ACCURATE NEO ORBITS FROM OCCULTATION OBSERVATIONS

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Version of 2021 May 13

Outline

- IOTA & Asteroidal Occultations Introduction & History
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- Improvement of Phaethon's orbit – A2 acceleration
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- Almost lost it – 2nd Positive Occ'n, 2021 Mar. 22
- 2021 April Occultations – Apophis Orbit Nailed
- Conclusions
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IOTA and Asteroidal Occultations Introduction

- The observer network that became IOTA formed in 1960’s
- to observe lunar grazing occultations with mobile efforts
- The mobile techniques to observe lunar grazes, were used effectively to observe asteroidal occultations in the late 1970’s
- Starting in the 1980’s, IOTA began recording occultations with video equipment, improving the observations
- Using stars and the Earth’s rotation to pre-point stationary telescopes at multiple locations
- Working with the NASA PDS Small Bodies Node and the Minor Planet Center, IOTA archives all asteroidal occultation observations
- ESA’s Hipparcos and Gaia missions have greatly improved prediction accuracy, resulting in a large increase in observed occultations
- The sizes, shapes, and accurate positions of hundreds of asteroids have been determined
- Dozens of close double stars have been discovered, the diameters of several stars have been measured, and some asteroidal satellites have been discovered, and several characterized.

Lunar Occultation Geometry

IOTA started in the early 1960’s by observing lunar occultations, especially grazing ones

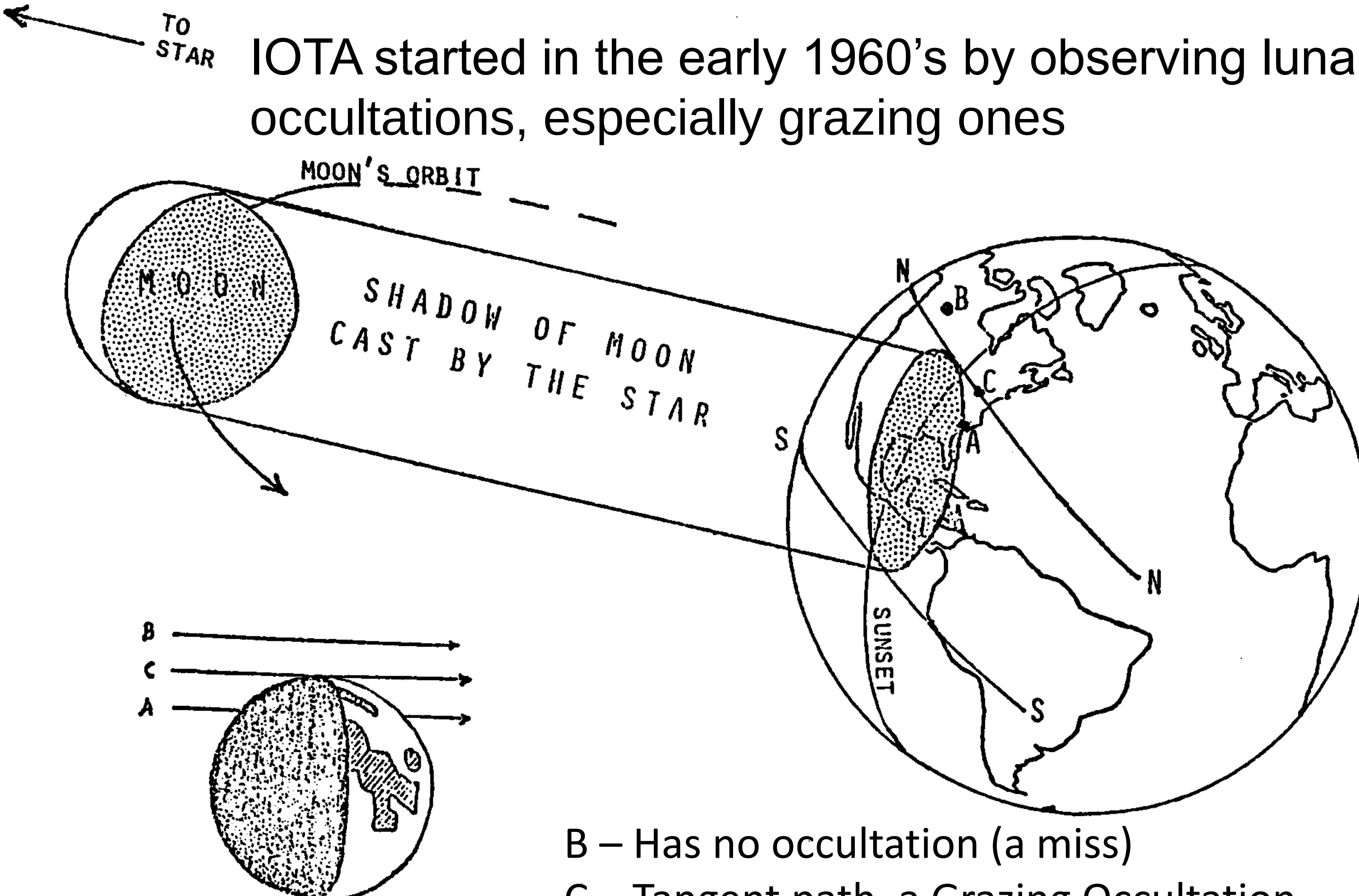


Figure 2-1b

B – Has no occultation (a miss)

C – Tangent path, a Grazing Occultation

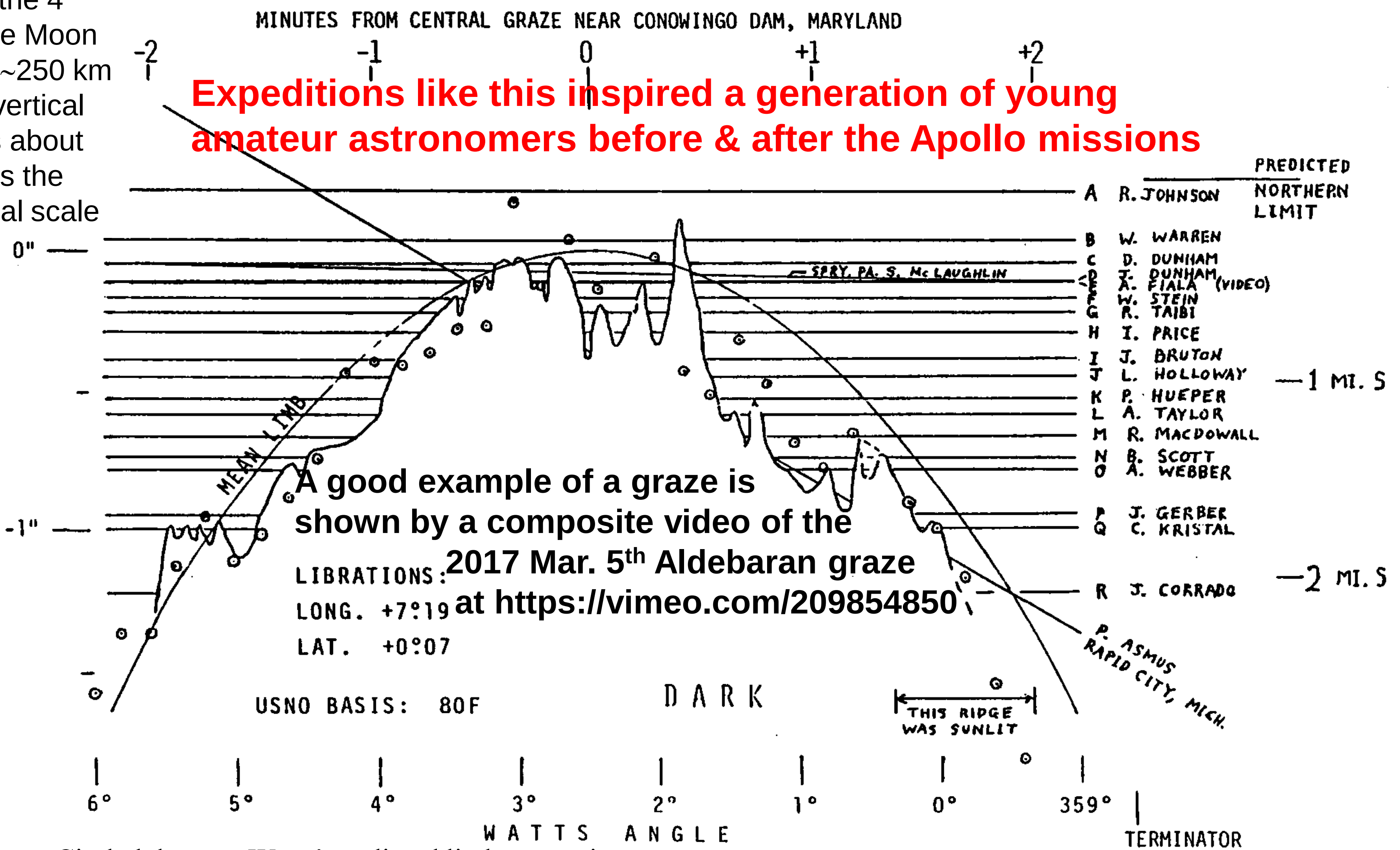
A – Total Occultation

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



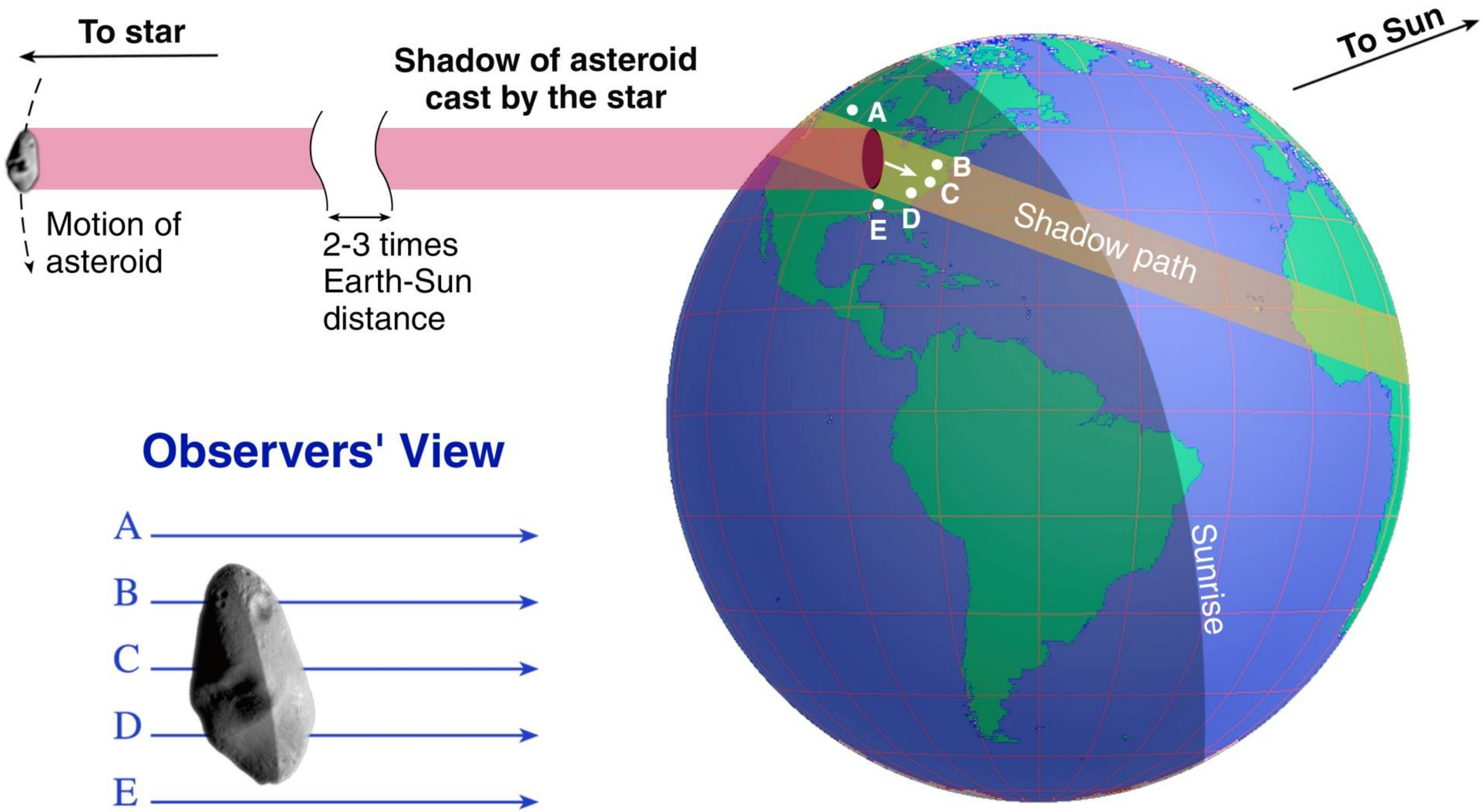
Circled dots are Watts' predicted limb corrections

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.

Geometry of an Asteroid Occultation

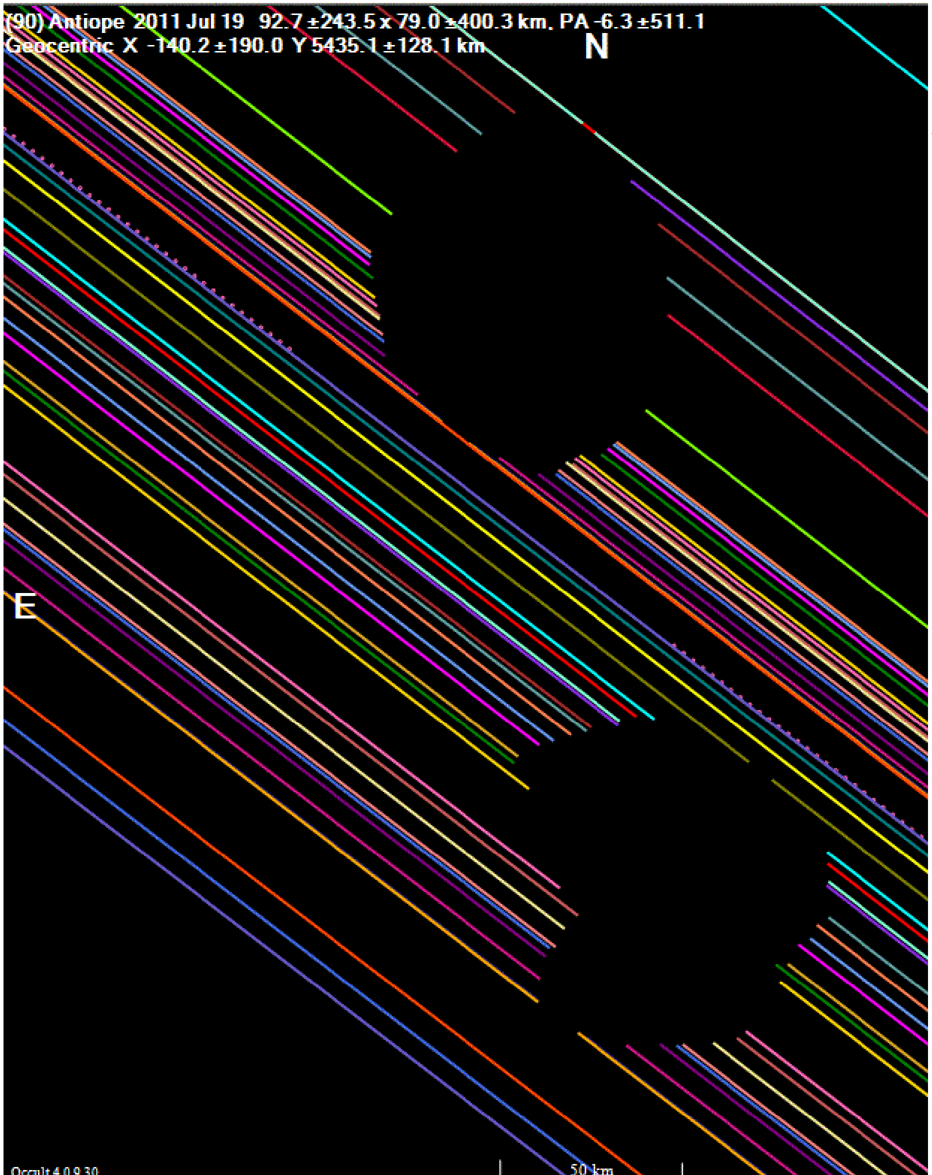
IOTA began observing asteroidal occultations in the late 1970's



The more stations that can be deployed, the better the resolution of the asteroid's shape

Many Occultations of Interesting Main Belt Objects

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



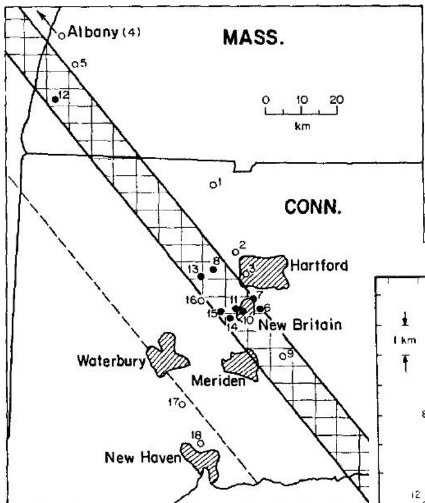
Technology now allows observers to record transient astronomical phenomena more precisely and to fainter magnitudes than ever before. A small, inexpensive, yet very sensitive camera (RunCam Night Eagle Astro) will allow you to participate in IOTA's programs to accurately record occultations and eclipses, 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.

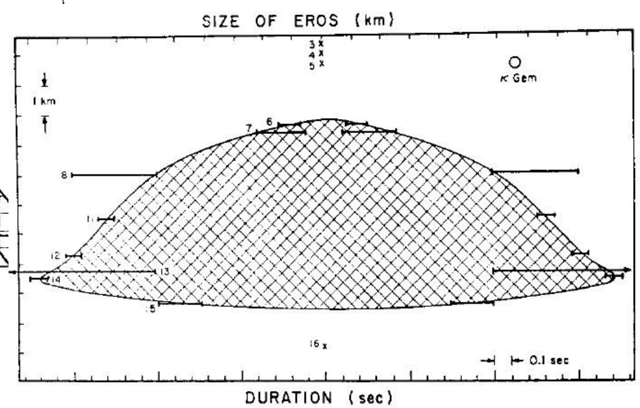
Remote Stations for Asteroidal Occultations

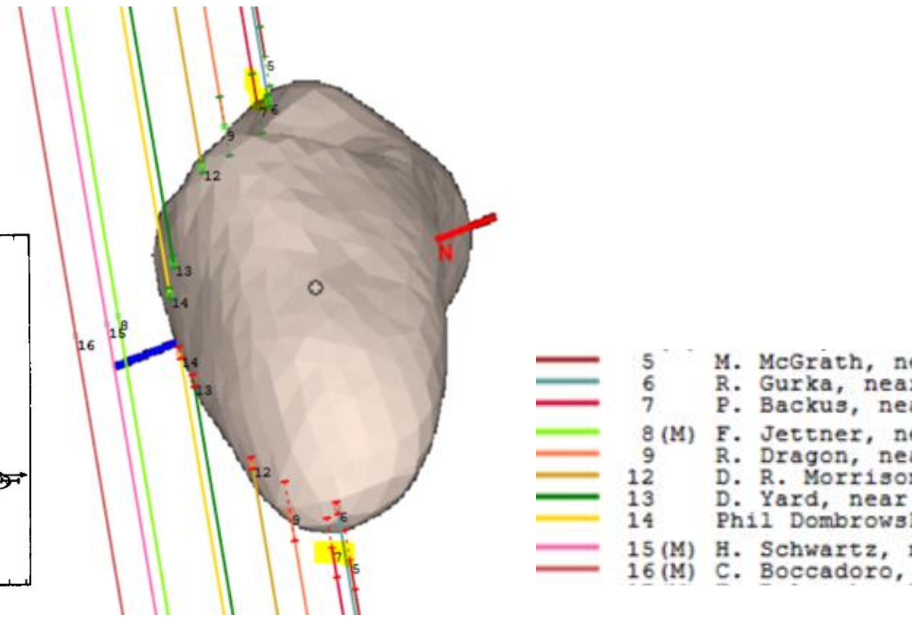
- Separation should be many km, much larger than for grazes, so tracking times & errors are too large
- Unguided is possible since the prediction times are accurate enough, to less that 1 min. = ¼° (now the prediction time errors are only a few seconds)
- Point telescope beforehand to same altitude and 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

First observed occultation by a NEO, 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 NEO would be observed.

(3200) Phaethon

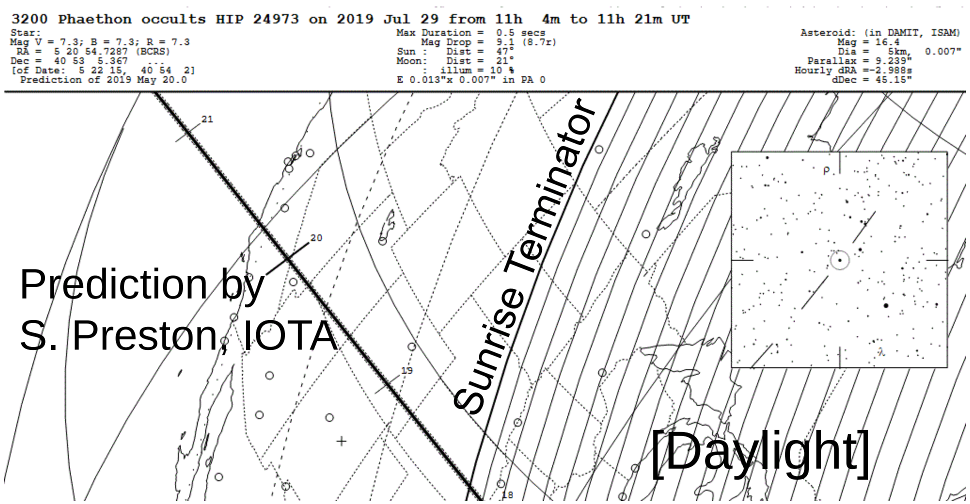
- (3200) Phaethon was the first asteroid to be discovered by a spacecraft (IRAS).
- Phaethon is the parent body of the Geminids meteor stream that puts on one of the largest annual meteor displays
- This mysterious object may be a (nearly) dead comet nucleus, or a very active asteroid, throwing off boulders 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.

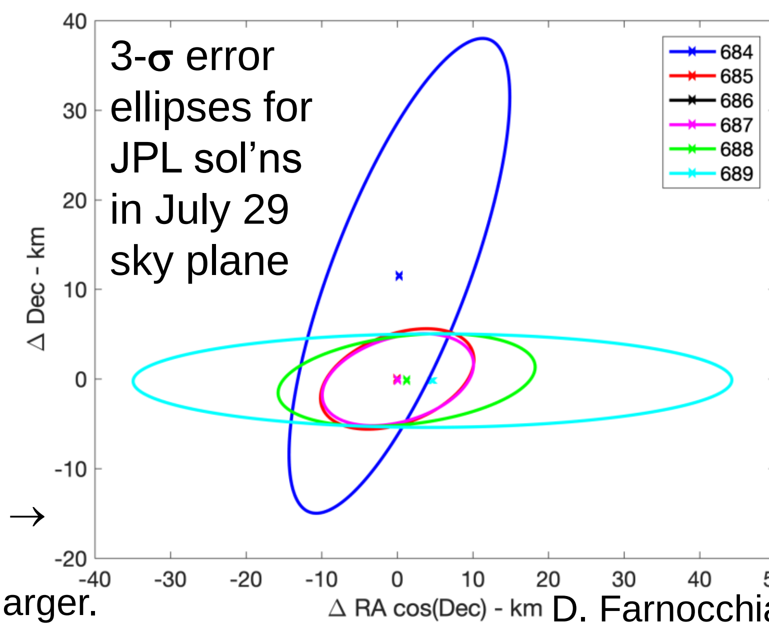
- JAXA’s DESTINY+ spacecraft plans to launch in 2024 and fly by Phaethon in 2025 -see https://en.wikipedia.org/wiki/DESTINY+
- Radar observations show Phaethon to be nearly spherical with a diameter of nearly 6 km
- Thermal IR data give a diameter of ~4.5km

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

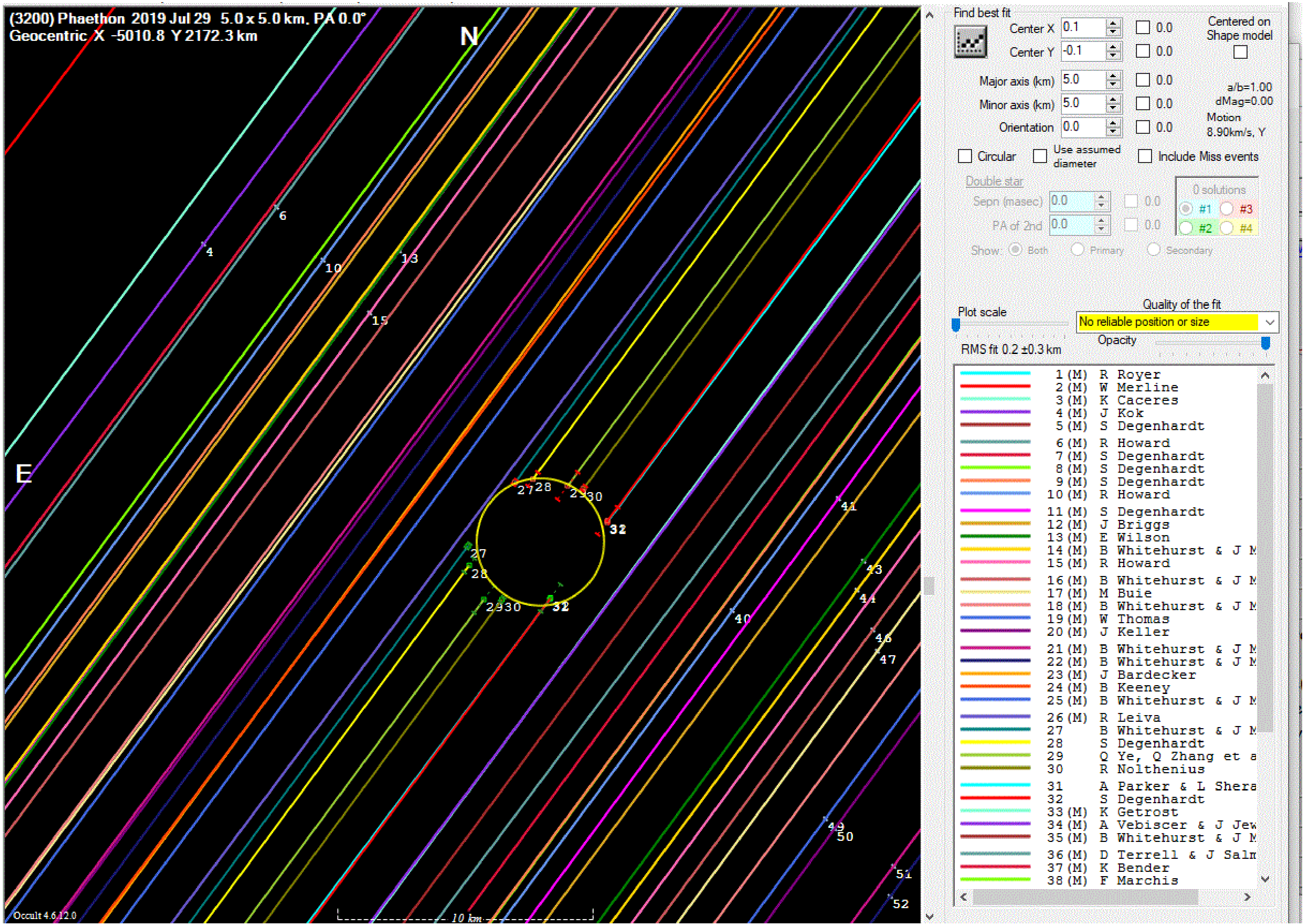
- This event was first identified by Isao Sato in Japan. In January 2019, he alerted US observers via a message that he sent to the IOTAoccultations list server.
- To obtain an accurate astrometric point for orbit improvement, and to resolve the diameter discrepancy, Tomoko Arai, PI of DESTINY+, requested 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 <u>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.</u> 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 adding Gaia astrometry; this was key.
- Adding new astrometric observations just confirmed JPL 685, so it was used for the final prediction.





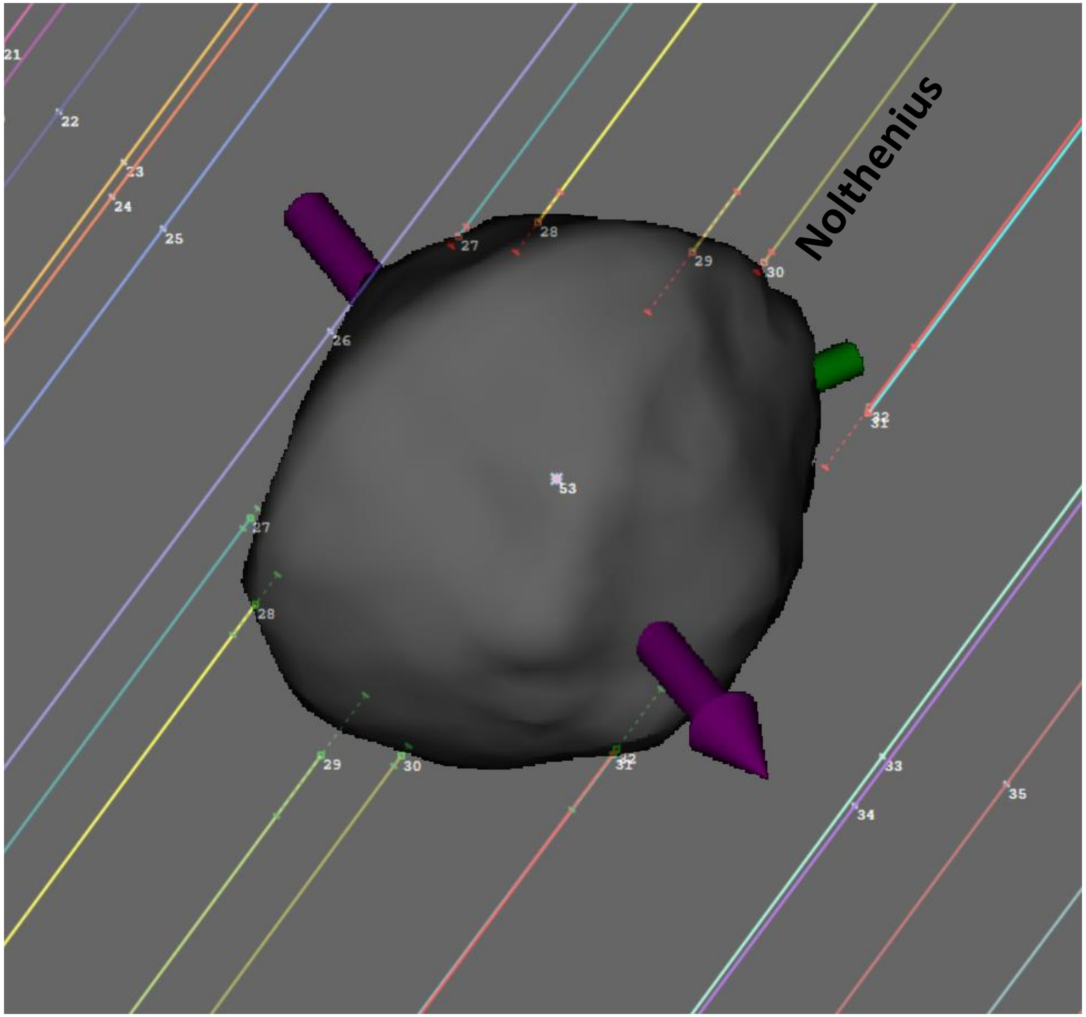
Phaethon's motion was from lower left to upper right, →
so the 3σ limits (JPL 685) were 8 km + Phaethon's
radius from center; the ground projection was a little larger.

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



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.

All Observed Occultations by (3200) Phaethon

Date	Star mag.	# stations positive/all	Locations(s)	Remarks
2019 July 29	7.3	6/52	s.w. USA	8 SwRI 16in., 44 IOTA stations
2019 Sept. 29	12.0	3/4	s. California	2 pre-pointed 10in. scopes, 2 8in. SCTs
2019 Oct. 12	11.3	2/2	Virginia	UVA expedition with 14in. SCTs
2019 Oct. 15, 17h	11.5	2/2	Japan	Clouds at more stations that tried
2019 Oct. 15, 19h	11.1	3/3	DE, FR, Algeria	In FR, a 1m portable scope was used
2019 Oct. 25	11.3	3/3	Italy, Algeria	2nd Phaethon occ'n for D. Baba Aissa
2020 Oct. 5	11.2	1/4	s. Mississippi	R. Venable, pre-pointed 11 & 14in SCTs

To ensure success, the first event needed a deployment across 4 States by scores of professional and amateur observers, forming a network of stations with an unprecedentedly small spacing between them. After the 2019 July 29th success, it was possible to predict the Sept. 29th event, and then each of the others, with better improvement each time as more observations were added to the orbit solutions.

"Star mag." measures the star's magnitude, with lower numbers for brighter stars, like rankings. The first event was visible with binoculars; all the others needed telescopes.

Positive chords recorded the occultation, while **all** includes negative observations; SCT= Scmidt-Cassegrain Telescope.

More about these observations is in the longer presentation I gave at the 2020 meeting of the International Occultation Timing Association. It is the 4th from the bottom, on the 2020 IOTA presentations page at:

http://occultations.org/community/meetingsconferences/na/2020-iota-annual-meeting/presentations-at-the-2020-annual-meeting/ .

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.

Future Phaethon Occultations

3200 Phaethon occults HIP 16761 on 2021 Nov 13 from 6h 38m to 6h 46m UT

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Star:                                  Max Duration =  0.2 secs           Asteroid: (in DAMIT, ISAM)
Mag V = 8.9; B = 9.0; R = 8.8             Mag Drop =  8.4 (8.0r)                  Mag = 17.3
 RA =  3 35 42.0373 (astrometric)      Sun :   Dist = 158°                        Dia =    5 ±1km, 0.005"
Dec =  39 18 34.995   ...              Moon:   Dist =  81°                   Parallax = 6.716"
[of Date:  3 37  9,  39 22 56]            :  illum = 68 %                Hourly dRA =-7.248s
  Prediction of 2020 Oct 17.0          E 0.001"x 0.001" in PA 90                  dDec =-20.64"
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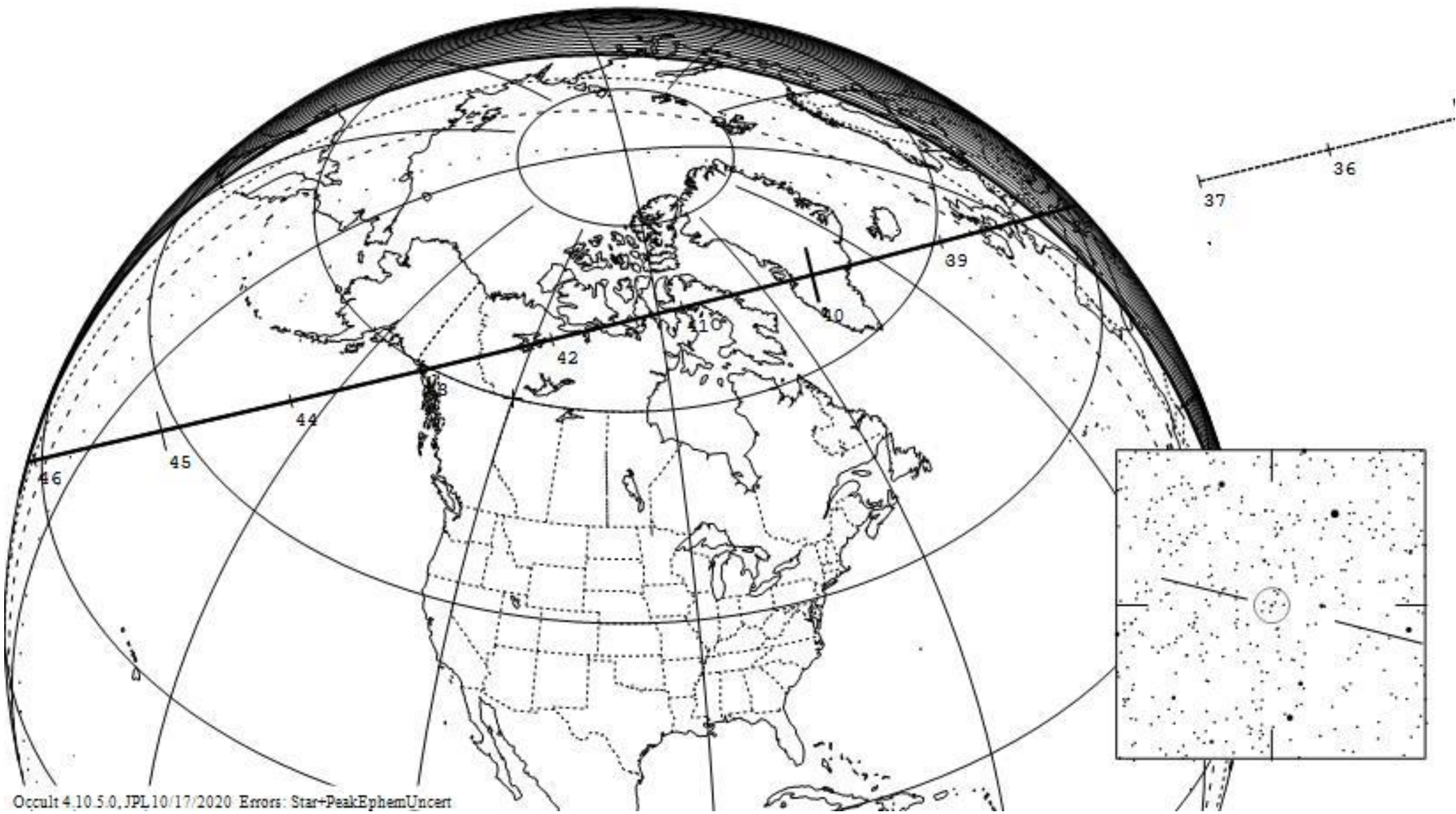
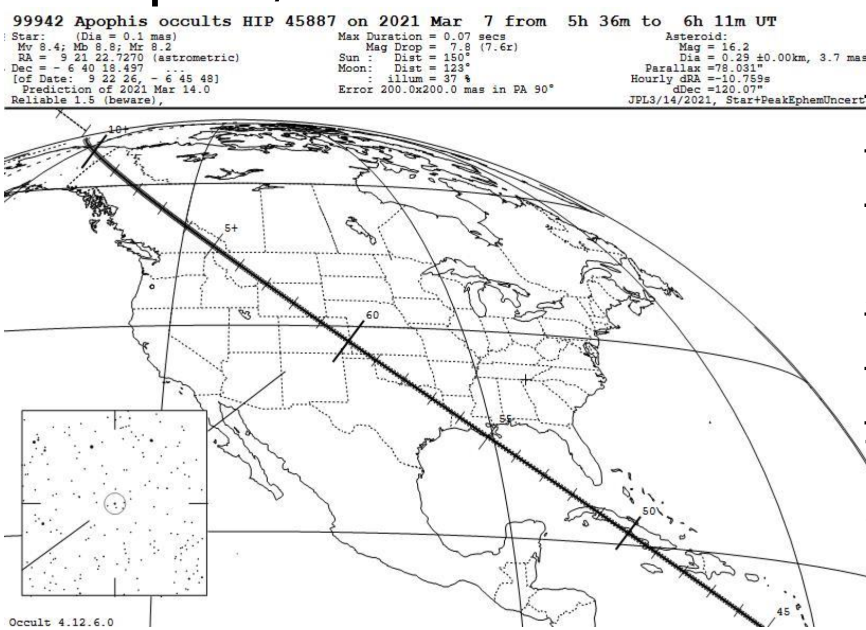


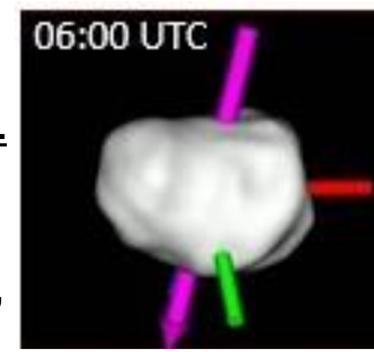
Predictions for 10 more Phaethon occultations in late 2021 are at **http://iota.jhuapl.edu/2020-2022Phaethon.htm**, including the one above.

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
- If impact, total destruction to 25km; severe damage to 300 km

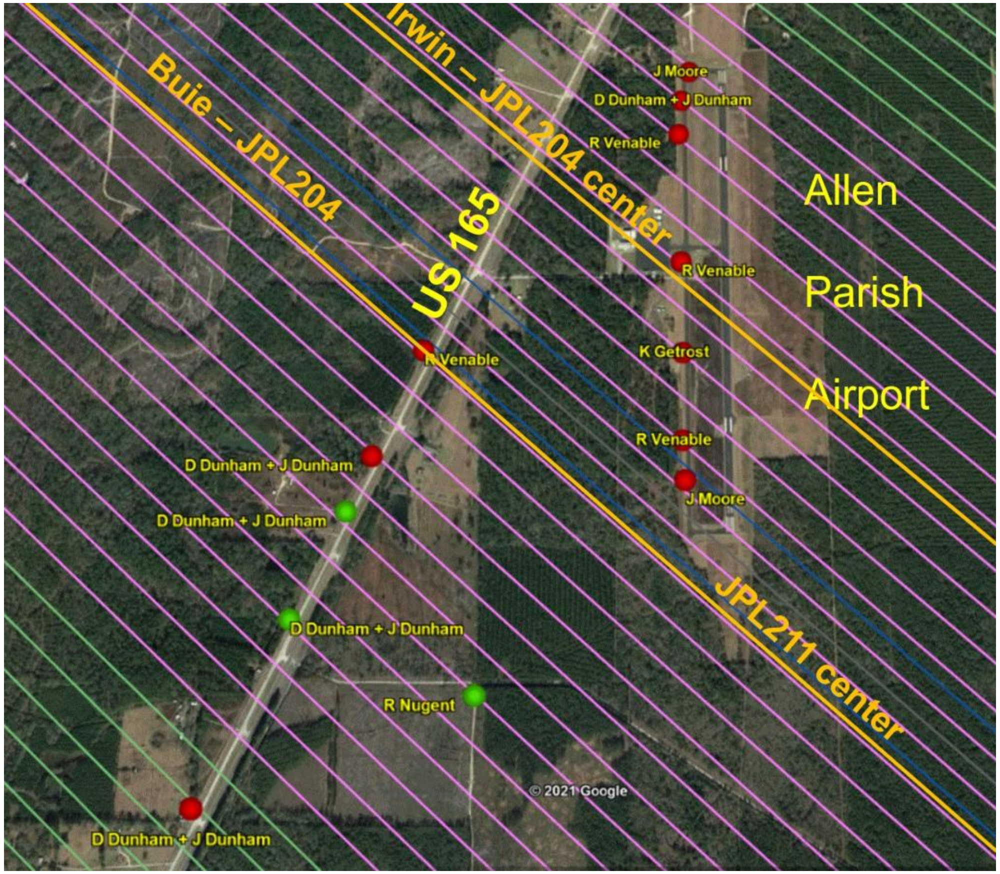


Paris Obs.’s Lucky Star Project found a 7th-mag. occ’n across N. America on 2021 Feb. 22, but without radar, it could not be predicted well. They found another event, star mag.8.4, with map at left, and radar data were expected a few days before. The shape model with new spin state, aspect for the event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

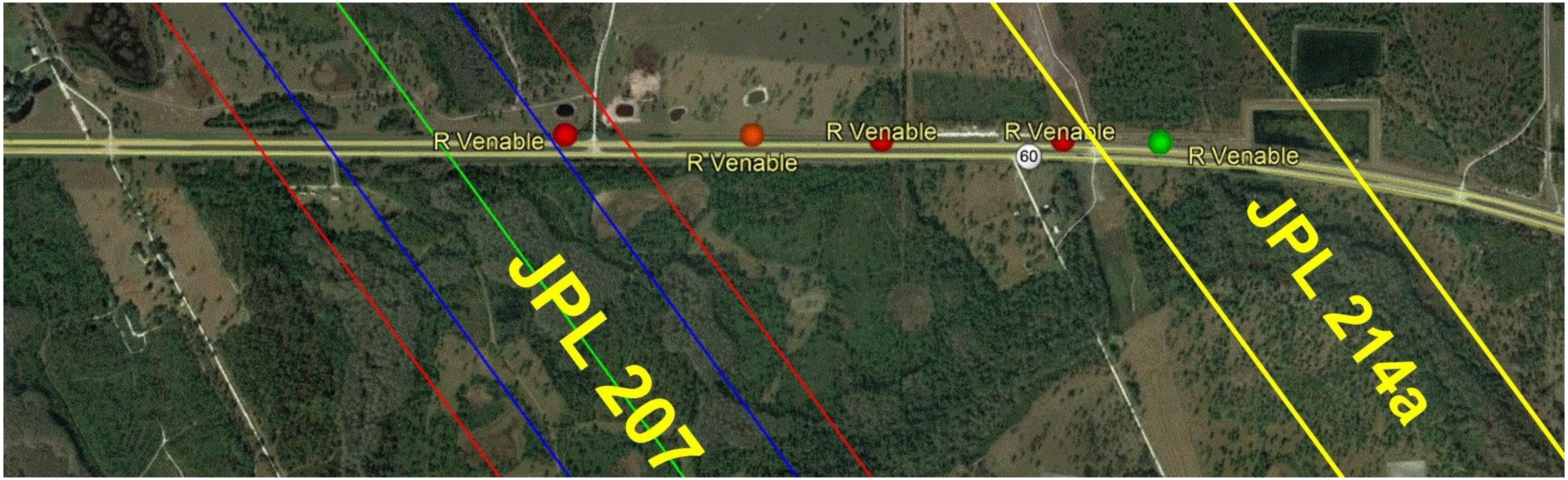


6 IOTA observers deployed telescopes at a small airport and along US 165 south of Oakdale, Louisiana. Red dots mark stations that had a miss, while 3 green dots mark 3 that recorded the occultation. The station locations were selected to be close to the diagonal tracks shown on the map, 107 meters apart 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

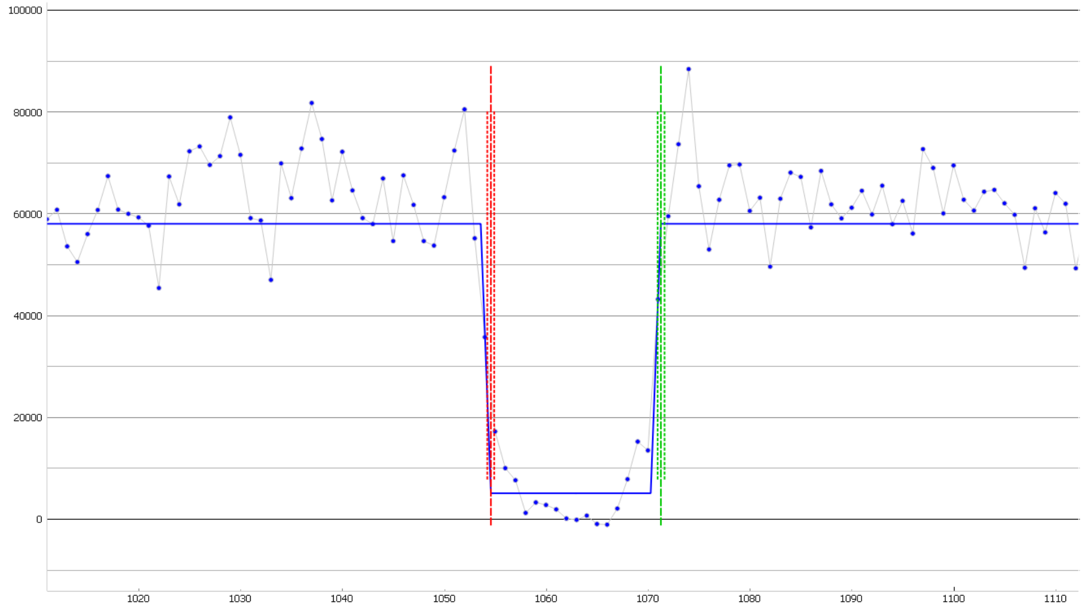
David and Joan Dunham's equipment used on line A30 (northern, left) and line A28 (southern, right). Both stations used 80mm f/5 refractors with f/0.5 focal reducers, small video cameras, an IOTA video time inserter (VTI) for accurate time-stamping of the videos with GPS 1PPS (the VTI is under the towel at A28), and iView "stick" Win10 computers to record the video. 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.

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



The March 7th observations were quickly analyzed to update the orbit, as 4 nights later, there was an Apophis occultation in Europe. Two observers from Thessaloniki, Greece traveled to the path predicted by the new orbit JPL207, but both had a miss. 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. **R. 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 used later occultation observations. **By spreading his scopes out enough, Venable saved Apophis' accurate orbit;** the JPL 207 error apparently was due to error in Gaia's position of NY Hya caused by its duplicity (eclipsing binary) that was occulted on Mar. 7.

2021 April 11 Apophis occultation in New Mexico



With Apophis' orbit 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 that 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.

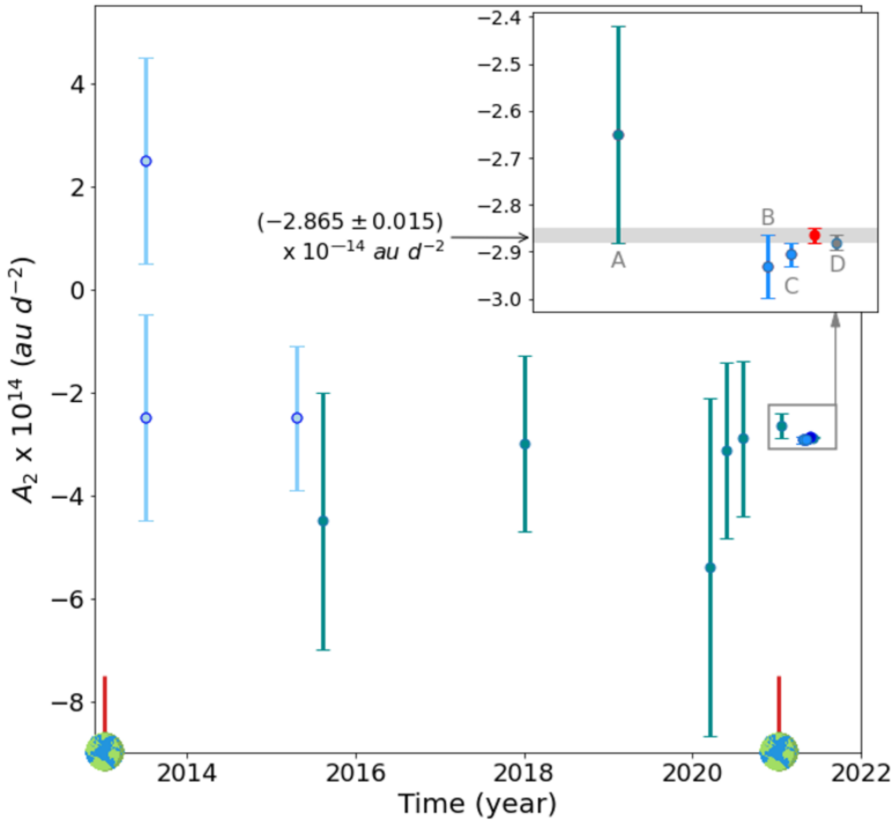
[3] The O-C residuals are relative to JPL orbit 214a, in mas, but in seconds for Δt.

[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 17 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 19). 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 NEOs.

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, DART/Hera target Didymos should be next for occ’ns

Evolution in time of our knowledge of the average Yarkovsky acceleration for 99942 Apophis. 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. 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. For more, see https://www.cosmos.esa.int/web/gaia/iow_20210329.

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]
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]

[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

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 students 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.
- A longer more detailed version of this presentation (Power Point) is at **http://iota.jhuapl.edu/PDC2021NEOoccultationsDunhamPresentationLong.pdf**

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**
- RECON TNO/Centaur occultations Web site (Mainly, w. USA events): **https://www.boulder.swri.edu/~buie/recon/reconlist.html**
- Lucky Star TNO/Centaur/Trojan occultations Web site: **https://lesia.obspm.fr/lucky-star/predictions.php**

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