7th IAA Planetary Defense Conference – PDC 2021
26-30 April 2021, Vienna, Austria

IAA-PDC-21-6-09
ACCURATE NEO ORBITS FROM OCCULTATION OBSERVATIONS

David Dunham[(1),(2)], Joan Dunham[(2)], Marc Buie[(3)], Steve Preston[(2)], Dave Herald[(2),(4)], Davide Farnocchia[(5)], Jon Giorgini[(5)], Tomoko Arai[(6)], Isao Sato[(6)], Richard Nolthenius[(2),(7)], John Irwin[(2)], Scott Degenhardt[(2)], Sean Marshall[(8)], John Moore[(2)], Skip Whitehurst[(2)], Roger Venable[(2)], Michael Skrutskie[(9)], Franck Marchis[(10)], Quanzhi Ye[(11)], Paulo Tanga[(12)], Josselin Desmars[(13)], D. Baba Aissa[(14)], Z. Grigahcene[(14)], and Hiroyuki Watanabe[(15)]

[(1)]*KinetX Aerospace, Inc., 2050 E. ASU Circle, Suite 107; Tempe, AZ 85284, USA, +1-301-526-5590, david.dunham@kinetx.com*
[(2)]*International Occultation Timing Association, P.O. Box 423, Greenbelt, MD 20768, USA, +1-301-526-5590, dunham@starpower.net*
[(3)]*Southwest Research Institute, 1050 Walnut St., Suite 300; Boulder, CO 80302, USA, +1-720-240-0122, buie@boulder.swri.edu*
[(4)]*Trans Tasman Occultation Alliance, 3 Lupin Pl., Murrumbateman, NSW 2582, Australia, +61-2-6227-5974, D.Herald@bigpond.com*
[(5)]*Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA, +1-818-354-0081, davide.farnocchia@jpl.nasa.gov*
[(6)]*Planetary Exploration Research Center, Chiba Inst. of Technology, Chiba, Japan +81-47-478-0320, tomoko.arai@it-chiba.ac.jp*
[(7)]*Astronomy Dept., Cabrillo College, 6500 Soquel Dr, Aptos, CA 95003, USA, +1-831-319-6994, rinolthe@cabrillo.edu*
[(8)]*Arecibo Observatory, PR-625, Arecibo, PR 00612, USA, +1-787-878-2612, ext. 207, smarshal@naic.edu*
[(9)]*Univ. of Virginia, 4110 Bleak House Rd, Earlysville, VA 22936, USA, +1-434-924-7494, skrutskie@virginia.edu*
[(10)]*SETI Institute, 189 Bernardo Ave, Suite 200, Mountain View, CA 94043, USA, +1-510-599-0604, franck.marchis@unistellaroptics.com*
[(11)]*Dept. of Astronomy, Univ. of Maryland, College Park, MD 20742, USA, +1-301-405-1549, qye@astro.umd.edu*
[(12)]*Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, CS 34229 06304 Nice Cedex 4, France, +33 4 92 00 30 42, paolo.tanga@oca.eu*
[(13)]*Paris Observatory, 77 avenue Denfert Rochereau, 75014 Paris, France, +33 1 45 07 71 24, josselin.desmars@obspm.fr*
[(14)]*Center of Research in Astronomy, Astrophysics, and Geophysics, Algiers Observatory, bp - 63 Route de l'Observatoire, Bouzareah, Algeria, +213 23 18 90 99, baba.aissa.djounai@gmail.com*
[(15)]*Japanese Occultation Information Network, watan@he.mirai.ne.jp*

Abstract Precise orbit determination is very important for planetary defense against Potentially Hazardous Asteroids (PHAs), to determine their probability of impact at close approaches to Earth as far as possible into the future. Orbits of NEOs are generally best improved by radar observations, but these are only possible when the NEO is relatively close to the Earth. A threatening NEO can be out of radar range for decades, during which its orbit might evolve from YORP perturbations and other small non-gravitational forces. Now that we have precise stellar data from ESA's

Gaia mission, observations of occultations of stars by NEOs can provide astrometric points at least as accurate as the size of the NEO as seen from the Earth, normally about a milliarcsecond, or less. Well-observed occultations can also give information about the size, shape, and multiplicity of the object. For more than half a century, occultations of stars by asteroids have been observed, and at an accelerating rate as star catalogs have been improved by ESA space astrometry missions, first by Hipparcos and more recently, by Gaia. On 2019 July 29, an occultation of 7.3-mag. SAO 40261 by the six-kilometer NEO (3200) Phaethon occurred across the southwestern USA. The Southwest Research Institute (SwRI) and the International Occultation Timing Association (IOTA) deployed 52 telescopes across the path, and its wide uncertainty, that all recorded the star with accurate timing. Six of the stations recorded the occultation, allowing a dramatic improvement of the orbit that in turn resulted in the observation of six more occultations. The orbit determination from these events improved the accuracy of the small A2 non-gravitational term by more than a factor of three. Since our abstract was submitted, the much smaller (~350m) PHA (99942) Apophis passed rather close to the Earth, allowing new radar observations in early March. These allowed a good prediction of an occultation of an 8th-magnitude star on 2021 March 7, resulting in 3 positive observations that resulted in three later occultations being observed. The radar observations, along with the occultation data, collapsed the error of the detemination of Apophis' Yarkovsky acceleration and permitted propagating the orbit accurately well beyond the 2029 close approach, showing for the first time that Apophis poses no risk of impact for at least the next 100 years. Similar occultation observations can be made of more NEOs, to better determine their long-term orbits, a new exciting goal for occultation astronomy.

Keywords: *NEOs, occultations, orbits, Phaethon, Apophis*

1. INTRODUCTION

The first observed occultation of a star by an asteroid occurred on 1961 October 2 when (2) Pallas covered a 9.1-mag. star that was recorded photoelectrically from Naini Tal, India [1]. Claims of an occultation observed earlier, in 1958, have been shown to be wrong [2]. The International Occultation Timing Association (IOTA), in collaboration with the Small Bodies Node of NASA's Planetary Data System, maintains an archive of all observed asteroidal occultations; this, and the analysis of the observations, were described in a recent paper [3]. Most asteroidal occultations are currently observed mainly by amateur astronomers from fixed observatories. However, IOTA had its foundations in work during the 1960's with lunar grazing occultations that nearly always require observation from precisely located mobile sites [4, 5]. This ability to observe with mobile equipment has proven to be critical for observing occultations by NEO's. Curiously, the first successful effort to observe an asteroidal occultation from mobile sites took place in southern New England for an occultation by one of the largest NEOs, (433) Eros, when it occulted 4th-mag. kappa Geminorum on 1975 January 24 [6]. [6] gave incorrect dimensions of Eros due to a critical false negative visual observation, as shown from the actual dimensions of Eros that were measured by the NEAR-Shoemaker mission; a fit of the 1975 observations to the NEAR-Shoemaker shape model is shown in Fig. 1.

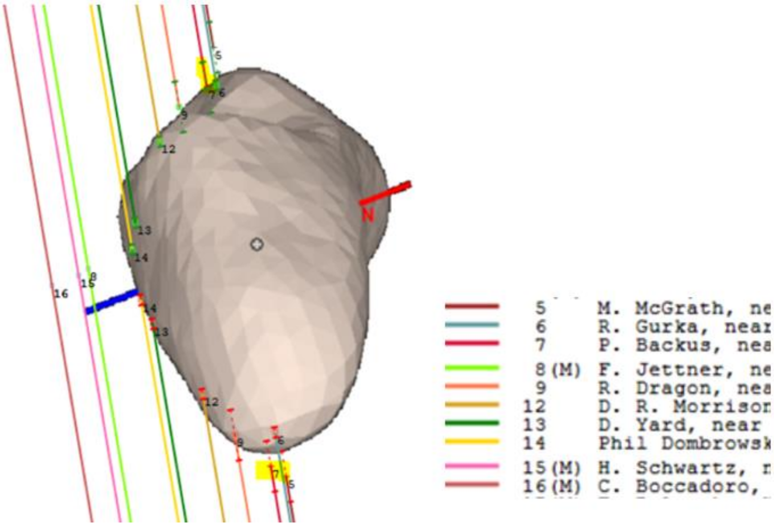


Fig. 1. Sky plane plot of the 1975 Jan. 24th occultation chords fitted to Eros' shape model derived from NEAR-Shoemaker data.

A key to the success of the NEO occultations observed so far has been the ability of IOTA observers to deploy multiple stationary telescopes with recording systems that can record video at pre-set times and that are pre-pointed to the altitude and azimuth of the occultation using stars [7]. In some cases, special compact telescopes have been constructed, to facilitate transport and, in some cases, to allow pre-pointing on nights before the night of the event, providing much more time for this task [8]. After the 1975 Eros occultation, IOTA and others considered NEO's much too small for occultation observations, and only occultations by main-belt asteroids, and some more distant objects, were observed during the following decades. The errors in both the NEO orbits, and the available star catalogs, were generally dozens of times larger than the object, making the probability of success too low to warrant mounting observational campaigns for NEO occultations. We knew the occultation durations would be too short to obtain good size and shape determinations, like we had obtained for the larger, more distant objects. ESA's Hipparcos mission helped the astrometric situation considerably with the release of its data in 1997, but the errors were not decreased far enough, and on a large enough scale, until Gaia's first data release in 2016. With a concerted effort, a campaign to observe an occultation by a NEO might be practical; a good first event was needed to demonstrate the possibilities.

2. (3200) PHAETHON

Phaethon, the source of the strong annual Geminids meteor shower, is also a flyby target of JAXA's DESTINY+ mission. The dust trail from Phaethon was imaged by the Parker Solar Probe in 2019 November [9].

2.1 2019 July 29 Occultation

This rare occultation of a 7th-mag. star by Phaethon 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. A few months before the occultation, Dr. Tomoko Arai, PI of DESTINY+, contacted NASA and the International Occultation Timing Association (IOTA), asking if they could organize a campaign to observe the rare event. The goal was to obtain an accurate astrometric point for orbit improvement, and to resolve a discrepancy between the diameter determined from radar and the value determined from IR observations. 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 to producing an orbit with small-enough errors to make a campaign practical. Adding new astrometric observations just confirmed JPL 685, so it was used for the final prediction. Fig. 2 shows the JPL orbit solutions projected in the sky plane for the 2019 July 29th occultation.

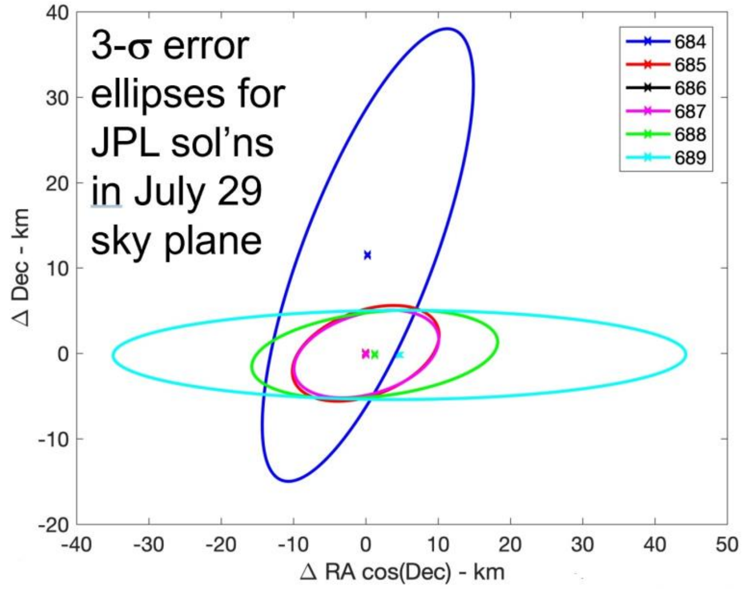


Fig. 2. By Davide Farnocchia. Phaethon's motion was from lower left to upper right, so the 3σ limits (JPL 685) were 8 km plus Phaethon's radius from center; the ground projection was a little larger.

The Southwest Research Institute (SwRI) and IOTA managed to deploy 52 telescopes across the path, and its wide uncertainty, that all recorded the star with accurate timing. Fig. 3 is a map showing the planned network of parallel lines used for the deployment and Fig. 4 shows the sky plane coverage of the observations.

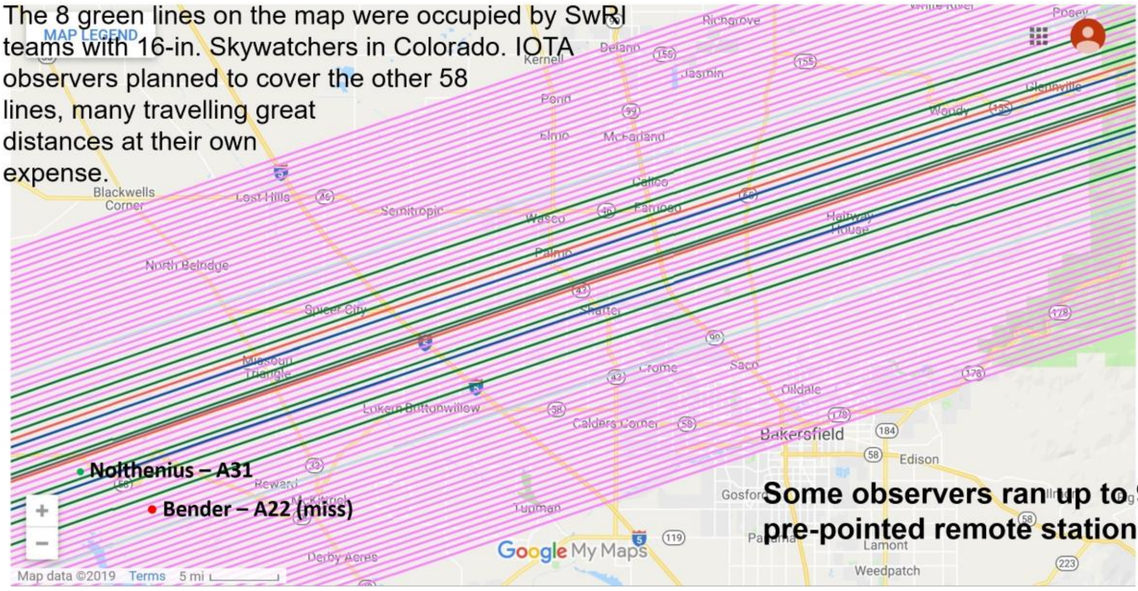


Fig. 3. Google Map from SwRI, like those used for their Arrokoth campaigns. To cover the 3σ zone + many more km to the north and south, to guard against stellar duplicity and other possible unmodelled errors, this pattern of 66 lines, with selected spacing 680m, at the time was the smallest ever achieved for an occultation, numbered from south to north, 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 could not be filled for various reasons, and another 10 failed to get data.

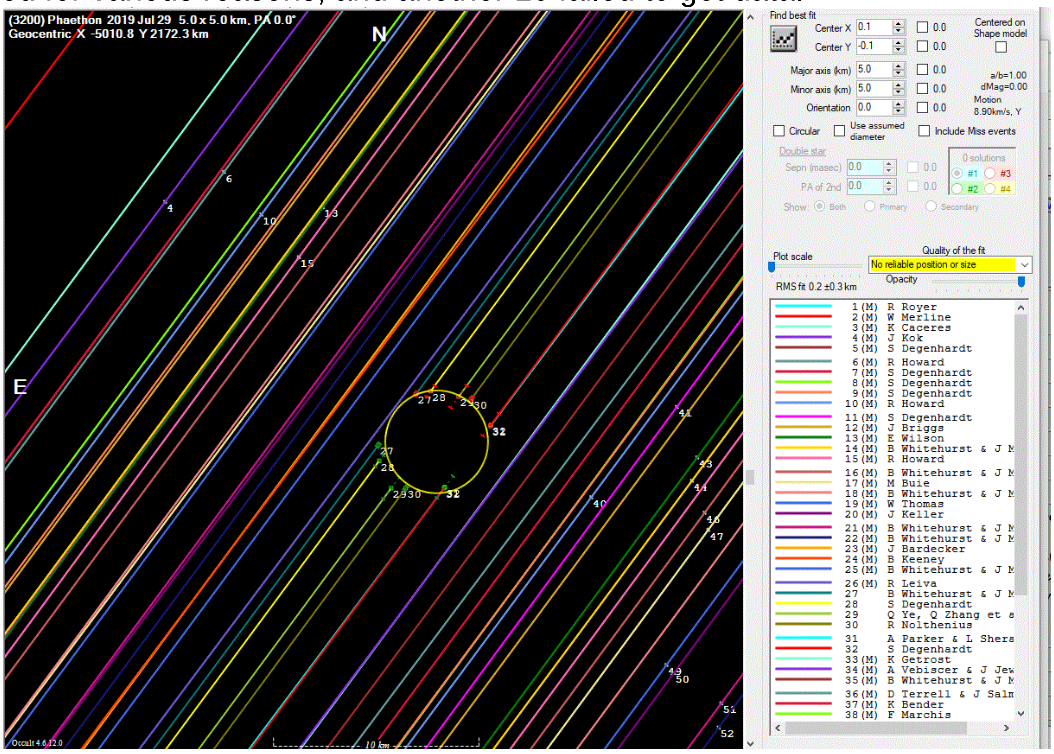


Fig. 4 The plane-of-sky coverage of the area around Phaethon, including the 6 positive chords. Those chords fit well with Phaethon's shape model determined from 2017 Arecibo radar observations. The JPL "Horizons" prediction was accurate to less than the radius of Phaethon (& under 1.5 km), thanks to Gaia and radar

observations. The spacing is uneven since most neglected correcting for elevation above sea level, significant at this spacing, and as a result, two positive chords landed on top of each other. Plot by John Moore, IOTA.

2.2 2019 September 29 Occultation

The accurate astrometric point determined from the July 29th occultation allowed predicting and observing an occultation of a 12th-mag. star two months later; see Fig. 5. There was less than 3 hours of usable dark time before the event, so D. and J. Dunham set up stations A01, A04, and A09 on paver stones the night before, with 12cm telescopes that would be marginal for this event. On event night, they set up and pre-pointed 10-in. (25cm) suitcase telescopes at remote stations A05 and A06, and then set up A02 with a 12cm refractor, their attended site. There was significant wind, but no shaking at event time for all critical sites. The observations were too poor to improve the size and shape of Phaethon but allowed defining a second accurate astrometric point, aided by Bob Jones' negative (miss) observation at A07.

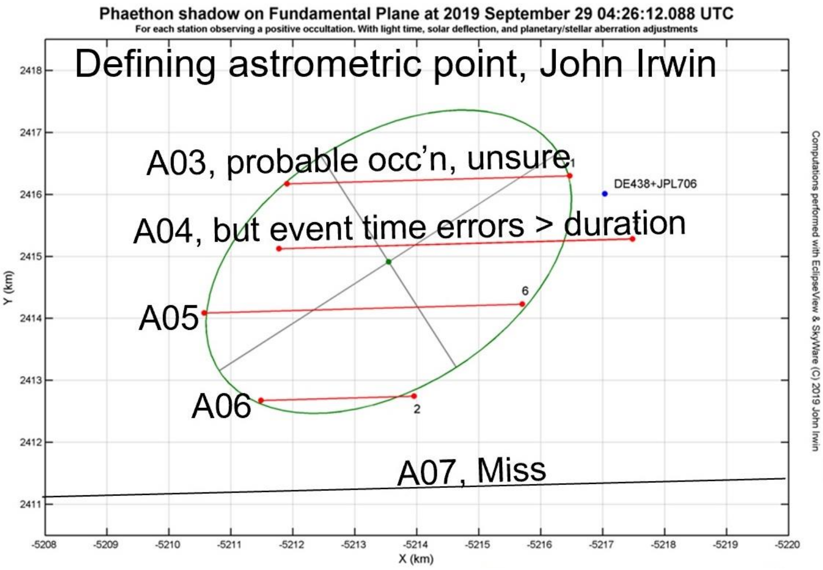


Fig. 5. Sky plane plot of observations of the 2019 Sept. 29 occultation.

2.3 2019 October and 2020 Occultations

The Sept. 29th second success was key to securing the orbit well enough to predict four occultations during 2019 October that were successfully observed, as summarized in Table 1; the central duration was 0.3s for each occultation. An IOTA meeting presentation has more information about these events [10].

Table 1. 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 1-meter portable telescope used to observe the 2nd October 15th occultation near Saint-Barnabé, France, is shown in [11].

On 2020 October 5, another occultation was observed from 4 stations (one positive) set up by Roger Venable in Mississippi, with the sky plane plot shown in Fig. 6.

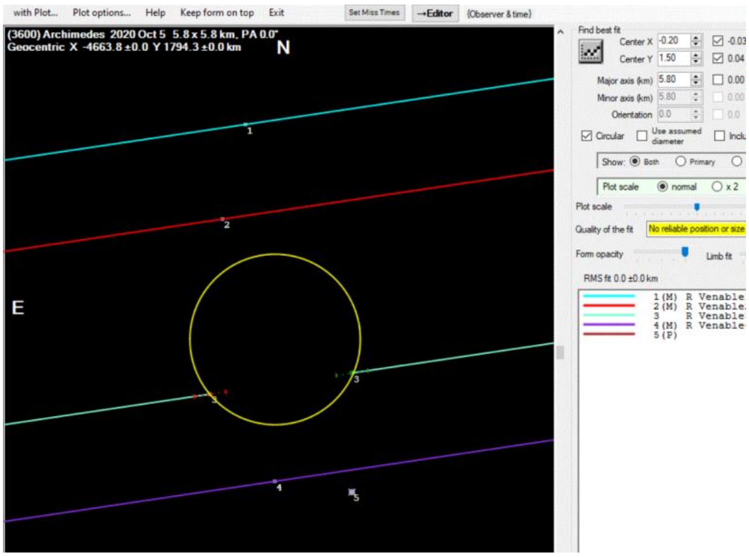


Fig. 6. Sky plane plot for observations of the 2020 October 5 Phaethon occultation.

2.4 Improvement of Phaethon's Orbit

The resulting precise astrometric points improved the accuracy of determination of the A2 non-gravitational term of Phaethon's orbit by a factor of 3, from 3 sigma to ~10 sigma; see Table 2. A presentation about this was given at the 2020 October DPS meeting, with a press release pointing to much more information about the Phaethon occultations [12].

Table 2. Determinations of the A2 non-gravitational term of Phaethon's orbit; values of A2, and of the standard errors (Sigma), are in units of AU/day^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

2.5 Future Phaethon Occultations and other NEA occultations

Predictions for some more occultations by Phaethon, later in 2021, are at http://iota.jhuapl.edu/2020-2022Phaethon.htm. We will soon extend those predictions for a few years. With the Phaethon occultation successes, we are predicting occultations by other NEAs. Some first predictions are at http://iota.jhuapl.edu/Apophis2021.htm. Astronomers in Algeria have computed some occultations by the PHAs (3122) Florence and (159402) 1999 AP10, and tried to observe them, but without success. Occultations by (65803) Didymos are being investigated [11].

3. (99942) APOPHIS

Since its discovery in 2004, the asteroid (99942) Apophis, found to be about 350 m across from Arecibo radar observations made in 2011, has been of concern to the planetary defense community. A very close approach to the Earth in April 2029 was quickly identified and for a short time, had a non-zero risk of impact, until further observations showed that the closest approach would be near the ring of geostationary satellites. It will provide a great view, and opportunity for extensive study, but will pose no risk that year. However, it could pass through a “keyhole” such that the heliocentric period could be a rational fraction of a year, allowing Apophis to encounter the Earth in the future. At first, it was thought that the 2036 encounter could be threatening, but again, more observations showed the asteroid would pass far from the Earth then. But a small chance of an impact in 2068 remained. It was not until radar observations made in March this year, in a Greenbank/Goldstone collaboration, that the 2068 risk was finally retired [13].

The new radar observations also allowed the orbit of Apophis to be known well enough to predict the paths of occultations with enough accuracy to deploy a reasonable number of stations with a good chance of securing observations. In a collaboration with the Southwest Research Institute (SwRI), IOTA already had one success with a near-Earth asteroid, (3200) Phaethon, with several occultations observed in 2019. But Phaethon is over 5 km across; Apophis is more than an order of magnitude smaller and the occultation was expected to last no more than 0.09s; could the small systems that IOTA observers can deploy, record such a short event? A much tighter spacing would be needed as Apophis’ minimum cross-section is only about 170m across. The path location shifts with elevation above sea level, depending on the direction to the star as seen from the path. Fortunately, John Irwin had already generated Google Earth scripts that took this into account, that he had developed for detailed plotting of the limits of the 2017 August total solar eclipse, and he was able to do this as well for the closely-spaced tracks that were needed for deploying stations for the Apophis occultations. Marc Buie created similar files for the early March Apophis events.

3.1 First Observed Apophis Occultation, 2021 March 7

Josselin Desmars, of the Lucky Star Project, found that on March 7th, Apophis would occult 8.4-mag. NY Hydrae (HIP 45887) in a path crossing the central USA. He also found an occultation of a 7th-mag. star on a similar path on February 22, but without a radar update, the uncertainty in the location for that path were too large to warrant a large campaign to observe it (a few tried, and had no occultation). For the March 7th occultation, clouds threatened much of the path, but it was expected to be clear over western Louisiana. IOTA observers converged on Oakdale, La., and deployed telescopes along the taxiway of the Allen Parish Airport south of town, as well as along and near the wide shoulder of the US 165 highway; see Figure 7.

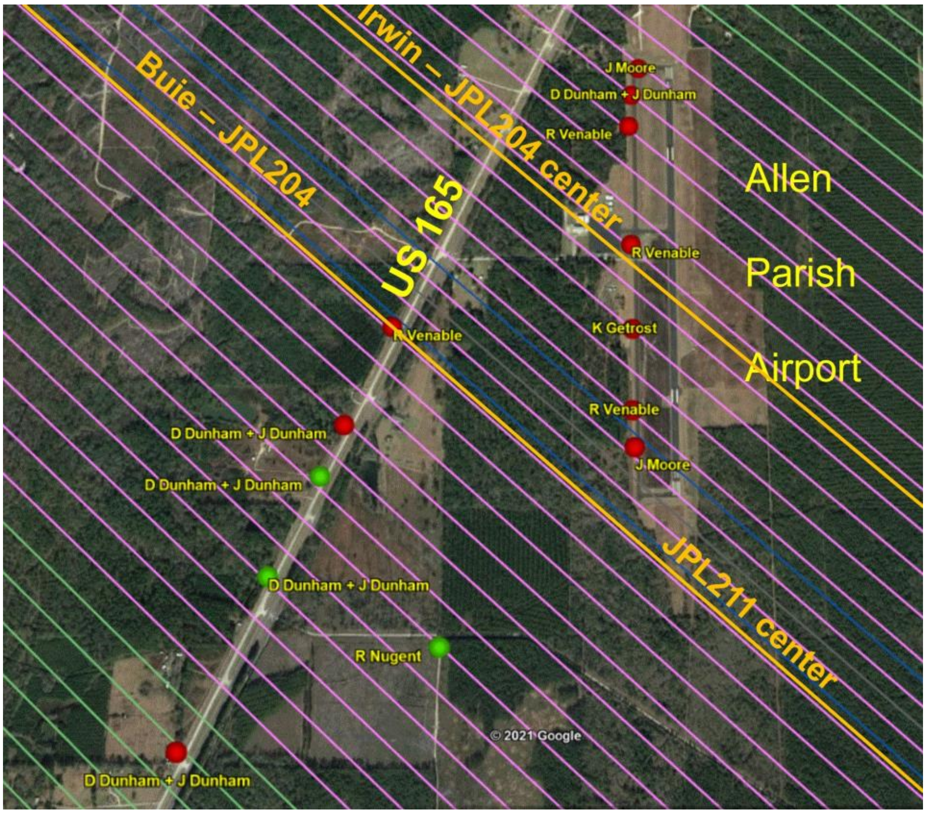


Fig. 7. Six IOTA observers set up 13 telescopic stations south of Oakdale, Louisiana. Red dots mark stations that had no occultation, while 3 green dots mark 3 that recorded an occultation. The station locations were selected to be close to the diagonal tracks shown on the map, 107 meters apart as projected on the ground. They were 80 meters apart on the plane of the sky, which gave us a good chance of recording the occultation at 3 stations. Orange lines show 3 predictions, two based on JPL orbit 204 computed on March 5 refined with the Goldstone-Greenbank radar observations made during 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; see the discussion with Table 3 below. Some of the lines were covered by observers in Oklahoma and Colorado.

As seen in Fig. 7, the actual path was south of the predicted path; the Dunhams were fortunate that two of their stations recorded the occultation, both using pre-pointed 80mm short-tube refractors, small sensitive video cameras, 1PPS GPS video time inserters, and small iView ”stick” Windows 10 computers. The setups, as tested 4 nights before, are shown in Figure 8. In addition, Richard Nugent recorded the occultation from the line between these stations using a 20cm SCT. Light curves for the 3 positive stations are shown in Figure 9.

Fig. 8. David and Joan Dunham's equipment used on line A30 (northern, left) and line A28 (southern, right).

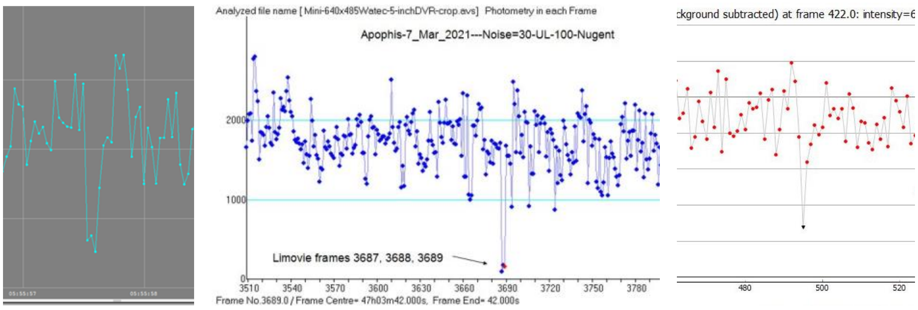
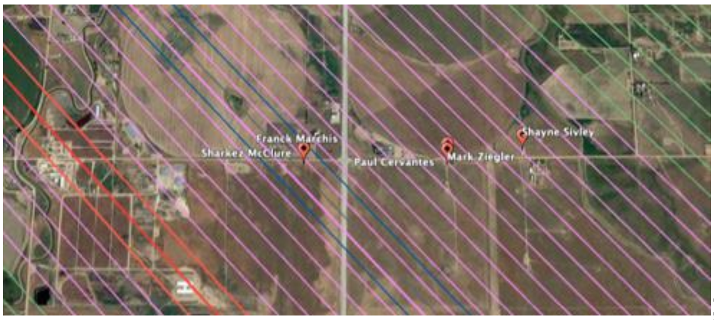


Fig. 9. Light-curves obtained at the three positive stations showing the brief occultation by Apophis. Left, station A30, Dunhams; Center, A29, Nugent; Right, A28, Dunhams.

Besides IOTA's efforts in Louisiana and Oklahoma, and SwRI's in Colorado, Unistellar's Franck Marchis organized six pairs of stations with eVscopes in Colorado; see Fig. 10 [14]. Since they were all located north of the actual path, they all had no occultation.



;

Fig. 10. Map showing locations of some of the Unistellar eVscopes in Colorado.

The positive observations provided an accurate astrometric point in the sky plane, nicely complementing the line-of-sight radar data to refine Apophis' orbit. The IOTA and SwRI observations in the sky plane are shown in Fig. 11.

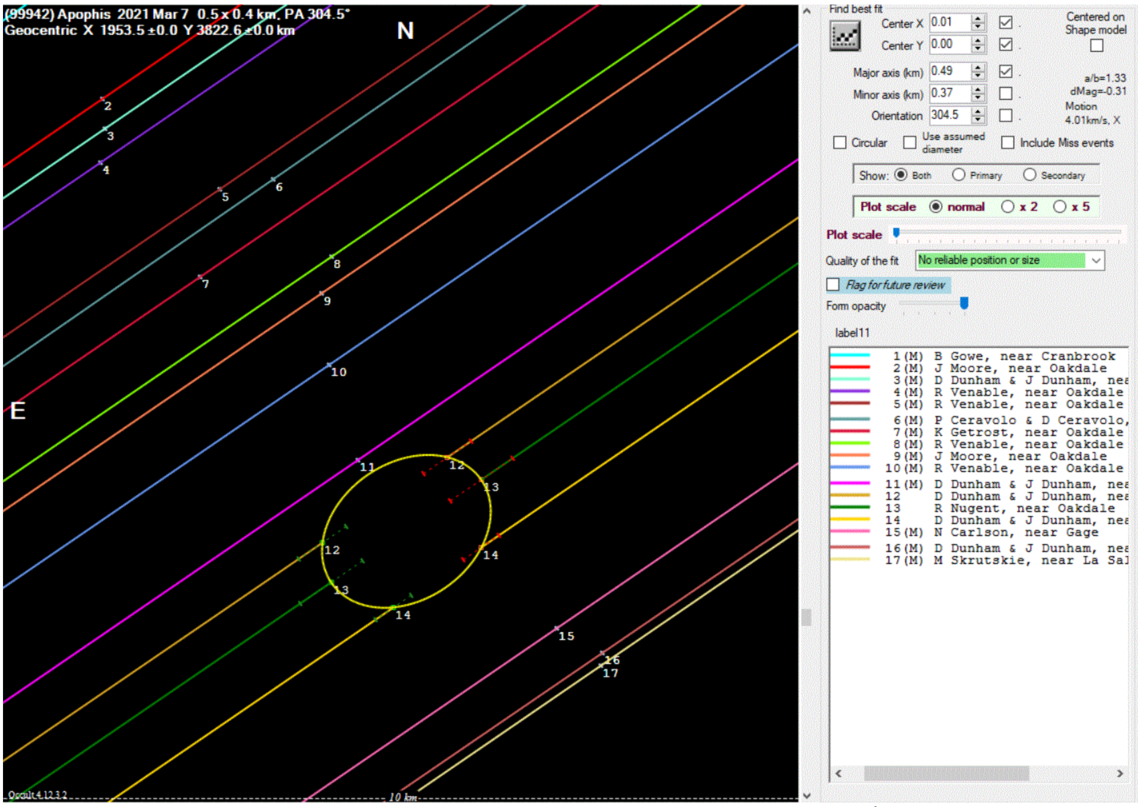


Fig. 11. Sky Plane Plot of the observations of the 2021 March 7th occultation.

3.2 Second Observed Apophis Occultation, 2021 March 22

After the first success, we were anxious to observe a second occultation. The March 7th observations were quickly analyzed to update the orbit, since four nights later, there was an opportunity in Europe involving a 9th-mag. star. Overcast skies hampered nearly all who tried, but it was clear in northeastern Greece. Two observers from Thessaloniki traveled to the path predicted by the new orbit JPL207, but no occultation occurred at both stations. This was disappointing, considering the good prediction of the 2019 Sept. 29th Phaethon occultation using the July 29th success for that asteroid.

On March 22nd, an occultation of a 10.0-mag. star was predicted for the eastern USA. Forecasts of "iffy" weather over much of the path added drama, with the forecasts not being consistent until the day before the occultation. Some tried the event in northeastern Alabama and Illinois, where they had a miss. Roger Venable deployed five telescopes near Yeehaw Junction, Florida, as shown in Fig. 12. Only his easternmost telescope recorded the occultation. The sky plane plot of all of the observations is in Fig. 13.

Fig. 12. Map showing Venable's sites along Highway 60 near Yeehaw Junction, Florida. 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 from JPL orbit 214a that added an astrometric point from the April 4th occultation observations noted below.

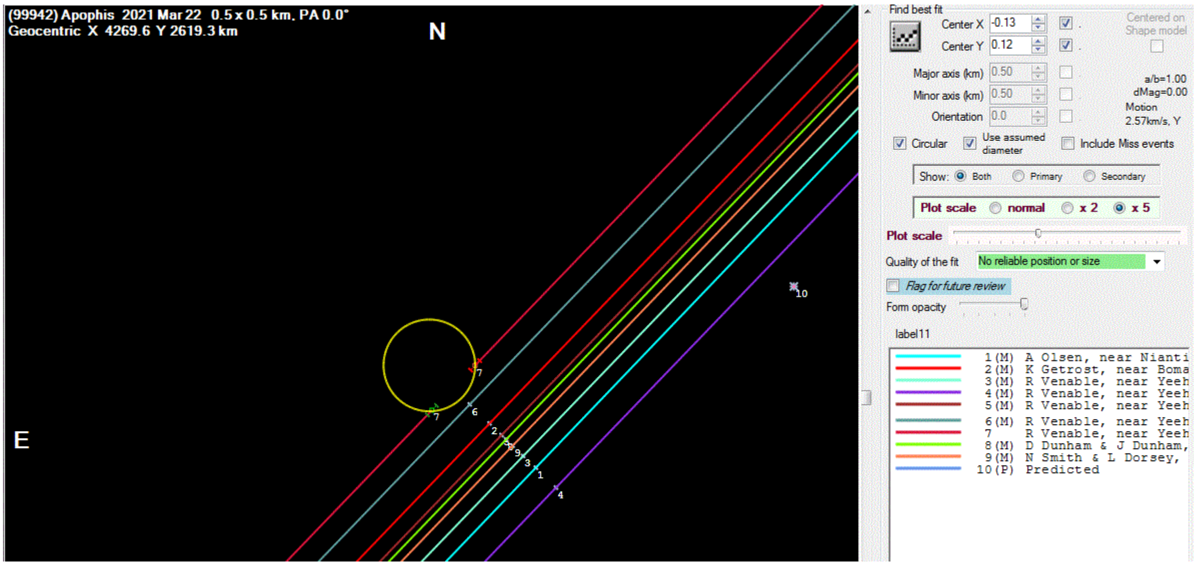


Fig. 13. Sky Plane Plot of the observations of the 2021 March 22nd occultation.

3.3 Apophis Occultations during 2021 April

After the second success, that was incompatible with the first occultation result, we were anxious to observe a third occultation. We had two opportunities in the western USA, with similar south-to-north occultation paths predicted to cross western New Mexico on April 4 and 11 UT; there was also a difficult event with a faint star in Japan on April 10. Since the RUWE, a measure of the quality of the Gaia EDR3 astrometric solution, was a little outside the estimated "good" range for NY Hydrae, and the fact that the star is a close eclipsing binary [15], we decided to down-weight the March 7th astrometric point relative to the March 22nd one for the JPL solution 211 that was used to predict the April occultations. This resulted in very accurate predicted paths, as shown by the successful observations in Figures 14, 17, and 18.

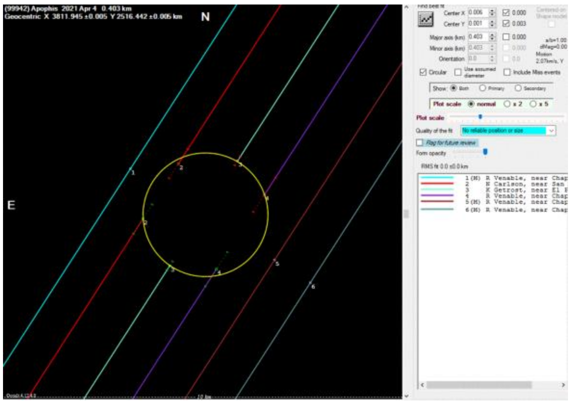


Fig. 14. Sky Plane Plot of the observations of the 2021 April 4th occultation of an 11.0-mag. star observed from southern New Mexico. The actual center was only about 100m east of the predicted center.

The April 10th occultation in Japan was very difficult, with the star's magnitude 12.6 and the event occurring in bright evening twilight. See Fig. 15 and 16.

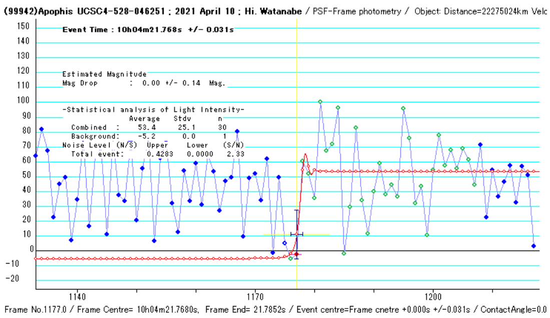


Fig. 15. Light-curve of the occultation recorded in bright twilight by Hidehito Yamamura in Japan by on 2021 April 10th. The red line shows a theoretical model, including Fresnel diffraction, fitted to the possible occultation reappearance. The possible event is similar to other noise drops so it is uncertain whether this is actually the occultation by Apophis.

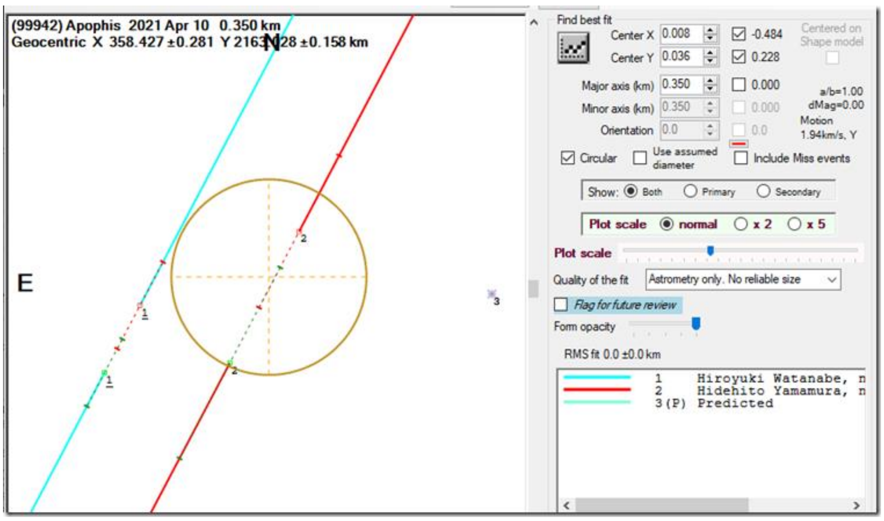


Fig. 16. Sky Plane Plot of the observations of the 2021 April 10th observed in Japan. Following closer examination of Hiroyuki Watanabe's low-contrast light curve, and a

poor match with the well-observed April 11th occultation (see below), led to the conclusion that no occultation likely occurred at Watanabe's site. Fig. 17 shows a great light curve for the April 11th Apophis occultation, and the sky plane plot for the event is in Fig. 18.

Fig. 17. Kai Getrost's light curve of the occultation of a 10.1-mag. star recorded with 100 frames per second on 2021 April 11 from Farmington, New Mexico with a QHY 174M GPS camera attached to a 20-inch Dobsonian telescope. Effects of Fresnel diffraction are evident.

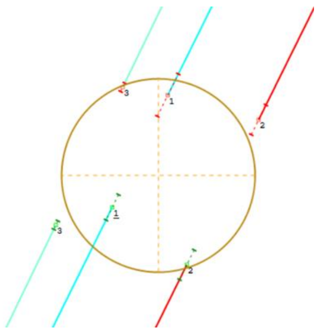


Fig. 18. Sky Plane Plot of the observations of the 2021 April 11th occultation of a 10.1-mag. star observed from New Mexico.

On 2021 May 6, an occultation of an 11.6-mag. star by Apophis was recorded from at least 3 stations in Arizona and Mexico. This will add another good astrometric point, with the analysis of the observations currently in progress.

3.4 Summary of the Observed Apophis Occultations

Different orbits have been generated by the JPL Horizons team to support the occultation efforts using radar data and the available occultation observations. JPL orbit 214 included the astrometric points generated from the occultations observed before April 11 (to support that, and later, occultation efforts), but down-weights the March 7th point relative to the others, and used the recently updated DE441 planetary ephemeris file. Another similar orbit was computed the same way, but not using the March 7th point at all; we call it Apophis JPL orbit 214a. The residuals from that orbit are shown in Table 3, which also summarizes all of the observed Apophis occultations with positive observations. More information, including the IOTA reports (giving the coordinates of the station, the times of disappearance and reappearance, and equipment details) and light curves for each positive station, as well as Google Earth path files and other prediction information, are given in IOTA's Apophis occultations page [16].

Table 3, Summary of all observed positive Apophis occultations

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
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.

The star on March 7th was NY Hydrae, an eclipsing binary with equal Sun-like components and period 4.8 days [15]. We believe this, more than the RUWE value, is the main explanation of the anomaly for the event. Fig. 7 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, since with it being the only occultation result we had at the time, we assumed that it was accurate. But it caused 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 (see Fig. 12, that shows the JPL 207 path based on the Mar. 7 result, and the JPL 214a path), so we sorted this out for the next events, with orbit 214a confirmed well by the occultations observed in April. The table shows that the residuals for March 7th stick out like a sore thumb; this occultation has independently measured the error of a Gaia star position, demonstrating the astrometric power of observations of occultations by small NEOs. Perhaps the position angle of the line of apsides of the NY Hydrae binary pair can be crudely determined.

These observations, along with the radar observations, have dramatically collapsed the uncertainties of Apophis' orbit, retiring the risk of Earth impact by the object for at least the next 100 years [13]. Fig. 17 includes a plot of the value and error of Apophis' A2 Yarkovsky acceleration, showing how the error became miniscule after the March 7th occultation result became available [17].

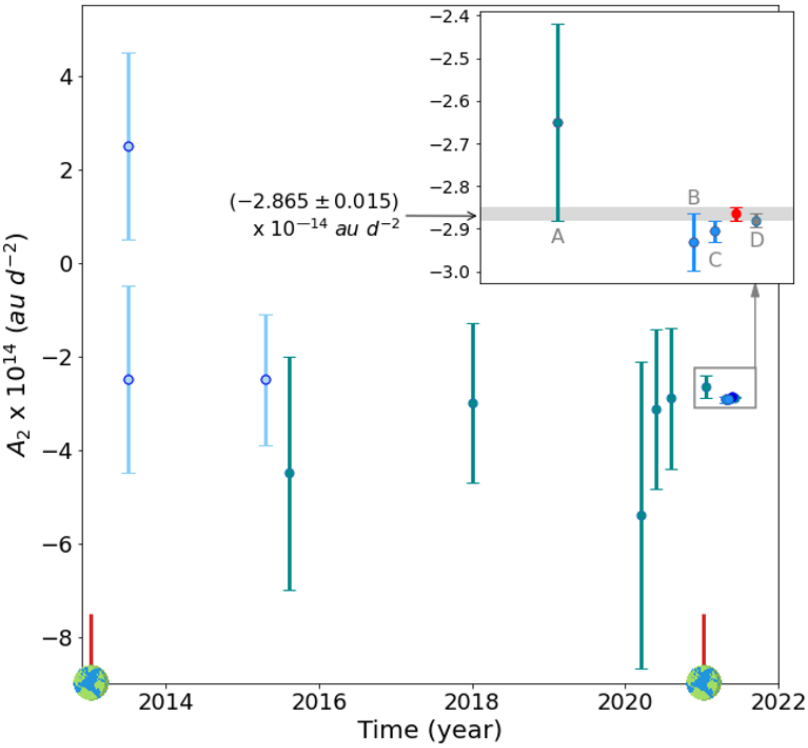


Fig. 17. Evolution in time of our knowledge of the average Yarkovsky acceleration for 99942 Apophis. The light blue data represent the early theoretical estimates from approximate models of the physical properties of Apophis. Note that the sign of the acceleration is not known for the early estimates. 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. The other values shown here are the best measurements available in January (A), the improvement with subsequent optical data during the close encounter (B), and with the addition of radar (C). Considering the occultation results, the error is reduced by nearly a factor 2 (red point) with respect to (C), and a factor 20 compared to (A). The (D) solution, with the same data used for our red point, but computed independently by JPL, is compatible with our results, within the error bars. Image credit: P. Tanga, based on existing data and additional measurements [17].

3.5 Future Apophis Occultations

Table 4 gives predictions for Apophis occultations for the next few months.

Table 4. Future occultations by Apophis.

2021 Date	U.T.	mag. [1]	Location [2]	duration, sec.	Event Notes
May 20	18.0h	10.6	Oman, e. TR, e. UA	0.10	[3]
Sep. 5	1.6h	6.4	S. Sudan, Ethiopia	0.02	[4]
Sep. 27	7.7h	8.5	n. Florida, s.e. GA	0.02	[5]

[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] 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.
[4] 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.
[5] 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, where some predictions of occultations by the large NEO Sisyphus are also given [16].

4. CONCLUSIONS

Results from the Phaethon and Apophis occultation campaigns have demonstrated the power of occultation observations for refining NEO orbits, allowing this to be accomplished when the NEO is out of radar range. The implications for planetary defense are clear, allowing accurate propagation of the NEO trajectory far into the future. For the first occultation by a given NEO, a large campaign is needed, to cast a large-enough net to reliably record the occultation, preferably from 2 or more stations. Once a first success is achieved, it is important to observe a second occultation relatively soon, before the orbital geometry changes too much. A sizeable effort should be made for the 2nd event, in case of a star position problem for the first event, like we had for Apophis on March 7th. Roger Venable, with his ability to set up and pre-point 5 large telescopes on March 22nd, saved the day for Apophis, with his single chord at his easternmost station; without that, the accurate orbit of Apophis might have been lost. Venable again saved the day on April 4th, when one of his scopes recorded one of the 3 positives for that event, as well as bracketing negatives on both sides of the actual path. That confirmed the orbit so that only 3 observers were needed for the April 11th event, all of them recording positives. The efforts vindicated the ability of some IOTA observers to set up and run multiple pre-pointed telescopes, extending that ability, developed for occultations by main-belt asteroids, now to NEOs. We hope that these successes will spark interest in occultations in a new generation of professional and amateur astronomers, so that they learn our techniques, and improve upon them with new technology. Observing NEO occultations is a new activity requiring mobile efforts and careful planning. Maybe someday, you, or one of your students, will secure the orbit of a threatening asteroid and save the planet (or part of it).

5. ACKNOWLEDGMENTS

We thank Joel Johnson, manager of the Allen Parish Airport, for allowing us to set up scopes at the edge of the taxiway. We thank Marshal Eubanks for pointing out to us the duplicity of NY Hydrae. We thank the many observers who participated in the Apophis occultation campaigns, recorded the target star at the expected time, but have so far recorded no occultation by Apophis, listed here: C. and C. Bicknell, M. Buie, D. Ceravolo, P. Ceravolo, P. Cervantes, L. Dorsey, B. Gowe, J. Horst, D. Irwin, R. MacArthur, P. Maley, F. Marchis, R. McClure, J. Moore, A. Olsen, R. Sandy,

S. Sivley, M. Skrutskie, N. Smith, R. and S. Tirashi, J. and E. Visser, H. Watanabe, and M. Ziegler. Their contributions were crucial for casting a large-enough net with the coordinated group effort to obtain the positive observations, and to better define the edges of the actual occultation paths.

REFERENCES

1. Sinvhal, S., Sanwal, N., and Pande, M., "Observations of the Occultation of BD -5 5863 by Pallas", *The Observatory*, Vol. 82, pp. 16-17, 1962.
2. Herald, D., "The first observed asteroidal occultation", J. for Occultation Astronomy, Vol. 4, No. 4, pp. 9-12 (2014).
3. Herald, D., Gault, D., Anderson, R., Dunham, D., Frappa, E., Hayamizu, T., Kerr, S., Miyashita, K., Moore, J., Pavlov, H., Preston, S., Talbot, J., and Timerson, B, "Precise astrometry and diameters of asteroids from occultations – a data set of observations and their interpretation", *M.N.R.A.S.,* Vol. 499, No. 3, pp. 4570-4590, December 2020.
4. Bell, T., "Have Telescope, Will Travel: The Origin of U.S. "Graze-chasing" Expeditions", Griffith Observer, No. 7, pp. 3-21, 2001.
5. Appleby, G. and Morrison, L., "Analysis of lunar occultations – V. Grazing occultations 1964-1977, *M.N.R.A.S.,* Vol. 205, No. 1, p. 57, October 1983.
6. O'Leary, B., Marsden, B., Dragon, R., Hauser, E., McGrath, M., Backus, P., and Robkoff, H., "The occultation of Kappa Geminorum by Eros", *Icarus*, Vol. 28, pp. 133-146, 1976.
7. Degenhardt, S., "Multi-Station Occultation Observing with Galileo Sized Optical Systems", in *Small Telescopes and Astronomical Research*, Collins Foundation Press, Santa Margarita, Calif., 2009,
8. Broughton, J., "Ultra-Portable Telescopes for Occultation Expeditions", presented at the 14th Trans-Tasman Symposium on Occultations, 2020 April 13, http://www.occultations.org.nz/meetings/TTSO14/UltraPortableTelescopes.mp4, accessed 2021 May 14.
9. Battam, K., Knight, M., Kelley, M., Gallagher, B., Howard, R., and Stenborg, G., "Parker Solar Probe Observations of a Dust Trail in the Orbit of (3200) Phaethon", arXiv:1912.08838v2 [astro-ph.EP], 2020 Jan. 5.
10. Dunham, D., "3200 Phaeton – First Successful Occultation Observations of a Small NEA", https://occultations.org/community/meetingsconferences/na/2020-iota-annual-meeting/presentations-at-the-2020-annual-meeting/ and click on 4th presentation from the bottom, accessed 2021 May 14.
11. Tanga, P., Tsiganis, K., Spoto, F., Ferreira, J., Souami, D., and Bouquillon, S., "Stellar occultations by NEAs, challenges and opportunities", 7th Planetary Defense Conference, 2021 April.
12. Dunham, D. et al., "First Occultation Observations by a Small Near-Earth Object, (3200) Phaethon", A.A.S. Division for Planetary Science meeting, 2020 October, http://iota.jhuapl.edu/PhaethonLinksAndGraphics.htm accessed 2021 May 14.
13. Tholen, D. and Farnocchia, D., "Detection of Yarkovsky Acceleration of (99942) Apophis, 7th Planetary Defense Conference, 2021 April.
14. Marchis, F., "We Got It!", https://www.seti.org/we-got-it, 2021 March 10, accessed 2021 May 14.
15. Clausen, J., Helt, B., and Olsen, E., "Absolute dimensions of solar-type eclipsing binaries. I. *uvby* light curves for HS Aqr, KX Aqr, AL Ari, V963 Cen, MR Del, NY

Hya, DU Leo, UW LMi, and V358 Pup”, *Astronomy & Astrophysics*, Vol. 374, pp. 980-996, 2001.

16. Dunham, D., “Occultations by (99942) Apophis during early 2021”, http://iota.jhuapl.edu/Apophis2021.htm, last updated 2021 Apr. 9.
17. Tanga, P. et al., “Apophis’ Yarkovsky Acceleration Improved through Stellar Occultation”, Gaia Image of the Week, https://www.cosmos.esa.int/web/gaia/iow_20210329, 2021 March 29, accessed 2021 May 14.