# TRAJECTORY MONITORING AND CONTROL OF THE NEW HORIZONS PLUTO FLYBY

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***Abstract:*** *The New Horizons spacecraft made the first flyby of Pluto on July 14, 2015 after a 9.5-year journey traveling 5.25 billion kilometers across the solar system. The nominal Pluto flyby trajectory designed for the first Pluto reconnaissance mission included Pluto occultations by both the Earth and Sun and Charon occultations by both the Earth and Sun for Pluto and Charon atmosphere measurements. Three backup SHBOT (Safe Haven By Other Trajectory) trajectories were prepared but not used. Unlike other planetary missions, knowledge of the Pluto ephemeris had large uncertainty. This required periodic spacecraft trajectory evaluation relative to the updated Pluto ephemeris during the Pluto approach phase. Accurate trajectory correction maneuvers placed the New Horizons spacecraft close to the desired Pluto flyby trajectory, enabling the achievement of all science objectives. The mission design strategy of completing the detailed design of the entire trajectory from launch to Pluto and integrating it to the launch target effectively reduced post-launch trajectory adjustments. Trajectory corrections consumed only 19% of the budgeted $\Delta V$, leaving more $\Delta V$ for the extended mission to explore Kuiper Belt objects.*

***Keywords:*** *New Horizons, Pluto Flyby, Trajectory Design, Mission Design, Trajectory Correction Maneuver, Flight Path Control.*

## 1. Introduction

New Horizons (NH) is the first mission to explore the Pluto system. The NH spacecraft made the flyby of the Pluto system on July 14, 2015 after a long journey, traveling 5.25 billion kilometers across the solar system for over 9.5 years. It was launched on January 19, 2006 by the most powerful launch system then available, the Atlas V 551 launch vehicle by Lockheed Martin with a Star 48B upper stage by Boeing, at a record high $C_3$ of 157.75 $km^2/s^2$ [1]. The New Horizons mission, NASA's first New Frontiers class mission, is led by Principal Investigator Alan Stern of Southwest Research Institute [2], and is managed, developed, and operated by the Johns Hopkins University Applied Physics Laboratory (APL) [3]. The Mission Design Team (MD) at APL provided the design of the launch window and launch targets [1,4,5], the Earth-to-Pluto interplanetary transfer trajectory including a Jupiter gravity-assist flyby [1,6], the Pluto flyby trajectory [1,5,6], the Pluto B-plane target [1,5], and the trajectory correction maneuvers [4,5]. Spacecraft navigation is provided by KinetX, Inc., also known as the PNAV Team [7]. For the Pluto flyby, independent orbit determination (OD) solutions were provided by the Jet Propulsion Laboratory (JPL), called the INAV Team.

Because of the high Pluto arrival velocity, it is not feasible with current technology to place the spacecraft into an orbit around Pluto. Hence the first exploration of the Pluto system was conducted using a flyby, which made the flyby trajectory design of critical importance to the successful accomplishment of the mission's science objectives. Primary science objectives for the Pluto system flyby included conducting an initial reconnaissance of the Pluto system and investigating the geology, surface composition, and atmosphere of Pluto and its largest moon Charon. When the New Horizons mission was formulated, Charon was the only known moon of Pluto. Since then four new moons of Pluto have been discovered: Nix (discovered in 2005), Hydra (2005), Kerberos (2011), and Styx (2012). In addition, in the years leading up to the Pluto flyby, scientists speculated that the discovery of new moons of Pluto could indicate the existence of dust rings surrounding Pluto. To avoid damage from dust particles, alternative Safe Haven By Other Trajectories (SHBOT) were considered as backup.

Successful observation and measurement of the Pluto system for the planned science investigations were accomplished during the New Horizons Pluto flyby. Measurement of the surface composition and geology of the bodies was conducted by the New Horizons onboard optical instrument LORRI (Long Range Reconnaissance Imager), as well as through the remote sensing instruments, the Ralph telescope and Alice ultraviolet spectrometer. Measurement of the atmosphere of Pluto and Charon required carefully timed coordination of the REX (Radio Science Experiment) instrument, two Deep Space Network (DSN) stations, and the Sun. The atmosphere measurement was achieved by analyzing the media, radio waves and ultraviolet (UV) light, after passing through the Pluto and Charon atmospheres. Radio waves from two DSN stations were transmitted simultaneously to the NH spacecraft when Pluto and Charon passed between Earth and the NH spacecraft, i.e., during the Earth occultation by Pluto and the Earth occultation by Charon. The UV light from the Sun was analyzed by the Alice instrument when Pluto and Charon passed between the Sun and the NH spacecraft, i.e., during the Sun occultation by Pluto and the Sun occultation by Charon. The Pluto flyby trajectory design including the nominal trajectory that enabled all desired science measurements and the backup SHBOT contingency trajectories is presented in Section 3.

In the nominal flyby trajectory design the time of closest approach (CA) to Pluto was fixed, constrained by the Sun-Earth-Pluto-spacecraft geometry needed for the atmosphere measurement [1]. When the predicted Pluto arrival time was different from the selected arrival time, the flight trajectory had to be adjusted with a trajectory correction maneuver (TCM) to modify the Pluto-relative speed of the NH spacecraft. The NH spacecraft position and velocity was tracked from the three NASA DSN stations located in Goldstone (USA), Canberra (Australia), and Madrid (Spain) through a two-way non-coherent Doppler and ranging technique using X-band radio waves. The DSN tracking provided data that helped determine the spacecraft's orbit relative to Earth. The ephemeris of Pluto based on Earth-based ground measurements, the only measurement source before this mission, had large uncertainties. Images acquired by the NH spacecraft's optical instruments tied the spacecraft position directly to Pluto and its moons. This combined ground radio tracking of the spacecraft and onboard optical images improved the accuracy of both the spacecraft position with respect to Pluto, as well as the accuracy of the orbits of Pluto and its moons. As the NH spacecraft approached Pluto, a series of optical images devoted for orbit determination were acquired in accordance with the planned TCMs. Estimates of spacecraft position and Pluto position were updated periodically. Change in knowledge of the

Pluto system barycenter location and change in knowledge of the orbits of Pluto and Charon with respect to the Pluto system barycenter could affect the planned science observations and measurements. With each OD solution update, the nominal Pluto encounter trajectory was updated or revised to preserve compliance with the Pluto flyby scientific requirements. Discussions of trajectory evaluation and nominal trajectory update are presented in Section 4.

The estimated NH trajectory from navigation OD, including propagation to the future, was compared with the nominal trajectory in terms of the Pluto B-plane target parameters. The difference between predicted and nominal Pluto B-plane target parameters indicated the current flight path's offset from the desired flight path and the required trajectory correction. The description of the trajectory correction maneuver design is presented in Section 5. The performed trajectory corrections and final flight path control to Pluto are presented in Section 6. The initial estimate of the Pluto flyby path based on reconstructed OD is reported in Section 7. After the Pluto flyby, the NH spacecraft will explore the Kuiper Belt as an extended mission pending NASA approval. The trajectory change maneuvers planned to target a close flyby of a Kuiper Belt Object are presented in Section 8.

## 2. Mission Design Overview

The New Horizons mission trajectory was designed as a ballistic flight from Earth to Pluto with a Jupiter gravity-assist flyby in order to shorten the flight time to Pluto [1]. There were no deep space maneuvers on the mission trajectory. The launch system delivered the NH spacecraft to the target interface point (TIP) at the required "launch target" state as specified by the Mission Design Team.

A primary mission design strategy was to reduce the $\Delta V$ (NH velocity change) requirement as much as possible for post-launch trajectory adjustments. While the nominal trajectory required no deterministic $\Delta V$, statistical $\Delta V$s were budgeted for correcting launch injection errors, navigation errors, and trajectory perturbations due to unpredictable non-gravitational forces. The primary mission trajectory from Earth departure to Pluto flyby, down to the second of the Pluto closest approach time, was optimized and integrated with operational high-fidelity models available at the time for every day of the 35-day launch period. The launch targets determined from these integrated trajectories were delivered to NASA Kennedy Space Center/Lockheed Martin/Boeing and were loaded to the launch vehicle for launch.

On the launch day, the Atlas V 551 and Star48B upper stage injected the NH spacecraft to the required launch target with less than 1-sigma injection error [1,4], setting New Horizons on track to the planned Jupiter gravity-assist trajectory to fly by Pluto on July 14, 2015, as shown in Fig. 1. The NH spacecraft reached Earth departure velocity at 16.2 km/s, passed the Moon's orbit in less than 9 hours, and was the fastest spacecraft ever launched from Earth. After the injection errors were corrected, The NH spacecraft flew by Jupiter on February 28, 2007 as planned, at the closest approach distance of 2,304,505 km from Jupiter center. The Jupiter flyby was 1173.5 km off from the desired aim point and 1 minute and 53 seconds later than the design value [4,5], still within design tolerance. The gravity-assist flyby of Jupiter achieved the trajectory adjustment objective and the NH spacecraft gained a Sun-relative speed increase of 3.83 km/s. The Jupiter flyby error was small and was corrected seven months later.

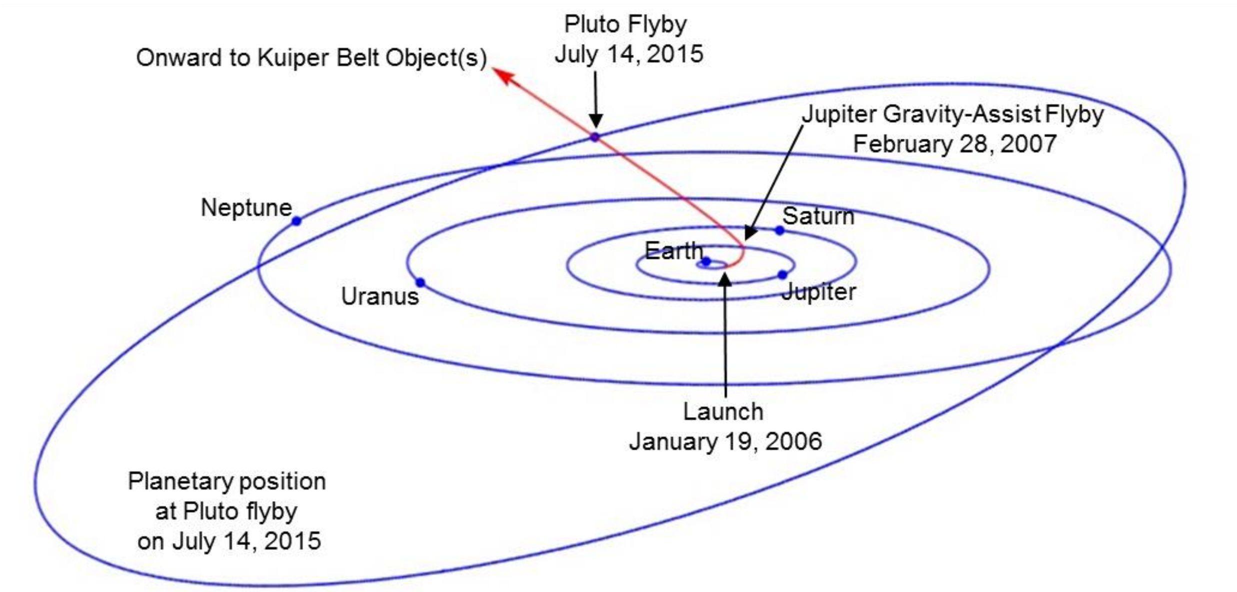


**Figure 1. New Horizons Mission Trajectory**

## 3. Pluto Flyby Trajectory Design

### 3.1. The Nominal Pluto Flyby Trajectory

The Pluto flyby trajectory was designed to accomplish the science objectives planned for the first Pluto reconnaissance mission. There were 15 itemized Pluto/Charon science objectives [1] identified in the original NASA Announcement of Opportunity for the mission, including the geology, surface composition, and atmosphere of Pluto and Charon. Enabling these science measurements with their required geometry and trajectory conditions on a single Pluto flyby is not trivial, as it involves the relative motion of the NH spacecraft with respect to the other four bodies, Sun, Earth, Pluto, and Charon, and to two DSN stations rotating with Earth. The orbits of the bodies are not co-planar. Because of the required Earth- and Sun-relative geometry, the Pluto arrival time became a design parameter and had to be carefully selected. Detailed design of the Pluto flyby trajectory is described in previous papers [1,6,8].

As described in [6], the Pluto flyby trajectory design developed before launch had Pluto closest approach on July 14, 2015 at 11:59:00 UTC, with the Pluto flyby distance at 11,095 km from Pluto's surface. The simulated science measurements supported by this flyby trajectory were presented in [8]. After the Jupiter gravity-assist flyby, from spring 2007 to early 2008, the Science Team conducted comprehensive trade studies in order to map all the science measurements to the 15 science objectives. Each objective was scored and rated based on the measurement quantity (time, number of opportunities) and quality (geometry, resolution). The overall science return was evaluated based on the scores of the science objective groups. Group 1 has the highest priority and is required by the mission, and Group 2 has lower priority and is desired but not required. Group 3 has the lowest priority and is desired, but also not required [1].

The Mission Design Team developed 23 different Pluto flyby trajectories on 21 different Pluto arrival dates from July 7 through July 21, 2015 for the science trades. The science trade study concluded that the initial selection of the Pluto arrival date of July 14 was the best. The Pluto flyby distance was moved from 11,095 km to 12,500 km to allow more observations to fit within the short flyby period near the closest approach to Pluto for an overall better science return.

The designed NH Pluto flyby trajectory, also called the nominal trajectory, and the Pluto system with Pluto and its five moons in their orbits is shown in Fig. 2. The trajectory goes through the Pluto system at about 43° from the plane of the moons' orbits, crossing the plane just outside Charon's orbit. Charon is at the opposite side of the orbit, farther away from Pluto than NH. Both Pluto and Charon are on the same side of the NH trajectory, which minimizes the slew time when switching from imaging Pluto to imaging Charon. The flyby sequence starts with the closest approach to Pluto, followed with CA to Charon, Pluto-Sun occultation, Pluto-Earth occultation, Charon-Sun occultation, and Charon-Earth occultation. The key flyby events from Pluto CA to the Charon-Earth occultation took place within a 3-hour period. The Pluto B-plane data file, including the Pluto CA time and Pluto B-plane target, of the nominal trajectory was delivered to the PNAV and INAV Teams as the Pluto aim point for navigation. The nominal trajectory was also used for science planning and served as the basis in building the onboard Pluto flyby sequences containing all planned science measurements.

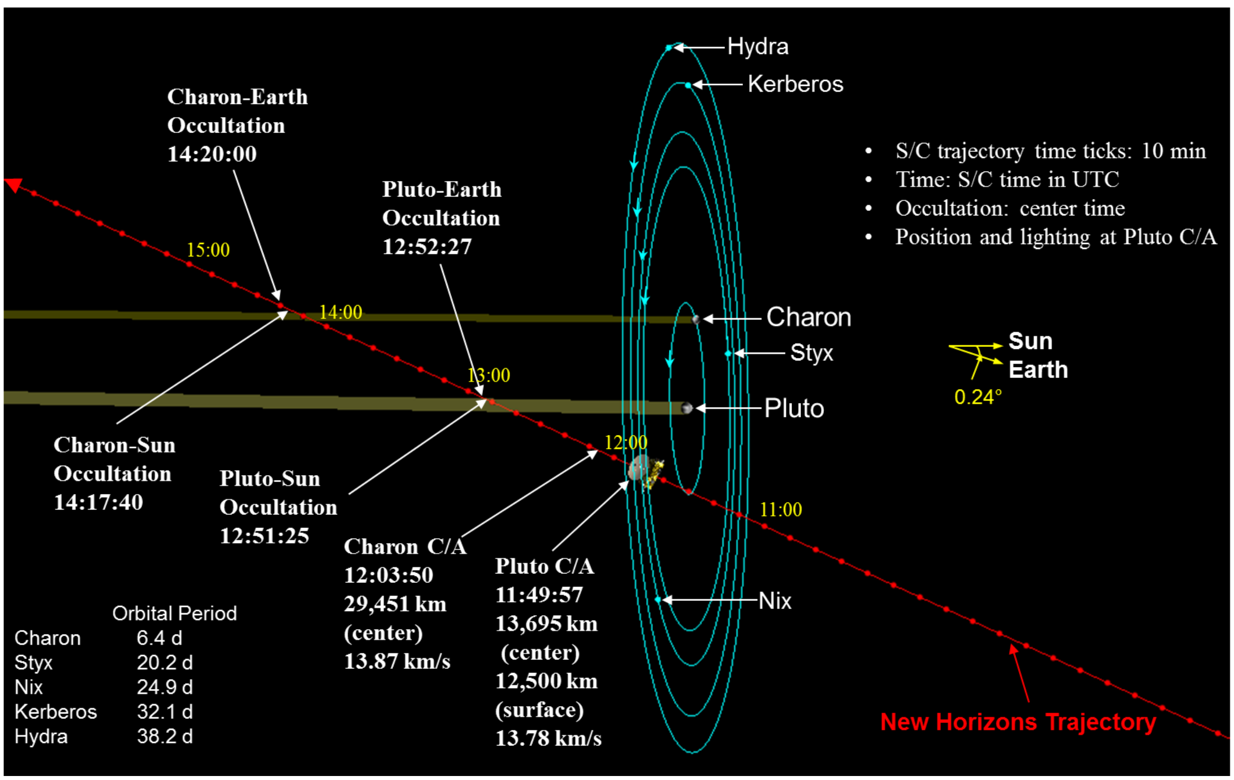


**Figure 2. New Horizons Pluto Flyby Trajectory**

### 3.2. SHBOT Trajectories

As more moons were discovered in the Pluto system, a concern was raised regarding NH spacecraft safety during the Pluto flyby due to the risk of damage from impact with high-velocity dust particles as the NH spacecraft passed through the Pluto system at a speed of nearly 14 km/s. To mitigate the risk of potential hazards, alternative SHBOT trajectories were designed as a backup to the nominal trajectory. On the approach to Pluto, if the latest images of the Pluto system, taken by the onboard cameras, showed a high potential hazard of dust particles to the spacecraft along the planned nominal trajectory path, the NH spacecraft could change its course to switch to one of the candidate SHBOT trajectories.

The three candidate SHBOT trajectories, along with the nominal trajectory, are plotted in Fig. 3. In the depicted Pluto system barycenter inertial reference frame the binary system feature of Pluto and Charon is clearly revealed. Both Pluto and Charon are orbiting around the Pluto system barycenter, as well as the other small moons. The small moons are all located outside Charon's orbit. The SHBOT trajectory was selected to go through the region where no dust was expected or the probability of dust being there would be very low predicted by orbit dynamics analysis. The highest priority concern for the SHBOT trajectory was spacecraft safety, with achieving science objectives being second. The science observations are degraded and some measurements would have been partially or fully lost due to the SHBOT trajectory lacking the necessary NH trajectory geometry and conditions. Of the many SHBOT trajectories considered and analyzed, three were selected as candidates for flight operations.

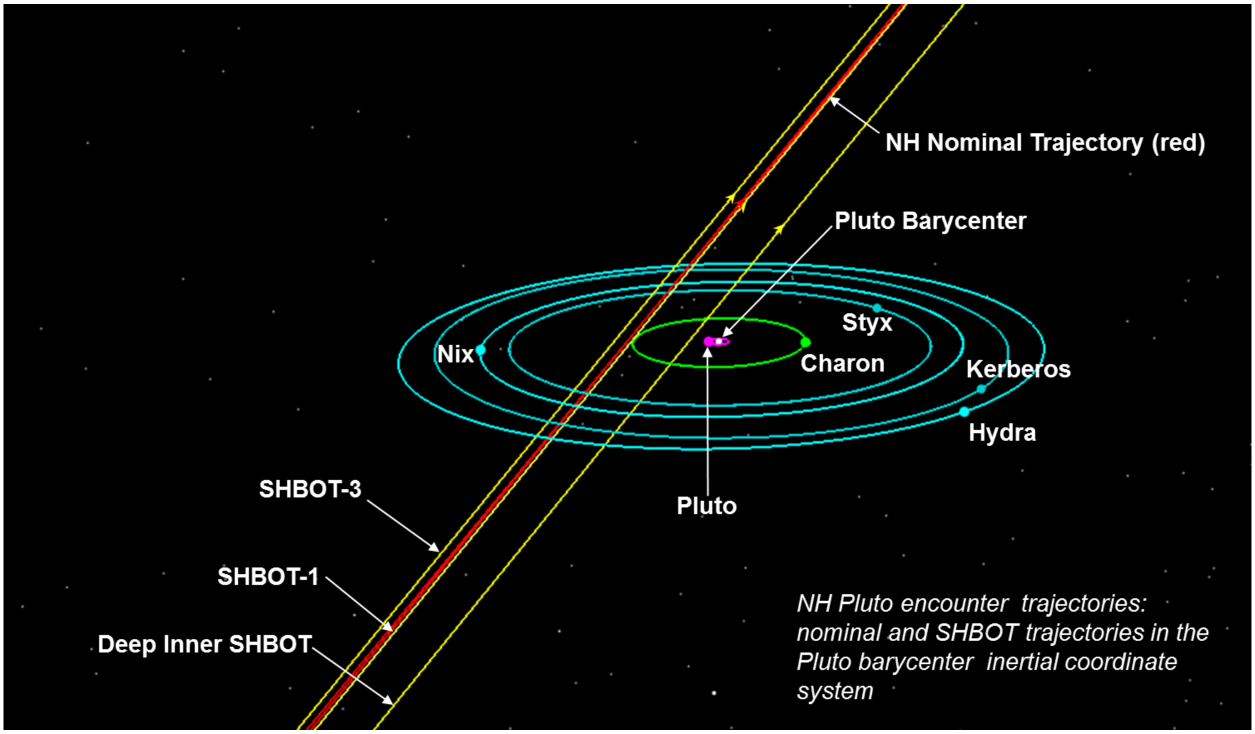


**Figure 3. SHBOT and Nominal Trajectories**

The SHBOT trajectories are defined by their ring plane crossing distance. The ring plane is the plane containing the orbits of the Pluto system bodies. The desired ring plane crossing distance for each SHBOT trajectory was received from the Science Team. The deep inner SHBOT trajectory would cross the ring plane from inside Charon's orbit, at the ring plane crossing distance of 4000±300 km from Pluto center. The SHBOT-1 trajectory goes through the region centered on Charon's orbit. Its ring plane crossing distance is 17,531±600 km from the Pluto barycenter. The SHBOT-3 trajectory goes through a region called the "Charon instability strip" at the ring plane crossing distance of 21,615±600 km from the Pluto system barycenter. The same Pluto CA time as the nominal trajectory is kept for the SHBOT trajectories, thereby reducing the $\Delta V$ needed for changing from the nominal trajectory to the SHBOT trajectory. Besides the ring plane crossing distance and the Pluto CA time being fixed, the trajectory is optimized to retain the science measurements planned with the nominal trajectory as much as possible.

There were three decision points planned for switching from the nominal trajectory to a SHBOT trajectory, at P-30d (30 days prior to Pluto CA time), at P-20d, and at P-14d. Such a trajectory switch could be made through a trajectory correction maneuver that would direct the spacecraft to a new Pluto B-plane target of the selected SHBOT trajectory. Fortunately no hazardous dust was observed and the NH spacecraft kept on the nominal trajectory course and flew through the Pluto system along that path.

### 3.3. Pluto B-plane Target

The Pluto B-plane is used in targeting the New Horizons' Pluto flyby and is defined as the plane perpendicular to the incoming asymptote of the hyperbolic flyby trajectory and containing the center of mass of Pluto. Using the Earth Mean Equator of J2000 (EME2000) as the reference frame, the horizontal T-axis of the B-plane is along the direction of the incoming asymptote vector S crossing the Z-axis of EME2000. The vertical R-axis of the B-plane is along the direction of vector S crossing T. The designed Pluto flyby trajectory, either the nominal or the three SHBOT trajectories, are specified in terms of the **B•R** and **B•T** value of the trajectory in the Pluto B-plane at the time of closest approach to Pluto. The three parameters, **B•R**, **B•T**, and Pluto CA time, as a set, are referred as the Pluto B-plane target, or the Pluto flyby aim point. The Pluto B-plane target determined from the designed Pluto flyby trajectory served as the Pluto flyby target for monitoring and controlling the New Horizons flight path, checking the difference of the predicted trajectory versus the desired nominal trajectory in terms of the B-plane target offset and making a trajectory correction to remove the offset.

## 4. Trajectory Evaluation and Pluto B-plane Target Update

The NH spacecraft trajectory was evaluated and assessed prior to each scheduled TCM opportunity to determine if a TCM should be performed. Each assessment started with a new OD solution set delivery by the PNAV Team. The OD solution set included the latest NH spacecraft ephemeris, the updated Pluto system barycenter ephemeris, and the updated ephemerides of Pluto, Charon, and the other Pluto moons with respect to the Pluto system barycenter. These ephemeris updates were determined from the latest ground-based radio tracking and onboard Optical Navigation (OpNav) data. Sometimes an OD solution set was also delivered by the

INAV Team. The INAV OD solution set was examined for comparison and was not used for the Pluto flyby trajectory and B-plane target revision and TCM design.

**Table 1. Pluto Barycenter Position Change with Respect to the de418 Ephemeris**

| Source | Ephemeris File | R (km) | T (km) | N (km) |
|---|---|---|---|---|
| JPL DE | de418 | 0 | 0 | 0 |
| | de432 | 1510 | -714 | 1458 |
| | de433 | 289 | -242 | 1400 |
| PNAV | NavPE_de433_OD085 | 350 | -73 | 1709 |
| | NavPE_de433_OD086 | 359 | -79 | 1713 |
| | NavPE_de433_OD087 | 365 | -84 | 1716 |
| | NavPE_de433_OD088 | 365 | -86 | 1717 |
| | NavPE_de433_OD089 | 434 | -111 | 1734 |
| | NavPE_de433_OD090 | 417 | -84 | 1765 |
| | NavPE_de433_OD091 | 553 | -128 | 1792 |
| | NavPE_de433_OD092 | 499 | -112 | 1784 |
| | NavPE_de433_OD093 | 389 | -83 | 1767 |
| | NavPE_de433_OD094 | 360 | -75 | 1767 |
| | NavPE_de433_OD095 | 344 | -71 | 1767 |
| | NavPE_de433_OD096 | 441 | -97 | 1771 |
| | NavPE_de433_OD097 | 545 | -124 | 1775 |
| | NavPE_de433_OD098 | 555 | -127 | 1776 |
| | NavPE_de433_OD099 | 566 | -130 | 1777 |
| | NavPE_de433_OD100 | 577 | -133 | 1777 |

Notes:

- Pluto barycenter position changes are evaluated at the Pluto CA time on July 14, 2015 at 11:49:57 UTC in the RTN (R-radial, T-transverse, N-normal) coordinate system
- Pluto barycenter position changes are with respect to de418, as the original NH nominal trajectory design was based on de418 and plu017

Changes of Pluto barycenter position from the ephemeris updates are listed in Table 1. Changes of Pluto and Charon position relative to the Pluto system barycenter from the ephemeris updates are listed in Table 2. The listed ephemeris updates are from one year before the Pluto flyby through the last trajectory correction at P-14d. The largest change from the ephemeris updates was the position of the Pluto system barycenter. Table 1 shows the Pluto system barycenter position changes from the ephemeris updates with respect to the de418 ephemeris, which was used up to the summer of 2014. Because of Pluto's great distance and limited observation time span (less than 85 years since Pluto discovery out of the 248-year orbit) of Pluto's orbit, the predicted position of Pluto based on the ground observations had a very large uncertainty. In preparation for the encounter, JPL used ground-based observation and delivered the de433 ephemeris to provide the best a priori solution for navigation. The Pluto system barycenter was refined using the OpNav images taken by the NH spacecraft during its approach to Pluto. For each solution on approach, PNAV delivered an update to de433, as shown in Table 1. The relative positions of Pluto, Charon, and the other Pluto moons with respect to the Pluto system barycenter were also refined at the same time. Ground measurements from past stellar occultations refined Charon's orbit about Pluto to a good accuracy. The position changes of Pluto and Charon relative to the Pluto barycenter were relatively small from the ephemeris updates, as shown in Table 2. JPL provided the a priori plu017 and plu043 solutions and PNAV refined the ephemeris for each solution using OpNav data.

**Table 2. Pluto and Charon Position Change with Respect to the plu017 Ephemeris**

| Source | Ephemeris File | Pluto | | | Charon | | |
|---|---|---|---|---|---|---|---|
| | | R (km) | T (km) | N (km) | R (km) | T (km) | N (km) |
| JPL Plu | plu017 | 0 | 0 | 0 | 0 | 0 | 0 |
| | plu043 | 50 | 13 | -1 | -96 | 137 | 10 |
| PNAV | NavSE_plu043_OD085 | 50 | 13 | -1 | -96 | 135 | 10 |
| | NavSE_plu043_OD086 | 50 | 14 | -1 | -96 | 138 | 10 |
| | NavSE_plu043_OD087 | 50 | 14 | -1 | -96 | 138 | 10 |
| | NavSE_plu043_OD088 | 50 | 14 | -1 | -96 | 138 | 10 |
| | NavSE_plu043_OD089 | 50 | 13 | -1 | -96 | 137 | 10 |
| | NavSE_plu043_OD090 | 50 | 13 | -1 | -96 | 137 | 10 |
| | NavSE_plu043_OD091 | 50 | 13 | -1 | -96 | 137 | 10 |
| | NavSE_plu043_OD092 | 50 | 13 | -1 | -96 | 137 | 10 |
| | NavSE_plu043_OD093 | 50 | 13 | -1 | -97 | 135 | 10 |
| | NavSE_plu043_OD094 | 50 | 13 | -1 | -97 | 133 | 11 |
| | NavSE_plu043_OD095 | 50 | 13 | -1 | -97 | 135 | 11 |
| | NavSE_plu043_OD096 | 50 | 13 | -1 | -97 | 135 | 11 |
| | NavSE_plu043_OD097 | 50 | 13 | -1 | -97 | 135 | 11 |
| | NavSE_plu043_OD098 | 50 | 13 | -1 | -97 | 134 | 11 |
| | NavSE_plu043_OD099 | 50 | 13 | -1 | -97 | 134 | 11 |
| | NavSE_plu043_OD100 | 50 | 13 | -1 | -97 | 135 | 11 |

When the ephemerides of Pluto and Charon changed, the trajectory geometry for the science measurements and flyby conditions for the Pluto and Charon occultation could be different. The Pluto flyby trajectory design was reviewed and assessed for each new OD solution set delivery. The Pluto flyby trajectory was computed with respect to the updated ephemerides for Pluto and Charon. The flyby geometry and occultation conditions were checked against the science measurement requirements. The trajectory path was adjusted to meet the science requirements with the new Pluto barycenter ephemeris and Pluto system ephemeris, and the Pluto B-plane target was updated accordingly. The updated Pluto B-plane target was then used for the trajectory correction maneuver design.

## 5. Trajectory Correction Maneuver Design

The Mission Design Team's trajectory correction maneuver (TCM) design includes the determination of the $\Delta V$ value of the required trajectory correction maneuver, i.e., the theoretical or ideal $\Delta V$, and the implementation of the ideal $\Delta V$ into a NH spacecraft maneuver.

The ideal ΔV was determined based on an initial NH state from the current OD solution and the updated Pluto B-plane target, and targeting to the Pluto B-plane target with the TCM at the scheduled time. The trajectory propagation was modeled including perturbations from solar radiation pressure (SRP), thermal re-radiation from the radioisotope thermoelectric generator (RTG), and small forces due to unbalanced thruster firings. There are no wheels onboard the NH spacecraft and any attitude change required firing of the Attitude Control System (ACS) thrusters. All science instruments are fixed to the spacecraft and have no moving parts. Any science instrument pointing requires moving the entire spacecraft. Science observations and data downlink to Earth involve spacecraft attitude change and ACS thruster firing. The Mission Design Team used the predicted accelerations from SRP, RTG, and small forces from PNAV, which were updated and delivered with each OD solution. The predicted small forces were approximated based on future spacecraft attitude activities.

The NH spacecraft has four TCM thrusters in two pairs and twelve ACS thrusters in four groups, as shown in Fig. 4. As the name indicated, the TCM thrusters, each providing 4.4 N of thrust, are mainly used for TCMs, and the 0.8-N ACS thrusters are mainly used for spacecraft attitude control. The ACS thrusters can also be used for TCMs, but with less efficient lower specific impulse ($I_{sp}$). The thruster configuration allows the NH spacecraft to produce thrust in any of its principal axes. The TCM thruster F1/F2 pair has a canted angle of 45°, costing more fuel than any other NH thruster set, and hence is never used. All the TCMs, except for one, were executed using the TCM thruster C4/D4 pair. The C4/D4 thrusters were used for all TCMs that targeted the Pluto flyby. The NH propulsion system [9] is a hydrazine monopropellant system with a sphere-shaped tank located in the center of the spacecraft. The tank pressure is in blow-down mode and drops as propellant is used. Thrust and $I_{sp}$ of the thrusters are functions of the tank pressure and temperature. TCMs were modeled as finite maneuvers with the NH propulsion system and actual thruster configuration using the anticipated performance calibrated by flight performance. Different gain factors were used for the C4/D4 thrusters in matching their actual thrust level.

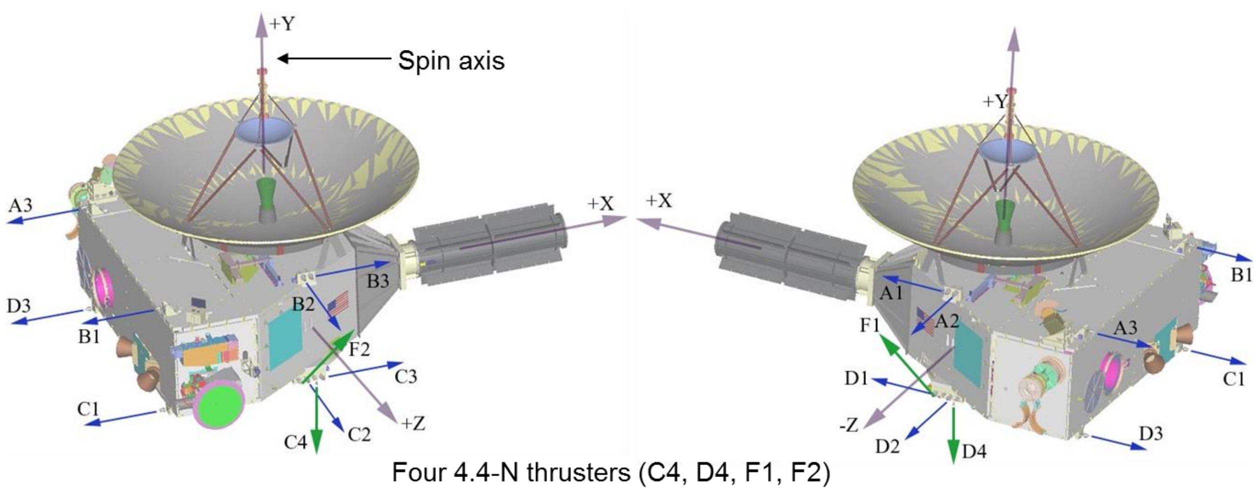


**Figure 4. Thruster Configuration**

The trajectory propagation modeling, TCM ΔV design, and maneuver implementation modeling were integrated in the same mission design software. The TCM design came from the trajectory optimization that delivered the NH spacecraft to the Pluto B-plane target with a minimal maneuver ΔV using the selected thrusters. The ΔV values, ΔV magnitude and ΔV unit vector, of the TCM design were delivered in the Maneuver Interface File (MIF) to the PNAV Team for the MD-NAV ideal ΔV verification using independent software. The maneuver ΔV and implementation parameters, including burn duration, fuel usage, thruster set, TCM mode, and spacecraft attitude during the maneuver burn, were delivered in the Maneuver Parameter File (MPF) to the Guidance-and-Control Team (G&C) for the MD-G&C TCM implementation testing and verification. The verified TCM parameters were then delivered from G&C to the Mission Operations Team for inclusion in a spacecraft command load for TCM execution.

**Table 3. TCM Schedule and Status**

| Maneuver | Function | Time | Date | TCM Mode | ΔV (m/s) | Thruster | Burn Duration (s) | Comment |
|---|---|---|---|---|---|---|---|---|
| TCM1-A | Injection correction | L+9d | 1/28/2006 | PS-TCM | 5 | C4D4 | 276 | Executed |
| TCM-1B | Injection correction | L+11d | 1/30/2006 | PS-TCM | 13.3 | C4D4 | 751 | Executed |
| TCM2 | Cleanup of TCM-1 | L+27d | 2/15/2006 | 3A-TCM | | C4D4 | | Canceled |
| TCM3 | Cleanup of TCM-1 | L+49d | 3/9/2006 | 3A-TCM | 1.16 | C4D4 | 76 | Executed |
| TCM4 | Jupiter targeting | J-76d | 12/14/2006 | AS-TCM | | ACS | | Canceled |
| TCM5 | Jupiter targeting | J-20d | 2/8/2007 | 3A-TCM | | ACS | | Canceled |
| TCM6 | Cleanup of TCM5 | J-5d | 2/23/2007 | 3A-TCM | | ACS | | Canceled |
| TCM7 | Jupiter Correction | J+15d | 3/15/2007 | 3A-TCM | | TCM | | Canceled |
| TCM8 | Jupiter Correction | J+209 d | 9/25/2007 | 3A-TCM | 2.37 | A2D2 | 938 | Executed |
| TCM9 | Cruise correction | P-7y | 10/15/2008 | 3A-TCM | | ACS | | Canceled |
| TCM10 | Cruise correction | P-6y | 10/15/2009 | 3A-TCM | | ACS | | Canceled |
| TCM11 | Cruise correction | P-5y | 6/30/2010 | 3A-TCM | 0.44 | C4D4 | 34 | Executed |
| TCM12 | Cruise correction | P-4y | 6/1/2011 | 3A-TCM | 0.42 | ACS | | Removed |
| TCM13 | Cruise correction | P-3y | 6/6/2012 | 3A-TCM | 0.42 | ACS | | Removed |
| TCM14 | Cruise correction | P-2y | 6/14/2013 | 3A-TCM | 0.58 | ACS | | Removed |
| TCM15 | Cruise correction | P-1y | 7/15/2014 | 3A-TCM | 1.08 | C4D4 | 88 | Executed |
| TCM15B1 | Pluto targeting | P-6m | 1/13/2015 | 3A-TCM | | TCM | | Removed |
| TCM15B2 | Pluto targeting | P-4m | 3/10/2015 | 3A-TCM | 1.14 | C4D4 | 94 | Executed |
| TCM16 | Pluto targeting | P-60d | 5/15/2015 | 3A-TCM | | TCM | | Canceled |
| TCM16B1 | Pluto targeting | P-40d | 6/4/2015 | 3A-TCM | | TCM | | Canceled |
| TCM16B2 | Pluto targeting | P-30d | 6/14/2015 | 3A-TCM | 0.53 | C4D4 | 45 | Executed |
| TCM17 | Pluto targeting | P-20d | 6/24/2015 | 3A-TCM | | TCM | | Canceled |
| TCM17B1 | Pluto targeting | P-14d | 6/30/2015 | 3A-TCM | 0.27 | C4D4 | 24 | Executed |
| TCM17B2 | Pluto targeting | P-10d | 7/4/2015 | 3A-TCM | | TCM | | Canceled |
| TCM18 | Cleanup of TCM17 | P-7d | 7/7/2015 | 3A-TCM | | TCM | | Removed |

## 6. Trajectory Correction

The New Horizons TCM schedule, a complete list of planned TCMs up to the Pluto flyby, maintained by the Mission Design Team since launch is shown in Table 3. The rows colored in green are the executed TCMs, and the uncolored rows are TCMs canceled or removed as the schedule was updated. In the case of cancelled TCMs, both OD and maneuver solutions were analyzed carefully prior to the decision of cancelling was made. TCMs for NH's launch correction and cruise are described in early papers [1,4,5]. The focus here is on trajectory correction during the final approach to Pluto starting one year prior to the Pluto flyby. The last four trajectory corrections made at P-1y, P-4m, P-30d, and P-14d are described in the following sections.

### 6.1. Trajectory Correction at One Year Prior to Pluto

One year before the Pluto flyby, TCM-15 was executed on July 15, 2014, with a maneuver of 1.08 m/s performed using the TCM thruster set C4/D4 for an 88-s-long burn. The $\Delta V$ change was mostly in the spacecraft velocity direction, which speeded up the spacecraft slightly. This trajectory correction adjusted NH's course to the desired Pluto B-plane target and arrival time.

NH was put into hibernation after the Jupiter flyby for its long cruise to Pluto and was awakened for spacecraft system and instruments checkout for three months every year. During the annual checkout period a TCM slot was reserved for potential cruise trajectory correction. TCM-15 was the last scheduled cruise correction maneuver for the last checkout in summer 2014. The previous three cruise TCMs were not needed and were canceled, and the last trajectory correction before TCM-15 was made four years ago, on June 30, 2010 with TCM-11. The next TCM opportunity after TCM-15 would be six months later, on Jan 13, 2015.

At that time a newer ephemeris for Pluto was available and the project decided to switch the planetary and Pluto ephemeris files from de418/plu017 to de432/plu043 for the design of TCM-15 and to use the new ephemeris pair for flight operations after TCM-15. The ephemeris change added the need to revise the NH Pluto flyby trajectory. The Pluto flyby trajectory was revised to satisfy the design requirements for the science measurements planned at Pluto and Charon based on the Pluto and Charon orbits described by de432 and plu043. The trajectory correction by TCM-15 adjusted NH's course to the revised flyby trajectory and targeted at the new Pluto B-plane target for the de432/plu043 ephemerides.

Small forces were first included in the design of TCM-15. Since the NH spacecraft has no wheels, it must fire the ACS thrusters for any attitude change, including spin-up/spin-down, slew, instrument pointing, etc. [10]. Because the thrusters are not perfectly balanced, there are always unwanted forces produced when thrusters are fired. Although the unwanted forces are small, the accumulated effects on orbit perturbation are notable. The small forces were introduced in the modeling of future trajectory propagation, hoping for better accuracy in trajectory prediction. However, with the small-force modeling complexity and very limited flight data, accurate prediction and modeling of future small forces turned out to be challenging, which was learned in the design of subsequent TCMs.

### 6.2. Trajectory Correction at 4 Months Prior to Pluto

After the successful execution of TCM-15, TCM-15B1 scheduled on Jan 13, 2015 at P-6m was canceled. The next trajectory correction was made by TCM-15B2 on March 10, 2015 at P-4m.

The 94-s maneuver imparted 1.14 m/s in ΔV using the C4/D4 thrusters. This trajectory correction accounted for the planetary ephemeris (de file) update, the planetary and Pluto system ephemeris updates from the onboard OpNav data, and corrected the over-burn from TCM-15 due to small-force modeling error. Without this maneuver, the Pluto CA time would be 872 s early and the B-plane offset from the target would be 3,442 km.

**Table 4. Nominal Pluto Flyby Trajectory Parameters**

| | | **Nominal Trajectory** (de433-OD085, plu043-OD085) | **Required/Desired** |
|---|---|---|---|
| Pluto | CA Time | 2015-07-14T11:49:57 | |
| | CA distance (km) | 13695 | **13695** |
| | CA velocity (km/s) | 13.779 | |
| Charon | CA time | 2015-07-14T12:03:50 | |
| | CA distance (km) | 29451 | |
| | CA velocity | 13.874 | |
| Pluto-Earth occultation | Center time | 2015-07-14T12:52:27 | |
| | Start time | 2015-07-14T12:46:48 | |
| | End time | 2015-07-14T12:58:05 | |
| | Duration (s) | 677 | |
| | Offset from center (km) | 0.150 | **<1** |
| | Spacecraft distance (km) | 53440 | |
| | Scan rate (km/s) | 3.531 | |
| Pluto-Sun occultation | Center time | 2015-07-14T12:51:25 | |
| | Start time | 2015-07-14T12:45:51 | |
| | End time | 2015-07-14T12:56:57 | |
| | Duration (s) | 666 | |
| | Offset from center (km) | 55.087 | **<1100** |
| | Spacecraft distance (km) | 52616 | |
| | Scan rate (km/s) | 3.586 | |
| Charon-Earth occultation | Center time | 2015-07-14T14:20:01 | |
| | Start time | 2015-07-14T14:18:06 | |
| | End time | 2015-07-14T14:21:54 | |
| | Duration (s) | 228 | |
| | Offset from center (km) | 438.848 | **<500** |
| | Spacecraft distance (km) | 117148 | |
| | Scan rate (km/s) | 3.498 | |
| Charon-Sun occultation | Center time | 2015-07-14T14:17:41 | |
| | Start time | 2015-07-14T14:16:28 | |
| | End time | 2015-07-14T14:18:52 | |
| | Duration (s) | 144 | |
| | Offset from center (km) | 535.372 | **<500** |
| | Spacecraft distance (km) | 115280 | |
| | Scan rate (km/s) | 3.554 | |

The planetary ephemeris used for the TCM design was changed from de432 to de433. Ephemeris de433 was believed to be the best estimate for Pluto that could be derived from ground-based observation data. It was also the last de ephemeris update before the Pluto flyby. Thereafter, the Pluto ephemeris updates would only be from the NH onboard OpNav data. From de432 to de433, the Pluto system barycenter position was shifted by 1310 km (Table 1), mostly in the radial direction. This barycenter position change mainly affected the Pluto arrival time, causing it to move earlier by about 87 s.

For the first time the planetary and Pluto system ephemerides were updated using the NH OpNav data. The updated planetary ephemeris (NavPE-de433-OD085) was a result of the combination of de433 and the navigation OpNav data. The updated Pluto system ephemeris (NavSE-plu043-OD085) was a result of combining the plu043 ephemeris and the navigation OpNav data. The NH OpNav images from OpNav Campaigns 1 and 2 were included in the ephemeris updates for the TCM-15B2 design.

A revision was made to the Pluto flyby trajectory and the Pluto B-plane target for TCM-15B2. The Pluto flyby trajectory was adjusted based on the new NavPE-de433-OD085 and NavSE-plu043-OD085 ephemerides. The Pluto B-plane target was also revised for TCM-15B2. Per Science Team request the design requirement for the Pluto-Earth occultation had been tightened such that the NH trajectory must go through the Pluto shadow within 1 km from the center. Key parameters of the nominal Pluto flyby trajectory after this revision are summarized in Table 4.

Comparing the NH state from the current OD solution, determined by both the radial tracking data and OpNav data, with NH states derived from previous OD solutions, it appeared that the assumed small forces used in the TCM-15 design were greater than actually observed. Before TCM-15, NH moved slower than planned, resulting in the predicted Pluto arrival time later than desired. The current estimate showed NH was moving faster and its Pluto arrival was hundreds of seconds earlier than the targeted time after the contribution of the Pluto barycenter position shift being excluded. The over-burn part of TCM-15 due to overestimated small forces was corrected with TCM-15B2.

### 6.3. Trajectory Correction at 30 Days Prior to Pluto

TCM-16, scheduled at P-60d on May 15, 2015, was canceled since there were no significant changes on the updated Pluto and Charon ephemerides. The TCM-16 final design showed the B-plane offset was 204 km from the target and the Pluto CA time was 22 s later than desired. These offsets were within the OD 1-sigma error. The $\Delta V$ required to make the trajectory correction was 6.9 cm/s. Delaying the trajectory correction to TCM-16B1, the $\Delta V$ would increase to 10.3 cm/s. The $\Delta V$ penalty was not significant for delaying the correction.

The NH spacecraft switched from 3-axis mode to spin mode on May 16, 2015 and stayed in spin mode until May 27, 2015. There were no new OpNav images taken during that time period. With little new data, the OD solution was not expected to change much for the TCM-16B1 design. So TCM-16B1 scheduled at P-40d on June 4, 2015 was also canceled.

The trajectory evaluated for TCM-16B2, scheduled at P-30d on June 14, 2015, showed an increase in the B-plane target offset to 755 km and a shift in the Pluto CA time by 84 s early. The required ΔV of TCM-16B2 for correcting these offsets was 0.52 m/s, which was not so great that the trajectory correction could wait another 10 days until TCM-17. Furthermore, the OD uncertainties were still above the requirement, indicating a preference to postpone the TCM to a later opportunity. However, at this point other factors were considered. Table 5 lists the possible options for go/no-go for TCM-16B2 and the associated pros and cons from a maneuver's perspective. Option 1 was to execute TCM-16B2 to correct current trajectory errors and to be followed with a final clean-up of trajectory correction by TCM-17B1 at P-14d. Because of processing time required for OD, maneuver design and spacecraft commanding, this strategy ensured a good delivery accuracy by allowing an opportunity to perform a final clean up at P-14d and leave the P-10d opportunity only for contingencies.

**Table 5. TCM Options within One Month of Pluto Arrival**

| TCM Opportunity | Time | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|---|
| **TCM-16B2** | 6/14 (P-30d) | Correction | | | |
| **TCM-17** | 6/24 (P-20d) | | Correction | Correction | Correction |
| **TCM-17B1** | 6/30 (P-14d) | Final Clean-up | | | Final Clean-up |
| **TCM-17B2** | 7/4 (P-10d) | | | Final Clean-up | |
| **Comments** | | Ensure good delivery accuracy | Lower delivery accuracy | Higher risk than Option 1 | Final clean-up not helpful as DCO was 6/25 |

The TCM-16B2 no-go option expanded to three options with the remaining TCMs before Pluto. Option 2 delayed the trajectory correction to P-20d by TCM-17 and no more corrections after TCM-17. This option would have lower delivery accuracy. Option 3 added a final clean-up correction at P-10d by TCM-17B2, though it would improve the delivery accuracy but increase operational risk compared to Option 1. Option 4 added a final clean-up correction at P-14d with TCM-17B1, which was six days after the previous correction. Since the data cut-off (DCO) for TCM-17B1 was on June 25, 2015, one day from the previous maneuver, the final clean-up would add little improvement. For the remaining TCM opportunities, the trajectory correction strategy of Option 1 looked best. TCM-16B2 was executed with good performance. The offset of Pluto arrival time and B-plane target were removed with the execution of TCM-16B2.

### 6.4. Trajectory Correction at 14 Days Prior to Pluto

After determining that the accumulated trajectory error since TCM-16B2 was small, as expected, TCM-17 at P-20d was canceled. The final trajectory correction before the Pluto flyby was made by TCM-17B1 at P-14d on June 30, 2015. The last OD solution set used for designing TCM-17B1 with DCO on June 26 showed the predicted Pluto arrival time was 20 s late and the Pluto B-plane target error was 184 km. Without the trajectory correction, there would be no Charon-Sun and no Charon-Earth occultation. TCM-17B1 was executed as a 0.27 m/s ΔV that targeted NH to the desired Pluto B-plane target and arrival time. It was the smallest maneuver NH ever performed. Like the previous TCMs, TCM-17B1 completed successfully with good performance. TCM-17B2, scheduled at P-10d on July 4, 2015, as the backup for TCM-17B1 was no longer needed and was canceled. Performance of TCM-17B1, TCM-16B2, TCM-15B2, and TCM-15 are summarized in Table 6.

**Table 6. Performance of Last Four TCMs**

| Maneuver | Parameter | Nominal | Estimated | Difference |
|---|---|---|---|---|
| TCM-15 | ΔV (m/s) | 1.0807 | 1.0778 | -0.0030 |
| | RA (deg) | 294.0962 | 294.2517 | 0.1556 |
| | Dec (deg) | -4.0739 | -4.8207 | -0.7468 |
| TCM-15B2 | ΔV (m/s) | 1.1435 | 1.1434 | -0.0001 |
| | RA (deg) | 102.1755 | 101.1848 | -0.9906 |
| | Dec (deg) | 26.3763 | 26.3679 | -0.0084 |
| TCM-16B2 | ΔV (m/s) | 0.5246 | 0.5273 | 0.0027 |
| | RA (deg) | 117.4405 | 117.2563 | -0.1842 |
| | Dec (deg) | -5.5205 | -5.9896 | -0.4691 |
| TCM-17B1 | ΔV (m/s) | 0.2677 | 0.2722 | 0.0045 |
| | RA (deg) | 274.1295 | 273.9897 | -0.1398 |
| | Dec (deg) | 18.8424 | 20.3506 | 1.5082 |

## 7. Flight Performance

### 7.1. Delta-V Used for Trajectory Correction

From launch to Pluto flyby there were 25 TCMs planned (Table 3) over the 9.5-year trajectory. Nine of these TCMs were carried out for the trajectory correction. Of the nine TCMs, three corrected launch injection error, one corrected Jupiter gravity-assist flyby errors, two corrected the cruise trajectory, and three targeted the Pluto flyby. The total ΔV used for the 9 TCMs was 25.3 m/s, far lower than the 131 m/s ΔV budgeted for the primary mission to Pluto. The New Horizons flight trajectory was very close to the designed trajectory. The trajectory correction over its journey to Pluto was much less than expected. The ΔV usage for trajectory correction is only 19% of that budgeted, leaving more for the extended mission to the Kuiper Belt objects.

### 7.2. Estimated Pluto Flyby Trajectory

From the reconstructed Pluto flyby OD solution (P+90d, OD122) derived from radio tracking data and OpNav data, the estimated Pluto flyby trajectory was about 41.5 km, with 1-sigma estimate uncertainty of +/-3.5 km, from the designed Pluto B-plane target. The B-plane offset in the B normal direction, perpendicular to the B-vector, was 35.6 km, and the offset of the B magnitude, along the B-vector direction, was -21.2 km. The estimated flyby distance from Pluto center was 13,673.8 km, about 21.3 km smaller than the desired value of 13,695 km. The determined Pluto radius [11] of 1187±4 km indicated a 12,486.8 km CA distance from Pluto's surface, which was only 13.2 km off the 12,500 km target CA distance.

The estimated Pluto CA time was 11:48:28.774 UTC, with 1-sigma uncertainty of ±0.6 s, according to the reconstructed OD122 solution, which was 88.2 s earlier than the targeted time of

11:49:57 UTC [7]. The measurements conducted during the Pluto solar occultation and the immediate playback of the occultation data to the ground allowed a quick-look estimate of the flyby time the next day after the flyby before the orbit reconstruction took place. The estimated flyby time from the Pluto solar occultation was about 91 s earlier than the targeted time.

The reconstructed Pluto B-plane offset shifted in a favorable direction for the Charon occultation. All four Pluto and Charon occultations by Earth and Sun were achieved during the Pluto flyby. The NH trajectory path, designed versus achieved, and the occultation geometry is illustrated in Fig. 5, and the occultation offsets are listed in Table 7. The estimated Pluto-Earth diametric occultation had an offset of 36.9 km, and the Pluto solar occultation became more centered. The offset for the Pluto-Earth occultation was less than the allowed delivery error of 100 km and fully satisfied the science atmosphere investigation for deriving a vertical profile of the Pluto atmosphere.

**Table 7. Occultation Results**

| | Nominal | Estimate (OD122) |
|---|---|---|
| Pluto-Earth occultation offset (km) | 0.4 | 35.2 |
| Pluto-Sun occultation offset (km) | 55.4 | 19.6 |
| Charon-Earth occultation offset (km) | 439.1 | 383.5 |
| Charon-Sun occultation offset (km) | 535.6 | 479.9 |

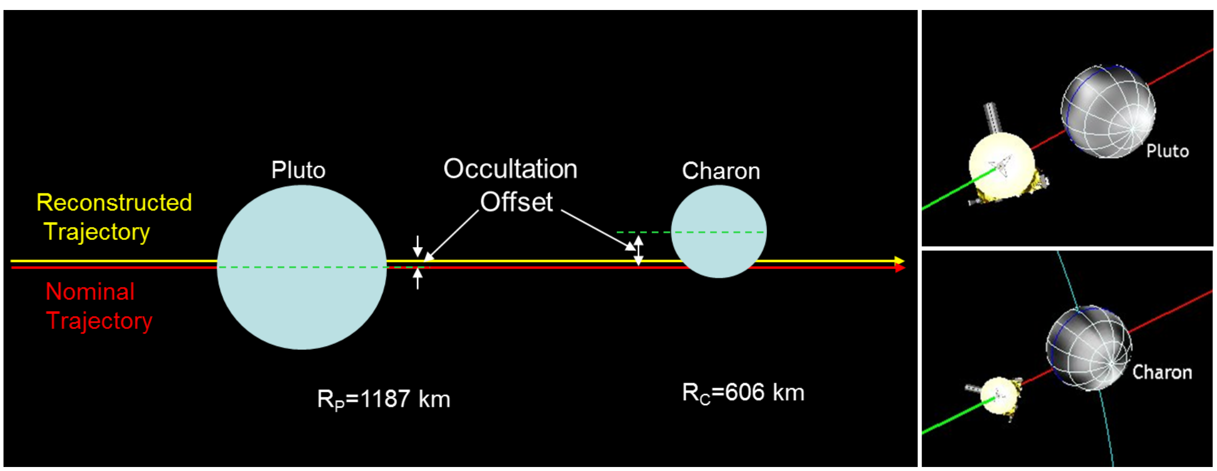


**Figure 5. Trajectory Flyby Path and Occultation Geometry (View from Earth)**

## 8. Post-Pluto Trajectory Change to Kuiper Belt Object

After the Pluto flyby, the NH spacecraft continued its course flying through the unexplored Kuiper Belt region. On an extended mission - pending NASA approval - the NH spacecraft will visit a Kuiper Belt Object (KBO) at close range for the first time. The KBO target was selected recently to be 2014 MU69, one of the three potential candidates analyzed by the team. The trajectory change will be made soon, in October-November 2015, to target New Horizons to a close flyby of KBO 2014 MU69.

The initial KBO targeting maneuver to alter the NH trajectory to reach the selected KBO target requires a ΔV of 57 m/s. The maneuver (TCM-20) will be divided into four burn segments, as shown in Table 8. The burns are separated by 3 days for the first three segments and by 7 days for the last segment in order to allow for an update based on estimated performance of the prior three burn segments. The first segment is scheduled on October 22, 2015, and the last segment on November 4, 2015.

**Table 8. KBO Targeting Maneuver**

| | TCM20-A | TCM20-B | TCM20-C | TCM20-D | Total |
|---|---|---|---|---|---|
| Burn Start Time (UTC) | 22 Oct 2015 17:50:00 | 25 Oct 2015 17:30:00 | 28 Oct 2015 17:15:00 | 4 Nov 2015 16:45:00 | |
| ΔV (m/s) | 10.29 | 15.94 | 18.67 | 12.11 | 57.01 |
| Burn Duration (s) | 950 | 1500 | 1800 | 1192 | 5442 |

The KBO flyby will be on January 1, 2019, at a distance of 43.3 AU from the Sun and 44.3 AU from Earth. The round trip light time then will be 12.3 hours. The flyby speed will be 14.4 km/s, slightly greater than the Pluto flyby speed.

## 9. Summary

The designed nominal Pluto flyby trajectory, trajectory evaluation and updates performed in the approaching phase, and trajectory corrections executed for the New Horizons flyby of the Pluto system are presented. All of the science measurements desired for the first Pluto reconnaissance mission were fully supported by the carefully chosen nominal Pluto flyby trajectory, including the requirements for Pluto occultation by both Earth and Sun and Charon occultation by both Earth and Sun for the atmosphere investigation. The New Horizons' reconstructed flight path was close to the targeted nominal trajectory and achieved all four occultations. The mission design strategy of completing the detailed design of the entire trajectory from launch to Pluto and integrating it to the launch target effectively reduced post-launch trajectory adjustments. Post-launch trajectory corrections consumed only 19% of the budgeted ΔV. The trajectory performance was better than expected, and 16 of 25 planned TCMs were found not needed and were canceled. Extensive preparation and implementation of a comprehensive strategy for targeting the Pluto system flyby proved essential since there was no opportunity to recover from a mistake at a critical time.

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