NEW NEA AND OTHER ASTEROID RESULTS FROM OCCULTATIONS RECORDED BY IOTA OBSERVERS

Paper ACM-23-2363 (Session NEO III: NEAs to Meet You)

14th Asteroids Comets Meteors Conference – ACM 2023

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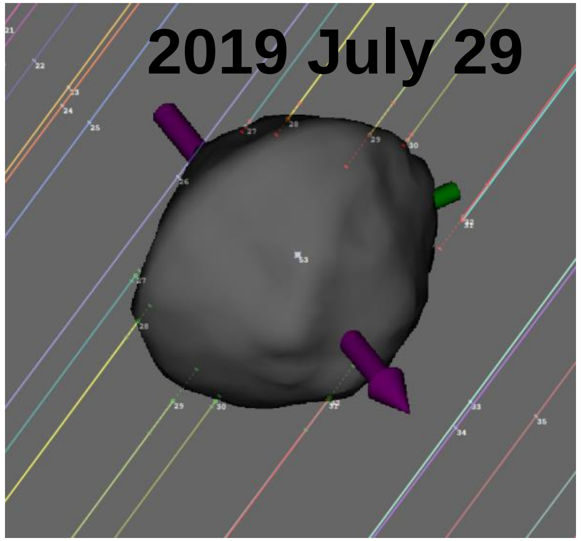
David W. Dunham[1], Fumi Yoshida[2,4], T. Hayamizu[3], T. Arai[4], Hiroyki Watanabe[5], Hayato Watanabe[5], J. Dunham[1], R. Venable[6], S. Chesley[7], J. Irwin[8], D. Herald[9], R. Nolthenius[10], N. Carlson[11], K. Getrost[12], S. Messner[13], R. Jones[14], R. Anderson[15], T. Blank[16], P. Maley[17], and S. Preston[18]

[1]International Occultation Timing Assoc. (IOTA), 16348 E Glenbrook Blvd, Fountain Hills, AZ 85268, USA, **dunham@starpower.net**, [2]S School of Medicine, Univ. of Occupational and Environmental Health, Yahata, Kitakyusyu, Japan, [3]Saga Hoshizora Astronomy Center, Nishiyoka, Saga, Japan, [4]Planetary Exploration Research Center (PERC), Chiba Inst. of Tech., Japan, [5]Japan Occultation Information Network (JOIN), [6]IOTA, Chester, GA, USA, [7]Jet Propulsion Lab., Pasadena, CA, USA, [8]IOTA, Bramley, Guilford, UK, [9]Trans Tasman Occultation Alliance, Murrumbateman, NSW, Australia, [10]Cabrillo College & IOTA, Aptos, CA, USA, [11]IOTA, Tucson, AZ, USA, [12]IOTA, Cleveland, OH, USA, [13]IOTA, Northfield, MN, USA, [14]IOTA, Running Springs, CA, USA, [15]IOTA, Lake Oswego, OR, USA, [16]IOTA, Fountain Hills, AZ, USA, [17]IOTA, Carefree, AZ, USA, and [18]IOTA, Medina, WA, USA

INTERNATIONAL OCCULTATION TIMING ASSOCIATION

PERC
PLANETARY EXPLORATION RESEARCH CENTER

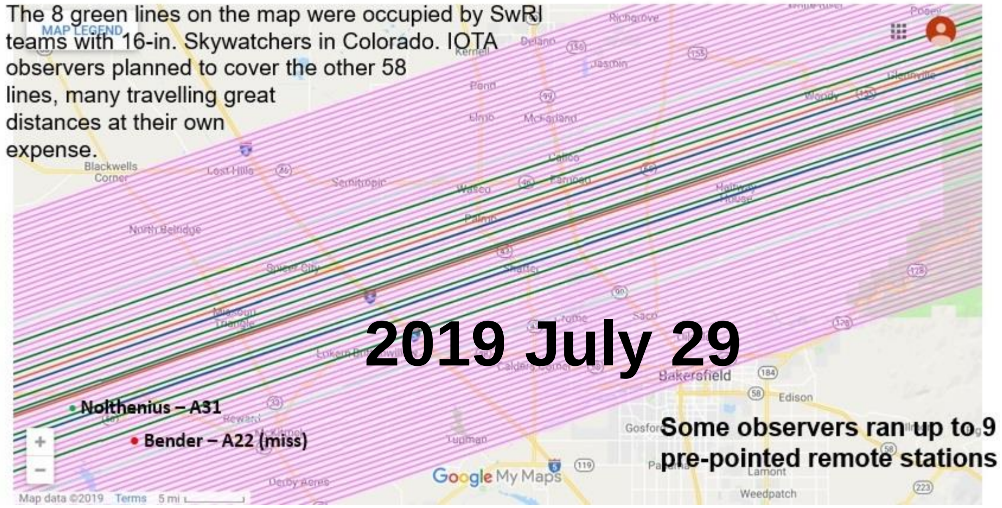
First Occultations by (3200) Phaethon described at PDC 2021



Left: Sky-Plane plot of central timings fitted to Sean Marshall's Phaethon shape model.

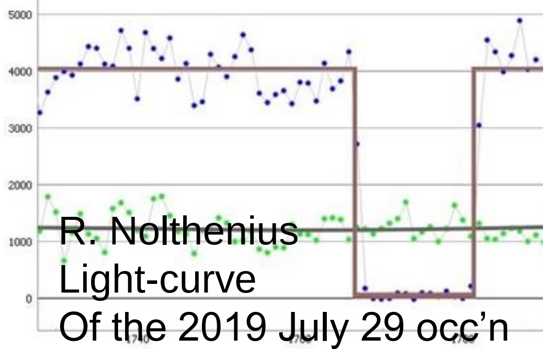
Right: Map showing planned observer lines, central California.

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



The 1st occultation, of 7.3-mag. SAO 40261 whose path crossed the southwestern USA on 2019 July 29, was found by Isao Sato in Japan. The orbit was refined by the planetary ephemeris team at JPL that provided a prediction that was much more accurate than expected. Almost 70 telescopes were set up, 8 by SwRI and the rest by IOTA, to record the event from a span of 45 km, with the 6 central stations recording the event. The scopes at ~20 unattended stations were pre-pointed to the alt/az of the occultation using Guide star charts with the "pre-point line of declination" plotted. We hope that new plate-solving techniques will enable more to make these multi-station deployments; we seek help in finding solutions that work with simple video systems in the field. Five more Phaethon occultations were observed in late 2019 and one in 2020 that resulted in a 3-times reduction of the error of the determination of the A2 non-gravitational parameter of Phaethon's orbit, with a table of the observed events on the lower left.

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

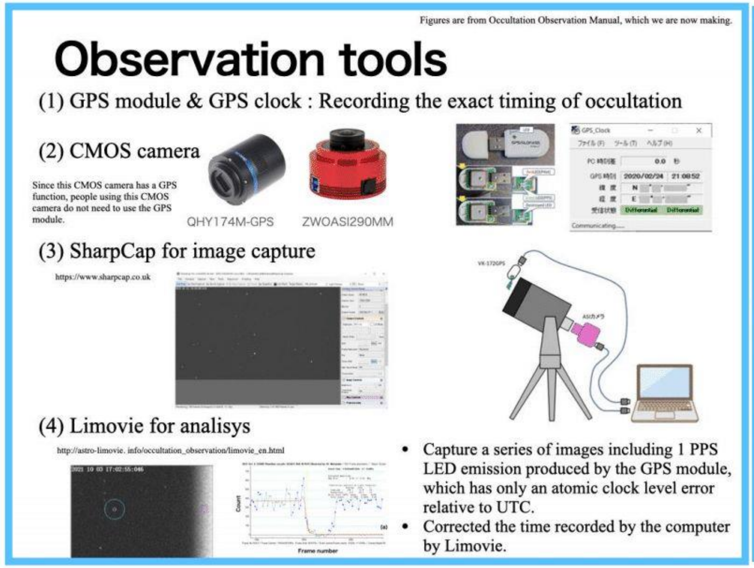


Occultation observation in Japan → East Asia

The Japanese Occultation Information Network (JOIN) seeks outreach to neighboring countries

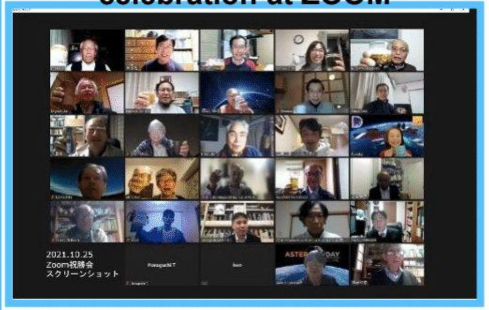
IOTA/EA International Occultation Timing Association/East Asia **Founding**

Equip and develop observation and analysis tools

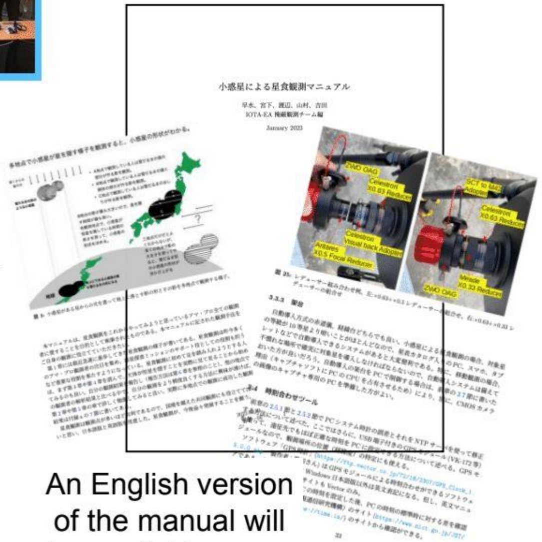


Workshop on Occultation Observations

Pre-observation meeting, observation study session, and celebration at ZOOM



Writing of observation manuals



An English version of the manual will be available soon.

- After many occultation observations of Phaethon, a mixed pro-am team of occultation observers was formed in Japan. Japanese amateur observers have long experience in occultation observation. They have developed their own observation aids (GPS receiver, time imposer) and analysis software. Such tools are now shared among the team.
- We have also begun holding occultation observation workshops to educate newcomers to the field. The number of occultation observers gradually increased.
- We held zoom meetings before and after observation campaigns to discuss observations, provide guidance and unify observation methods, and hold victory parties after observations.
- We have also prepared an observation manual and are working on an English version so that people overseas can read it as well.

This major movement was triggered by Phaethon's occultation observations for the DESTINY+ mission. Now we are moving toward the establishment of the IOTA/EA involving not only Japan but also neighboring countries.

We will continue observations of stellar occultation by Phaethon until the flyby with the IOTA/EA team.

DESTINY+ provides some support via the Planetary Exploration Research Center (PERC)

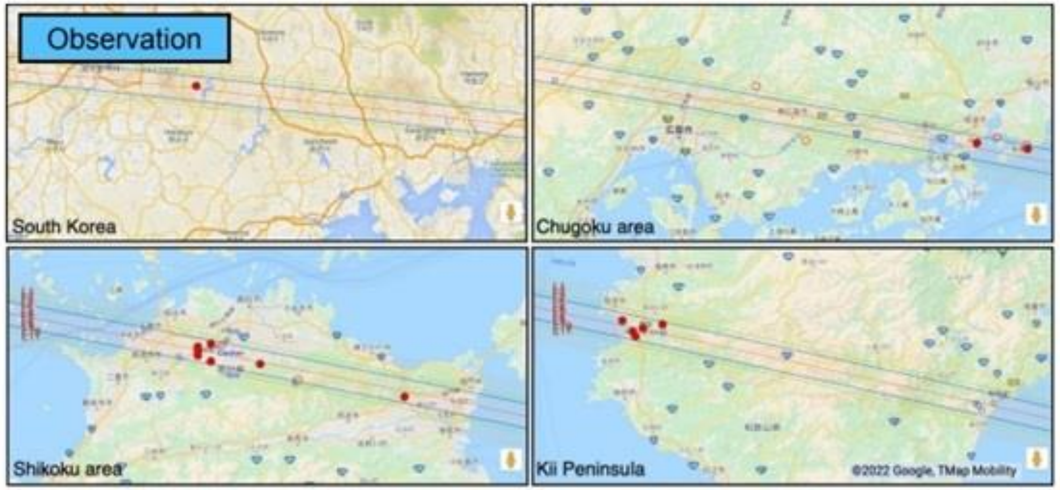
2021 October 3 (UT)

UCAC4 646-021974 (12.0 mag)

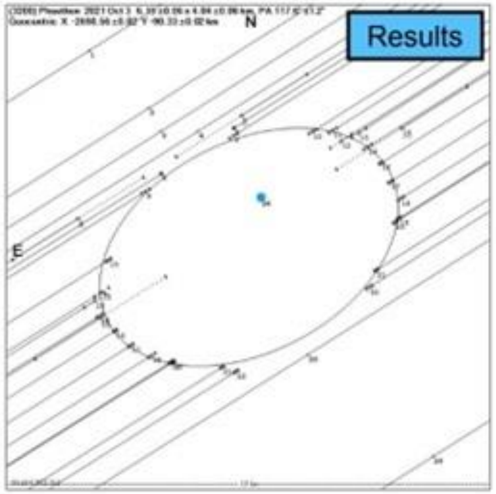
Best-observed Phaethon occultation

Yoshida et al. PASJ, 2022, psac096,
https://doi.org/10.1093/pasj/psac096

Phaethon occults a 12.0 mag star along a path across Japan, Korea and China at 16:58 UT on 3 October 2021. When the occultation occurs, the star is dimmed 6.5 mag. **The maximum duration time is 0.68 seconds.**



Seventy-two people observed the occultation event at 36 separate sites from Japan to Korea. 18 sites had positive detection, while seven were negative.

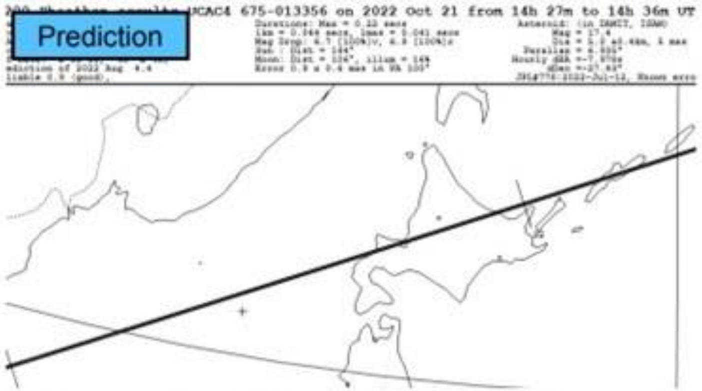


- The Phaethon's cross section at the time of the stellar occultation on October 3 (UT) would be fitted approximately by an ellipse with a **major diameter of** 6.12 ± 0.07 **km** and a **minor diameter of** 4.14 ± 0.07 **km**.
- This is the first successful ultra-precise measurement of stellar occultation by an asteroid 5-6 km in diameter using a CMOS camera and a GPS module. The large number of observation points and the high-precision time keeping method enabled us to obtain a high-resolution outline of Phaethon. The measurement error of each observation point is about 80-140m.

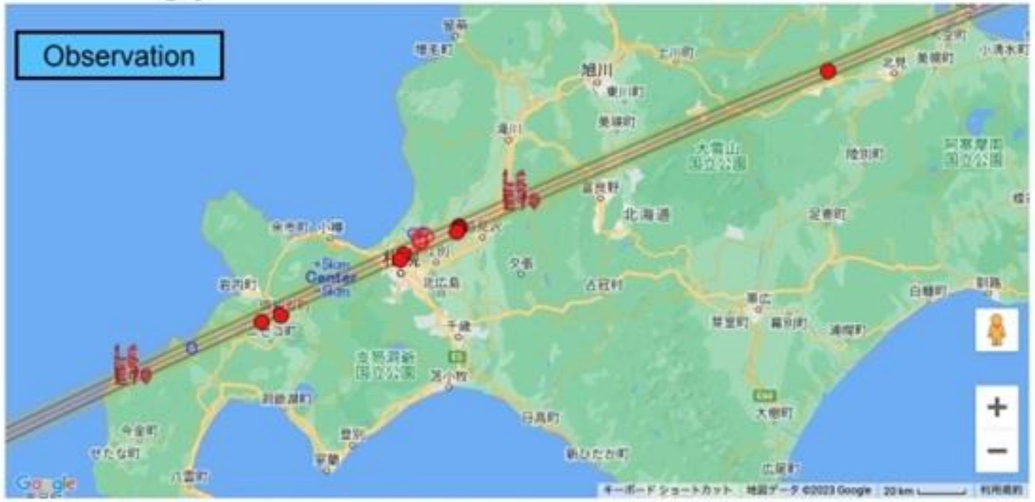
2022 October 21 (UT)

<u>This well-observed occultation had an unexpected large path shift</u>

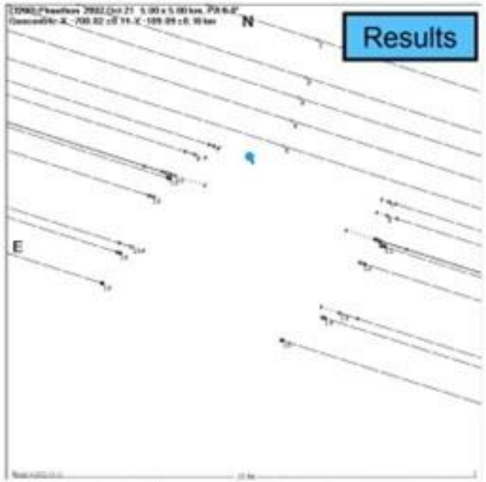
TYC 2844-0735-1 (10.8 mag)



Phaethon occults a 10.8 mag star along a path across Hokkaido Japan, at 14:32 UT on 21 October 2022. When the occultation occurs, the star is dimmed 6.7 mag. **The maximum duration time is 0.22 seconds.**



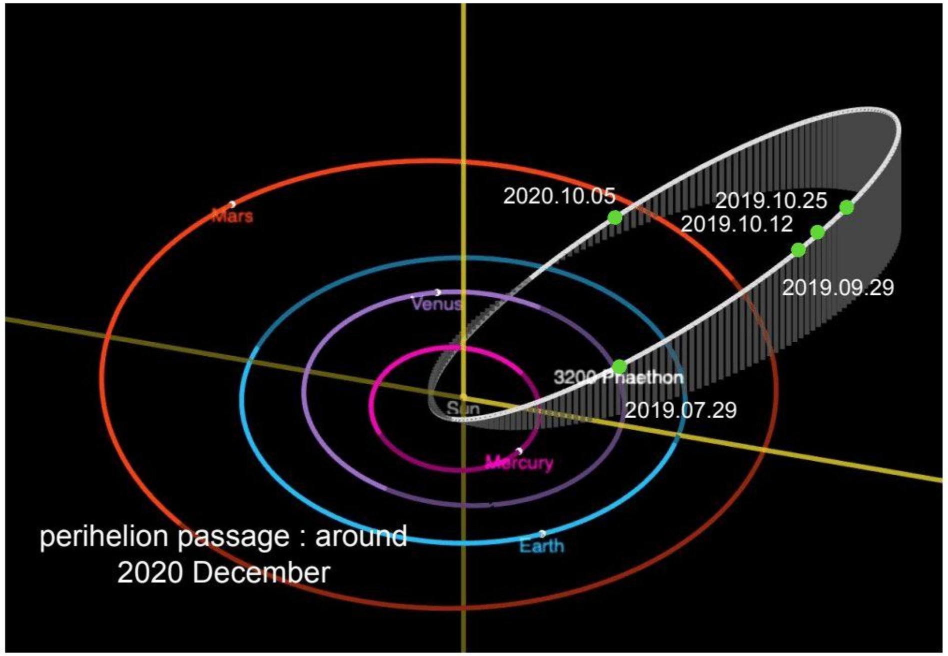
Thirty-nine people observed the occultation event at 19 separate sites in Hokkaido. 9 sites had positive detection, while five were negative.

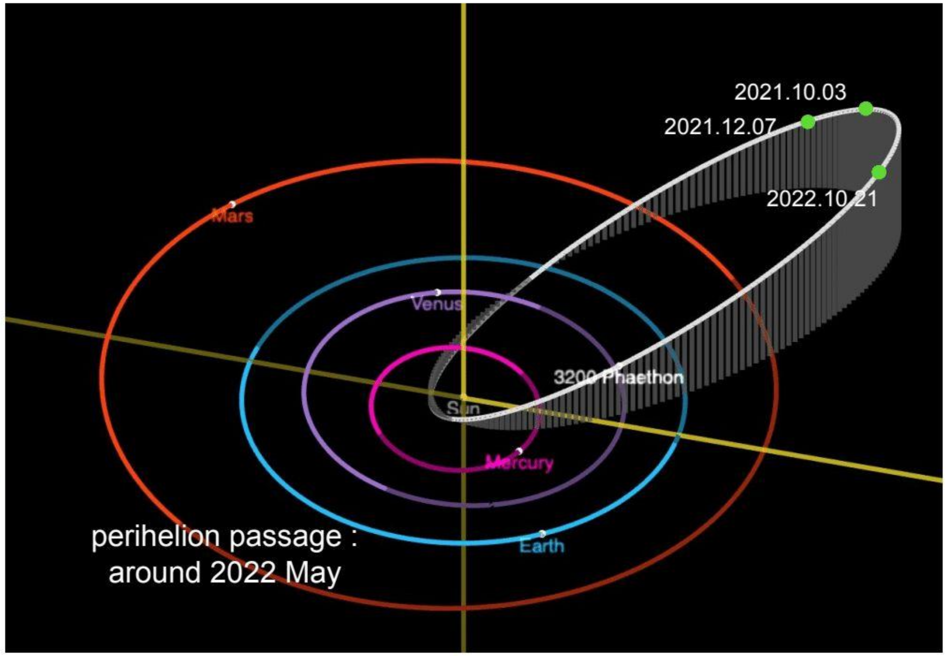


- Starting observations in July 2019 and continuing through October 2021, stellar occultations by Phaethon were occurring almost exactly as predicted in the predicted occultation zone. This suggests that Phaethon's orbit was extremely well determined.
- However, the October 2022 observations showed that the predicted occultation zone was shifted to the south by the radius of Phaethon (about 2km or so). Therefore, we were unable to measure the entire cross-sectional shape of Phaethon.
- The measurement error of each observation point is about 45-700m.

Why did the occultation zone shift?

One possibility is that there may have been some change in Phaethon's orbit at the time of the perihelion passage?

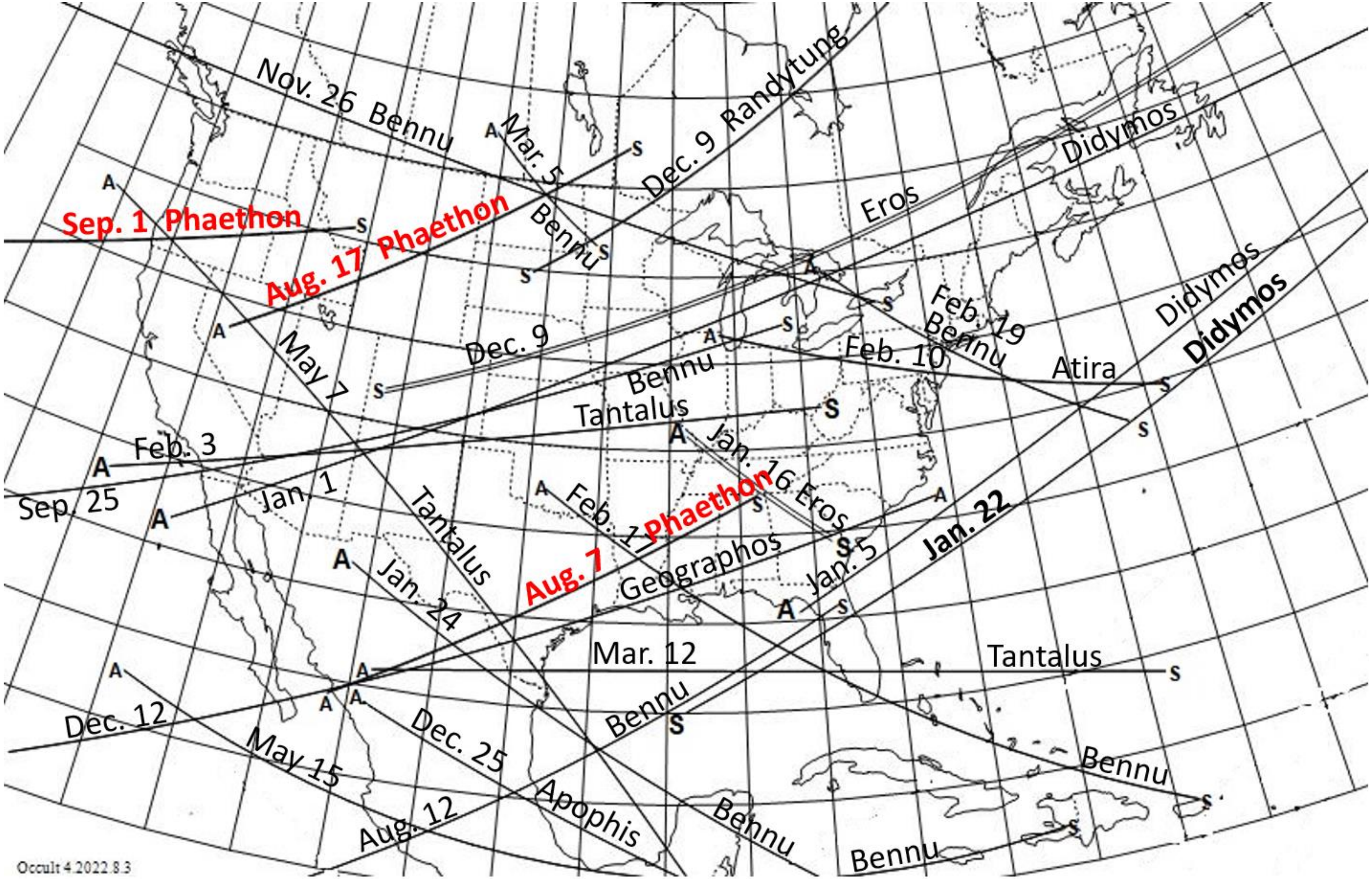




- Before the observation in October 2021, we asked the international occultation community to improve Phaethon's orbit and update the prediction. By the time of the October 2022 observation, I thought that Phaethon's orbit has been well determined, so we just used the usual software to make the prediction. That may be why we did not notice that Phaethon's occultation zone had shifted.
- As I recall, Phaethon's orbit was first improved and the prediction was carefully checked at the time of the 2019 observation. The position of the occultation zone did not shift much until the 2020 observation. Phaethon did not pass the perihelion during this period.
- Phaethon passed the perihelion between the 2021 and 2022 observations, which may have caused a slight orbit change, since Phaethon has been observed to be active near perihelion in the past.

A lesson for the future is that astrometry for orbit improvement is essential before occultation observations.

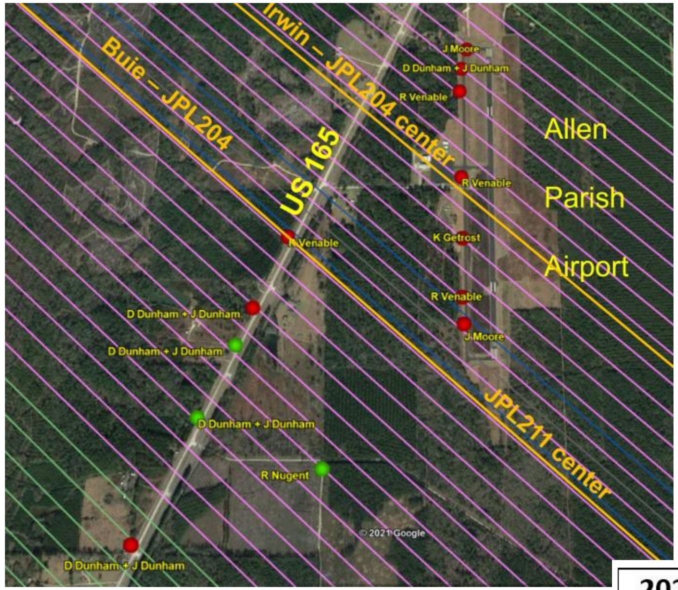
Occultations by NEAs in North America during 2023
to mag. 12.0 (to mag. 13.0 for Phaethon; 3 chances for it highlighted)



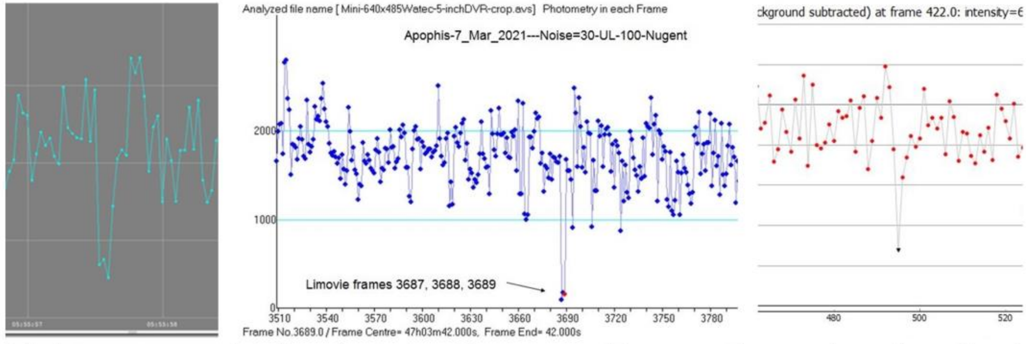
This map is adopted from one that we published in the Royal Astronomical Society of Canada's Observer's Handbook for 2023. It is also available on IOTA's NEA occultations page at https://occultations.org/publications/rasc/2023/nam23NEAoccs.htm along with much more about NEA events worldwide. For more predictions, see https://occultations.org/publications/rasc/2023/ACM2023.htm . IOTA will prioritize the NEAs with uncertain futures given in ACM2023 #2312 presented on Monday in the NEO I session, & mission targets

2021 Occultations by (99942) Apophis from PDC 2021-1

The 1st observed event on March 7th benefitted from a JPL prediction based on radar data from Mar. 4-6; the star was 8.4-mag. NY Hydrae, an eclipsing binary with high Gaia RUWE.



Above, the 2 pre-pointed 8cm Dunham unattended systems that recorded positives; 3 others they deployed had misses.



Above, the 3 positive light curves for the March 7th . occultation.

Left: Stations near Oakdale, Louisiana with the planned lines; Green dots mark positive sites, red dots mark sites that had no occultation (negatives).

Right: Residuals from the first 5 Apophis occultations from the JPL 214a orbit that gave 0 weight to Mar. 7 since the star's Gaia RUWE was high. The high-precision orbit, with radar & occultations, retired the risk of impact with Earth for at least a century.

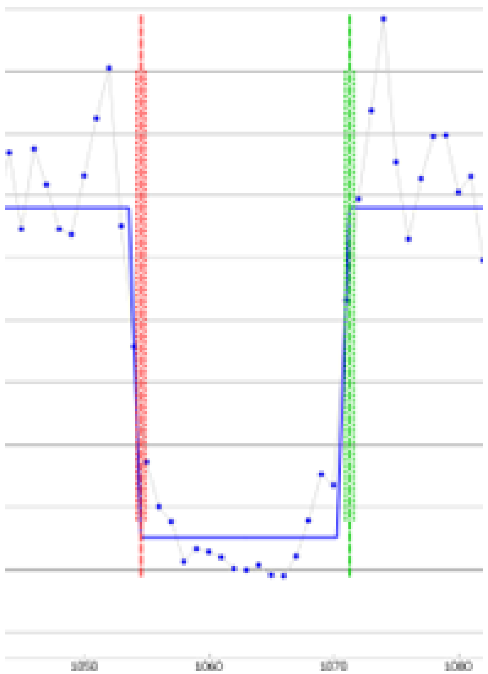
2021 Date	mag. [1]	Loc. [2]	Total #	# pos.	Δα [3]	Δδ [3]	Δt [3]	RUWE [4]
March 7	8.4	LA,OK,CO,BC	29	3	-11.0	+1.2	+0.17	1.45 [5]
March 22	10.0	FL,AL,IL	9	1	+0.4	-0.5	-0.02	1.15
April 4	11.0	NM	8	3	+0.3	-0.1	-0.01	0.90
April 10	12.6	Japan	2	1?	marginal detection, not used			
April 11	10.1	NM	3	3	+0.5	-0.5	-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.

Much information about past observed Apophis occultations ia at **http://iota.jhuapl.edu/Apophis2021.htm.**

2021 Occultations by (99942) Apophis from PDC 2021-2

The 1st observed event on March 7th benefitted from a JPL prediction based on radar data from Mar. 4-6; the star was NY Hydrae, Hydrae, an eclipsing binary with high Gaia RUWE. On 2021 Mar. 22, R. Venable recorded the occultation of a 10.0-mag. star from 5 locations with large pre-pointed telescopes in Florida (**below**); he covered the east side of the predicted (JPL207) path while others covered the west side. To the **right** is Venable with one of his 14-in. Fastar (f/2.1) SCT's with specially-built low mount that adds stability and facilitates quick set-up. His fence of telescopes extended just far enough east to catch the critical occultation observation (green dot, positive) while the others were negative (red dots). With this effort, Venable saved Apophis' accurate orbit that helped retire its risk of impact; the subsequent events listed on the previous slide secured the orbit. Venable's subsequent deployments of his systems have led to other NEA occultation successes, especially for Didymos and Dimorphos; see the next talk by Damya Souami.



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

Above right, April 11 near Farmington, NM, light curve of the occultation of a 10.1-mag. star by Apophis, by Kai Getrost, recorded with 100 frames per second with a QHY 174M GPS camera attached to a 20-inch Dobsonian telescope. Effects of Fresnel diffraction are evident.

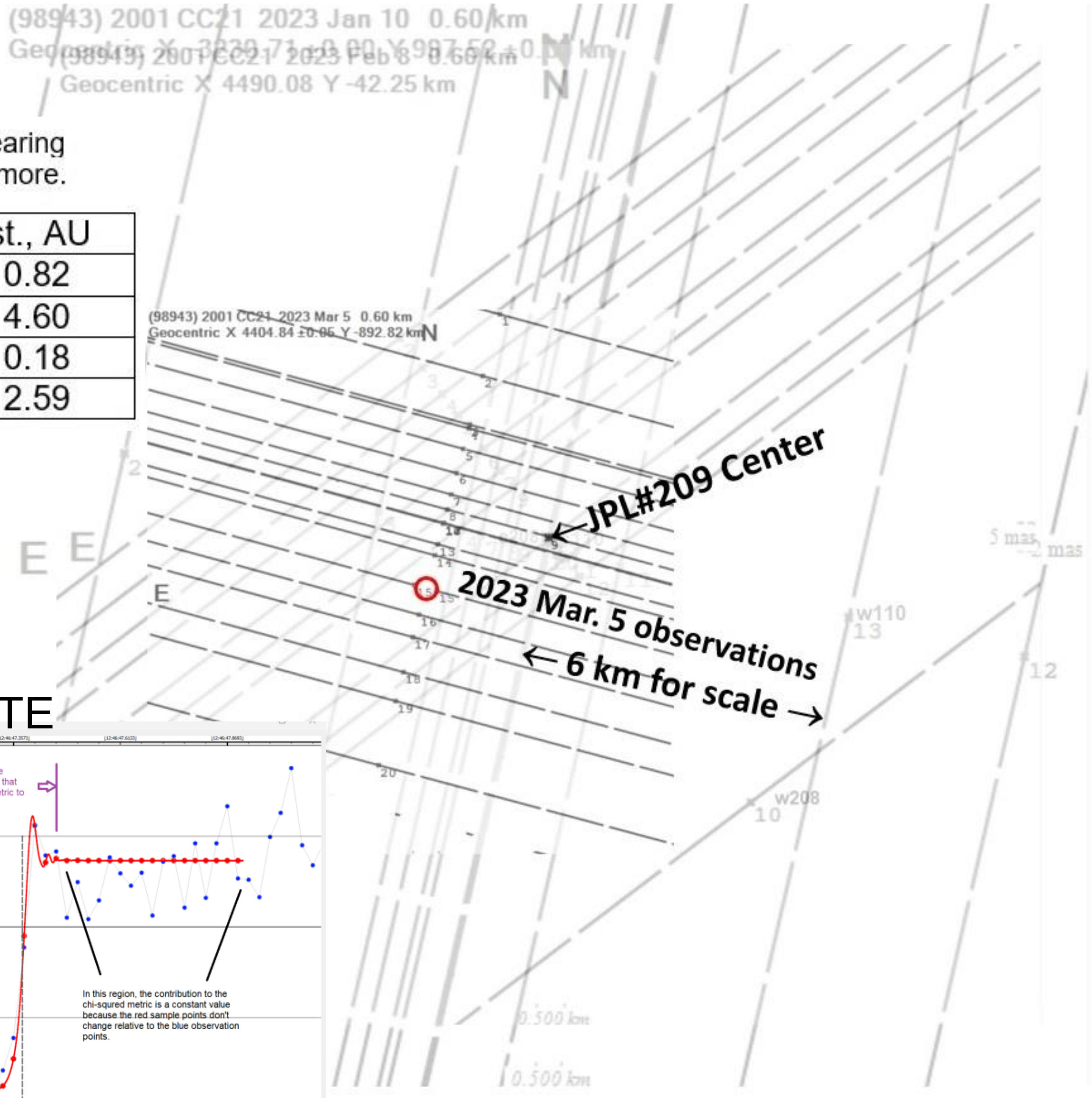
See the next talk by Damya Souami for the remarkable Reduction of Apophis' orbital errors from the addition of IOTA's asteroidal occultation observations.

1st Observed Occultation by 2001 CC21, NEA flyby target of Hayabusa2

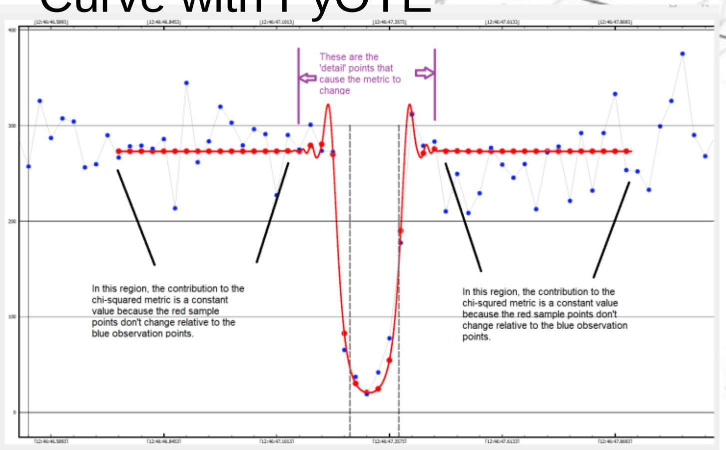
Sky Plane Plot for 2023 Mar 05 occultation observations in Japan with past observations

Distance for 4 NEA's beyond which diffraction smearing becomes significant; see our PDC 2023 paper for more.

NEA	Rast, m	FL, m	Dist., AU
Apophis	169	192	0.82
Didymos	400	455	4.60
Dimorphos	80	91	0.18
2001 CC21	300	341	2.59



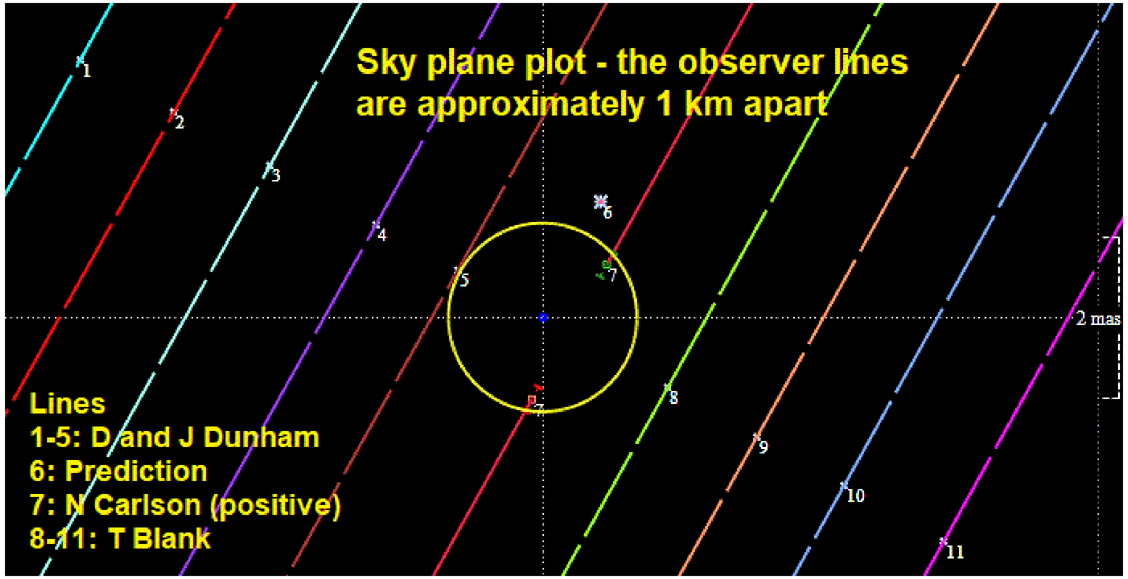
Below: Fresnel Diffraction Model fitted To Ida's Light Curve with PyOTE

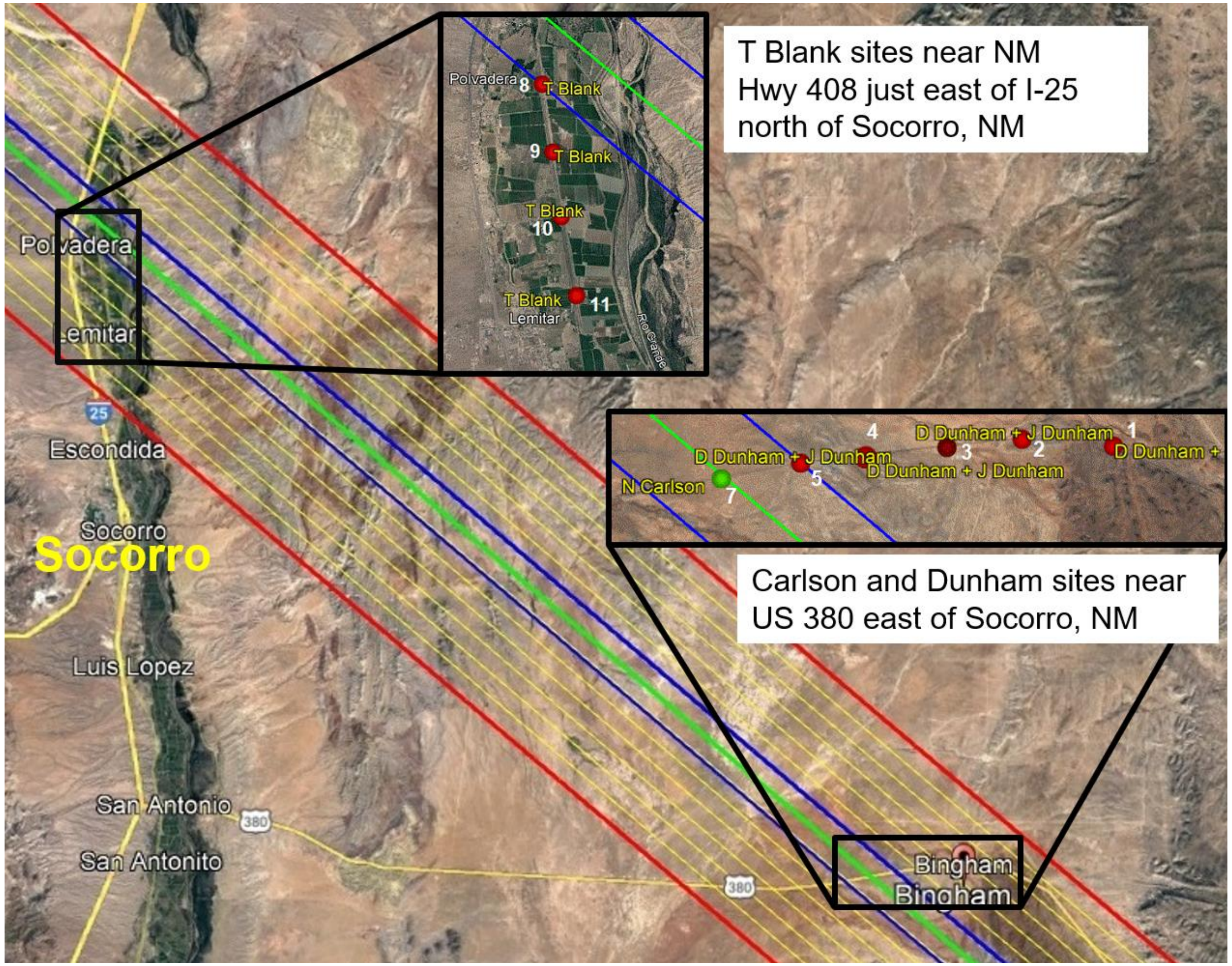


The previous observations, also in Japan, were all misses (negative), made on 2023 Jan. 10 and Feb. 8.

The red circle shows the location of 2001 CC21 according to Miyoshi Ida's observation on 2023 March 5, in a gap of the coverage by the earlier observations.

Occultation of 8.4-mag. SAO 164452 (= HIP 106281) by (2102) Tantalus, 2023 May 7





(2102) Tantalus is a 1.4-km PHA in a highly inclined (64° to the ecliptic) orbit that won't be in radar range again until 2038. This bright event provided a chance to record an occultation with easily-transported 8cm systems, like those we used for Apophis in 2021 March. IOTA members Ted Blank, and David and Joan Dunham, deployed and pre-pointed 10 of these systems near Socorro, N. Mex., to cover most of the 1-σ path error zone while Norm Carlson set up his larger (20cm) scope on the predicted center. We used a predicted 2-km diameter for our planning but later we found a better recently-published radar diameter of 1.4 km; also, the real error was much less than 1-σ. Next time, we'll have more concentration near the center.

On 2022 Nov. 26, IOTA member Steve Messner recorded the 1st occultation by 7-km NEA (1866) Sisyphus in Minn.

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

Discovery by Peter Nosworthy & Dave Gault, May 19, west of Sydney, NSW, Australia
Confirmation by Richard Nolthenius and Kirk Bender, June 9, central California, USA

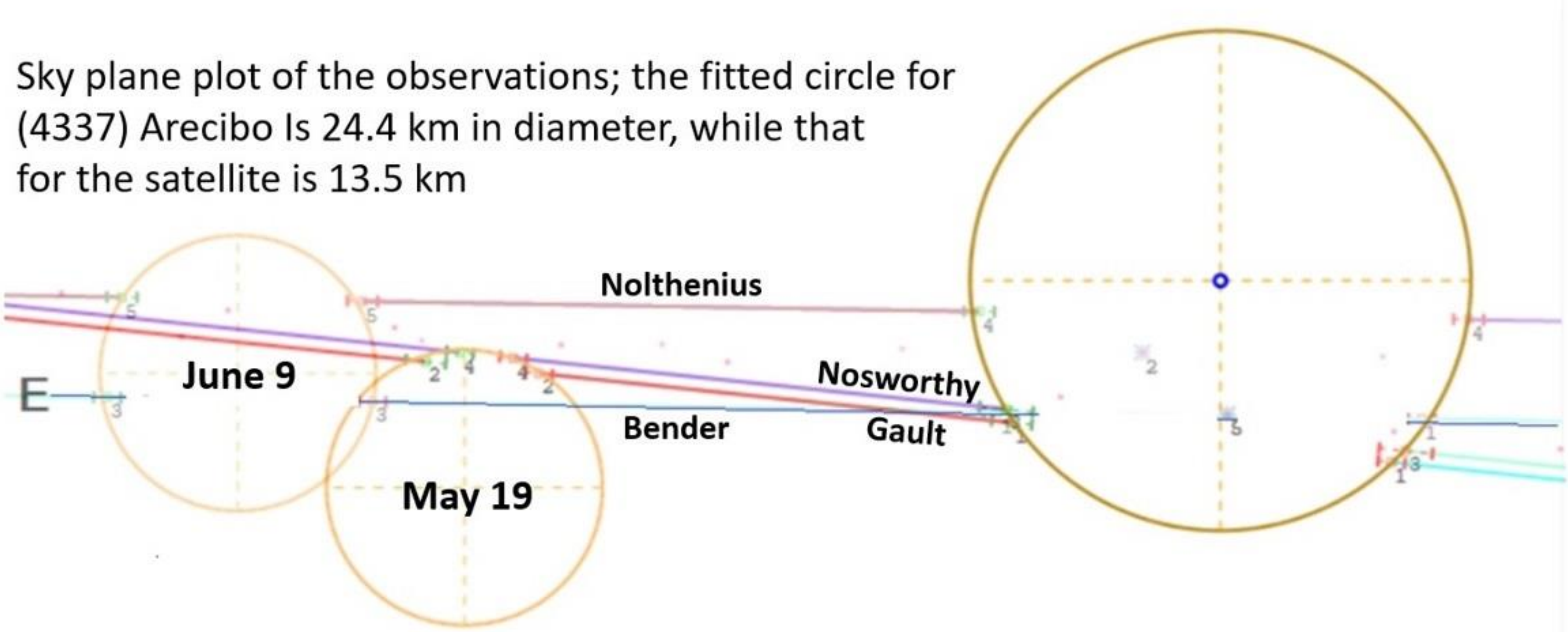
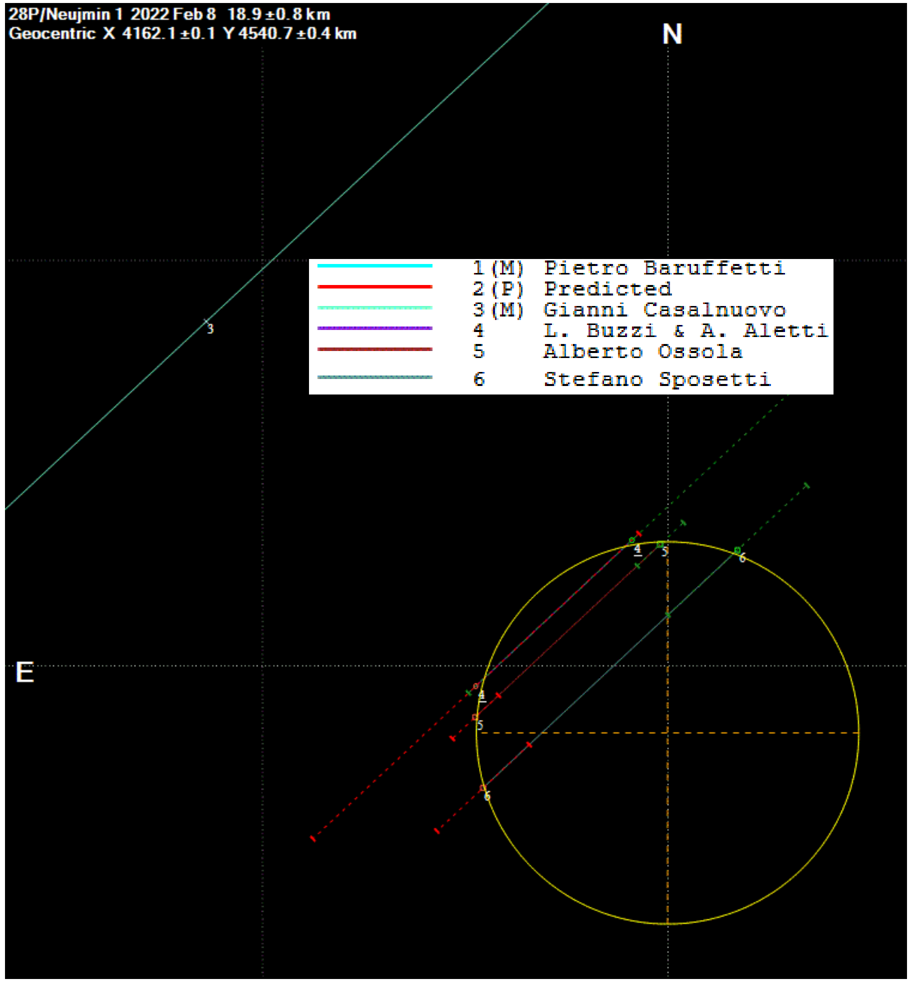
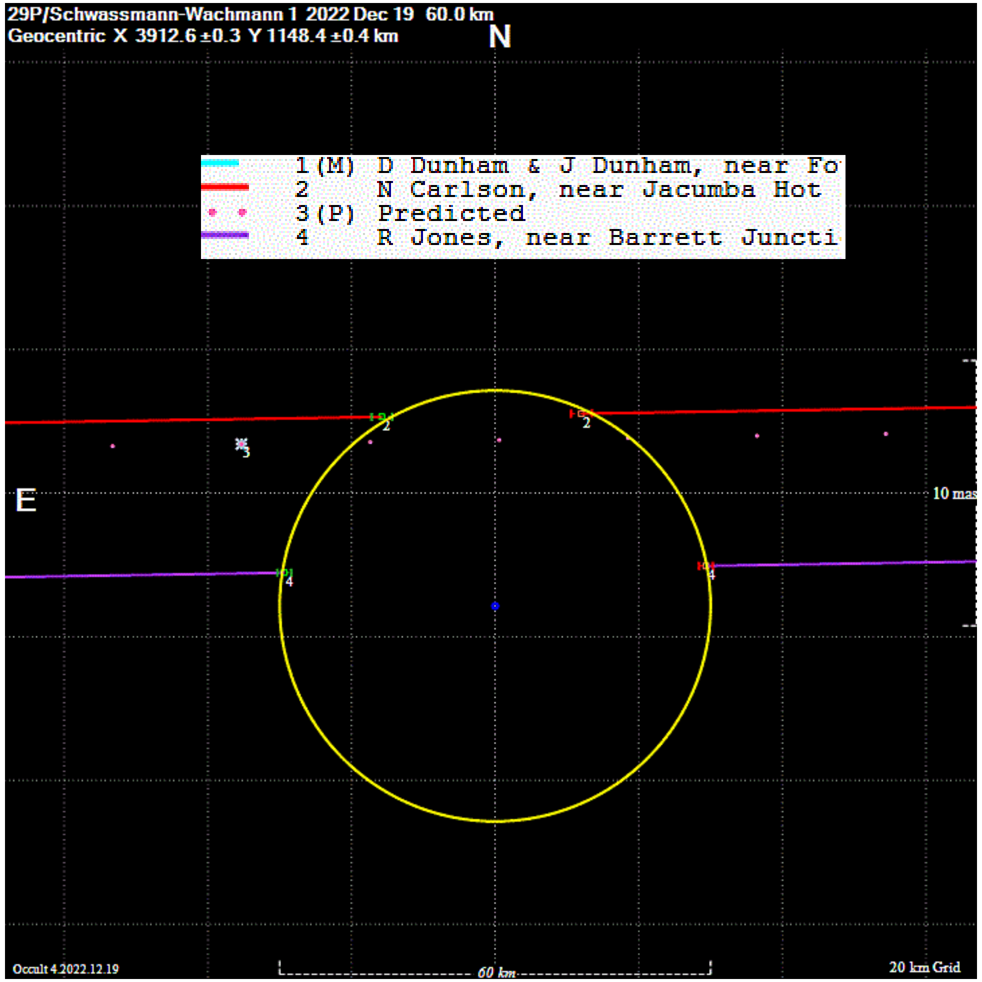


Diagram by Dave Herald using the Occult4 program. For more, including the videos, please visit https://www.youtube.com/watch?v=w_Cc5Or1FFw . Gaia confirmed the duplicity from the small wobble of the center of figure, finding a period of 1.3 days. On 2022 May 16, Nosworthy and Gault found from another occultation that (172376) 2002 YE25 is likely a binary with ~3-km objects about 15 km apart; see http://hazelbrookobservatory.com/ye25/#:~:text=Introduction,is%20probably%20two%20smaller%20objects.

IOTA Observations of Occultations by Comets

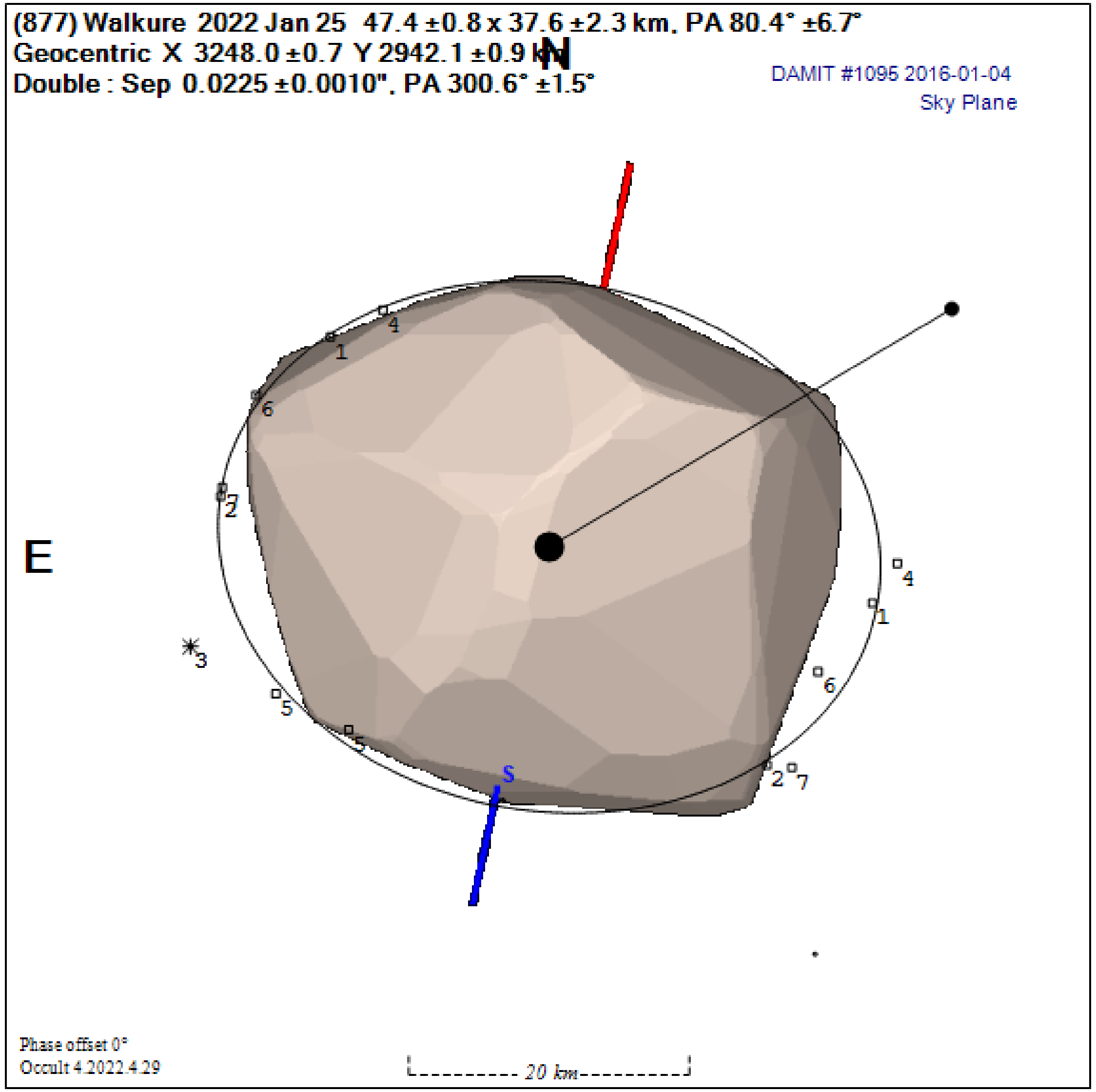


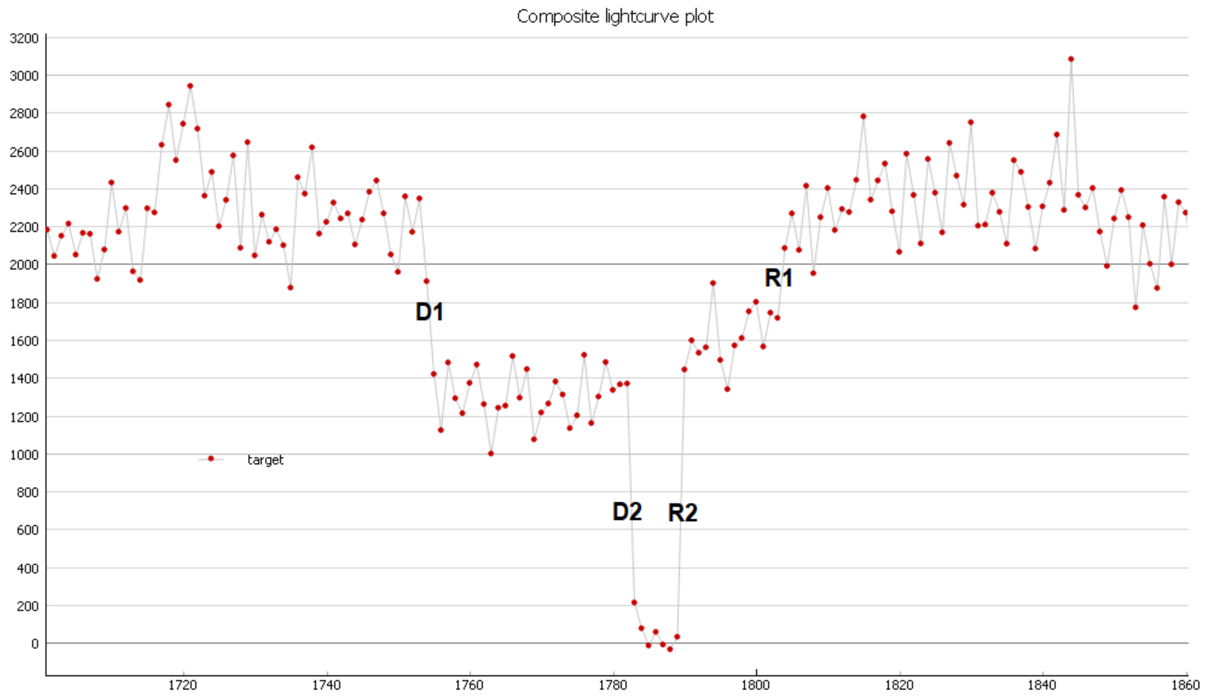


On 2022 February 8, 3 amateur observers in Europe working with IOTA obtained what we believe to be the first unambiguous observations of an occultation by the nucleus of a comet, 28P/Neujmin 1.

On 2022 Dec. 19, IOTA observers worked with Lucky Star & others to record the 1st multi-chord occultation by 29P/Schwassman-Wachmann 1 (SW1). IOTA observed at least 2 more SW1 events, on 2022 Dec 29 in NM and 2023 May 7 in the UK. But for the best info. about SW1 occultations, see Buie et al.'s ACM 2023 E-Poster #2445.

2022 Jan. 25 Occultation of SAO 110026 by (877) Walkure, Double Resolved





In 1984, D. Evans recorded a lunar occultation of SAO 110026 (= UCAC4 480-002385) photoelectrically at McDonald Obs., showing the star to likely be double with a sep. of 0.05″. For the 2022 event by Walkure, Paul Maley video recorded occultations of both components, shown in his light curve above. Also observing near Tucson was Norm Carlson, while D. and J. Dunham deployed 3 pre-pointed 8cm systems. On the left is the sky plane Plot of the timings, with station numbers: 1, Dunham1, Picacho Peak; 2, Carlson; 3, the predicted center; 4, Maley star 1; 5, Maley star 2; 6, Dunham2, Rillito; and 7, Dunham3, Cortaro. The Walkure shape model used for the fit is DAMIT #1096. IOTA has discovered many doubles during asteroidal occultations, see MNRAS **https://arxiv.org/abs/2010.06086.**

Conclusions

- The rare bright 2019 July 29th occultation was the first successful campaign for a small NEO; until Apophis in 2021, it was the smallest asteroid with multiple timed chords during an occultation. One of the larger collaborations of amateur and professional astronomers for an occultation enabled that success.
- The radar size and shape were verified, and the improved orbit allowed a good prediction for the next occultation, then subsequent events, and an improvement of Phaethon's A2 non-gravitational parameter by a factor of 3.
- But recent observations show that sudden changes might occur to Phaethon's orbit near perihelion, so more observations by this enigmatic object are needed.
- The occultation technique was successfully applied to Apophis, which is more than 10 times smaller than Phaethon, and also smaller Didymos, further demonstrating the astrometric power of observations of NEO occultations for planetary defense; the next presentation will give more information about this.
- 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
- We encourage as many others as possible to time occultations by NEA's, TNO's and by other asteroids (and sometimes comets) from their observatories
- We want others to learn to make the necessary mobile observations, including the multi-station techniques pioneered by IOTA, to observe NEA and other occultations, to support planetary defense and asteroid science.

Please visit https://occultations.org/publications/rasc/2023/ACM2023.htm to get this presentation, and for links to IOTA's, and other's, Web sites that have predictions and much other information that will allow you, and others at your institution, to take part in this exciting field of astronomy. Contact: dunham@starpower.net; cell +1-301-526-5590