Image-Based Deep Space Navigation

Finding our Way Around the Solar System One Picture at at Time

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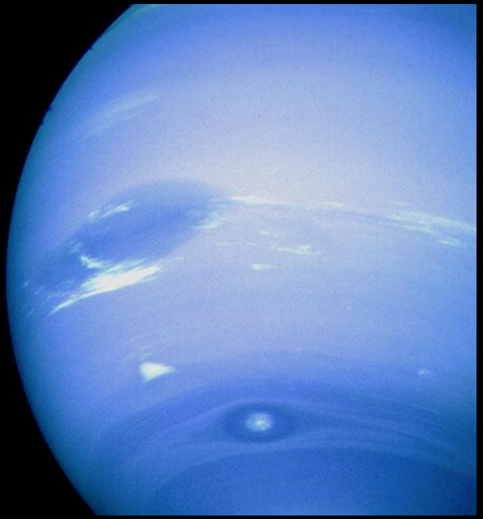
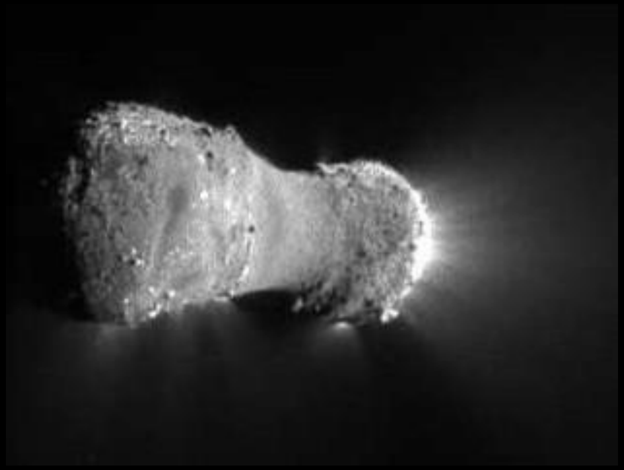
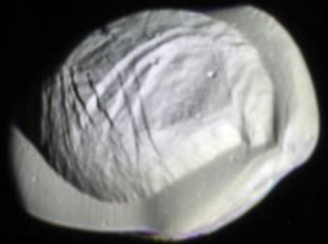
- Focus of this talk is on space imaging for navigation
  - Specifically, images taken by a camera onboard a spacecraft flying in space
  - Also won't cover images taken by landed spacecraft (e.g, Mars rovers)
- Most images taken by spacecraft are used by scientists
- And of course, images released are great PR!







What is “deep space navigation”?

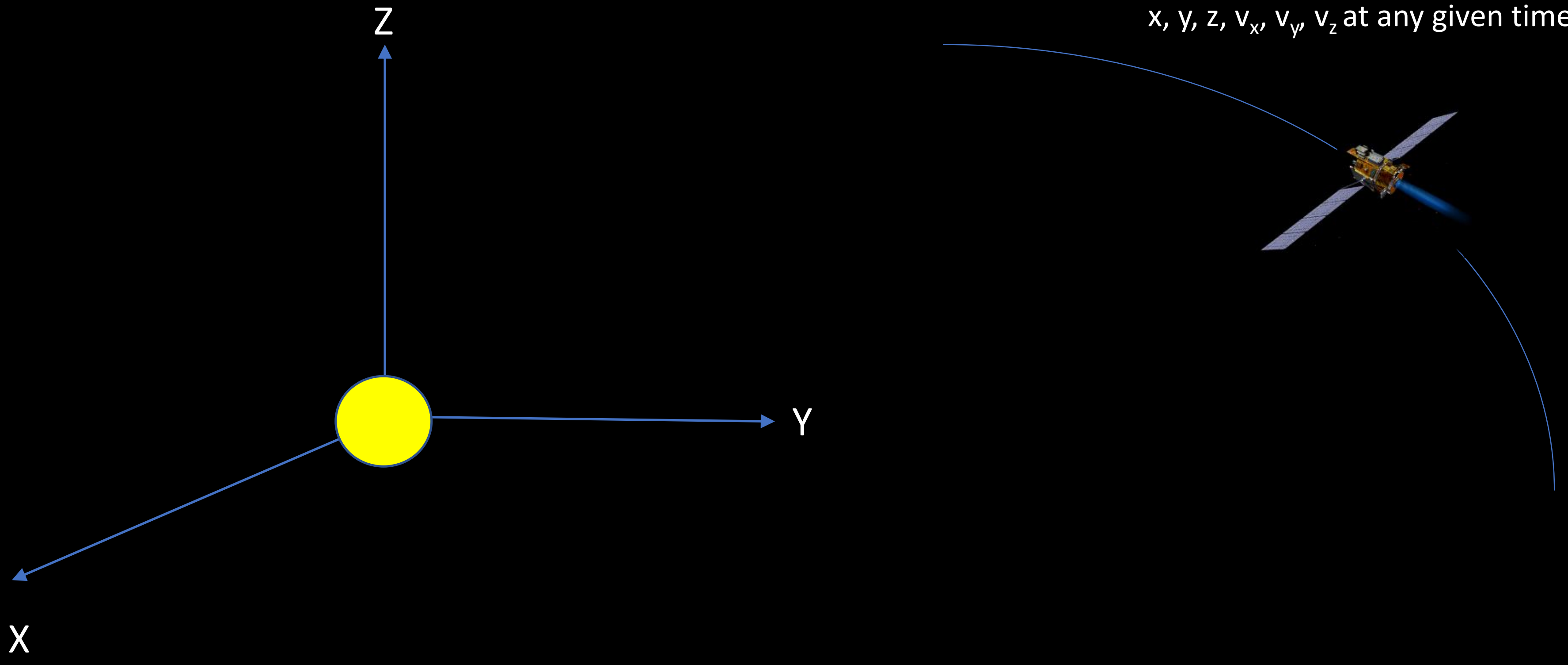
- Navigation for spacecraft at Lunar distances all the way out to the edges of the Solar System
- For vicinity of the Earth → GPS
- Deep space navigation relies primarily on radiometric data
- Images taken by an onboard camera, however, can be a critical data for many missions for navigation

Deep Space Navigation – a little background

- Spacecraft move in orbits around the Sun, planet, planetary satellites, or small bodies (asteroids and comets)
- These orbits can be described via a set of mathematical equations which ultimately provide the position and velocity of the spacecraft in a defined coordinate system
- Typically, the coordinate system is Cartesian, with the origin at the body the spacecraft is orbiting
  - At any given time, t, the position and velocity is given by the X, Y, Z components of position, and Vx, Vy, Vz, the velocity
- So we first start with a mathematical "map" of the spacecraft orbit, which is a table of the position and velocity over time of the orbit we would like to fly

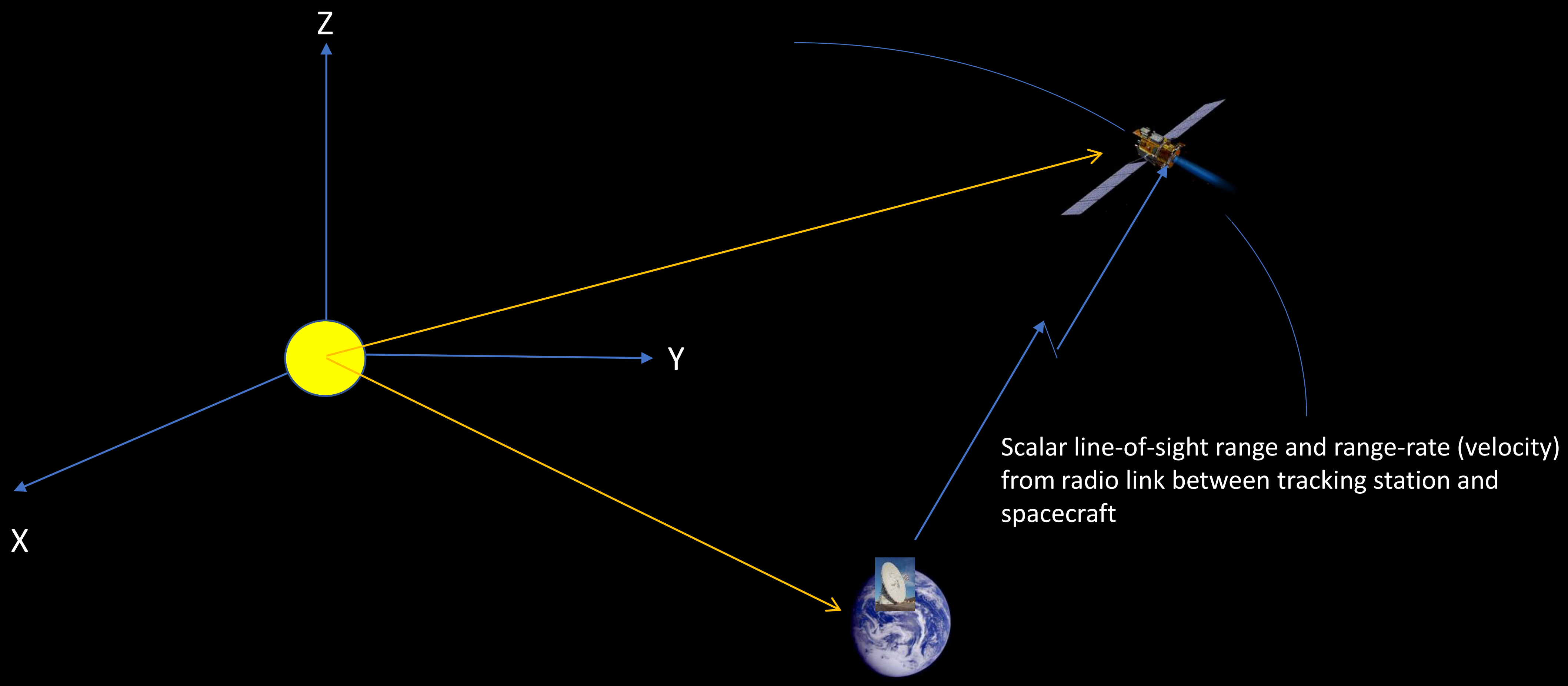
Spacecraft position and velocity can be described in Sun-centered Cartesian Coordinates as a function of time

x, y, z, v_x, v_y, v_z at any given time, t

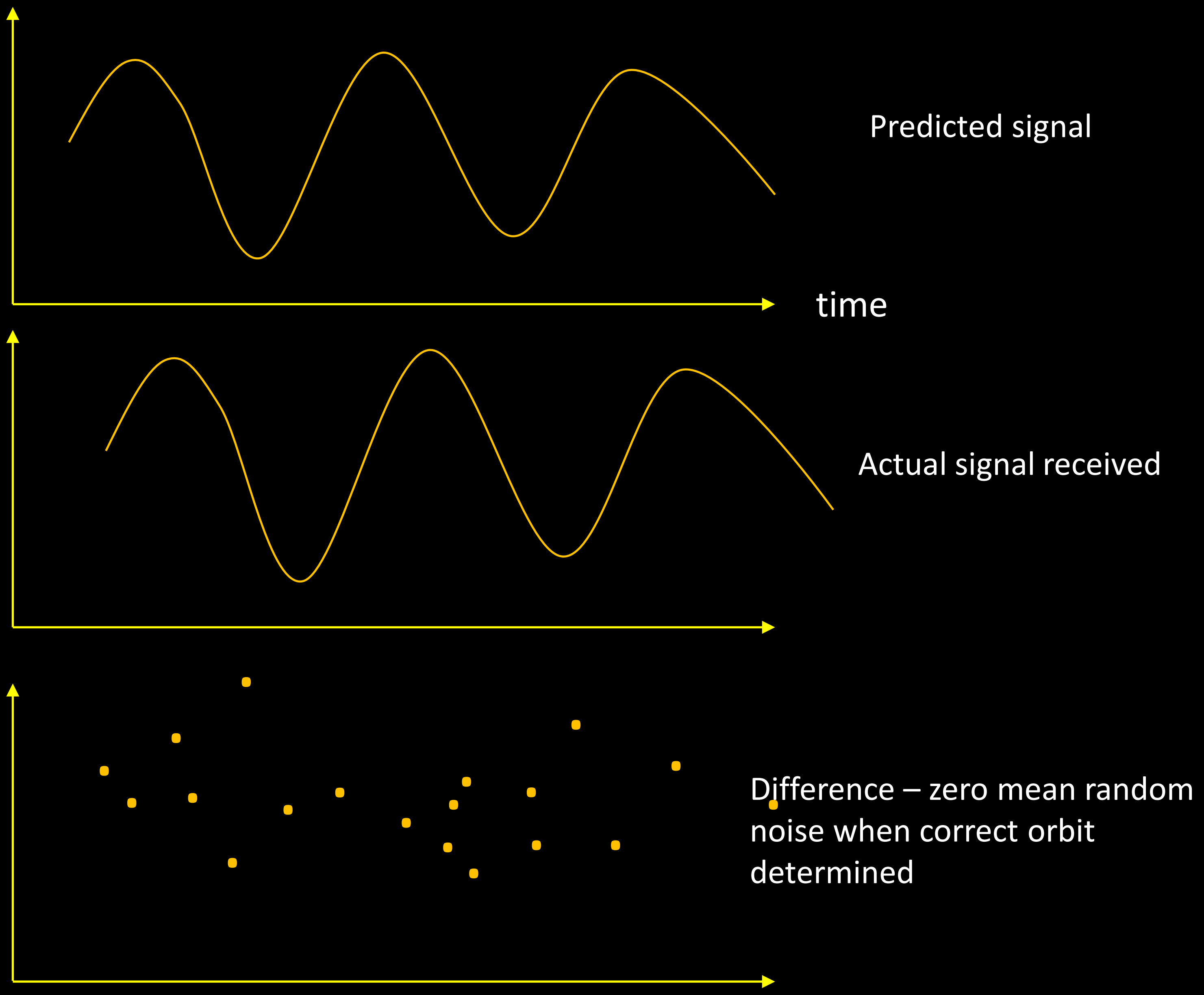


Deep Space Navigation – a little background

- The primary means of navigation is through a 2-way radio link between antennas on the Earth and on the spacecraft
- This link allows the measurement of the Doppler shift (velocity), and range, from the tracking station to the spacecraft
- These measurements are scalar, only determining the line-of-sight velocity and range from the tracking station to the spacecraft

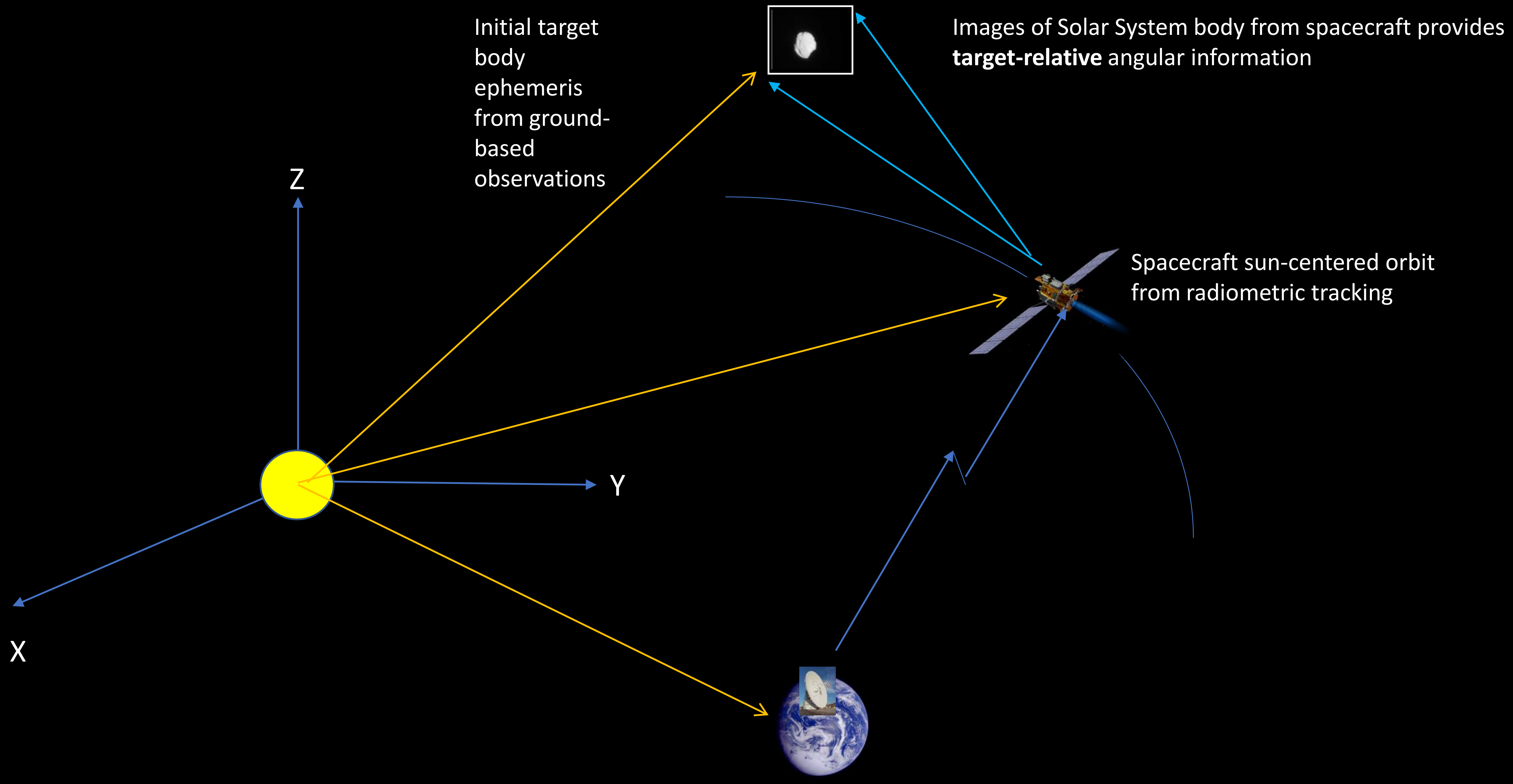

Z
Y
X
Scalar line-of-sight range and range-rate (velocity) from radio link between tracking station and spacecraft

- In order to determine the orbit, we difference the predicted LOS velocity and range based on our reference orbit, with the observed values obtained from the tracking data
  - If we were exactly on the reference orbit, this difference would be 0 (with random noise)
  - The difference of course, is never 0, so we adjust the parameters of the orbit until we get 0 (with random noise), using a least-squares technique
- Once we get the correct orbit, we can predict the future course, and use the corrected orbit as our new reference
- We also compute maneuvers to retarget the orbit if the course is not where we want to go



Images from an onboard camera

- Since the very early days of the space age, Doppler and ranging have been the primary, and often the sole, data used for navigating spacecraft in deep space
- From the late 60s, it was realized that images taken from an onboard camera, could also be used as a navigation aid
- The technique is known as optical navigation (OpNav), and is a critical capability for certain scenarios, enabling missions that otherwise would be difficult, if not impossible, to do with just radiometric data



Initial target body ephemeris from ground-based observations
Images of Solar System body from spacecraft provides **target-relative** angular information
Z
Spacecraft sun-centered orbit from radiometric tracking
Y
X

Benefits of OpNav

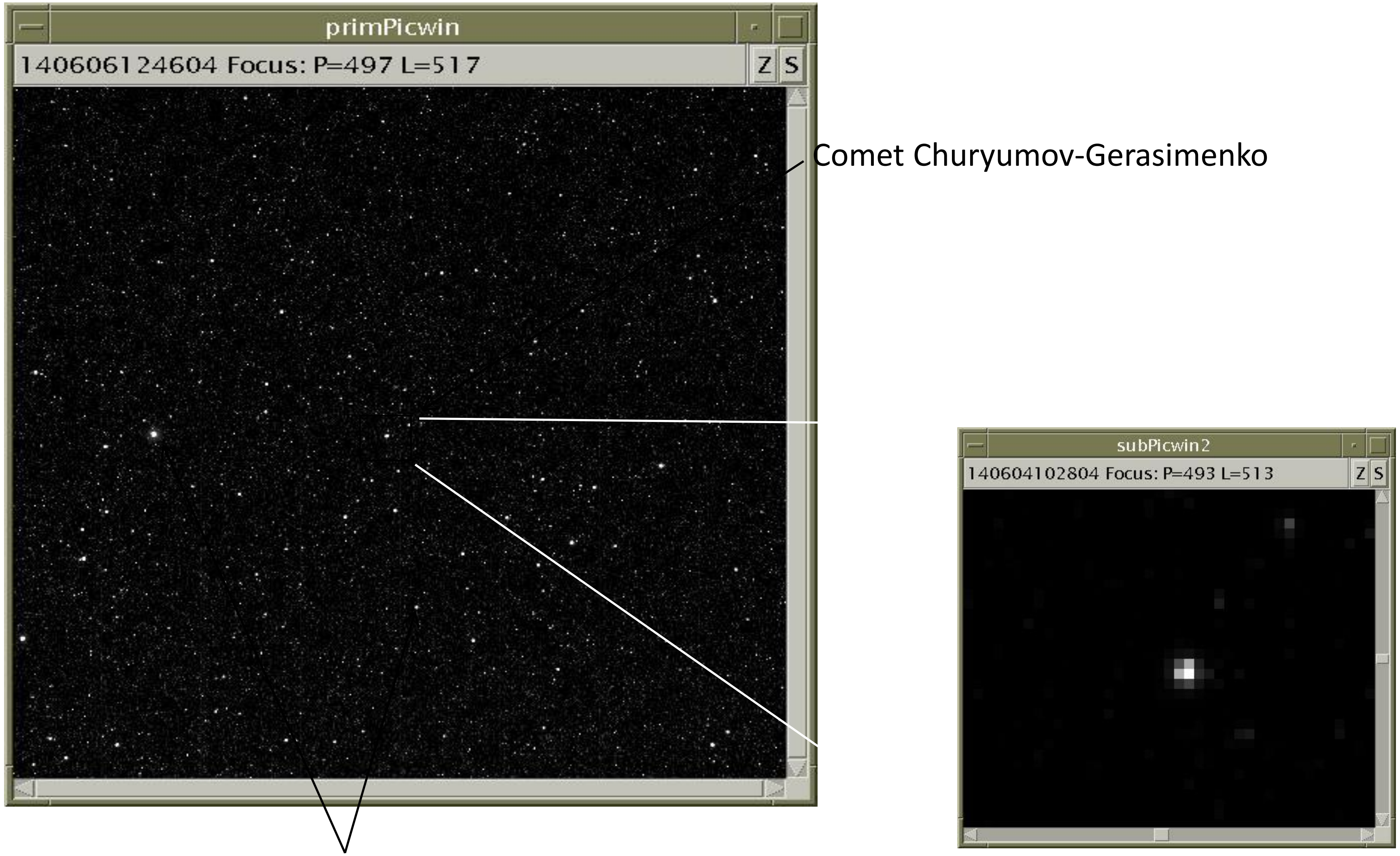
- Target body ephemeris currently not a major issue for the inner planets, Jupiter, and Saturn, which have 100s of years of observations from the Earth to determine their orbits, as well as many spacecraft visiting them
- Very much an issue for Uranus, Neptune, planetary satellites, asteroids, and comets, which are more difficult to observe from the Earth, often have shorter observation spans, and generally have poorer estimates of their orbits
- OpNav provides the only **target-relative** measurement, which is critical for these missions

OpNav Basics

- OpNav data used the same way as radiometric data – predicted vs observed location of body used to adjust spacecraft and/or target location
- Apparent shift of body in camera FOV from its predicted location to where it actually is can be due to one of two things
  - Either the body or the spacecraft is not where it was predicted to be
  - The direction the camera was pointing was not where it was predicted to be
- We can eliminate the 2nd source *if* there are stars in the camera FOV
  - Stars are, for all practical purposes, at an infinite distance, so there is no discernible parallax due caused by the star or spacecraft position
  - Can use stars in FOV to adjust the inertial pointing knowledge to eliminate it as a source of error
- If stars are not available, then the camera pointing direction must also be solved for in the least squares filter, degrading the accuracy of the solution

Centerfinding

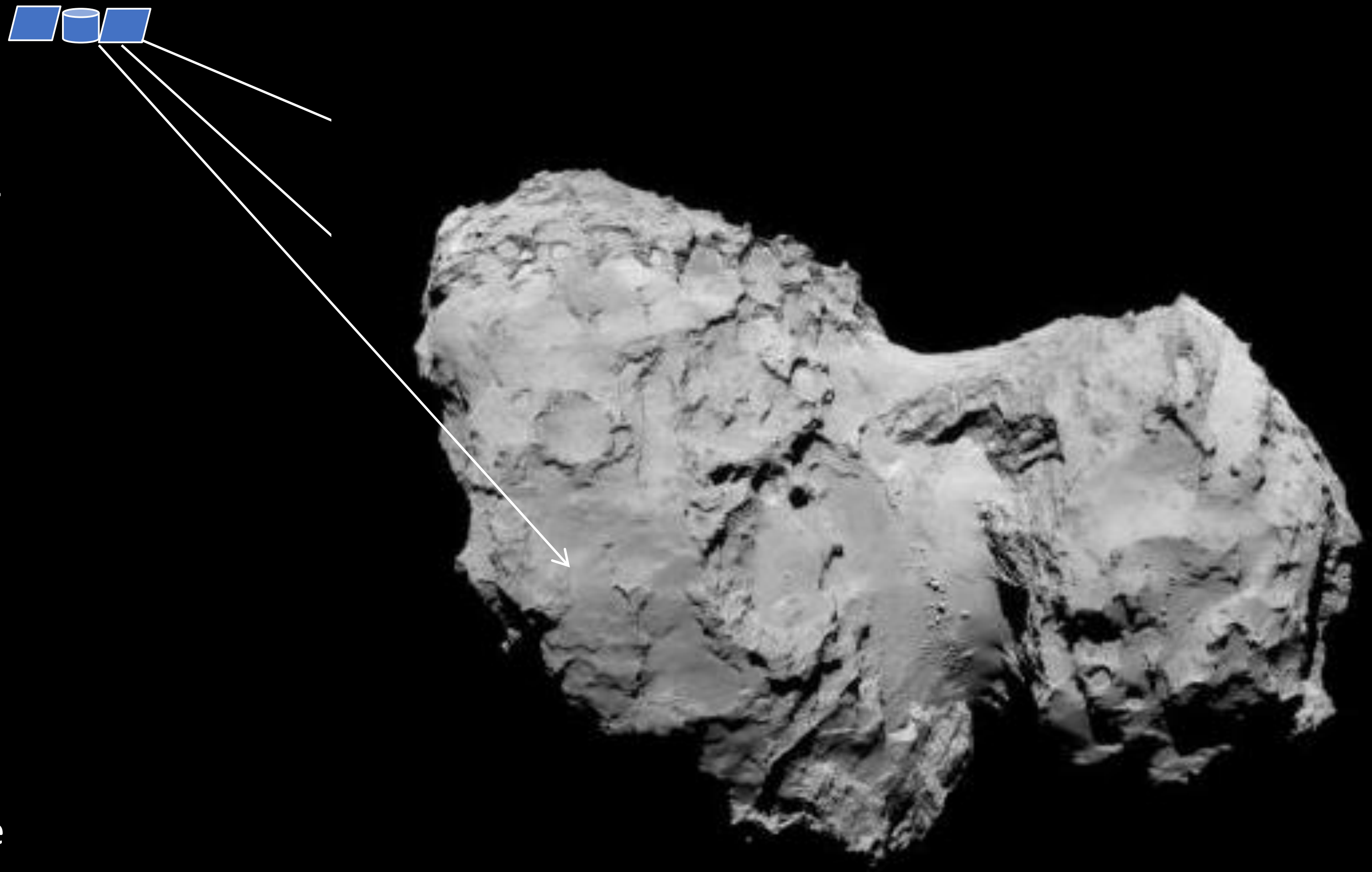
- Determining the precise location of the target body in the camera frame provides, to accuracies at the sub-pixel level, is called "centerfinding"
- For point sources (stars, distant Solar System bodies), correlate a Gaussian signal to the point source image in the camera


primPicwin
140606124604 Focus: P=497 L=517
Z S
Comet Churyumov-Gerasimenko
subPicwin2
140604102804 Focus: P=493 L=513
Z S

Centerfinding for unknown body with irregular shape

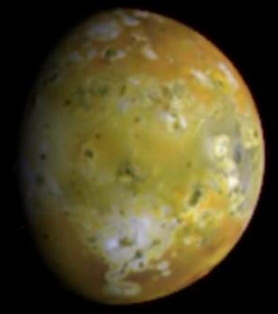
Special Case – Proximity Operations around Small Bodies (Asteroids and Comets)

- First determine landmarks in body-fixed frame of body
  - Can be located either manually or by some automated means, e.g., stereo-photoclinometry (SPC)
- With known landmarks, localizing landmarks in camera frame provides LOS vectors from camera to landmark
- Two LOS vectors provide geometric fix of spacecraft position
- Adding more landmarks, spacecraft location can be determined using least-squares filter
- Knowledge of bodies pole orientation and spin rate provide inertial reference
- Stars may or may not be visible



Missions Using OpNav

- **1969: Mariner Mars – 1st demonstration of OpNav capability**
- **1976: Viking orbiters** demonstrated optical navigation using Phobos and Deimos.
- **1978-1989: Voyager** requires optical navigation to meet mission objectives at Jupiter, Saturn, Uranus and Neptune.
- **1991-1996: Galileo Mission** utilizes optical navigation to capture images of Gaspra and Ida, and to accurately achieve orbit and satellite tours.
- **1996-1998: Deep Space 1** optical navigation used in cruise flight in 1999, and approach to comet Borrelly
- **1997-2001: NEAR** optical navigation used for flyby of Mathilde and approach to Eros
- **2002-present: Cassini** optical navigation extensively used for satellite tour
- **2004: Stardust** optical navigation used for approach to comet Wild 2
- **2005: Deep Impact** optical navigation used for approach to comet **2006: MRO** performs demonstration navigation with the Mars Optical Navigation Camera (ONC).
- **2005**: Hayabusa (JAXA) used OpNav for proximity operations around asteroid Itokawa
- **2008-2014: Rosetta** used optical navigation for flybys of asteroids Leutetia and Steins, and approach to comet Churumov-Gerasimenko
- **2011 – 2015: Dawn** used optical navigation for approach to Vesta and Ceres
- **2015: New Horizons Pluto** used optical navigation, imaging Pluto, Charon, Nix and Hydra on approach to the Pluto system
- **2018 – OSIRIS-Rex** spacecraft will use OpNav for approach and proximity operations around asteroid Bennu
- **2018 : New Horizons KBO** will use OpNav for flyby of MU69



Voyager 1 at Jupiter, 1980

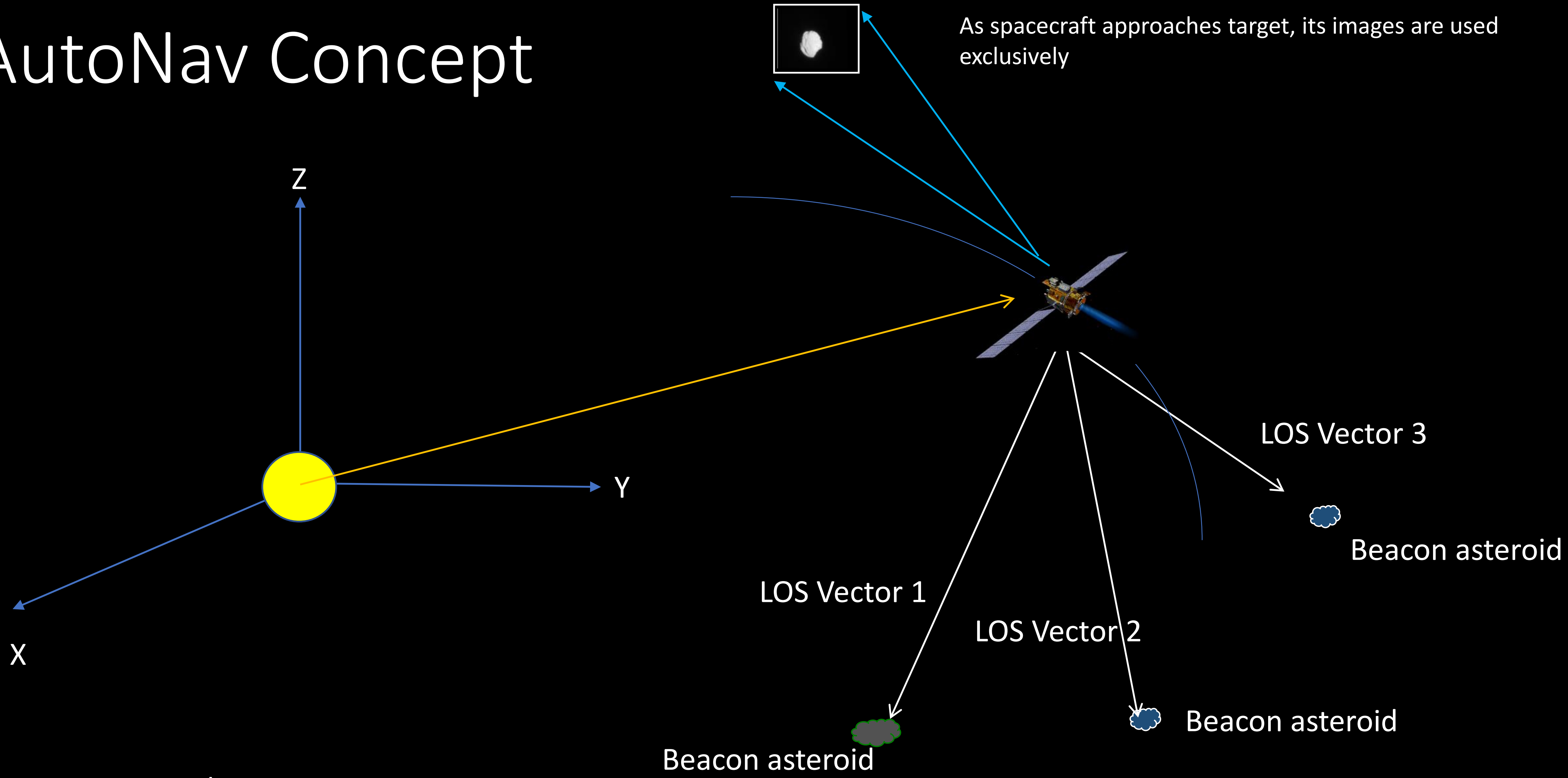
Galileo at Gaspra, 1991

Stardust at Wild 2, 2004

Autonomous Navigation

- Just as with self-driving cars, we can envision a system where the navigation of the spacecraft is done entirely onboard (AutoNav)
- Unlike with radiometric data, which relies on contact with the Earth, an OpNav based AutoNav system can be completely self-contained on the spacecraft, relying only on images taken to self-navigate
- All image processing, orbit determination, and maneuver planning and execution functions done onboard
- The key to the system is to make it robust and tolerant to errors
- We have developed such a system, and have used it successfully in certain limited circumstances

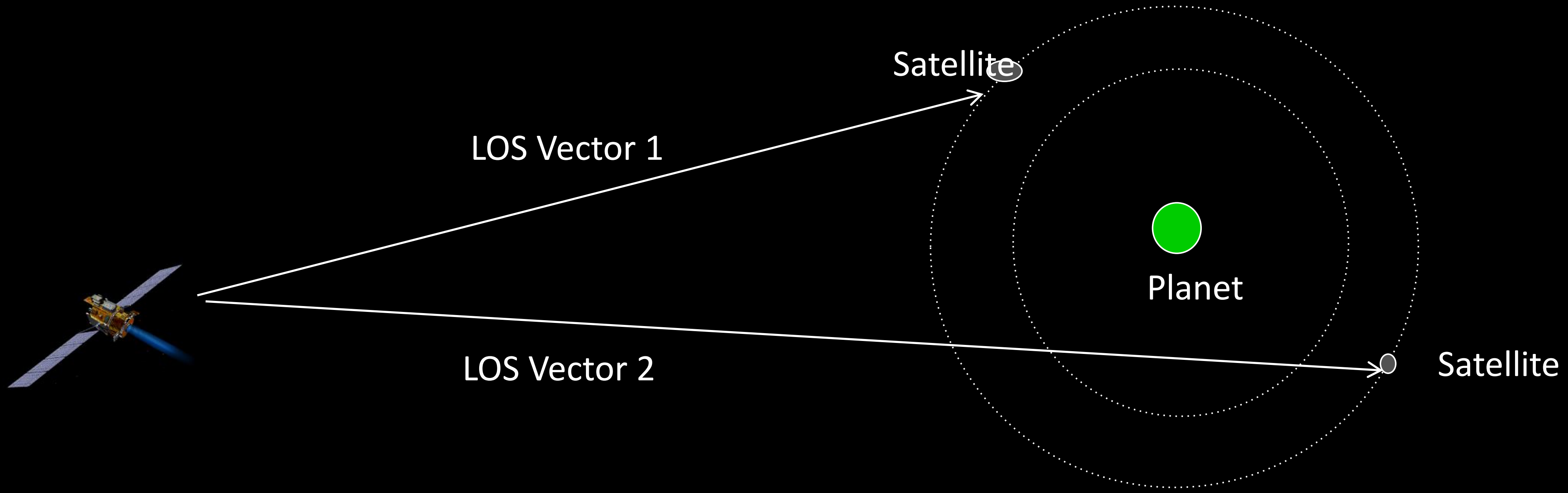
AutoNav Concept



Interplanetary cruise scenario
Technique used on DS1

- Main belt asteroids provide good beacon sources
- Ephemerides are reasonably well known
- Lots of asteroids to chose from

AutoNav Concept



Approach and/or tour of planetary system containing
Satellites
Technique partially validated on groundusing Phobos/Deimos images for MRO approach to Mars

Benefits of AutoNav

- Enables some kinds of missions that would not be possible with standard ground-based navigation due to light-time or other constraints
- Enhances science return
- Provides navigation robustness
  - Maintains navigation solution onboard at all times so that in high dynamic environments, can detect and respond to imminent danger
- Reduce mission costs
  - Reduce the need for ground personnel to perform navigation functions

Mission Results

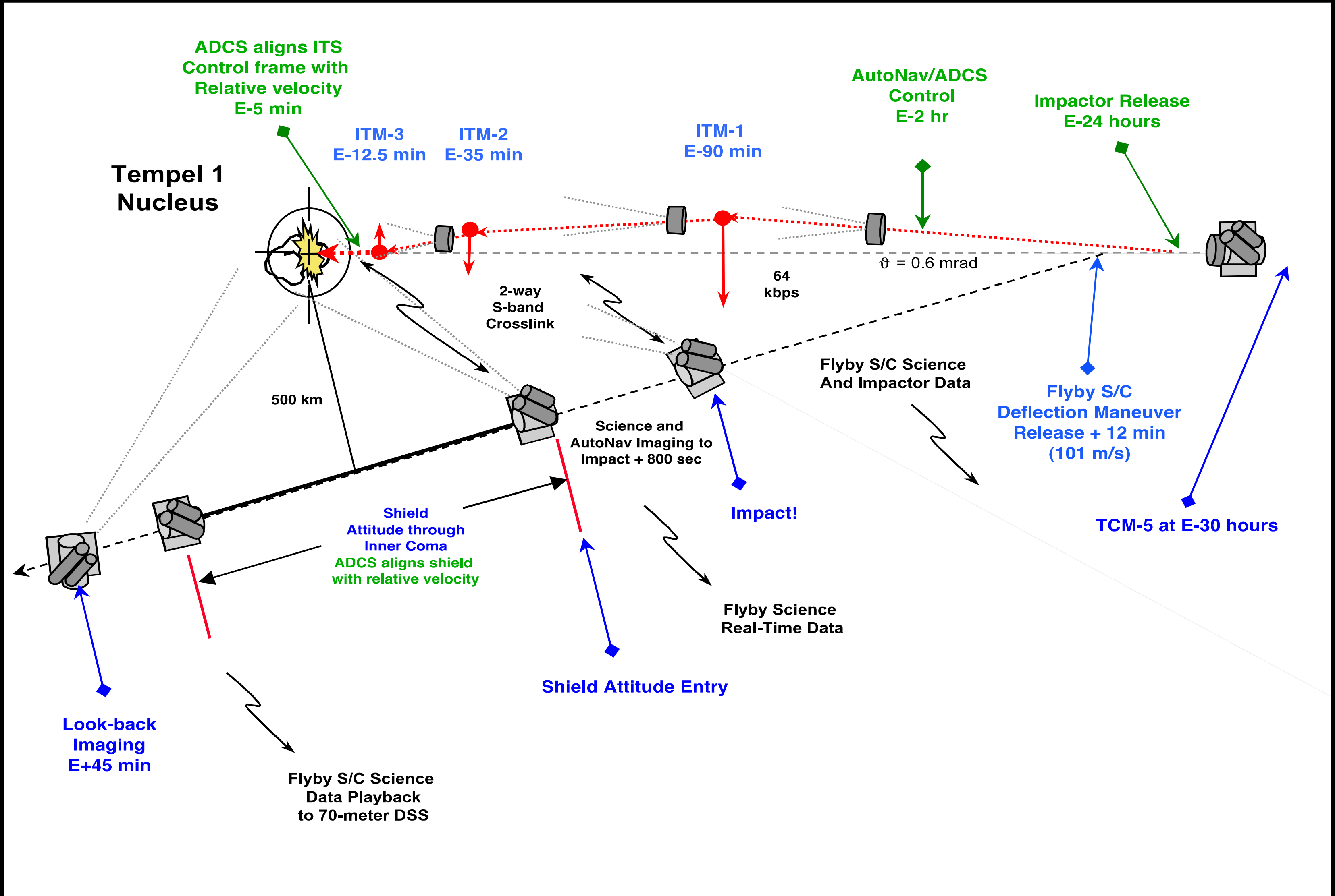
- 5 missions using 4 different spacecraft have used AutoNav during the mission
  - Deep Space 1 (cruise and flyby of comet Borrelly)
  - Stardust (flyby of asteroid Annefrank and comet Wild 2)
  - Deep Impact (Impactor and Flyby spacecraft imaging for comet Tempel 1)
  - EPOXI (flyby of comet Hartley 2)
  - Stardust NExT (flyby of comet Tempel 1)
- Flyby mission parameters

Mission/Target	Flyby Radius (km)	Flyby Velocity (km/s)	Approach Phase (deg)
DS1/Borrelly	2171	16.6	65
STARDUST/Anne frank	3076	7.2	150
STARDUST/Wild 2	237	6.1	72
DI/Tempel 1	500/0	10.2	62
EPOXI/Hartley 2	694	12.3	86
STARDUST NExT/Tempel 1	182	10.9	82

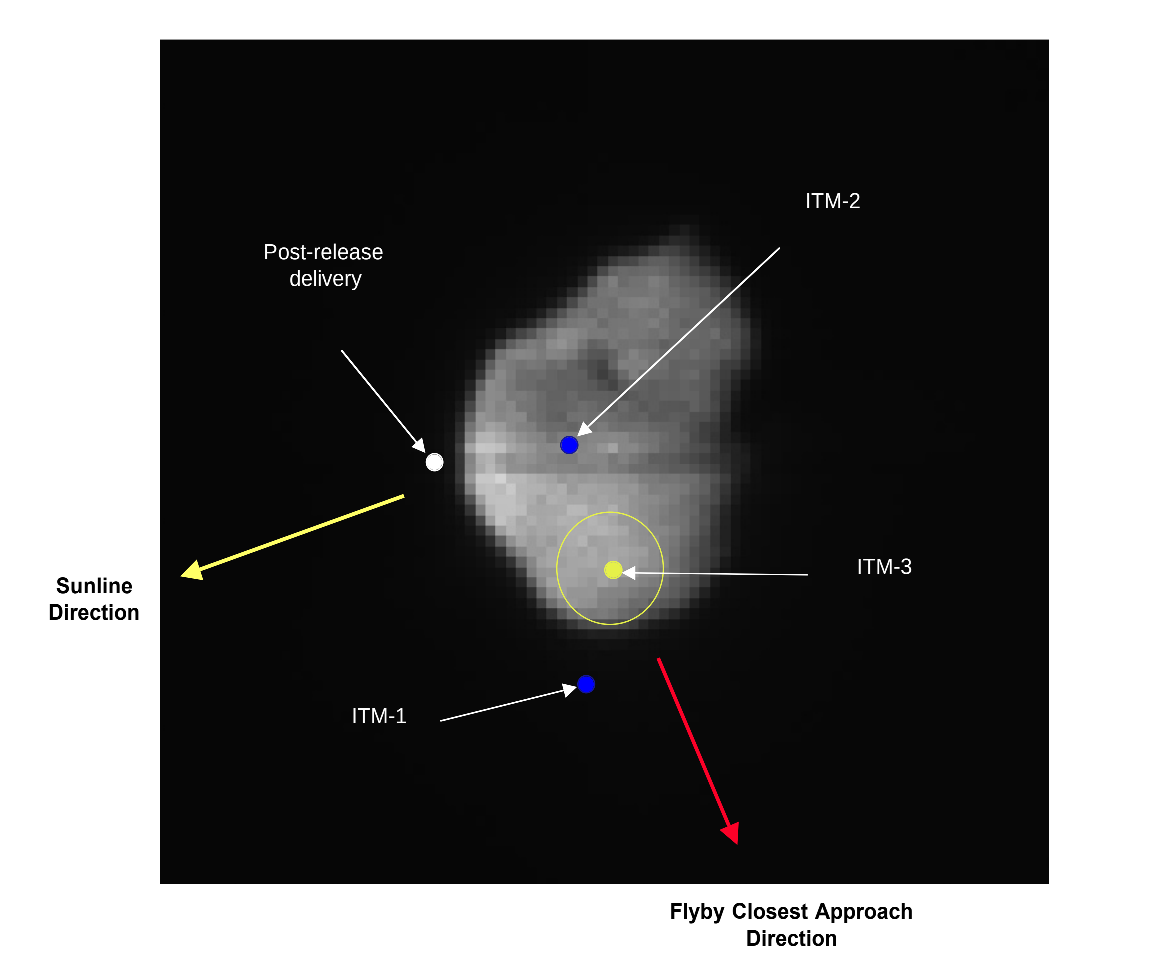
Example of AutoNav Enabling Capability: Deep Impact

- Goal of mission was to impact the comet Tempel 1 with one spacecraft at a speed of 10 km/s (~36,000 mph) while imaging the impact event with another traveling at roughly the same speed
- Impactor released from Flyby spacecraft at E-1 day. Flyby performs burn to slow down so that the impact can be observed prior to passing through closest approach

Deep Impact (cont.)



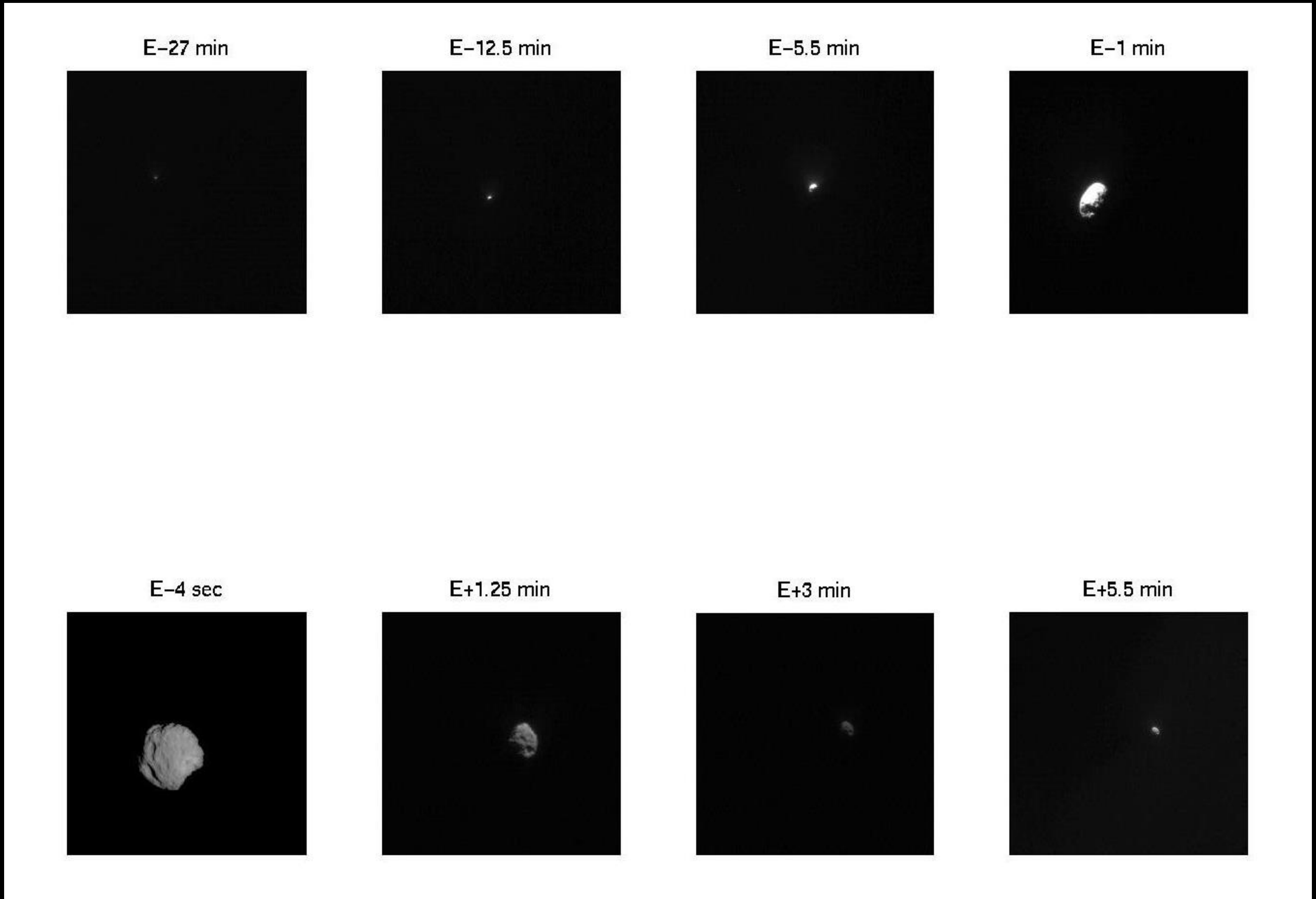
Deep Impact (cont.)



Example of AutoNav Enhancing Science: STARDUST

- STARDUST spacecraft's goal was to flyby the comet Wild 2 and collect samples of the cometary dust as it flow through the coma
- Additionally, the spacecraft camera had to maintain visual lock on the comet nucleus as it flew by at a distance of ~230 km at a speed of 6 km/s (~13,000 mph)
- Without AutoNav, the lack of precise knowledge of where the comet is relative to the spacecraft would require mosaicking to capture the nucleus

Stardust (cont.)



OpNav Cameras

- Although in principle, OpNav could use cameras specifically designed for navigation, in practice, OpNav is almost always done with science cameras that double as OpNav cameras
  - Reduces cost, mass, power, volume requirements on spacecraft
  - Results in some compromises on performance, but an overall successful strategy
- Older cameras (circa 1960s – 1990s) were vidicon
- Current cameras are primarily Charged-Coupled-Device (CCD)
- Moving into using CMOS

The Future of Space Imaging for Navigation

- Autonomy!
  - More capable onboard processors means more of the image processing and orbit determination can be done onboard
  - Smaller, cheaper, more frequent spacecraft will overtax current radiometric network, increasing the need for autonomy
  - Optical alone, or optical plus one-way radiometric or other Earth-relative sensors (e.g., pulsar navigation) can handle most navigation needs
- Smaller, lightweight cameras
- Improvements in image processing techniques to improve accuracies