
52. Interplanetary navigation

THE PAST FEW DECADES have seen many spacecraft sent out to orbit, land on, or simply fly past all of the major and many of the minor bodies of our solar system: these include landers on the Moon and Mars, flybys and orbiters of Jupiter, Saturn, Uranus and Neptune, and landers on Saturn's moon Titan in 2005, and on comet 67P/Churyumov–Gerasimenko in 2014. There have been visits to comets Giotto, Grigg–Skjellerup, Tempel 1 and Wild 2, and to asteroids Annefrank in 2002, Lutetia in 2010, Vesta in 2011, Ceres in 2015, Bennu in 2018, and Ryugu in 2019.

One of the most impressive achievements in interplanetary navigation has been NASA's New Horizons mission to the dwarf planet Pluto. Launched in 2006, it flew past Pluto nearly a decade later, on 14 July 2015, just 12 500 km above its surface. It captured images, and collected data on the atmospheres, surfaces, interiors, and environments of both Pluto and its moons.

Having completed its flyby of Pluto, New Horizons was then re-maneuvred for a flyby of the Kuiper belt object Arrokoth (also known as Ultima Thule). This occurred on 1 January 2019, when it was more than 40 au (i.e. 40 times the Sun–Earth distance) from the Sun.

IN ADDITION TO THE ENGINEERING challenges of the spacecraft itself, and the many impulse manoeuvres needed to set it on its way and adjust its flight path *en route*, there are two basic navigational ingredients required for these remarkable space rendezvous. The first is an accurate knowledge of the target object's own position and orbital motion around the Sun. The second is an up-to-date knowledge of the spacecraft's own position and orbital motion along its pursuit path.

FOR THE FORMER, precise orbits of many solar system objects are calculated, compiled and maintained, independently by the Jet Propulsion Laboratory (JPL, California), and by the Institute for Celestial Mechanics (IMCCE, Paris). Specified at regular intervals spanning a certain period of time, these estimated positions and orbits are referred to as the object's 'ephemerides'.

Precision ephemerides of the Sun, the planets, the Moon, and other solar system objects are also used as the basis of the *Astronomical Almanac*, with its various civilian applications such as the positions of the planets, and predictions of the phases of the Moon and of civilian twilight. Ephemerides provide the positions, velocities and accelerations of each object at equally spaced intervals over a specified period. They take account of all available knowledge including their masses, the oblateness of the Sun, and relativistic corrections.

Observational data used in the fits include transit and CCD observations of planets and small bodies, lunar laser-ranging, radar-ranging, and distances measured by radio signals from interplanetary spacecraft themselves. Angular accuracies reach around 0.001 seconds of arc (arcsec) for the inner planets (1 km at the distance of Mars), and some 0.1 arcsec for the outer planets.

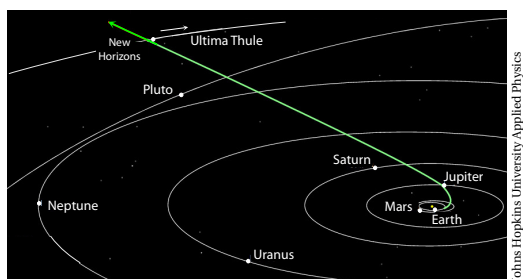
FOR THE LATTER, establishing the position and velocity of the spacecraft itself as it travels to its rendezvous makes use of various techniques. For spacecraft near to the Earth, radar tracking using ground-based antenna can be used to determine the spacecraft's instantaneous distance via the signal's time delay, and its radial velocity via the Doppler effect. Accuracies of 1 m in distance and 1 mm s^{-1} in velocity can be routinely achieved, further augmented through the use of two or more ground stations to allow triangulation. Tracking the spacecraft over time allows its orbit to be computed.

For more distant spacecraft further out in the solar system, radar tracking is supplemented by 'delta-differential one-way ranging', which uses two or more widely-spaced ground stations to interpret the spacecraft signal. The time-delay between the receipt of the signal establishes the angular position of the spacecraft, which can then be related to the known positions of distant quasars lying within a few degrees of the line-of-sight. Angular accuracies of around 10 nano-radians (2 milli-arcsec) can be achieved, corresponding to a transverse positional accuracy of 1.5 km for a spacecraft at 1 astronomical unit from the Earth.

ULTIMATELY, both the spacecraft orbit, and the target celestial object's orbit, are referenced to the position of background stars and quasars on the sky. Progress in interplanetary navigation rests on the accuracy of the best star catalogues available at that time.

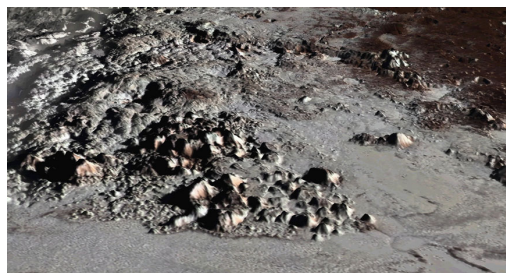
The New Horizons fly-by of Pluto was based on the JPL solar system ephemerides DE430, finalised before the Pluto encounter (Folkner et al., 2014), and itself based on the celestial reference frame materialised by the Hipparcos star positions from the late 1990s.

For New Horizons, attitude *determination*, i.e. knowing which direction it's pointing, uses star-tracking cameras, gyroscopes and accelerometers. Attitude *control* is accomplished using (hydrazine gas) thrusters. The star-tracking cameras store a map of about 3000 star positions. Every 0.1 second, this is compared to a wide-angle image of space. The spacecraft's actual orientation is determined on-board, and the hydrazine thrusters can be fired to reorient the spacecraft as required. All this allowed the spacecraft to be piloted for the fly-by of Pluto, in turn leading to the spectacular and unprecedented images of its surface, and a whole host of other scientific results enabled by the spacecraft's instruments.



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AROKOTH (formally 486958 Arrokoth; also known as 2014 MU₆₉, and as Ultima Thule) is a trans-Neptunian object within the Kuiper belt. It is a contact binary, composed of two planetesimals 21 km and 15 km in size, joined along their major axes, and with an orbital period around the Sun of about 298 years. It was discovered in 2014 by Marc Buie and colleagues using the Hubble Space Telescope as part of a search for a Kuiper belt object to be targeted for a further flyby beyond Pluto.



Paul Schenk/Lunar and Planetary Institute

Pluto's surface imaged by New Horizons in 2019: mountains rise 6 km above plains of nitrogen-ice

THE EVENTUALLY HIGHLY SUCCESSFUL flyby was based on star occultation campaigns in Argentina, Senegal, South Africa and Colombia in 2017–18, which themselves made use of the Gaia DR2 star positions provided to the New Horizons team before their general release. Images from the spacecraft's Long-Range Reconnaissance Imager, 6.5 minutes before closest approach, provided a high-spatial resolution of 30 m per pixel, along with a favourable viewing angle.

According to Science Magazine (24 Nov 2020), Marc Buie persuaded the New Horizons team to trust the new Gaia stellar framework, and a correction based on the Gaia positions was sent to the spacecraft. The article continues: When the closest flyby images came back, Arrokoth was framed perfectly. *'None of that would have happened if we hadn't had the Gaia catalogue'*, Buie says. *'It's a fundamental rewriting of how we do positional astronomy'*.



NASA/JHU-APL/SwRI/Roman Tkachenko

Ultima Thule

Scientifically, the surfaces of each lobe of Arrokoth display regions of varying brightness along with various geological features such as troughs and hills, thought to have originated from the clumping of smaller planetesimals to form its lobes. The brighter surface regions may be material that rolled down from its higher peaks, under gravity. The interior is believed to be composed of amorphous water ice and rocky material.

While moons and asteroids in the inner solar system suggest a violent collisional past, the surfaces of objects in the Kuiper Belt around Pluto and beyond reveal a more tranquil environment, due to their lower space densities and smaller orbital speeds. Pluto confirmed this through its relative lack of impact scars, while the surface of Ultima Thule supports the same ideas.

FOR DEEP SPACE NAVIGATION, beyond the solar system, spacecraft will be too distant to rely on Earth-based tracking. Traveling to the nearest stars, signals will be too weak, and light travel times will be of order years. An interstellar spacecraft will instead have to navigate autonomously, using other information to decide when to make course corrections or to activate instruments.

Radio pulsars have been considered as a solution to this future problem, employing an approach somewhat analogous to global positioning systems on Earth, but using pulsars rather than an artificial satellite constellation as navigation beacons.

Another approach to deep space navigation is via direct triangulation of stars, using the full three-dimensional positions of a set of stars relative to some well-defined reference frame. A recent feasibility study based on the accurate star positions being provided by Gaia is given by Bailer-Jones (2021).