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INDEPENDENT NAVIGATION TEAM CONTRIBUTION TO NEW HORIZONS' PLUTO SYSTEM FLYBY*

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The New Horizons spacecraft made its closest approach to Pluto on 14 July 2015. The most significant challenge of this mission was that the Pluto system ephemeris was initially known with a precision of ~1000 km. This needed to be improved significantly on approach in order to meet the science requirements. During the final six months leading to the flyby, a JPL Independent Navigation (INAV) Team was included in the ephemeris knowledge update process as a cross-check on the Project Navigation (PNAV) Team's results. This paper discusses the INAV team's experiences and challenges navigating New Horizons through the Pluto planetary system encounter.

INTRODUCTION

Launched in 2006, the New Horizons spacecraft was the first mission selected in the NASA New Frontiers Program, and the first spacecraft to visit the Pluto system. After a cruise of over nine years, the New Horizons spacecraft made its closest approach to Pluto on 14 July 2015. Since launch, the primary navigation for the spacecraft has been provided by the PNAV team from the Space Navigation and Flight Dynamics Practice of KinetX, Inc. During the months leading into the Pluto flyby, a team of JPL navigators, the Independent Navigation (INAV) Team, were included in the ephemeris knowledge update process. The INAV team independently produced orbit solutions using the same data set, but with different software and strategies. These

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were then compared against the PNAV results. If any large discrepancies were found, an attempt would be made to resolve, or at least understand, the differences between the two teams.

There were a number of challenges navigating the encounter. First, there was the long one-way light time, approaching 4.5 hr at the time of the Pluto encounter. Most of the resulting radiometric (Doppler and range) data was three-way (when the signal is received from a station at a different complex than was transmitted) with limited periods of two-way (when the uplink and downlink stations are the same). Furthermore, the spacecraft uses a non-coherent transceiver instead of a coherent deep space transponder as is of the more commonly used for interplanetary missions. Before use by the navigation teams, the Doppler data from the Deep Space Network (DSN) was processed in tandem with other spacecraft telemetry in order to create two-way and three-way Doppler measurements for ingestion into our navigation software. The range was unaffected by the process.

Another challenge was the unbalanced thrusters. They were in near-continuous use in the last six months for attitude control and for the slewing necessary for science data collection. This produced a perturbing force in the spacecraft responsible for the largest uncertainty in the future spacecraft trajectory. Particularly challenging was trying to measure the off-Earth line components of this effect. An interferometric data type, Delta-Differential One-way Range (DDOR), effectively measures the plane-of-sky angle between the spacecraft and nearby quasar. They were only able to resolve the trajectory at the level of 10-30 km.

And finally, the most challenging part of the mission was improving the ephemeris knowledge of the Pluto system barycenter with respect to the Sun and, to a much lesser extent, the Pluto satellites relative to one another. Through a combination of using an updated Pluto system planetary ephemeris, an updated Pluto satellite ephemeris, and an extensive optical navigation imaging campaign of Pluto and four of its satellites, the delivery and knowledge requirements for the ephemeris were met.

This paper discusses the INAV team's experience on this mission and these challenging aspects of flying the New Horizons spacecraft through the Pluto planetary system encounter. We show how the ephemeris knowledge was improved upon approach to the Pluto planetary system and we show how that history compares to a reconstruction of the flyby. The PNAV experience is discussed elsewhere[1].

RADIOMETRIC DATA PROCESSING

Doppler Data

The New Horizons spacecraft uses a non-coherent transceiver built by JHU/APL instead of the more common coherent transponder used for deep space missions. The DSN radio metric tracking data must be pre-processed with additional spacecraft telemetry; a process done at JHU/APL and referred to as telemetry aided Doppler tracking (TADT)[2]. The downlink carrier phase measurements were processed in such a way to generate data functionally equivalent to what would have been provided by a transponder. Only after this process was complete were the navigation teams able to use the data for orbit determination (OD). Range and DDOR data were unaffected and they did not require any additional telemetry aided processing. In the case of the INAV team, all data was processed to produce an OD solution using the latest version (v109.2) of the Mission analysis and Operation Navigation Toolkit Environment (MONTE)[3].

Under nominal circumstances the TADT processing worked well. The noise level of the residuals in the OD fit was comparable to the level we are used to seeing for coherent data on other missions (Figure 1). Automated processing made data available for use 30-120 minutes after the

end of a tracking pass, in most cases. However, anything that interferes with part of this process may significantly delay or make the data unrecoverable. We no longer get Doppler data as a by-product of the coherent link in this situation – supplemental data from spacecraft telemetry is necessary to properly calibrate the Doppler data. This limitation became most apparent during the safe mode entry on 04 July 2015, only two weeks prior to the Pluto encounter. Because of this event, there was no timing telemetry available for nearly a 24-hr period and that prevented us from having useful Doppler data. This is something that would be problematic under other circumstances, for example, immediately following a maneuver for orbit insertion. However, for New Horizons the critical data immediately prior to the encounter was optical navigation (opnav) data – the largest error source in the Pluto-spacecraft relative trajectory was the Pluto barycenter ephemeris. Doppler data was helpful in tracking spacecraft activity but by this point in the mission the spacecraft activity was of secondary importance.

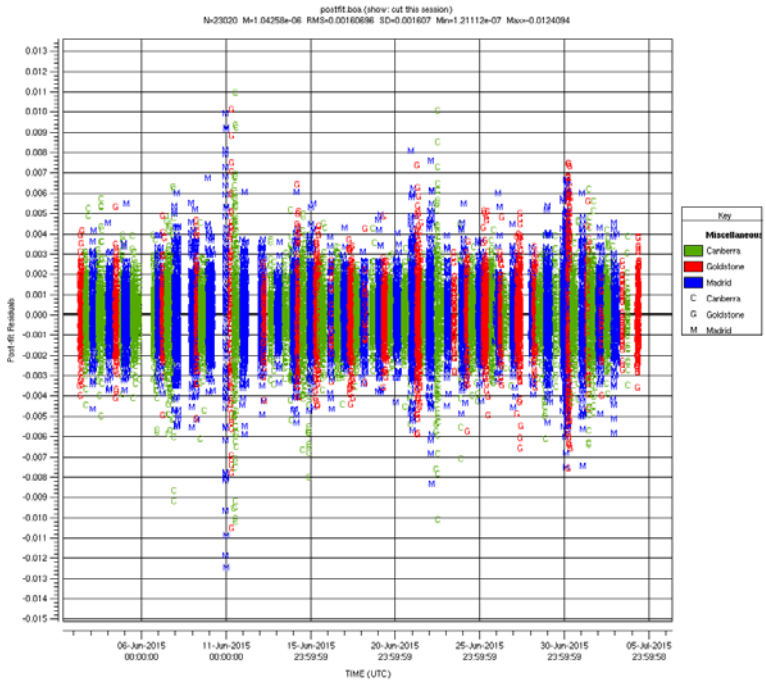


Figure 1. Postfit residuals of Doppler in Hz for a selected part of the OD data arc used for Pluto approach. The entire data arc is not shown.

Ranging Data

Between the Jupiter flyby and the Pluto encounter, there was a transition from two-way range to three-way range comprising the bulk of the ranging measurements. Three-way data involves an uplink from one DSN complex to another DSN complex. There were some two-way ranging measurements, but they were very limited in number as the spacecraft approached Pluto thanks to the long round-trip light time (about nine hours by the Pluto encounter). The theoretical basis for constructing three-way range observables has been documented elsewhere[4]. However, this data type has not been used in practice to produce OD solutions since the Voyager 2 flyby of Neptune. Because of this, our OD software had to be updated with this capability, tested, and verified during operations. We used the uplink and downlink range phase data and combined it to create a

three-way range observable within MONTE. By doing this we avoided a need for the special DSN product of derived three-way range observables (e.g., see Reference 1).

Another complication with three-way range is that the range calibration conducted during a DSN tracking pass is delivered in the TRK-2-34 data file as a round-trip range bias, that is, assuming a two-way link using the same station. However, since this is three-way data, the up and down links were at different stations. We constructed our three-way calibration by taking half the two-way range calibration on each DSN TRK-2-34 file for the two stations in the link and combining. This total bias is removed from the range measurement. In practice, this method of computing the path bias appeared to still leave more biased error in the measurement than would be normally observed in two-way range data. Furthermore, there was inconsistency in the contents of the TRK-2-34 data; sometimes the calibration data wasn't contained in one or both of the files for the two DSN stations. In those instances, we had to use an educated best guess at what the calibration would have been, normally taken to be the same value as observed in a previous pass for the same DSN station. Because of all of these issues, residual postfit biases in the range data as large as 500 Range Units (RU) were not uncommon (Figure 2). For reference, one RU is equivalent to seven meters.

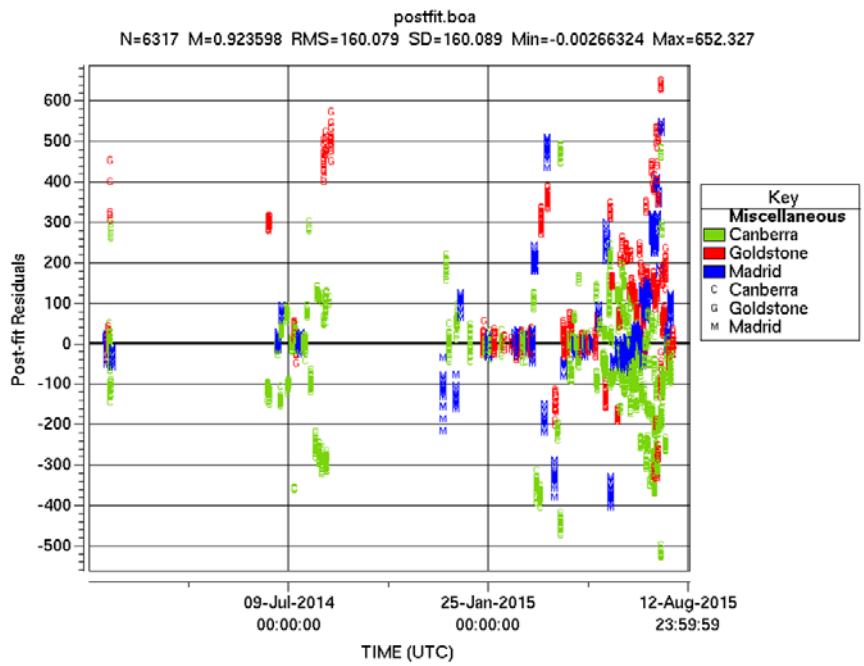


Figure 2. Postfit residuals of three-way range in RU for the entire OD data arc used for reconstruction of the flyby.

THRUSTER ACTIVITY

Given that the first operational OD solutions were delivered by the INAV team in January 2015 but the first set of opnavs were in mid-July 2014, the starting epoch for the OD solution was chosen to be 01 January 2014. From this time onward, the largest uncertainty in perturbing forces acting on the spacecraft was due to thruster activity. This was particularly important during the last six to seven months leading into the Pluto encounter as the nominal operation of the spacecraft was three-axis stabilized for attitude control, which is accomplished with the thrusters.

There was also frequent turning for imaging and other science observations. Spin-stabilized mode was used only sporadically to improve downlink capability for short periods.

The thrusters were unbalanced enough that it would produce a small velocity change with every event, producing a net accumulated delta-V over time. During the very busy few months prior to the encounter there were as many as 600-1,000 individual thrusting events per day. Furthermore, we found that the small forces telemetry for the thrusting events significantly underreported the delta-V. For reconstruction during the data arc we assumed *a priori* that there was a mean acceleration for a long time period lasting days to several weeks. On top of this mean acceleration, frequent impulsive delta-V events were also included in the filter. The total of these two models combined in the filter to reconstruct the acceleration profile for the data arc.

Given the frequent events, the highly variable nature of the type of activity, and the limited value of the delta-V reported in telemetry, the uncertainties on the thruster model were relatively large compared to other perturbing forces (e.g., gravity, solar radiation pressure, and thermal radiation due to the radioisotope thermoelectric generator). Using Doppler data, we were able to precisely characterize the effect in the Earth-line direction. This was not only useful in reconstructing the trajectory but also helped us improve our predictions of future thruster activity. The most difficult aspect was that a large component of the effect was off Earth-line, particularly when the spacecraft was pointed off Earth for the purpose of taking images of the Pluto system or other science observations. Even with DDORs, our ability to observe the off-Earth components was limited. Given the distances involved, DDORs were only able to resolve the trajectory to the level of 10-30 km. Since DDORs are an angular measurement, the precision in terms of a distance can be calculated from knowing the distance of the Earth baseline (the range between the two DSN stations), the range to New Horizons from the Earth, and taking the data weight as the angular precision. For New Horizons DDORs, the N/S baseline observations were weighted at 0.06 ns while the E/W baseline observations were weighted at 0.2 ns.

After 24 May 2015 there were no more DDOR observations taken. Instead, the opnav images were the only means to observe the spacecraft trajectory perturbations off the Earth-line. As will be discussed in the following sections, the planetary and satellite ephemerides were corrected via the opnav observations of the Pluto system. The opnavs do not simply measure the position of the bodies independent of the spacecraft, instead they give a geometric measure of the spacecraft relative to the bodies in the Pluto system. Without other observations to separately measure the spacecraft trajectory relative to the Earth-line (e.g., DDORs), there was no way to confidently say if the spacecraft should move in response to the opnavs or the Pluto system should move.

Figure 3 shows the accumulated delta-V in the period roughly from the time of the last DDOR through the Pluto flyby. Notice that there is a lot of complexity in the Y-direction as that was the best observed by frequent Doppler measurements; the Y-direction was defined as Earth-pointed and X & Z were the off-Earth components. The relatively flat period in July for a few days was due to the safe mode entry when the spacecraft was spin stabilized (no thruster activity).

Regardless of the OD solution strategy, the Y-direction was well determined by the wealth of Doppler data. However, the accelerations and delta-V calculated in the X & Z directions for a particular OD solution were highly dependent on things such as assumed uncertainties in delta-V, opnav data used, and opnav data weighting. We could get an order of magnitude difference in the overall accelerations for off-Earth components in our OD solutions when compared to PNAV and even within our own set of OD solutions. This issue was significantly mitigated by the fact that the knowledge of the ephemeris of the spacecraft relative to the Sun was not a requirement. What was important was the trajectory of the spacecraft relative to the Pluto system.

While the details of the spacecraft dynamics in the off-Earth directions could not be completely separated from the corrections in the Pluto system ephemeris, an adjustment in one would always lead to an adjustment in the other. Also, we were helped by the effect of a decreasing time to go to the encounter – there was less time for a velocity difference to propagate into a trajectory difference. Even when significant differences were observed between the teams in the heliocentric spacecraft trajectory, the spacecraft-Pluto relative trajectories were in much better agreement. This effect highlighted that you could not pick and choose between individual ephemeris files of the two teams or between any two OD solutions. You had to consider the entire set of spacecraft, Pluto barycenter, and Pluto satellite ephemerides as a single delivered product.

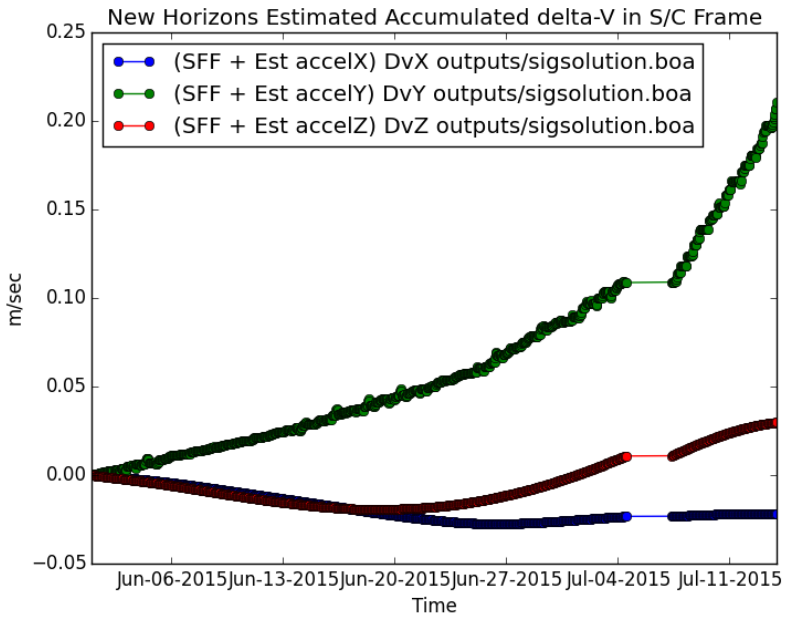


Figure 3. Spacecraft accumulated delta-V due to thrusting during period where no DDORs were available. The Y-dir is Earth pointed and X & Z are off Earth.

KNOWLEDGE UPDATES

The most challenging aspect of the mission was due to the uncertainty of the Pluto system ephemeris (the Pluto system barycenter relative to the Sun). The long 248-yr period of the Pluto system means that there are limited observations of the full orbit around the sun. The uncertainty is relatively larger than is encountered with other planets, particularly in the radial direction. The Pluto barycenter was only known to a precision of ~1000 km at the start of the New Horizons mission, much of which translated into an error in the time of closest approach. This ephemeris knowledge needed to be improved significantly in order to meet the requirements of tightly sequenced science activities. In particular, it had been shown by PNAV's prior covariance analysis that the Pluto time of closest approach (TCA) would not be determined well enough via optical navigation images to meet science requirements until three or four days prior to closest approach[5,6].

There were two sets of navigation requirements: one for control and one for knowledge. The first, control, was a requirement on how accurately the spacecraft was actively targeted to the

Pluto encounter. It was requirement for trajectory correction maneuvers (TCMs) to target the encounter and the control requirement used as one criteria to help make decisions about executing TCMs. The second set of requirements, knowledge, was for uncertainty in the trajectory relative to the nominal target and was to be used as one of the criteria to update the spacecraft onboard ephemerides. All of the control and knowledge criteria were referenced to the Pluto encounter B-plane, the plane perpendicular to the Pluto relative, spacecraft trajectory asymptote. For a detailed discussion of the definition of the B-plane and its application to spacecraft navigation, see Reference 7. These requirements are listed in Table 1, where "B mag" is the magnitude of the B-vector pointing from the nominal target to Pluto center of mass, "B norm" is in the B-plane perpendicular to the B-vector, and the "time of flight" error is relative to the time of closest approach.

Table 1. Navigation requirements, one-sigma

	Control	**Knowledge**
B mag	100 km	33 km
B norm	150 km	66 km
Time of Flight	150 s	100 s

The nominal flyby trajectory into the Pluto system was produced by the Mission Design team at JHU/APL to meet the science requirements, which results in a Pluto B-plane and time of closest approach (TCA) as the target for navigation. Given that we were updating the Pluto planetary and satellite ephemeris, this could result in an updated nominal trajectory and a new target in order to meet requirements. In this way, a trajectory correction maneuver could be required in order to adjust an error in the spacecraft trajectory or a change in the nominal flyby target because the Pluto system has moved.

There were four dedicated opnav campaigns during approach. The first three were designed to image at least one orbit period of Pluto and Charon about the Pluto system barycenter, which is 6.387 days. These started on 19 July 2014, 25 January 2015, and 12 April 2015, respectively. These campaigns all contained useable images of Pluto and Charon. The fourth campaign began on 28 May 2015 and lasted through 12 July 2015, or two days before the Pluto encounter (P-2 days). While images did include the other satellites, it wasn't until the fourth campaign when the Nix and Hydra images were first used in the INAV OD solutions. In addition to these dedicated opnav campaigns, the science images taken during this time were using the same camera system. As long as the science images contained enough stars to properly register the target body relative to the background stars, we were able to use these as "bonus" opnavs to provide a lot more coverage beyond the planned opnavs.

All the opnav images that we used were taken with the LOng Range Reconnaissance Imager (LORRI), a 1024x1024 CCD. This had two modes of binning: 1x1 and 4x4. The 1x1 images were full resolution while the 4x4 mode summed the signal, reducing the noise and downlink required at the expense of resolution. As will be discussed later, INAV solutions didn't use the Pluto opnavs except as a diagnostic tool. We used Charon 1x1 opnavs beginning in the first campaign and continuing through the flyby. The Nix and Hydra satellites were more difficult to detect and the first opnavs we used were taken in 4x4 bin mode, beginning on 28 May 2015 during the fourth campaign. The 1x1 opnavs of Nix and Hydra we deemed to be useable beginning around P-4 weeks. Using opnavs in conjunction with the radiometric data, we simultaneous solved for corrections to the spacecraft trajectory, corrections to the Pluto barycenter ephemeris

relative to the Sun, and corrections in the Pluto satellites' ephemeris relative to the Pluto barycenter.

The reference planetary ephemeris used by the navigation teams is provided by the Solar System Dynamics group (SSD) at JPL. Each ephemeris delivery is designated as "DExxx", where xxx are sequential numbers to distinguish the ephemeris solutions. Similarly, SSD produces Pluto satellite ephemerides, designated as PLUxxx. Beginning in January 2015, we switched our nominal planetary ephemeris from DE432 to DE433, an ephemeris which contained more recent ground observations of the Pluto system in support of the New Horizons mission. For most of the approach, the satellite ephemeris we used was PLU043, but we switched to PLU047 which was delivered to us a couple of weeks prior to the flyby. Not only was the PLU047 based on more recent data, we found that OD solutions using PLU043 as the nominal were resulting in an updated satellite ephemeris that was closer to PLU047.

Previous analysis had shown that the B-mag and B-norm requirements for targeting and knowledge were expected to be largely met by the end of the third opnav campaign, based on Pluto and Charon opnavs. The TCA uncertainty would be relatively untouched. Instead, opnavs of the outer satellites of Pluto, specifically Nix and Hydra, could be used to reduce this uncertainty. This effect was due to the geometry of the flyby: the spacecraft was approaching the Pluto system orbit plane at a steep angle nearly normal to that plane. Most of the unresolved uncertainty in the Pluto barycenter (relative to the Sun) was also largely parallel to the alongtrack component of the spacecraft trajectory. While using Charon would only help to resolve the position of the Pluto system relative to the background stars, the parallax provided by the more outer satellites (i.e., Nix and Hydra) could help resolve the position in the alongtrack direction. In other words, the TCA would be better determined.

Even with the help of Nix and Hydra opnavs, it had been shown that the knowledge requirement for time of flight (Table 1) might only be achieved by images taken at P-2 days, worst case. Because of this challenge, a process was put into place that required daily OD deliveries based on daily opnavs beginning around P-10 days. This was in support of the daily Knowledge Update (KU) process for selecting the appropriate set of ephemeris files and TCA to be placed onboard the spacecraft (technically, it wasn't the TCA that was updated but a timing update that was onboard to slide the science observations as a block, forward or backward in time). This KU process was the primary reason for the involvement of the INAV team. While there was no nominal plan for the INAV ephemeris products to be placed onboard the spacecraft, our results were used as an independent verification of the accuracy and precision of the PNAV solutions. Our OD results contributed to the decision process of sending (or not sending) a KU to the spacecraft.

PLUTO APPROACH

As mentioned before, only PNAV solutions were planned to be uplinked to the spacecraft; the INAV solutions were never used for that purpose. While the INAV solutions could have been used in principle for the onboard KU, they were intended to be used as a comparison on the ground to the PNAV solutions. We used different software, personnel, filter assumptions, and data assumptions. We were also not directly involved in the TCM design and decision process. However, the INAV team was co-located at APL with the PNAV team beginning around P-4 weeks. This allowed us to begin comparisons of our OD results and to exercise the KU process prior to the critical two weeks before Pluto encounter.

One of the first things we learned about the Pluto system on approach was that Pluto and Charon did not appear to be featureless, homogenous spheres. This was readily apparent once the bodies were several pixels in diameter in the LORRI frame and we had to start treating them as

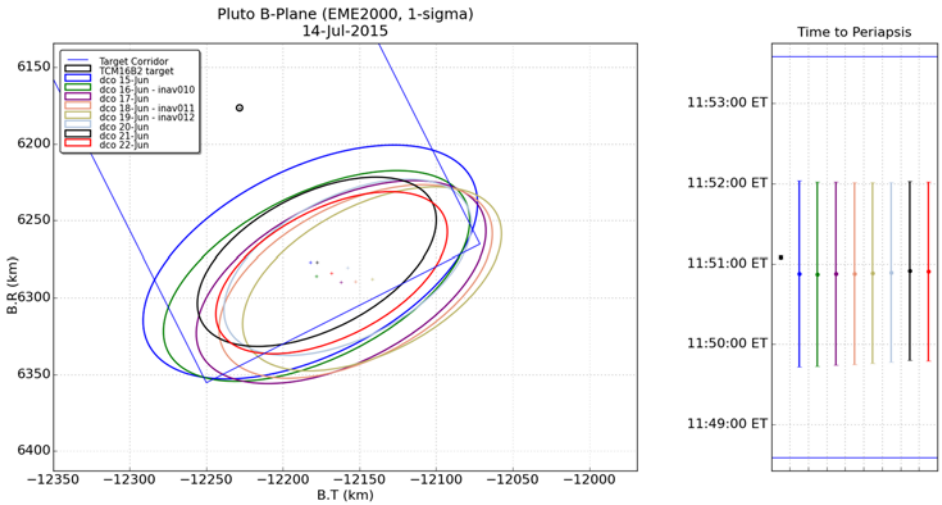
extended bodies instead of point sources. Then the center-finding technique we used, limb scanning, was challenged by the fact that there were large and complex albedo variations in Pluto and Charon.

In hindsight, we now know that Pluto and Charon have complex geologic process making for a variety of different colored terrains, complex topography, and even an atmosphere in the case of Pluto. In the absence of hindsight, what we could see on approach in the opnavs were large albedo variations without necessarily knowing the cause. Was it simply discoloration? Was it topographic? Or was it something else? We couldn't be sure without additional information that was unavailable at the time of the opnav observations.

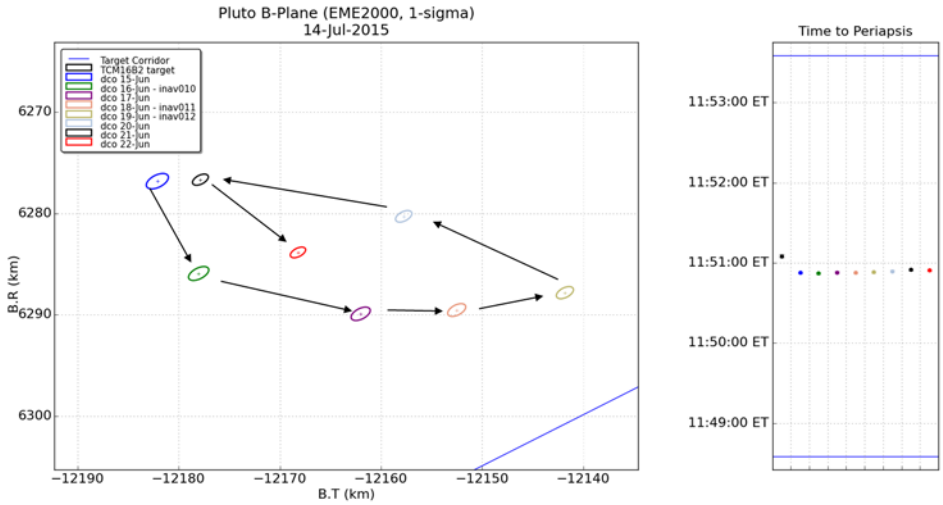
What we saw because of this complexity was evident in the Pluto B-plane mappings of our OD solutions. The spacecraft-Pluto relative trajectory was tracking the orbital motion of Pluto-Charon (Figure 4). Over the course of one period (6.387 days or roughly one week of observations), there was a clear oscillation observed in the B-plane. Figure 4a shows the progression of the one-sigma error ellipses during a little more than one Pluto-Charon period. As the uncertainties in the ephemeris were still large at this time, it is difficult to see what is happening in the trajectory relative to the error ellipses. Zooming in by artificially downsizing the ellipses, Figure 4b highlights the cyclic nature of the trajectory variations. The lesson we quickly learned was that something which looked like a trend for a few days could simply be a part of a larger cycle. It was important to look at the average effect over one Pluto-Charon period and not over-interpret changes over just a few days. In this case shown, the net movement in the predicted trajectory was much less than the amplitude of the oscillation in the trajectory related to the Pluto-Charon orbit period.

All of the solutions shown in Figure 4 used only opnavs of Charon. Even though the cyclic motion could be observed, it was small enough that we could confidently use the Charon observations without having these systematic biases corrupt the overall result. The same could not be said for the Pluto observations. The orbit period related motion introduced into the solutions by the Pluto opnavs was too large and could not be accommodated by OD solutions.

While the solutions shown in Figure 4 cover a span of only one week, the residuals shown for Pluto opnavs in Figure 5 cover a longer time span over much of opnav campaigns 3 and 4. These are pass-thru residuals. That is, an OD solution was produced using opnavs which did not include Pluto and the Pluto opnavs were then passed through to compute residuals relative to the OD. The residuals are plotted in terms of right ascension (RA) and declination (DEC) in order to put them in the context of how Pluto looks relative to the spacecraft treated as a non-rotating platform. At first it seemed during opnav campaign 3 that it might be possible to find a model that could remove the periodic signature. However, as we approached Pluto and entered opnav campaign 4, it was evident that trying to include Pluto opnavs did more harm than good. While we continued processing Pluto opnavs, our preferred OD solutions did not include them. Note that it is not unusual exclude the central body from opnav observations, e.g., Voyager 2 did not use opnavs of the central body for outer planet flybys.



(a)



(b)

Figure 4. Progression of OD solutions in the Pluto B-plane during one period of Pluto-Charon. (a) One-sigma error ellipses shown on the top, and (b) artificially reduced ellipses shown on the bottom, highlighting the cyclic nature of OD solutions that correlated with Pluto-Charon motion.

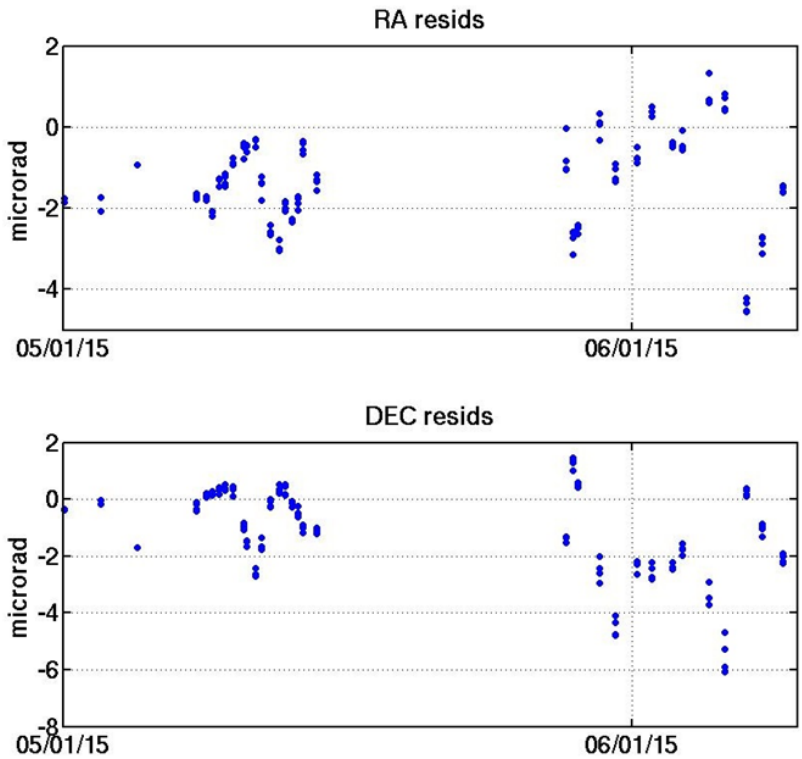


Figure 5. Passthru residuals of Pluto opnavs, in right ascension (top) and declination (bottom), relative to OD reconstruction of the flyby. The OD only contained opnavs of Charon, Nix, and Hydra.

The plan was for there to be at least one KU sent to the spacecraft after the final targeting maneuver, with updates sent to the spacecraft as needed to meet the knowledge requirements (Table 1). As often happens in planetary missions, events onboard overtake the best of plans. There were a number of opportunities for TCMs to target the best trajectory for the Pluto flyby (see Reference 1), with the final targeting maneuver, TCM-17B1, taking place 30 June 2015. Soon after this, a safing event occurred on 04 July 2015. A few days were taken to diagnose the problem, recover from safe mode, and fully reactivate the encounter sequence. The cause of the safing event was found to be an overloading of the processor, something which could potentially occur again simply due to loading a new KU onboard. As a result of the safe mode and the circumstances associated with it, the project was more hesitant to send further KUs to the spacecraft unless absolutely necessary.

The history of the INAV KU solutions after TCM-17B1 are shown in Figure 6. Fortunately, the effect of TCM-17B1 was not only to put it within the targeting requirement (red box), the OD solutions after that also stayed close enough to the intended target to remain within the knowledge requirement (black box). With one caveat: by the time of the final KU opportunity, the expected TCA along with its associated uncertainty were just over the edge of the requirement. While this may have technically triggered the need for a KU to be uploaded, the risk associated with another spacecraft anomaly was judged to outweigh the slight benefit of the KU. The final KU sent to the spacecraft was from an OD used to design TCM-17B1 with the predicted effect of a perfect TCM-17B1 included.

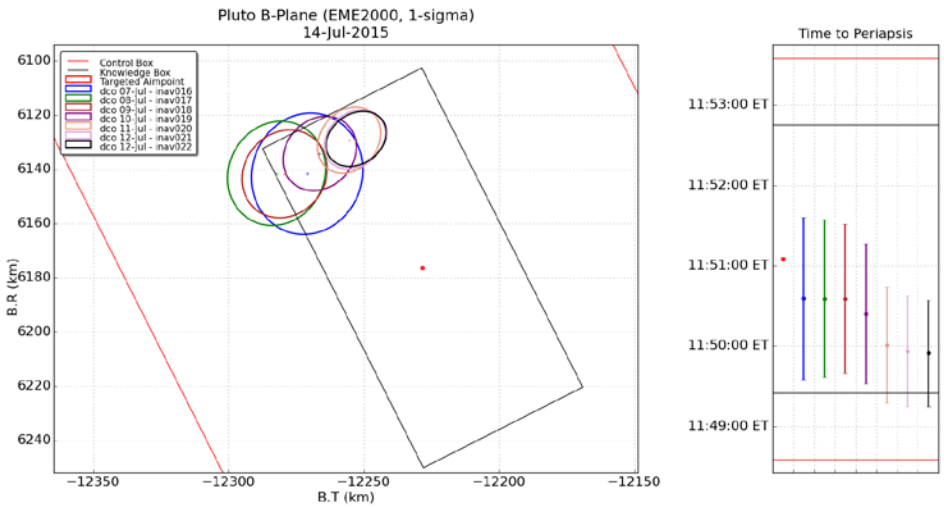


Figure 6. Progression in B-plane of knowledge update INAV ODs, one-sigma errors. Also showing the control requirement (red) and knowledge requirement (black).

RECONSTRUCTION

Figure 7 shows a comparison in the Pluto B-plane of our final KU solution and different varieties of a post-flyby reconstruction. The nominal target is indicated by a red dot. The final INAV KU solution at P-2 days is the black ellipse – it is the same OD solution represented by a black ellipse in Figure 6. The blue ellipse is an OD that contained no further opnavs – it only contained radiometric data from after the flyby. This was enough to move the reconstructed trajectory relative to the final KU OD, even the TCA, but it was not able to reduce the uncertainty. Then we include a post-flyby Charon opnav (green ellipse). Given the distance of the spacecraft from Charon and the high phase angle of the observation, it was of minimal use and had to be significantly down weighted. The most useful data turned out to be observations of Nix and Hydra only hours before the flyby, but too late to be used in any potential KU. These observations of Nix and Hydra allowed us to reduce the TCA uncertainty in the reconstruction to 2.9 sec.

From our preferred reconstruction, we can calculate the improvement in our knowledge in the planetary and satellite ephemerides. The "a priori" half of Table 2 gives a measure of the uncertainty in the Pluto system prior to any improvement from ingesting New Horizons' opnavs. It is a representation of the *a priori* uncertainty in DE433 and PLU047. The results are given in a radial, transverse (or downtrack), and normal frame of the body relative to a center. All results taken to be at the nominal, targeted closest approach time of 14 July 2015 at 11:51:05 ET. The right half of the table is our reconstructed knowledge. From this can been seen that our uncertainty in the position of the Pluto system barycenter improved considerably.

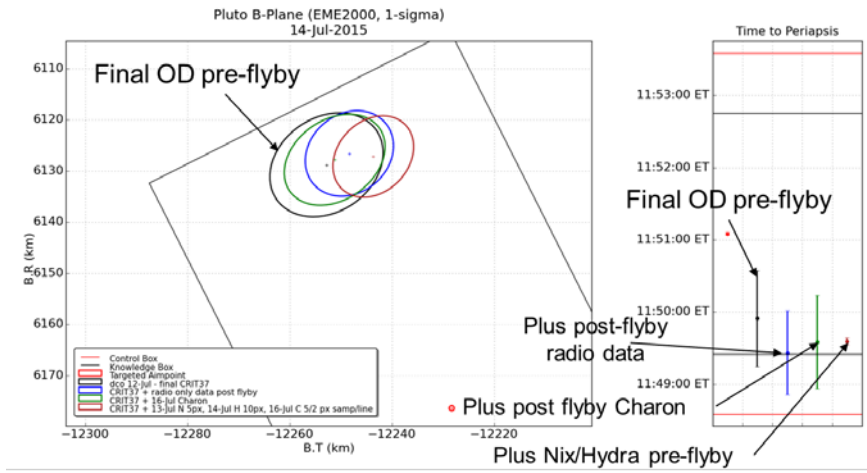


Figure 7. Sensitivity of flyby reconstruction to different data. Showing the final OD pre-flyby (black), followed by reconstructions using different post-flyby data: only radio data after the flyby (blue), then adding post flyby Charon (green), and finally adding pre-flyby Nix and Hydra (red).

To summarize, the final Pluto flyby target was based on a PNAV OD with a data-cutoff of 26 June 2015 and included a model of perfect TCM-17B1 execution. The targeted time of closest approach was 14 July 2015 at 11:51:05 ET. Our final KU opportunity predicted a TCA of 14 July 2015 at 11:49:54 ET with an uncertainty of 39.9 s. And our reconstruction gave us the final TCA of 14 July 2015 11:49:35 ET, or 90 s early with respect to the target, with an uncertainty of 2.9 s. This is well within the knowledge requirement of 100 s.

Table 2. Ephemeris knowledge from reconstruction of the flyby in a radial, transverse, and normal (RTN) frame based on the body trajectory relative to the center.

		A priori Uncertainty			Post-fit Uncertainty (km)		
Body	**Center**	**R**	**T**	**N**	**R**	**T**	**N**
Pluto	Sun	891.7	380.7	1007.1	38.1	21.8	14.2
Pluto	Pluto BC	5.6	0.52	0.18	3.2	0.40	0.15
Charon	Pluto BC	5.9	4.1	1.5	3.5	3.2	1.2
Nix	Pluto BC	10.5	23.5	16.0	4.6	8.5	7.5
Hydra	Pluto BC	10.4	28.9	17.7	5.0	8.6	8.6
Kerberos	Pluto BC	21.1	134.7	56.0	8.4	31.8	24.1
Styx	Pluto BC	49.3	510.4	186.1	10.7	42.3	16.6

SUMMARY

The flyby of the Pluto system by the New Horizons spacecraft was highly successful. Targeting and knowledge requirements were met even with the challenges of recovering from a safe mode event two weeks prior to the encounter. Even though none of the knowledge updates were found to be necessary to send to the spacecraft, the PNAV and INAV teams worked well together

to enhance confidence in the KU OD solutions leading up to the Pluto encounter. A reconstruction of the flyby indicates that the TCA relative to Pluto was 90 s early when compared to the intended target. The uncertainty was reduced significantly to 2.9 s, mostly due to the help of a Nix opnav and Hydra opnavs well after the final KU opportunity but prior to the flyby.

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