straight edge aligned with the chord direction, that could be a possibility. Most shape models are computed on a convex basis, and will not show concave profiles.
- If a shape model is available, the two light drops will need to be within the size of the asteroid.
- If no shape model....

Graze considerations #2

If no shape model, what other info might indicate its elongate?

- Rotational light curve data
  - ➢Asteroid Light Curve data
  - ➢Web site of Raoul Behrend [Geneva Obs]



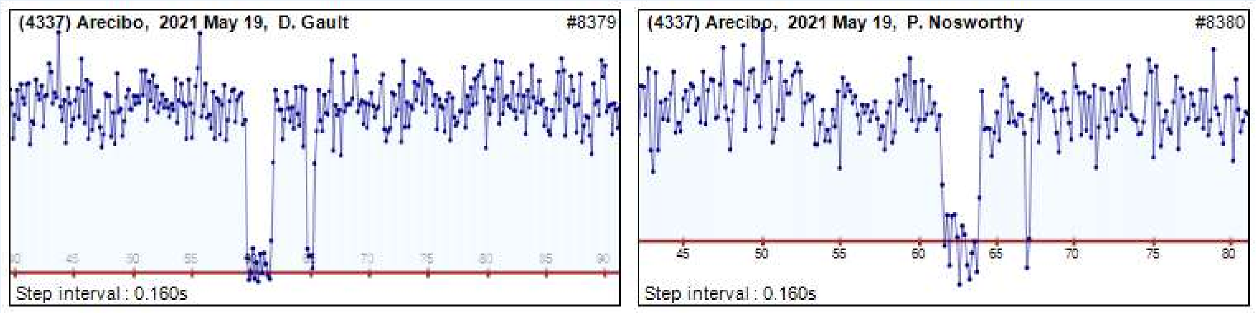
- Significant light variation => elongate asteroid => possible graze
- Small light variation => round asteroid => graze unlikely
- Both events should fall within length of long axis (or a bit more)

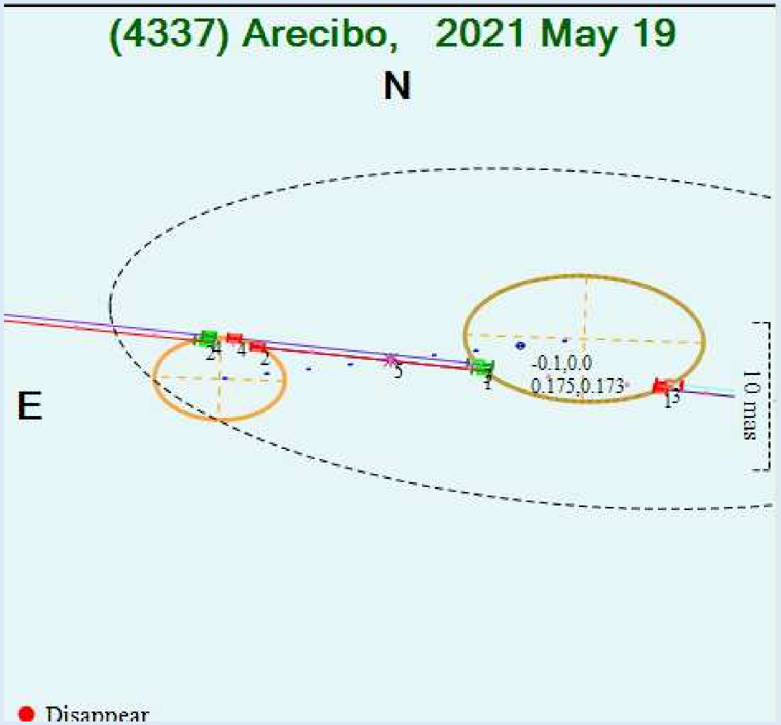
Mag variation	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Axis ratio	1.2	1.4	1.7	2.1	2.5	3.0	3.6

Satellite consideration

- If its not a double star, and not a graze, then a satellite

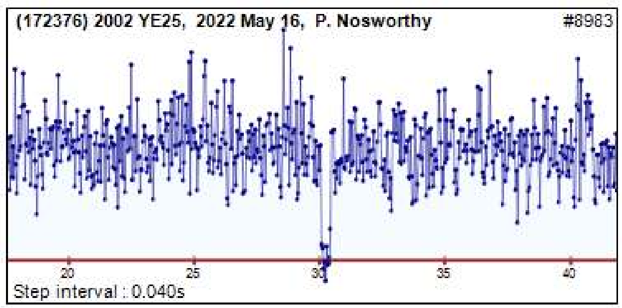
Real-life situations

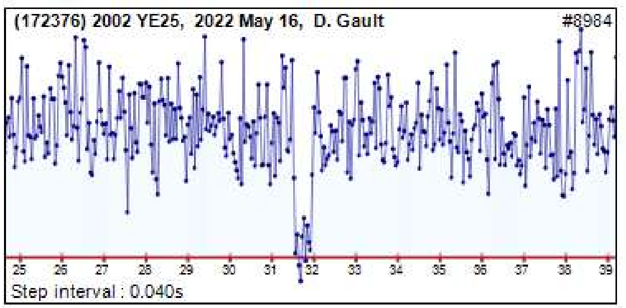


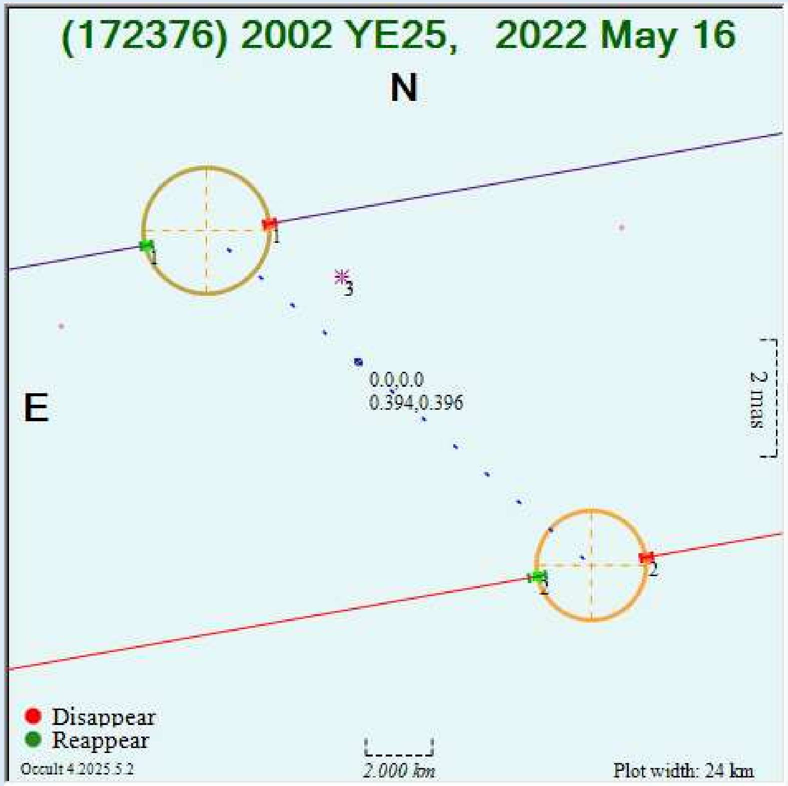


Two observers, both recording two events, with chords fully aligned.

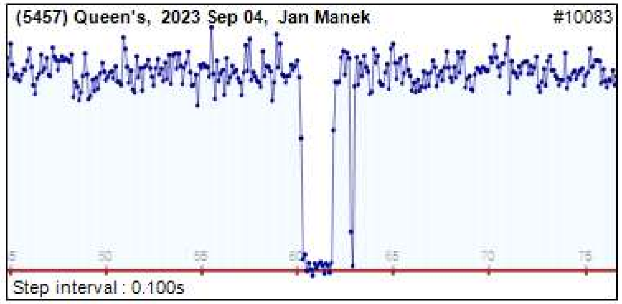
Light drops too large for a double star.

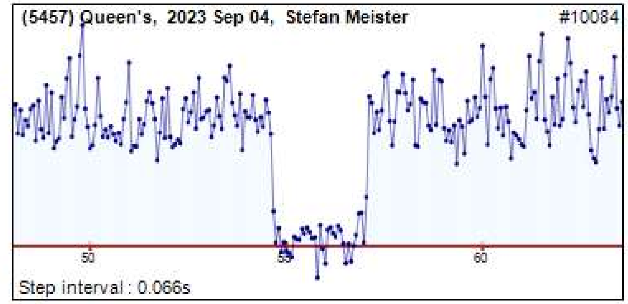


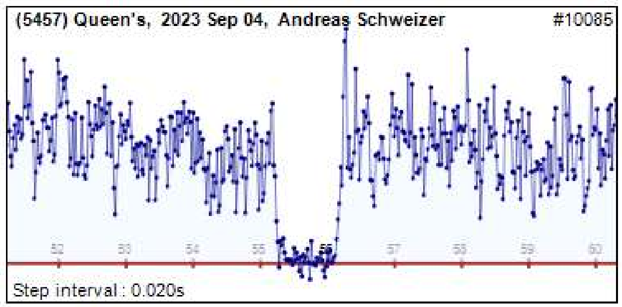


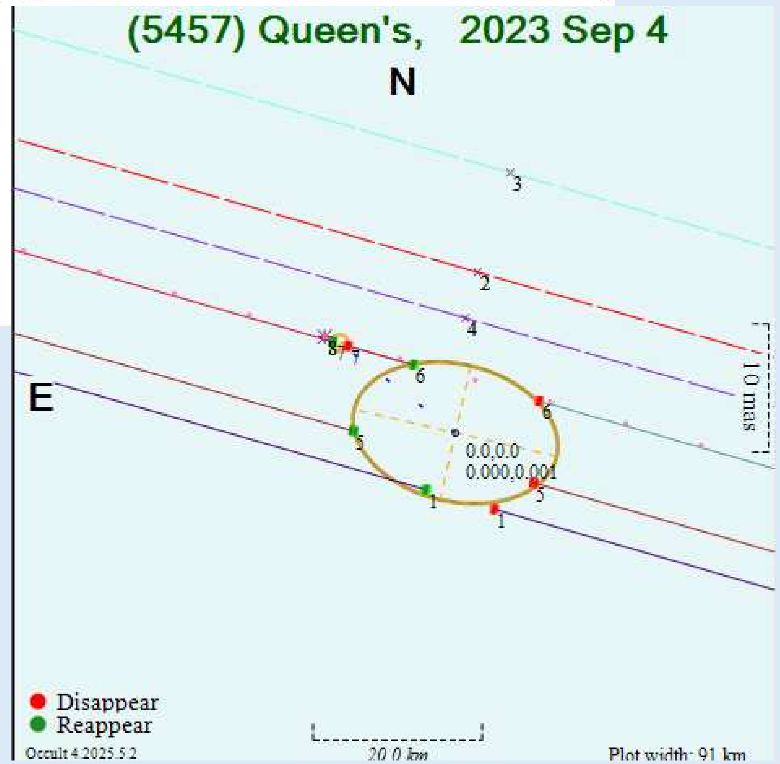


- Light drops too deep for a double star
- Observer separation ***much*** greater than asteroid diameter

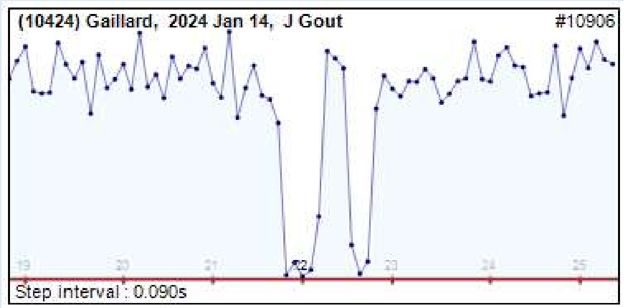


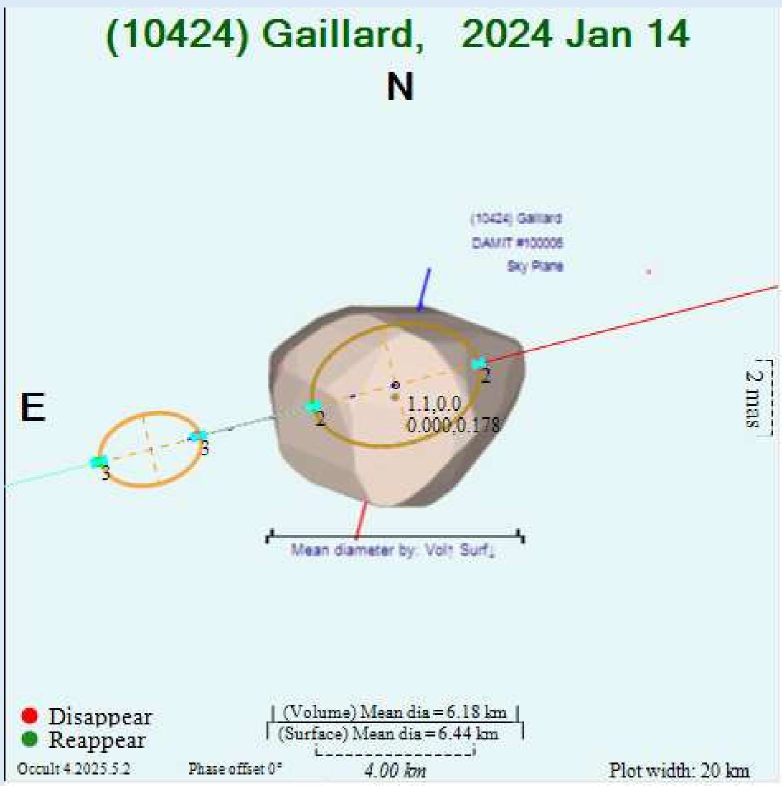




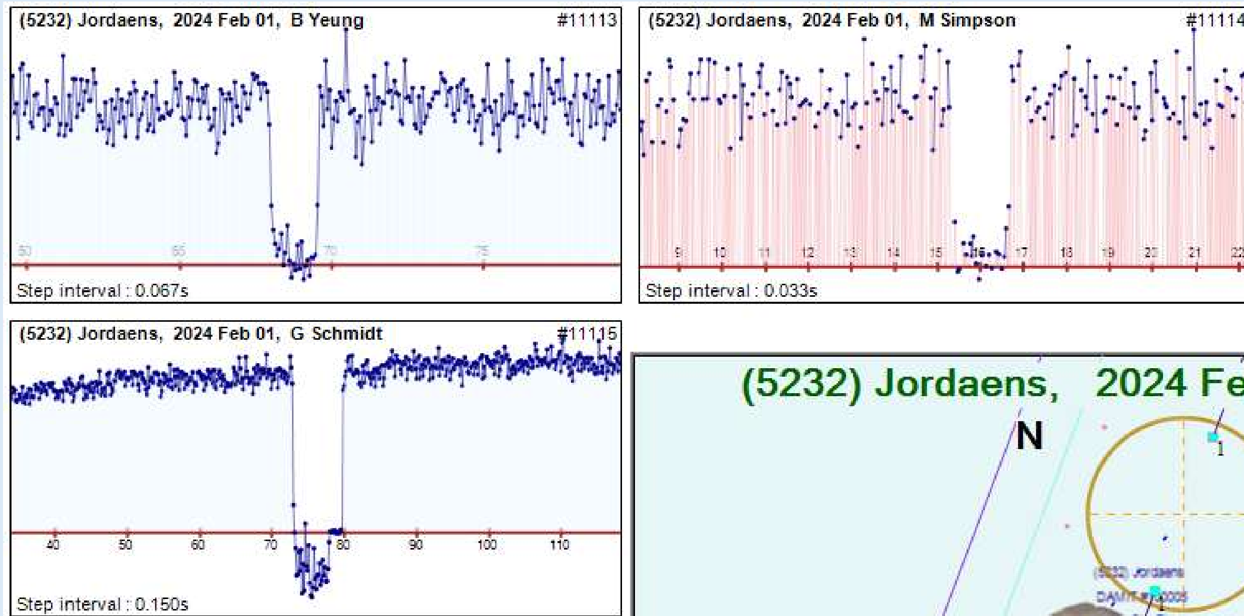


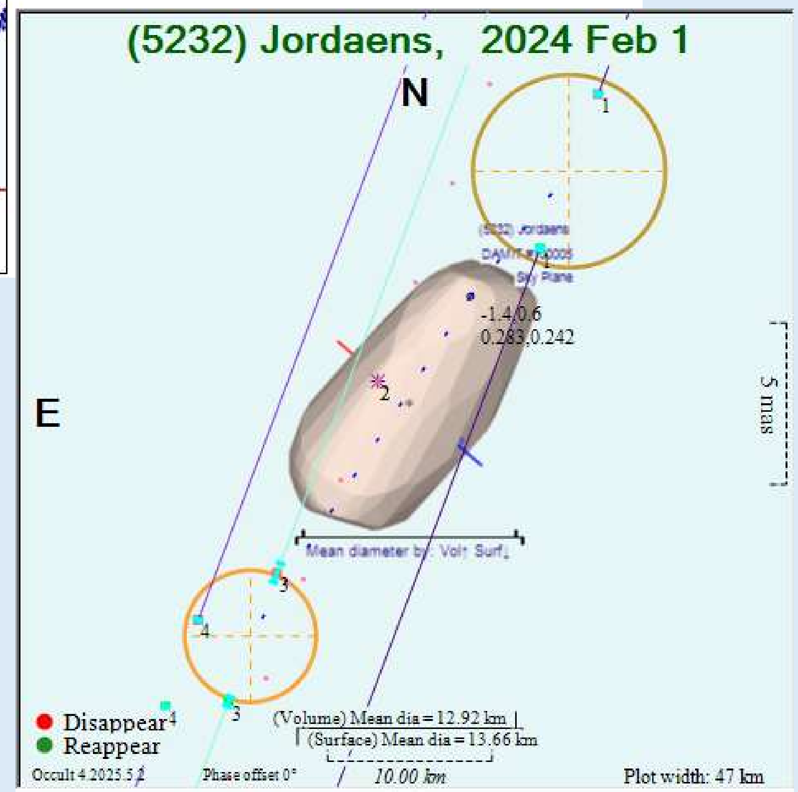
- Three chords of the main body.
- One chord has an extra, 2-frame drop
- Miss chords #2 and #4, and chord 5, exclude the possibility of a double star



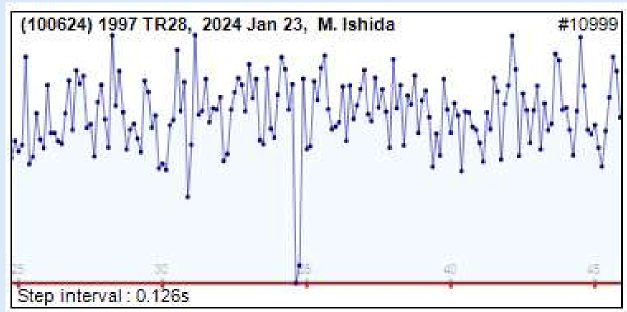


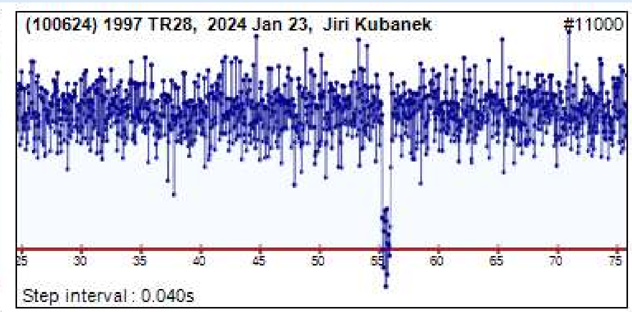
- Light drops too deep for a double star
- Chord separations too large for a graze, plus shape models do not suggest a profile that might support a graze



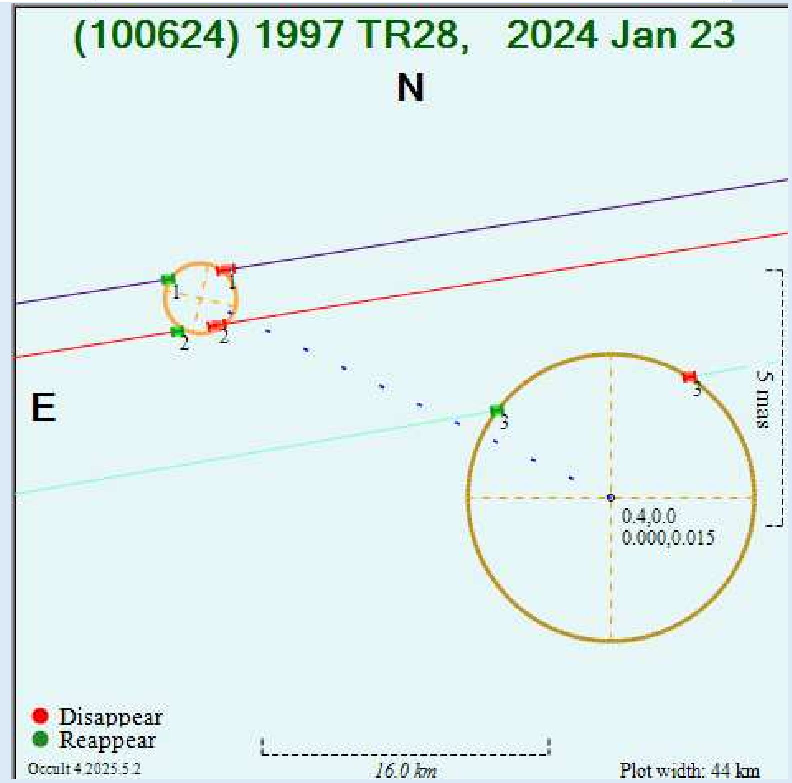


- Separate chords on two bodies
- Configuration of chords 1 and 2 exclude a graze explanation (as well as the large separation) The shape model (if larger) would potentially raise the issue of a graze
- Chord for main body degraded by large number of missing exposures
- One chord for 2[nd] body not relied upon because of concerns about its time base

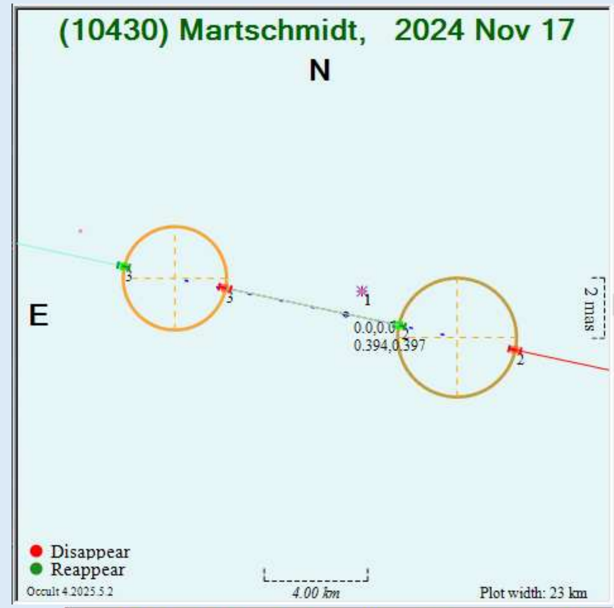


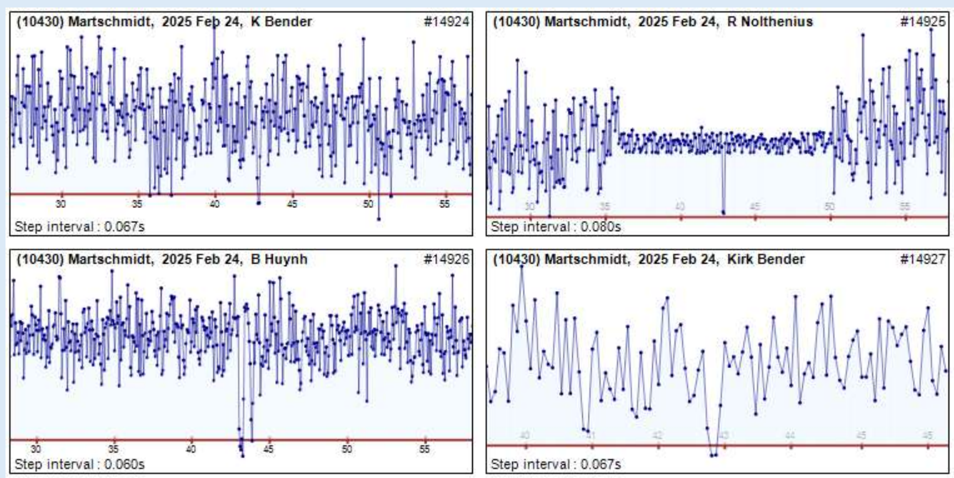


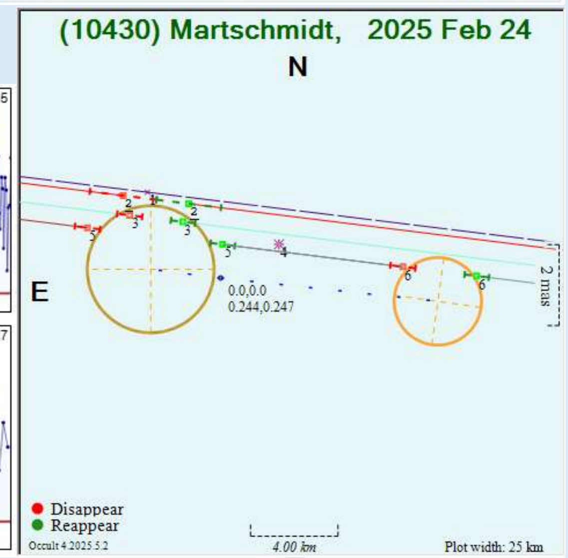
- Main body detected in Europe, 2nd body in Japan
- Trojan asteroid
- Position of the main body to one side of the chords as a result of the JP chords
- Configuration of the two chords for the 2nd body inconsistent with a double star
- + mag drops too deep for a double star



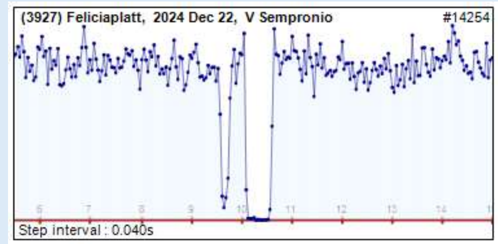
- Much discussion with first event, re whether the recording went deep enough to reliably measure light drops
- Confirmed by light curve photometry
- Subsequent confirming occultation

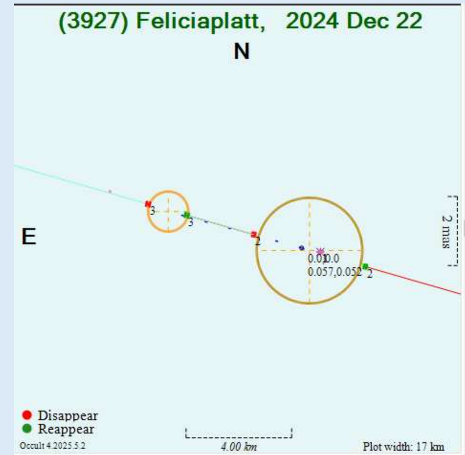


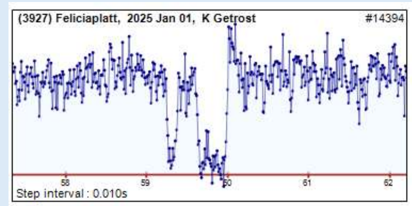


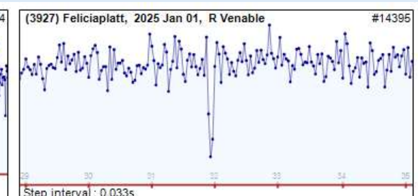


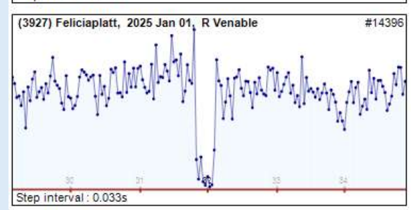
- Single chord discovery observation
- Both drops too deep for a double star
- Longer chord length slightly longer than expected diameter of the asteroid. When considered with the length and separation of the 2nd chord, a graze explanation is excluded
- Secondary drop not as deep because of Fresnel diffraction around the 1.7km satellite
- Confirming occultation 10 days later
- Grazing chord 1 light drop only 75% - Fresnel diffraction.
- 1st light drop in chord 2 not as deep because of Fresnel diffraction
- First CBET to include graphics of light curves and sky-plane configuration

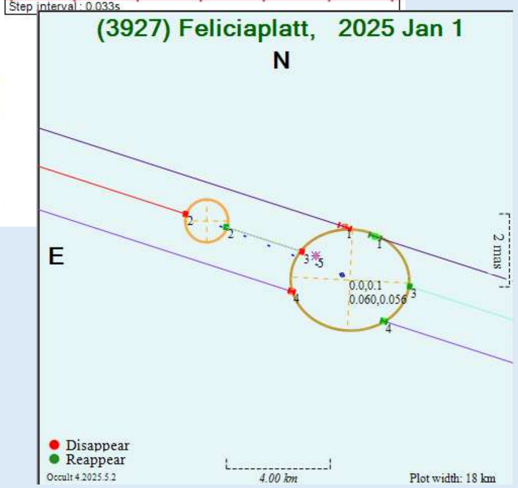


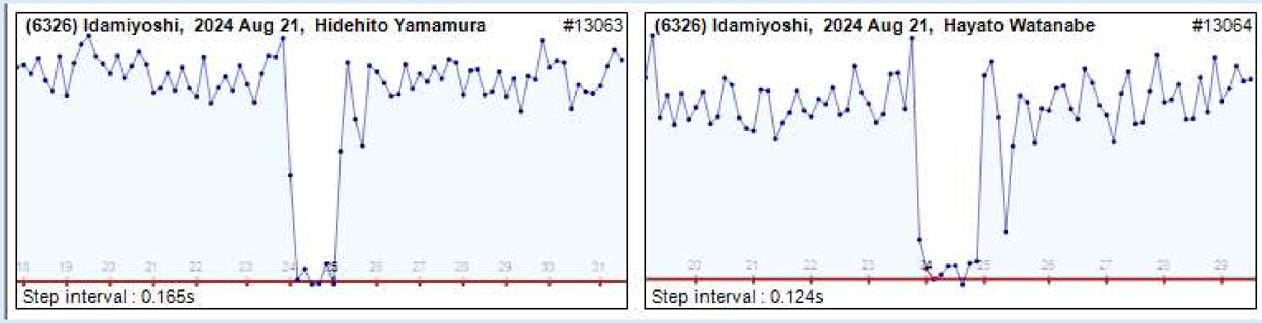




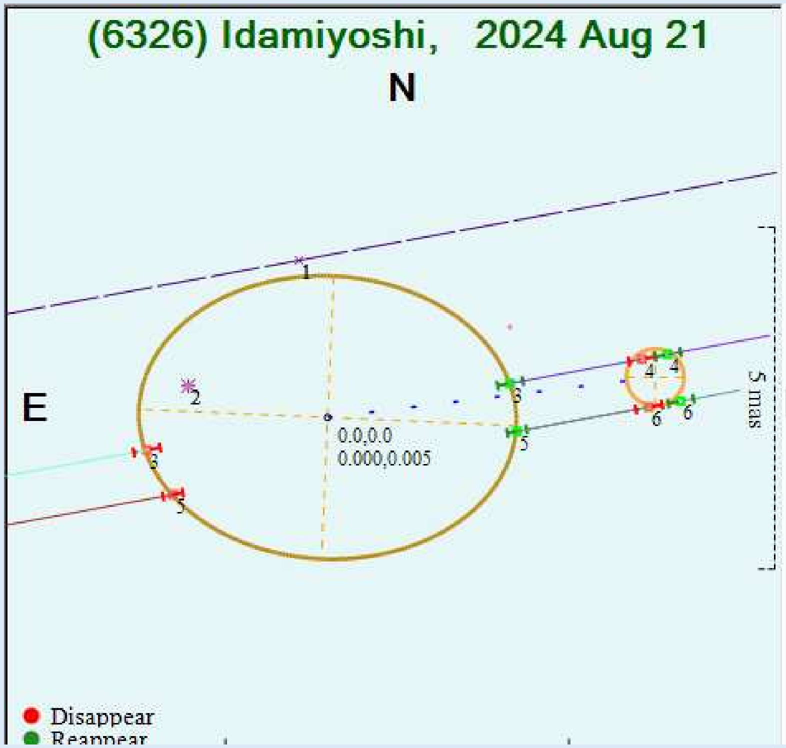




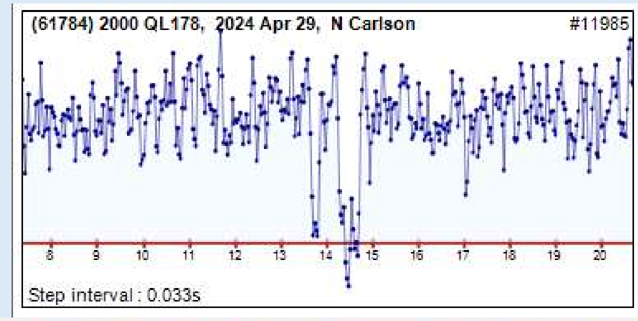


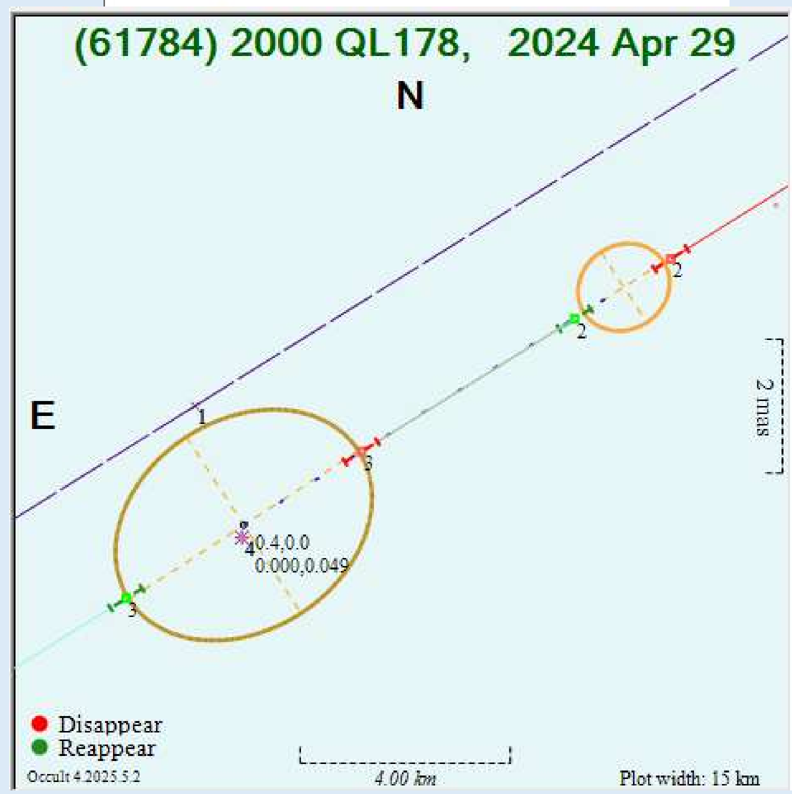


- Two light curves with a drop after the main event
- Drops are far less than a full drop. However they align perfectly
- Satellite size when fitted to the two chords - 1.3km, with events being grazing to the satellite
- Reduced light drop due to Fresnel diffraction modeled by Kazuhisa Miyashita
- Positioning and configuration of the satellite chords excludes a double star explanation

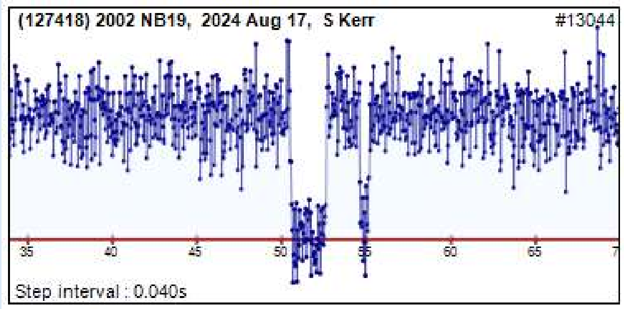


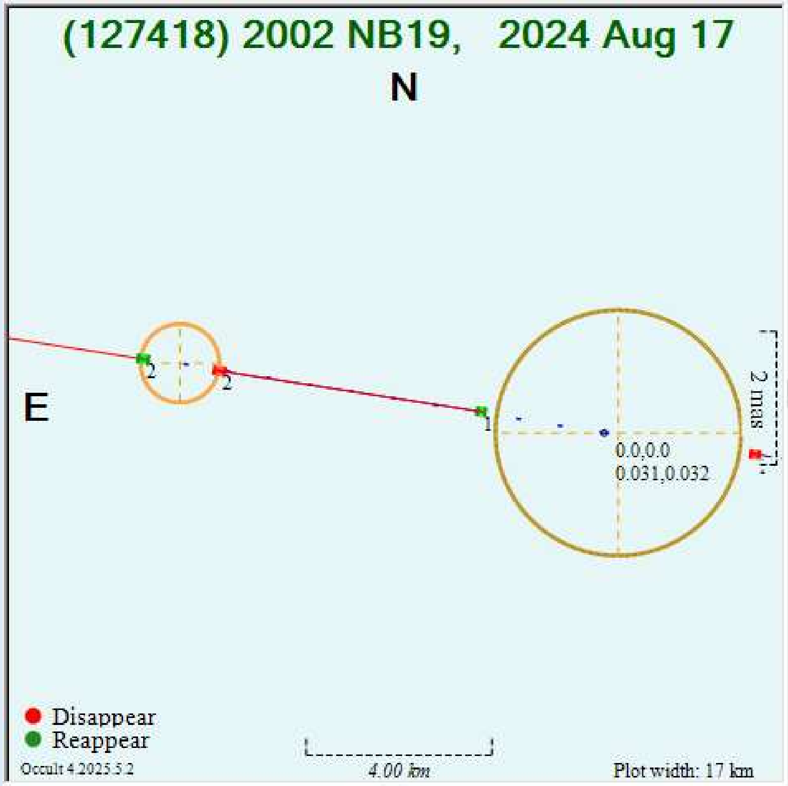
- Picked up in the final stage of adding observations to the main data base, solely because of the availability of the light curve
- Double star excluded by light curve drops being deep enough – *but only just*
- Ellipse major axis corresponds to NEOWISE diameter. Miss chord constrains whether the minor axis, or its location (assuming it is circular)



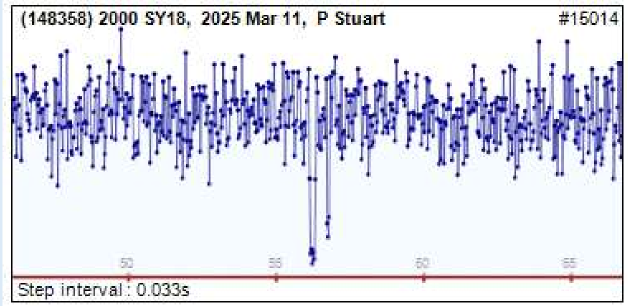


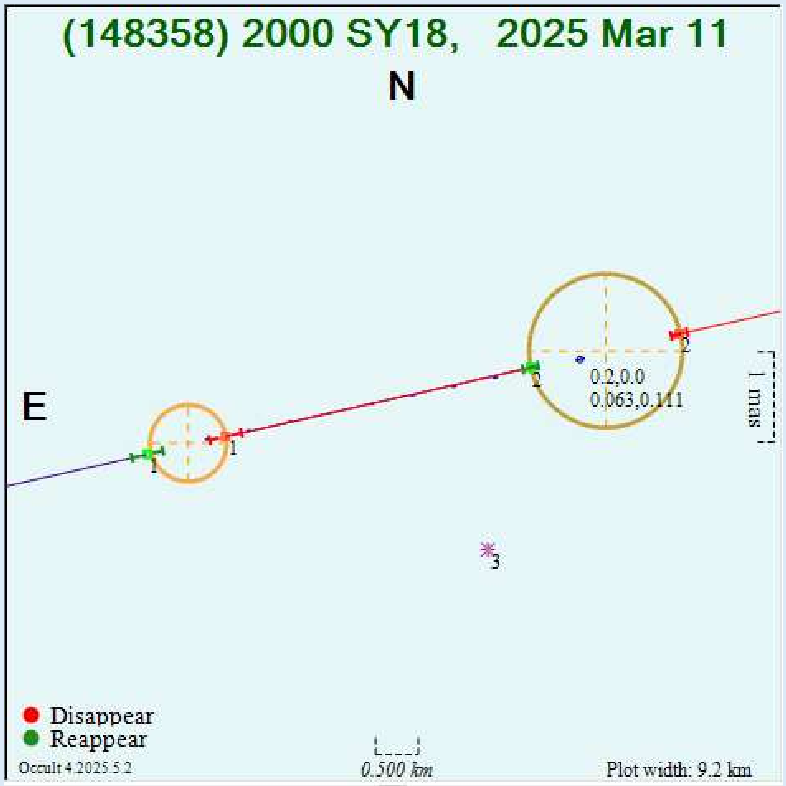
- Lengthy investigation/debate about the light drop levels, and concern about whether the zero light level on the light curve was ‘correct’

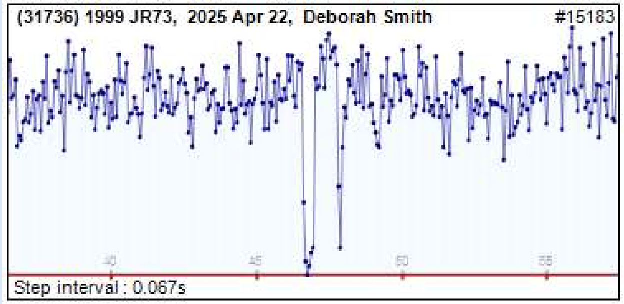


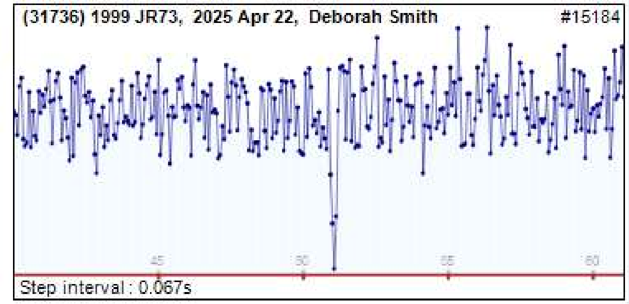


- Light drops unequal
- Both bodies small (4.7 & 0.9 km)
- Fresnel diffraction affects light drop depths
- Flux drops derived using comparison stars, and even without Fresnel diffraction corrections, the drops were deep enough to exclude double star

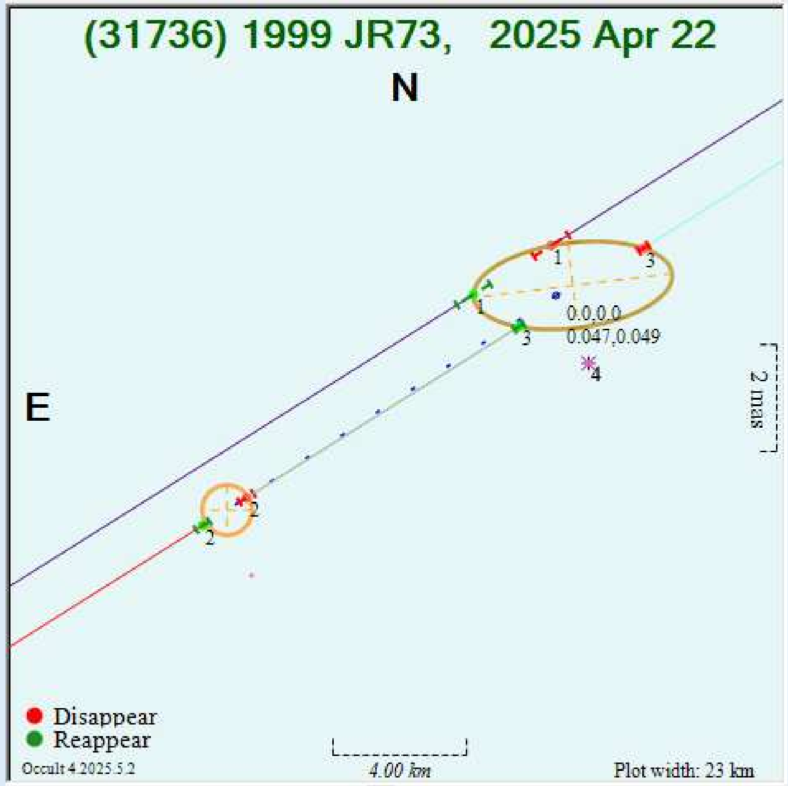


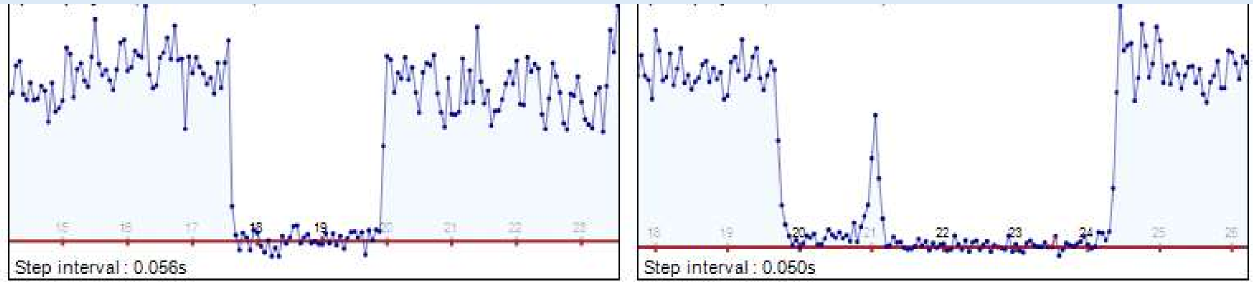


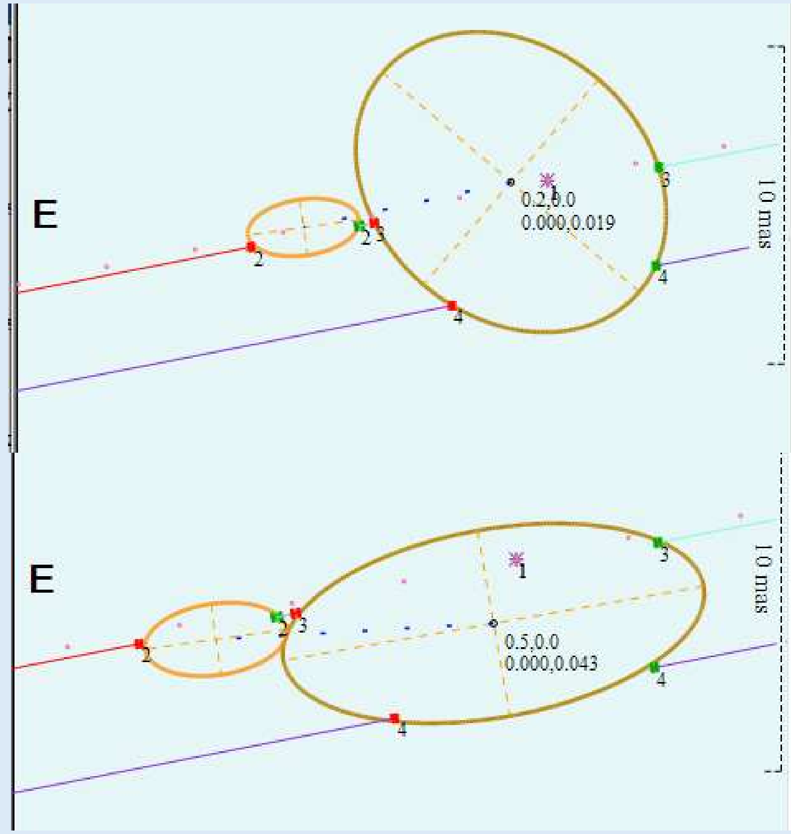




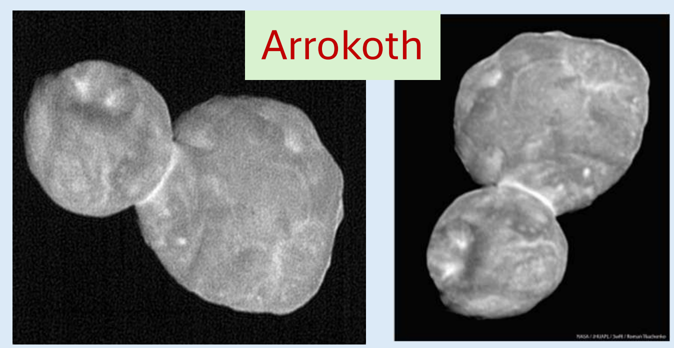
- Non-equal light drop.
- Satellite chord length 1.5km, so Fresnel diffraction explains slightly smaller light drop
- Light drops measured using comparison stars, to be greater the 2.7, excluding double star

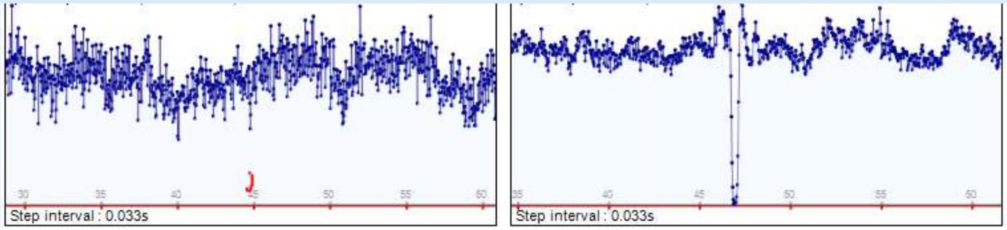


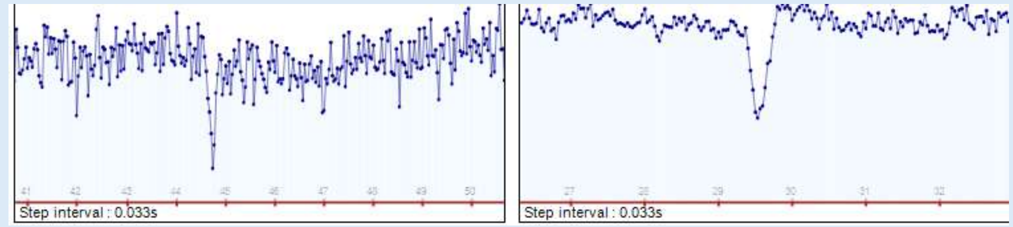




- A REALLY challenging situation
- Main body has two possible ellipse fits, both plausible given the NEOWISE diameter, although the above plot is more consistent
- The bottom plot potentially allows for a graze explanation
- All ellipses fitted to the bottom are smaller than the NEOWISE diameter. The angle of incidence would suggest gradual D & R – but that's not in the light curve. Therefor top configuration.
- Light drop for first section not as deep as for 2nd – hope this will allow its across-path width to be estimated.
- Is it a satellite optically positioned in line with the main body, or is it a contact binary?







- No doubt, from chords 1 and 3, that it is a satellite. A graze is excluded by Chord 3. Chords 1 to 3 establish maximum size, which is much less than the main body – which excludes the double star explanation.
- Star has a significant diameter. 1.17mas, main body 6 mas. So light curve modelling is important
- Modeling of light curve for chord 3 indicates the orientation of main body is 90° different to that plotted. This also affects PA and separation measurement
- Satellite diameter might be smaller than the star's diameter. Need to model light curve for the satellite to properly assess its diameter and location.