NEO ORBITS AND SIZES FROM IOTA OCCULTATION OBSERVATIONS

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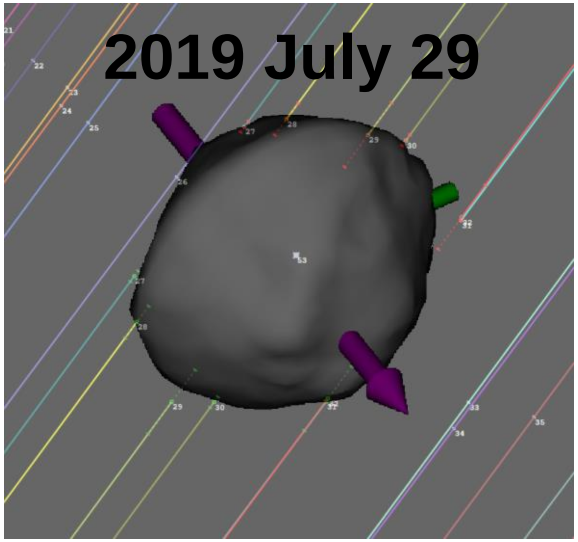
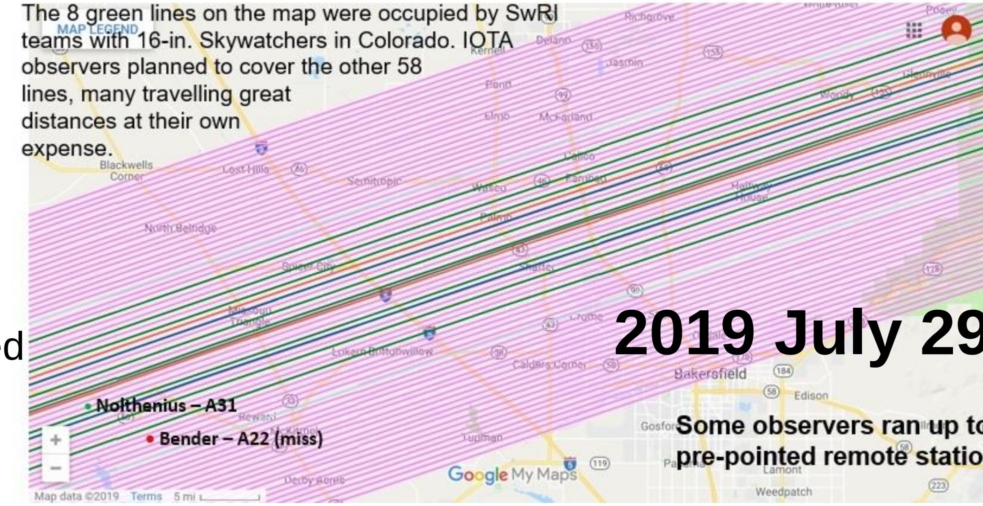
First Occultations by (3200) Phaethon described at PDC 2021



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

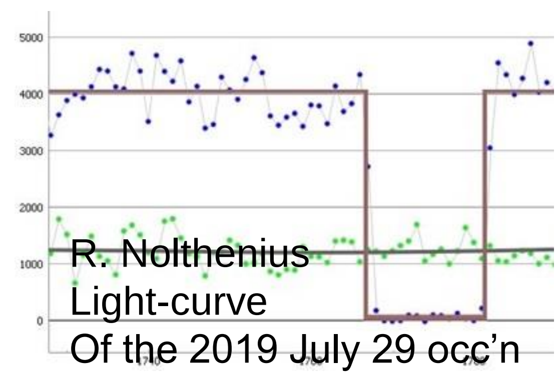
Right: Map showing planned observer lines, central Calif.

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 tele-scopes 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. 5 more occultations were then observed in late 2019 and 1 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

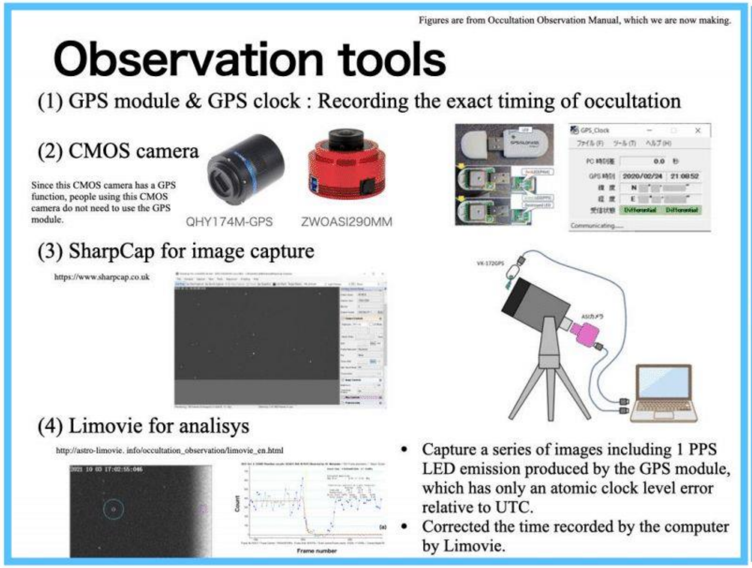


Occultation observation in Japan → East Asia

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)

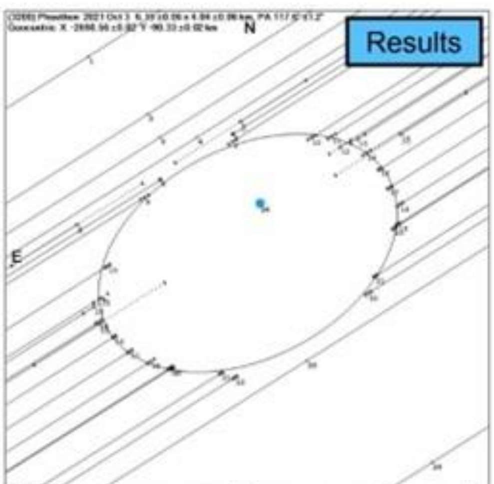
UCAC4 646-021974 (12.0 mag)

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.

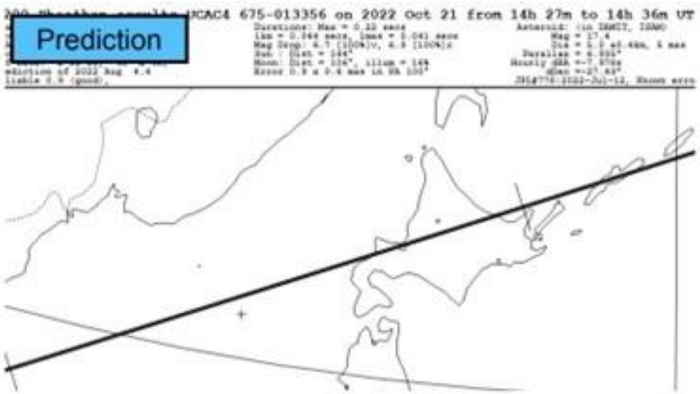


- The Phaethon's cross section at the time of the stellar occultation on October 3 (UT) would be fitted approximately by an ellipse with a **major diameter of** 6.12 ± 0.07 **km** and a **minor diameter of** 4.14 ± 0.07 **km**.
- This is the first successful ultra-precise measurement of stellar occultation 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.

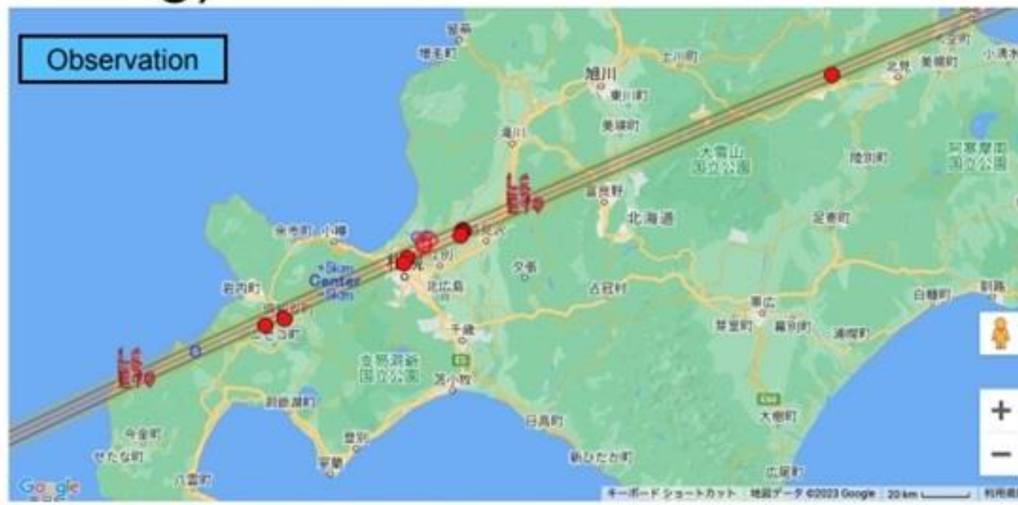
2022 October 21 (UT)

This well-observed occ-ultation had an Unex-pected large path shift

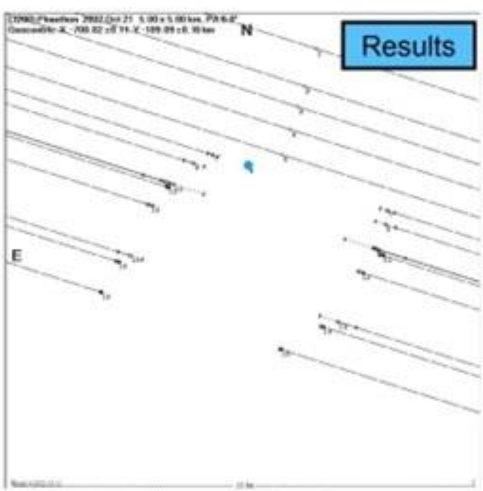
TYC 2844-0735-1 (10.8 mag)



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.**



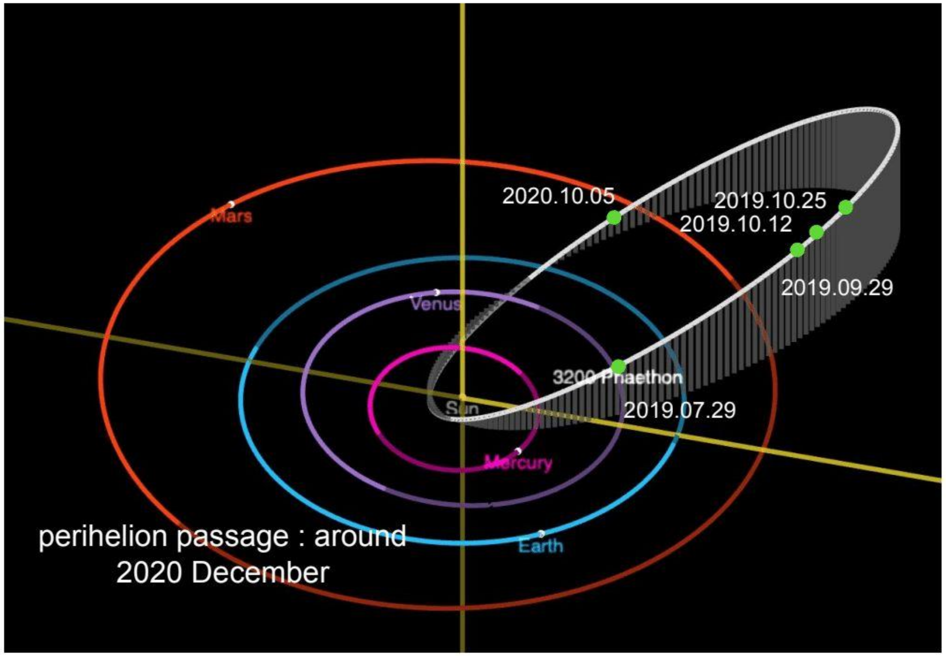
Thirty-nine people observed the occultation event at 19 separate sites in Hokkaido. 9 sites had positive detection, while five were negative.

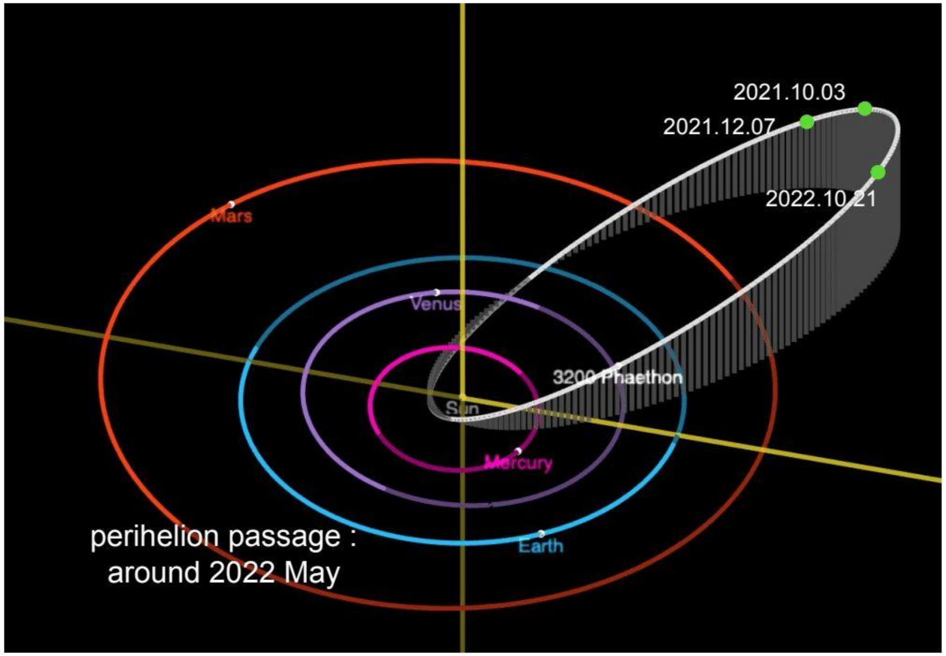


- Starting observations in July 2019 and continuing through October 2021, stellar occultations by Phaethon were occurring almost exactly as predicted in the predicted occultation zone. This suggests that Phaethon's orbit was extremely well determined.
- However, the October 2022 observations showed that 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?



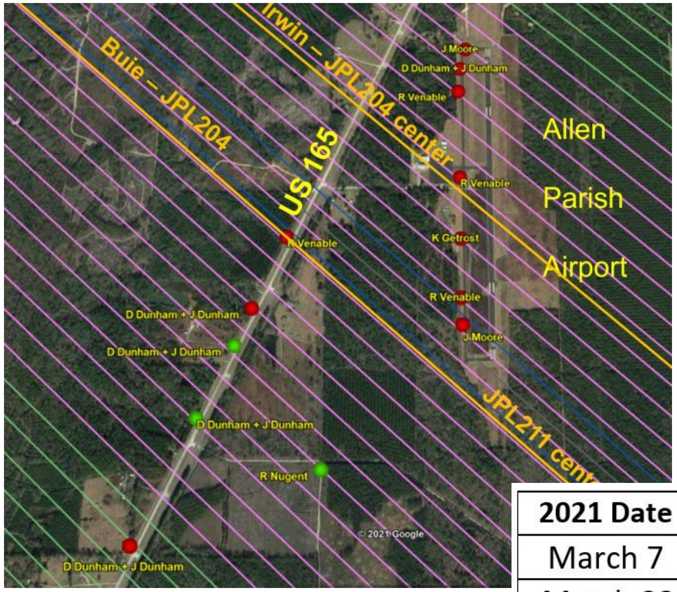


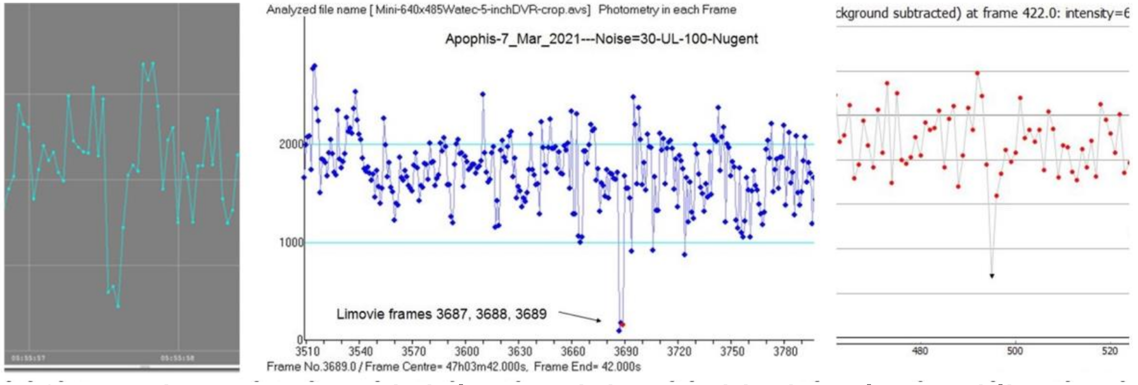
- Before the observation in October 2021, we asked the international occultation community to improve Phaethon's orbit and update the prediction. By the time of the October 2022 observation, I thought that Phaethon's orbit has been well determined, so we just used the usual software to make the prediction. 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.

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.





Left: Stations near Oakdale, Louisiana with the planned lines; Green dots mark positive sites, red ones negatives. **Above,** the 3 positive lightcurves, 2 with pre-pointed 80mm scopes set up by D. and J. Dunham, for the March 7th occultation.

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.

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.

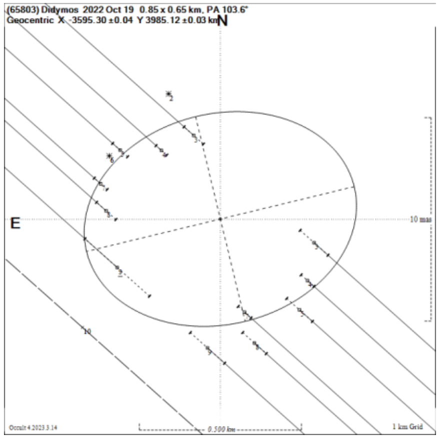
Much information about past observed Apophis occultations ia at **http://iota.jhuapl.edu/Apophis2021.htm.**

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

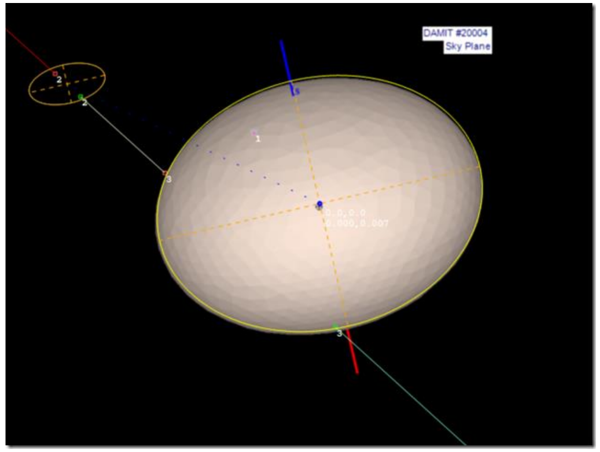
The 1st observed event on March 7th benefitted from a JPL prediction based on radar data from Mar. 4-6; the star was NY Hydrae, an eclipsing binary with high Gaia RUWE. On 2021 Mar. 22, R. Venable recorded the occultation of a 10.0-mag. star from 5 locations with large pre-pointed telescopes in Florida (**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 shown on the next slide.

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

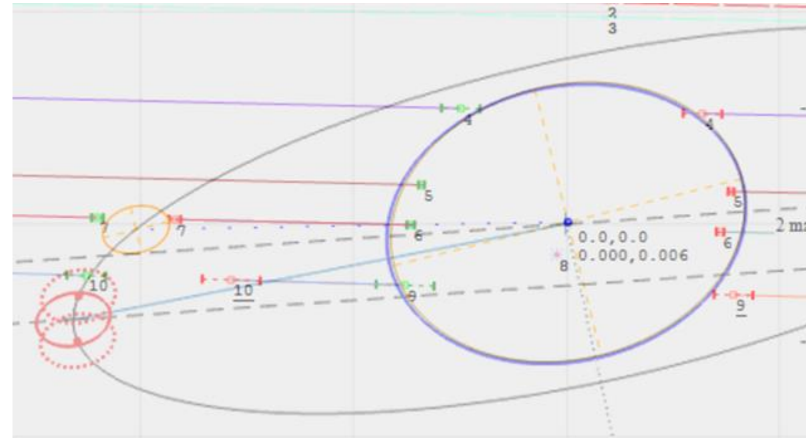
Occultations by the Didymos/Dimorphos System, 2022-2023



Sky plane plot of the Didymos occultation of an 11.2-mag. star in Japan, 2022 Oct. 18, one of the better-observed Didymos occultations.

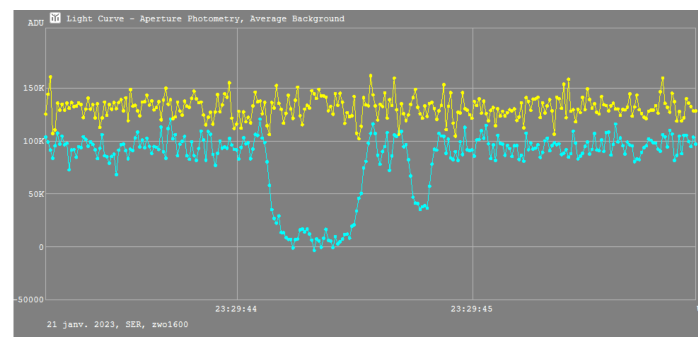


Sky-plane plot of the first observed occultation by Dimorphos, upper left, shortly before the occulta- tion by Didymos, R. Venable, Crawford, FL, 2022 Oct. 19.



Sky plane plot of the occultation of a 9th-mag. star by Dimorphos and Didymos, observations organized by ACROSS in France by P. Tanga et al., 2023 Jan. 21.

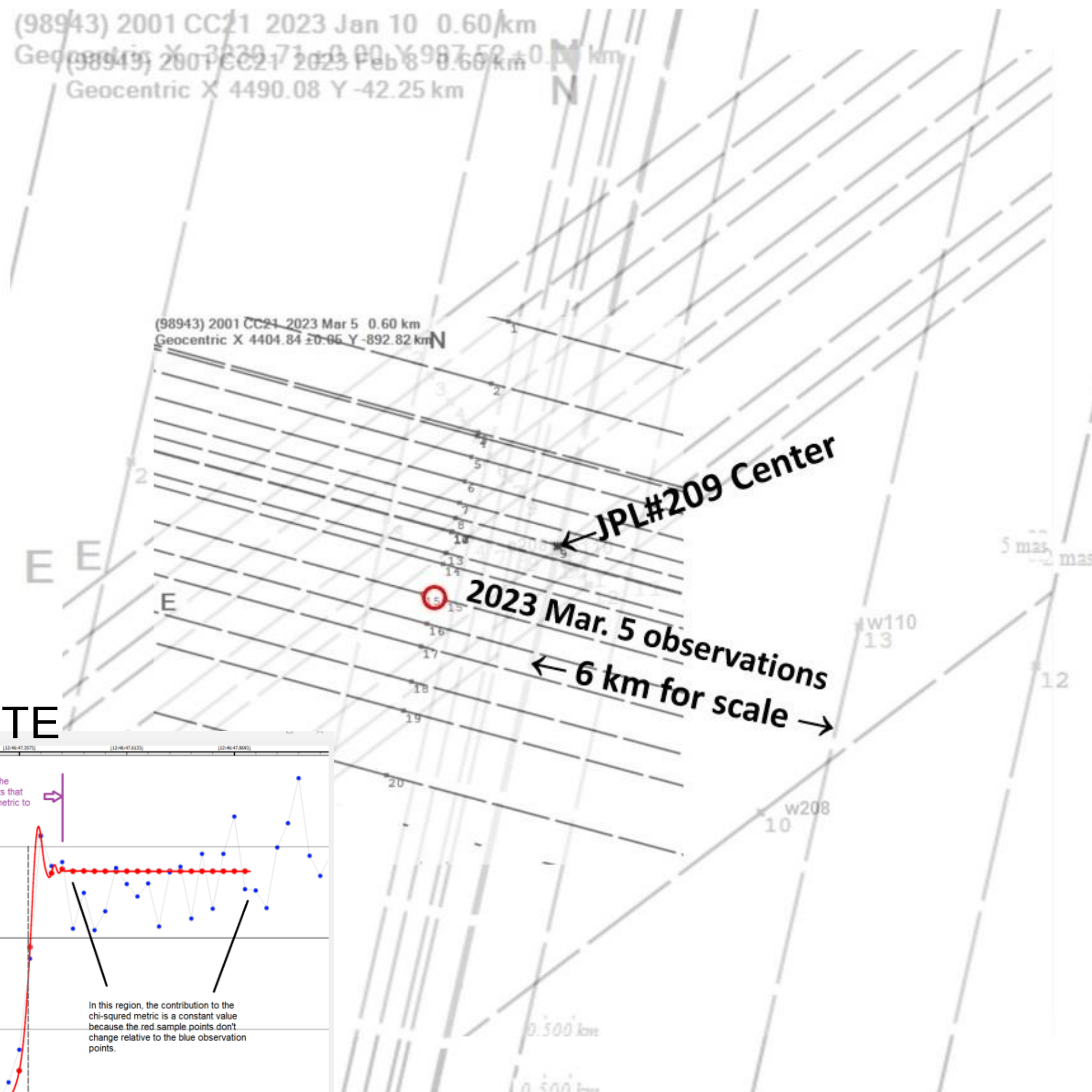
Far right: Lionel Rousselot's light curve of the 2023 Jan 21 Occ'n by Didymos and Dimor-phos near Perigueux, France



Several other Didymos occ'ns have been observed around the world; for more about results from them, especially on the orbits, see papers by Chesley (PDC 2023; ACM 2023); the poster by Tanga et al., "the ACROSS network"; and more ACROSS by Souami et al. (ACM 2023)

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

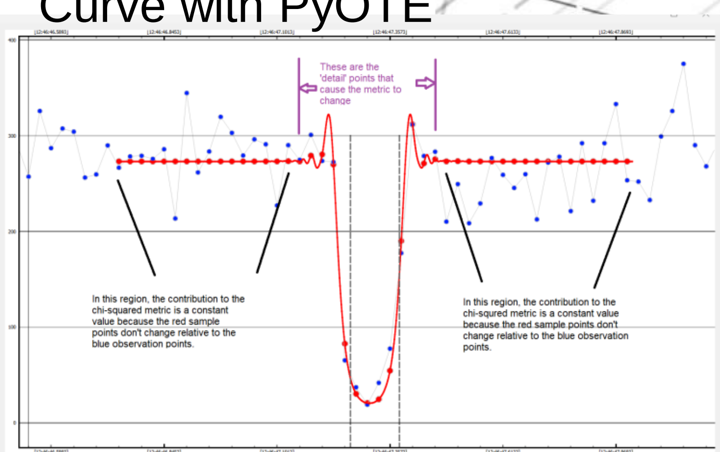
Sky Plane Plot for 2023 Mar 05 occultation observations in Japan with past observations



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

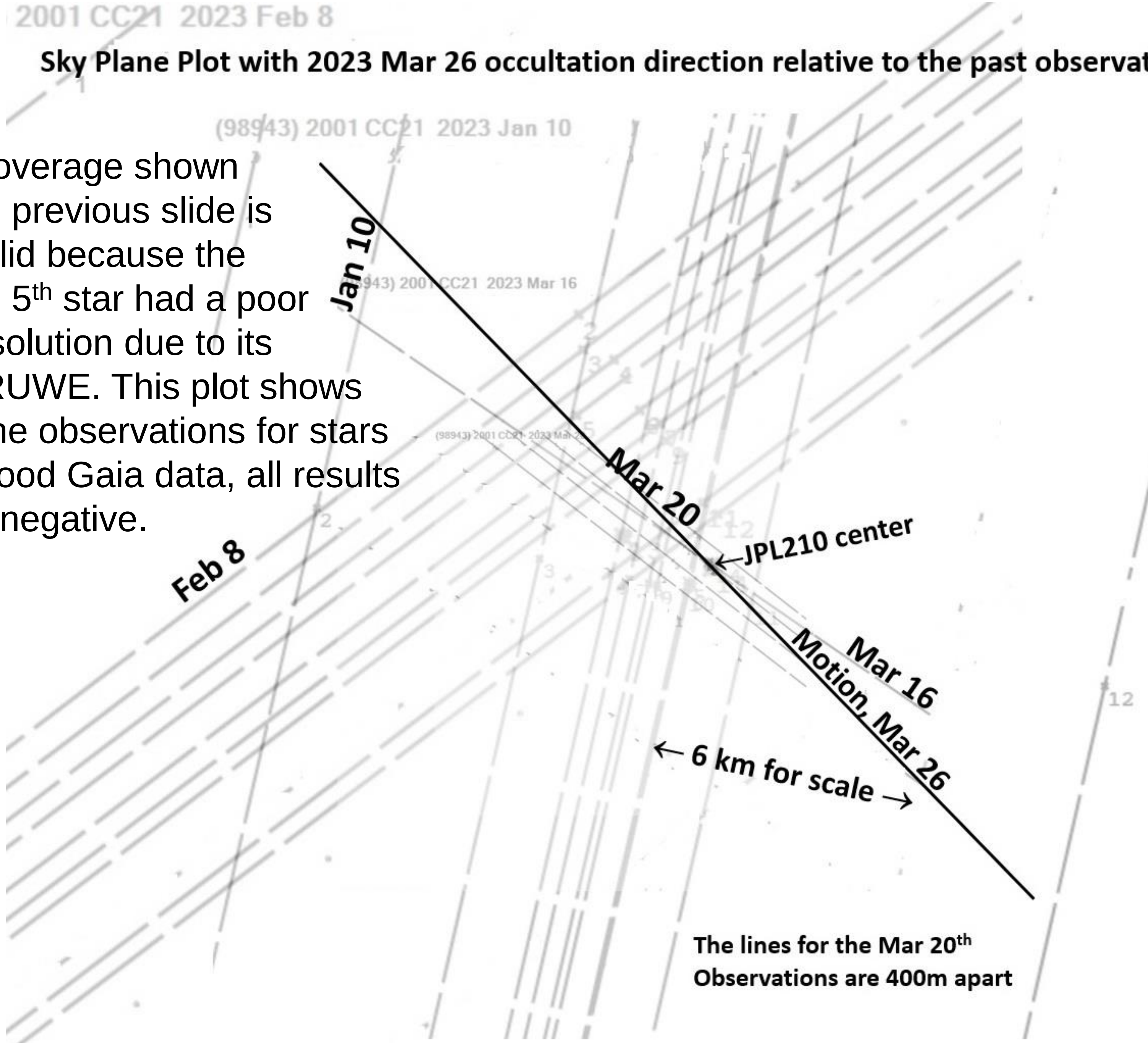
The red circle shows the location of 2001 CC21 according to Miyoshi Ida's observation on 2023 March 5, in a gap of the coverage by the earlier observa-tions.

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



Sky Plane Plot with 2023 Mar 26 occultation direction relative to the past observations

The coverage shown on the previous slide is not valid because the March 5th star had a poor Gaia solution due to its high RUWE. This plot shows only the observations for stars with good Gaia data, all results being negative.



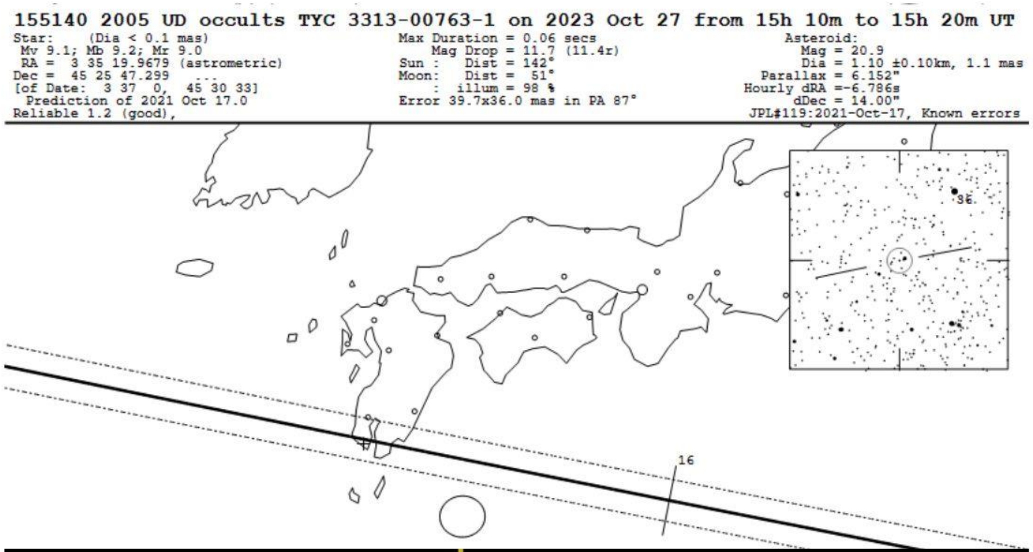
Stellar occultation observation of 2005UD

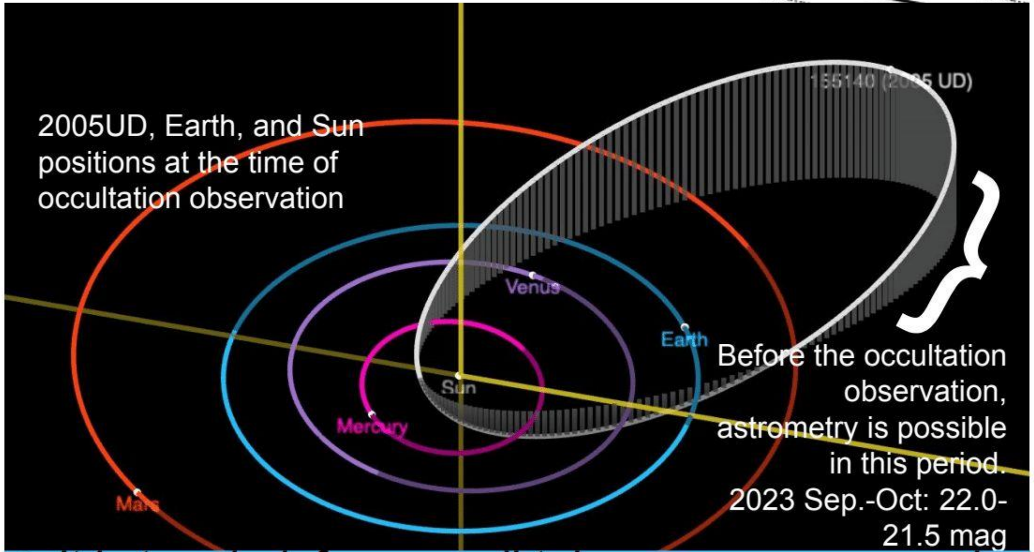
- As mentioned earlier, the occultation by Phaethon will continue to be observed, and in 2023 there will be a chance to observe a stellar occultation by 2005UD, which has a very similar orbit to Phaethon and is considered to be a break-up body from Phaethon.

- 2005UD is also a flyby candidate for the DESTINY+ extended mission after the Phaethon flyby.

- So far, we have only investigated observation opportunities in Japan, but we plan to investigate observation opportunities in other countries and announce an observation campaign. Before that, however, the orbital accuracy of this asteroid is still not good, and we need to perform astrometry observations before occultation observations to improve its orbital accuracy.

- We cannot perform flyby or occultation observations until we have narrowed down the orbital accuracy (error range of the occultation zone) to the same level as that of Phaethon.





- *It is too dark for a small telescope, so we need someone to help us with astrometry observations.*
- *Is there anyone?*

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 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.
- The occultation technique was successfully applied to Apophis, which is more than 10 times smaller than Phaethon, and Didymos/Dimorphos, 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 our PDC 2021 presentation 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 NEA occultations**: https://occultations.org/publications/rasc/2023/nam23NEAoccs.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**
- ACROSS (Asteroid Collaborative Research via Occultation Systematic Survey) **https://lagrange.oca.eu/fr/home-across**

Updated 2023 April 4