ACCURATE NEAR-EARTH ASTEROID ORBITS FROM OCCULTATIONS

Adopted from Paper IAA-PDC-21-6-09

(7th Planetary Defense Conference, held online, April 2021)

August 28, 2021 to ESOP XL (Białystok, Poland) via Zoom

David W. Dunham[1&2], J. B. Dunham[1], M. Buie[3], S. Preston[1], D. Herald[1,4], D. Farnocchia[5], J. Giorgini[5], T. Arai[6], I. Sato[6], R. Nolthenius[1,7], J. Irwin[1], S. Degenhardt[1], S. Marshall[8], J. Moore[1], S. Whitehurst[1], R. Venable[1], M. Skrutskie[9], F. Marchis[10], Q. Ye[11], P. Tanga[12], J. Ferreira[12], D. Vernet[12], J.P. Rivet[12], E. Bondoux[12], J. Desmars[13], D. Baba Aissa[14], Z. Grigahcene[14], and H. Watanabe[15]

[1]International Occultation Timing Assoc. (IOTA, P. O. Box 423, Greenbelt, MD 20768, USA, iotatreas@yahoo.com), [2]KinetX Aerospace (**david.dunham@kinetx.com** or **dunham@starpower.net**), [3]Southwest Research Inst., Boulder, CO, [4]Trans Tasman Occultation Alliance, [5]Jet Propulsion Lab., [6]Planetary Exploration Res. Ctr. (PERC), Chiba Inst. of Tech., Japan, [7]Cabrillo College, Santa Cruz, CA, [8]Arecibo Obs., [9]Univ. of Virginia, [10]SETI Inst. and Unistellar, [11]Univ. of Maryland,[12]Obs. de la Côte d'Azur, [13]Paris Obs., [14]Algiers Obs. – CRAAG, [15]Japanese Occultation Information Network

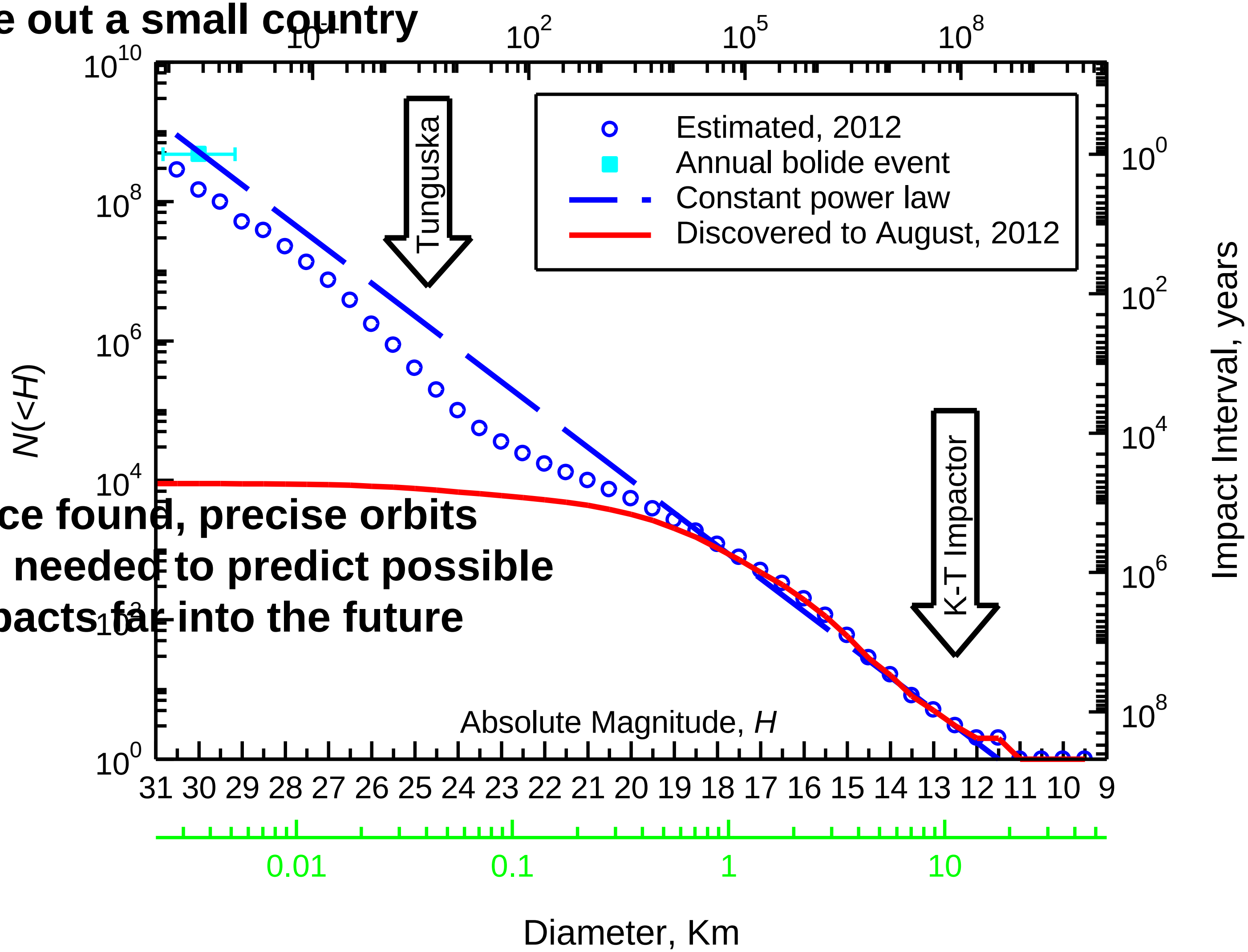
2021 August 28

The Chicxulub Impact

10km NEA (or 6km comet) hit shore of Yucatan 65 million years ago.
Over 70% of plant and animal species perished from the blast, worldwide wide fires (from impact debris re-entering the atmosphere), and the collapse of photosynthesis in the cold dark years that followed. The dinosaurs died, and now humans rule, because they had no space program, no planetary defense.

Cumulative Population

Astronomers are trying to find most NEA's >140m that can wipe out a small country



Once found, precise orbits are needed to predict possible impacts far into the future

The cumulative population is the running sum of the differential population. The number *N* is the total number of NEAs larger than the specified size (*H* or Diameter).

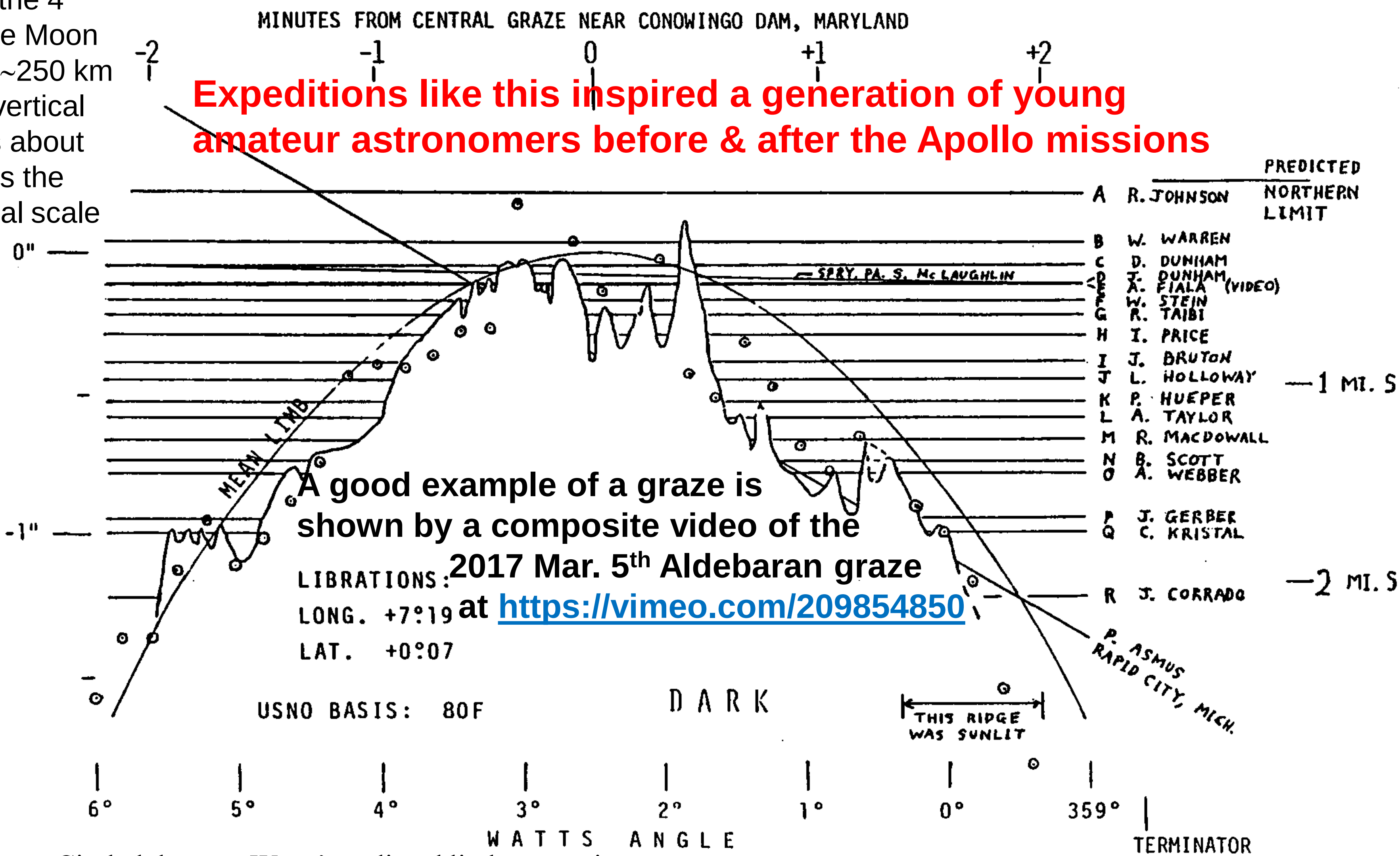
Outline

- IOTA & Asteroidal Occultations Introduction & History
- The 1975 Jan. 24 Occ’n of κ Gem by Eros
- The 2019 July Occ’n by Phaethon, 1st small NEO occ’n
- The 2019 Sept. 29th Phaethon Occultation in California
- Phaethon occultations in 2019 Oct. and 2020 Oct.
- Improvement of Phaethon’s orbit – A2 acceleration
- First Observed Occultation by Apophis, 2021 Mar. 7
- Almost lost it – 2nd Positive Occ’n, 2021 Mar. 22
- 2021 April Occultations – Apophis Orbit Nailed
- Predictions of upcoming occultations
- How to observe/time/record occultations
- Conclusions
- Additional Resources

Lunar Profile from Graze of delta Cancri – 1981 May 9-10 Alan Fiala, USNO, obtained the first video recording of multiple events during this graze, with 7 D's and 7 R's

During the 4 min., the Moon moved ~250 km so the vertical scale is about 40 times the horizonal scale

Expeditions like this inspired a generation of young amateur astronomers before & after the Apollo missions



A good example of a graze is shown by a composite video of the 2017 Mar. 5th Aldebaran graze at https://vimeo.com/209854850

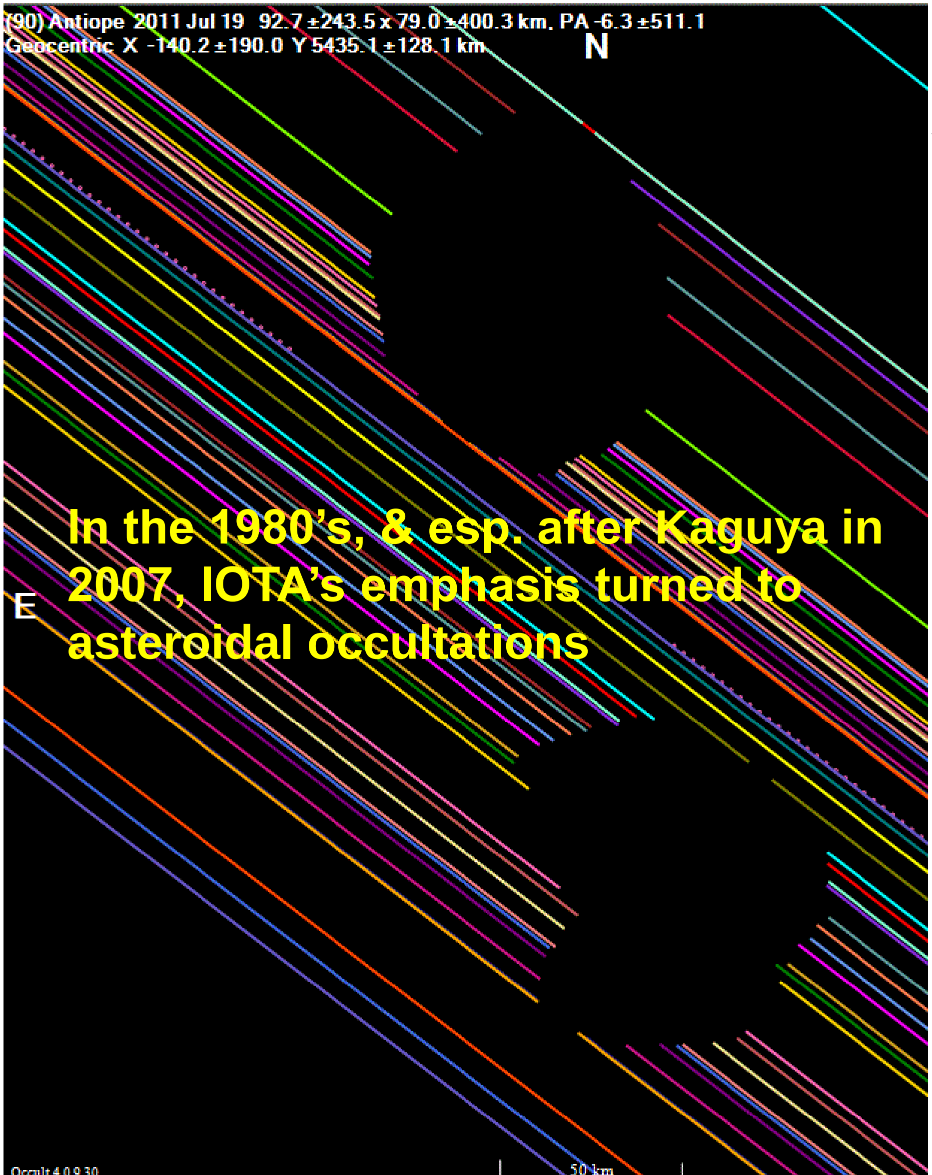
Circled dots are Watts' predicted limb corrections

Starting in 1965, cable systems were developed for observing grazing occultations, first at USNO, then by 3 clubs in California (Riverside, Santa Barbara, and Mount Diablo Astronomical Society), and Milwaukee, Wisconsin

This is a Riverside A.S. expedition near Adelanto in 1966. Mobile observation was needed since graze paths were narrow. The observations were visual, with audio tones recorded at the central station for this cable system.

Many Occultations of Interesting Main Belt Objects

2011 July 19 occ'n of LQ Aquarii by the Binary Asteroid (90) Antiope



Technology now allows observers to record transient astronomical phenomena more precisely and to fainter magnitudes than ever before. A small, inexpensive, yet very sensitive camera (RunCam Night Eagle Astro) will allow you to participate in IOTA's programs to accurately record occultations and eclipses, to measure the sizes and shapes of hundreds of asteroids, discover duplicity of both close double stars and asteroids with satellites, and measure the angular diameters of many stars. Occultations provide excuses for travel, or you can just observe them from home, to further astronomical knowledge. Some use specially-made easily-transported telescopes; there is room for innovative design & construction of equipment & software to record asteroidal occultations.

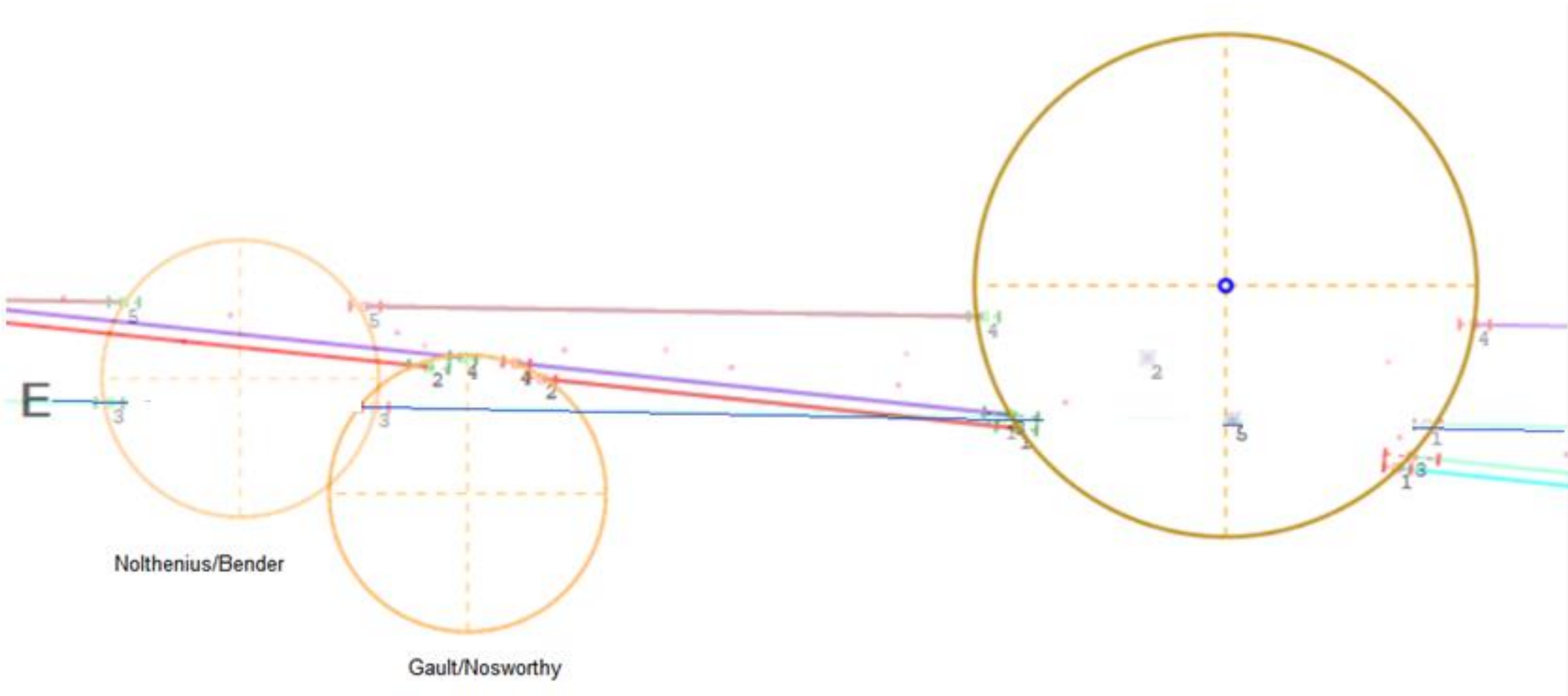
Near left: 10-in suitcase tele-scope deployed for an asteroidal occultation in the Australian Outback.

Remote Stations for Asteroidal Occultations

- Separation should be many km, much larger than for grazes, so tracking times & errors are too large
- <u>Unguided is possible since the prediction times are accurate enough, to less that 1 min. = ¼°</u>
- **Point telescope beforehand to same altitude and azimuth that the target star will have at event time and keep it fixed in that direction**
- Plot line of target star's declination on a detailed star atlas; Guide 8 or 9, or C2A can be used to produce the charts
- From the RA difference and event time for the area of observation, calculate times along the declination line
- Adjust the above for sidereal rate that is faster than solar rate, add 10 seconds for each hour before the event; done automatically by Guide & C2A
- Can usually find "guide stars" that are easier to find than the target
- Find a safe but accessible place for both the attended & remote scopes
- Separation distance limited by travel, set-up, & pre-pointing time, but we have had success with software to control small Win10 computer recordings; then the main limit is battery life, which can be several hours
- Sometimes it is better to have remote sites attended for starting equipment later (allows larger separations) and security, if enough people can help

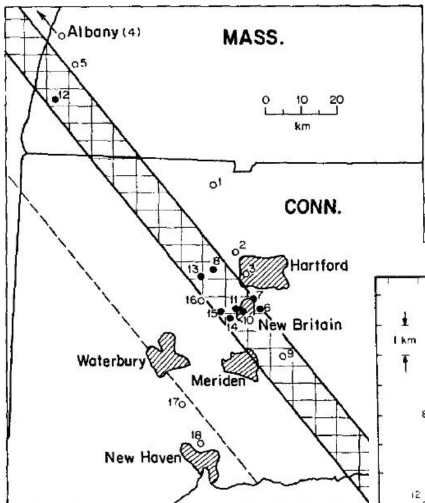
Discovery and confirmation of the satellite of (4337) Arecibo, 2021

Discovery by Peter Nosworthy & Dave Gault, May 19, w. of Sidney, AU
Confirmation by Richard Nolthenius and Kirk Bender, June 9, cen. Calif.

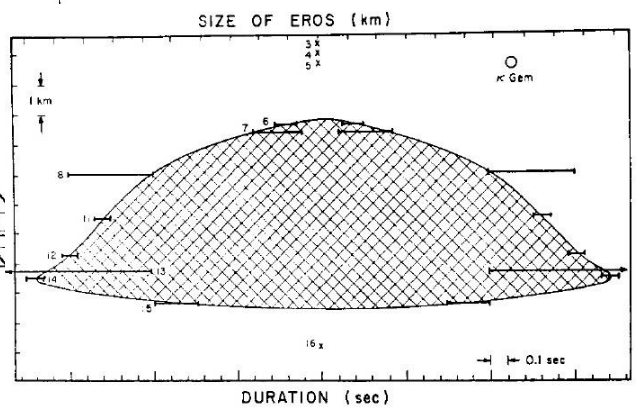


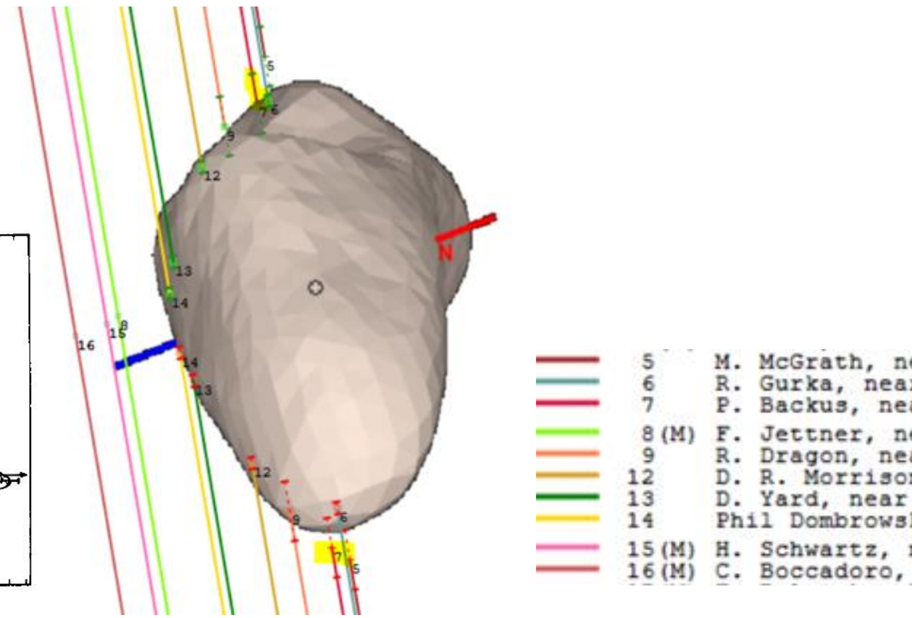
See https://www.youtube.com/watch?v=w_Cc5Or1FFw
Next: 13.6-mag. occ'n, cen. FL, Sep. 3 8:50pm EDT
Next I find in Europe: 14.4-mag. occ'n, England, Denmark, & s. Finland (low) on 2022 Dec. 4 at 20:10 UT

First observed occultation by a NEA, 1975 Jan. 24, κ Gem occulted by Eros



from O'Leary et al., **Icarus**, Vol. 28, pp. 133-146 (1976)





Left, map of observers & sky plane plot from the 1976 Icarus paper. Right, modern sky plane plot of the chords fitted to Eros' shape model derived from NEAR-Shoemaker data. This was the first occultation by ANY asteroid that was observed from multiple stations. Especially, the stations deployed by the Pioneer Valley Colleges led by Brian O'Leary was the first successful coordinated effort to observe such an event by mobile observers. A crucial observation, now known to be a false negative, resulted in the wrong squashed shape shown by O'Leary et al. It would be 44 years before an occultation by another NEA would be observed.

(3200) Phaethon

- (3200) Phaethon was the first asteroid to be discovered by a spacecraft (IRAS).
- **Phaethon is the parent body of the Geminids meteor stream** that puts on one of the largest annual meteor displays
- This mysterious object may be a (nearly) dead comet nucleus, or a very active asteroid, throwing off boulders like has been observed on Bennu by OSIRIS-REx
- Phaethon is an Apollo asteroid with a **perihelion of only 0.14 AU,** <half Mercury's, with aphelion 2.4 AU in the Main Belt. The extreme thermal changes near perihelion likely drive its shedding of pebbles and dust, creating the trail imaged by the Parker Solar Probe. Small non-gravitational forces on its orbit have been detected.

- JAXA's DESTINY+ spacecraft plans to launch in 2024 and fly by Phaethon in 2025 -see https://en.wikipedia.org/wiki/DESTINY+

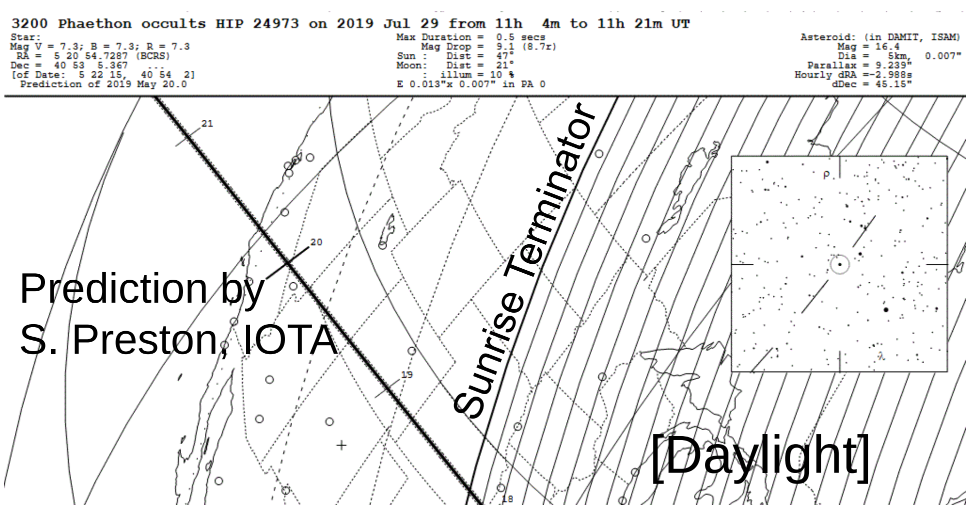
- Radar observations show Phaethon to be nearly spherical with a diameter of nearly 6 km

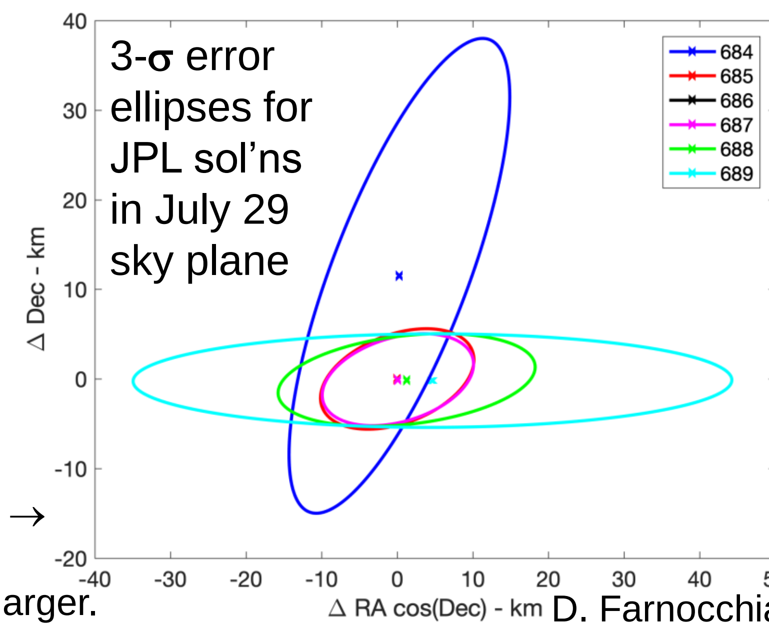
- Thermal IR data give a diameter of ~4.5km

Radar image of 3200 Phaethon taken by Arecibo, December 17, 2017

THE 2019 JULY 29 OCC'N OF 7.3-MAG. SAO 40261 BY PHAETHON

- This event was first identified by Isao Sato in Japan. In January 2019, he alerted US observers via a message that he sent to the IOTAoccultations list server.
- To obtain an accurate astrometric point for orbit improvement, and to resolve the diameter discrepancy, Tomoko Arai, PI of DESTINY+, requested that NASA & IOTA try to observe this rare bright occultation by the small NEO in the sw USA.
- This was by far the smallest object that IOTA had tried to predict and observe; we needed help.
- Those who predicted this occultation, and analyzed the observations of it, all had to modify their software, to take into account previously-neglected effects that weren't significant for occultations by all of the larger objects studied in the past. Even the difference in the gravitational bending of light by the Sun, for the star and Phaethon, was noticeable.
- Jon Giorgini computed JPL solution 684 after including radar measurements made in 2017. Then Davide Farnocchia computed JPL 685, manually including Gaia astrometry; this was key.
- Adding new astrometric observations just confirmed JPL 685, so it was used for the final prediction.





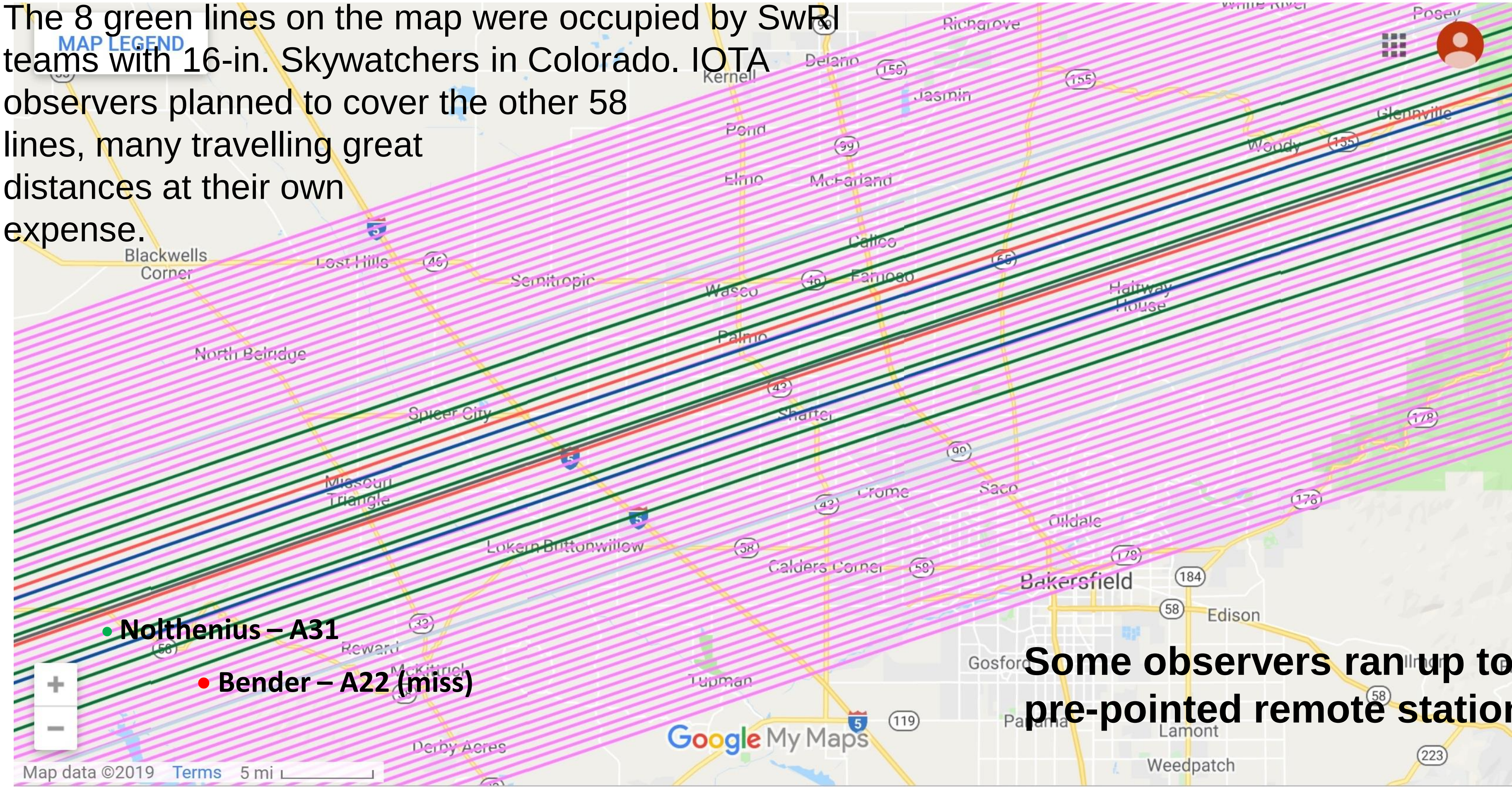
Phaethon's motion was from lower left to upper right, →
so the 3σ limits (JPL 685) were 8 km + Phaethon's
radius from center; the ground projection was a little larger.

D. Farnocchia

2019 July 29 Phaethon occ'n, s. San Joaquin Valley

Most stations were n. of Las Vegas; others were n. of Ridgecrest and near Pueblo, Colo.

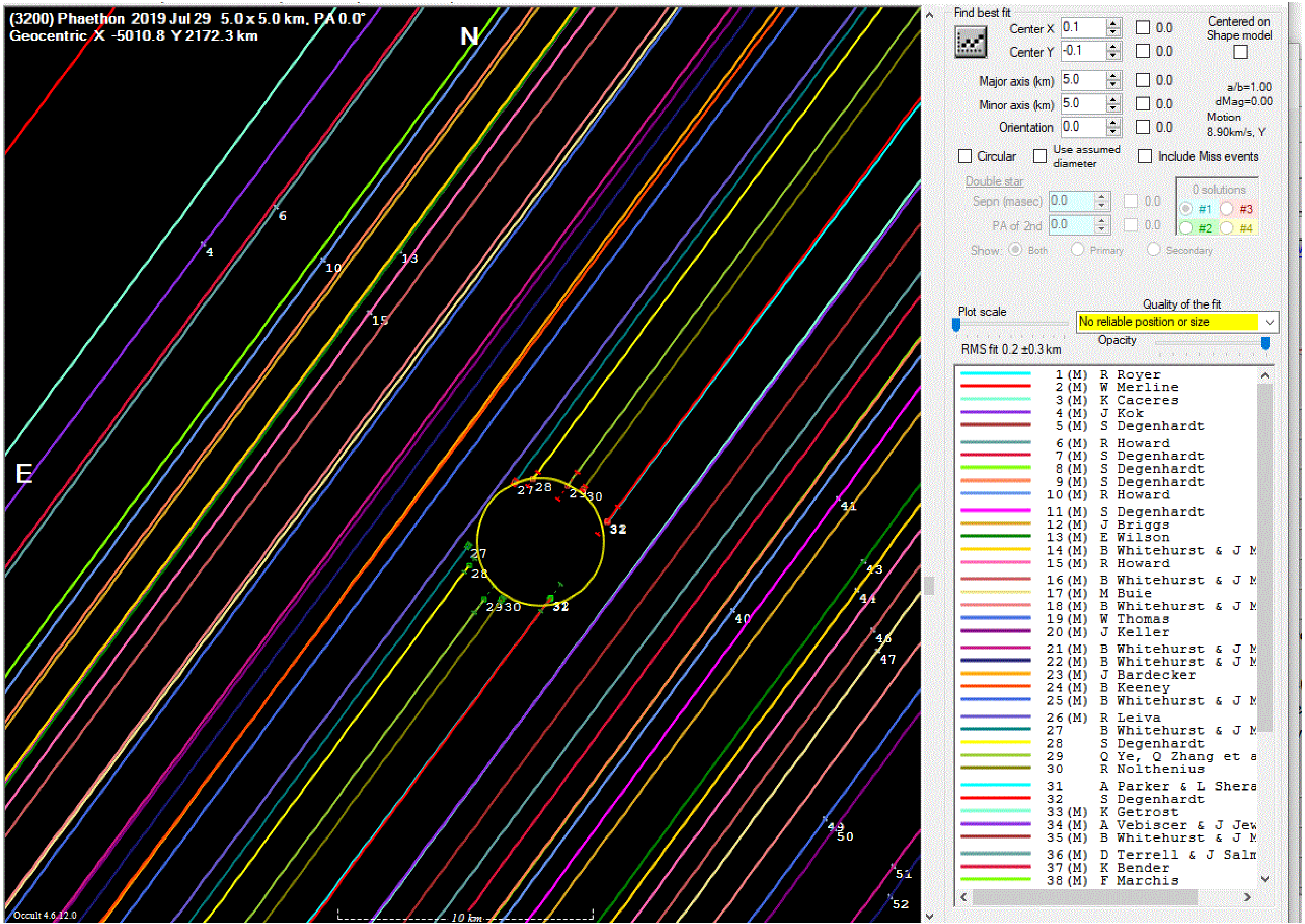
The 8 green lines on the map were occupied by SwRI teams with 16-in. Skywatchers in Colorado. IOTA observers planned to cover the other 58 lines, many travelling great distances at their own expense.



Some observers ran up to 9 pre-pointed remote stations

Google Map from SwRI, like those used for their Arrokoth campaigns. To cover the 3σ zone + many more km to the north and south, to guard against stellar duplicity and other possible unmodelled errors, this pattern of 66 lines, with selected spacing 680m, <u>the smallest ever achieved for an occultation</u>, numbered from s. to n., A01 to A66. Observers were asked to select sites within 100m of their line. All 66 lines were assigned to the many mobile observers who volunteered, plus 4 more between or outside this range. About 9 lines couldn't be filled for various reasons, and another 10 failed to get data. One station run by IOTA observer Richard Nolthenius, on track A31, recorded the occultation, shown on the next slides.

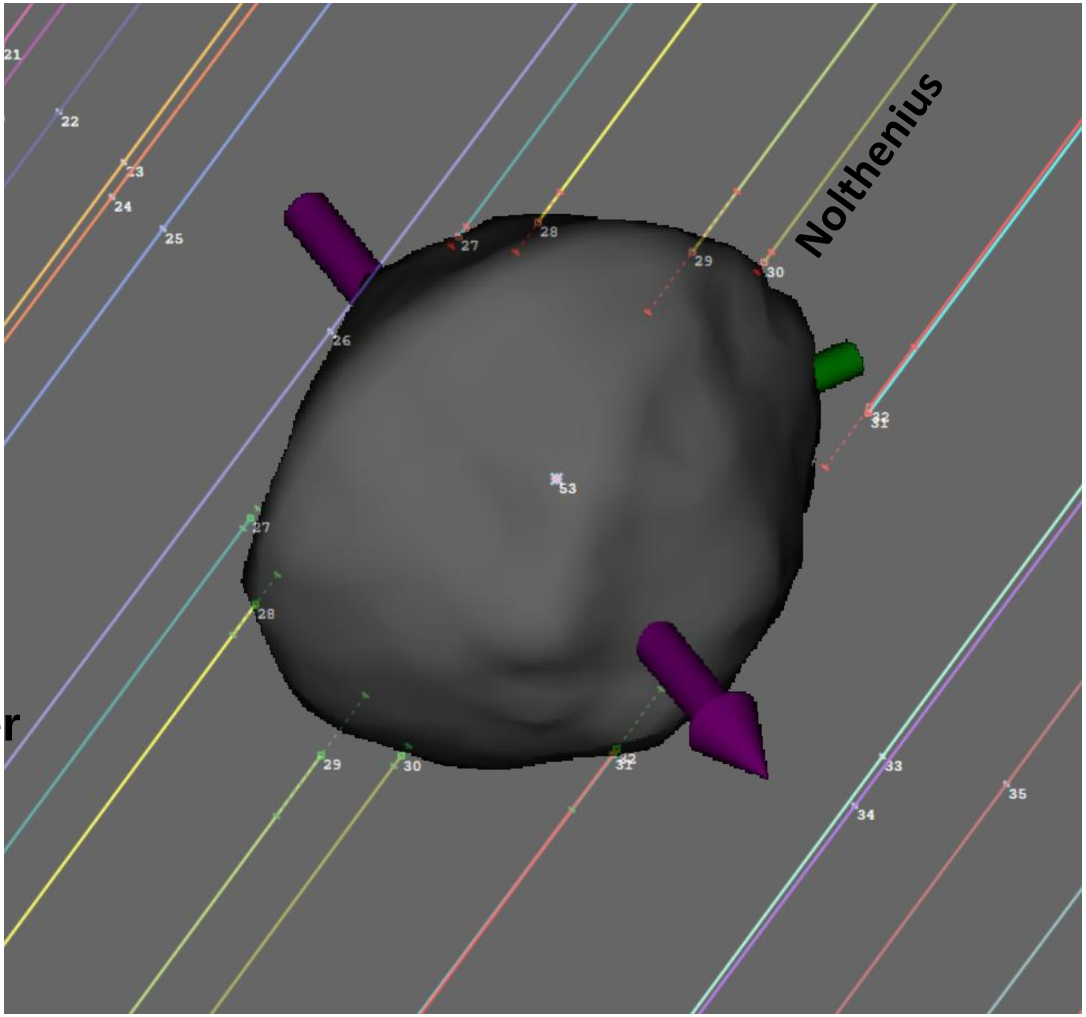
2019 July 29 Phaethon occ'n, all successful chords



2019 July 29 Phaethon occultation, positive chords

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

A 2nd occ'n, of a 12.6-mag. star, was recorded from s. Calif. 2 months later, providing another astrometric point that nailed the orbit



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.

Phaethon Occultations Observed during October 2019

UT 2019 Oct.	Star mag.	# positive chords	Locations(s)	Remarks
12	11.3	2	w. Richmond, VA	UVA expedition
15, 17h	11.5	2	Japan	Clouds at more stations
15, 19h	11.1	3	Germany, France, Algeria	In FR, 1m portable scope
25	11.3	3	Italy, Algeria	2nd Phaethon occ'n for Djounai Baba Aissa

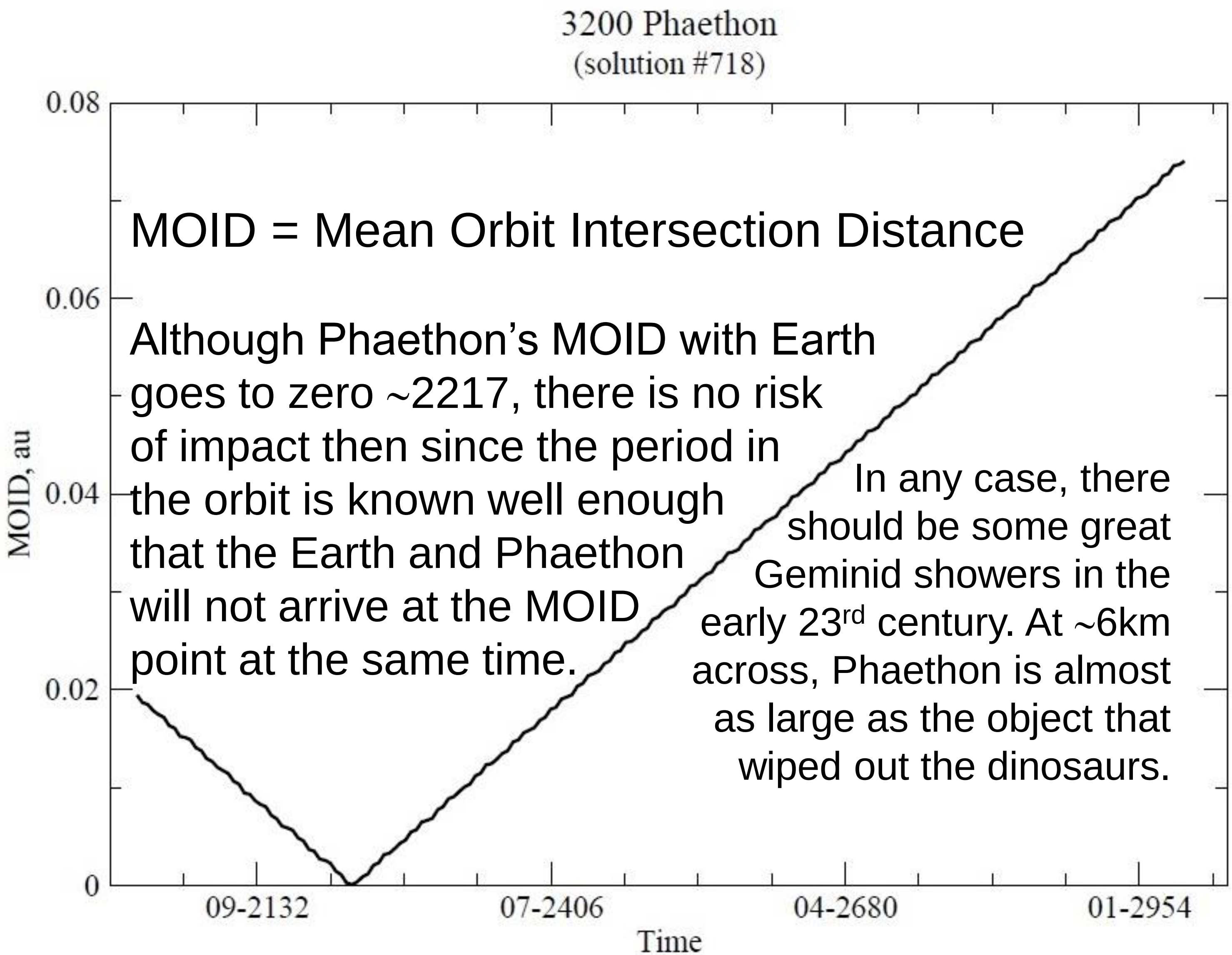
The predicted central duration for all of these was 0.3 second.
More about these observations is in the longer presentation I gave at the 2020 meeting of the International Occultation Timing Association. The link to that is on the last slide of this presentation. Prediction details for all of the 2019 occultations are at http://iota.jhuapl.edu/2019Phaethon.htm .

Phaethon Orbit A2 Determinations

(units au/d^2 $x10^{-15}$)

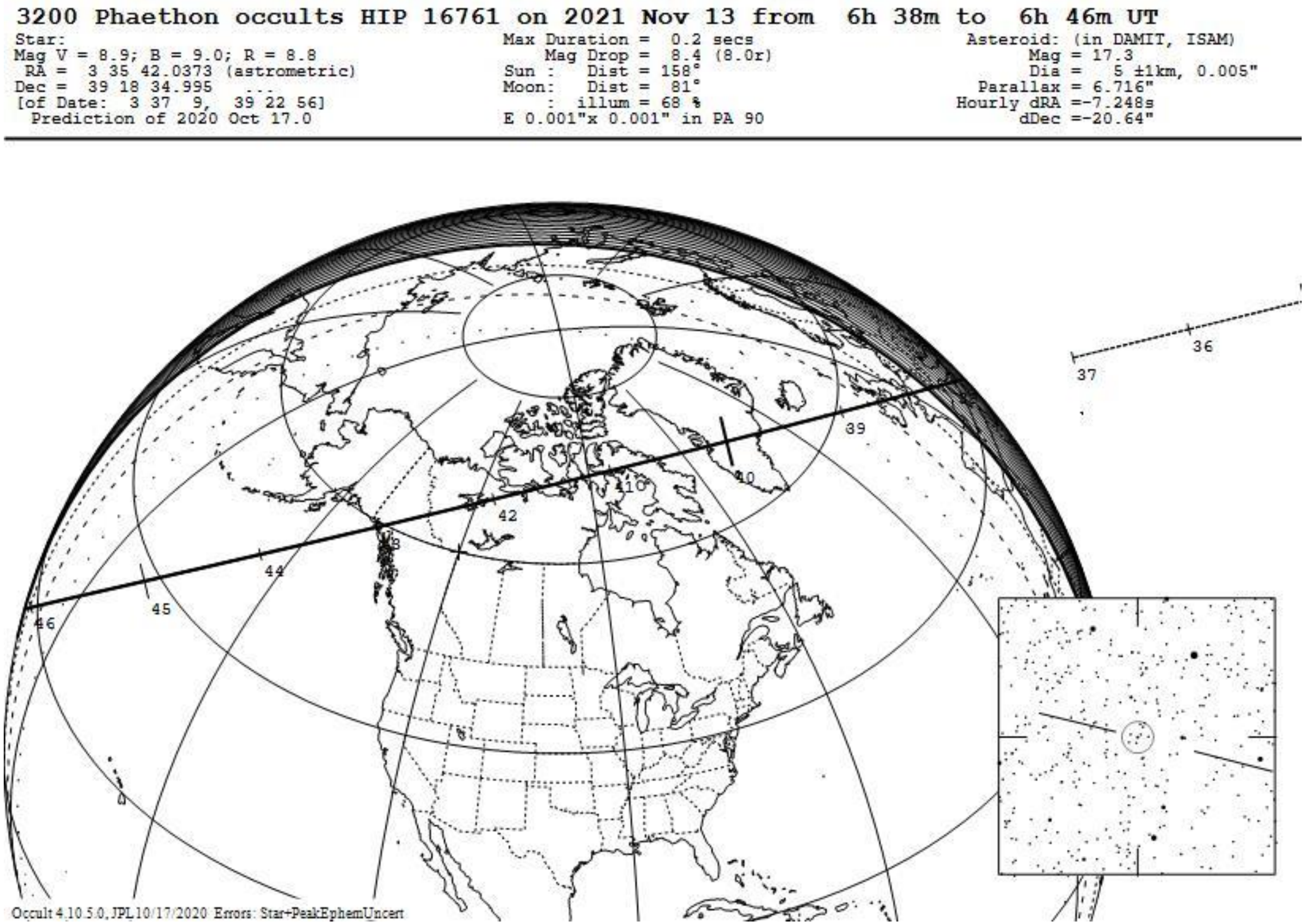
JPL sol. #	Value	Sigma	Value in sigma's	Basis
684	-4.84	±1.39	3.48	MPC obs. & 2017 radar
685	-3.76	±1.74	2.16	Adds Gaia obs.
707	-5.60	±0.67	8.41	Adds 2019 7/29 occ'n point
712	-5.44	±0.59	9.22	Adds 2019 7/29 & 9/29 occ'ns
718	-6.27	±0.61	10.28	Adds the 4 2019 Oct. occ'ns
742	-5.71	±0.87	6.56	Adds more Gaia obs. and 2020 Oct. 5 occ'n point

The A2 term for most NEO's is caused by the Yarkovsky effect, but for Phaethon, mass loss due to strong thermal heating near perihelion is likely the main driver, as evidenced by the Geminids & the Phaethon dust trail imaged by the Parker Solar Probe.



We should keep close tabs on Phaethon since its A2 term could change; its rubble pile structure could change with the severe thermal shocks it suffers, so such a change might alter the orbit period enough to be a concern in 200 years.

Future Phaethon Occultation



Predictions for 10 more Phaethon occultations in late 2021 are at **http://iota.jhuapl.edu/2020-2022Phaethon.htm**, including the one above.

Apophis will pass near the geosat ring on 2029 April 13

It will be about 3rd mag. as seen from Europe and Africa

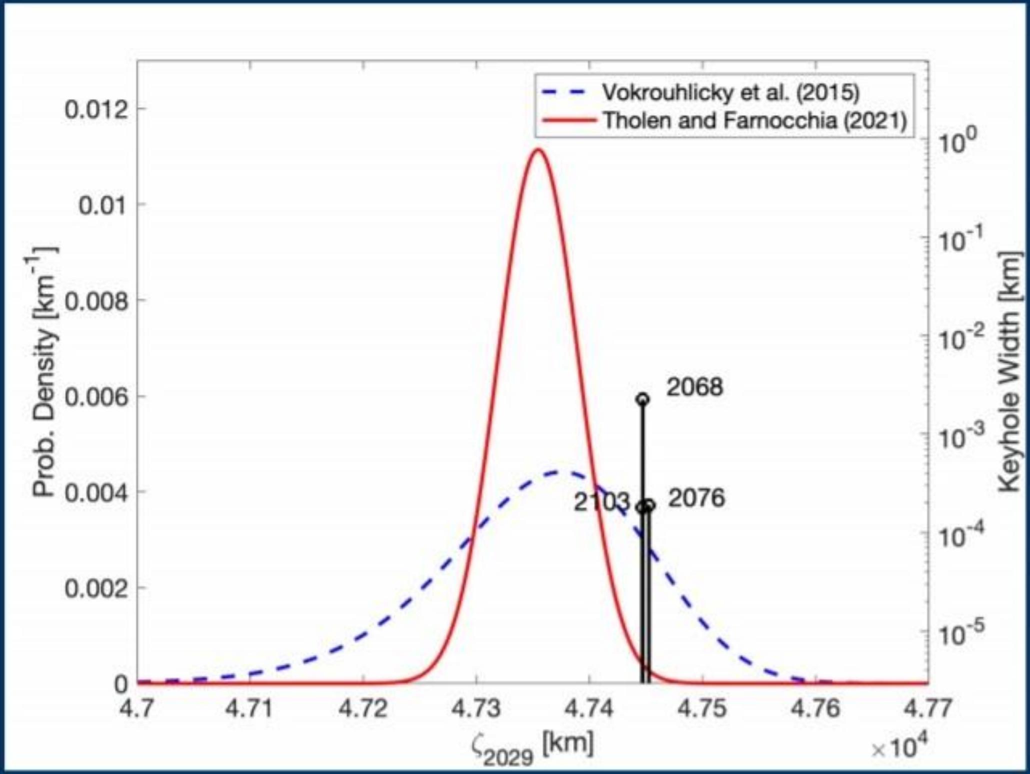
The approach will be about 0.1 lunar distance,

It's the closest approach by an asteroid this large in 1000 years

2013 radar observations showed Apophis to be ~340m across

An impact would destroy everything within 25 km, and produce severe damage out to 300 km from the impact point

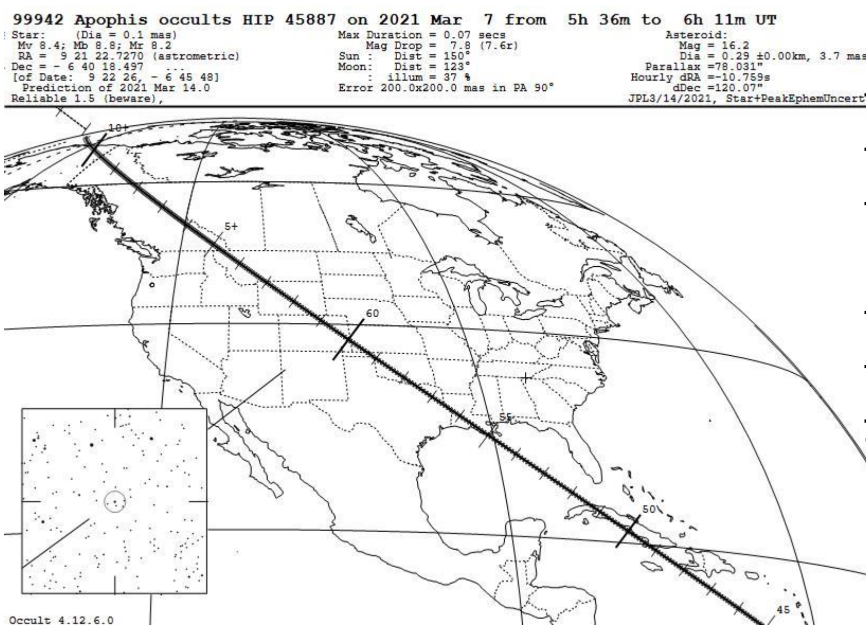
Keyhole Map for 2029 Close Approach



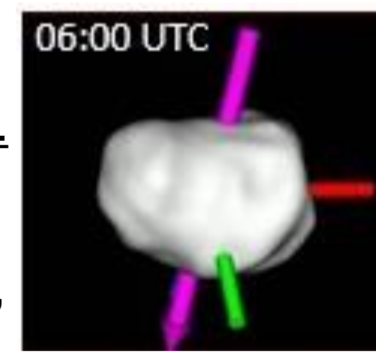
Tholen & Farnocchia, Planetary Defense Conference, 2021

Occultations by (99942) Apophis

- Discovered in 2004; very close approach in 2029 identified
- Elongated object, about 350m x 170m, from 2011 radar obs.
- 2029 flyby near ring of geosats; no threat, but great sci. opp.
- But could pass through “keyhole” into a resonant orbit
- With the best orbit before 2021, small chance of 2068 impact

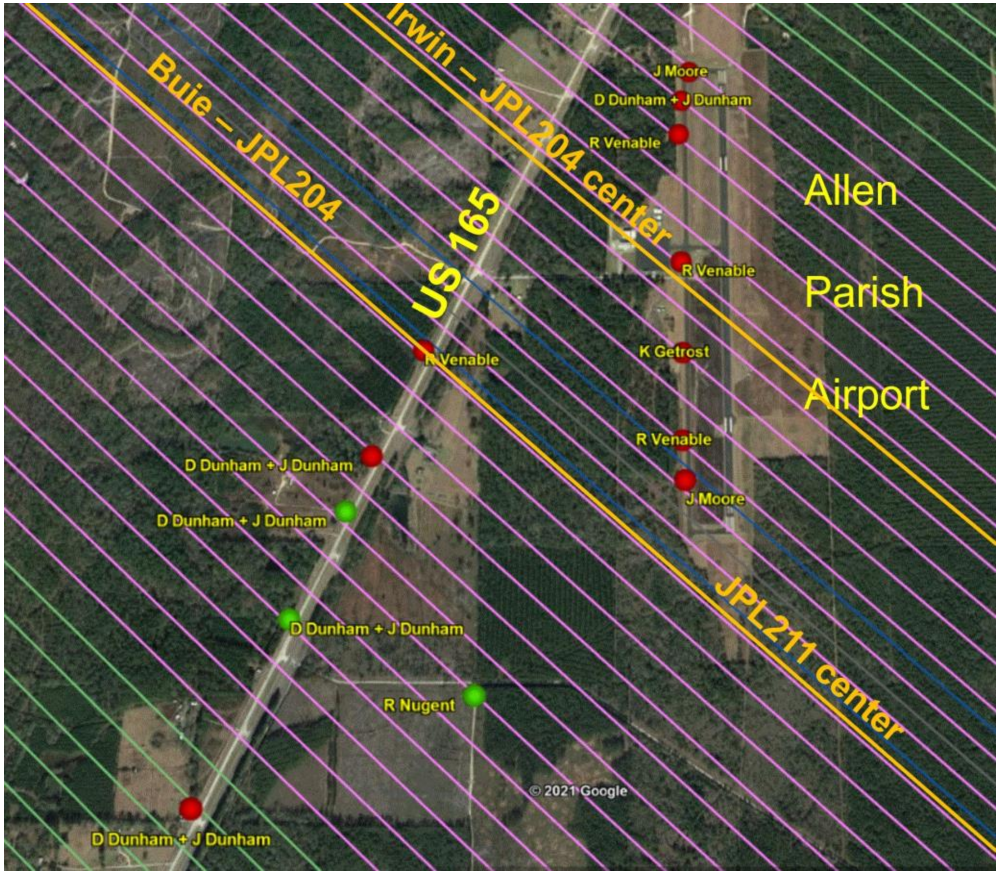


Paris Obs.’s Lucky Star Project found a 7th-mag. occ’n across N. America on 2021 Feb. 22, but without radar, it could not be predicted well. They found another event, star mag.8.4, with map at left, and radar data were expected a few days before. The shape model with new spin state, aspect for the event from Marina Borzovic, is at right.



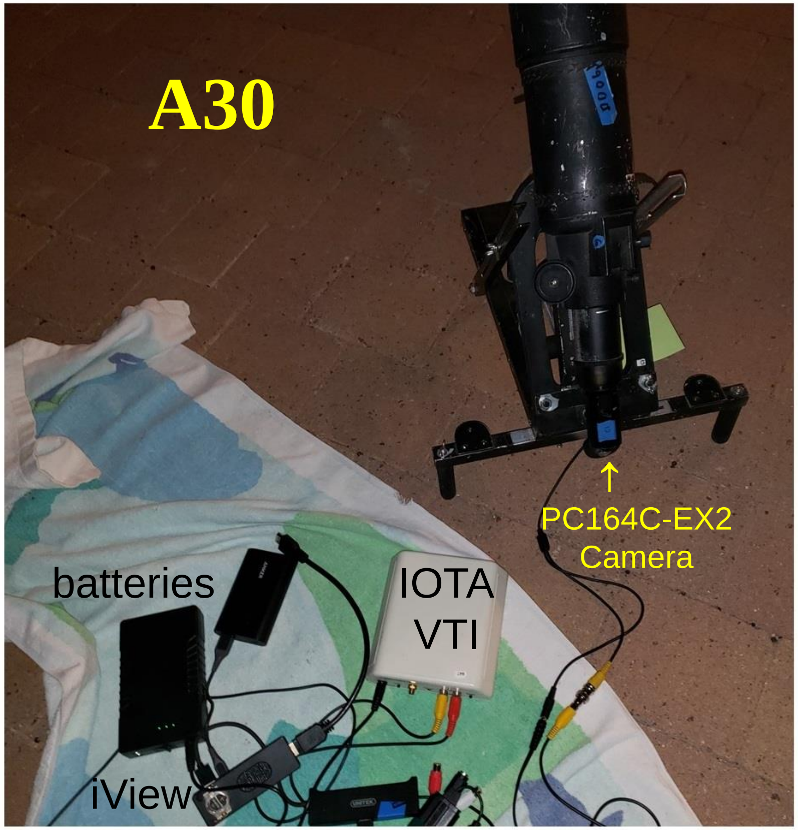
Much information about past observed Apophis occultations, and predictions for future ones, are at **http://iota.jhuapl.edu/Apophis2021.htm.**

2021 March 7 Stations near Oakdale, Louisiana



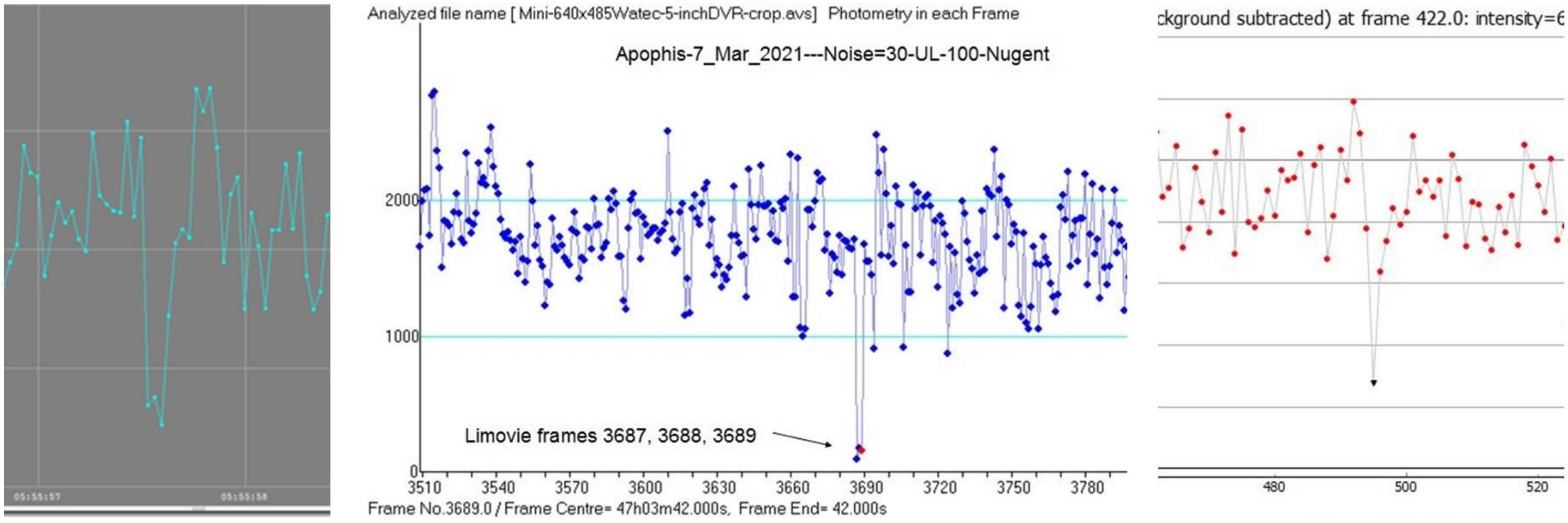
6 IOTA observers deployed 13 stations along the taxiway of the Allen Parish Airport, and beside US 165. Red dots mark stations that had a miss, while green dots mark 3 that recorded an occultation. The station locations were selected to be close to the diagonal tracks shown on the map, 107 meters apart as projected on the ground. They were 80 meters apart on the plane of the sky. J. Moore pre-pointed 2 systems that recorded the star, R. Venable 4, and D & J Dunham, 5, 2 of which (green dots) recorded the occultation, as did R. Nugent between them. K. Getrost recorded a miss. Orange lines show 3 predictions, two based on JPL orbit 204 computed on March 5 refined with the radar obs. made the previous 3 nights. JPL orbit 211 shows a later prediction that should be close to where the path would have been, if the Gaia position for NY Hydrae had been correct, as noted below. Some of the lines were covered by observers in Oklahoma, Colorado, and British Columbia; their observations were all negative.

Dunham “Mighty Midi” Systems at A30 & A28



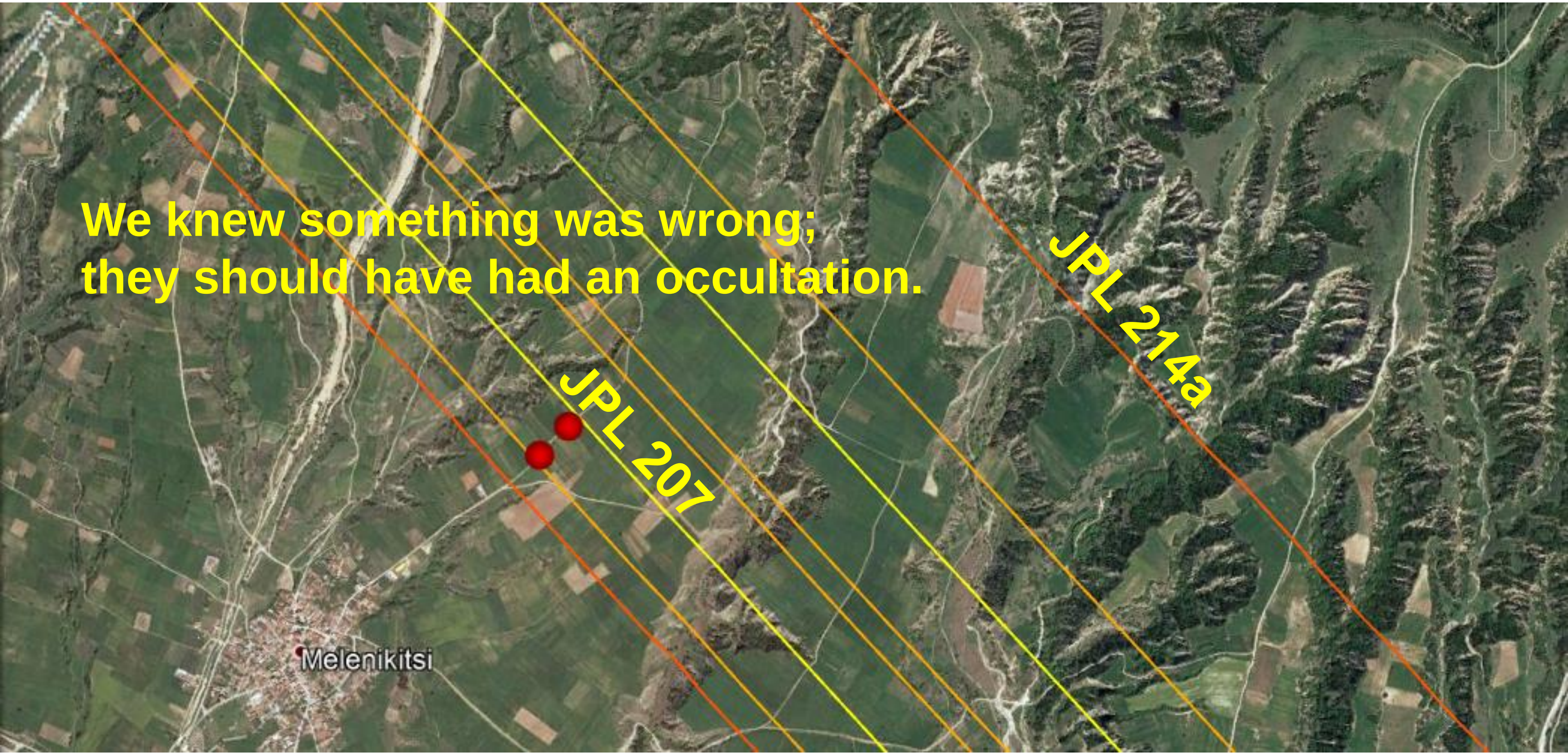
David and Joan Dunham’s equipment used on line A30 (northern, left) and line A28 (southern, right). Both stations used 80mm f/5 refractors with f/0.5 focal reducers, small video cameras, an IOTA video time inserter (VTI) for accurate time-stamping of the videos with GPS 1PPS (the VTI is under the towel at A28), and iView “stick” Win10 computers to record the video with a Startech SVID2USB23 video capture device. Except for the cameras, the equipment was the same at the two stations. These pictures were taken during a practice run at their home 3 nights before the occultation.

Positive Station Occultation Lightcurves



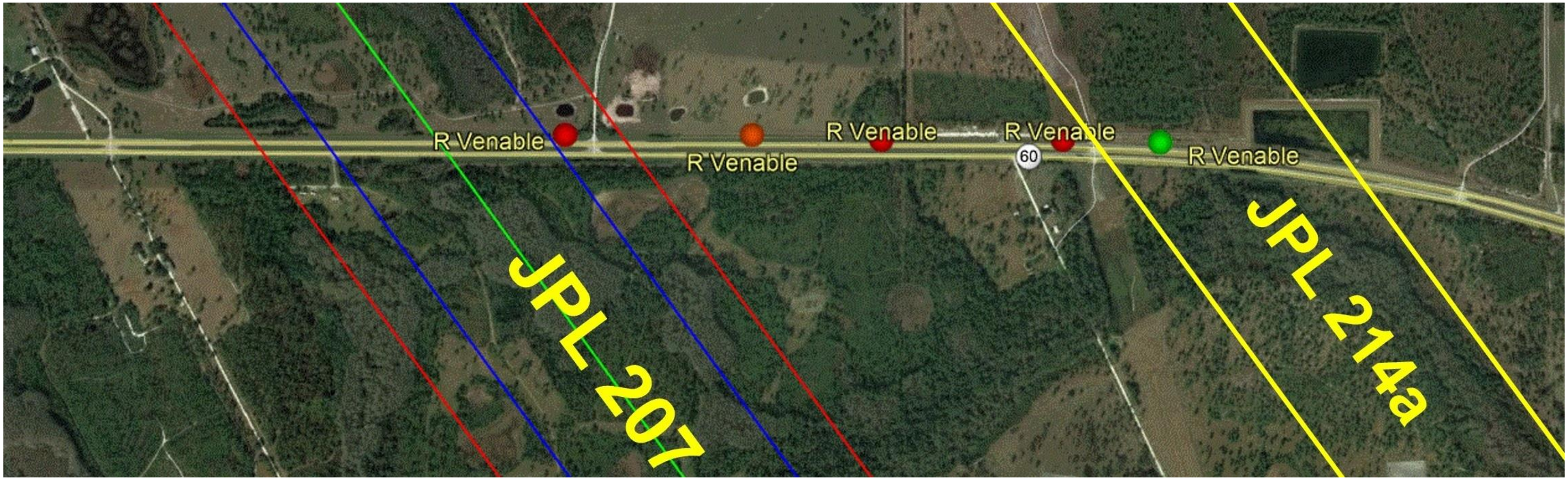
Lightcurves obtained at the three positive stations showing the brief occultation by Apophis. Left, station A30, Dunhams; Center, A29, Nugent; Right, A28, Dunhams.

March 11th Apophis occultation of a 9th-mag. star attempted in Greece



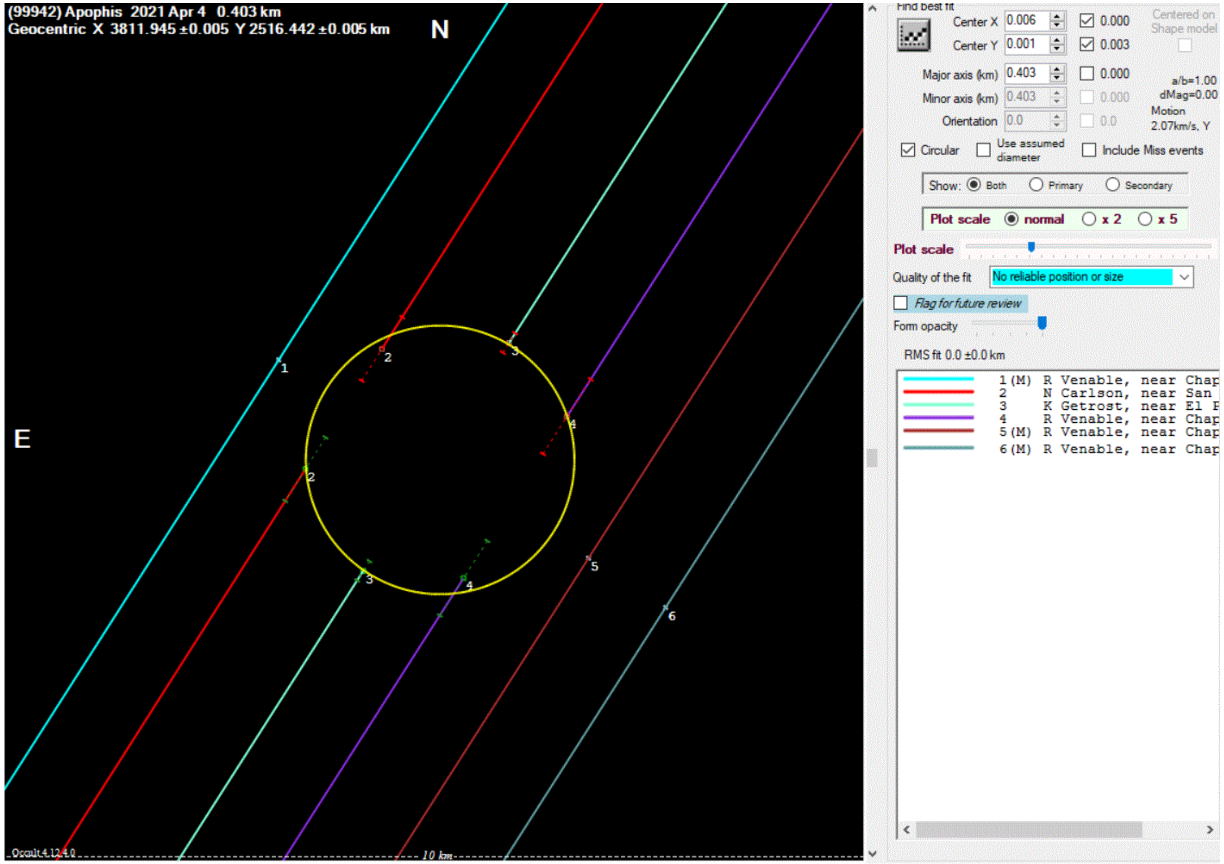
The two observers, from Thessaloniki, both had no occultation. Many others across Europe, and in Israel, were clouded out. JPL 207 was the path updated with the Mar. 7th obs.; JPL 214a is based on a later orbit that was likely where the actual path was, as I'll explain in the next slides.

Venable's 2021 Mar. 22 stations, Yeehaw Jct., Florida



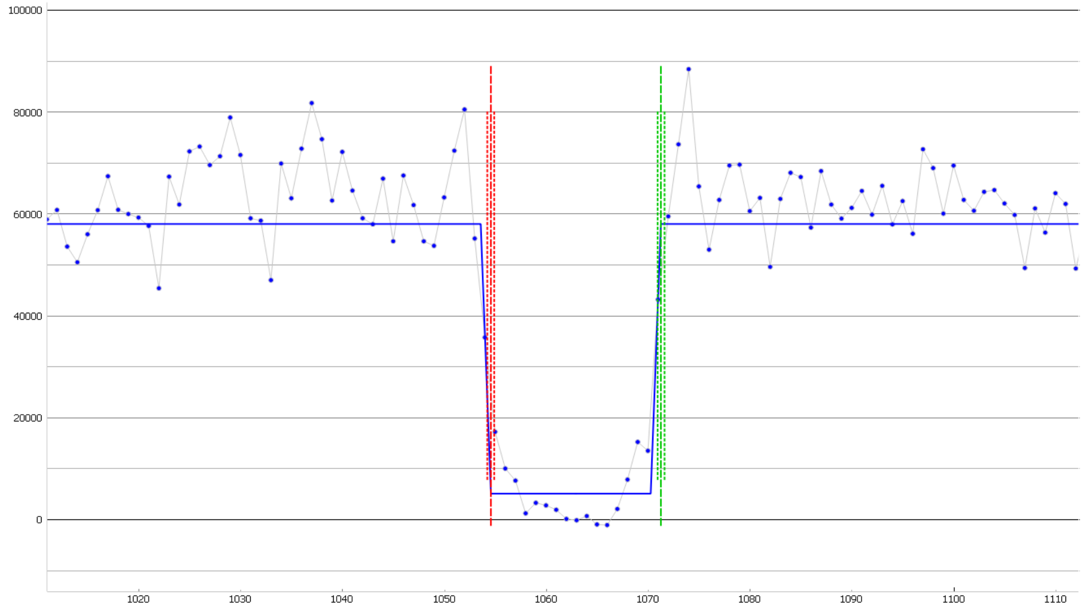
On March 22nd, an occultation of a 10.0-mag. star was predicted for the eastern USA. Some tried the event in n.e. Alabama and Illinois, where they had a miss. Roger Venable deployed 5 telescopes near Yeehaw Junction, Florida, as shown above. Only his easternmost telescope recorded the occultation. The path between the blue lines was computed from JPL orbit 207 (updated using the March 7th observations) and used for planning. The better path between the yellow lines was computed later from JPL orbit 214a that added astrometric points from this event, and from the April 4th occultation observations noted in the next slide. **With these observations, Roger Venable and his 5 large scopes saved Apophis' accurate orbit.**

2021 April 4 Apophis occultation in s. New Mexico



We suspected a problem with the Gaia data for NY Hydrae so we gave the Mar. 22nd observation higher weight for JPL orbit 211, used to predict this event. 8 stations were set up at 140m intervals on the sky plane (conservative due to the discrepancy between the Mar. 7 & 22 results), 5 stations by R. Venable. The star was 11.0 magnitude, fainter than the earlier events, so larger telescopes were needed. The 3 positive observations show that the actual path was only about 100m east of the JPL 211 path.

2021 April 11 Apophis occultation in New Mexico



With Apophis' orbit finally nailed by the April 4th observations, we were able to accurately locate the three observers, each with one telescope, for the April 11th occultation of a 10.1-mag. star, so that each had occultations. Above is Kai Getrost's light curve of the occultation was recorded with 100 frames per second from Farmington, New Mexico with a QHY 174M GPS camera attached to a 20-inch Dobsonian telescope. Effects of Fresnel diffraction are evident.

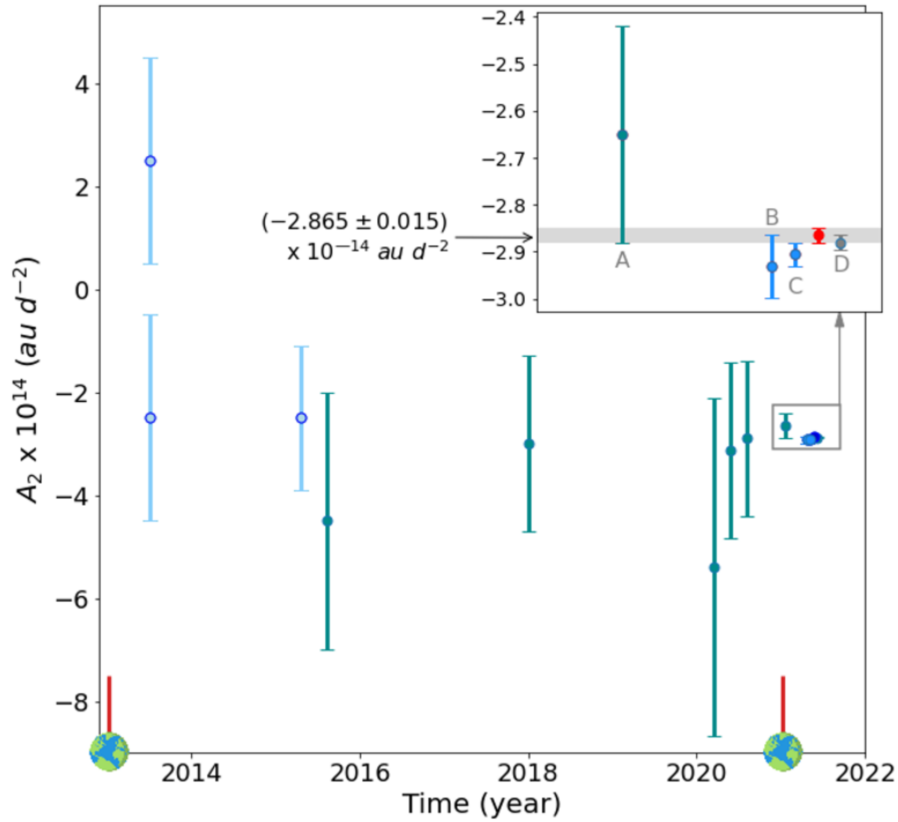
Summary of all observed positive Apophis occultations with O-C's from JPL 214a

2021 Date	mag. [1]	Loc. [2]	Total #	# pos.	Δα [3]	Δδ [3]	Δt [3]	RUWE [4]
March 7	8.4	LA,OK,CO,BC	29	3	-11.0	+1.2	+0.17	1.45 [5]
March 22	10.0	FL,AL,IL	9	1	+0.4	-0.5	-0.02	1.15
April 4	11.0	NM	8	3	+0.3	-0.1	-0.01	0.90
April 10	12.6	Japan	2	1?				
April 11	10.1	NM	3	3	+0.5	-0.5	-0.03	0.85

[1] This is the Gaia g magnitude of the occulted star.
[2] For location, the country is given, or 2-letter US State/Canadian Province codes.
[3] The O-C residuals are relative to JPL orbit 214a, in mas, but in seconds for Δt.
[4] The RUWE is for the Gaia 3rd Early Data Release (EDR3); values >1.40 indicate stars that are likely to have positional errors larger than the formal errors from the Gaia astrometric solution.
[5] The star is NY Hydrae, an eclipsing variable with a 4.8-day period.

We believe NY Hydrae's duplicity, more than the RUWE value, is the main explanation of the large residuals on Mar. 7. Slide 36 shows the path (JPL 211, which was almost the Same as JPL 214a) that would have occurred on March 7th, if the Gaia position of NY Hydrae had NOT been in error. That threw us off after that event, causing the observers in Greece for the Mar. 11 occultation, to be in the wrong place and have a miss. Fortunately, Venable was able to spread his stations out far enough on Mar. 22 to catch that occultation (slide 40). The table shows that the residuals for March 7th stick out like a sore thumb, demonstrating the astrometric power of observations of occultations by small NEAs.

Occultations helped retire the risk of Apophis



Gaia Image of the week, 2021 Mar. 29. “Apophis’ Yarkovsky acceleration improved through stellar occultation”

Also, please see Tanga et al’s poster, “Stellar occultations by NEAs, challenges and opportunities” that notes, <u>DART/Hera target Didymos should be next for occ’ns</u>

Evolution in time of <u>our knowledge of the average Yarkovsky acceleration for 99942 Apophis.</u> The light blue data represent the early theoretical estimates from approximate models of the physical properties of Apophis1. The other data are measurements enabled by the collection of more optical and radar astrometry. On the horizontal axis, close encounters with the Earth (enabling collection of accurate astrometry) are marked. <u>The inset shows the last estimates compared to our value, in red, obtained from all the observations available on March 15, including the occultation observed on March 7, 2021</u>. For more, see <u>https://www.cosmos.esa.int/web/gaia/iow_20210329.</u>

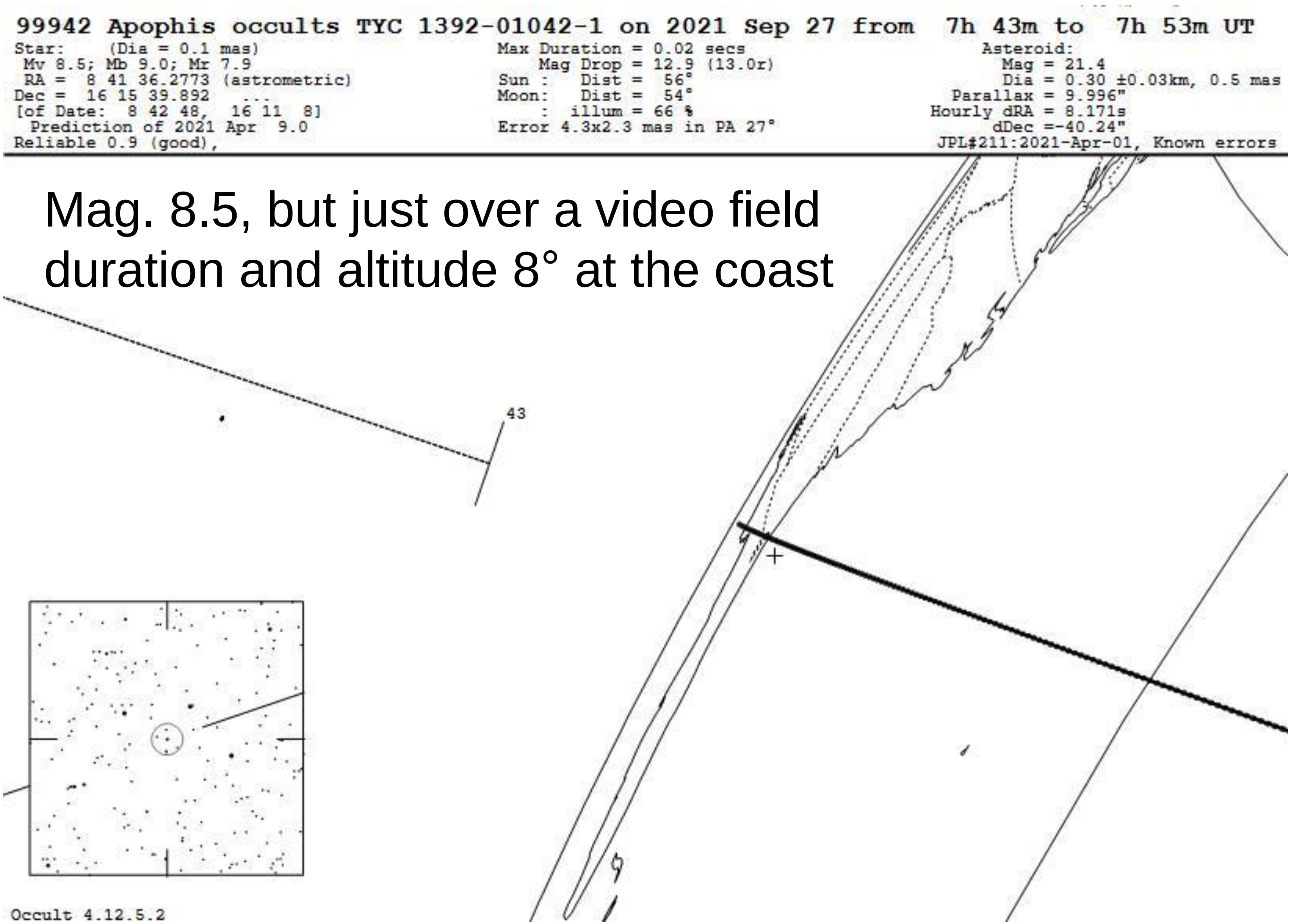
Predictions of future Apophis occultations

2021 Date	U.T.	mag. [1]	Location	duration, sec.	Event Notes
May 4	3.1h	8.7	cen. Chile, Baja, s. CA	0.17	[3]
May 6	3.1h	11.6	n. Chile, Sonora, s.AZ	0.16	[4] **4 +'s in AZ, MX**
May 20	18.0h	10.6	Oman, e. TR, e. UA	0.10	[5]
Sep. 5	1.6h	6.4	S. Sudan, Ethiopia	0.02	[6]
Sep. 27	7.7h	8.5	n. Florida, s.e. GA	0.02	[7] **Next US event**

[1] This is the Gaia g magnitude of the occulted star.
[2] For location, the country or its 2-letter code is given, or 2-letter US State code.
[3] The star is SAO 79801 = XZ 11903, spectral type F0. Near Borrego Springs, CA, the Sun alt. is -8°. In Chile, the path is over Santiago and Vina del Mar, star alt. 9°.
[4] On the coast south of Antofagasta, Chile, the star alt. is 9°. In southern Arizona, the Sun alt. is -11°; the path passes over the town of Sells, & Goodyear.
[5] In eastern Turkey, the Sun alt. is -16°; west of Kharkiv, Ukraine, it is -7°. The path is also over w. U.A.E., n. Qatar, and e. Iraq.
[6] The star is ZC 1125 = SAO 79386, spectral type F6V. The Gaia EDR3 RUWE is high, 2.5, so the path may be a few km off.
[7] The star is SAO 98045. The star altitude is 9° at the Atlantic coast.

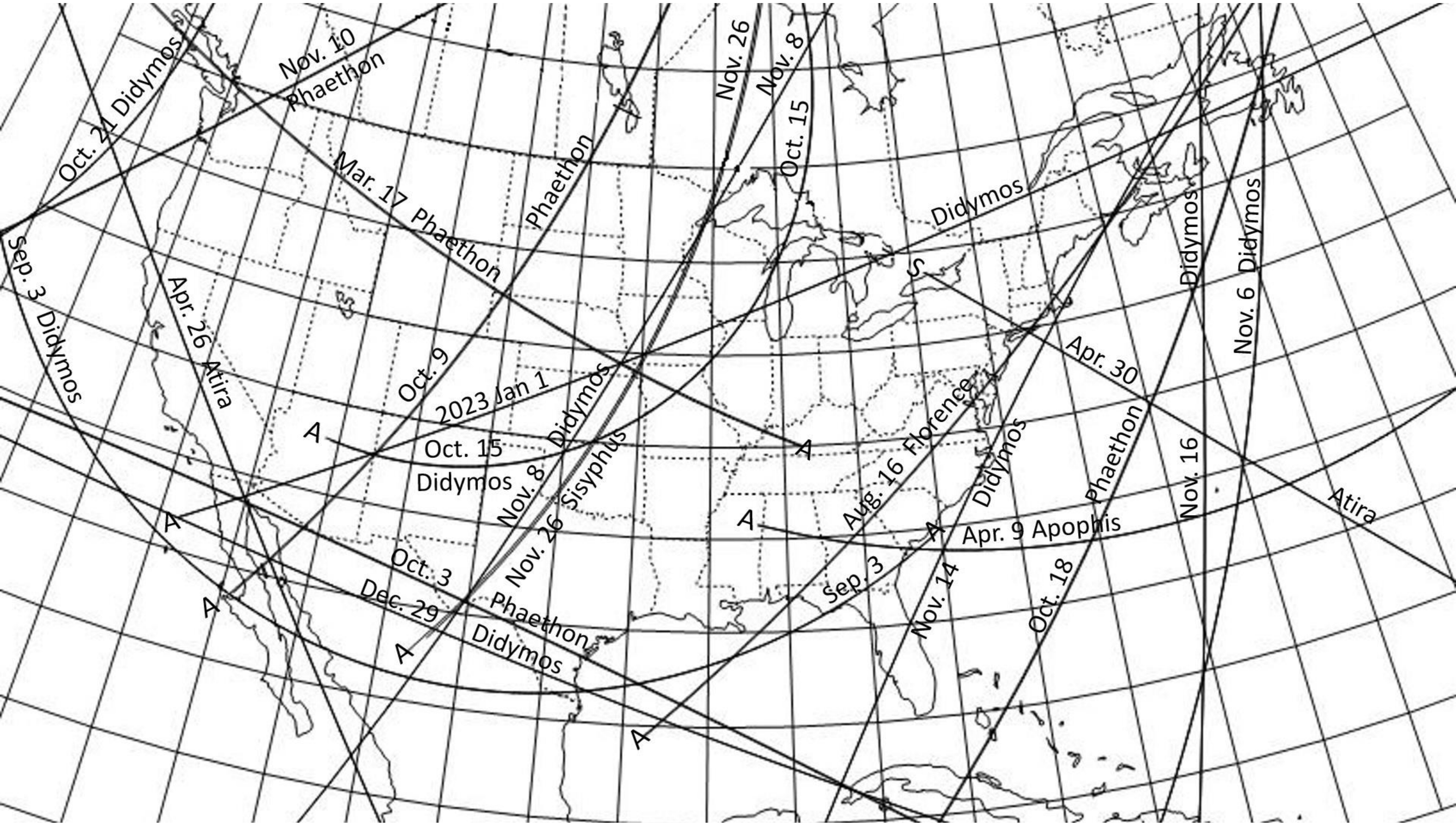
During June, July, and August, Apophis is too close to the Sun so no observable occultations occur then. In September, the event durations become much shorter so only brighter stars have a reasonable chance to be observed with video. Maps and path details are on the IOTA Apophis page at **http://iota.jhuapl.edu/Apophis2021.htm**

The next Apophis occultation in the USA



Mag. 8.5, but just over a video field duration and altitude 8° at the coast

Near-Earth Asteroidal Occultations in 2022 for RASC Handbook



These paths are very narrow; you have to travel to them, to observe these Occultations, preferably in groups to set up multiple mobile stations.

Didymos Occultations in 2022 in Europe, mag. <12.1

These paths are very narrow; you have to travel to them, to observe these occultations, preferably in groups to set up multiple mobile stations.

Didymos Occultations in 2022 in Europe, mag. <12.1

Only 3 occur before the planned late September DART impact

Date y m d	U.T. h m	Diameter km	Diameter "	Durn sec/m	Star mag	Mag-Drop V	Mag-Drop R	Elon o	% Ill	Star No.	d	Rely <1.4	Planet No	Planet Name	Min D	Error	Moon Dist	Moon ill	§ ●	R.A. (J2000) h m s	Dec. ° ' "
2022 Feb 28	3 6.6	0.90	0.001	0.03s	11.7	10.8	10.8	64		UCAC4 335-152656		0.65	65803	Didymos	0.53	±0.00	31	9	☾	18 21 34.931	-23 6 56.34
2022 Jul 23	21 20.3	0.80	0.003	0.19s	11.9	5.8	5.7	146		UCAC4 352-188683		1.60	65803	Didymos	0.75	±0.00	95	20	☾	22 37 14.915	-19 43 51.45
2022 Sep 14	2 59.6	0.79	0.011	0.16s	10.3	4.5	4.3	140		TYC 7004-00662-1	s	1.00	65803	Didymos	0.83	±0.00	51	84	☾	1 13 59.954	-34 43 5.69
2022 Oct 4	0 22.4	0.80	0.015	0.13s	11.8	2.9	2.7	113		TYC 6468-00564-1		0.90	65803	Didymos	0.79	±0.00	112	61	☾	4 46 18.336	-26 38 58.11
2022 Oct 6	[illegible] 26.8	0.80	0.015	0.14s	11.5	3.3	3.1	110		UCAC4 332-006897		1.10	65803	Didymos	0.37	±0.00	98	[illegible]	☾	[illegible] .437	-23 43 42.91
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2022 Oct 8	23 40.4	0.80	0.015	0.14s	11.0	3.9	3.8	106		TYC 5925-01562-1		1.10	65803	Didymos	0.93	±0.00	79	99	☾	5 37 20.499	-19 [illegible] 57.46
2022 Oct 11	2 22.5	0.80	0.015	0.14s	11.5	3.5	3.4	104		TYC 5931-00048-1		1.00	65803	Didymos	0.94	±0.00	64	98	☾	5 56 7.215	-16 49 51.37
2022 Oct 11	2 29.6	0.80	0.015	0.14s	11.2	3.8	3.7	104		UCAC4 366-010390		1.35	65803	Didymos	0.64	±0.00	64	98	☾	5 56 8.621	-16 48 54.63
2022 Oct 11	5 43.6	0.79	0.015	0.14s	10.8	4.2	4.1	104		TYC 5931-01088-1	s	0.90	65803	Didymos	0.37	±0.00	63	98	☾	5 57 13.213	-16 37 23.45
2022 Oct 13	1 52.0	0.80	0.014	0.15s	11.9	3.3	3.0	102		TYC 5374-01066-1		1.70	65803	Didymos	0.90	±0.00	51	89	☾	6 12 8.602	-14 2 42.20
2022 Oct 14	0 21.4	0.80	0.014	0.15s	10.8	4.4	4.1	102		TYC 5371-00235-1		0.90	65803	Didymos	0.71	±0.00	45	83	☾	6 19 14.300	-12 44 46.94
2022 Oct 15	5 23.0	0.80	0.014	0.16s	11.9	3.3	3.2	101		UCAC4 395-013672		1.00	65803	Didymos	0.79	±0.00	40	73	☾	6 27 49.557	-11 8 26.37
2022 Oct 16	3 44.8	0.80	0.014	0.16s	11.5	3.8	3.6	100		UCAC4 401-013999		0.85	65803	Didymos	0.54	±0.00	37	65	☾	6 34 7.927	- 9 55 6.37
2022 Oct 16	5 30.6	0.79	0.014	0.16s	12.0	3.3	3.3	100		UCAC4 401-014078	s	1.10	65803	Didymos	0.25	±0.00	37	64	☾	6 34 34.559	- 9 49 15.21
2022 Oct 16	23 38.6	0.80	0.013	0.16s	11.3	4.1	3.8	100		UCAC4 406-016112		1.15	65803	Didymos	0.93	±0.00	37	57	☾	6 39 33.562	- 8 52 10.88
2022 Oct 17	3 37.4	0.79	0.013	0.16s	11.6	3.7	3.8	100		UCAC4 407-016500	s	1.10	65803	Didymos	0.83	±0.00	37	55	☾	6 40 34.116	- 8 39 57.49
2022 Oct 17	5 38.3	0.80	0.013	0.16s	11.7	3.7	3.3	100		TYC 5378-01537-1		1.05	65803	Didymos	0.60	±0.00	37	55	☾	6 41 4.063	- 8 33 29.77
2022 Oct 17	23 57.5	0.79	0.013	0.17s	11.5	3.9	3.8	100		UCAC4 412-018678	s	0.95	65803	Didymos	0.78	±0.00	38	47	☾	6 45 50.357	- 7 36 37.55
2022 Oct 18	2 30.3	0.80	0.013	0.17s	11.3	4.1	3.7	99		TYC 4812-03777-1		1.20	65803	Didymos	0.68	±0.00	38	46	☾	6 46 25.875	- 7 29 14.79
2022 Oct 18	3 45.8	0.80	0.013	0.17s	9.9	5.5	5.1	99		TYC 4812-03513-1		8.30	65803	Didymos	0.41	±0.00	39	46	☾	6 46 42.441	- 7 25 17.05
2022 Oct 18	4 29.6	0.79	0.013	0.17s	11.6	3.8	3.9	99		UCAC4 414-019075	s	1.10	65803	Didymos	0.54	±0.00	39	46	☾	6 46 53.356	- 7 23 21.59
2022 Oct 19	2 17.5	0.80	0.013	0.17s	11.7	3.8	3.5	99		UCAC4 419-021485		7.55	65803	Didymos	0.75	±0.00	42	37	☾	6 52 12.637	- 6 18 48.56
2022 Oct 19	2 13.7	0.80	0.013	0.17s	10.5	5.0	4.6	99		UCAC4 419-021480	W	1.20	65803	Didymos	0.48	±0.00	42	37	☾	6 52 11.543	- 6 18 25.50
2022 Oct 19	3 28.4	0.80	0.013	0.17s	11.9	3.6	3.6	99		UCAC4 419-021548		1.20	65803	Didymos	0.25	±0.00	43	37	☾	6 52 27.221	- 6 14 42.10
2022 Oct 19	4 11.1	0.80	0.013	0.17s	11.1	4.3	3.9	99		TYC 4813-03010-1		0.95	65803	Didymos	0.84	±0.00	43	36	☾	6 52 39.134	- 6 13 33.77
2022 Oct 19	4 20.5	0.79	0.013	0.17s	11.1	4.3	4.2	99		TYC 4813-02802-1	s	1.05	65803	Didymos	0.26	±0.00	43	36	☾	6 52 38.943	- 6 12 18.57
2022 Oct 19	5 5.3	0.79	0.013	0.17s	11.1	4.3	4.2	99		TYC 4813-02134-1	s	1.05	65803	Didymos	0.04	±0.00	43	36	☾	6 52 48.080	- 6 9 56.49
2022 Oct 19	5 32.8	0.80	0.013	0.17s	11.0	4.4	4.0	99		TYC 4813-02102-1		1.00	65803	Didymos	0.01	±0.00	43	36	☾	6 52 54.197	- 6 8 37.23
2022 Oct 20	4 18.0	0.79	0.013	0.17s	8.6	6.9	6.5	99		HIP 33538	v	3.15	65803	Didymos	0.77	±0.00	49	27	☾	6 58 11.890	- 5 4 29.29
2022 Oct 21	1 54.7	0.80	0.012	0.18s	11.2	4.3	3.9	99		TYC 4822-01913-1		0.95	65803	Didymos	0.92	±0.00	55	20	☾	7 2 57.680	- 4 4 46.13
2022 Oct 21	3 55.7	0.80	0.012	0.18s	11.6	4.0	3.8	99		UCAC4 431-026403		0.80	65803	Didymos	0.75	±0.00	56	19	☾	7 3 22.020	- 3 59 14.79
2022 Oct 22	5 45.6	0.80	0.012	0.18s	11.1	4.5	4.1	99		TYC 4819-01556-1		1.25	65803	Didymos	0.51	±0.00	65	12	☾	7 8 42.033	- 2 50 30.53
2022 Oct 22	23 30.5	0.80	0.012	0.19s	11.9	3.8	3.3	99		TYC 4819-02776-1	W	0.95	65803	Didymos	0.90	±0.00	73	7	☾	7 12 16.669	- 2 5 0.16
2022 Oct 24	5 23.2	0.79	0.012	0.19s	10.1	5.5	5.3	99		TYC 4816-00453-1	s	1.00	65803	Didymos	0.00	±0.00	85	2	☾	7 17 48.417	- 0 50 38.63
2022 Oct 25	0 27.4	0.80	0.011	0.20s	11.7	4.0	4.0	99		UCAC4 450-034167		0.90	65803	Didymos	0.74	±0.00	94	0	☾	7 21 19.129	- 0 5 31.50
2022 Oct 25	0 42.6	0.79	0.011	0.20s	9.8	5.9	5.7	99		TYC 4816-00694-1	s	0.85	65803	Didymos	0.62	±0.00	94	0	☾	7 21 21.136	- 0 4 50.42
2022 Oct 29	1 29.3	0.80	0.011	0.22s	11.7	4.2	4.0	99		TYC 182-02279-1		0.90	65803	Didymos	0.76	±0.00	141	16	☾	7 36 38.114	3 23 57.89
2022 Oct 29	6 7.9	0.80	0.010	0.22s	10.1	5.7	5.1	99		G073712.9+033353	D	7.15	65803	Didymos	0.16	±0.00	143	18	☾	7 37 12.851	3 33 52.13
2022 Oct 29	6 8.0	0.80	0.010	0.22s	10.3	5.6	4.9	99		G073712.9+033352	D	10.8	65803	Didymos	0.16	±0.00	143	18	☾	7 37 12.878	3 33 52.03
2022 Nov 1	5 44.8	0.80	0.010	0.23s	11.3	4.7	4.4	101		TYC 192-00355-1		1.40	65803	Didymos	0.47	±0.00	157	49	☾	7 46 38.360	5 48 5.05
2022 Nov 3	6 33.4	0.80	0.010	0.25s	11.6	4.4	4.2	101		TYC 192-00978-1		0.95	65803	Didymos	0.07	±0.00	138	72	☾	7 52 14.586	7 12 27.67
2022 Nov 16	5 9.3	0.79	0.008	0.34s	10.6	5.5	5.5	110		TYC 806-00262-1	s	1.35	65803	Didymos	0.07	±0.00	20	54	☾	8 16 18.963	14 21 1.93

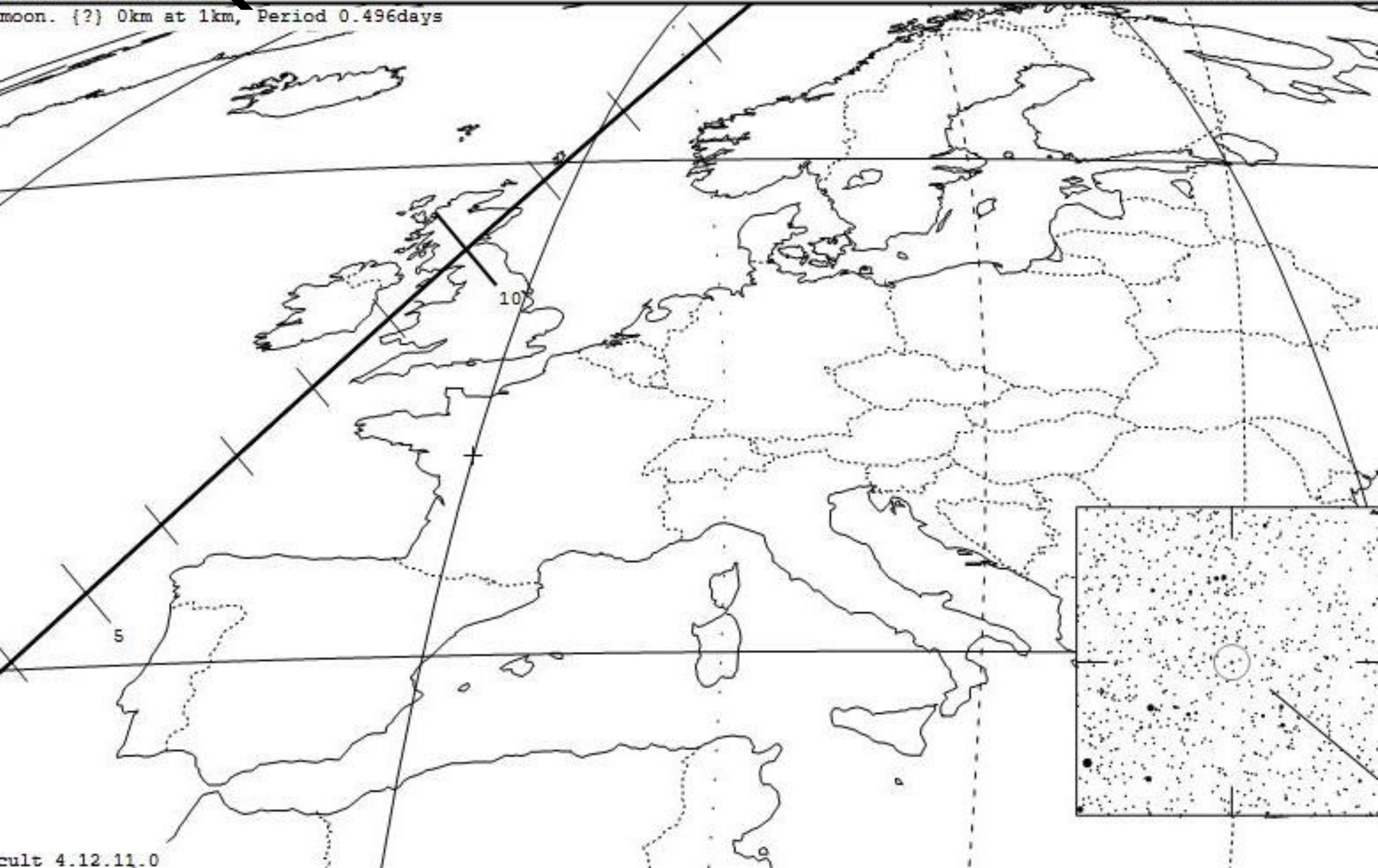
These paths are very narrow; you have to travel to them, to observe these occultations, preferably in groups to set up multiple mobile stations.

5803 Didymos occults HIP 33538 on 2022 Oct 20 from 3h 45m to 4h 15m UT

ar: (Dia = 0.1 mas)
v 8.6; Mb 8.8; Mr 8.5
A = 6 58 11.8895 (astrometric)
c = - 5 4 29.294 ...
f Date: 6 59 19, - 5 6 8]
Prediction of 2021 Aug 20.0
liable 3.2 (beware)

Max Duration = 0.17 secs
Mag Drop = 6.9 (6.5r)
Sun : Dist = 99°
Moon: Dist = 48°
: illum = 27 %
Error 4.7x0.8 mas in PA 106°

Asteroid:
Mag = 15.5
Dia = 0.79 ±0.10km, 12.6
Parallax =100.735"
Hourly dRA =13.475s
dDec =167.98"
JPL#181:2021-Feb-13, Known erro



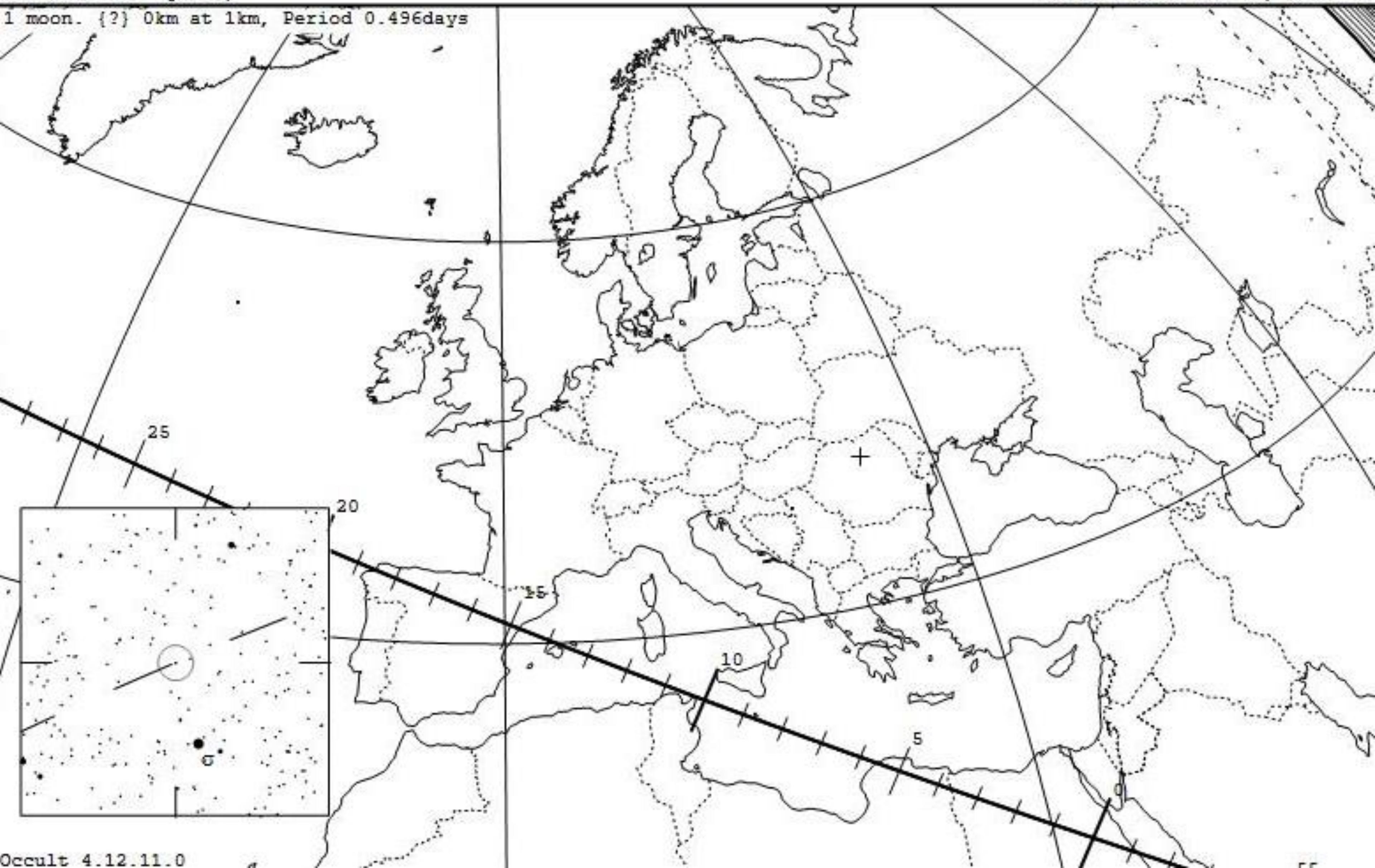
65803 Didymos occults HIP 37693 on 2023 Jan 1 from 0h 42m to 1h 46m UT

Star: (Dia = 0.1 mas)
 Mv 9.0; Mb 9.4; Mr 8.7
 RA = 7 43 58.9874 (astrometric)
Dec = 29 24 21.677   ...
[of Date: 7 45 26, 29 21 2]
  Prediction of 2021 Aug 20.0
Reliable 1.3 (good),

Max Duration = 0.25 secs
   Mag Drop = 7.4 (7.2r)
Sun :   Dist = 165°
Moon: Dist = 79°
     : illum = 70 %
Error 4.7x0.6 mas in PA 106°

Asteroid:
  Mag = 16.4
  Dia = 0.78 ±0.10km, 4.
Parallax =33.349"
Hourly dRA =-4.289s
dDec = 23.87"
JPL#181:2021-Feb-13, Known er

1 moon. {?} 0km at 1km, Period 0.496days



Occult 4.12.11.0

Conclusions

- The rare bright 2019 July 29th occultation was the first successful campaign for a small NEO; it's the smallest asteroid with multiple timed chords during an occultation. One of the largest collaborations of amateur and professional astronomers for an occultation enabled this success.
- The radar size and shape were verified, and the improved orbit allowed a good prediction for the Sept. 29th occultation, then subsequent events, and an improvement of Phaethon's A2 non-gravitational parameter by a factor of 3.
- Recently, the occultation technique was successfully applied to Apophis, which is more than 10 times smaller than Phaethon, further demonstrating the astrometric power of observations of NEO occultations for planetary defense.
- Information about the sizes, shapes, rings, satellites, and even atmospheres of Kuiper Belt objects, Centaurs, Trojans, and other asteroids is proportional to the number of stations that can be deployed for occultations by them
- So we encourage as many others as possible to time occultations by TNO's and by other asteroids from their observatories
- We want amateurs to learn to make the necessary mobile observations, including the multi-station techniques pioneered by IOTA, to observe NEO occultations; someday, one or more of them might observe an occultation that will save the world, or part of it.
- We hope that the pursuit of NEO occultations will inspire a new generation of astronomers to learn, apply, & improve the techniques for mobile occultation observation, like lunar grazing occultations did for us in the 1960's and 1970's.

Additional Resources

- A longer and more detailed version of the Phaethon presentation is available, 4th from the bottom, on the presentations page of the 2020 IOTA meeting at: **http://occultations.org/community/meetingsconferences/na/2020-iota-annual-meeting/presentations-at-the-2020-annual-meeting/** Another interesting talk there describes a fully automatic portable system, by A. Knox, the 4th from the top.
- IOTA Apophis occultations Web page: **http://iota.jhuapl.edu/Apophis2021.htm**
- MNRAS paper about IOTA's/NASA's asteroidal occultation archive and results: **https://arxiv.org/abs/2010.06086**
- IOTA main Web site, especially the observing pages: **http://occultations.org/**
- Occult Watcher for finding asteroidal occultations for your observatory and area, and for coordinating observations: **http://www.occultwatcher.net/**
- Link to George Viscome's occultation primer: **http://occultations.org/documents/OccultationObservingPrimer.pdf**
- IOTA YouTube videos (Tutorials and notable occultations): **http://www.asteroidoccultation.com/observations/YouTubeVideos.htm**
- SwRI Lucy Mission Trojan occultations Web site (SwRI expeditions planned for many of them): **http://lucy.swri.edu/occultations.html**
- My 7th Planetary Defense Conference paper on NEO occultations **http://iota.jhuapl.edu/NEOoccultationsDunham.pdf**
- Lucky Star TNO/Centaur/Trojan occultations Web site: **https://lesia.obspm.fr/lucky-star/predictions.php**

Updated 2021 April 26