New Horizons Mission Design

YANPING GUO and ROBERT W. FARQUHAR

Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, U.S.A.

(e-mail: yanping.guo@jhuapl.edu, robert.farquhar@jhuapl.edu)

Abstract The mission design for the New Horizons mission went through more than five years of numerous revisions and updates before its launch on January 19, 2006. For the baseline mission design, the New Horizon spacecraft is expected to fly by Jupiter on February 28, 2007 to gain a needed speed boost and encounter Pluto on July 14, 2015 after a 9.5-year journey from launch, followed by extended mission to Kuiper Belt objects. In order to meet the New Horizons mission design objectives, requirements and goals, various mission design scenarios regarding routes to Pluto and launch opportunities have been investigated. 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 are found for the Pluto-Charon encounter in the baseline design to enable all of the desired science measurements for the mission. The New Horizons mission trajectory was designed as a thrust-free flight from Earth to Pluto. 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 New Horizons spacecraft's flight so far has been extremely smooth, with the needed trajectory error correction ΔV being much less than the amount budgeted for.

Table of Contents

1. Introduction

The early mission design work for New Horizons mission was started in late 2000, shortly after NASA terminated the "Pluto-Kuiper Express" program due to unmanageable cost increases. A team at the Johns Hopkins University Applied Physics Laboratory (JHU/APL), that had just successfully completed the NEAR project with an unprecedented asteroid landing, was assembled to put together a feasible mission implementation plan, including the early mission design concept, hoping to save the long-sought mission to Pluto, the only remaining planet (at the time Pluto was still the 9th planet) not yet visited. Urged 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 was evolved and became a part of New Horizons mission proposal, led by Principal Investigator Alan Stern of Southwest Research Institute. The proposal was submitted to NASA and was selected for a three-month concept study (Phase-A). 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 successfully launched on January 19, 2006. It was launched atop a three-stage rocket in accordance with an updated baseline mission design utilizing a Jupiter-gravity-assist trajectory to Pluto. The spacecraft is expected to fly by Jupiter on February 28, 2007 to gain a needed speed boost and encounter Pluto on July 14, 2015 after a 9.5-year journey from launch, followed by extended mission to Kuiper Belt objects, all as planned. In this paper, New Horizons mission design objectives, requirements and goals are discussed, and various mission design scenarios regarding routes to Pluto and launch opportunities are reviewed. Among them, the baseline mission design is described in detail, covering the key aspects of launch window, interplanetary trajectory, Jupiter gravity assist flyby, Pluto-Charon encounter with science measurement requirements, and extended mission to the Kuiper Belt and beyond. Analyses o the launch data and the early post-launch flight results are also presented.

2. Mission Design Requirements

The scope of the PKB mission, the science requirements, and 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 further identified as either a requirement (an objective that must be accomplished by the mission) or a goal (a desirable objective). The tasks of the New Horizons mission design, especially the launch window design, the interplanetary trajectory design, the Pluto encounter and the ΔV budgeting, were in principle guided and bounded by mission objectives, program requirements and constraints identified in the AO.

2.1 Mission Scope and Objectives

The principal goal of the PKB mission is to perform high-quality scientific investigations of the Pluto-Kuiper Belt region of the solar system according to the NASA AO (NASA, 2001). Pluto was discovered by Clyde Tombaugh in 1930 and is currently located more than 31 Astronomical Units (AU) from the Sun. Spacecraft have been sent to the other eight planets but not yet 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). The Pluto mission is certainly one of the most challenging deep space missions. Our current knowledge about Pluto is based on observations taken from the ground and Earth orbits. Pluto orbits the Sun in 248 earth years in one revolution in an elliptical orbit of with a perihelion of 29.7 AU and aphelion of 49.4 AU. Its orbit is inclined 17 degrees from the ecliptic plane in contrast to the other planets which reside within a few degrees of the 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 was often regarded as a binary system because the center of mass of the system 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 as the Kuiper Belt. It was named after Gerald Kuiper, who predicted in 1951, as a hypothesis, that the short-period comets originate from a collection of material left over from the formation of the solar system. Kuiper's theory was proved with the discovery of the first Kuiper belt object by David Jewitt and Jane Luu (Jewitt and Luu, 1993) in 1992. Since then, numerous Kuiper Belt Objects (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. For the first time, the PKB mission aims to explore the Kuiper Belt region by visiting one or more KBOs in an extended mission following the Pluto-Charon encounter. The KBO encounter is a highly desired mission goal, 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.

Table 1. Science Objectives at Pluto and Charon

Group 1 Objectives: • Characterize the global geology and morphology of Pluto and Charon; • Map surface composition of Pluto and Charon; and • Characterize the neutral atmosphere of Pluto and its escape rate.
Group 2 Objectives: • 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, H2, 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; and • Map the surface temperatures of Pluto and Charon.
Group 3 Objectives: • Characterize the energetic particle environment of Pluto and Charon; • Refine bulk parameters (radii, masses, densities) and orbits of Pluto and Charon; • Search for magnetic fields from Pluto and Charon; and • Search for additional satellites and rings.

2.3 Program Requirements and Constraints

The Pluto-Kuiper Belt mission is divided into two mission phases in terms of program requirements: the primary mission to Pluto, a mission requirement, and the extended mission to the Kuiper Belt objects, a mission goal. The total cost for the mission was required to be capped at $500 Million of FY2001 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 AO for the PKB mission were the new Evolved Expandable Launch Vehicles (EEVL) classes, either Atlas V or Delta IV. The upper kick stage was not included in the launch vehicle package but was a choice of the mission implementation team.

The NASA AO set a firm deadline for the time of Pluto-Charon encounter. The mission is required to arrive at Pluto as early as possible, not later than the 2020 timeframe. This is mainly driven 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. The planet's highly eccentric and inclined orbit causes its environment to change dramatically 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, the shadow covering Pluto's northern cap will increase in size as its north pole tilts farther away from the Sun. More surface area will fall into the shadow, and consequently less surface area can be imaged.

3. Mission Design Scenarios

Various trajectory options to get to Pluto and the associated launch opportunities were analyzed in order to determine and select the best mission design that will not only meet the 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 has been revised many times, and several mission 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 is so far one of the most demanding launches of all the interplanetary missions. The launch energy required for a direct flight to Pluto tops all those required to any other planet due to Pluto being the most distant planet. This imposes a significant challenge to the performance of available launch vehicles. In order to ease the high launch energy demand, alternative routes that require lower launch energy are always preferable over the direct flight.

In terms of launch energy, the best route to Pluto is via a Jupiter gravity assist (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 requiring lower launch energy compared to a direct flight of the same time of flight. The launch energy difference made by the JGA trajectory is indispensable and sometimes crucial for mission feasibility, especially when launch vehicle's performance is insufficient for 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 3-year ΔV-Earth-JGA approach (Farquhar and Stern, 1990) and the Venus-Venus-Earth-JGA trajectory (Weinstein, 1992). These indirect JGA trajectories include additional Earth or Venus-and-Earth flybys before approaching Jupiter, further reducing the launch energy to the level that a small launch vehicle would be sufficient. However, 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-JGA trajectory type.

In general, there are other options of trajectories utilizing 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 radiation doses.

As long as Jupiter is positioned in phase with Earth and Pluto, the JGA launch opportunity occurs about once every 13 months as a result of the Earth orbit period (12 months) relative to the motion of Jupiter, as the angular displacement of Pluto in 13 months is insignificant. The next JGA launch opportunity was found to be in January 2006, which was also the last chance for a launch onto a JGA trajectory to reach Pluto by 2020, though the velocity boost gained from the Jupiter flyby would not be as great as that of the 2004 launch because Jupiter was gradually moving out of phase.

Due to 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 2-3 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 would be infeasible to consider any indirect JGA trajectories. On the other hand, the use of Radioisotope Thermoelectric Generator (RTG) as the onboard power supply also disfavors the indirect JGA trajectories that would include an Earth flyby.

For launches later than 2006 with arrival at Pluto before 2020, the Pluto-direct trajectory must be used. Launch opportunity for the Pluto-direct trajectory is once every twelve months. Since there is no gravity assist flyby to gain 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 the 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 Kuiper Belt objects 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 was then revised to launch in January 2006, the last launch opportunity for the JGA trajectory, pushing the earliest Pluto arrival to late 2015. Since the speed boost by Jupiter is much less than that of the 2004 launch case, much higher launch energy is required for the 2006 launch. At the time, the launch vehicle had not yet been selected, and the mission design was required to accommodate whichever launch vehicle NASA would select. The most capable launch vehicles from the two candidate EEVL launch vehicle classes, Delta IV Heavy, and Atlas V 551, were considered as a reference for designing the mission. The 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 their individual full potentials, two baseline mission designs respectively tailored to the specific performances of the two vehicles were developed (Guo and Farquhar, 2002). For the Delta IV Heavy, the baseline mission was to launch in January 2006 and arrive at Pluto in 2015-2016, while for the Atlas V 551, the arrival time was one year later in 2016-2017.

In July 2003 NASA selected Atlas V 551 as the launch vehicle for the New Horizons mission. Injected with several enhancements tailored specifically to the New Horizons payload, the performance of the Atlas V 551 had been improved significantly and an updated launch vehicle performance curve was provided by NASA Kennedy Space Center. Based on the latest Atlas performance, the baseline mission design as well as the backup mission design was 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 that a new KBO object is discovered near the predicted NH trajectory path. But eventually, 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 had always been carried on with the primary launch design, given the potential of launch uncertainty and the critical Pluto arrival time constraint. The backup design associated with the baseline 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 two launch days, all using the Pluto-direct trajectory. Other mission scenarios analyzed in details are listed in Table-2.

Table 2. Analyzed Alternative Mission Options to Pluto and KBO

Mission Scenario	Launch Window	Launch C3 (km2/s2)	Encounter Body	Encounter Year
2006 Launch JGA → Pluto → KBOs	20 days (Jan 10-29)	166	Pluto	2015
	20 days(Jan 9–28)	156.7	Pluto	2016
2006 Launch (extended launch window) Pluto-direct → Pluto → KBOs	16 days (Jan 30 – Feb 14)	166	Pluto	2019
	4 days (Feb 5 – 8)	156.7	Pluto	2020
2006 Launch 2+year ΔVEGA → Pluto → KBOs	20 days (Jan 7 -26)	28.2	Pluto	2015
	20 days (Jan 3 – 22)	28.4	Pluto	2016
	20 days (Dec 24 – Jan 13)	28.8	Pluto	2020
2006 Launch 3+year ΔVEGA → Pluto → KBOs	20 days (Jan 18 – Feb 6)	50.4	Pluto	2015
	20 days (Jan 13 – Feb 1)	50.6	Pluto	2016
	20 days (Jan 4 – 23)	51	Pluto	2020
2006 Launch 4+year ΔVEGA → Pluto → KBOs	20 days (Jan 27 – Feb 15)	65.1	Pluto	2015
	20 days (Jan 22 – Feb 10)	65.3	Pluto	2016
	20 days (Jan 10 – 29)	65.8	Pluto	2020
2007 Launch Pluto-direct → Pluto → KBOs	10 days (Feb 4–13)	165	Pluto	2019
	10 days (Feb 4-13)	162.3	Pluto	2020
2008 launch Pluto-direct → Pluto & KBOs	10 days (Feb 7 – 16)	168.5	Pluto	2020
2008 launch JGA → Neptune → KBOs	20 days (Mar 15 - Apr 3)	161	Neptune	2018
2008 launch JGA → Uranus → KBOs	20 days (Mar 9 - 28)	109	Uranus	2015
2008 launch JGA → KBO (1992 QB1)	20 days (Mar 8 - 27)	99	1992 QB1	2025
2009 launch SGA → Pluto → KBOs	20 days (Nov 18 - Dec 7)	148	Pluto	2022
2010 launch SGA → Pluto → KBOs	20 days (Nov 30 - Dec 19)	143	Pluto	2024

Note:
JGA = Jupiter gravity assist, SGA = Saturn gravity assist,
2+, 3+, 4+year ΔVEGA = deep space burn – Earth gravity assist trajectory with time of flight more than 2, 3, or 4 years of the Earth return orbit

4. Baseline Mission Design

The goal for the baseline mission design was to get to Pluto at the earliest time possible with the given launch vehicle performance and the required spacecraft launch mass, and to also maintain a very high launch probability. The baseline mission design consists of a 35-day launch period starting on January 11, 2006 for the earliest Pluto arrival in 2015 via a Jupiter gravity assist flyby trajectory and ending on February 14 for the latest Pluto arrival in 2020 via a Pluto-direct trajectory, as shown in Figure 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 km^2/s^2 and allows for spacecraft wet mass of 478 kg. The mission is divided into 7 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.

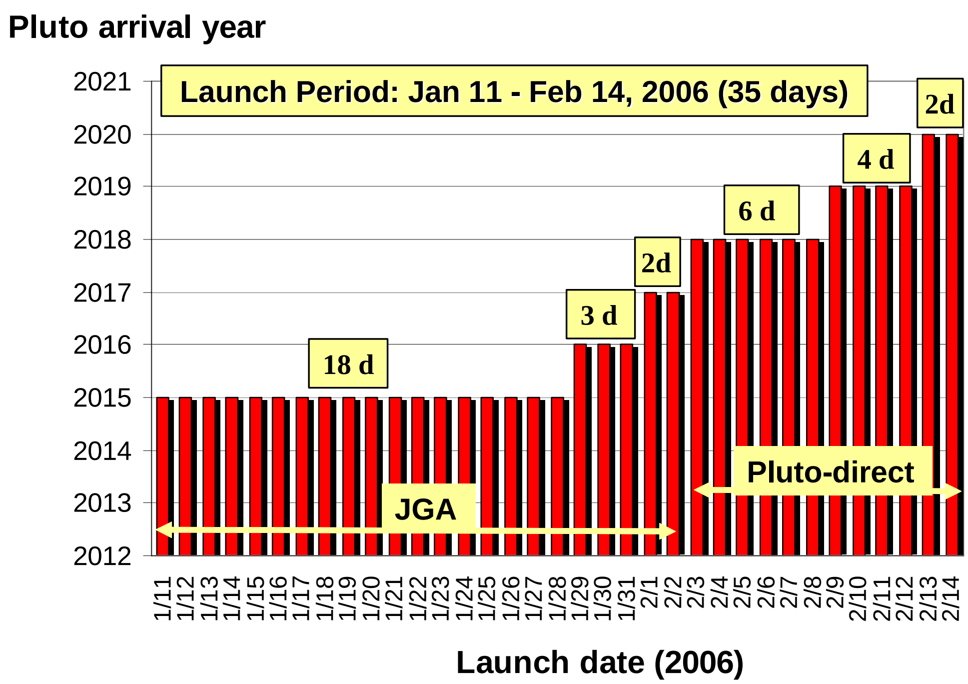


Figure 1. New Horizons Baseline Mission Design

4.1 Launch

A prolonged launch period was selected for New Horizons from January 11, 2006 to February 14, 2006, a total of 35 days, almost twice as long as a typical launch period usually set 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) uses the JGA trajectories that get to Pluto as early as 2015, and the later part of the launch period (February 3-14) uses the Pluto-direct trajectories with the Pluto arrival time in 2020 as the latest, the AO deadline. Experiences with past mission launches indicate there is a much higher chance to be launched in the early days of the launch period. This 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 didn't require extra launch energy, and was made possible by a) combining the launch opportunities of two different types of trajectories together, and b) not fixing but varying the Pluto arrival time, as illustrated in Figure 1. The dominant Pluto arrival time is 2015, which occurs for the primary launch period of the first 18 days from January 11 to January 28, 2006 by means of the JGA trajectory. When the 2015 arrival window closes after January 28, the later Pluto arrival times are considered. Continuing with the JGA trajectory, five more days are added to the launch period, 3 days for the 2016 arrival and 2 days for the 2017 arrival. When the launch window for all JGA trajectories closes, the Pluto-direct trajectory is considered to further extend the launch period. This results in 12 extra launch days until the Pluto arrival year reaches 2020, which still meets the mission requirement for the latest Pluto arrival time. The Pluto arrival time in Figure 1 is not a continuous curve but jumps from year to year, due to certain science geometry requirements at the Pluto flyby. More on the selection of the Pluto arrival time is described in Section 4.4.2.

New Horizons' launch energy requirement is the highest of all space launches made to date, about 10 times of that for 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 calculated for each launch day for the designed trajectory, whether it is a JGA trajectory or a Pluto-direct trajectory, are shown in Figure 2. Also included in Figure 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 that there is no launch penalty.

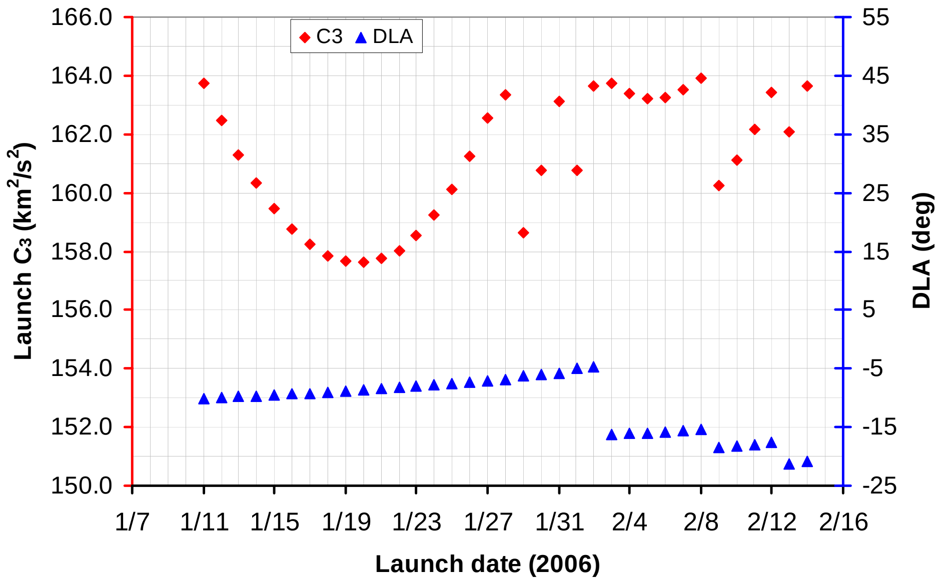


Figure 2. Launch C3 and DLA Requirements

The C3, DLA, and the right ascension of the launch asymptote (RLA), specify New Horizons launch requirements, referred to as the launch targets to which the spacecraft must be delivered by the launch vehicle. The New Horizons mission trajectory was designed as a thrust-free 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 requires 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 the 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 is first placed into an Earth parking orbit by the first stage and the Centaur's first burn, and 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: the JGA trajectory for the primary launch period for a fast flight to Pluto and the Pluto-direct trajectory for the extended launch period. The January 19 launch has put the NH spacecraft into the favorable early Pluto arrival JGA trajectory that is to fly by Jupiter on February 28, 2007 and encounter Pluto and Charon on July 14, 2015, as shown in Figure 3. The flight from Earth to Jupiter only takes 404 days; no spacecraft has ever reached Jupiter from Earth in such a short time with such a fast speed.

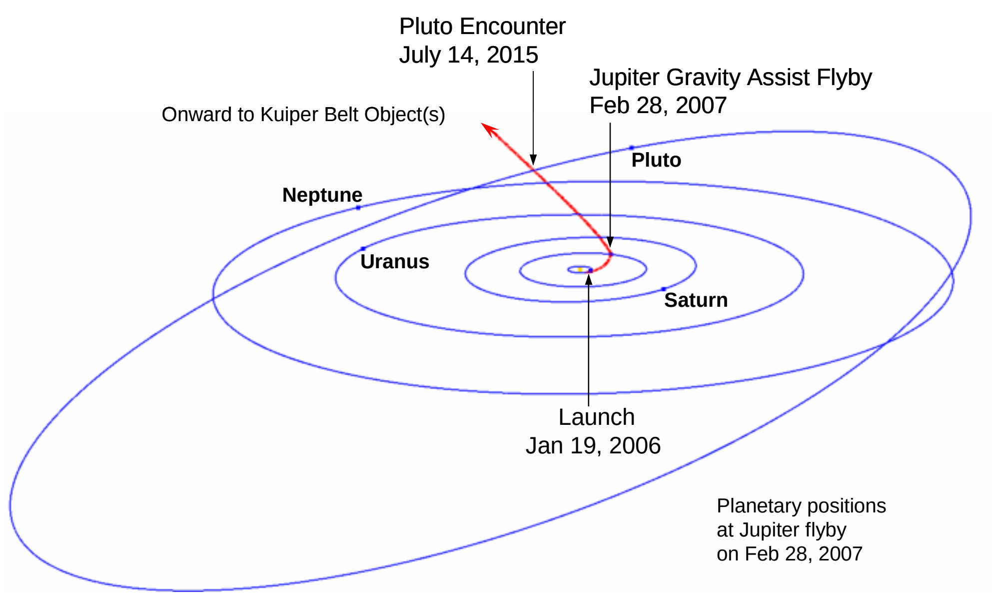


Figure 3. Interplanetary Trajectory

However, by nature, New Horizons cannot maintain the same high speed for its flight. During the interplanetary flight towards Pluto, the spacecraft is immersed in the Sun's gravity field which slows down the spacecraft along its path as it moves away from the Sun. By design, the close flyby of Jupiter is to inject a speed boost from the appropriate body motions relative to Jupiter. The heliocentric speed of the spacecraft, magnitude of the spacecraft velocity vector with respect to the Sun, versus the solar distance during the flight from Earth to Pluto and beyond is plotted in Figure 4. The highest heliocentric speed, as shown in Figure 4, is at the beginning when the spacecraft is injected into the heliocentric trajectory at launch. The speed then decreases until it reaches Jupiter. The speed "jump" is clearly observed at the Jupiter flyby in Feb-March 2007. An acceleration of 3.83

km/s is to be gained at the JGA flyby. After that, the speed decreases again due to 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 Figure 4. After Pluto, the speed continues to decrease as the spacecraft moves into the Kuiper Belt region and beyond.

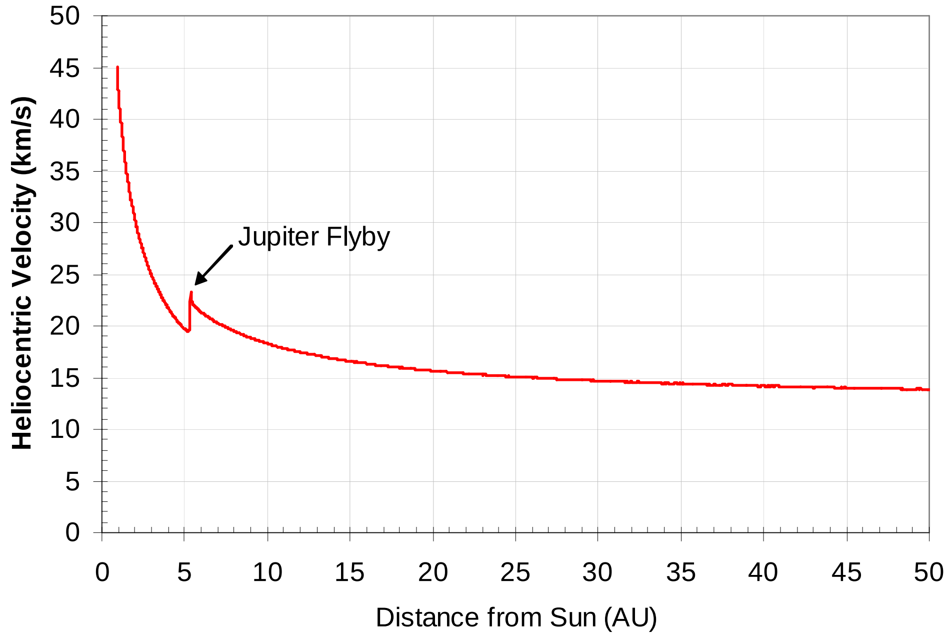
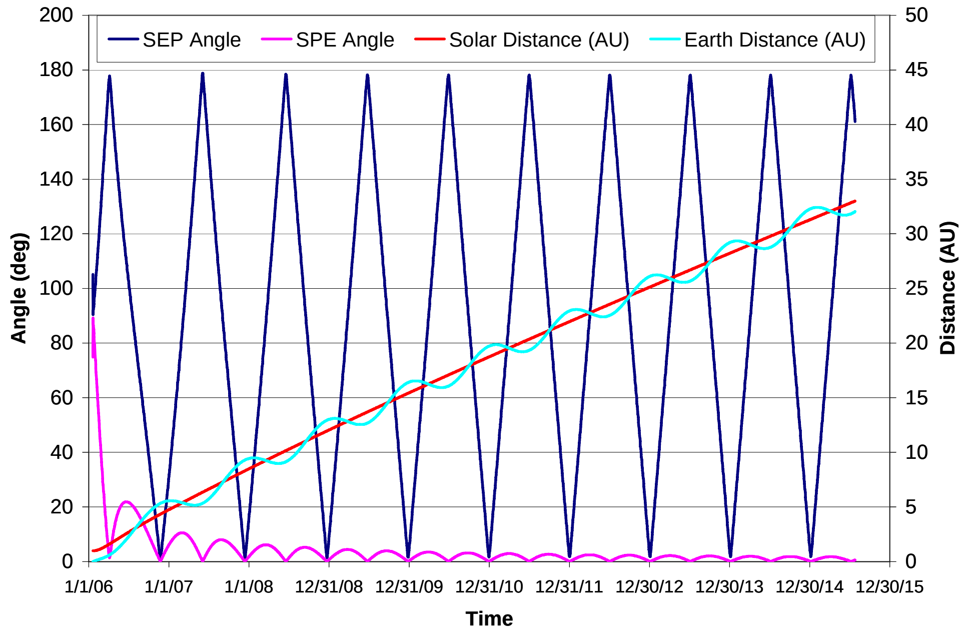


Figure 4. Heliocentric Velocity of the New Horizons Spacecraft over the flight from Earth to Pluto

The plot in Figure 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, as expected, increases monotonically, while the distance from Earth plot showing a oscillating feature which is due to the periodic motion of the Earth around the Sun. Both the SEP and SPE angles are periodic. The solar conjunction occurs at the minima of the SEP angle. The predicted solar conjunction periods are defined to be when the SEP angle is less than 3 degrees and are listed in Table 3. There will be no communications with the spacecraft during the solar conjunction periods. The solar opposition occurs at the maxima of SEP angle; the predicted solar opposition dates are listed in Table 4.



Note: plots are generated based on New Horizons nominal trajectory ephemeris.

Figure 5. New Horizons Mission Profiles of the Distances from Sun and Earth, the Sun-Earth-Probe (SEP) and Sun-Probe-Earth (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 NH solar conjunction dates are predicted dates when communications between NH spacecraft and Earth are blocked by the Sun.
2. The conjunction time is computed down to hours with Sun-Earth-Probe (SEP) angle less than 3 degrees.

Table 4. Dates of Solar Opposition

Solar Opposition Time (UTC) (Max SEP Angle)	Sun-Earth-Probe Angle (deg)	NH-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

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

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

4.3 Jupiter Gravity Assist Flyby

The Jupiter flyby is aimed at a point slightly below Jupiter's equatorial plane and over 2.3 million km from Jupiter's center, as illustrated in Figure 6. The Jupiter flyby trajectory design uses the Jupiter gravity assist to accelerate the spacecraft and change the trajectory inclination to achieve the desired Pluto encounter. The closest approach to Jupiter will take place on February 28, 2007. Figure 7 displays the Jupiter flyby geometry at the closest approach as observed from above Jupiter's equatorial plane. The spacecraft flies by Jupiter outside the orbits of the Galilean satellites in 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.

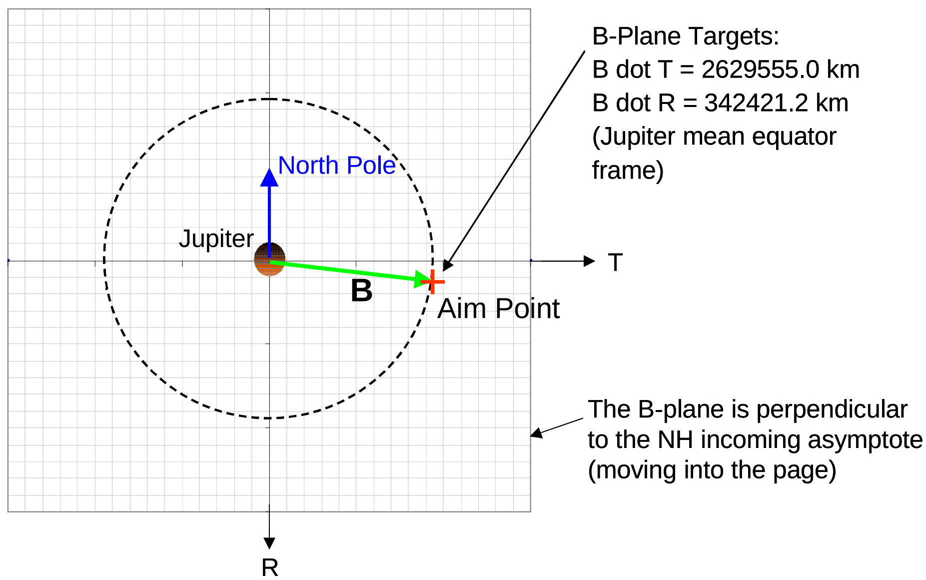


Figure 6. Jupiter B-plane Targeting

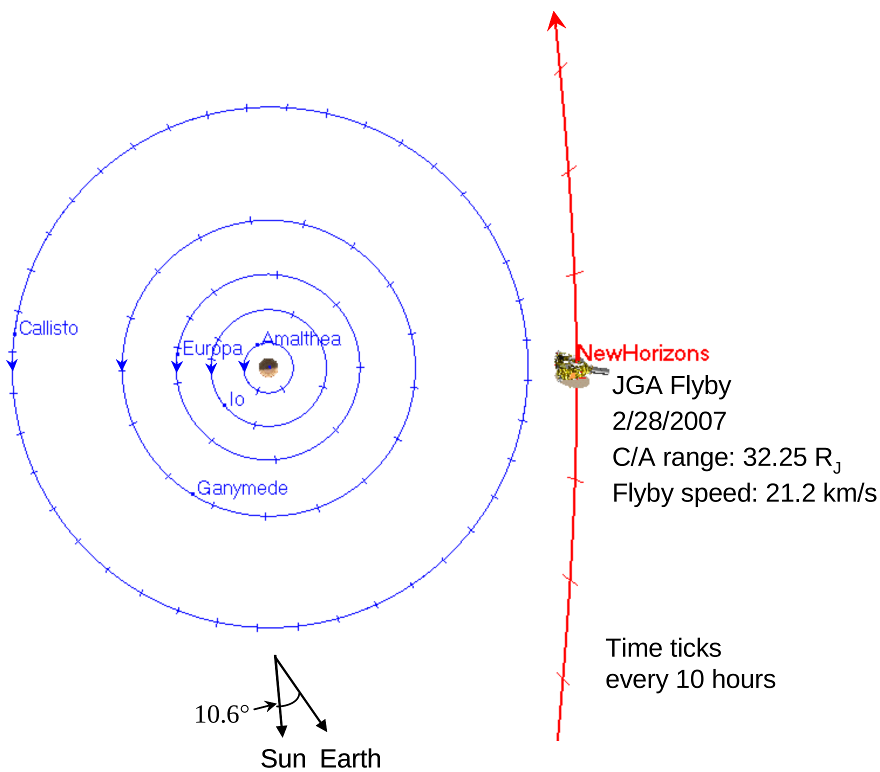
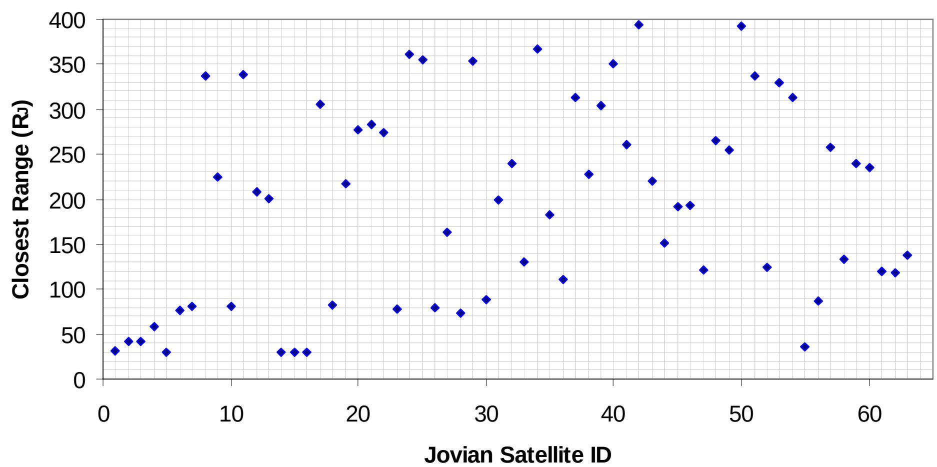


Figure 7. Jupiter Flyby Geometry

Besides the large Galilean satellites, there are numerous small irregular Jovian satellites, a total of 63 satellites discovered in the Jupiter system so far. Many of the small irregular ones were discovered in recent years and knowledge about them is very limited. It has always been in our interest and hope 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 is performed. The project decided not to expend more ΔV and to save it for the Kuiper Belt objects. Figure 8 shows the closest approach distances of the New Horizons spacecraft to the 63 Jovian satellites.



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	Eropa	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		

Figure 8. Jovian Satellite Encounter Profile

4.4 Pluto-Charon Encounter

The Pluto-Charon encounter trajectory design is the critical part of the mission design and directly affects how many of the science objectives and goals can be accomplished. There are 16 itemized science objectives (Table 1) defined for the Pluto-Charon science. The objective is to accomplish fifteen of them (except the search of magnetic fields) with this first Pluto reconnaissance investigation, which must be carried out during a brief Pluto-Charon flyby after a long journey of 9.5 years.

The design of the Pluto-Charon encounter trajectory is challenged by the many science requirements and goals and requires careful planning and trade-off, especially for observing two bodies in a single flyby by multiple instruments and conducting coordinated measurements involving four bodies: Earth, Sun, Pluto, and Charon. Based on the AO guideline and the capability and characteristics of New Horizons instruments, the mission design team and the science team worked out the derived science measurement requirements.

4.4.1 Science Measurement Requirements

4.4.1.1 Priority Ranking

In general, measurements associated with Pluto have higher priority than that of Charon. Among the Pluto measurements, Group 1 science has higher priority than Group 2; and Group 2 science has higher priority than 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 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. Since Charon also holds essential information for understanding the Pluto-Charon binary system, the mission seeks to take as many measurements at Charon as possible without undermining the fulfillment of Pluto objectives.

4.4.1.2 Requirements for Remote Sensing

The two onboard imaging instruments, PERSI and LORRI, are equipped with visible imaging, IR spectral mapping, and UV measurements and are responsible for carrying out 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 closest approach (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, the desired C/A distance from Pluto surface is about 10,000 km. An overall goal for remote sensing is to cover as much of Pluto and Charon's surfaces 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 is received on the spacecraft. The 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, for the REX experiments, which are uplink based and transmit high-powered signals from the Deep Space Network (DSN) station to the spacecraft, it is highly desirable to have two DSN stations simultaneously transmit RF signals to the spacecraft during the Earth occultation. This improves the signal-to-noise ratio and provide 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 closest approach distance to Pluto and enables the occurrence of Earth-Pluto occultation, Sun-Pluto occultation, Earth-Charon occultation, and the Sun-Charon occultation and the existence of simultaneous uplinks to the spacecraft from two DSN stations during the Earth occultation. These are very contingent 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 as described in the previous section, the time of Pluto arrival must be selected when Earth, Sun, and Pluto are positioned in such a geometry that can support the formation of the desired Earth and solar occultations by Pluto. The earliest year to reach Pluto depends on the launch date and the trajectory taken as shown in Figure 1. For each year, as the Earth orbits the Sun once, there are two opportunities for the desired occultation geometry--one in the summer and the other in the winter--when Earth and Sun are about in a line with Pluto, as illustrated in Figure 9, making it possible to achieve both the Earth and Sun occultations during the flyby of Pluto and Charon. The summer 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 favorable solar opposition geometry that is good for communications and for the REX measurements.

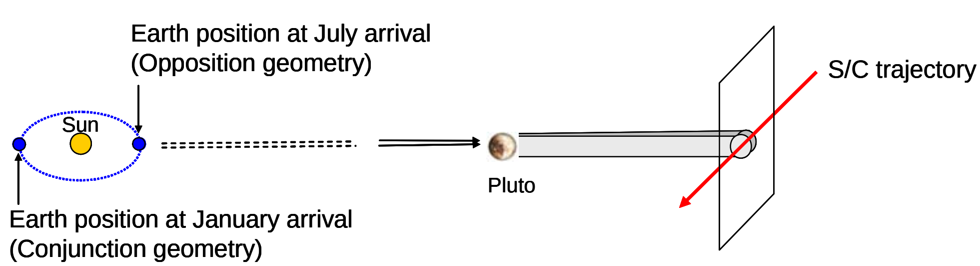


Figure 9. Options for Pluto Arrival Time Selection

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), one takes place 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 stations become candidates for the final encounter trajectory. The time of the Pluto arrival is eventually 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 NH spacecraft is to arrive at Pluto from a heliocentric transfer trajectory inclined 2.34 deg above the ecliptic plane and to approach Pluto from its southern hemisphere, as shown in Figure 10, at a solar phase angle of 15 deg, an excellent illumination condition for a full spectrum survey of Pluto and Charon on the approaching hemispheres. The sub-solar position is at a latitude of 49° south, showing that the southern hemisphere is sunlit and the north portion is in the permanent Sun shade. As Pluto rotates at a rate of about 6.4 earth days, different portion of its surface will be imaged.

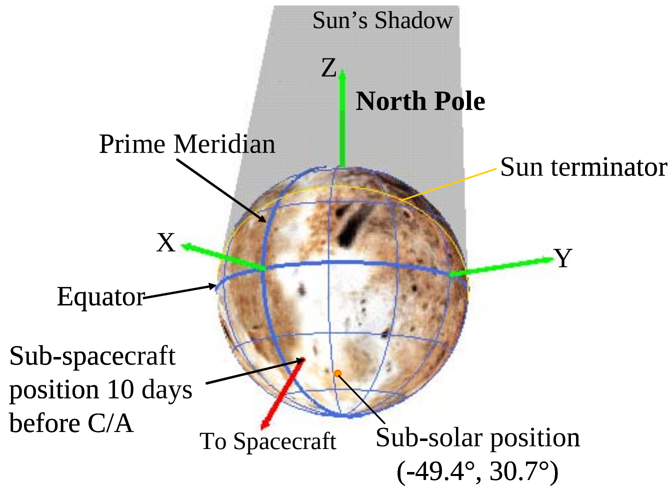


Figure 10. Pluto at Approach

4.4.4 Pluto Flyby Trajectory and Geometry

The goal of 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 trajectory design was further revised 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.

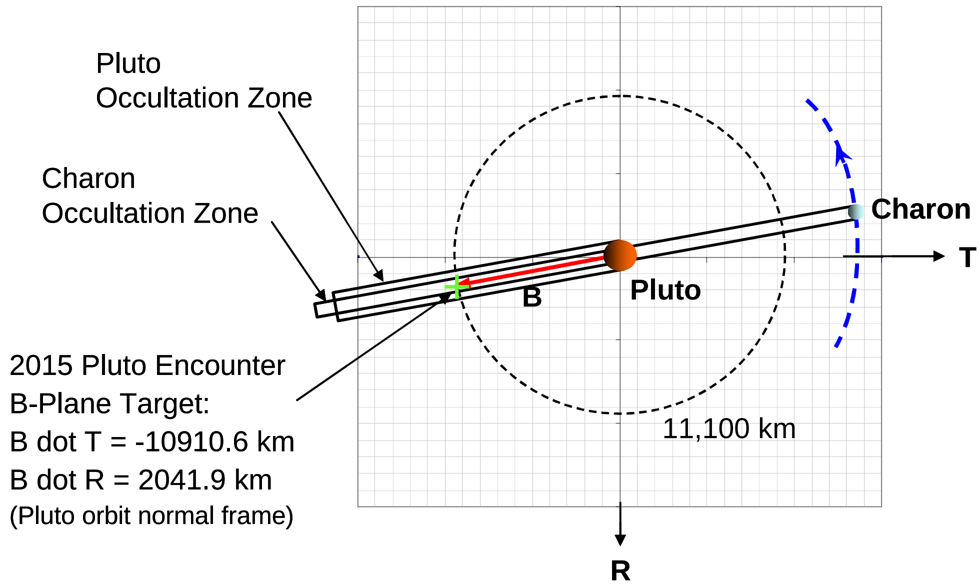


Figure 11. Pluto B-plane Targeting

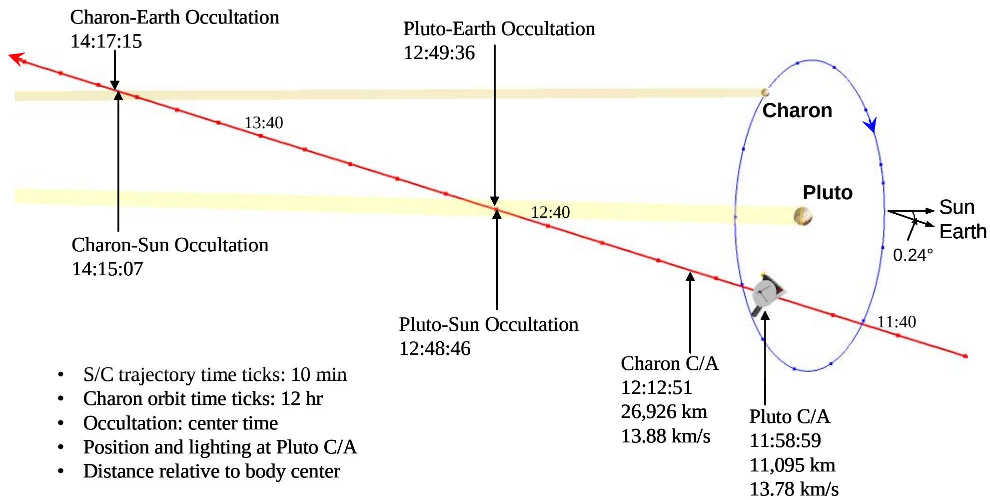


Figure 12. Pluto-Charon Encounter Geometry

New Horizons passes Pluto and Charon from the same side, convenient to switch the observation target from Pluto to Charon for imaging, inside Charon's orbit. Charon orbits Pluto in a circular retrograde orbit at a rate synchronized with Pluto's rotation period of 6.387 Earth days. The mean radius of Charon orbit is 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 Pluto, a unique situation in the solar 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°.

4.4.5 Encounter Sequence and Event Timeline

As shown in Figure 12, the flyby proceeds in a sequence of encounters, first with Pluto and then followed with Charon. The major flyby events start with the closest approach to Pluto on July 14, 2015 at 11:58:59 UTC of spacecraft time, at a distance of 11,095 km from Pluto center and a flyby speed of 13.78 km/s. It is shortly followed with the closest approach 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 behind Pluto and Charon. The Pluto occultation occurs first at about 36 minutes after Charon closest approach; 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 is going to carry on continuously from Pluto through Charon. More detailed encounter parameters and timeline of the Pluto-Charon flyby events are listed in Table-6.

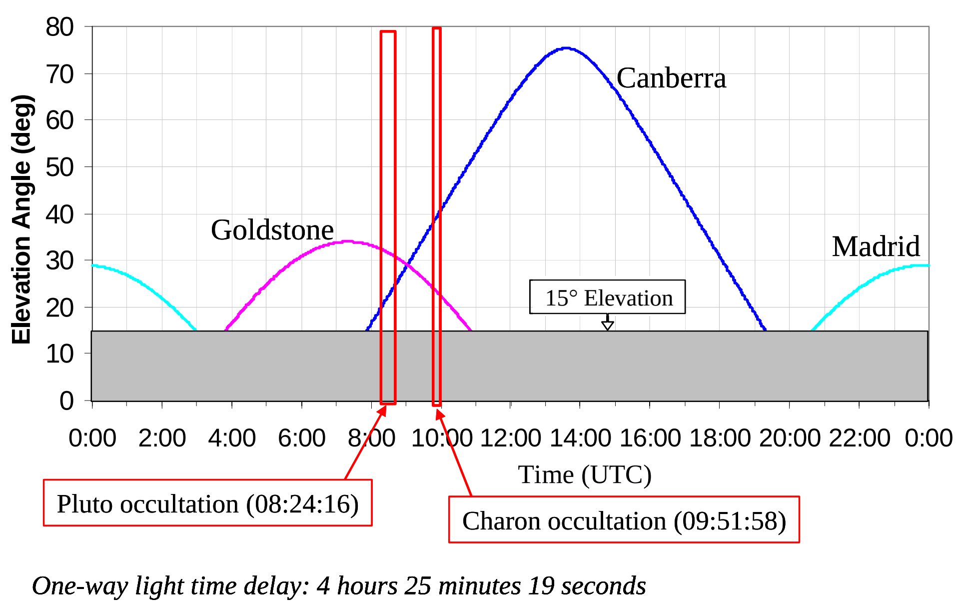


Figure 13. DSN Access Profile

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.

4.4.6 DSN Access Profile

During the Earth occultation, two DSN stations, Canberra and Goldstone, will be in the right position to be viewed with the NH spacecraft and be able to transmit RF signals to the spacecraft from both stations simultaneously. Their access profile is shown in Figure 13, where the spacecraft viewing elevation angle from the three DSN stations, Goldstone, Canberra, and Madrid, are plotted over a period of 24 hours on the day of the Pluto-Charon encounter. The ground transmission time indicated in Figure 13 is 4 hours and 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 degrees to assure adequate transmission of the RF signal from the stations, though lower elevation angles may also work. The shaded region in Figure 13 is for elevation angles less than 15°. As the elevation angle profile indicates, the overlapping period of about 3 hours between Goldstone and Canberra is the only time period when elevation angles are above 15° from two DSN stations. The Earth occultation by Pluto and Charon is targeted to take place within this time period. As Figure 13 indicates, the NH spacecraft is accessible simultaneously from Goldstone and Canberra for the time period from before Earth occultation by Pluto through after Earth occultation by Charon, with sufficient ingress and egress time margin at elevation above 15 degrees.

4.5 Extended Mission to the Kuiper Belt and Beyond

After 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 KBO Encounter

The flyby targets of KBO will be selected just prior to the Pluto encounter, as the trajectory to Pluto will not be changed regardless of the chosen KBO flyby target. The delay for making the decision on KBO target to 2015 allows for many more years of searching and discovering of 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. So far, 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 using the available onboard resources. The NH 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 NH spacecraft. Current estimates show that there will be as much as 250 m/s of Delta-V capacity left after the Pluto flyby, 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, analysis was performed to investigate if the direction of the outgoing trajectory of the spacecraft can be altered by the Pluto flyby by adjusting the B-plane aiming point so that the spacecraft could fly toward the first KBO target. Calculations indicate that Pluto can hardly bend the spacecraft flyby trajectory due to its low mass and the relatively high spacecraft flyby speed. This feature is clearly displayed in Figure 13, where the flyby trajectory is almost a straight line, implying the Pluto flyby cannot help to tune the spacecraft's trajectory towards 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) will be performed to target the spacecraft to the first KBO target in the region around the extended New Horizons trajectory path, as illustrated in Figure 14. Large ephemeris uncertainties are expected for the target KBO due to the short observation period and the KBO's great distance from Earth. The plan is to use onboard imagers MVIC and LORRI to acquire OpNav images of the KBO target as early as possible and to make the necessary trajectory corrections with minimum Delta-V. The high resolution imager LORRI is capable of detecting a KBO target 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.

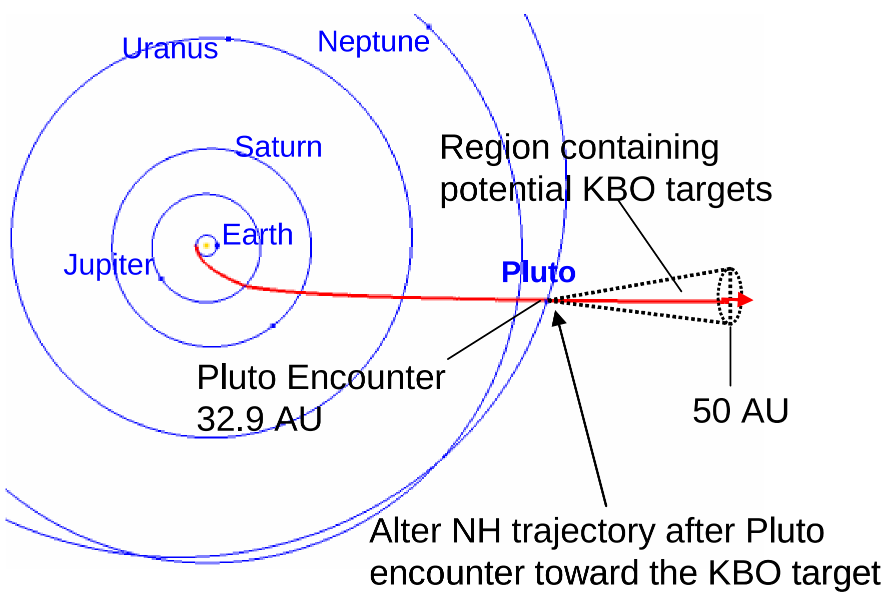


Figure 14. Mission to the Kuiper Belt Objects

The most likely KBO flyby is estimated in 2018 when New Horizons heliocentric distance reaches 42 AU where the distribution of KBO objects in heliocentric distance peaks (Spencer et al, 2003). Exploration of the Kuiper Belt objects is planned to go as far as 50 AU from the sun. The NH 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 NH 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 degrees and declination of 2.1 degrees 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 NH 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 for. After three trajectory corrections that took out the small injection errors, the spacecraft is now well on its course to fly by Jupiter on February 28, 2007 and encounter Pluto on July 14, 2015 as planned.

5.1 Launch and Orbit Injection

At 19:00 UTC (2:00 pm EST) of January 19, 2006, New Horizons lifted off from Launch Complex 41 at the Cape Canaveral Air Force Station, Florida, atop the STAR 48B aboard the Atlas V launch vehicle. It was first 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 was then 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 9 hours, it passed by the Moon at a distance of 184,700 km.

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 3-σ values are presented in Table 7. The orbit injection was remarkably accurate, with the orbit injection errors less than 1-σ.

Table 7. Launch Targets: Achieved versus Designed

Launch Targets	A - Designed	B- Achieved	Injection Error (B-A)	Predicted 3-σ Injection Error*
C3 (km^2/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

Note: A: Required launch target specified by NH Mission Design Team
B: Launch target derived from the determined trajectory (OD005 solution) provided by NH Navigation Team based on post-launch DSN tracking data
* Based on Boeing Trajectory Cycle 3 report

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 deg, 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 is now available and can be used for targeting the KBOs.

5.2 Summary of Trajectory Corrections

At the time this paper was written, a total of three trajectory corrections have been performed since launch through 3 trajectory correction maneuvers (TCMs). 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 minimizing 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 unstable the spacecraft and was limited to a magnitude of 5 m/s to avoid any chance of destabilizing the spacecraft. If the TCM executed as planned, TCM-1B would complete the needed ΔV by carrying out the remaining part of the Delta-V 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, 9 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.

Both TCM-1A and TCM-1B were terminated by timing. The results were about 6% underburn attributed to the thruster performance that was not matching the expected values estimated based on pre-launch thruster test results. 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 3-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. The next trajectory correction is planned in May 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 closest approach distance of 102,000 km, as shown in Figure 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. Another 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 was still restricted.

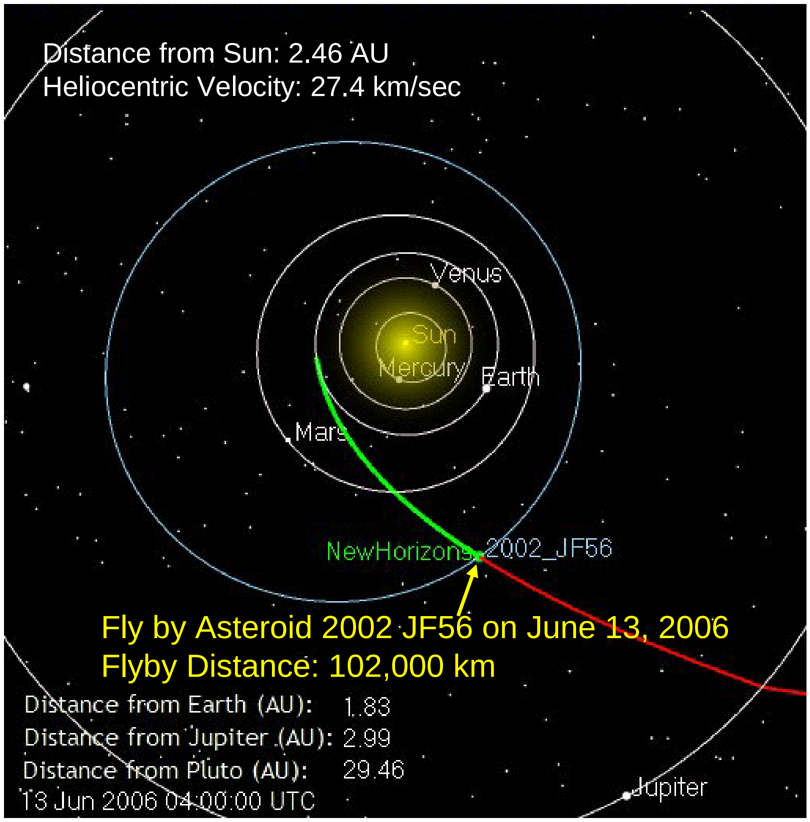


Figure 15. Flyby of Asteroid 2002 JF56 on June 13, 2006

5.4 Delta-V Status

At launch, a total of 76.85 kg of propellant was loaded on the NH spacecraft. The propellant is for trajectory correction maneuvers and for spacecraft attitude maneuvers. The NH spacecraft has a blow-down monopropellant propulsion system consisting of a central tank, twelve 0.8-N attitude control system (ACS) thrusters and four 4.4-N TCM thrusters. The propellant usage for the trajectory corrections has been much less than the pre-launch budgeted. So far, about 9 kg of propellant has been used. Furthermore, it is estimated there will be as much as 47 kg propellant remaining after the Pluto flyby for the Kuiper Belt mission, corresponding to a ΔV capacity of 230 m/s.

6. Conclusion

New Horizons was launched on January 19, 2006 and successfully injected into the favorable fast route to Pluto through a Jupiter-gravity-assist trajectory in accordance with the baseline mission design. It is expected to fly by Jupiter on

February 28, 2007 to gain a significant speed boost and encounter Pluto on July 14, 2015.

The New Horizons spacecraft became the fastest space vehicle ever launched from Earth, with an Earth departure speed of 16.2 km/s. The spacecraft passed the orbit of the Moon in just nine hours, passed the orbit of Mars in 78 days, and is to reach Jupiter 13 months from launch.

In the baseline mission design, a prolonged launch period was arranged for New Horizons, a total of 35 days, in order to ensure a very high probability of being launched within the 2006 launch opportunity. This unusually long launch period did not require extra launch energy; it was made possible by a) combining the launch opportunities of two different types of trajectories together, with the JGA trajectory for the primary launch period for a fast flight to Pluto and with the Pluto-direct trajectory for the extended launch period; and b) not fixing but appropriately varying the Pluto arrival time.

The Jupiter flyby is designed to aim at a point slightly below Jupiter's equatorial plane and over 2.3 million km from Jupiter's center on the right outer bound. The Jupiter gravity assist will accelerate the spacecraft and change the trajectory inclination to achieve the desired Pluto encounter. The speed increase of about 4-km/s gained through the Jupiter flyby shortens the time of flight to Pluto by 3 years.

The design of the Pluto-Charon encounter is optimized in its encounter geometry, flyby trajectory and arrival time to enable all of the desired science measurements under various arrival constraints. The constraints include the desired closest approach distance to Pluto, the existence of simultaneous uplinks to the spacecraft from two DSN stations during the Earth occultation, and occurrences of the Earth-Pluto, Sun-Pluto, Earth-Charon, and Sun-Charon occultations. The New Horizons will approach Pluto from its southern hemisphere at a solar phase angle of 15 deg, an excellent illumination condition for a full spectrum survey of Pluto and Charon on the approaching hemispheres.

New Horizons passes Pluto and Charon from the same side, convenient to switch the observation target from Pluto to Charon for imaging, inside Charon's orbit. The major flyby events start with the closest approach to Pluto on July 14, 2015 at a distance of 11095 km from Pluto center and a flyby speed of 13.78 km/s, followed shortly by the closest approach to Charon 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 behind Pluto and Charon.

After a flyby of the Pluto system, New Horizons will continue its journey to explore the Kuiper Belt as an extended mission. Exploration to the Kuiper Belt objects is planned to go as far as 50 AU from the sun. The NH spacecraft will reach the 50-AU distance in 2021 with an expected encounter of one or more KBOs. It will eventually depart our solar system.

Since its launch, the New Horizons spacecraft's flight so far has been extremely smooth, with the needed injection error correction Delta-V being only about one fifth of what was budgeted. As a result, a significant amount of propellant is now available and can be used for enhancing the efforts of targeting the KBOs in the future.

Acknowledgements

The authors would like to thank New Horizons Principal Investigator, Alan Stern, and the science team for their support and review of the Pluto-Charon encounter design and JPL for providing the planetary and satellite ephemerides. The authors would also like to thank Tom Strikwerda for review and helpful edits on this manuscript. This work was supported by NASA under contract # NAS5-97271.

References

Farquhar R. W. and Stern S. A.: 1990, Pushing Back the Frontier: A Mission to the Pluto-Charon System, Planetary Report, July 1990, pp. 18-23.

Guo Y. and Farquhar R.W.: 2002, New Horizons Mission Design for the Pluto-Kuiper Belt Mission, AIAA/AAS paper, AIAA-2002-4722, AIAA/AAS Astrodynamics Specialist Conference, August 5-8, 2002, Monterey, California.

Guo Y. and Farquhar R.W.: 2005, New Horizons Pluto-Kuiper Belt Mission: Design and Simulation of the Pluto-Charon Encounter, Acta Astronautica 56, 2005, pp 421-429.

Guo Y. and Farquhar R.W.: 2006, Baseline Design of New Horizons Mission to the Kuiper Belt, Acta Astronautica 58, 2006, pp 550-559.

Jewitt D.C. and Luu J.X.: 1993, Discovery of Candidate Kuiper Belt Object 1992 QB1, *Nature*, 1993, pp. 362-730.

Keller, J. Warren: 1971, Grand Tour Surveys of the Outer Solar System, Advances in the Astronautical Sciences, Vol. 29, Part I, Edited by Juris Vagners, pp. 37-47.

Long, E. James: 1969, To the Outer Planets, Astronautics & Aeronautics 7, June 1969, pp. 32-47.

Minovitch M. A.: 1994, Fast Mission to Pluto Using Jupiter Gravity-Assist and Small Launch Vehicles, Journal of Spacecraft and Rockets, vol. 31, No. 6, 1994, pp.1029-1037.

NASA: 2001, Announcements of Opportunity, Pluto-Kuiper Belt Mission, 01-OSS-01, January 19, 2001.

Spencer J., Buie M., Young L., Guo Y., and Stern A.: 2003, Finding KBO Flyby Targets for New Horizons, Earth, Moon and Planets 92, 483-491, 2003.

Staehle R. L., Terrile R. J., and Weinstein S. S.: 1994, To Pluto by Way of a Postage Stamp, Planetary Report, Sept./Oct., 1994, pp. 4-11.

Stern S. A. and Mitton J.: 1998, Pluto and Charon, John Wiley & Sons, Inc, New York, 1998. Jewitt D.C. and Luu J.X.: 1993, Discovery of Candidate Kuiper Belt Object 1992 QB1, Nature, pp. 362-730, 1993.

Weinstein S.: 1992, Pluto Flyby Mission Design Concepts for Very Small and Moderate Spacecraft, AIAA/AAS paper, AIAA-92-4372, August 10-12, 1992.