Leveraging Gaia Data for Deep Space Navigation

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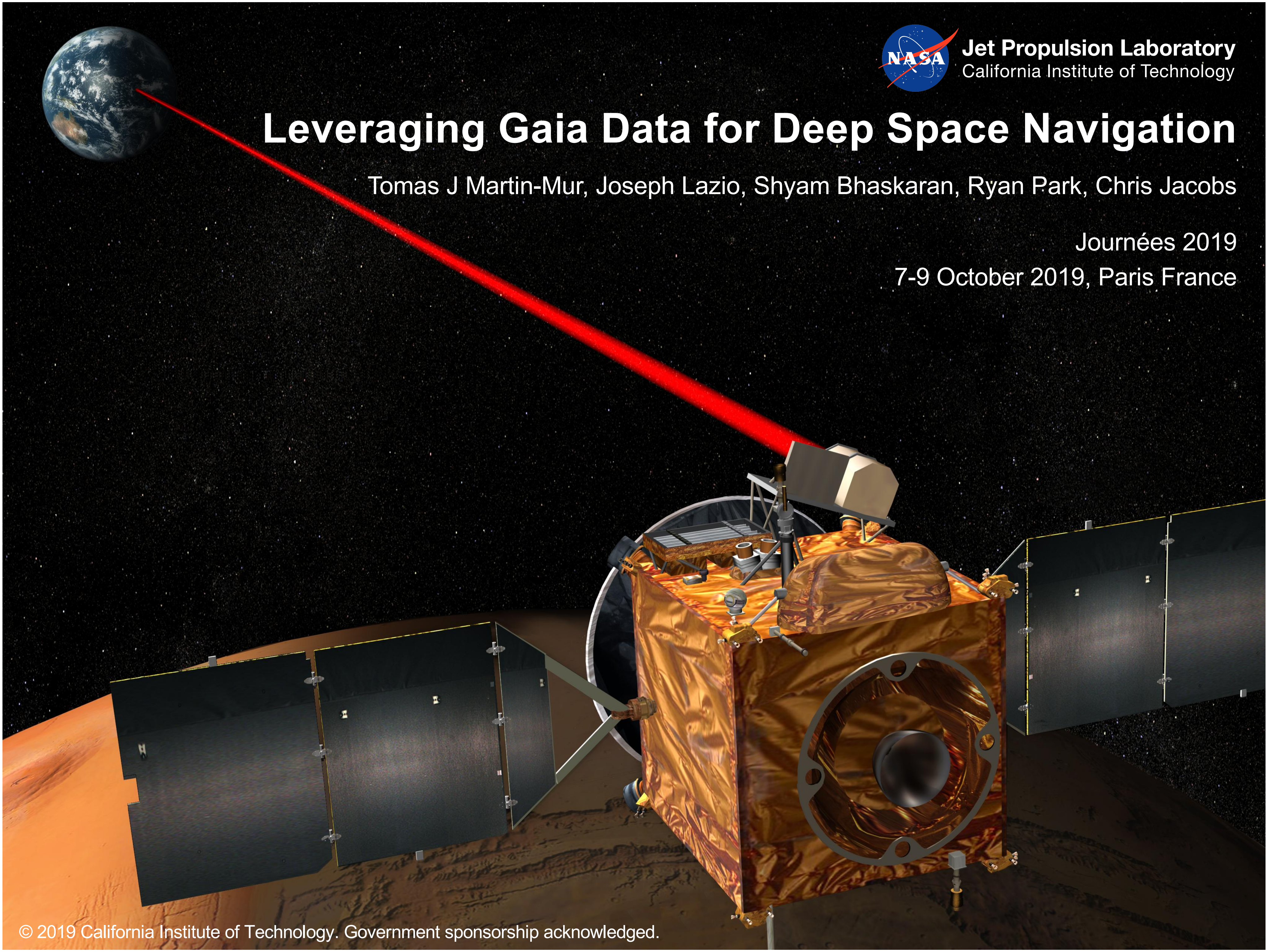


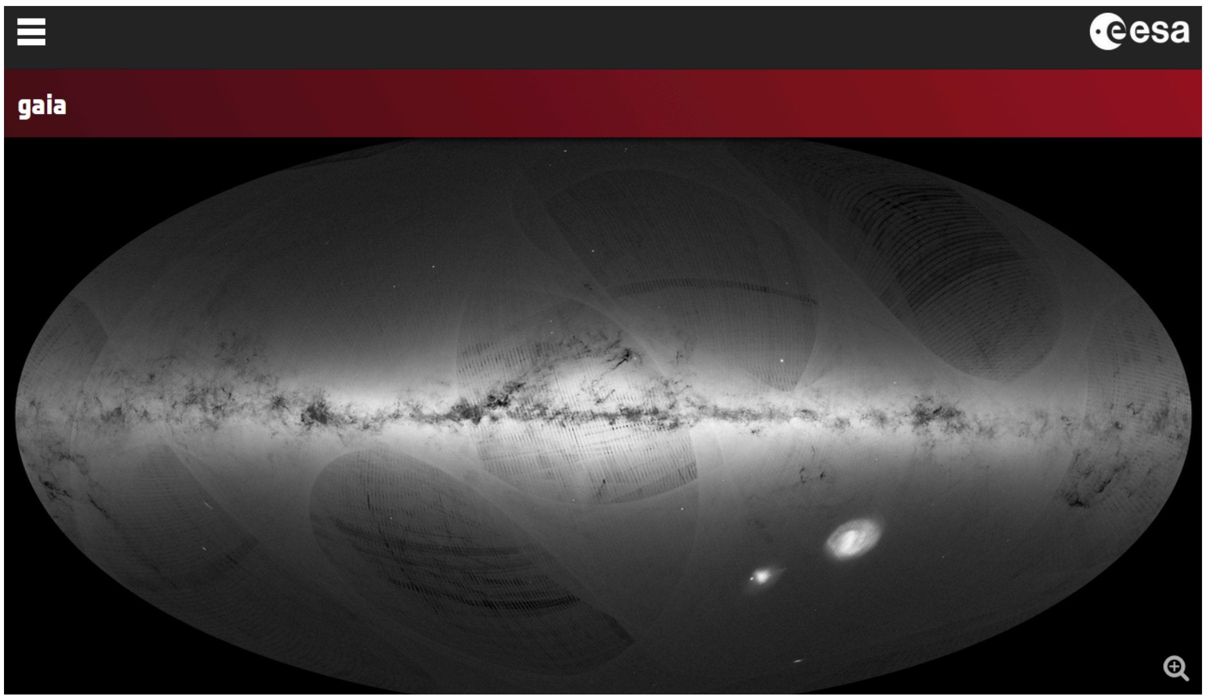
Introduction

- Current use of star catalogs for deep space navigation:
  - Attitude determination using star trackers – not discussed in this presentation
  - Optical navigation using on-board cameras

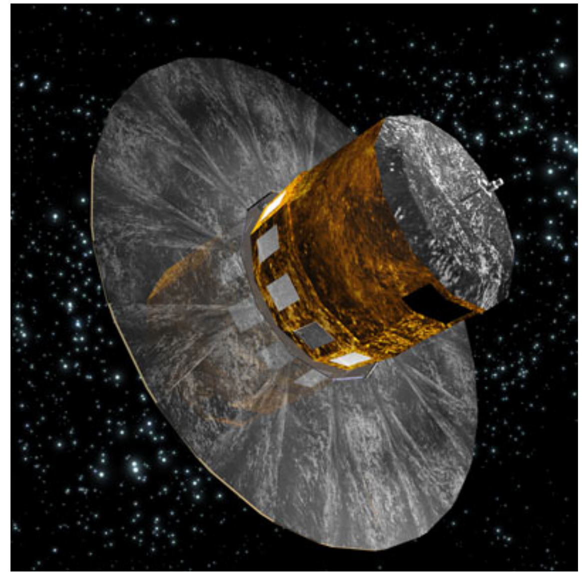
- In the future: astrometry of deep-space spacecraft carrying laser communications equipment

Opportunity: ESA's Gaia Star Catalog

Will provide reference star positions than could be used to perform spacecraft astrometry at a level comparable to that possible with VLBI



Gaia sources
Image courtesy: ESA



The Gaia spacecraft
Image courtesy: ESA

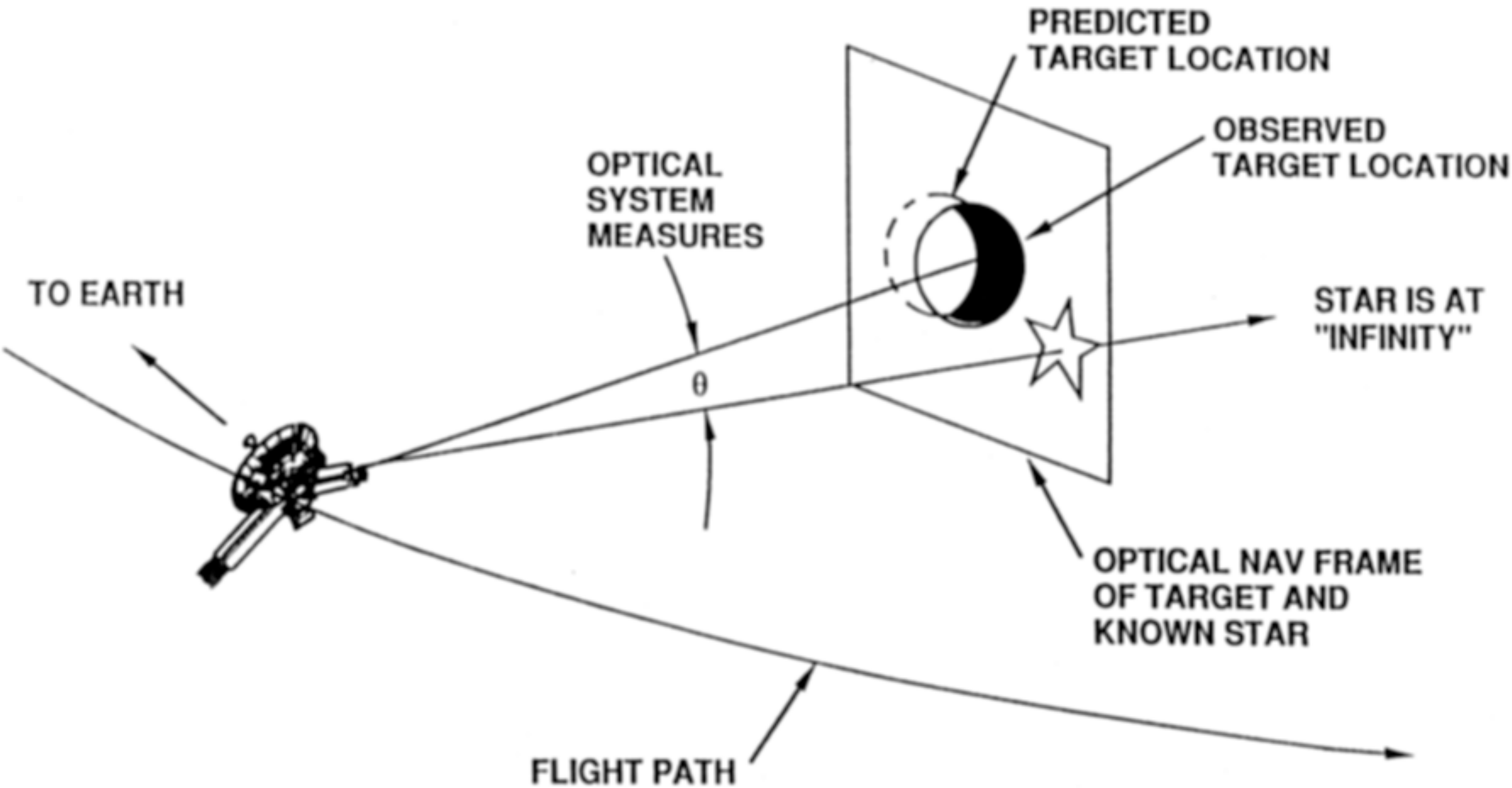
~37 million stars down to 15^m, accurate to 0.12 nrad

>1 billion stars down to 20^m, accurate to 2 nrad

550,00 quasars

Mignard et al, Gaia DR2:
The Celestial Reference Frame,
A&A, 616, 2018.

Spacecraft On-Board Optical Navigation



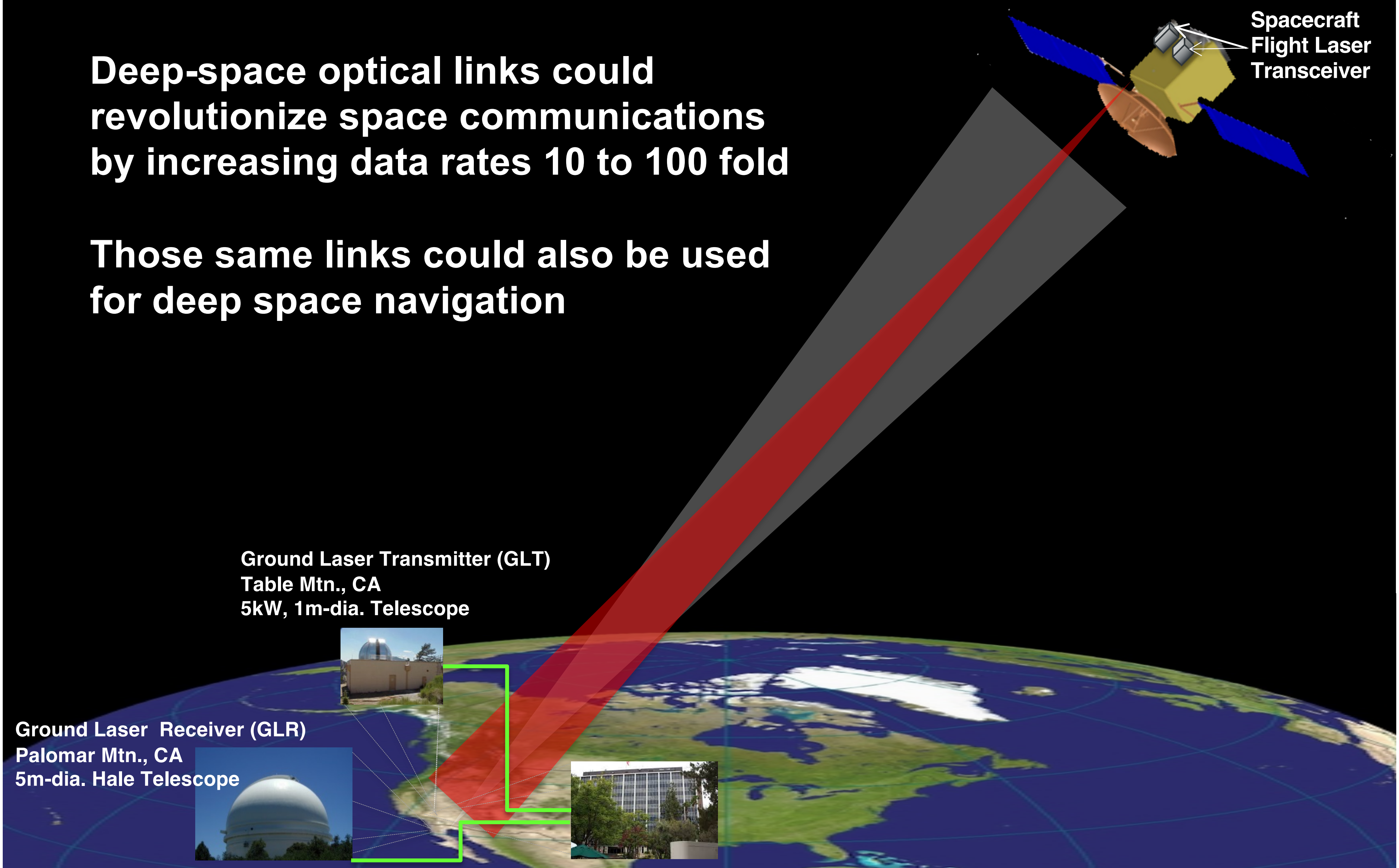
On-Board Optical Navigation with Gaia Data

- On-board optical imaging uses small apertures and its accuracy is limited by pixel size, so existing cameras would not be able to benefit from accuracy improvements for sources already in pre-Gaia star catalogs.
- Gaia will provide better determined (and additional) solar system objects to use as targets, since Gaia also determines the orbits of asteroids and satellites, and will also provide a denser set of star sources.
- In the future, we could use a smaller field of view or a higher resolution detector to image fainter solar system targets and stars, now known with better accuracy.
  – Cassini NAC: 6 μrad/pixel
  – New Horizons LORRI: 5 μrad/pixel
  – Possible using Gaia: 1 μrad/pixel or better

Opportunity: Optical Communications Systems

Deep-space optical links could revolutionize space communications by increasing data rates 10 to 100 fold

Those same links could also be used for deep space navigation

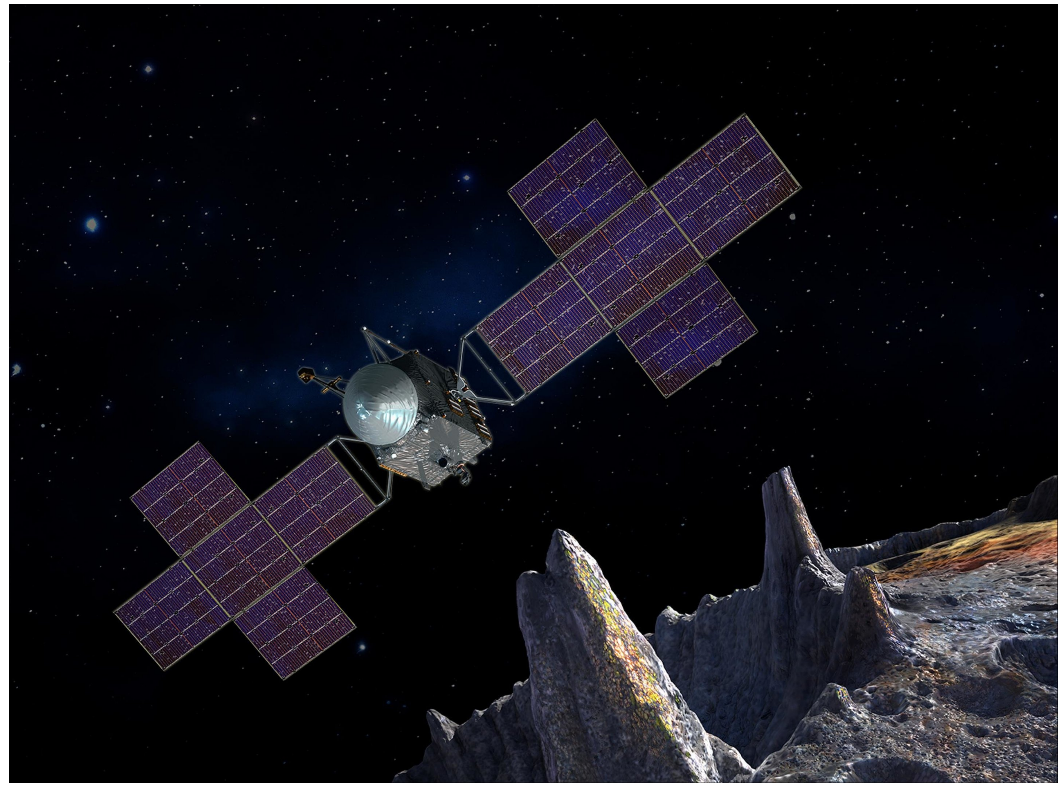


https://www.nasa.gov/directorates/spacetech/tdm/feature/Deep_Space_Communications

DSOC on Psyche

- A Deep Space Optical Communications (DSOC) terminal will be carried as a demonstration by NASA's Psyche mission, launching on 2022.

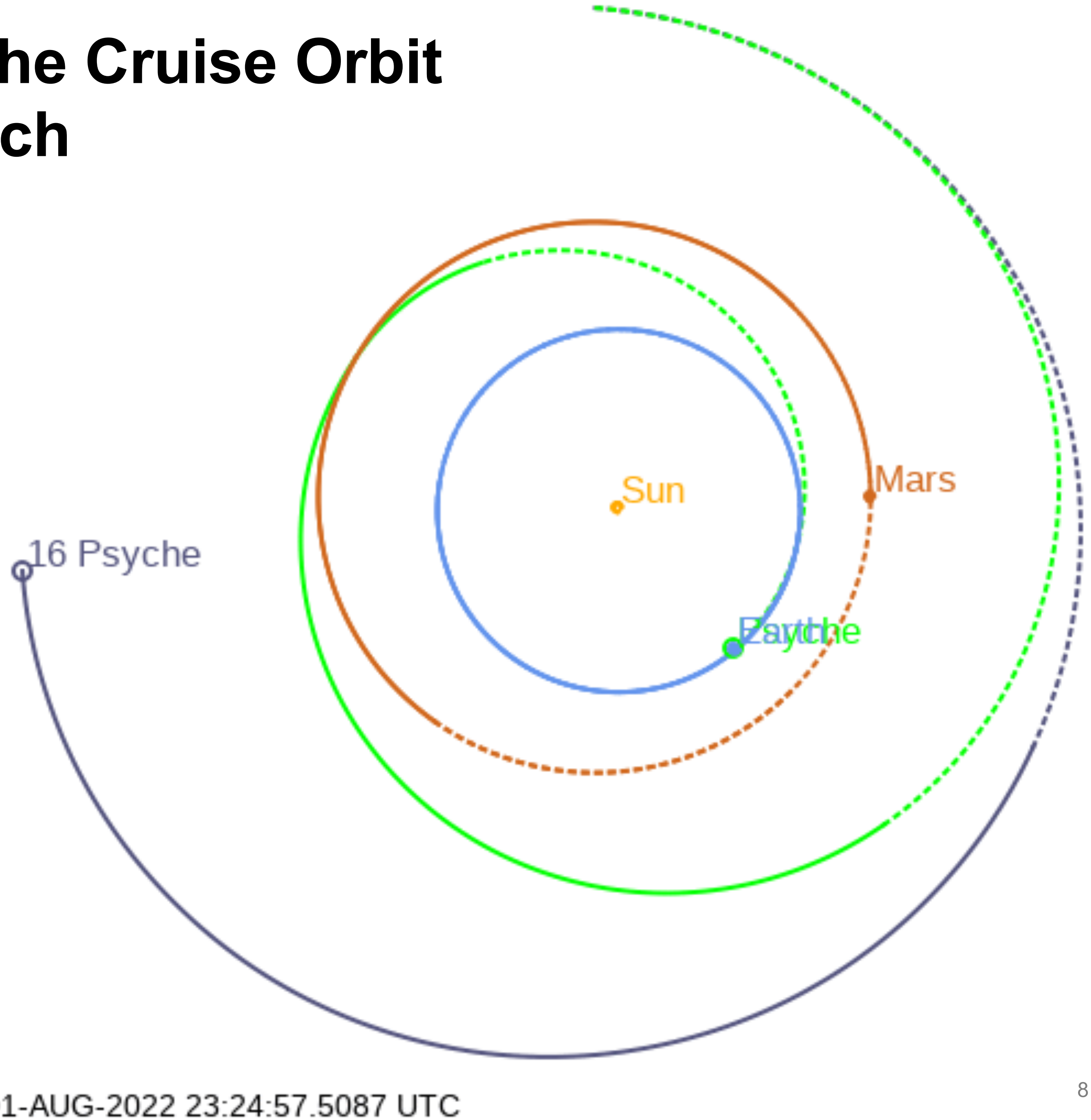
- Optical communication tests will be performed over distances between 0.1 and 2.5 AU.



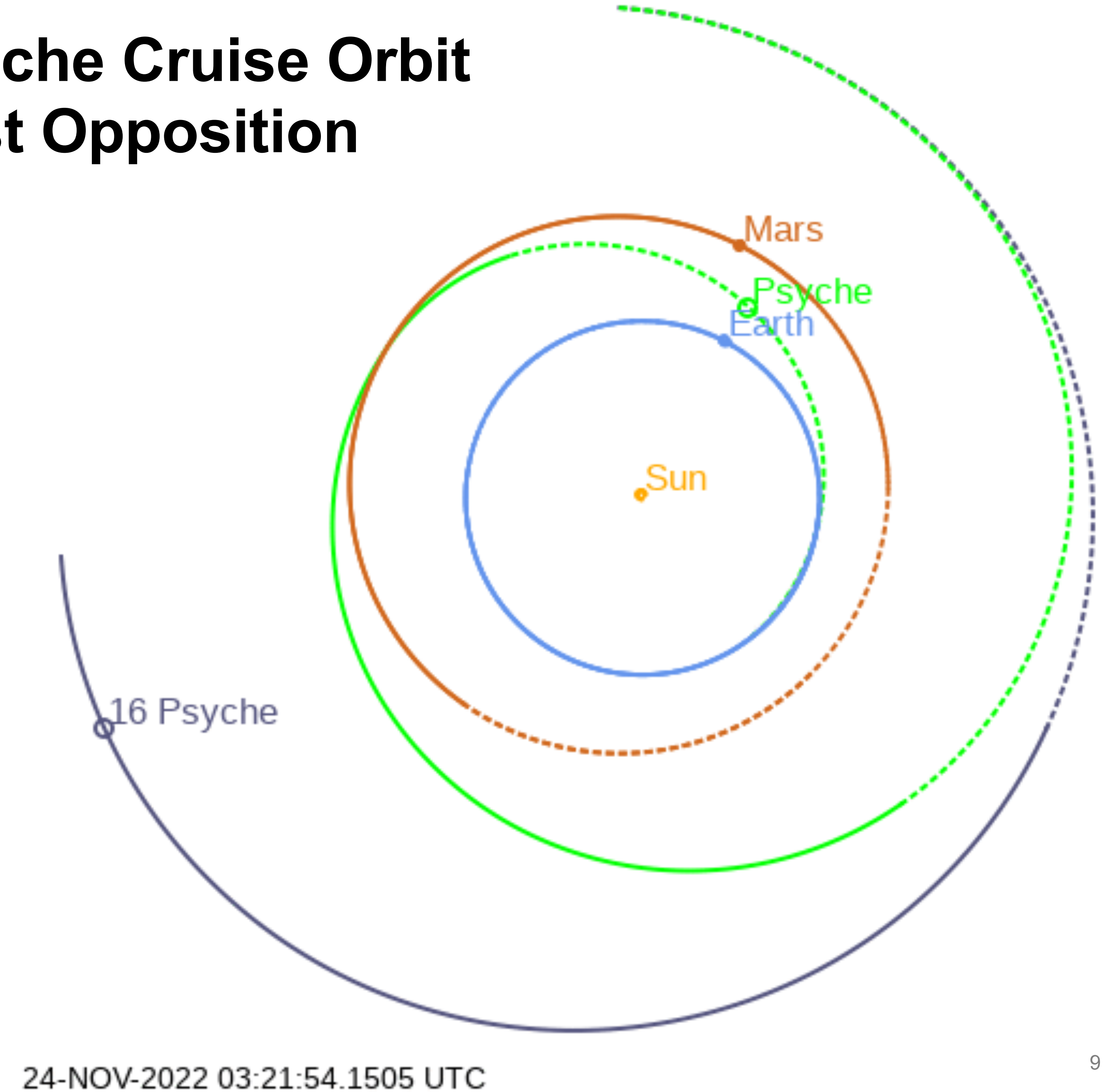
Credit: SSL/ASU/P. Rubin/NASA/JPL-Caltech

https://www.nasa.gov/directorates/spacetech/tdm/feature/Deep_Space_Communications

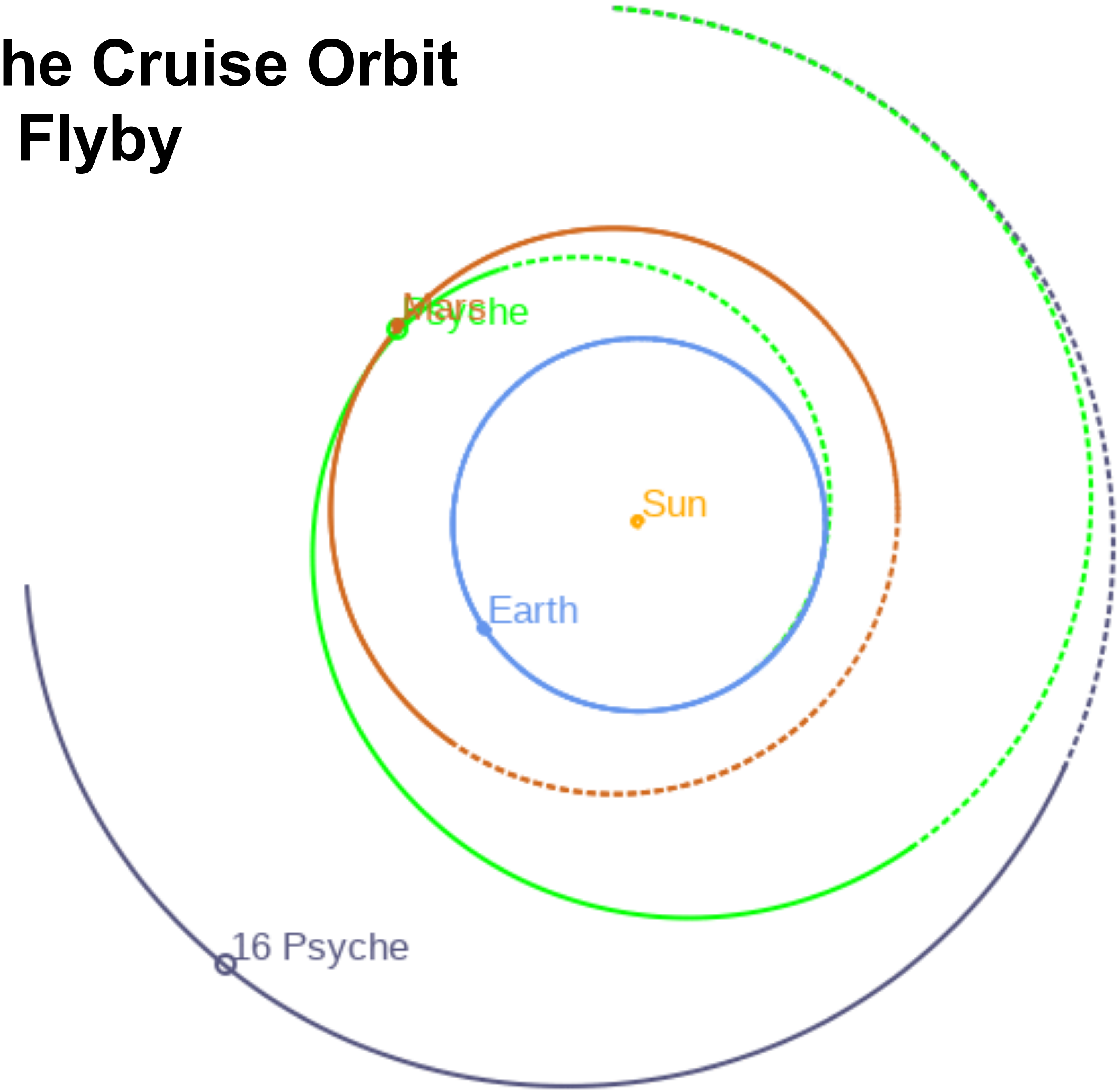
Psyche Cruise Orbit
Launch



Psyche Cruise Orbit
First Opposition

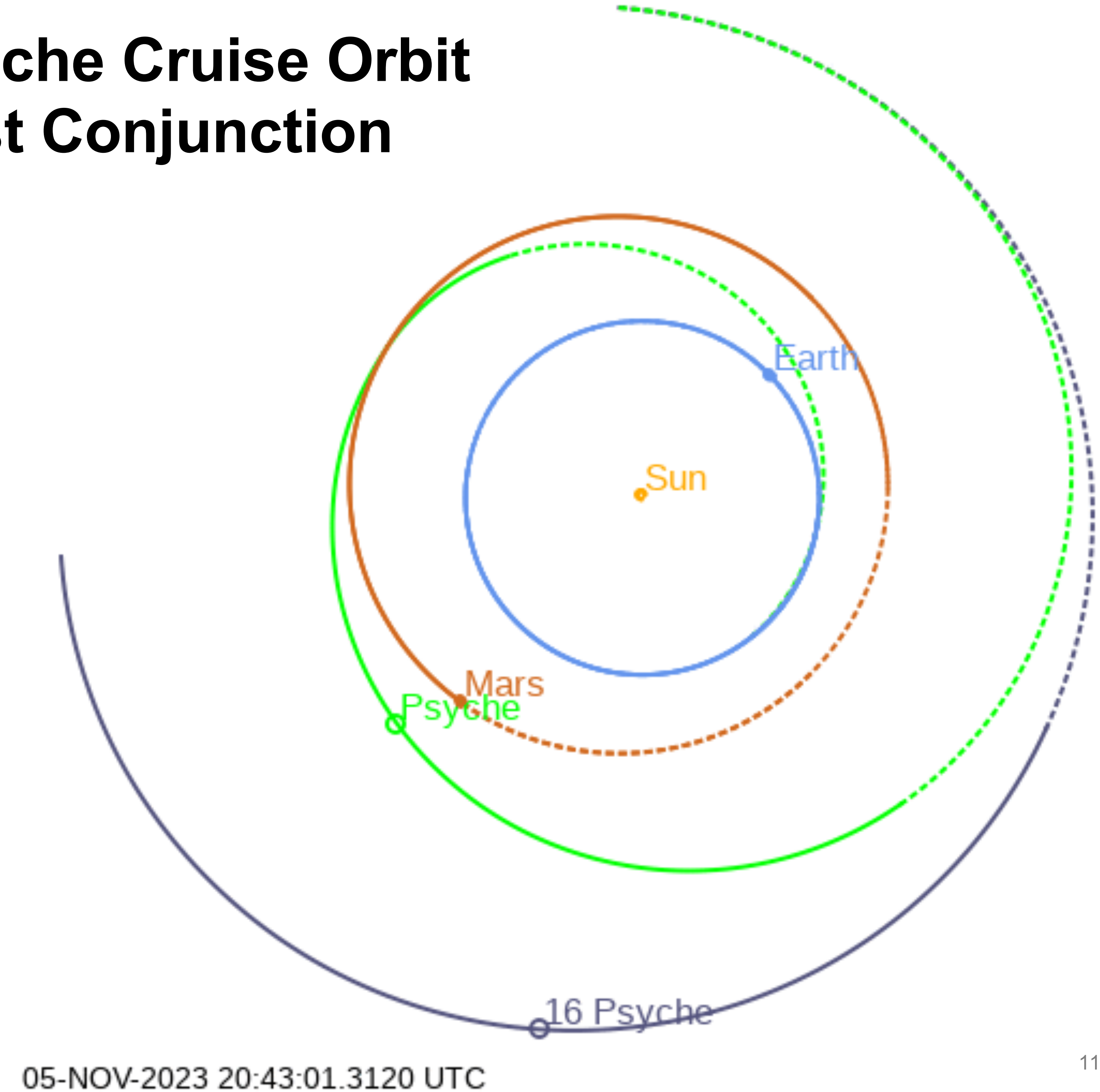


Psyche Cruise Orbit
Mars Flyby

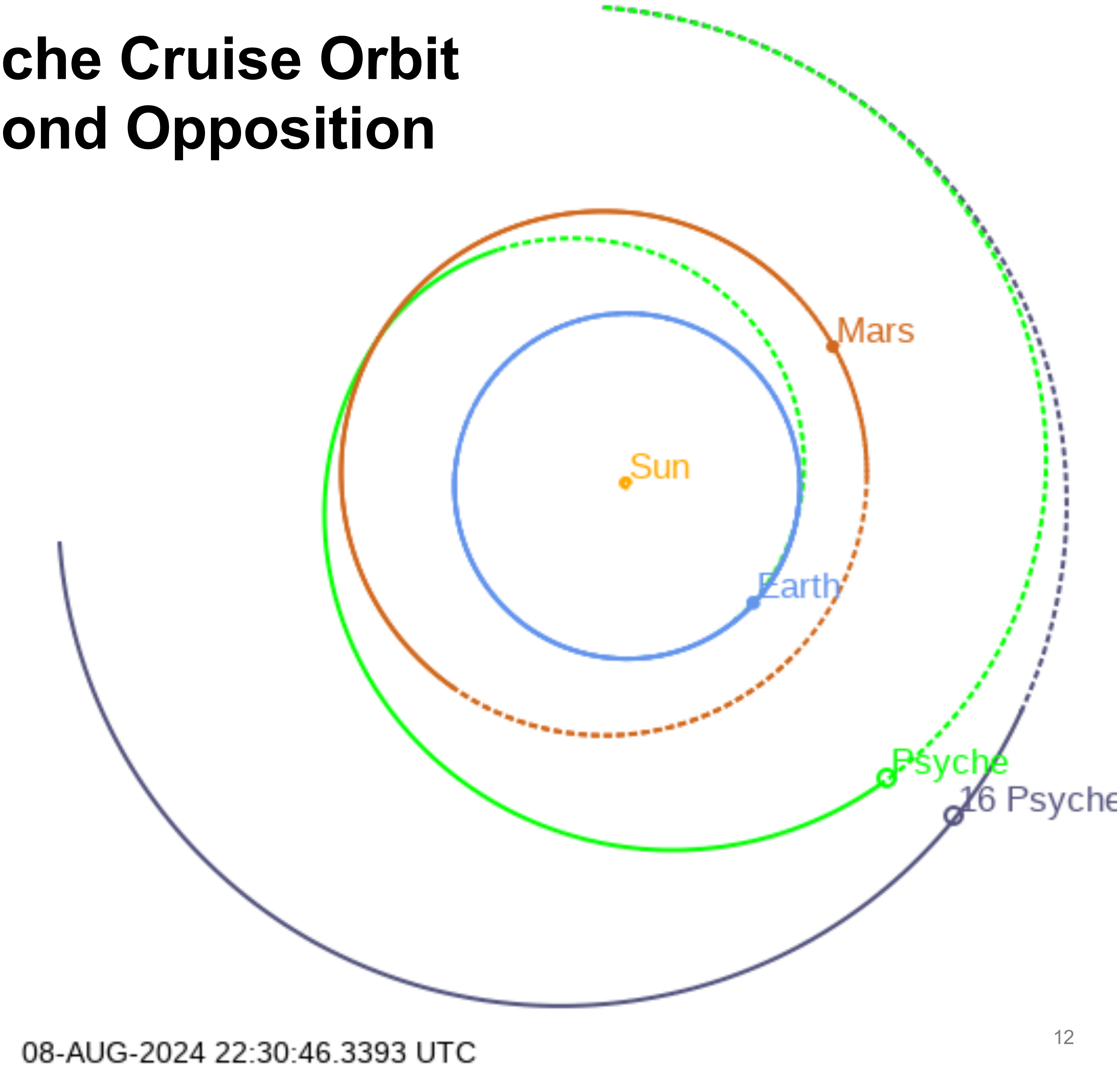


25-APR-2023 20:26:08.1987 UTC

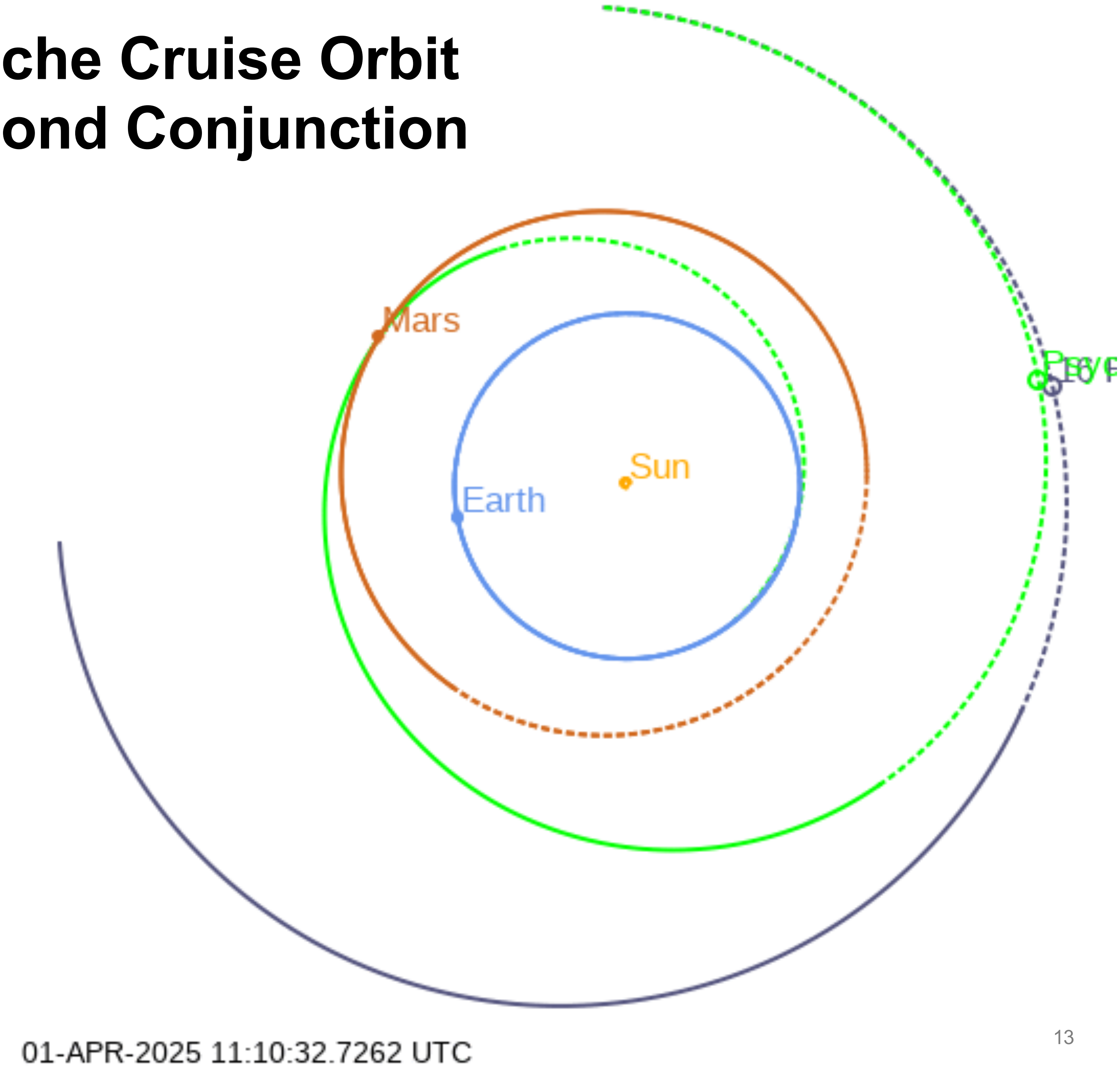
Psyche Cruise Orbit
First Conjunction



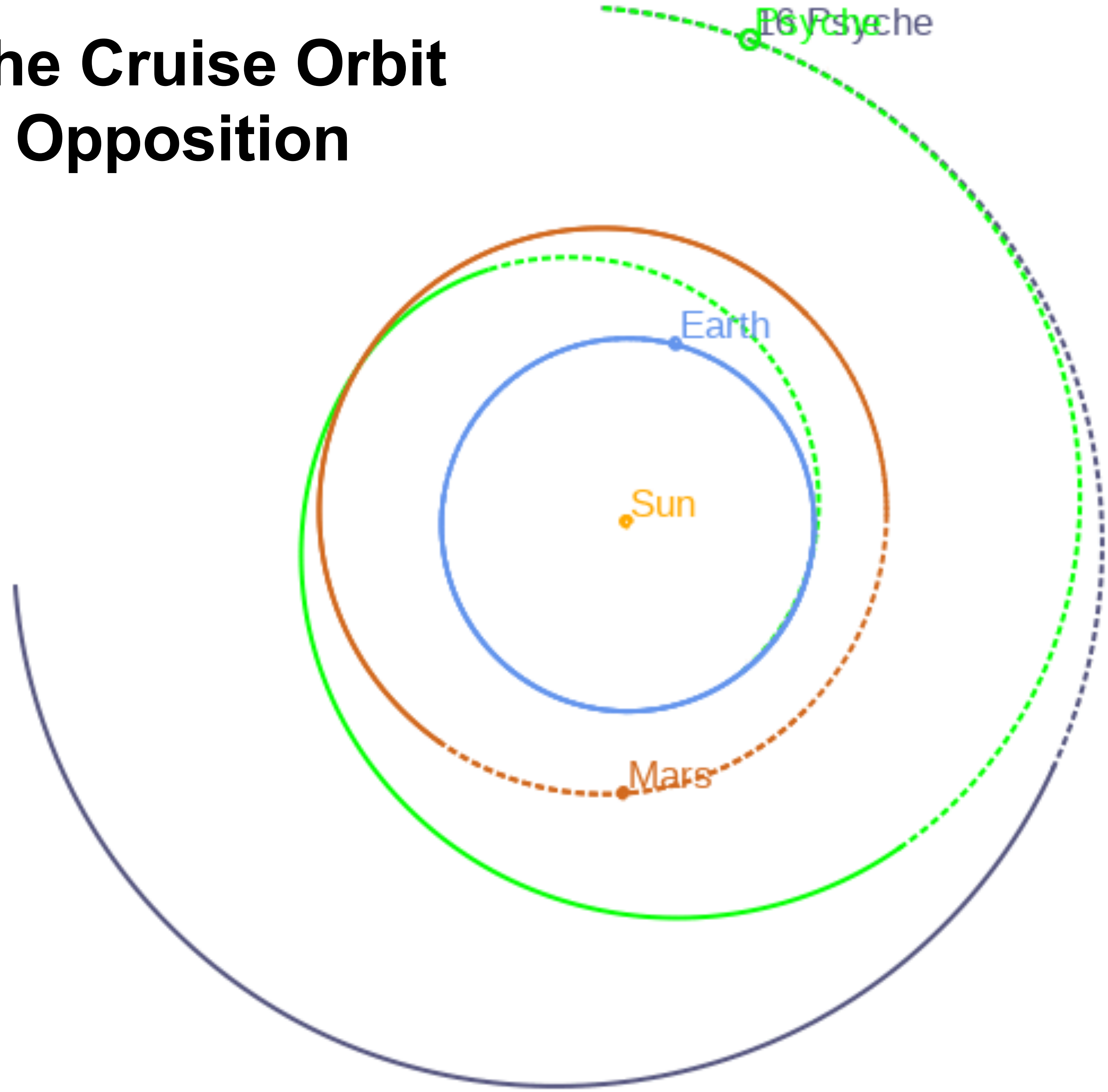
Psyche Cruise Orbit
Second Opposition



Psyche Cruise Orbit
Second Conjunction



Psyche Cruise Orbit
Third Opposition



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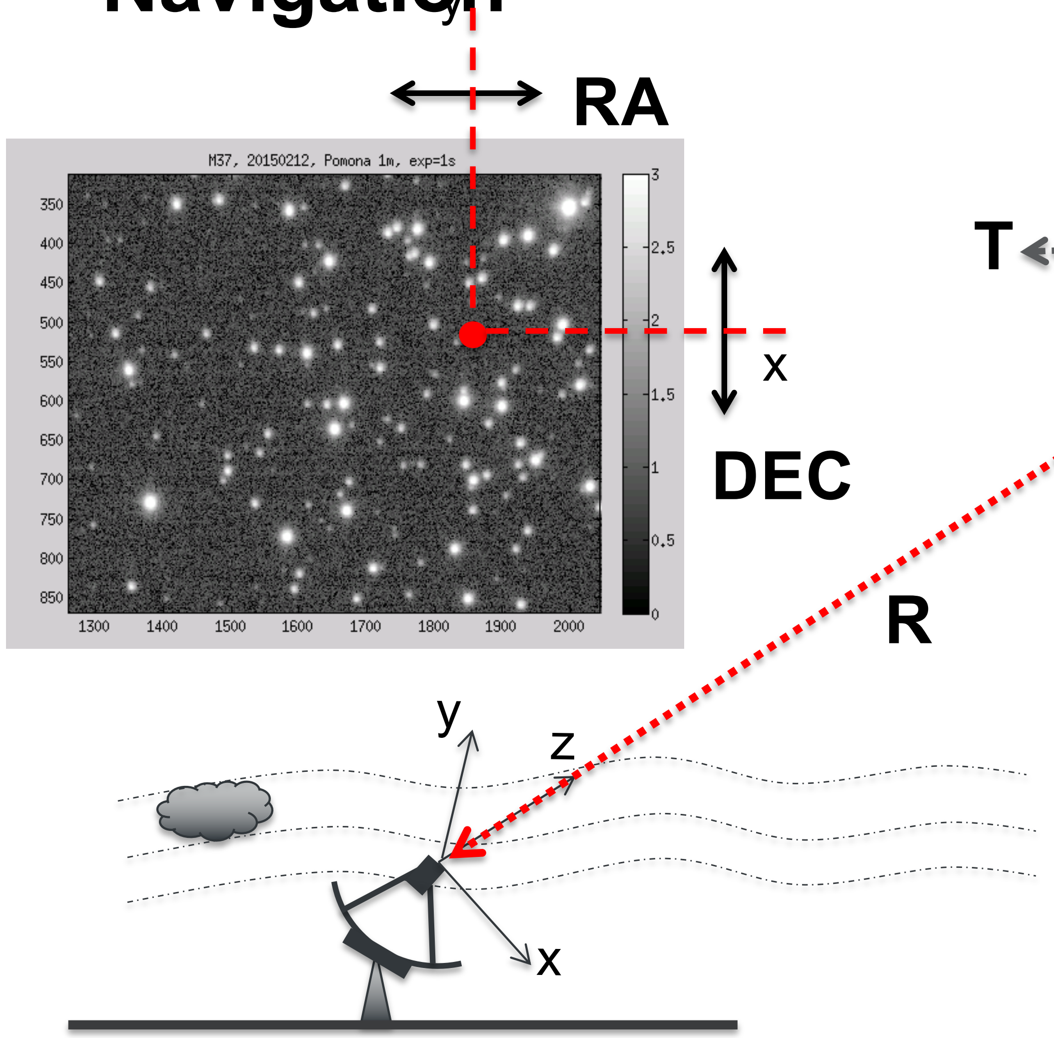
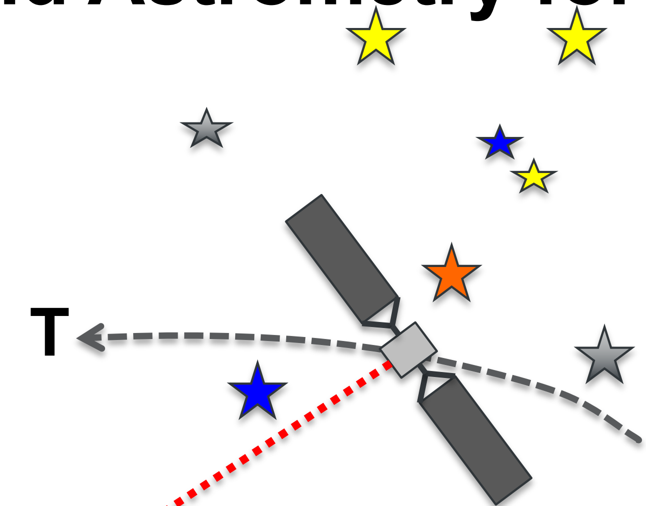
Ground Optimetrics and Astrometry for Navigation





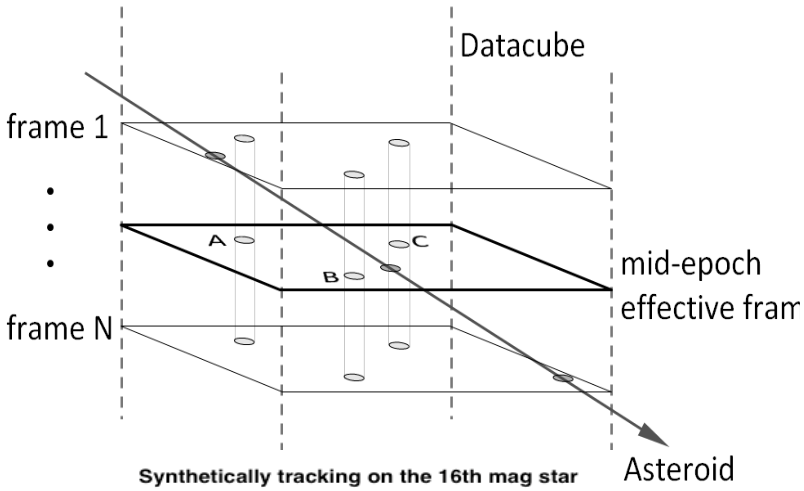
- **Spacecraft position components relative to telescope can be measured optically:**
  - **LOS Range (R) and Doppler (D)**
  - **POS Astrometry (RA, DEC)**
- **Background star locations req'd for pointing knowledge and frame tie**
- **Measurements processed on-board or on-ground to determine trajectory**

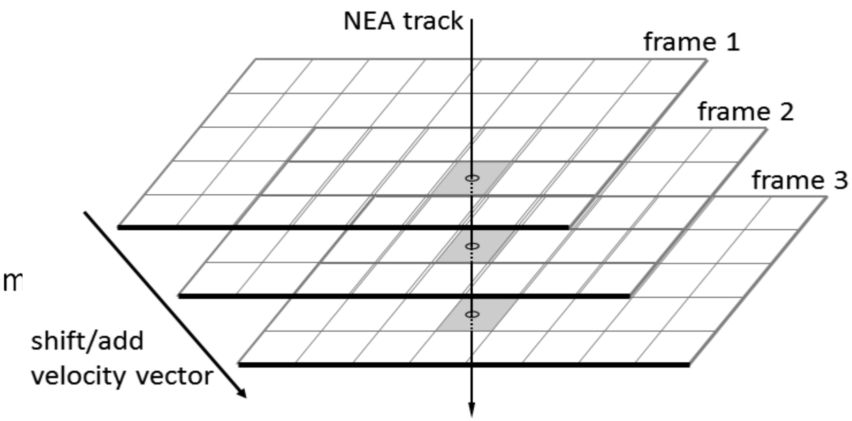
(x, y) define plane-of-sky (POS)
z defines line-of-sight (LOS)

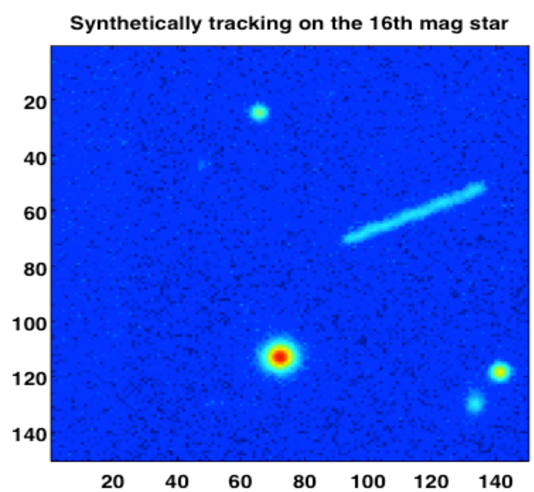
Credit: Chengxing Zhai

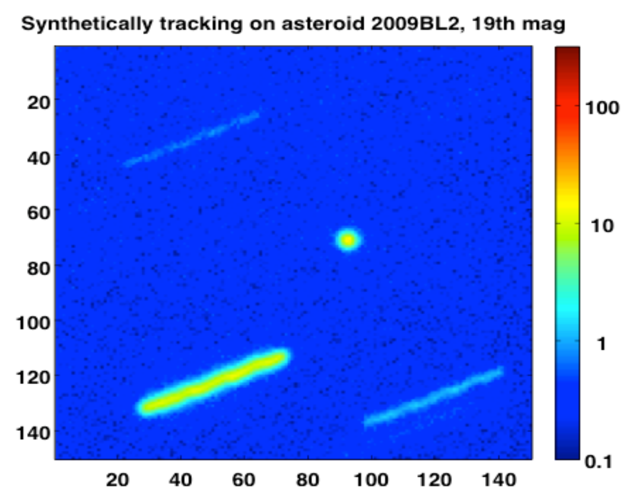
Synthetic Aperture Tracking

Both back ground stars and moving objects can be tracked, so no streaked images are used for centroid estimation.





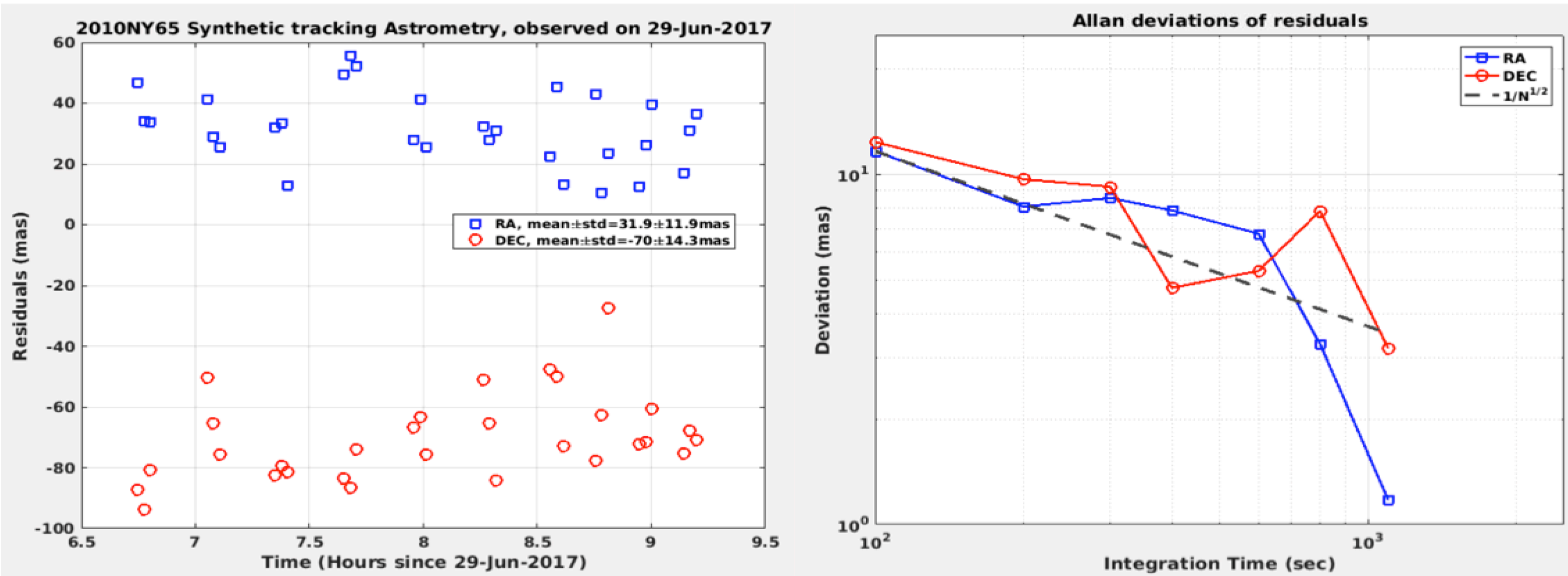




from Zhai, C. et al, *"Accurate Near-Earth-Object Astrometry using Synthetic Tracking and Applications"*, presented at the 2019 EPSC-DPS, Geneva.

Asteroid Synthetic Aperture Tracking

State-of-the-art results using the 1m Table Mountain Observatory telescope:



from Zhai, C. et al, *"Accurate Near-Earth-Object Astrometry using Synthetic Tracking and Applications",* presented at the 2019 EPSC-DPS, Geneva.

Advantages of Using Gaia for Ground Astrometry

- Denser, more accurate set of sources
- Can use smaller fields of view, reducing differential atmospheric turbulence effects
- Can use densely populated regions to calibrate camera field distortion
- Can use the sources to determine more accurately the plane-of-sky position of the spacecraft

Asteroid vs. Spacecraft Astrometry

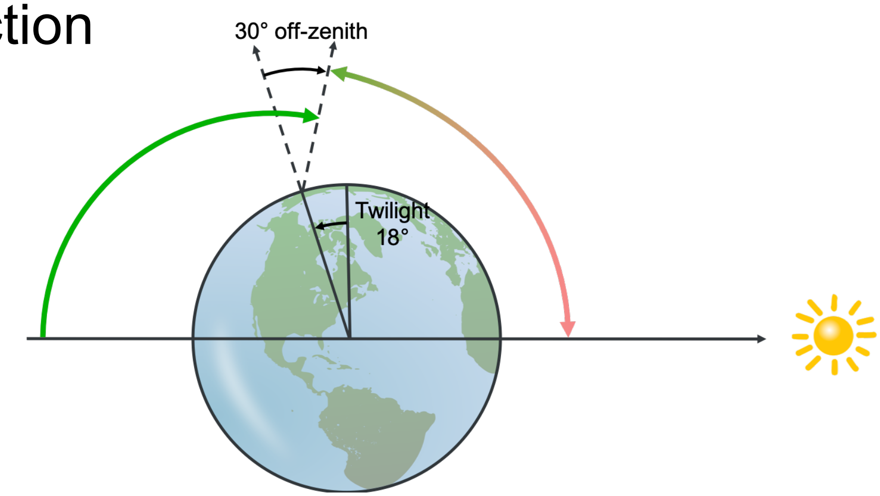
- Asteroid:
  - Spread spectrum
  - Visible and infrared
  - Phase angle and rotation

- Laser-equipped spacecraft
  - Narrow frequency band
  - Usually in the near infrared
  - Point source optimally pointed to a particular region of the Earth

Optical Astrometry vs. VLBI Tracking

- Two plane-of-sky coordinates determined at once with astrometry
  - 5-meter telescopes may provide similar plane-of-sky performance as the current VLBI system
- VLBI requires dual-complex overlap, astrometry just one telescope
- Optical astrometry requires darkness and clear skies
  - May require regional diversity to ensure tracking during mission-critical phases
  - Precludes using optical astrometry for missions flying to the inner solar system or around conjunction

- The optical and the VLBI celestial reference frames are already aligned in ICRF3



Conclusion

- Gaia can benefit on-board optical navigation.
- Optical communications infrastructure used in conjunction with Gaia data has the potential to provide viable deep-space navigation data types with performance comparable to that achievable with radio.
- Ground optical tracking of spacecraft will be affected by some unique operational constraints that will limit its availability:
  - Cloud cover
  - Sky brightness for astrometry

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