Occultation astrometry by 'not-so-amateur' astronomers

the DART mission

Astrometry from an occultation

- When an asteroid occults a star, the calculations are done on the 'Fundamental Plane'
- The positions of the observers on the Earth's surface for each event time are mapped to this plane
- As seen from the center of that shadow, the asteroid is perfectly aligned with the star
- The astrometry report is the RA/Dec of the star and the (x,y,z) coords of the shadow center
- The star position is from Gaia – so very accurate
- Accuracy greater than all other optical methods. ADES was modified to include factors not available in other methods – such as reporting the center of mass position for an asteroid

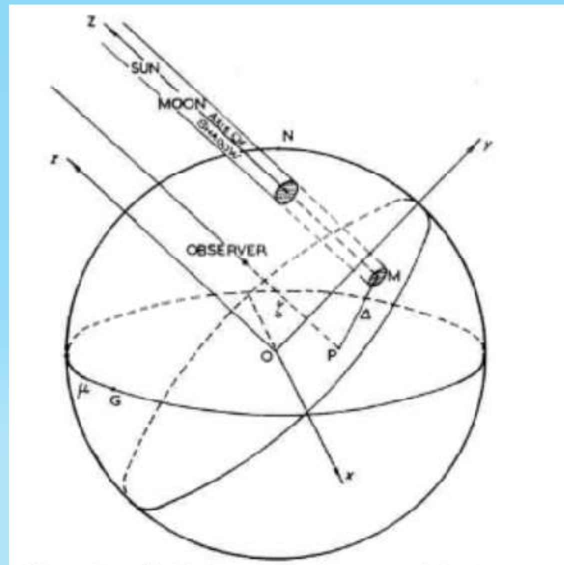

Figure 9.2. *Projection of the observer and shadow on the fundamental plane*
P Projection of observer (ξ, η)
M Projection of axis of shadow (x, y)

Astrometry reports
Occultation vs Optical CCD

Optical CCD

Residuals : 20221111 K74 0.1- 0.2+

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- <dec>11.79286</dec>
- <rmsRA>0.37</rmsRA>
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- <astCat>Gaia3E</astCat>
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Occultation

Residuals : 20221112 275 0.0   0.0

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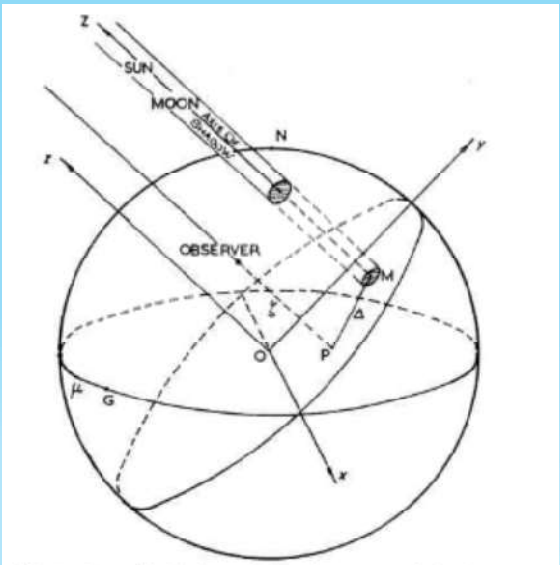

Figure 9.2. *Projection of the observer and shadow on the fundamental plane*
P   Projection of observer (ξ, η)
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DART

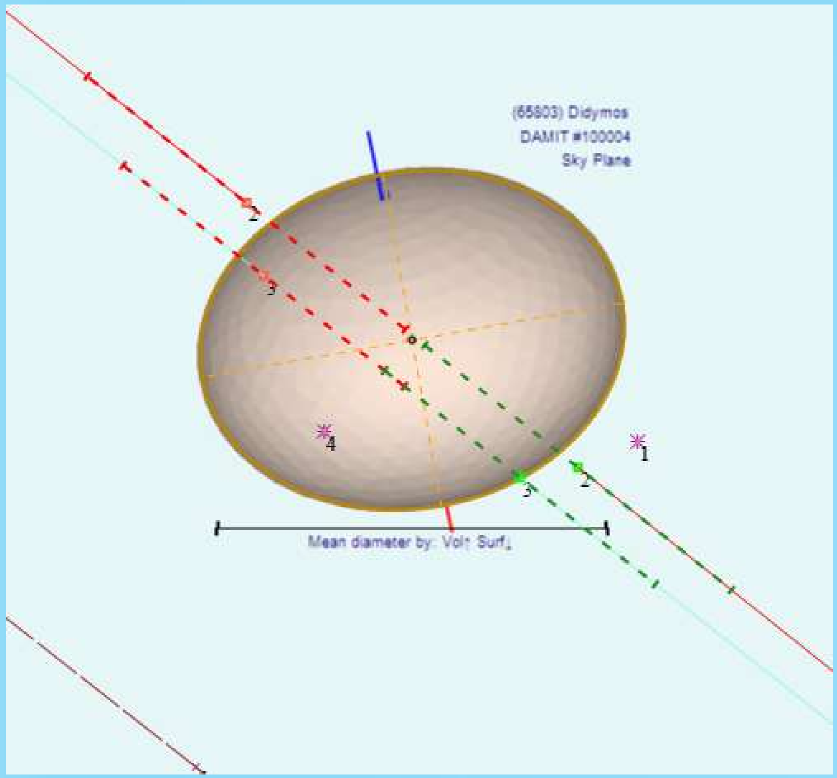
Double **A**steroid **R**edirection **T**est

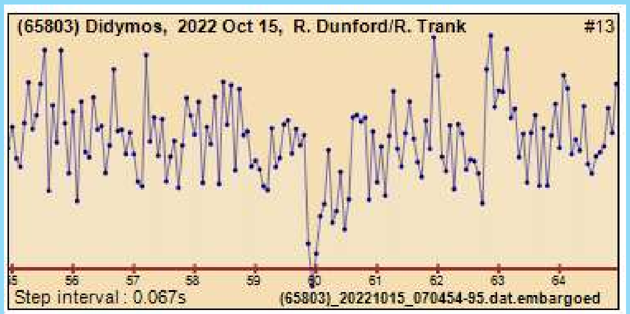
- Designed to test the ability to deflect an asteroid by hitting it.
- Target was the satellite of an asteroid. Didymos oblate spheroid axes 851 x 620 m. Dimorphos axes 160 x 120 m.
- Primary objective: impact Dimorphos, and measure the resulting change in its motion about Didymos
- Orbit of the satellite was such that it regularly underwent eclipses and occultations with the main body as seen from the Earth
- From light curves, the orbital period could be easily measured. It was reduced by 33 minutes, from 715 minutes. About a 5% change.
- *It was also anticipated the impact would change the heliocentric motion of the asteroid*

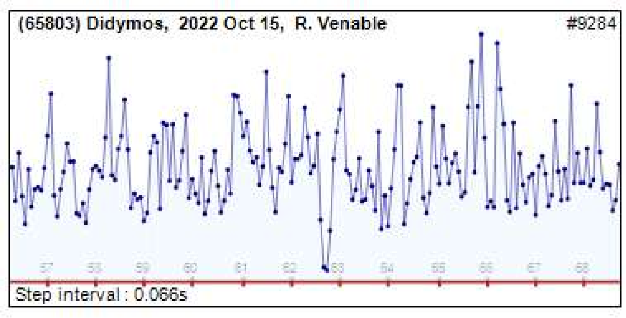
IOTA's involvement

- IOTA was asked to try to observe occultations. Aim was to get precise astrometry, to assist with sending the HERA spacecraft to Didymos. HERA is a follow-up mission from the ESA, with the objective of visiting Didymos to assess what the impact did.
- Request was followed up enthusiastically by IOTA members around the world
- European Space Agency apparently did not believe Occultations could provide accurate / useful results
- Orbit updates from the occultation astrometry were undertaken at JPL. Multiple updates, with many being made within a day or two of an event
- Astrometry was derived using OCCULT functionality
- At the start of 2024, the astrometry was indicating 'interesting' changes in the position of Didymos

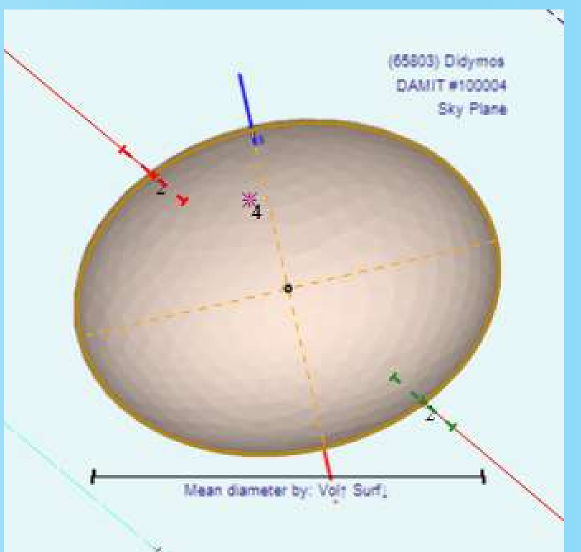
First occultation detection 2022 Oct 15

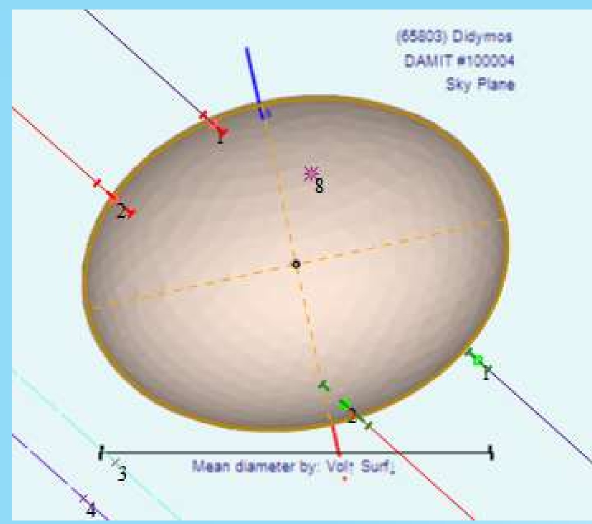




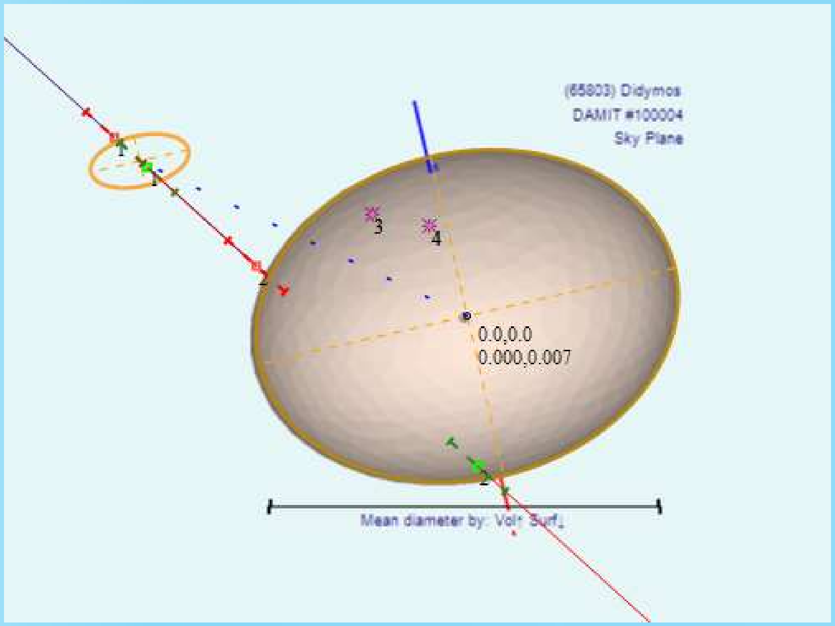


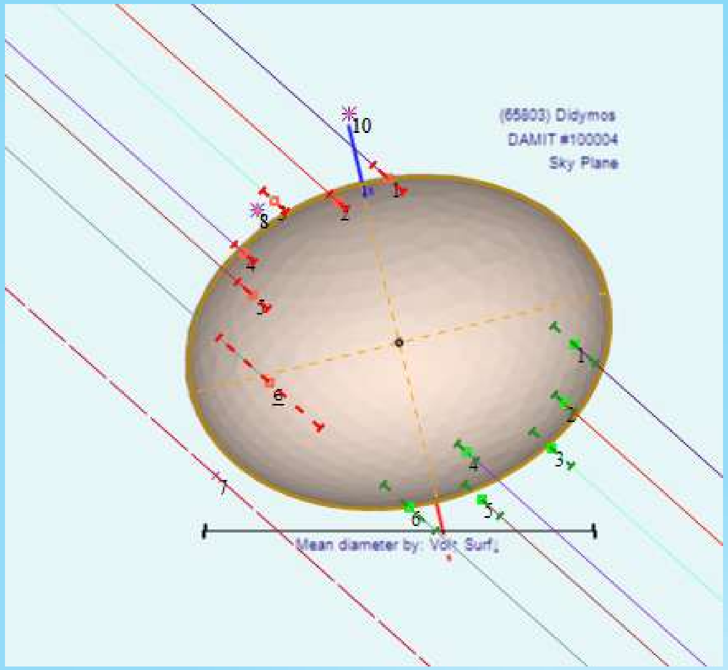
… followed by two on Oct 18 (EU & JP)

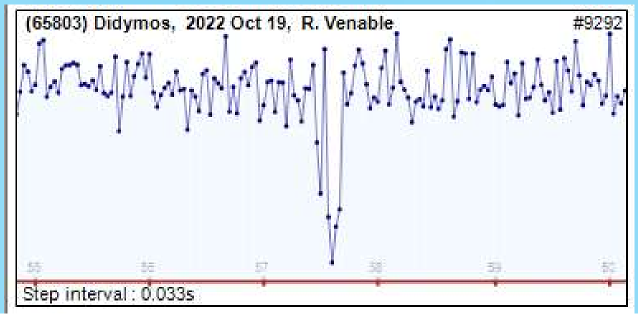




… and another two on Oct 19 (US & JP)



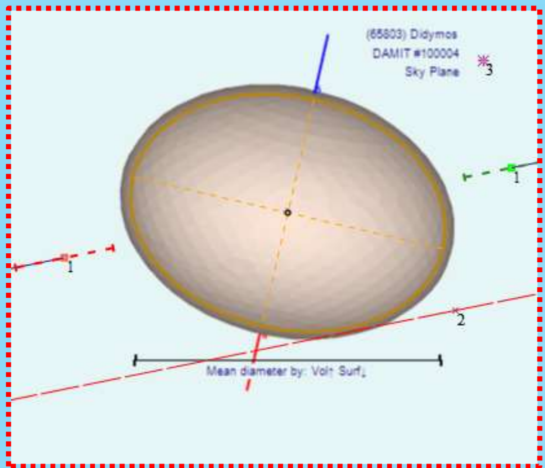


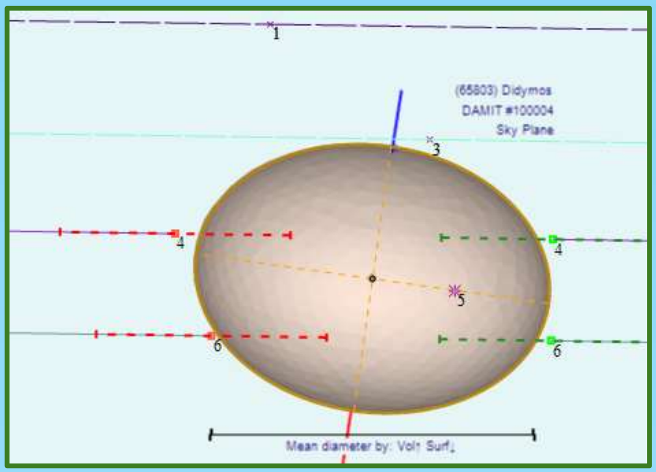


2024/5 events

2024 May 5 (AU)

Only one +'ve chord. First indication of unexpected motion. Thoroughly investigated



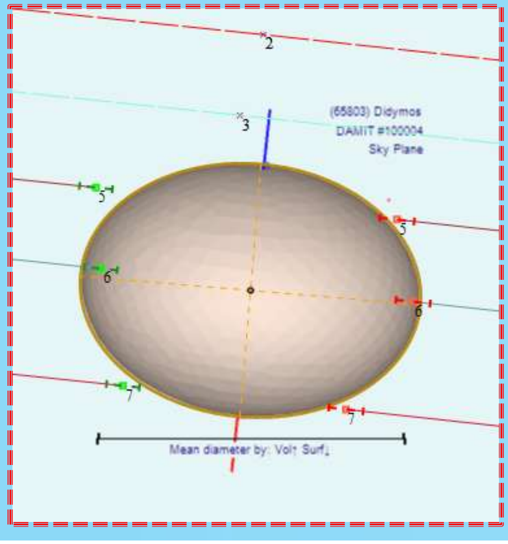


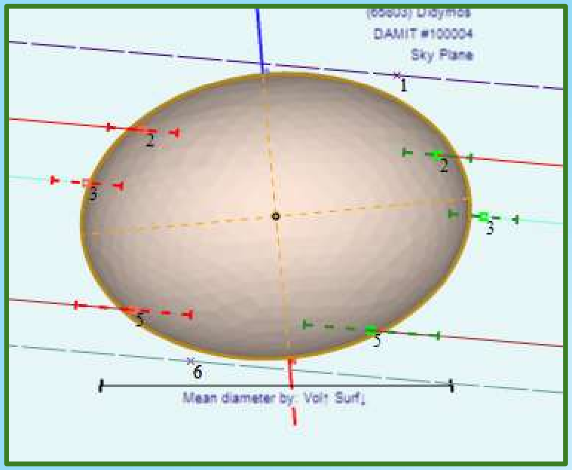
2024 Sep 22 (US)

2024 Sep 22 (AU)

Excellent observation. However the position couldn't be reconciled with the other observations

Thoroughly investigated. Over several months. No cause found.

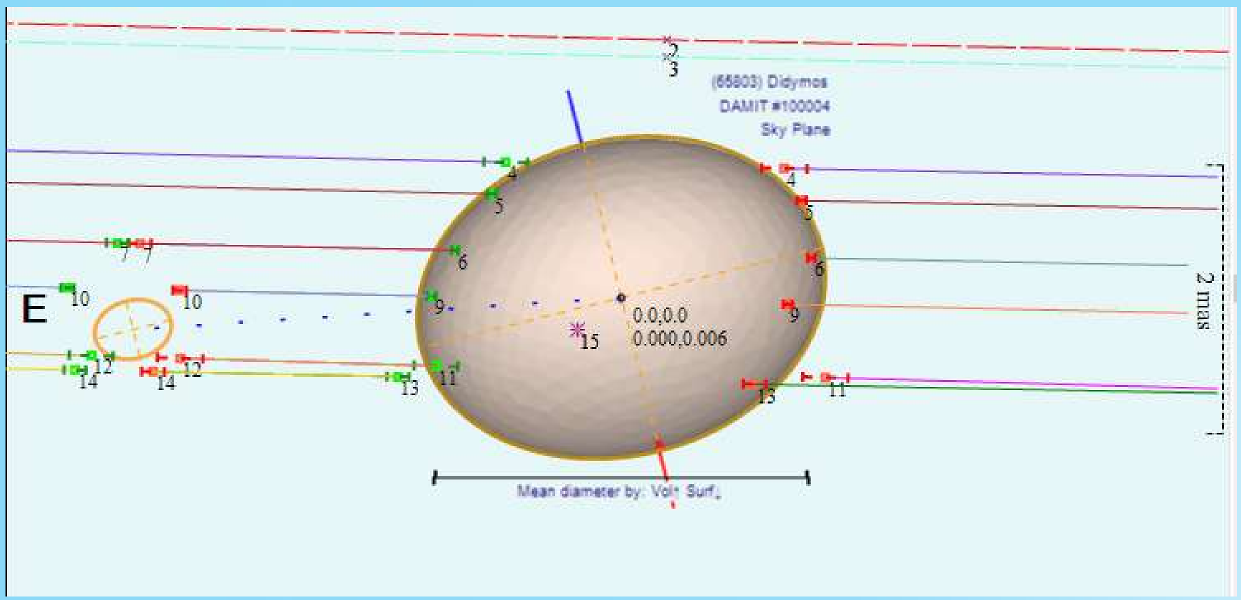




2025 Mar 11 (JP)

The best Didymos event
2023 Jan 21, Europe

- Dimorphos clearly detected. Chords that physically missed Dimorphos had dips because of Fresnel diffraction by a small body



Astrometry for Didymos

As of 2025 May 1

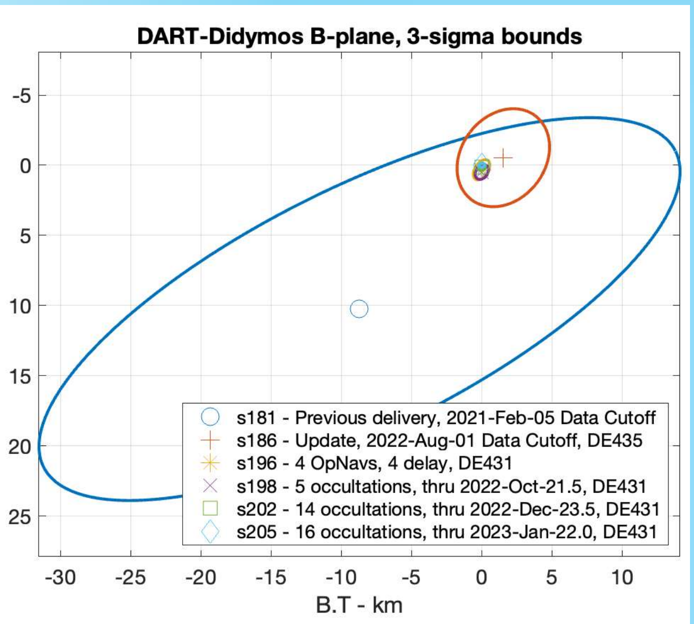
- 5955 ground-based Right Ascension/Declination measurements
- 22 stellar occultation measurements
- 3 optical navigation measurements from the DART spacecraft during approach
- 9 ground-based radar delay measurements

Orbit fit to Occultation astrometry

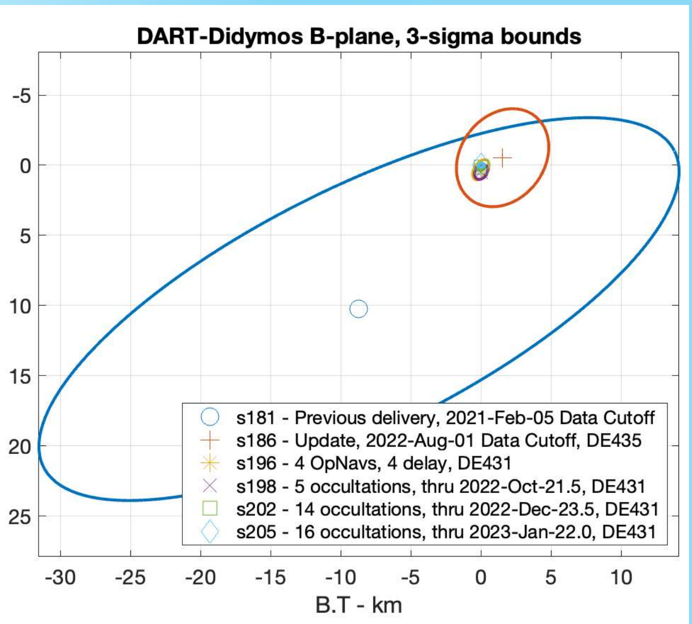
Most residuals < 1.5 mas

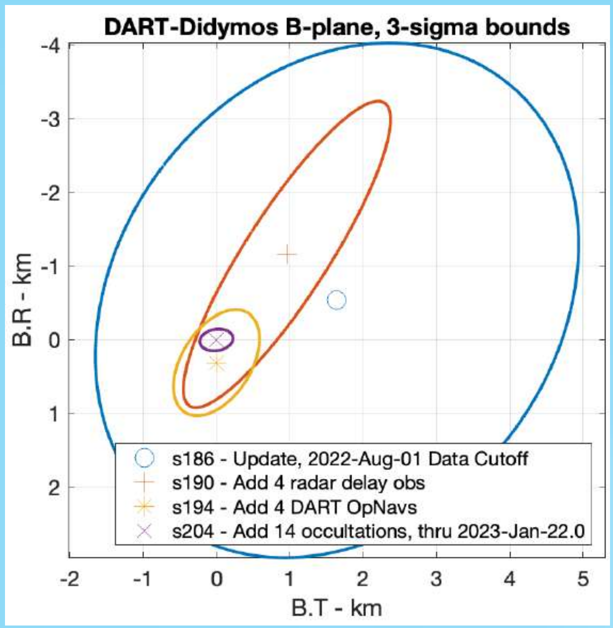
Time [UTC]	α [deg]	δ [deg]	σ_α [mas]	σ_δ [mas]	Δ_α [mas]	Δ_δ [mas]	WRSS
2022-10-15 07:03:31.42	97.1041455	-11.0346223	6.2	6.0	1.6	0.0	0.3
2022-10-18 01:17:38.09	101.5510585	-7.5427614	3.5	4.2	1.5	-1.6	0.4
2022-10-18 17:56:52.70	102.5657452	-6.7124245	1.9	2.1	2.2	-1.2	1.2
2022-10-19 08:19:57.53	103.4219904	-6.0093145	3.6	4.1	-2.0	-2.6	1.8
2022-10-19 17:02:14.52	103.9292382	-5.5934691	0.7	0.6	0.3	-0.1	0.5
2022-10-21 11:35:38.56	106.2559304	-3.6321584	4.1	4.4	1.0	0.8	0.4
2022-10-26 06:48:48.50	111.6241512	1.0639910	1.2	1.2	-1.2	-1.1	1.3
2022-10-27 09:47:04.85	112.6897403	2.0416663	1.7	1.8	1.5	0.7	1.5
2022-10-27 19:07:02.46	113.0441130	2.3712576	1.8	1.9	0.3	1.0	0.6
2022-11-12 10:08:27.04	122.8098608	12.5080567	1.4	1.2	0.2	0.2	0.3
2022-11-14 10:51:24.79	123.5309687	13.5150630	2.7	1.9	-1.3	1.2	0.6
2022-11-15 08:50:22.17	123.8426617	13.9522922	1.0	1.1	0.2	-0.1	0.2
2022-12-17 17:50:13.62	121.9657045	26.1740939	0.9	0.8	0.0	-1.1	1.5
2022-12-19 10:31:06.53	121.3261161	26.6496702	1.4	1.6	0.1	0.6	0.5
2022-12-23 11:27:00.02	119.6945635	27.6902112	1.2	1.6	1.1	1.6	1.0
2023-01-18 06:43:02.36	109.8460358	30.8253237	1.4	0.8	0.2	-0.6	0.7
2023-01-21 23:29:17.42	109.0118486	30.8469606	0.3	0.2	-0.1	0.0	0.3
2024-05-05 15:13:09.38	285.2062425	-23.1264033	0.2	0.3	0.1	-0.5	1.8
2024-09-22 02:22:35.36	269.6924187	-29.2163833	0.6	0.4	0.2	0.4	0.9
2025-03-11 12:35:52.01	77.5835568	26.5572911	0.2	0.1	-0.1	-0.0	0.4

Orbit solutions for Didymos

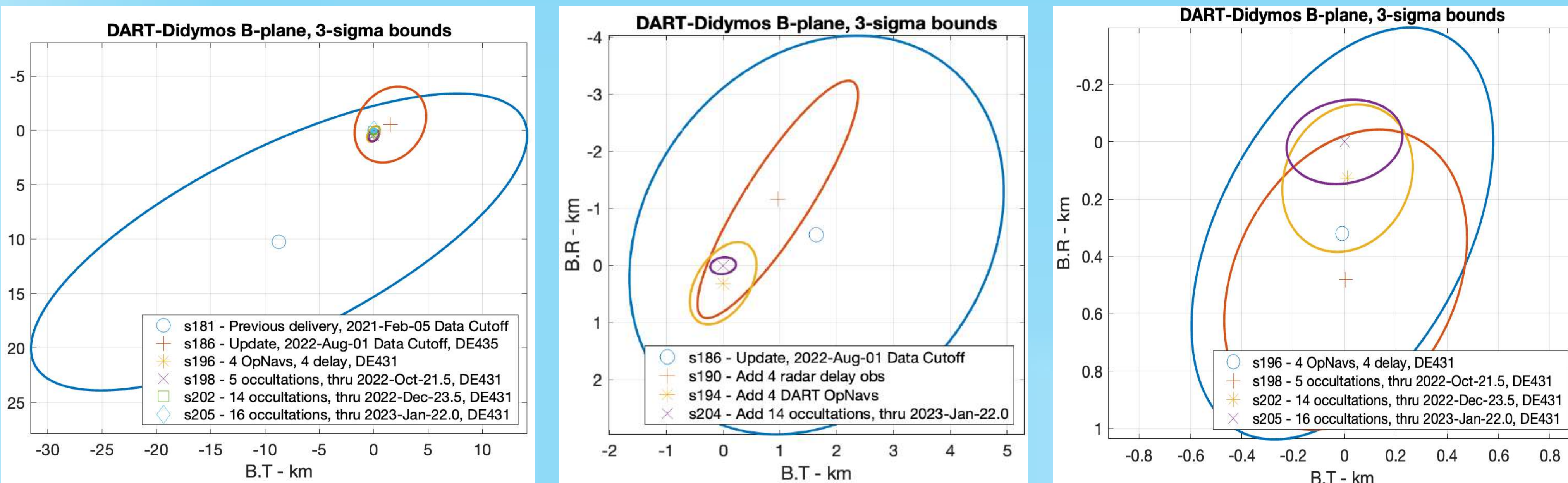


Orbit solutions for Didymos





Orbit solutions for Didymos



β_d β_s ρ_1 ρ_2 M_1 M_2 Δv_d Δv_s

What has been learnt ?

In Summary

First-ever measurement of a human-caused change in an asteroid's heliocentric orbit, as a result of:

- ***Occultation*** astrometry – which has extremely high precision. A precision greater than can be achieved by *any* on-Earth fixed observatory
- using portable telescopes having apertures generally between 20 and 35 cm

relying on the efforts of a world-wide collection of highly committed 'not-so-amateur' astronomers, to go out into 'the middle of no-where' and observe the necessary stellar occultations.