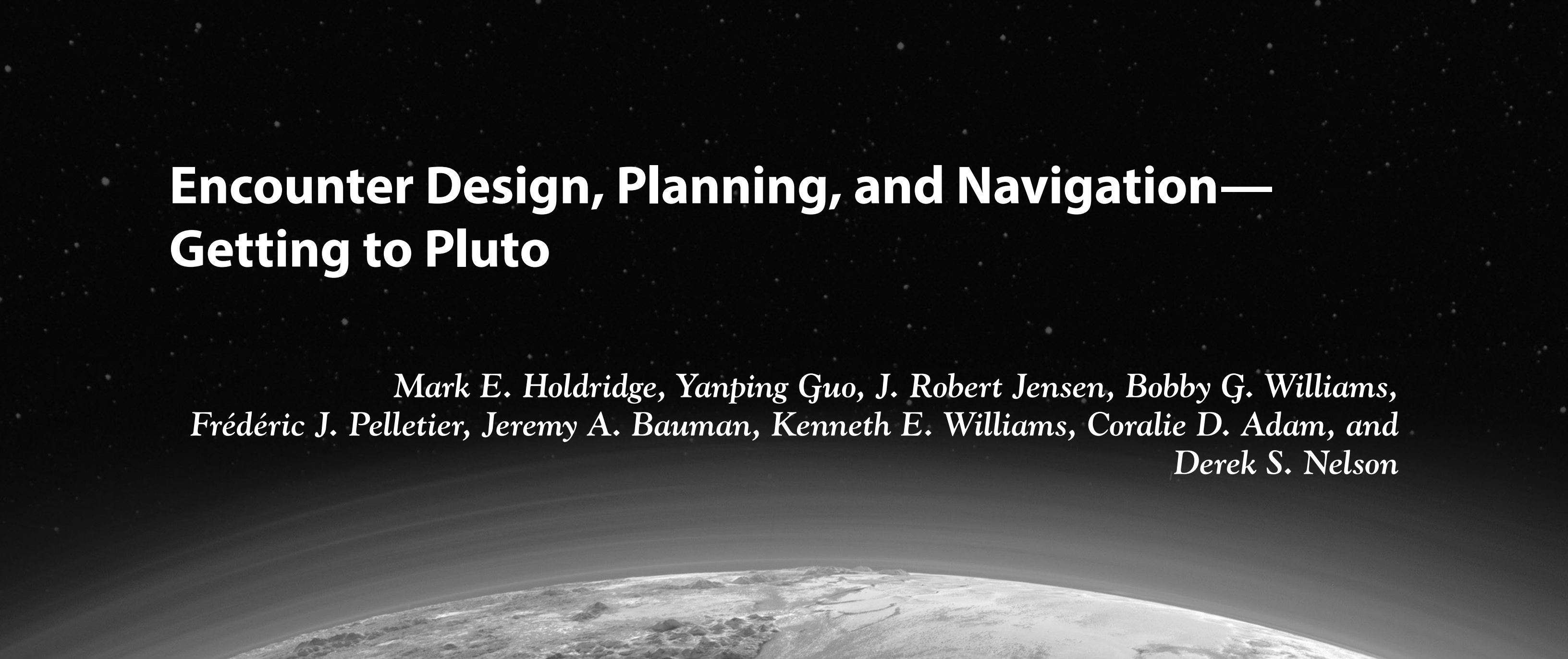

Encounter Design, Planning, and Navigation—Getting to Pluto

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ABSTRACT

New Horizons was the first mission with primary science objectives to explore the Pluto–Charon system and, in an extended mission, to observe a Kuiper Belt object (KBO). This article summarizes the challenges in planning and targeting the New Horizons spacecraft for the Pluto encounter and how the team addressed these challenges, reducing mission risk to ensure a successful encounter that fully met its science objectives. It also presents the navigation accuracies achieved and the lessons learned, which were later applied to planning and conducting the flyby of a newly discovered KBO, Arrokoth, during New Horizons' first extended mission.

INTRODUCTION

New Horizons was the first mission in NASA's New Frontiers Program and also the first mission with primary science objectives to explore the Pluto–Charon system. After the January 2006 launch and a nearly 10-year interplanetary cruise, New Horizons approached and flew by Pluto, and the team has since assessed the navigation results and science data. This article summarizes the challenges in mission design (MD) and planning and navigation analysis for this historic encounter with Pluto. It describes how the team addressed these challenges and reduced mission risk to ensure a successful encounter that met its science objectives. It also presents the approach's accuracy and flyby trajectory. Finally, it details the lessons learned, which were later applied to solve the challenges of targeting and conducting a flyby of a newly discovered Kuiper Belt object (KBO) in New Horizons' first extended mission.

PLUTO ENCOUNTER MISSION DESIGN

The Pluto flyby trajectory was designed to accomplish 15 science objectives,[1] including studying the geology, surface composition, and atmosphere of Pluto and its largest satellite, Charon. Enabling these science measurements, with their required geometry and trajectory conditions, on a single Pluto flyby is not trivial—it must account for the relative motion of the spacecraft with respect to the Sun, Earth, Pluto, and Charon, as well as two Deep Space Network (DSN) stations rotating with Earth. These bodies' orbits are not co-planar. Because of the required Earth–Sun relative geometry, the spacecraft's arrival time at Pluto had to be carefully selected. References 1–4 detail the design of the Pluto flyby trajectory, including the scientific rationale.

Since New Horizons did not include an auto-tracking algorithm for instrument pointing, precise knowledge of the spacecraft position relative to Pluto was required for accurate instrument pointing in all observations. This predictive knowledge was required to have errors smaller than 33 km × 66 km in the two dimensions of the B-plane box the spacecraft was to fly through at Pluto. Furthermore, the time of the Pluto flyby was to be determined in advance to an accuracy of 100 s along the trajectory track of the spacecraft (see Figure 1). The pointing of each instrument during an observation was then determined by computing the pointing direction based on the predicted spacecraft position at the time the observation was made relative to the observed target (i.e., Pluto, Charon).

Nominal Pluto Flyby Trajectory

Figure 1 shows the designed Pluto flyby trajectory, also called the nominal trajectory, and the Pluto system with the planet and its five moons in their orbits. The trajectory goes through the 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 New Horizons. Both Pluto and Charon are on the same side of the New Horizons trajectory, which minimizes the slew time when switching from imaging Pluto to imaging Charon. The flyby starts with the closest approach (CA) to Pluto, followed by CA to Charon, Pluto–Sun occultation, Pluto–Earth occultation, Charon–Sun occultation, and Charon–Earth occultation. The key events from Pluto CA to the Charon–Earth occultation occurred within a 3-h period. The resulting Pluto B-plane target definition, including the Pluto CA time and Pluto B-plane target, was provided to the project navigation (PNAV) and independent navigation (INAV) teams as the Pluto aimpoint for navigation. The nominal trajectory was also used for science planning and for building the onboard Pluto flyby sequences containing planned science measurements.

Safe Haven by Other Trajectories

The discovery of more moons in the Pluto system raised a concern that the spacecraft could be damaged from impact with high-velocity dust particles as it passed through the system at nearly 14 km/s. To mitigate this risk, the team designed alternative trajectories, also called safe haven by other trajectories, or SHBOTs, as a backup to the nominal trajectory. On the approach to Pluto, if the onboard cameras' latest images of the system detected any additional moons that could have generated debris (dust particles) along the spacecraft's planned trajectory, the spacecraft could change its course to one of the SHBOTs.

The three SHBOTs, along with the nominal trajectory, are plotted in Figure 2. In the depicted Pluto system's center of mass (or barycenter) inertial reference

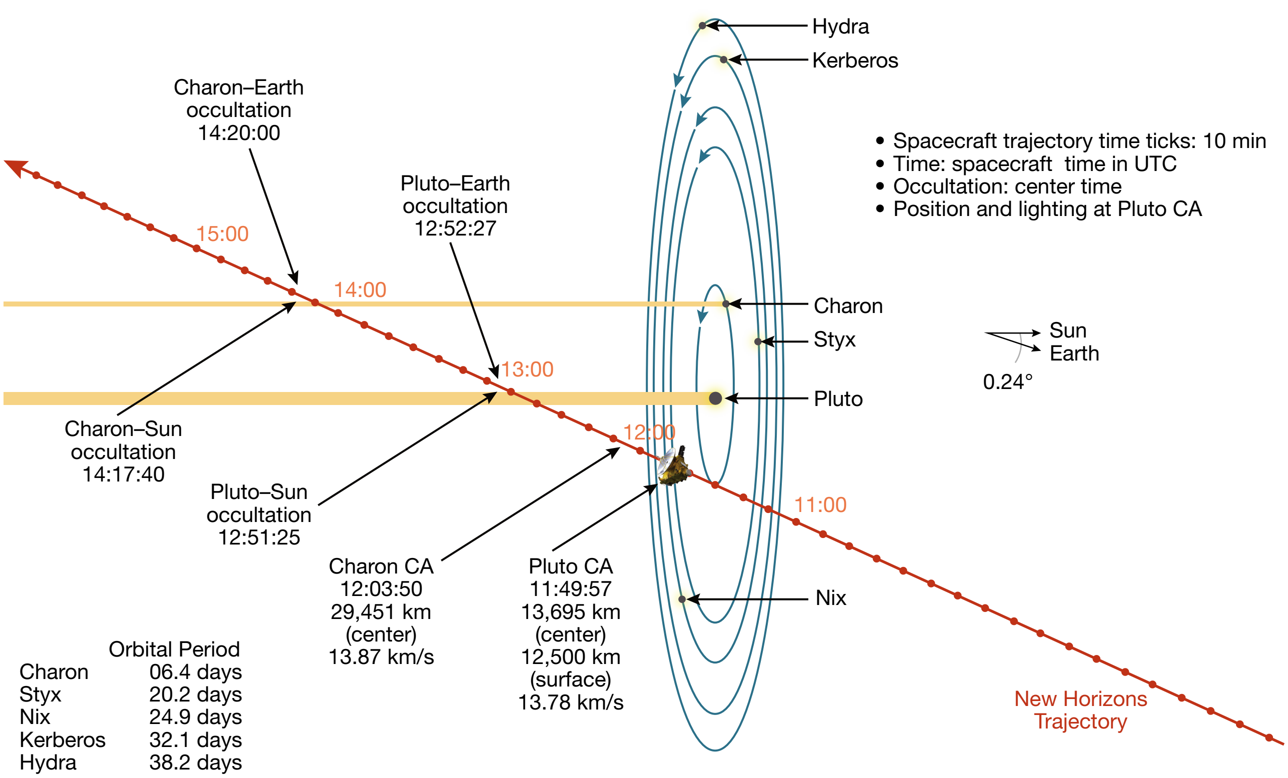

Figure 1. New Horizons Pluto flyby trajectory. This figure shows the designed Pluto flyby trajectory, also called the nominal trajectory, and the Pluto system with the planet and its five moons in their orbits.

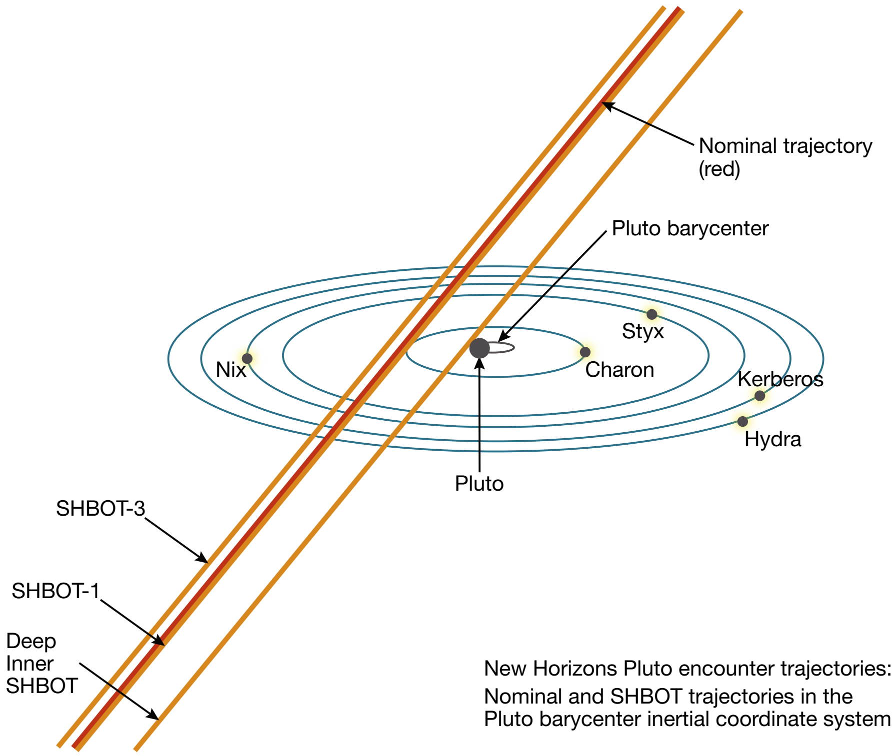

Figure 2. SHBOT and nominal trajectories. On the approach to Pluto, if the onboard cameras showed an abundance of dust particles along the nominal trajectory path, the spacecraft could change its course to one of the SHBOTs.

frame, the binary system feature of Pluto and Charon is clearly revealed. Both Pluto and Charon are orbiting around the Pluto system barycenter, as are the other smaller moons. The small moons are outside of Charon's orbit. The SHBOT, if selected, would go through the region where orbit dynamics analysis predicted a very low likelihood of dust. The foremost concern in selecting the trajectory was spacecraft safety, with achieving science objectives second. Because the SHBOTs lacked the necessary spacecraft trajectory geometry and conditions, science observations would have been degraded and some measurements partially or fully lost if an SHBOT had to be selected. After considering many SHBOTs, the team selected three as candidates for flight operations.

The SHBOTs are defined by their equatorial plane crossing distance. The equatorial plane contains the orbits of the Pluto system bodies. The desired equatorial plane crossing distance for each SHBOT was provided by the science team. The deep inner SHBOT trajectory would cross the equatorial plane from inside Charon's orbit at a distance of 4,000 ± 300 km from Pluto's center. SHBOT-1 goes through the region centered on Charon's orbit. Its equatorial plane crossing distance is 17,531 ± 600 km from the Pluto barycenter. SHBOT-3 goes through the Charon instability strip at the equatorial plane crossing distance of 21,615 ± 600 km from the Pluto system barycenter. The SHBOTs keep the same Pluto CA time as the nominal trajectory, reducing the velocity change (ΔV) needed when switching from the nominal trajectory to the SHBOT. Other than the fixed equatorial plane crossing distance and the Pluto CA time, the SHBOT trajectory can be optimized to ensure the science measurements planned for the nominal trajectory as much as possible.

Unique Navigation Challenges

Modeling of Small Forces Affecting Spacecraft Trajectory

While the spacecraft spent most of the cruise phase in spin mode for attitude stabilization, it switched to three-axis thruster-controlled attitude mode for most of the final approach to Pluto. Although thruster attitude control used coupled thrusters, small misalignments in the thrusters and plume impingement resulted in small translational ΔVs during three-axis mode. These changes were estimated within the orbit determination (OD) data arc. It was necessary to predict these nongravitational forces to accurately propagate the trajectory to the Pluto encounter during cruise and approach, but especially during the design of trajectory correction maneuvers (TCMs) for the final approach phase that started in late 2014.

On the seventh annual checkout during the summer of 2013, the team rehearsed both the onboard and ground activities planned for last 10 days of the final approach to Pluto. The PNAV and INAV teams used the rehearsal's realistic timing and simulation to refine flyby procedures and planned interactions. During the rehearsal, the spacecraft executed the planned flyby sequence including the attitude control thrusting, enabling the navigation (Nav) team to calibrate the small ΔVs resulting from residual uncoupled thrusting during different attitude control modes. The PNAV team developed a small forces model from this calibration to predict trajectory perturbations during the actual flyby in 2015.

Pluto System Orbit Uncertainties—Role of Optical Navigation in OD

Pre-approach analysis revealed that (1) meeting the Pluto targeting delivery and knowledge requirements would necessitate use of optical navigation inputs (OpNavs) in addition to radiometric data; (2) the estimated position of the trajectory target point in the Pluto B-plane would be well determined during the third OpNav campaign; and (3) the Pluto time of CA (TCA) would not be determined well enough to meet requirements until 3 or 4 days before CA.[5,6] The third finding was the most troublesome since resolving it required either a very late TCM to control the target time or a means to update the onboard sequence to control pointing at the correct time to acquire Pluto and its satellites in the instruments' field of view (FOV). The team chose the latter method, which became known as the knowledge update (KU) process, to correct for timing offset of the sequence.

Execution of the science sequence during the Pluto flyby precluded any DSN radiometric tracking from 2 days before to 1 day after CA. The Pluto system's small overall gravitational acceleration on the spacecraft trajectory made it impossible to detect the approaching planet and, thus, determine the time of periapsis from the available radiometric data, so precise OD estimates of the Pluto TCA depended on OpNav processing. The early discovery of two additional small satellites of Pluto, Nix and Hydra, allowed earlier detection and estimation of the time of periapsis through optical parallax by providing objects with a longer "baseline" from Pluto than that available from Charon alone.[7] Later discovery of two more satellites, Kerberos and Styx, also promised to aid in better determination of the TCA, but further analysis showed that the OpNav imagers could detect these smaller, dimmer satellites only in the LORRI camera's 4 × 4 mode until the spacecraft was very close to Pluto. Thus, OpNav images of Kerberos and Styx were relatively ineffective compared with the LORRI 1 × 1 images of Pluto, Charon, Nix, and Hydra.[7]

Because of the large uncertainties in the a priori Pluto ephemeris, the PNAV team developed a constrained OD strategy for the Pluto approach. With historical observations of Pluto spanning such a small arc of less than one orbit about the Sun, the radial distance of Pluto from the Sun had an uncertainty more than twice that of its positional uncertainty in the downtrack orbit direction. The OD strategy required that Pluto's inertial position and velocity be estimated concurrently with the spacecraft trajectory. Because of the relative motion of Pluto and Charon around the system's barycenter, the OD filter had to account for uncertainties in the motion of both the barycenter and Pluto and its satellites. The team decided to treat the uncertainty in the Pluto barycenter ephemeris about the Sun separately from the uncertainty in the satellite ephemerides about the barycenter. The Solar System Dynamics Group at the Jet Propulsion Laboratory (JPL) provided fully correlated covariance matrices for the a priori barycenter and satellite ephemeris files. The PNAV team used these files in its OD processing starting in July 2014 until JPL provided a more precise satellite ephemeris, plu047, and its associated covariance on July 2, 2015.

The a priori uncertainty in the ephemeris position of the Pluto system barycenter was improved by approach OpNav images in the B-plane 'B' vector and B normal directions, but it was not improved in the time-of-flight (TOF) direction until 5–7 days before CA. To mitigate the negative impact of a potential large TOF error, KUs could be uplinked to the spacecraft to restore the planned instrument pointing.

The appropriate fully correlated covariance was used in the OD filter as an a priori constraint on the Pluto system state while estimating the spacecraft state and Pluto system parameters. Offsets of Pluto and its satellites observed in OpNav images on approach could have been caused by trajectory errors or Pluto ephemeris errors. The radiometric tracking data before the OpNav images tended to fix the trajectory inertially relative to the Sun, while the constraint on the Pluto ephemeris tended to allow movement of the Pluto system barycenter in the least known direction affecting the time of CA (the radial direction from the Sun). This was the result observed as the OpNav tracking began to dominate the solution during the final days before Pluto CA, as discussed in the section on navigation operations.

Unique Mission Planning Challenges

- The mission's success depended on a successful Pluto flyby the first and only time on July 14, 2015. Flawless trajectory control and updated onboard spacecraft trajectory target knowledge were essential to mission success.
- Because of systems engineering and mission operations constraints, spacecraft trajectory corrections could not be made inside 10 days of the flyby.
- Hazard avoidance measures included the requirement to change the encounter aimpoint to one of several options at multiple times on approach. This significantly complicated the TCM decision criteria and processes.
- All navigation was performed with ground-in-the-loop operations; no navigation was performed onboard the spacecraft. This, combined with the spacecraft being 30 astronomical units (au) from Earth, resulted in very long round-trip light times (RTLTs), ~9 h, and very low downlink data rates for reception of tracking and OpNav images.

How the team mitigated these Pluto encounter planning challenges is discussed next, along with a timeline of events.

Pluto Encounter Timeline of Events—2015

OpNav and Trajectory Corrections

As shown in Figure 3, approach operations were divided into logical time periods referred to as approach phases (APs). AP1 began in January 2015, marking the start of Pluto approach operations. The primary navigation-related operations during AP1 were to measure and update estimates of the spacecraft and target body orbits (Pluto and its moons) and remove errors as they were observed. However, two key navigation-related events took place 6 months before AP1: a Pluto targeting TCM[8] (TCM-15) was performed on July 15, 2014, solely based on Pluto ground-based observations, to remove errors in flyby targeting and timing; and OpNav Campaign 1 (C1) was performed after TCM-15 from July 18 to 24, 2014. OpNav accuracy a year out was insufficient to surpass and correct estimates made with Earth-based and Hubble Space Telescope (HST)-based observations of Pluto, but it served as a test of the OpNav process and an independent check on the Pluto orbit solutions that relied on decades of ground-based observations of Pluto, including more recent HST observations. Independently checking solutions was key to mitigating risk in the navigation process. Other examples are discussed later.

Each subsequent OpNav campaign further refined estimates of the orbits of Pluto and its moons and provided valuable data to target and control the spacecraft's trajectory via TCMs, which typically followed each campaign. As the spacecraft closed in on Pluto, the power of OpNav gradually increased, and eventually the accuracy of LORRI's observations surpassed the accuracy of those obtained with terrestrial observatories. The next TCM, TCM-15 B2, was the first performed primarily based on in-flight OpNav results obtained during OpNav campaign C2, which ran from January 2015 to March 2015. TCM-15 B2 was successfully performed on March 10, 2015, 4 months before the Pluto encounter.

Two more OpNav campaigns were planned (C3 and C4), along with six more TCM opportunities, enabling the team to incrementally measure and remove predicted delivery errors at Pluto. These additional campaigns and TCMs (shown in Figure 4) were necessary because, to meet the encounter's science goals, the spacecraft had to be controlled to fly through a delivery

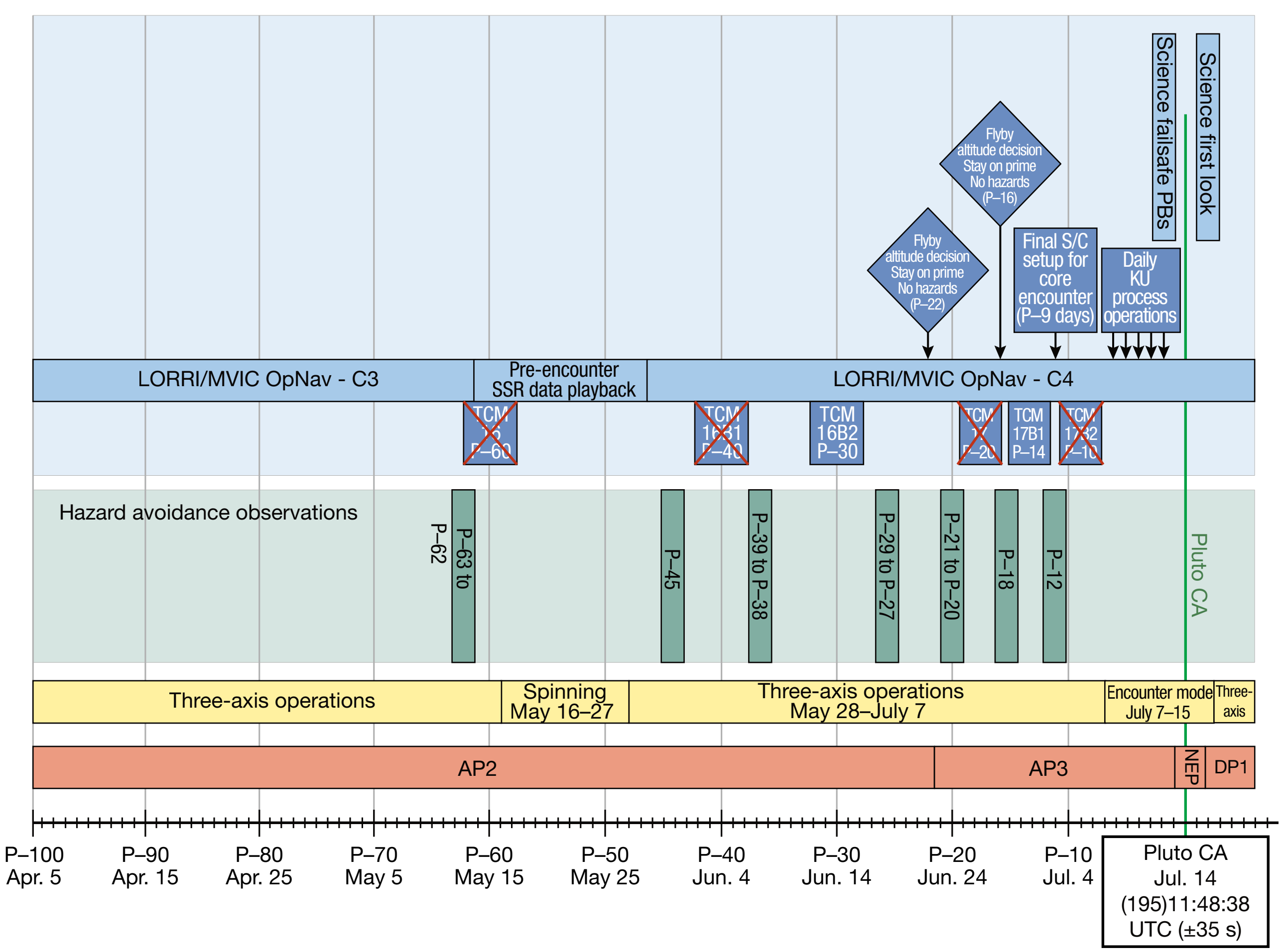

Figure 3. Approach timeline (as flown). Approach operations were divided into logical time periods referred to as approach phases, or APs.

box measuring only 100 km by 150 km at Pluto. Only the final OpNav and TCM opportunities were accurate enough to permit this precision, but waiting until those final stages to remove trajectory errors would have increased cost (in propellant). Removing trajectory errors incrementally helped preserve propellant for and enabled the extended mission to the Kuiper Belt.

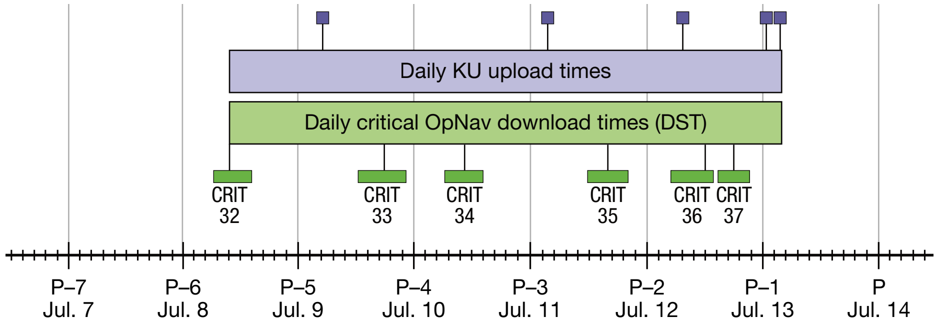

Figure 4. Orbit KU timeline. Orbit KUs were planned for the final week of approach operations.

Refined trajectory estimates were performed leading up to each of the TCM opportunities, with separate go/no-go reviews held for each. Only two of the six remaining TCM opportunities were required and given the go-ahead for execution. These were TCM-16B2 on June 14, 2015, and TCM-17B1 on June 30, 2015, which completed the trajectory adjustment portion of the flyby. The trajectory was continuously monitored after TCM-17B1. The contingency opportunity on July 4 was not required, so the New Horizons spacecraft coasted for the remaining 2 weeks leading up to the Pluto encounter and successfully flew within the 100 km × 150 km box.

Hazard Avoidance

While refining orbit estimates and performing TCMs, at seven points on the Pluto approach, the science team took long-exposure deep images of the Pluto system to look for signs of new moons or other potential hazards to the spacecraft as it flew past Pluto. Dozens of long-exposure images were downlinked and co-added on the ground to bring out the faintest objects.

At two decision points (shown in Figure 3), one 22 days from Pluto encounter (P–22 days) and the other 16 days out (P–16 days), results were scheduled to be evaluated for signs of hazards, the probability of space debris impact would be calculated, and NASA would decide whether to stay on the current nominal trajectory or divert to an SHBOT. The results of the final hazard analysis cycles fed directly into the P–20 and P–10 day TCM design points, permitting those two TCM opportunities to be used for trajectory cleanup, hazard avoidance, or both.

As events unfolded on approach, the hazard analysis did not reveal any new moons or other concerns for mission safety. The spacecraft remained on the nominal flyby path throughout the encounter and flew past Pluto at the nominal and optimal altitude of 12,500 km.

Orbit Knowledge Updates

While the spacecraft coasted during the final 2 weeks of approach, navigation efforts did not end. They transitioned from measuring and removing observed trajectory errors to continuously refining estimates of the orbits of Pluto and its moons so they could be updated onboard the spacecraft. These KU operations enabled more accurate pointing of the spacecraft to its intended targets during the most challenging period of the encounter—when the spacecraft would fly past Pluto at ~14 km/s.

This flyby speed makes it extremely challenging to point the spacecraft and keep the cameras centered on Pluto and its moons and capture the observations, given expected residual trajectory errors. As mentioned, the predicted orbit knowledge onboard the spacecraft was required to have errors smaller than 33 km × 66 km in the two dimensions of the B-plane box the spacecraft was to fly through. Modeling and analysis performed years before predicted that these accuracies could not be observed and corrected using the high-resolution LORRI camera OpNav images of the Pluto system until ~3 days before the flyby. And once those images were taken, they still had to be downlinked and processed, and orbit solutions had to be refined, reviewed, and tested before results could be uplinked to the spacecraft before the encounter. These operations were highly choreographed to ensure that adequate time was allocated to each step to prevent errors from entering into the uplinked solutions.

Figure 4 shows the timeline for orbit KU opportunities planned for the final week of approach operations and the critical OpNavs (CRIT) that fed into each KU uplink opportunity. Modeling demonstrated that the final two KUs using CRIT 36 and 37 would be accurate enough to meet the 33 km × 66 km knowledge requirement. Still, three additional opportunities were added before these to minimize risk and provide opportunities to reduce onboard orbit knowledge errors incrementally in case the final uplink opportunities could not be used for some reason (e.g., problems with DSN tracking facilities or other flight or ground issues).

Years of preparation and testing went into these KU operations for Pluto, but no KU uplinks were required during the Pluto encounter because those uplinked 9 days before the flyby, when the encounter command load was uplinked, met the desired specifications for position and timing accuracies. Nevertheless, the process was necessary to ensure mission success. These same KU update processes were reused during the later flyby of KBO Arrokoth. The KU used on final approach to Arrokoth greatly improved instrument pointing and increased flyby science returns.

Risk Mitigation and Mission Success Enablers

As mentioned, the mission's success depended on a successful Pluto system flyby. This created a push–pull relationship between the science team, which understandably wanted to maximize the science return from this rare opportunity to explore the Pluto system up close, and the mission operations and Nav teams, which needed to regularly perform OpNav and TCM operations. Increasing science returns typically meant packing as many science observations into the encounter as possible, particularly during the spacecraft's CA to Pluto. This often translated into the science and Nav teams competing for spacecraft data storage and downlink resources.

Detailed planning, testing, and review of all navigation-related activities was key to mission success. Early on, mission management facilitated negotiations between the science and Nav teams and agreed to navigation accuracy requirements that were achievable at appropriate risk levels. Maintaining this balance and the focus on preparing and validating the two key navigation activities, TCMs and KU operations, was instrumental to mission success.

The next section describes how the team addressed challenges and risks. While these techniques were developed for the Pluto encounter, they would later also be applied to reducing risk during the encounter with KBO Arrokoth in 2019.

TCM Risk Mitigation

As discussed, several TCMs[8] were required in the final Pluto approach phase to keep the spacecraft on course for the flyby. TCMs were also required if the mission had to divert to a safer trajectory to avoid hazards. Timely and accurate execution of TCMs was absolutely essential to getting the spacecraft within the 100 km × 150 km delivery box.

Implementation consistency: To achieve reliable TCM results, the team reused the same TCM implementation approach each time, using the same three-axis spacecraft operating mode and the same thruster complement for each TCM. This ensured consistent maneuver results from one TCM to the next and greatly reduced risk.

Backup opportunities: Navigation analysis showed that the TCMs at P–30 and P–14 days were the most likely to be required to meet the 150 km × 100 km targeting requirements. Each was followed by at least one backup opportunity, with the P–10 day opportunity slated to be used only in a contingency. Additional TCM opportunities upstream of the P–30 opportunity were included to provide occasions to remove trajectory errors as soon as they could reliably be estimated in order to minimize propellant usage.

Operational readiness testing (ORT): TCMs were familiar to the operations team, especially because of the standard well-proven TCM implementation approach used during cruise. However, ground operations that supported TCMs were highly unique and challenging for hazard avoidance operations and the Pluto final approach TCM opportunities, which were far more time and mission critical than the TCMs performed during cruise. Performing these encounter-unique TCM operations during ORTs trained the team, tested the software and procedures, and gave the team an opportunity to improve the operations and adjust timelines based on lessons learned during the testing.

Figure 3 shows the hazard decision points leading up to the reference TCM operations timeline and decision points. To improve the hazard assessment process, the data cut-off time for taking hazard assessment images was moved to be as late as possible. This tightened up the ground operations required for finalizing TCM designs and performing final testing and review steps before command uplink. Furthermore, the hazard team chose from multiple potential hazard flyby trajectory options, so the MD and Nav teams had to be prepared to perform a TCM that not only removed trajectory errors but also switched to an entirely different trajectory that the hazard team deemed safest for the flyby. This put even more pressure on the relatively modestly sized team to implement these safely and quickly. The process is shown in Figure 5.

Hazard decision TCM ORTs were conducted to test this process end to end, starting with image processing by the hazard team (shown in the pink boxes in the upper part of Figure 5). This was followed by the hazard decision, made by the mission principal investigator and approved by NASA. Because a trajectory change would affect the science data obtained, NASA needed to approve any changes from the nominal trajectory. The activities required to implement a TCM (if required for trajectory cleanup or hazard avoidance) are shown in yellow. To save time, the navigation OD update was performed in parallel with the science team's hazard assessment process to shorten the time for post-hazard decision TCM steps. Reducing the time between hazard decision and TCM execution was extremely important because it gave the science team more time at the front end of the process (pink boxes) to take and downlink the hazard images with a later data cut-off, resulting in images with better resolution and a greater chance of detecting any hazards. The following steps in the TCM process were

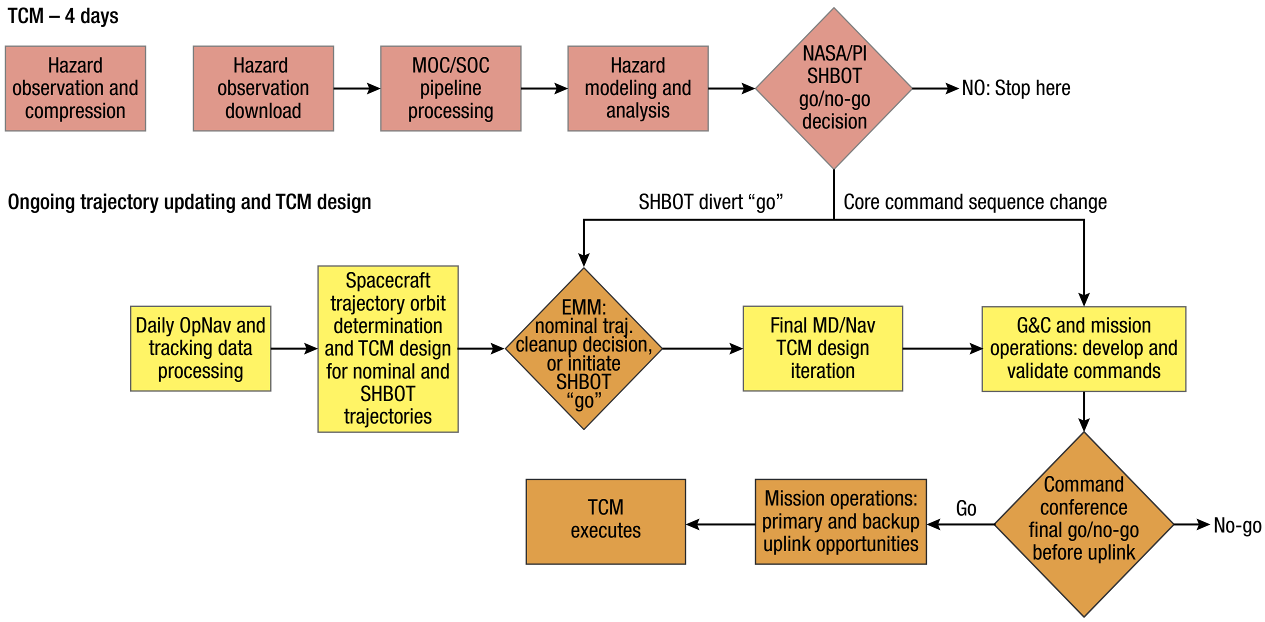

Figure 5. Science flyby hazard assessment feeding into and the navigation TCM decisional flow. Hazard decision TCM ORTs were conducted to test this process end to end, starting with image processing by the hazard team (pink boxes) and progressing to the activities required to implement a TCM (yellow and orange boxes). EMM, encounter mission manager; MOC, mission operations center; PI, principal investigator; SOC, science operations center.

for guidance and control (G&C) and mission operations to prepare, test, and uplink the commands.

Initially, the science team practiced the hazard portion of the TCM process in ORTs several times as a stand-alone process. Separate ORTs were performed for the second half of the TCM process (shown in yellow and orange boxes in Figure 5). The smaller portions helped expedite testing. After both the hazard team and the MD/Nav teams had performed the ORTs enough times to be assured they could perform the necessary steps in the times allocated, one last combined ORT was performed in real time with both sets of teams conducting their portions back to back.

TCM design cross-checking: To guard against systematic errors, all TCM designs developed by the MD team were also computed independently using Nav team personnel and software. The difference between the two solutions had to be smaller than a fixed convergence error limit to be deemed a success. This process helped mitigate any risk due to systematic errors from process, ground software, or system configuration errors. The MD team iterated with the Nav team until their designs converged. This process was tested in TCM ORTs many times until the teams worked out modeling differences that prevented convergence. After both teams' systems produced similar results, any changes were carefully controlled and communicated. This process ensured that TCM designs converged during the actual time-constrained operations during the Pluto encounter.

KU Risk Mitigation

KUs were required during the final Pluto approach phase to provide the onboard G&C system with the latest spacecraft and Pluto system orbit knowledge required to meet science target pointing requirements. This knowledge was used to point the instruments as accurately as possible, given the uncertainties in the targets' (Pluto and its moons) locations and timing. Reducing these uncertainties enabled predesigned science observation sequences to capture these science targets within the instrument FOVs during the flyby.

KUs were unique to flyby operations and were not performed during the cruise phase. Initial steps in the KU process cycle included the spacecraft pointing to the target (Pluto or its moons), taking the OpNav images, storing them onboard, and later downlinking them during a DSN contact. Ground processes involved processing OpNav images as they were transferred from the DSN to the mission operations center (MOC), comparing actual target locations with those expected in the LORRI camera's FOV, and Nav refitting orbits to the new observations and generating updated orbit and timing information. Finally, KU commands containing this orbit and timing information were prepared and verified by mission operations. The final steps included the KU command uplink at the DSN, reception by the spacecraft, and storage of the KU in the spacecraft's G&C subsystem for later use in target pointing and command sequence time shifting.

The KU process could not be performed in flight in advance of the Pluto flyby because, with such long distances to Pluto, it would be impossible to detect any motion of Pluto relative to the star background because of the spacecraft closing in on Pluto. All that could be detected early on was Pluto's apparent orbit motion relative to the stars, which revealed nothing about the spacecraft's distance to Pluto, a key product of the KU process. So testing of the KU ground processes used simulated OpNav images. As New Horizons closed in on the Pluto system in the final weeks, Pluto and its moons could gradually be detected to higher and higher accuracies, but as predicted, the LORRI camera could not determine the flyby timing to the required 100-s accuracy until orbit geometry was more favorable in the final 3–4 days. This process had to be performed flawlessly since there was little time in the final days to fix software or process errors.

KU operations timeline and built-in robustness to failure: KU processing was highly time critical. Every minute reduced from ground processing times permitted more accurate data to be taken down in advance of the process, downlinked, and used in the orbit update process, improving the accuracy of the results.

Figure 4 shows the six CRIT KU OpNav downlink and ground processing cycles that fed into five separate uplink opportunities. Notice that the final two KU cycles, CRIT 36 and 37, were followed by two uplink opportunities, a prime and a backup. Only one KU uplink needed to be performed using the best data available; however, earlier KU uplink opportunities were planned to capture and uplink any orbit improvements realized along the way in case a flight or ground problem prevented one of the later uplink opportunities. These early occasions also served as excellent junctures to adjust ground processes to account for real-world differences when comparing the OpNav data processed and Nav results computed from them to those used during earlier ORT testing with simulated data products. To further reduce risk, OpNav downlink timing used alternating DSN complexes to help guard against a single DSN site failure (e.g., caused by high winds) that could prevent DSN reception of OpNav data.

Team composition and solution cross-checking: As with the TCM designs, a dual-team approach was adopted for the mission-critical KU process. The PNAV team provided the solutions, and the INAV team processed the OpNav data using independent software tools to provide independent solutions for comparison. The two solutions were compared during each KU cycle. Any discrepancies between the two solutions were reconciled before the PNAV solution was used. This process helped guard against systematic solution errors and enabled more options for processing and comparing solutions. It also enabled greater collaboration. Both teams also collaborated with members of the science team, which was performing its own processing of OpNav images. The encounter mission manager fostered this cooperative and supportive work environment, which minimized risk and produced more accurate and credible solutions essential for mission success.

KU ORTs: ORTs were conducted to test the combined team's ability to perform the time-critical KU operations, validate ground software and procedures, and train all personnel. To further reduce mission risk, 2 years before the Pluto flyby, a 7-day flight test of the Pluto encounter exercised the encounter sequence onboard the spacecraft. All flight and ground KU steps were conducted during this highly realistic ORT. The entire process executed successfully.

The PNAV team performed initial ORTs only to test each step in its flow, starting with simulated OpNav images and continuing through the entire orbit fit process until completed. Later KU ORTs folded in other participants, including the INAV team, and the additional steps required for two teams to compare results and recommend the best solution. These tests were later timed to ensure the end-to-end process could be completed within the time allotted.

Gradually all KU process participants, including members from mission operations, MD, science operations, and G&C, participated in the ORTs to perform each step exactly as it would be carried out during the Pluto flyby. The primary difference between the ORTs and the actual flyby operations was the use of simulated OpNav scenes for ORTs. They were generated on the ground and released to the team at the same time in the timeline as they would be in the actual operations. Every step in the ~12-h end-to-end KU process was performed, including fully staffed results reviews at key gate points along the KU process.

The New Horizons hardware-in-the-loop simulator (NHOPS) was used to test the onboard operations that followed a KU command uplink before the actual uplink. Results from that test were reviewed at a command conference where the final go/no-go decision to uplink was made.

NAVIGATION OPERATIONS AND ACTUAL ACCURACIES VERSUS REQUIREMENTS

OD Performance

There was a known risk of a potential large undetected offset in Pluto's radial position and therefore in the encounter timing. Since science observations were tied to the encounter timing, a special KU process updated the onboard orbit knowledge just before the encounter. During final approach after July 6, new OpNav images were processed each day to perform a new OD solution, where the Pluto and satellite ephemerides solutions were also improved.

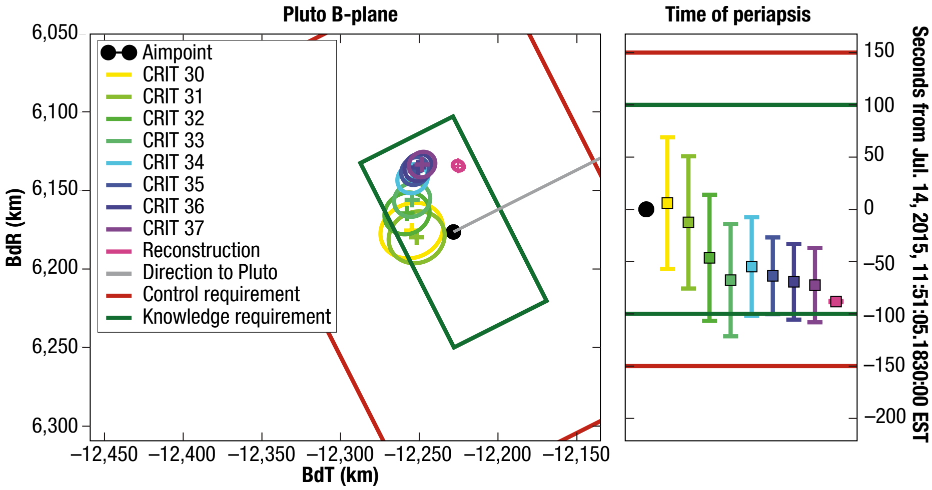

Figure 6. Pluto targeting (position and timing) solution sets for each daily CRIT OpNav update reconstructed after flyby. The knowledge requirement is shown as a green box/bar. The reconstruction indicates a final B-plane at about 45 km and 88 s off target. When compared with the last estimated solution before the Pluto encounter, CRIT 37, the reconstruction is different by only ~25 km and 16 s.

Eight OD solutions were performed between July 6 and July 12, each labeled by the number of the associated critical OpNav acquired that day (CRIT). The first two solutions did not include a new image because of the spacecraft anomaly on July 4 (see the article by Bowman, in this issue, for details). Figure 6 shows the B-plane and time-of-periapsis solutions for each solution. The knowledge requirement is shown as a green box/bar and is centered on the aimpoint because the June 30 TCM solution delivery was the last solution uploaded to the spacecraft. If an updated ephemeris set based on one of the CRIT solutions had been uploaded, the green box would have been recentered to that solution for the subsequent OD.

CRIT 32 was the first solution that included a post-spacecraft-anomaly OpNav, captured on July 7. The previous image used was captured on July 3. Despite the upward migration in the B-plane, all solutions stayed within the requirement box, so the June 30 TCM solution was retained (exactly centered on the aimpoint) as the nominal onboard pointing reference.

The final reconstruction is also shown in Figure 6, indicating a final B-plane at about 45 km and 88 s off target. When compared with the last estimated solution before the Pluto encounter, CRIT 37, the reconstruction is different by only ~25 km and 16 s.

Optical Navigation

The OD process[9] during final approach to Pluto was extremely complex and time constrained. The Nav team's first challenge was the center-finding process of the OpNav images, which led to much discussion and various OD experiments to determine whether some images should be de-weighted or simply deleted. With six bodies of the Pluto system in the OD estimated state, the new ephemerides resulting from each estimation had to be carefully analyzed. In addition, the Nav team still had to characterize the effect of small forces on the trajectory. As a result, it was difficult to assess in real time the cause of the day-to-day variations in the OD solutions. As the formal 1-σ values in the OD were becoming smaller, each new image had a significant effect on the solution. While the new data were powerful, they had to be carefully considered. As the imaged bodies became larger in the LORRI FOV, the center-finding process became quite challenging. Therefore, the OpNav data weights used had a per-diameter scale factor, but which value to actually use was decided day by day in light of all the evidence.

PNAV processed 883 images of the Pluto system, 850 from LORRI and 33 from the Multispectral Visible Imaging Camera (MVIC). Table 1 summarizes the images.

Analysis of the OD solutions revealed that the most prominent parameters being changed were the positions of Nix, Hydra, and the system barycenter.[7] As Nix's and Hydra's images were becoming more resolved in the FOV, they became a driver for the OD. Because Nix's and Hydra's orbital periods are larger than Charon's, observing the bodies in various locations in their orbits helped to determine the relative motion between New Horizons and Pluto.

The top image in Figure 7 shows the post-fit LORRI 1 × 1 residuals with respect to the post-Pluto reconstructed orbit solution in the frame of the imager and units of pixels. The horizontal and vertical dimensions of the detector correspond to the pixel and line dimensions, respectively. The bottom image corresponds to the same post-fit 1 × 1 residuals in inertial space and, thus, corrected for varying camera twist angles. These data are

Table 1. Optical images

	LORRI 4 × 4	LORRI 1 × 1	MVIC
Pluto	0	497	33
Charon	0	489	33
Nix	271	62	0
Hydra	282	71	0
Total[a]	317	533	33

[a] Multiple bodies were often included in a single image.

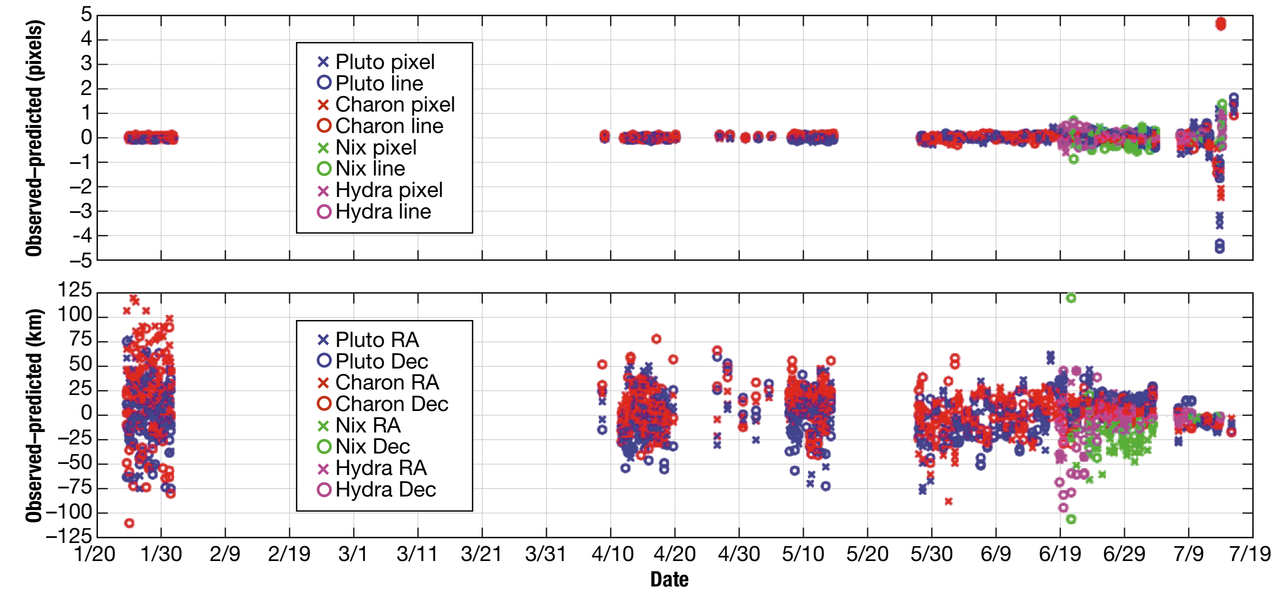

Figure 7. Final OpNav solution errors (observed–predicted). Top, the post-fit LORRI 1 × 1 residuals with respect to the post-Pluto reconstructed orbit solution in the frame of the imager and units of pixels. The horizontal and vertical dimensions of the detector correspond to the pixel and line dimensions, respectively. Bottom, data are presented in kilometers rather than an angular unit to illustrate how the decreased distance to the target affects the metric value of the residual. Dec, declination; RA, right ascension.

presented in kilometers rather than an angular unit to illustrate how the decreased distance to the target affects the metric value of the residual. To convert to kilometers, the angular residual is scaled by the distance to the body.

Small-Force-Modeling Accuracy

Figure 8 shows the detailed reconstructed small forces[10] (accumulated) against the final prediction model. Note that the small forces were primarily in the spacecraft *y* direction, along the axis of the high-gain antenna. Because of the line-of-sight nature of Doppler tracking, the observability of the small forces is also only in the *y*-axis direction. For those reasons, the predicted model estimates in the *x* and *z* axes were zero. The non-zero final estimates contributed to the reported OD errors, although the results are within the a priori error budget associated with the *x* and *z* small forces.

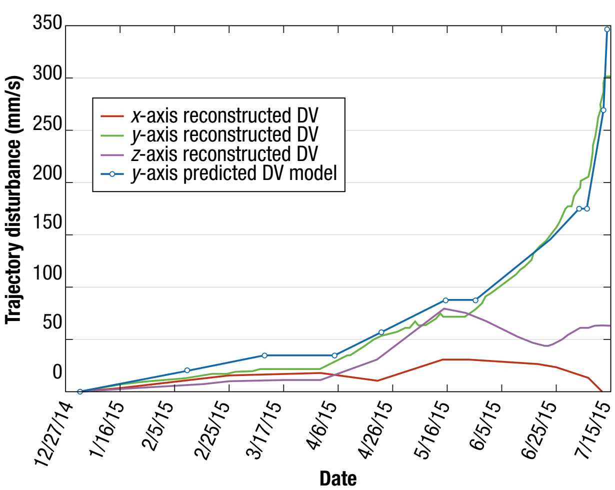

Figure 8. Predicted vs. actual (reconstructed) trajectory disturbances due to small forces. The small forces were primarily in the spacecraft *y* direction, along the axis of the high-gain antenna.

PLUTO LESSONS LEARNED

Many lessons were learned from the Pluto encounter. Many of these lessons were later applied when planning and conducting the 2019 encounter with KBO Arrokoth.

Mission Management

- Numerous ORTs were performed to prepare the team for the time-critical KU process as well as TCM operations. This testing initially identified process and software issues that needed to be modified and later served as an important means for currency training as the flyby approached.
- Co-location of navigation and science operations facilities improved time-critical cross-communications; however, it also increased background noise during critical events. Additional sound barriers were needed.
- Sharing the mission timeline, calendars, and data sheets across an institutionally and geographically diverse team was arduous and error prone because network security restrictions prevented use of a single tool that could store and share needed data across all institutions.

- Mission management used two Navigation teams, the PNAV and INAV teams, which had the following advantages during encounter planning and execution:
  - It facilitated determining the best means to jointly conduct navigation operations, including refining processes and software tools to be used.
  - It helped guard the mission from systematic errors in processes and tools by providing independent orbit solutions.
  - It permitted greater collaboration for problem-solving.
  - When the teams came up with solution differences that were greater than expected, the combined team had access to a broader set of tools and resources to explore and understand these differences quickly.

Navigation

- It was important to characterize undesired thruster-induced small forces. The Pluto flight rehearsal provided an excellent measure of these forces that was used during the Pluto encounter.
- It was important to take Delta-differential one-way ranging[11] observations as close to Pluto flyby as possible to improve accuracy in delivery and reconstruction.
- Interaction with JPL's Solar System Dynamics Group was very efficient for deliveries of both Pluto barycenter ephemerides and Pluto satellite ephemeris files to Nav.
- The INAV and PNAV teams needed a common format to exchange OpNav results to facilitate more automated and frequent comparisons.
- More post-encounter images should be included for trajectory reconstruction.

SUMMARY AND CONCLUSIONS

New Horizons' flyby of Pluto was a resounding success in terms of navigation planning, trajectory, predictions, and precision. After the spacecraft traveled 9.5 years and over 4 billion kilometers, the PNAV and INAV teams provided OD and TCM calculations that delivered it to a point reconstructed to be 45 km and 88 s off the MD team's aimpoint, which is well within the control requirements. It also met the knowledge prediction requirement by providing a final OD before the encounter that was ~25 km off in the B-plane and 16 s off in the time of the reconstructed periapsis conditions. As a result, even though an update capability existed and was exercised by the Nav team, the MD team, and the ground system teams during the last 10 days before Pluto flyby, no KUs were uplinked to the onboard sequence after the information associated with the final TCM was uploaded more than 14 days before CA to Pluto.

A side benefit to estimating the Pluto system ephemerides is that navigation corrected the Pluto barycenter knowledge by 1,030 km, and that was mostly in the radial direction to the Sun. This was an ~1-σ change to the a priori model provided by the JPL ephemeris group. The navigation solution to the Pluto system ephemerides was made dynamically consistent with the estimated trajectory of the New Horizons observatory and OpNav tracking data, reducing uncertainties for positions and masses of Pluto and its satellites, albeit over a relatively short data arc (the final approach and flyby) compared with more traditional astrometric determinations.

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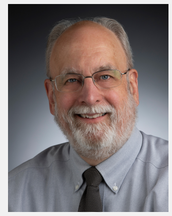

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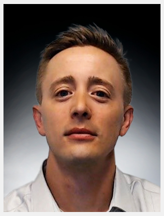

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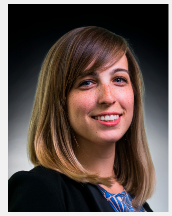

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