Space Sci Rev (2008) 140: 49–74
DOI 10.1007/s11214-007-9242-y

New Horizons Mission Design

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Received: 15 January 2007 / Accepted: 21 June 2007 / Published online: 29 August 2007

Abstract In the first mission to Pluto, the New Horizons spacecraft was launched on January 19, 2006, and flew by Jupiter on February 28, 2007, gaining a significant speed boost from Jupiter's gravity assist. After a 9.5-year journey, the spacecraft will encounter Pluto on July 14, 2015, followed by an extended mission to the Kuiper Belt objects for the first time. The mission design for New Horizons went through more than five years of numerous revisions and updates, as various mission scenarios regarding routes to Pluto and launch opportunities were investigated in order to meet the New Horizons mission's objectives, requirements, and goals. Great efforts have been made to optimize the mission design under various constraints in each of the key aspects, including launch window, interplanetary trajectory, Jupiter gravity-assist flyby, Pluto–Charon encounter with science measurement requirements, and extended mission to the Kuiper Belt and beyond. Favorable encounter geometry, flyby trajectory, and arrival time for the Pluto–Charon encounter were found in the baseline design to enable all of the desired science measurements for the mission. The New Horizons mission trajectory was designed as a ballistic flight from Earth to Pluto, and all energy and the associated orbit state required for arriving at Pluto at the desired time and encounter geometry were computed and specified in the launch targets. The spacecraft's flight thus far has been extremely efficient, with the actual trajectory error correction ΔV being much less than the budgeted amount.

Keywords Mission design · Trajectory design · New Horizons mission · Space mission · PKB mission · Pluto · Kuiper Belt objects

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1 Introduction

The early mission design work for the New Horizons mission began in late 2000, shortly after NASA terminated the “Pluto–Kuiper Express” program. A team at The Johns Hopkins University Applied Physics Laboratory (JHU/APL), which was wrapping up NASA’s Near-Earth Asteroid Rendezvous (NEAR) mission with an unprecedented soft landing on an asteroid, was assembled to put together a feasible mission implementation plan, including the early mission design concept. The team hoped to save the long-sought mission to Pluto, the only remaining planet not yet visited (at the time Pluto was still the ninth planet). Urged on by the science community, NASA issued an Announcement of Opportunity (AO) in January 2001 to solicit proposals for the so-called “Pluto–Kuiper Belt (PKB) Mission,” the first mission of NASA’s New Frontiers program. Later, the early mission design concept evolved and became a part of the New Horizons mission proposal, led by Principal Investigator Alan Stern of the Southwest Research Institute (San Antonio, TX). The proposal was submitted to NASA and was selected for a three-month concept study (Phase A), and on November 19, 2001, NASA concluded its rigorous evaluations on two final proposals and selected the New Horizons proposal for the PKB mission.

The mission design underwent numerous revisions and updates before the New Horizons spacecraft was launched successfully on January 19, 2006, aboard an Atlas V 551 with a Star 48B third stage, in accordance with an updated baseline mission design using a Jupiter gravity-assist (JGA) trajectory to Pluto. The spacecraft flew by Jupiter on February 28, 2007, to gain a needed speed boost and will encounter Pluto on July 14, 2015, after a 9.5-year journey from launch, followed by an extended mission to the Kuiper Belt objects (KBOs). This paper discusses the objectives, requirements, and goals of the New Horizons mission design and reviews various mission design scenarios regarding routes to Pluto and launch opportunities. The baseline mission design is described in detail, covering the key aspects of launch window, interplanetary trajectory, JGA flyby, Pluto–Charon encounter with science measurement requirements, and extended mission to the Kuiper Belt and beyond. This paper also presents analyses of the launch data and the early post-launch flight results.

2 Mission Design Requirements

The scope of the PKB mission, the science requirements, and the program schedule and constraints were defined in the NASA AO (NASA 2001), which also specified the candidate launch vehicles for the PKB mission. The mission objectives were classified further as either requirements (objectives that must be accomplished by the mission) or goals (objectives that are desirable but not required to be accomplished by the mission). The tasks of the New Horizons mission design—especially the selection of the launch dates, the design of the interplanetary trajectory and Pluto encounter, and the ΔV budgeting—in principle were guided and bound by the mission objectives, program requirements, and constraints identified in the NASA AO.

2.1 Mission Scope and Objectives

According to the NASA AO, the principal goal of the PKB mission is to perform high-quality scientific investigations of the PKB region of the solar system (NASA 2001). Spacecraft had been sent to the other eight planets but not to Pluto, although planning for a mission to Pluto dates as far back as the 1960s (Long 1969; Keller 1971; Farquhar and Stern 1990; Weinstein 1992; Staehle et al. 1994; Minovitch 1994; Stern and Mitton 1998). The Pluto mission certainly is one of the most challenging deep-space missions, because it requires extremely high launch energy, long flight time, observation of multiple bodies in a brief flyby with high flyby velocity, communications to Earth from great distances, and long light-time delay.

Pluto was discovered by Clyde Tombaugh in 1930 and currently is located more than 31 astronomical units (AU) from the Sun. Our current knowledge about Pluto is based on observations taken from the ground and from orbits around the Earth. Pluto orbits the Sun in 248 Earth years in one revolution in an elliptical orbit of perihelion at 29.7 AU and aphelion at 49.4 AU. Its orbit is inclined 17° from the ecliptic plane, in contrast to the other planets, which reside within a few degrees of the ecliptic plane. Pluto has a half-sized moon, Charon, discovered in 1978, and two recently discovered small moons, Nix and Hydra. Before the two new moons were discovered, Pluto often was regarded as a binary system because the system's center of mass is outside Pluto. Charon does not move around Pluto; instead, Pluto and Charon move around the center of mass of the Pluto system, the Pluto barycenter. The PKB mission is to carry out the first scientific reconnaissance of the Pluto system and accomplish the specified science objectives and goals through a close flyby of Pluto and Charon.

The outer space beyond the orbit of Neptune is referred to as the Kuiper Belt, named after Gerald Kuiper, who hypothesized in 1951 that the short-period comets originate from a collection of material left over from the formation of the solar system. Kuiper's theory was validated with the discovery of the first KBO by David Jewitt and Jane Luu (Jewitt and Luu 1993) in 1992. Since then, numerous KBOs have been discovered each year. So far, the number of KBOs identified is over 1000, which is believed to be only a very small fraction of the total number of KBOs. The PKB mission aims to explore the Kuiper Belt region for the first time by visiting one or more KBOs in an extended mission after the Pluto–Charon encounter. The KBO encounter is a highly desired mission goal but not one of the NASA AO's mission requirements.

2.2 Science Requirements

The science objectives at Pluto and Charon were identified by the NASA Science Definition Teams and categorized into three groups, listed in Table 1, according to their priorities (NASA 2001). The group 1 objectives have the highest priority and are required to be fully accomplished by the PKB mission, the group 2 objectives are desirable, and the group 3 objectives are optional. All group 1 objectives are requirements, and the group 2 and group 3 objectives are goals.

2.3 Program Requirements and Constraints

The PKB mission is divided into two mission phases in terms of program requirements:

(i) the primary mission to Pluto, a mission requirement, and
(ii) the extended mission to the KBOs, a mission goal.

The total cost for the mission was required to be capped at 500 million FY01 dollars, including launch vehicle and launch services, spacecraft and science instruments, full mission development, and flight operations for the primary mission to Pluto. Flight operations for the extended mission to the Kuiper Belt (Phase F) were excluded from the capped funding. Candidate launch vehicles suggested in the NASA AO for the PKB mission were the new Evolved Expendable Launch Vehicle (EELV) classes, either Atlas V or Delta IV. The upper kick stage was not included in the launch vehicle package but was to be chosen by the mission implementation team.

Table 1 Science objectives at Pluto and Charon

Group	Objectives
1	Characterize the global geology and morphology of Pluto and Charon
	Map surface composition of Pluto and Charon
	Characterize the neutral atmosphere of Pluto and its escape rate
2	Characterize the time variability of Pluto's surface and atmosphere
	Image Pluto and Charon in stereo
	Map the terminators of Pluto and Charon with high resolution
	Map the surface composition of selected areas of Pluto and Charon with high resolution
	Characterize Pluto's ionosphere and solar wind interaction
	Search for neutral species, including H, H_2, HCN, and CxHy, and other hydrocarbons and nitriles in Pluto's upper atmosphere and obtain isotopic discrimination where possible
	Search for an atmosphere around Charon
	Determine bolometric Bond albedos for Pluto and Charon
	Map the surface temperatures of Pluto and Charon
3	Characterize the energetic particle environment of Pluto and Charon
	Refine bulk parameters (radii, masses, densities, etc.) and orbits of Pluto and Charon
	Search for magnetic fields from Pluto and Charon
	Search for additional satellites and rings

The NASA AO set a firm deadline for the time of the Pluto–Charon encounter: the mission is required to arrive at Pluto as early as possible but no later than 2020. The deadline was driven mainly by the concern that Pluto's atmosphere may collapse after 2020. Since passing the perihelion in 1989, Pluto has been continuously moving farther away from the Sun, and the planet's highly eccentric and inclined orbit causes its environment to change with time. Scientists predict that Pluto's thin atmosphere will be frozen onto its surface around 2020. After that, the atmosphere will not reappear until two centuries later when Pluto returns from the aphelion and approaches perihelion. In addition, if the arrival at Pluto is too late, more of Pluto's northern polar regions will fall into shadow as its north pole tilts farther away from the Sun. More surface area will fall into the shadow and, consequently, less surface area will be able to be imaged.

3 Mission Design Scenarios

Various trajectory options to get to Pluto and the associated launch opportunities were analyzed to determine and select the best mission design that will not only meet the NASA AO requirements but also maximize the mission accomplishments under the program constraints. During the mission development phase, as the program progressed and design constraints evolved, the New Horizons mission design was revised many times, and several design scenarios were investigated and considered (Guo and Farquhar, 2002, 2005, 2006).

3.1 Routes to Pluto

Sending a spacecraft to Pluto requires extremely high launch energy and so far is one of the most demanding launches of all the interplanetary missions. Of the nine planets, Pluto is located outermost from the Sun and also is the most distant one from Earth. For a direct Earth-to-Pluto flight, the required launch energy is higher than any of the past missions to the other eight planets. This imposes a significant challenge to the capability of the launch vehicle. The most powerful launch vehicles available are the EELV classes, but none of them can provide the needed launch energy without adding an additional kick stage. Even with a kick stage, the spacecraft has to be light at greatly reduced launch mass. In order to ease the high launch energy demand, alternative routes that require lower launch energy always are preferable over the direct route.

For the combination of lower launch energy and required arrival time, the best route to Pluto is via a JGA flyby instead of flying directly from Earth to Pluto. The gravity assist received at the Jupiter swingby acts like a slingshot, accelerating the spacecraft to reach Pluto faster, and allows for lower launch energy compared to a direct flight with the same flight time. The launch energy savings provided by the JGA trajectory is indispensable and sometimes crucial for mission feasibility, especially when the performance of the launch vehicle is insufficient for a direct flight.

Besides the JGA trajectory (Minovitch 1994) that proceeds directly from Earth to Jupiter and then to Pluto, there are other indirect JGA trajectories, such as the three-year ΔV-Earth–Jupiter gravity-assist approach (Farquhar and Stern 1990) and the Venus–Venus–Earth–Jupiter gravity-assist trajectory (Weinstein 1992). These indirect JGA trajectories include additional Earth or Venus-and-Earth flybys before approaching Jupiter, further reducing the launch energy to a level such that a small launch vehicle would be sufficient. However, the indirect JGA trajectories were rejected because the further reduction of the launch energy comes at the cost of a longer flight time, necessary for completing the loops for the Earth and Venus flybys, and a sizable deep space maneuver, as for the ΔV-Earth–Jupiter gravity-assist trajectory type.

In general, there are other options of trajectories using flybys of other planets. However, the inner planets, notably the Earth, cannot provide a sufficient gravity assist, and a powered swingby of a significant ΔV would be required. As for the outer planets, no feasible flyby trajectories exist within the PKB mission schedule. Among the other mission options analyzed, the one closest to the required PKB mission schedule is the Saturn gravity-assist (SGA) flyby trajectory, but the earliest launch opportunity for a SGA trajectory is in 2009 with a Pluto arrival time no earlier than 2022.

3.2 Launch Opportunities

With either the direct or indirect JGA trajectories, Jupiter must be in the right phase with Earth and Pluto at the time of launch. Additional phase-matching is required if more planetary flybys are involved. An excellent launch opportunity for a JGA trajectory was found to exist in December 2004, when Earth, Jupiter, and Pluto formed an almost perfect phase, allowing a very powerful gravity assist at the Jupiter swingby while maintaining a reasonable distance from Jupiter to avoid high doses of radiation.

The JGA launch opportunity occurs every 13 months (one Earth–Jupiter synodic period), as long as Jupiter does not advance so far as to render its gravity assist unusable for reaching Pluto. The next JGA launch opportunity was found to be in January 2006, which also was the last chance for a launch onto a JGA trajectory to reach Pluto by 2020. However, the velocity boost gained from the Jupiter flyby in 2006 would not be as great as that of the 2004 launch because Jupiter was moving gradually out of phase.

Because of the extra flight time needed for completing the Earth or Venus flybys, the launch opportunity for an indirect JGA trajectory has to occur at least two to three years prior to the time of the direct JGA launch opportunity, assuming that the phasing for the Earth or Venus flybys are right (this would be in the time frame of 2001–2003). Given the

PKB mission schedule of starting Phase B in 2002, it was infeasible to consider any indirect JGA trajectories. Furthermore, the use of a radioisotope thermoelectric generator (RTG) as the onboard power supply also disfavors the indirect JGA trajectories that would include an Earth flyby.

Launches scheduled after 2006 with arrival at Pluto before 2020 required use of the Pluto-direct trajectory. Launch opportunities for the Pluto-direct trajectory occur once every 12 months, and because there is no gravity-assist flyby to gain an extra boost, the direct trajectory requires more launch energy.

3.3 New Horizons Approach

Multiple launch opportunities and trajectory options, including launches in 2004, 2006, and 2007, were considered during the mission planning and development phase. The first mission design developed in 2001 in the initial proposal and concept study was to launch in December 2004. New Horizons would arrive at Pluto in July 2014 through the JGA trajectory, completing the extended mission to the KBOs by 2019.

Because of insufficient funding, in early 2002 NASA directed that the PKB mission could not be ready for launch in 2004. The baseline mission then was revised to launch in January 2006, the last launch opportunity for the JGA trajectory, pushing the earliest Pluto arrival to late 2015. Because the speed boost by Jupiter is much less than that of the 2004 launch case, much higher launch energy was required for the 2006 launch. At the time, the launch vehicle had not been selected yet, and the mission design was required to accommodate whichever launch vehicle NASA would select. The most capable launch vehicles from the two candidate EELV launch vehicle classes, Delta IV Heavy and Atlas V 551, were considered as a reference for designing the mission. These two launch vehicles, however, have significant differences in launch capability, according to the estimated contract performance released from NASA. In order to take advantage of the full potential of each vehicle, two baseline mission designs tailored to the specific performances of each vehicle were developed (Guo and Farquhar 2002). For the Delta IV Heavy vehicle, the baseline mission was to launch in January 2006 and arrive at Pluto in 2015–2016, whereas for the Atlas V 551 vehicle, the arrival time was one year later in 2016–2017.

In July 2003, NASA selected the Atlas V 551 as the launch vehicle for the New Horizons mission. Outfitted with several enhancements tailored specifically to the New Horizons payload, the performance of the Atlas V 551 was improved significantly, and an updated launch vehicle performance curve was provided by NASA's Kennedy Space Center (Cape Canaveral, FL). Based on the latest Atlas performance data, the baseline mission design as well as the backup mission design were determined in October 2003. After that, there were times when alternative Pluto arrival times were studied and considered as possible options in response to concerns of possible lower RTG power and/or the possible situation in which a new KBO is discovered near the predicted New Horizons trajectory path. Eventually, however, the mission was implemented with the baseline mission design developed in October 2003, with some minor adjustments of the Pluto arrival time in response to an update of the new Pluto satellite ephemerides released in March 2005.

A design for a backup mission option was developed alongside the primary launch design, given the potential uncertainties regarding launch and the critical Pluto arrival time constraint. The backup design was planned for launch in February 2007 during a 14-day launch period: arrival at Pluto in 2019 for the first 12 launch days and arrival at Pluto in 2020 for the last 2 launch days, all using the Pluto-direct trajectory. The 2006 baseline, 2007 backup, and other mission scenarios analyzed in detail are listed in Table 2.

Table 2 Mission scenarios to Pluto and KBO

Mission scenario	Launch		Encounter	
	Period	C3 (km^2/s^2)	Body	Year
2006 Baseline JGA or Pluto-direct → Pluto → KBOs	35 days (January 11–February 14)	164	Pluto	2015–2020
2007 Backup Pluto-direct → Pluto → KBOs	14 days (February 2–15)	166.2	Pluto	2019–2020
2006 Launch	20 days (January 10–29)	166	Pluto	2015
JGA → Pluto → KBOs	20 days (January 9–28)	156.7	Pluto	2016
2006 Launch (extended launch period)	16 days (January 30–February 14)	166	Pluto	2019
Pluto-direct → Pluto → KBOs	4 days (February 5–8)	156.7	Pluto	2020
2006 Launch	20 days (January 7–26)	28.2	Pluto	2015
2+ year ΔV EGA → Pluto →	20 days (January 3–22)	28.4	Pluto	2016
KBOs	20 days (December 24–January 13)	28.8	Pluto	2020
2006 Launch	20 days (January 18–February 6)	50.4	Pluto	2015
3+ year ΔV EGA → Pluto →	20 days (January 13–February 1)	50.6	Pluto	2016
KBOs	20 days (January 4–23)	51	Pluto	2020
2006 Launch	20 days (January 27–February 15)	65.1	Pluto	2015
4+ year ΔV EGA → Pluto →	20 days (January 22–February 10)	65.3	Pluto	2016
KBOs	20 days (January 10–29)	65.8	Pluto	2020
2007 Launch	10 days (February 4–13)	165	Pluto	2019
Pluto-direct → Pluto → KBOs	10 days (February 4–13)	162.3	Pluto	2020
2008 Launch Pluto-direct → Pluto & KBOs	10 days (February 7–16)	168.5	Pluto	2020
2008 Launch JGA → Neptune → KBOs	20 days (March 15–April 3)	161	Neptune	2018
2008 Launch JGA → Uranus → KBOs	20 days (March 9–28)	109	Uranus	2015
2008 Launch JGA → KBO (1992 QB1)	20 days (March 8–27)	99	1992 QB1	2025
2009 Launch SGA → Pluto → KBOs	20 days (November 18–December 7)	148	Pluto	2022
2010 Launch SGA → Pluto → KBOs	20 days (November 30–December 19)	143	Pluto	2024

Notes: JGA, Jupiter gravity assist; SGA, Saturn gravity assist; 2+, 3+, 4+ year ΔV EGA, deep space burn-Earth gravity-assist trajectory with time of flight more than 2, 3, or 4 years of the Earth return orbit

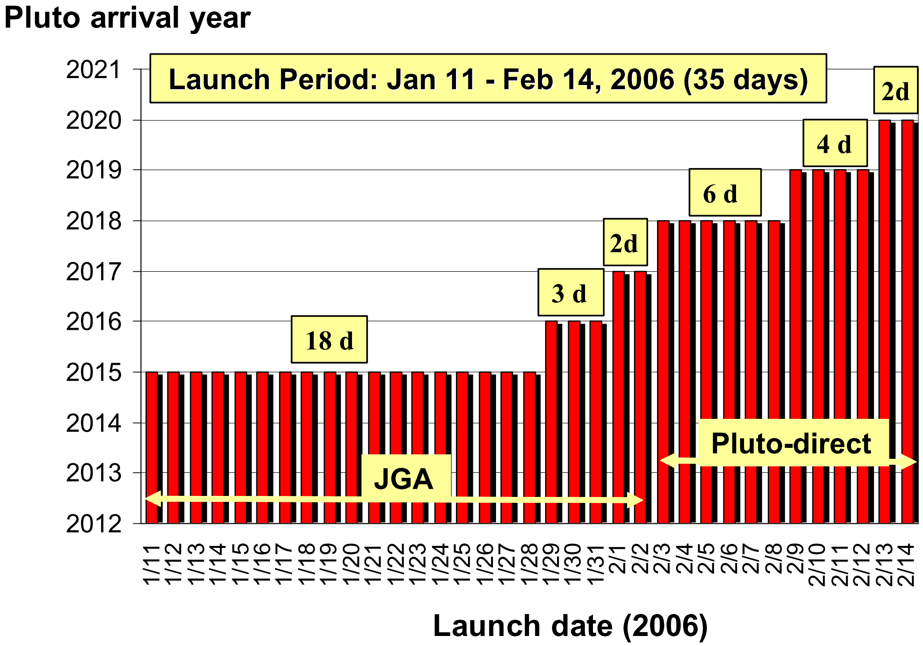


Fig. 1 New Horizons baseline mission design

4 Baseline Mission Design

The goal for the baseline mission design was to reach Pluto at the earliest time possible with the given launch vehicle performance and the required spacecraft launch mass as well as to have a long launch period to maintain a very high launch probability. The baseline mission design had a 35-day launch period starting on January 11, 2006, for the earliest Pluto arrival in 2015 via a JGA flyby trajectory, and ending on February 14, 2006, for the latest Pluto arrival in 2020 via a Pluto-direct trajectory, as shown in Fig. 1. All arrival times for the different arrival years were chosen at the favorable solar opposition seasons in the summer for the best science observations at Pluto–Charon flyby, achieving both Earth and solar occultations by both Pluto and Charon with the desired Pluto–Charon encounter geometry. The design requires maximum launch energy, C3, of 164 $\mathrm{km}^2/\mathrm{s}^2$ and allows for a spacecraft wet mass of 478 kg. The mission is divided into seven distinct phases: launch and early operations, first cruise to Jupiter, the Jupiter flyby, second cruise to Pluto, the Pluto–Charon encounter, post-encounter of science data playback, and the extended mission to KBOs.

4.1 Launch

A prolonged launch period of 35 days from January 11, 2006, to February 14, 2006, was selected for New Horizons, which is almost twice as long as a typical launch period (21 days) for interplanetary missions in order to ensure a very high probability of being launched within the 2006 launch opportunity. The first part of the launch period (January 11–February 2) used the JGA trajectories that get to Pluto as early as 2015, and the later part of the launch period (February 3–14) used the Pluto-direct trajectories with the Pluto arrival time in 2020 as the latest. Experiences with past mission launches indicate that there

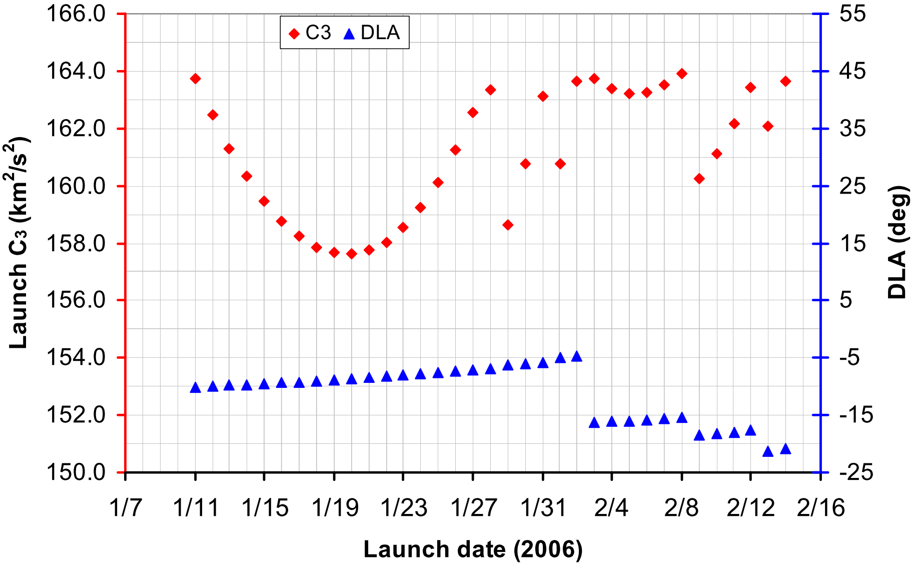


Fig. 2 Launch C3 and DLA requirements

is a much higher chance of launching in the early days of the launch period, which is reflected within the launch period design strategy that started with the earliest Pluto arrival and ended with the latest.

The unusually long launch period did not require extra launch energy and was made possible by

(i) combining the launch opportunities of two different types of trajectories together and
(ii) not fixing but varying the Pluto arrival time, as illustrated in Fig. 1.

The dominant Pluto arrival time is 2015, obtained in the first 18 days of the primary launch period, from January 11 to January 28, 2006, by means of the JGA trajectory. When the 2015 arrival window closed after January 28, the later Pluto arrival times were considered. Continuing with the JGA trajectory, five more days were added to the launch period: three days for the 2016 arrival and two days for the 2017 arrival. When the window for all JGA trajectories closed, the Pluto-direct trajectory was considered to further extend the launch period. This results in 12 extra launch days until the Pluto arrival year reached 2020, which still met the mission requirement for the latest Pluto arrival time. The Pluto arrival time in Fig. 1 is not a continuous curve but jumps from year to year because of certain science geometry requirements at the Pluto flyby. More on the selection of the Pluto arrival time is described in Sect. 4.4.2.

The launch energy requirement for New Horizons is the highest of all space launches to date, about 10 times more than a typical mission to Mars. The launch energy, C3, is defined as the square of the hyperbolic excess velocity (V_∞) of the spacecraft with respect to Earth, a measure related to how much velocity increase must be supplied to the spacecraft by the launch vehicle at launch. The C3 requirements for each launch day for the designed trajectory, whether it is a JGA trajectory or a Pluto-direct trajectory, are shown in Fig. 2. Also included in Fig. 2 are the values of the declination of launch asymptote (DLA) for all launch days. All of the DLA angles are less than the launch site latitude of 28.5°, indicating there is no additional launch penalty from having to perform a plane change.

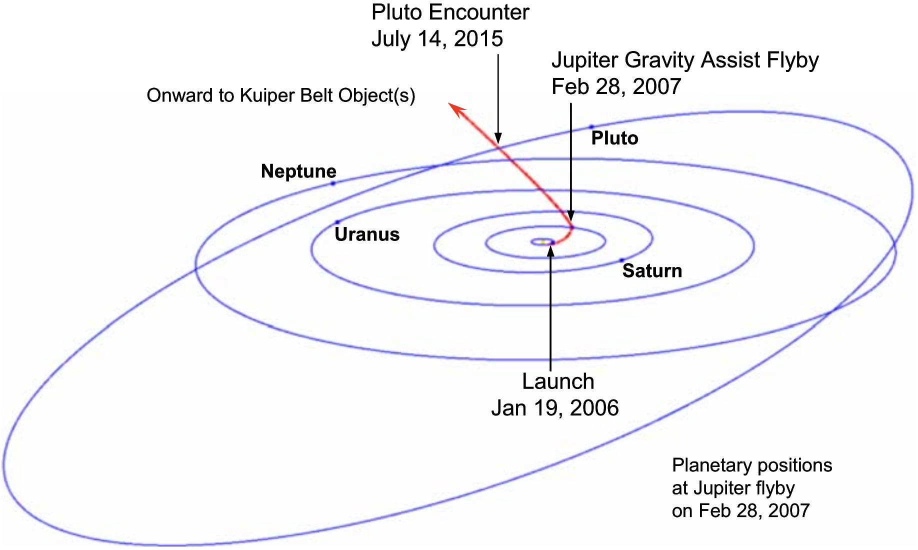


Fig. 3 Interplanetary trajectory

The C3, DLA, and the right ascension of the launch asymptote (RLA)—the launch targets to which the spacecraft must be delivered by the launch vehicle—specify the New Horizons launch requirements. The New Horizons mission trajectory was designed as a ballistic flight from Earth to Pluto with or without the Jupiter flyby. All energy and the associated orbit state required for arriving at Pluto at the desired time and encounter geometry were computed and specified in the launch targets that were provided to the launch vehicle provider. The New Horizons launch required a three-stage rocket consisting of the Atlas V 551 EELV launch vehicle and the Star 48B third stage. The Atlas V 551 is a two-stage rocket supplied by Lockheed Martin. The first stage consists of a common core booster and five strap-on solid rocket boosters, and the second stage is a powerful Centaur booster that has restart capability. The third stage Star 48B is a spin-stabilized solid rocket made by Boeing and customized for the New Horizons mission. The New Horizons spacecraft was placed into an Earth parking orbit by the first stage and the Centaur's first burn. It was then injected into the specified heliocentric trajectory through the combined injection burn supplied by the Centaur (second burn) and the Star 48B after a short coasting in the parking orbit.

4.2 Interplanetary Trajectory

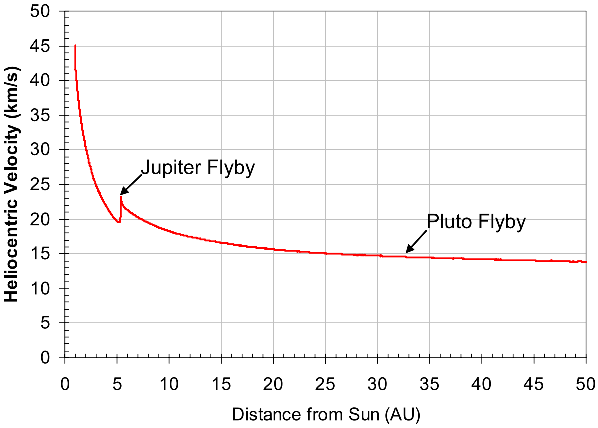
The baseline mission design considered two interplanetary trajectories:

(i) the JGA trajectory for the primary launch period for a fast flight to Pluto and
(ii) the Pluto-direct trajectory for the extended launch period.

The January 19, 2006, launch put the spacecraft into the favorable early Pluto arrival JGA trajectory that flew by Jupiter on February 28, 2007, and will encounter Pluto and Charon on July 14, 2015, as shown in Fig. 3. The flight from Earth to Jupiter only took 404 days; no spacecraft has ever reached Jupiter from Earth in such a short time with such a fast speed.

However, by nature, New Horizons cannot maintain this high speed for its entire flight. During the interplanetary flight toward Pluto, the spacecraft is immersed in the Sun's gravitational field, which slows down the spacecraft along its path as it moves away from the

Fig. 4 Heliocentric velocity of the New Horizons spacecraft over the flight from Earth to Pluto



Sun. The close flyby of Jupiter was designed to inject a speed boost from the appropriate body motions relative to Jupiter. The heliocentric speed of the spacecraft (the magnitude of the spacecraft velocity vector with respect to the Sun) is plotted in Fig. 4 against the solar distance during the flight from Earth to Pluto and beyond. The highest heliocentric speed, as shown in Fig. 4, is at the beginning when the spacecraft was injected into the heliocentric trajectory at launch. The speed then decreased until it reached Jupiter. The speed "jump" was clearly observed at the Jupiter flyby in February and March 2007. An acceleration of 3.83 km/s was gained at the JGA flyby. After that, the speed decreased again because of the Sun's gravity. When the spacecraft reaches Pluto, the heliocentric speed will go down to 14.5 km/s. The speed increase at the Pluto flyby is only a few meters per second, which is not visible from the plot in Fig. 4. After Pluto, the speed will continue to decrease as the spacecraft moves into the Kuiper Belt region and beyond.

The plot in Fig. 5 provides a mission profile showing the spacecraft's distances from the Sun and Earth as a function of time over the mission, along with the Sun–Earth–Probe (SEP) and Sun–Probe–Earth (SPE) angles. The solar distance increases monotonically, as expected, while the distance from Earth oscillates because of the periodic motion of the Earth around the Sun. Both the SEP and SPE angles are periodic. The predicted solar conjunction periods are defined to be when the SEP angle is less than three degrees and are listed in Table 3. There will be no communications expected with the spacecraft during the solar conjunction periods, which occur at the minima of the SEP angle. The solar opposition occurs at the maxima of SEP angle; the predicted solar opposition dates are listed in Table 4.

On the way to Pluto, the spacecraft crosses almost the entire solar system on a path within close proximity of the ecliptic plane. Although it has or will cross the orbits of five planets (Table 5), there will be no close flyby of the planets except for Jupiter. In most of the cases, the planet is very distant when the spacecraft crosses its orbit.

4.3 Jupiter Gravity-Assist Flyby

The Jupiter flyby was aimed at a point slightly below Jupiter's equatorial plane and more than 2.3 million km from Jupiter's center, as illustrated in Fig. 6. The Jupiter flyby trajectory design used the JGA to accelerate the spacecraft and change the trajectory inclination to achieve the desired Pluto encounter. The closest approach (C/A) to Jupiter took place on February 28, 2007. Figure 7 displays the Jupiter flyby geometry at the C/A as observed from above Jupiter's equatorial plane. The spacecraft flew by Jupiter outside the orbits of

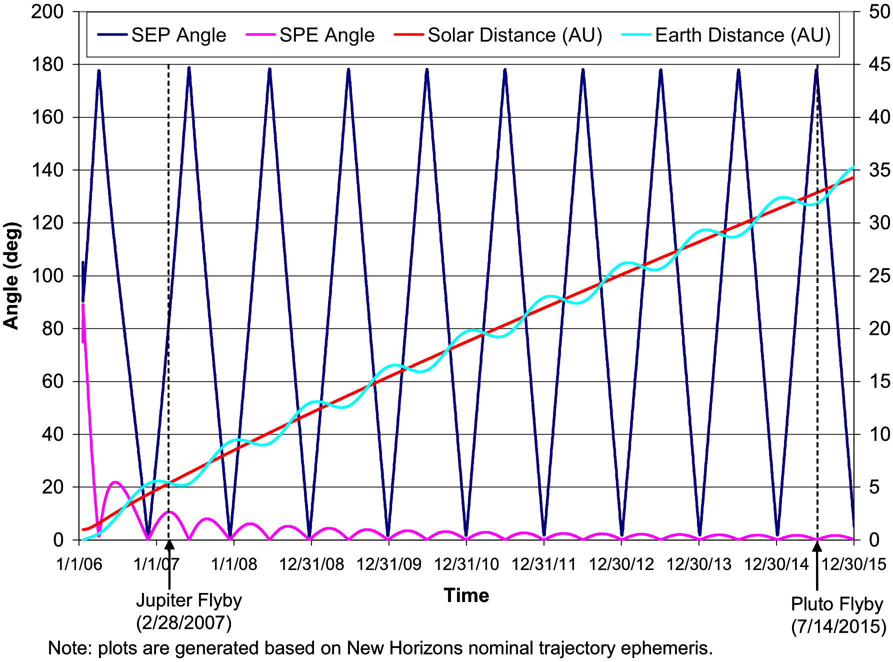


Fig. 5 New Horizons mission profiles of the distances from the Sun and Earth and the SEP and SPE angles

Table 3 Time of solar conjunction

Number of days	Start of conjunction (UTC)	End of conjunction (UTC)
8	11/19/2006 20:00	11/27/2006 12:00
6	12/11/2007 4:00	12/17/2007 11:00
6	12/19/2008 5:00	12/24/2008 21:00
5	12/24/2009 3:00	12/29/2009 12:00
5	12/27/2010 9:00	1/1/2011 13:00
5	12/29/2011 17:00	1/3/2012 17:00
5	12/30/2012 12:00	1/4/2013 10:00
5	12/31/2013 23:00	1/5/2014 19:00
5	1/2/2015 4:00	1/6/2015 23:00
5	1/3/2016 5:00	1/7/2016 23:00

Notes:

1. The listed New Horizons solar conjunction dates are predicted dates when communications between the spacecraft and Earth are blocked by the Sun
2. The conjunction time is computed down to hours with the SEP angle less than three degrees

the Galilean satellites at a speed of 21.2 km/s with respect to Jupiter and at a relatively large distance of 32.25 Jupiter radii (R_J). The radiation doses experienced by the spacecraft are very low at such a great distance.

Besides the large Galilean satellites, there are numerous small irregular Jovian satellites, for a total of 63 satellites discovered in the Jupiter system so far. Many of the small irregular

Table 4 Dates of solar opposition

Solar opposition time (UTC) (Max. SEP angle)	SEP angle (deg)	Spacecraft–Earth distance (AU)
2006-04-06 02:00	177.77	0.61
2007-06-04 12:00	178.87	5.34
2008-06-17 20:00	178.42	9.14
2009-06-24 13:00	178.26	12.68
2010-06-28 14:00	178.17	16.06
2011-07-01 09:00	178.12	19.34
2012-07-02 12:00	178.09	22.54
2013-07-04 04:00	178.06	25.68
2014-07-05 12:00	178.04	28.77
2015-07-06 16:00	178.03	31.83

Table 5 Planet orbit passing dates

Planet	Date	Days from launch
Mars	April 7, 2006	78
Jupiter	February 28, 2007	404
Saturn	June 8, 2008	871
Uranus	March 18, 2011	1884
Neptune	August 24, 2014	3139
Pluto	July 14, 2015	3463

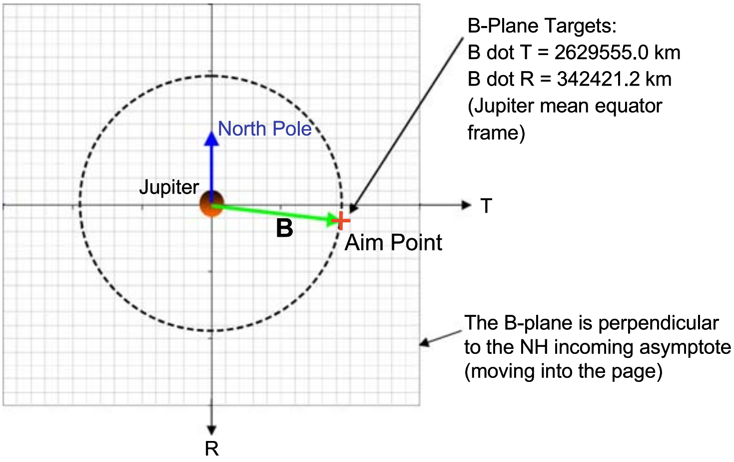


Fig. 6 Jupiter B-plane targeting

ones were discovered in recent years, and knowledge about them is very limited. We always have been interested in and hoped to find close-encounter opportunities with the Jovian satellites during the New Horizons Jupiter flyby. However, the trajectory analyses indicated there are no good close encounters with the Jovian satellites unless a trajectory adjustment

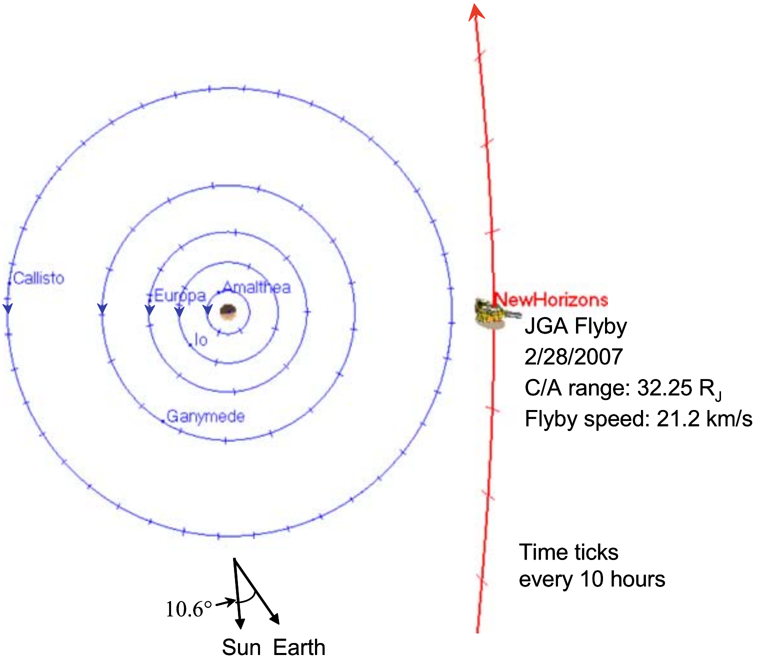


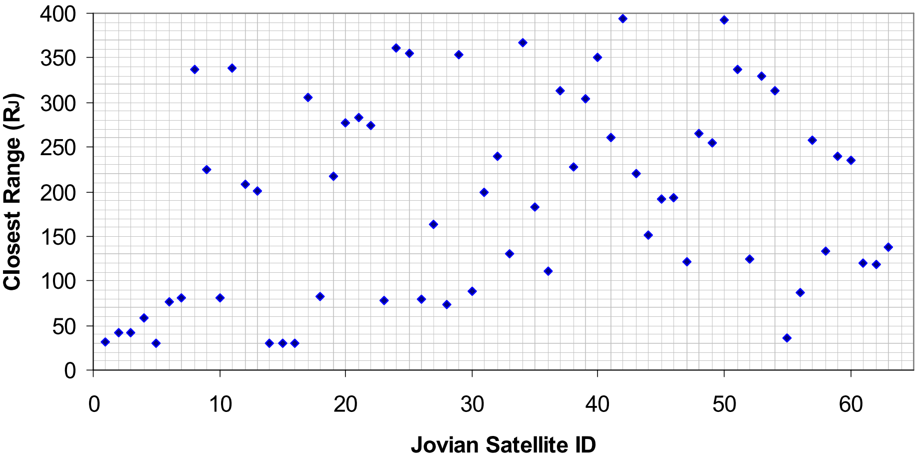
Fig. 7 Jupiter flyby geometry

is performed. The project decided not to expend more ΔV and to save it for the KBOs. Figure 8 shows the C/A distances of the New Horizons spacecraft to the 63 Jovian satellites.

4.4 Pluto–Charon Encounter

The design of the Pluto–Charon encounter trajectory in combination with the selection of the Pluto arrival date and C/A time is a critical part of the mission design because it directly affects how many of the mission's science objectives and goals can be accomplished in the brief Pluto flyby. There are 16 itemized Pluto/Charon science objectives (Table 1) identified in the original NASA PKB mission AO. The New Horizons mission seeks to accomplish 15 of the 16 set objectives (all except the search of magnetic fields) in this first Pluto reconnaissance investigation with seven onboard instruments: ultraviolet (UV) imaging spectrograph ("Alice"), visible and infrared (IR) imager ("Ralph"), Radio science EXperiment (REX), LOng Range Reconnaissance Imager (LORRI), Solar Wind Around Pluto (SWAP), Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI), and Student Dust Counter (SDC).

The Pluto–Charon encounter was challenged by the many science requirements and goals and required careful planning and compromise. The encounter design uses multiple instruments to observe two bodies in a single flyby while conducting coordinated measurements involving four bodies: the Earth, the Sun, Pluto, and Charon. Based on the NASA AO guidelines and the capability and characteristics of New Horizons instruments, the mission design team and the science team worked out the derived science measurement requirements.



ID	Name	ID	Name	ID	Name	ID	Name	ID	Name
1	Io	14	Thebe	27	Chaldene (S/2000_J10)	40	S2002_J1	53	S2003_J13
2	Europa	15	Adrastea	28	S/2000_J11	41	S2003_J1	54	S2003_J14
3	Ganymede	16	Metis	29	Autonoe (S2001_J1)	42	S2003_J2	55	S2003_J15
4	Callisto	17	S/1999_J1	30	Thyone (S2001_J2)	43	S2003_J3	56	S2003_J16
5	Amalthea	18	S/1975_J1	31	Hermippe (S2001_J3)	44	S2003_J4	57	S2003_J17
6	Himalia	19	Kalyke (S/2000_J2)	32	S2001_J4	45	S2003_J5	58	S2003_J18
7	Elara	20	Iocaste (S/2000_J3)	33	S2001_J5	46	S2003_J6	59	S2003_J19
8	Pasiphae	21	Erinome (S/2000_J4)	34	S2001_J6	47	S2003_J7	60	S2003_J20
9	Sinope	22	Harpalyke (S/2000_J5)	35	S2001_J7	48	S2003_J8	61	S2003_J21
10	Lysithea	23	Isonoe (S/2000_J6)	36	S2001_J8	49	S2003_J9	62	S2003_J22
11	Carme	24	Praxidike (S/2000_J7)	37	S2001_J9	50	S2003_J10	63	S2003_J23
12	Ananke	25	Megaclite (S/2000_J8)	38	S2001_J10	51	S2003_J11		
13	Leda	26	Taygete (S/2000_J9)	39	S2001_J11	52	S2003_J12		

Fig. 8 Jovian satellite encounter profile

4.4.1 Science Measurement Requirements

4.4.1.1 Priority Ranking In general, measurements associated with Pluto have higher priority than those associated with Charon. Among the Pluto measurements, group 1 science objectives have higher priority than those of group 2, and group 2 science objectives have higher priority than those of group 3; this also applies to the Charon measurements. When not all requirements can be achieved, the following priority ranking takes place:

A. Pluto Earth occultation
B. Pluto solar occultation
C. Two Deep Space Network (DSN) station coverage during Pluto Earth occultation
D. Charon solar occultation
E. Charon Earth occultation

In the encounter design, the observation selection follows the same priority order as defined for the science objectives. The highest priority is given to the observations for accomplishing the group 1 science objectives: the atmosphere of Pluto and global geology, morphology, and surface composition of Pluto and Charon. In the same measurement category, Pluto is considered the primary observation body. Because Charon also holds essential information for understanding the Pluto–Charon binary system, the mission seeks to take as many measurements of Charon as possible without undermining the fulfillment of the Pluto objectives.

4.4.1.2 Requirements for Remote Sensing The three onboard imaging instruments, Ralph, LORRI, and Alice, are equipped with visible imaging, IR spectral mapping, and UV measurements. They are responsible for implementing the investigation of the global geology, morphology, and surface composition of Pluto and Charon. The critical measurement conditions for the remote sensing are the solar phase angle and the flyby distance. The Pluto arrival condition determines the solar phase angle at encounter, while the appropriate flyby distance depends on the field of view (FOV) of the sensors. Distance from the surface must be less than 25,000 km for the visible imaging to achieve a resolution better than 1 km per pixel, and less than 161,300 km for the IR mapping to achieve a resolution better than 10 km per pixel. The C/A distance to the surface of Pluto is required to be no greater than 25,000 km. To match the instruments' performances and capabilities for imaging a fast-moving body, the desired C/A distance from Pluto's surface currently is selected at about 10,000 km to strike a balance between high spatial resolution and a lack of smear. An overall goal for remote sensing is to cover as much of the surfaces of Pluto and Charon as possible.

4.4.1.3 Requirements for Atmosphere Investigation The atmosphere investigation is carried out primarily by the REX experiments and supported by the Alice measurements. The REX experiments conduct the radiometric measurements of the atmosphere by analyzing the variation of the RF signals passing through the atmosphere that are received by the spacecraft. Alice measures the received UV signals emitted from the Sun and passing through the atmosphere. Both measurements must be performed when occultation takes place. For the Pluto atmosphere, the Earth–Pluto occultation is required for REX measurements and the Sun–Pluto occultation for Alice measurements. In addition, the REX experiments are uplink-based and transmit high-powered signals from the DSN to the spacecraft. Thus, it is highly desirable to have the RF signals transmitted to the spacecraft simultaneously from two DSN complexes during the Earth occultation. This improves the signal-to-noise ratio and provides redundancy, as the spacecraft is at a great distance of 32 AU away from Earth at the Pluto encounter. The search for atmosphere around Charon requires similar REX and Alice measurements at the Earth and Sun occultation by Charon.

In summary, the science measurements require a Pluto–Charon encounter trajectory that has the desired C/A distance to Pluto and enables the occurrences of Earth–Pluto occultation, Sun–Pluto occultation, Earth–Charon occultation, and Sun–Charon occultation as well as the existence of simultaneous uplinks to the spacecraft from two DSN complexes during the Earth occultation. These are very stringent constraints for a single flyby of two bodies. The goal for the Pluto–Charon encounter design is to optimize the encounter geometry and flyby trajectory under the arrival constraints to enable all of the desired science measurements.

4.4.2 Selection of Pluto Arrival Time

The Pluto arrival time is an encounter design parameter. Theoretically, the Pluto arrival can be at any time as long as launch energy permits it. However, to enable the required science measurements described in the previous section, the time of Pluto arrival must be selected when the Earth, the Sun, and Pluto are positioned in such a geometry that can support the formation of the desired Earth and solar occultations by Pluto as well as by Charon. The earliest year to reach Pluto depended on the launch date and the trajectory taken, as shown in Fig. 1. For each year, as the Earth orbits the Sun once, there are two opportunities for the desired occultation geometry when the Earth and Sun are about in a line with Pluto (one in the summer and the other in the winter, as illustrated in Fig. 9), making it possible to achieve both the Earth and the Sun occultations during the flyby of Pluto and Charon. The summer

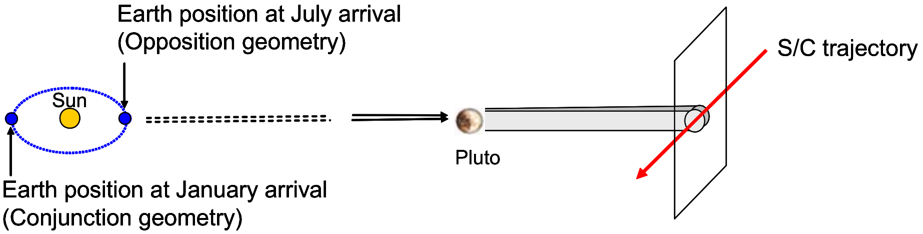


Fig. 9 Options for Pluto arrival time selection

opportunity corresponds to the solar opposition geometry with Earth in between the Sun and Pluto, and the winter opportunity corresponds to the solar conjunction geometry with the Sun positioned in the center between Earth and Pluto. The summer arrival time was selected for the solar opposition geometry, which is more favorable for communications and the REX measurements.

Inclusion of the Charon occultation in the flyby in addition to the Pluto occultation further constrains the time of arrival. There are only two possible times when the Charon occultation can occur during each Charon orbit (6.4 days), once before the spacecraft passes Pluto and the other after passing Pluto. The time of the Charon occultation after passing Pluto was selected for the preferred flyby sequence of approaching Pluto first and Charon second. This flyby sequence results in a flyby geometry of Pluto in front of Charon. The large disk of Charon, about half the size of Pluto, is believed to be able to shed adequate light for imaging the dark surface of Pluto.

Among the potential arrival time options separated by the Charon orbit period within the summer opportunity, only those that result in an Earth–Pluto occultation supported by uplinks from two DSN complexes became candidates for the final encounter trajectory. The time of the Pluto arrival eventually was selected in accordance with the encounter trajectory design that maximizes the overall science accomplishments.

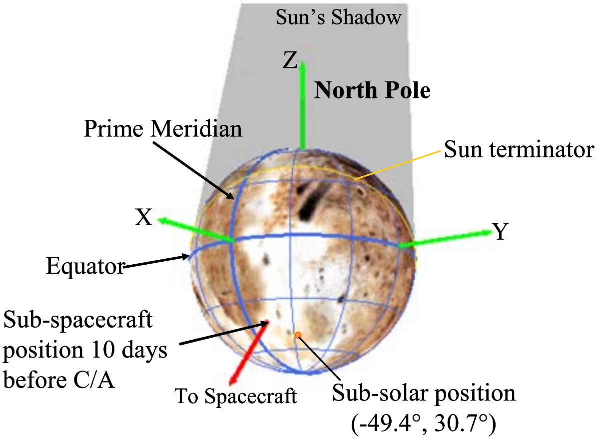
4.4.3 Pluto at Approach

The heliocentric transfer orbit determines the conditions upon arrival at Pluto, such as the solar phase angle and the direction of the incoming trajectory asymptote with respect to Pluto and Charon. The spacecraft is to arrive at Pluto from a heliocentric transfer trajectory inclined 2.34° above the ecliptic plane and to approach Pluto from its southern hemisphere (as shown in Fig. 10) at a solar phase angle of 15°, an excellent illumination condition for a full-spectrum survey of Pluto and Charon on the approaching hemisphere. The subsolar position is at the latitude of 49° south, showing that the southern hemisphere is sunlit and the north portion is in permanent Sun shade. As Pluto rotates at a rate of about 6.4 Earth days, different portion of its surface will be imaged.

4.4.4 Pluto Flyby Trajectory and Geometry

The goal of the Pluto flyby trajectory design is to maximize the required and desired science measurements at Pluto and Charon in accordance with the science measurement priority ranking and requirements as described in Section 4.4.1, providing the necessary supporting geometry and conditions for science measurements during the Pluto flyby. Prior to the delivery of the final launch targets to the launch vehicle provider, the Pluto–Charon encounter

Fig. 10 Pluto at approach



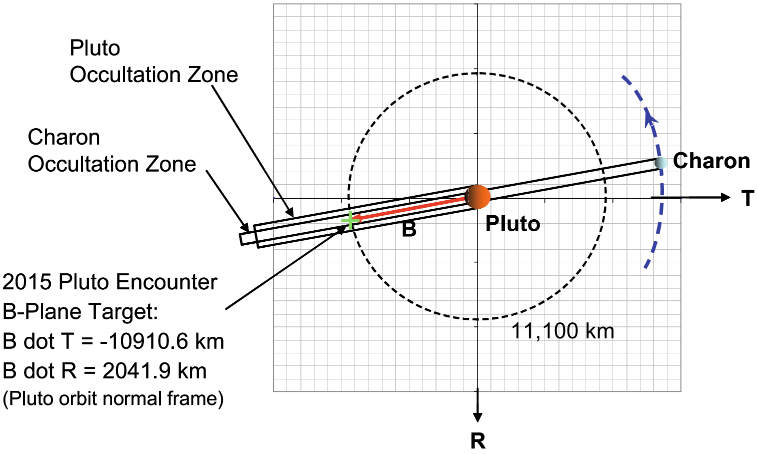


Fig. 11 Pluto B-plane targeting

trajectory design was revised further based on the latest updated planetary and Pluto/Charon ephemerides. Figure 11 illustrates the B-plane targeting at Pluto arrival, which defines the Pluto flyby trajectory. Figure 12 shows the Pluto flyby trajectory and close-encounter geometry, as viewed from the direction perpendicular to the Pluto–Sun line.

New Horizons passes by Pluto and Charon inside Charon's orbit from the same side, which is convenient for switching the observation target from Pluto to Charon for imaging. Charon orbits Pluto in a circular retrograde orbit at a rate synchronized with Pluto's rotation period of 6.387 Earth days, with a mean radius of 19,600 km. The considerable size of Charon (593-km radius) relative to Pluto (1195-km radius) causes the center of mass of the system to lie outside of Pluto, a unique situation in the planetary system. The trajectory crosses Charon's orbital plane at about 43°, and the angle between Charon's orbit normal and the trajectory outgoing asymptote is about 133°.

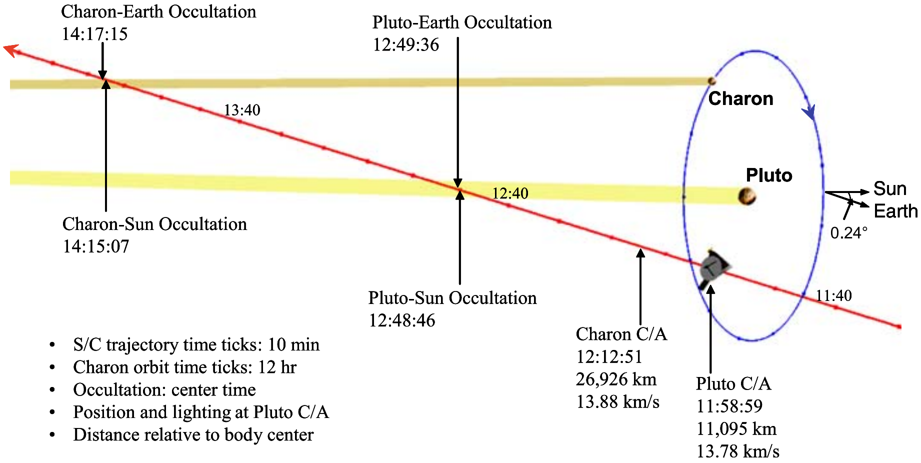


Fig. 12 Pluto–Charon encounter geometry

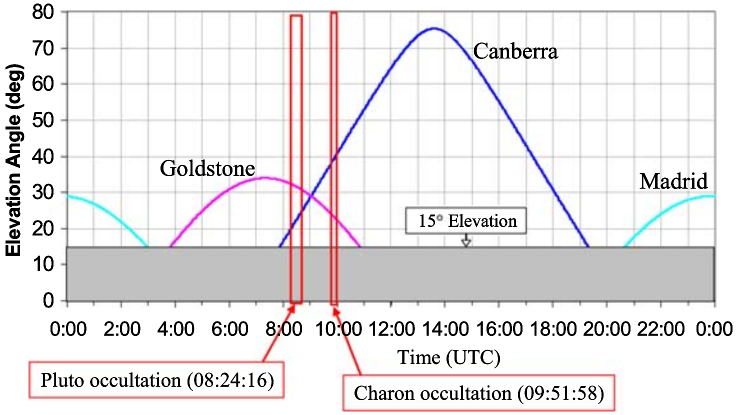
4.4.5 Encounter Sequence and Event Timeline

As shown in Fig. 12, the flyby proceeds in a sequence of encounters, first with Pluto and then followed by Charon. The major flyby events start with the C/A to Pluto on July 14, 2015, at 11:58:59 UTC of spacecraft time, at a distance of 11,095 km from the center of Pluto and a flyby speed of 13.78 km/s. It is followed shortly by the C/A to Charon at 12:12:51 UTC at a C/A range of 26,926 km. Within the next two hours, New Horizons travels through the solar and Earth occultation zones of Pluto and Charon, passing by behind Pluto and Charon. The Pluto occultation occurs first at about 36 minutes after Charon's C/A, and the Charon occultation takes place 1 hour and 26 minutes later. In both cases, the solar occultation starts before the Earth occultation but with a short time separation. During the Earth and solar occultations, the two responsible instruments, REX (which measures the radial signals from Earth) and Alice (which measures the UV signals from Sun), are configured to be capable of handling the measurements simultaneously. The atmosphere investigation will carry on continuously from Pluto through Charon. More detailed encounter parameters and a timeline of the Pluto–Charon flyby events are listed in Table 6.

4.4.6 Deep Space Network Access Profile

During the Earth occultation, two DSN complexes, Canberra and Goldstone, will be in view of the spacecraft and able to transmit RF signals to the spacecraft from both complexes simultaneously. Their access profile is shown in Fig. 13, in which the spacecraft elevation angle from the three DSN complexes, Goldstone, Canberra, and Madrid, are plotted over a period of 24 hours on the day of the Pluto–Charon encounter. The ground transmission time shown in Fig. 13 is 4 hours, 25 minutes, and 19 seconds earlier than the occultation time to account for the light's propagation time.

The desired elevation angle is above 15° to assure adequate transmission of the RF signal from the complexes, although lower elevation angles also may work. The shaded region in Fig. 13 is for elevation angles less than 15°. As the elevation angle profile indicates, the overlapping period of about three hours between Goldstone and Canberra is the only time period when elevation angles are above 15° from two DSN complexes. The Earth occultation



One-way light time delay: 4 hours 25 minutes 19 seconds

Fig. 13 DSN access profile

by Pluto and Charon is targeted to take place within this time period. As Fig. 13 indicates, the spacecraft is accessible simultaneously from Goldstone and Canberra for the time period from before Earth occultation by Pluto through after the Earth occultation by Charon, with sufficient ingress and egress time margins at elevation above 15 degrees.

4.5 Extended Mission to the Kuiper Belt and Beyond

After the flyby of the Pluto system, New Horizons will continue its journey to explore the Kuiper Belt as an extended mission. The plan for the Kuiper Belt exploration is to conduct similar science investigations as carried out at Pluto and Charon, using the same onboard instruments built for Pluto investigations, through a close flyby of one or more KBOs with a size of 50-km diameter or greater.

4.5.1 Plans for Kuiper Belt Object Encounter

The KBO flyby targets will be selected just prior to the Pluto encounter, because the trajectory to Pluto will not be changed regardless of the chosen KBO flyby target. Delaying the selection of the KBO target(s) until 2015 allows for many more years of searching for new KBOs. Plans and resources have been in place to conduct a series of KBO searches from near-Earth orbit (Hubble Space Telescope) and Earth-based observatories in the region of the sky where the New Horizons trajectory is predicted. No candidate KBOs have been identified yet.

One of the preparations for the KBO mission is to develop the strategy and plans to target KBOs with the available onboard resources. The spacecraft, including the communications system, is designed for the KBO mission to go as far as 50 AU from the Sun. However, the onboard power supply is expected to decrease in output as a function of time, so it may impose limitations on spacecraft and instrument operations at a later time. Onboard propellant is a key element that determines how many of the KBOs are accessible to the spacecraft. Current estimates show that there will be as much as 250 $\mathrm{m/s}$ of ΔV capacity left after the Pluto flyby, which is attributed mainly to the accurate orbit injection at launch.

Because of the small mass possessed by Pluto, the gravity assist to be gained from a Pluto flyby is negligible. During the Pluto encounter design, analyses were performed to

Table 6 Pluto–Charon encounter parameters

Pluto encounter date		2015-07-14
Pluto	C/A time	11:58:59
	C/A dist (km)	11095
	C/A vel (km/s)	13.78
Charon	C/A time	12:12:51
	C/A dist (km)	26926
	C/A vel (km/s)	13.88
Pluto–Sun occultation	Start time	12:43:12
	End time	12:54:18
	S/C dist (km)	42609
Pluto–Earth occultation	Start time	12:43:57
	End time	12:55:13
	S/C dist (km)	43272
Charon–Sun occultation	Start time	14:13:36
	End time	14:16:37
	S/C dist (km)	105307
Charon–Earth occultation	Start time	14:15:11
	End time	14:19:17
	S/C dist (km)	107032
Sun–Pluto–Earth angle		0.24°
Earth distance (AU)		31.9
Sun distance (AU)		32.9

Note: Time is spacecraft time in UTC. C/A distances are relative to object center

investigate whether the direction of the outgoing trajectory of the spacecraft could be altered by the Pluto flyby, through adjusting the B-plane aiming point so that the spacecraft could fly toward the first KBO target. The calculations indicated that Pluto can hardly bend the spacecraft flyby trajectory because of its low mass and the relatively high spacecraft flyby speed. This feature clearly is displayed in Fig. 13, where the flyby trajectory is almost a straight line, implying the Pluto flyby cannot help tune the spacecraft's trajectory toward the selected KBO target. Instead, trajectory change maneuvers must be applied for targeting the KBOs.

As soon as two weeks after the Pluto flyby, with the key science data transmitted back to Earth at the 24-hour-per-day continuous playback, a trajectory correction maneuver (TCM) can be applied to alter the spacecraft's trajectory toward the first KBO target. The more time between the execution of the TCM and the encounter date, the less ΔV is required for the needed trajectory adjustment. Limited by the available onboard ΔV capacity, the accessible KBO targets will be in the region near the extended post-Pluto trajectory path, as illustrated in Fig. 14. Large ephemeris uncertainties are expected for the KBO targets because of the short observation time and the targets' great distances from Earth. The plan is to acquire OpNav images of the KBO target by using onboard imagers Multispectral Visible

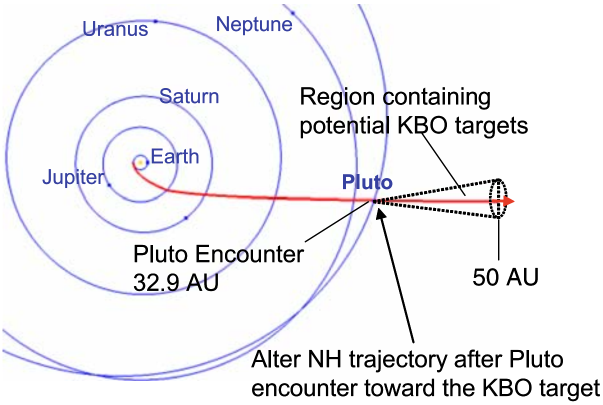


Fig. 14 Mission to the KBOs

Imaging Camera (MVIC) and LORRI to refine the spacecraft trajectory relative to the KBO target. The KBO OpNav images are desired as early as possible so that the trajectory can be corrected with minimum ΔV. Based on the current estimate, the high-resolution imager LORRI is capable of detecting a KBO target (visual magnitude 17.4) as far as 43 days out. Once the KBO OpNav images are obtained, a trim TCM will be executed to correct the KBO position errors. It will be followed with a cleanup TCM to refine the encounter targeting a few days prior to the encounter.

The most likely KBO flyby is estimated to occur in 2018 when New Horizons' heliocentric distance reaches 42 AU, where the distribution of KBO objects over heliocentric distance peaks (Spencer et al. 2003). Exploration of the KBOs is planned to go as far as 50 AU from the sun. The spacecraft will reach the 50-AU distance in 2021 and is expected to encounter one or more KBOs by then.

4.5.2 *Departing the Solar System*

After completing the primary mission to Pluto and the extended mission to the Kuiper Belt, the spacecraft will continue to move out of the solar system in a Sun-escape trajectory. Right after the Pluto flyby, its asymptotic solar system excess velocity is 12.5 km/s, in the direction of right ascension of 293° and declination of 2.1° in the Sun-centered mean ecliptic of J2000 reference frame. The trajectory adjustments to be performed for targeting the KBOs may alter the trajectory slightly, but the onboard propellant is insufficient to stop the spacecraft from escaping from the solar system.

5 Flight Results

New Horizons was launched on January 19, 2006, and successfully injected into the desired heliocentric trajectory as designed. The flight so far has been extremely smooth, and the needed trajectory maintenance has been less than what was planned. After three trajectory corrections that took out the small injection errors, the spacecraft flew by Jupiter on February 28, 2007, and will encounter Pluto on July 14, 2015, as planned.

5.1 Launch and Orbit Injection

At 19:00 UTC (2:00 p.m. EST) on January 19, 2006, New Horizons lifted off from Launch Complex 41 at Florida's Cape Canaveral Air Force Station atop the Star 48B aboard the

Table 7 Launch targets: achieved versus designed

Launch targets	A—Designed	B—Achieved	Injection error (B − A)	Predicted 3σ injection error*
C3 ($\mathrm{km}^2/\mathrm{s}^2$)	157.6561	157.7502	0.0941	0.4245
DLA (deg)	−8.8407	−8.8683	−0.0276	0.3307
RLA (deg)	209.3855	209.3124	−0.0731	0.3603

Notes: A, required launch target specified by the Mission Design Team; B, launch target derived from the determined trajectory (OD005 solution) provided by the Navigation Team based on post-launch DSN tracking data

*Based on Boeing Trajectory Cycle 3 report

Atlas V launch vehicle. It first was inserted into an elliptical Earth parking orbit of perigee altitude 165 km and apogee altitude 215 km. After a short coast in the parking orbit, the spacecraft then was injected into the desired heliocentric orbit by the Centaur second stage and Star 48B third stage. At the Star 48B burnout, the New Horizons spacecraft reached the highest Earth departure speed, estimated at 16.2 km/s, becoming the fastest spacecraft ever launched from Earth. In less than nine hours, it passed by the Moon at a distance of 184,700 km from Moon center.

The conditions for injection into the heliocentric orbit were defined as launch targets specified in C3, DLA, and RLA at the target interface point (TIP) defined as 10 minutes after Star 48B ignition. The designed and achieved launch targets along with the actual injection errors and the 3σ values are presented in Table 7. The orbit injection was remarkably accurate, with the orbit injection errors much less than 1σ.

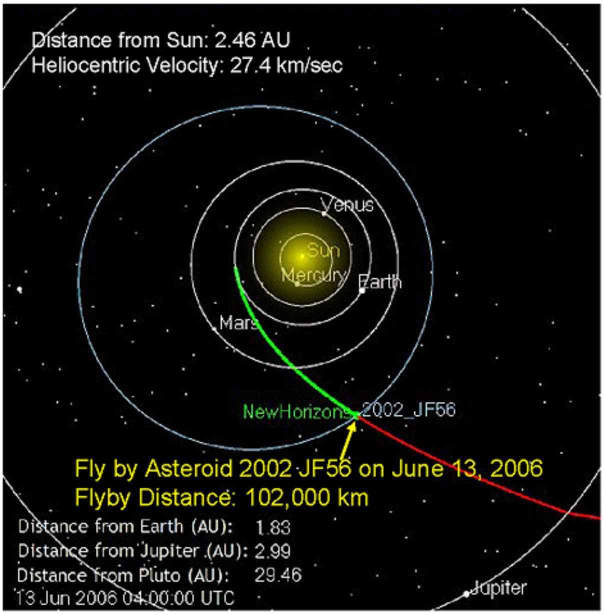
By targeting New Horizons to the designed Pluto B-plane aim point with an optimized Jupiter flyby from the injected TIP state, the ΔV required for correcting the injection errors at TIP was determined at 18.2 m/s. Most of the ΔV is for adjusting the velocity direction by 0.069°, or 1.2 mrad, and a small portion of it is for reducing the 4-m/s overburn. The ΔV budgeted for injection error correction was 92 m/s with 99% probability. Consequently, a significant amount of propellant now is available and can be used for targeting the KBOs.

5.2 Summary of Trajectory Corrections

Since launch, a total of three TCMs have been performed thus far. These trajectory corrections removed all the launch errors associated with orbit injection and placed New Horizons into the designed trajectory to Jupiter.

The first two TCMs, TCM-1A and TCM-1B, were designed together in a pair and implemented in a manner that minimized mission risk. The very first trajectory maneuver of the spacecraft was decided to be executed using the passive spin TCM (PS-TCM) mode, which is an open-loop axial ΔV execution without the guidance and control (G&C) system in control. TCM-1A served as a calibration burn to verify that the misalignment or unbalanced thruster performance of the paired thrusters would not make the spacecraft unstable and was limited to a magnitude of 5 m/s to avoid any chance of destabilizing the spacecraft. If the TCM was executed as planned, TCM-1B would complete the needed ΔV by carrying out the remaining part of the ΔV implemented in the same PS-TCM mode and the same pair of thrusters as used for TCM-1A. TCM-1A, with a nominal magnitude of 5 m/s, was executed successfully on January 28, 2006, nine days after launch, and TCM-1B, with a nominal magnitude of 13.32 m/s, was applied successfully two days later on January 30, 2006.

Fig. 15 Flyby of asteroid 2002 JF56 on June 13, 2006



Both TCM-1A and TCM-1B were terminated by timing. There was about 6% underburn attributed to thruster performance that did not match the expected values obtained from pre-launch thruster tests. TCM-2, originally scheduled on February 15, 2006, was canceled because the orbit solution at the time had an uncertainty that was comparable to the ΔV values. On March 9, 2006, TCM-3 was applied with a nominal magnitude of 1.16 m/s to make up the 6% underburn from the previous two TCMs. TCM-3 was implemented with the three-axis TCM (3A-TCM) mode, which is a closed-loop ΔV execution with G&C system in control of the burn. TCM-3 was very accurate, with only a small execution error (0.01%). Because the trajectory errors are so small, the project has decided not to perform any TCMs before the Jupiter flyby. TCMs-4, -5, -6, and -7, which were scheduled at 76, 20, and 5 days before the Jupiter flyby and 15 days after the Jupiter flyby, respectively, were canceled. The next trajectory correction (TCM-8) is planned in September 2007, after the Jupiter flyby.

5.3 Flyby of Asteroid 2002 JF56

On June 13, 2006, New Horizons flew by a small asteroid designated 2002 JF56 at a C/A distance of 102,000 km, as shown in Fig. 15. This unexpected close encounter offered a great opportunity for the New Horizons spacecraft to perform a Pluto-like pointing and tracking exercise to test both the G&C ability of attitude control of scanning and pointing and the instrument performance of Ralph imager. The high-resolution imager, LORRI, was unable to participate in this exercise because New Horizons was still too close (<3 AU) to the Sun, and door opening still was restricted.

5.4 ΔV Status

At launch, a total of 76.85 kg of propellant was loaded on the spacecraft. The propellant is for TCMs and for spacecraft attitude maneuvers. The spacecraft has a blow-down monopropellant hydrazine propulsion system consisting of a central tank, 12 0.8-N attitude control system (ACS) thrusters, and 4 4.4-N TCM thrusters. The propellant usage for the trajectory corrections has been much less than the pre-launch budgeted amount. So far, about 9 kg of propellant has been used. Furthermore, it is estimated that there will be as much as 47 kg of propellant remaining after the Pluto flyby for the Kuiper Belt mission, corresponding to a ΔV capacity of 250 $\mathrm{m/s}$.

6 Conclusion

After five years of planning and revisions, the New Horizons mission design was finalized, and the spacecraft was launched successfully on January 19, 2006. The spacecraft was injected into the favorable JGA trajectory to Pluto, flew by Jupiter on February 28, 2007, and gained a significant speed boost well on its way to encounter Pluto on July 14, 2015. Using Jupiter's gravity assist in the trajectory design shortened the time of flight to Pluto by three years and provided a great opportunity for preparing the team for the upcoming Pluto encounter and for acquiring a great deal of Jupiter science data as a bonus to the mission.

The launch of New Horizons used a strategy that combined the launch opportunities of two different types of trajectories and allowed the Pluto arrival time to vary from an early arrival to a late arrival. With this strategy, the launch energy good for an 18-day launch period also was adequate for a 35-day launch period, thus maintaining the early arrival preference and extending the launch period without increasing the required launch energy.

The high accuracy in trajectory simulation was maintained throughout the trajectory design by using a fully integrated trajectory with high-fidelity models updated with the latest planetary and Pluto ephemerides. High-precision computations of the trajectory for each of the 35 launch days, integrated from TIP to Jupiter flyby and to Pluto encounter and beyond, ensured minimum trajectory adjustments and corrections post-launch. Precisely specifying the launch targets for the orbit injection conditions and accurate delivery of the spacecraft by the launch vehicle and third stage resulted in a remarkable orbit insertion that saved significant onboard propellant. Since launch, New Horizons' flight has been extremely efficient, closely following the designed trajectory. Five of the eight planned TCMs from launch through post-Jupiter flyby were canceled because they were not needed. Many of the lessons learned and strategies used for the New Horizons mission design can be applied to the design of future missions.

Acknowledgements The authors thank New Horizons Principal Investigator, Alan Stern; the science team for their support and review of the Pluto–Charon encounter design; and the Jet Propulsion Laboratory for providing the planetary and satellite ephemerides. The authors also thank Tom Strikwerda for review and helpful edits on this manuscript. This work was supported by NASA under contract no. NAS5-97271.

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