NEW HORIZONS ENCOUNTER REHEARSAL PLANNING AND EXECUTION

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Abstract: *In 2012 and 2013 the New Horizons spacecraft performed rehearsals of the key closest approach observations that will occur during the 2015 flyby of the Pluto-Charon system. These rehearsals used modified versions of the encounter command sequence to test the spacecraft, operations team, and ground software and processes to reduce risk during the actual encounter. This paper will discuss the New Horizons spacecraft, its concept of operations during the flyby of the Pluto-Charon system, how the rehearsals were performed, and the lessons learned from those rehearsals. This paper is intended to demonstrate the importance of performing in-flight rehearsals as opposed to conducting mission simulations using hardware-in-the-loop simulators.*

Keywords*: New Horizons, Operations, Rehearsal*

1. Introduction

First in NASA's New Frontiers series of missions, the New Horizons spacecraft was successfully launched in 2006 and is scheduled to fly past the Pluto-Charon system in 2015. The spacecraft will begin to conduct approach phase science in January 2015, culminating in closest approach on July 14, 2015. Seven days prior to closest approach the spacecraft will be commanded into "Encounter State". This operational state contains special autonomy rules and macros as well as guidance and control (G&C) parameters not used in other spacecraft operational states. The purpose of having a dedicated Encounter State is to allow the spacecraft to continue to collect science data in the event of a severe anomaly such as a G&C sensor failure or command and data handling (C&DH) processor reset that would cause onboard autonomy rules and macros to suspend the command sequence and transition the spacecraft into a spin-stabilized safe mode. Normally it is sufficient for first time spacecraft activities to be only tested on a high-fidelity hardware-in-the-loop simulator prior to being loaded and executed on the spacecraft. However, because of the complexity of the Encounter Command Sequence (CORE), the limited amount of time New Horizons has been in Encounter State, the importance of successfully executing planned flyby science at the first and only opportunity, and the stressful environment that will be placed on both the spacecraft and the operations team during closest approach, it was important to rehearse portions of the CORE sequence on the spacecraft prior to the actual encounter. To date two such rehearsals have been conducted. Lessons learned from the first rehearsal were applied to the second rehearsal. This paper will discuss how the encounter rehearsals were planned and executed on New Horizons in 2012 and 2013. It will present an overview of the New Horizons spacecraft, the concept of operations for the 2015 closest approach activities, how the rehearsals were conducted to emulate the flyby as closely as feasible while protecting spacecraft health and safety, and how these activities were analyzed after the rehearsal to make adjustments to the spacecraft simulator and the CORE sequence.

2. Spacecraft Overview

The New Horizons spacecraft was successfully launched on January 19, 2006 from Kennedy Space Center in Florida aboard a Lockheed-Martin Atlas V [Series 551]. A part of NASA's New Frontiers program, the mission will be the first spacecraft to visit the Pluto-Charon system. New Horizons performed a gravity assist maneuver at Jupiter on February 28, 2007 and is scheduled to arrive at Pluto for a flyby on July 14, 2015, eventually continuing on to one or more Kuiper Belt Objects [1]. The spacecraft is carrying seven body-fixed science instruments, including a panchromatic imager, three spectrometers, a solar wind monitor, a radio science experiment, and a dust counter. To improve system reliability the spacecraft was designed to be as redundant as feasible, including two command and data handling (C&DH) processors, two 64 Gbit solid state recorder (SSR) cards, two traveling wave tube amplifiers (TWTA), etc. The two G&C processors are also separate from the C&DH processors, and telemetry exchanged between them assists in data retention if either processor has a reset or is switched to the auxiliary processor. The spacecraft is powered and heated by a single general purpose heat source radioisotope thermoelectric generator (GPHS-RTG) which is designed to provide approximately 200 W of power at closest approach.

The New Horizons G&C subsystem consists of two Galileo Avionica autonomous star trackers (ASTRs), two Honeywell Block 3 Miniature Inertial Measurement Units (IMU)s, a single mechanically and electrically redundant custom built Adcole Sun sensor assembly consisting of one Fine Sun Sensor assembly and one Sun Pulse Sensor assembly, twelve 0.8-N Aerojet MR-103H thrusters (ACS) used primarily for attitude control, four 4.4-N Aerojet MR-111C thrusters used exclusively for trajectory correction maneuvers (TCM)s, and two Mongoose V G&C processor cards for executing the G&C flight software. The ACS thrusters are fired in coupled pairs in order to minimize the amount of ΔV imparted upon the spacecraft during precession and 3-axis slewing activities. Figure 1 presents the New Horizons spacecraft configuration showing the orientation of the spacecraft body reference frame and the placement and orientation of the seven scientific instruments. Figure 2 presents the thruster locations and orientations.

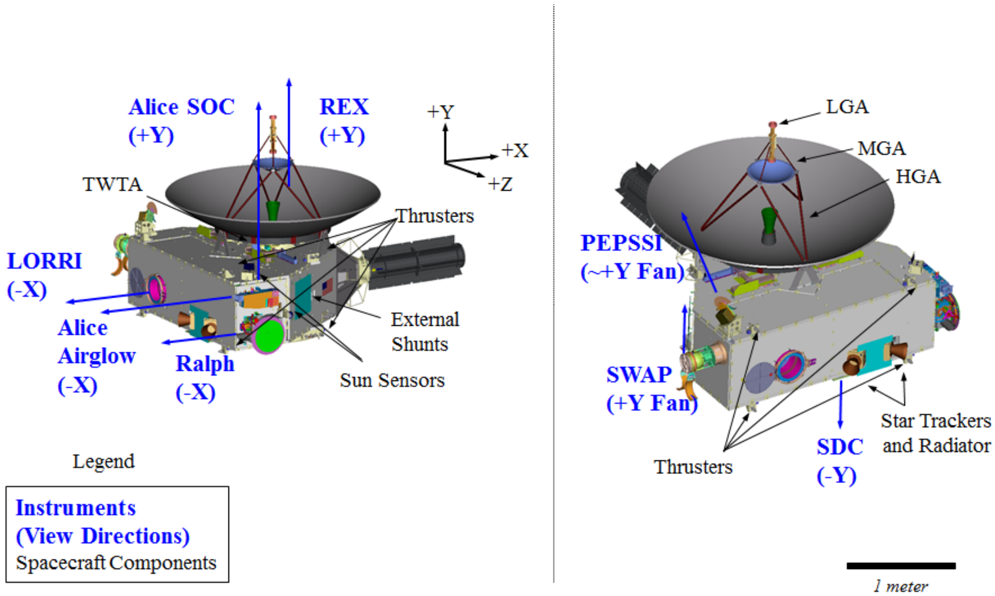

Figure 1. New Horizons Instrument Locations and Orientations. Spacecraft Spins Positively About the +Y-axis While Spin-Stabilized. Most Science Instruments are Oriented towards the -X-axis.

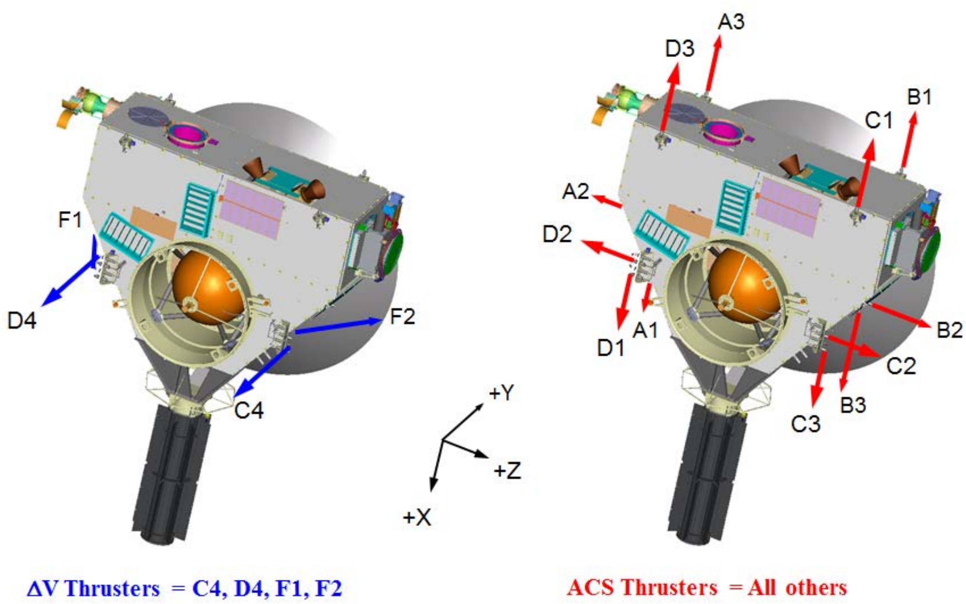

Figure 2. New Horizons Thruster Locations and Orientations. F1/F2 in Y/Z plane towards +Y.

New Horizons is a dual mode spacecraft that can operate in either a spin stabilized or 3-axis mode, depending on the phase of the mission. During calibration and pointed science collection periods the spacecraft will be in 3-axis mode. The spacecraft can point any body-defined vector (e.g. instrument boresight) to any inertial vector, or track locations on a celestial body whose physical position and rotational ephemeris parameters are loaded into the flight software. Scans and image mosaics, as well as an inertial hold mode are also available as pointing options. When 3-axis pointing is not required the spacecraft is placed into a spin-stabilized mode to reduce propellant consumption and to preserve the life of the thrusters by reducing the number of open/close cycles that are executed. During active "cruise" periods the spacecraft spins at approximately 5 RPM and periodically tweaks its orientation to keep the high gain antenna (HGA) to within 0.3° of the Earth for deep space network (DSN) contacts. In addition to pointing to Earth in both nominal and Earth Acquisition safe mode, the spacecraft can orient its spin axis towards the Sun for a Sun Acquisition safe mode. New Horizons can also orient its spin axis towards an inertial right ascension and declination for TCMs, "hibernation" state, and plasma and particle science observations. Following the Jupiter flyby the spacecraft has been periodically placed into Hibernation State, where the G&C system is powered off to preserve hardware life. The spacecraft remains spin stabilized at 5 RPM for months with no thruster firings, transmitting only housekeeping data or a beacon carrier tone through the spacecraft's medium gain antenna (MGA). Figure 3 presents the ten operational modes and states of the spacecraft.

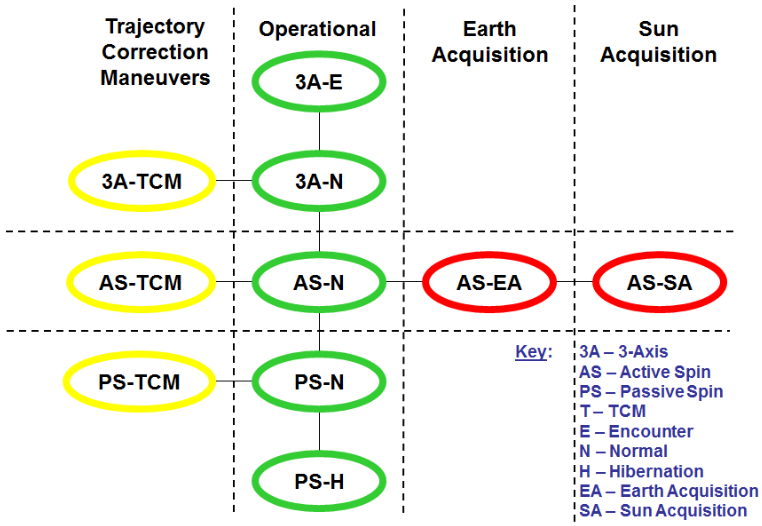

Figure 3. New Horizons Operational Modes and States.

The spacecraft has a very robust autonomy and fault protection system. Though major elements of fault protection are implemented by flight software running on the C&DH processors, the power distribution unit (PDU) has the ability to monitor bus traffic and can switch C&DH processors if necessary. The flight software autonomy evaluates telemetry data provided by the various subsystems in real time and, based upon a set of onboard rules, can take corrective actions to protect the health and safety of the mission. During the cruise phase of the mission this would involve suspending any onboard command sequences currently executing and placing the spacecraft into either Earth Acquisition or Sun Acquisition State to wait for commands from the mission operations team. However, during the CORE encounter period when the spacecraft is in Encounter State any autonomy actions would be to preserve as many of the science observations as feasible while not suspending the command sequence.

New Horizons uses a single, spacecraft-wide time that is critical to successful operations. The onboard mission elapsed time (MET) is updated by an ultra-stable oscillator (USO). New Horizons has two USOs onboard for redundancy. The USOs provide the 1 pulse per second signal to all sensors and instruments, and ensures onboard correlation to better than ±4 seconds with respect to Earth ground time, and post-facto time correlation of science data to better than ±10 msec. MET was set to zero at launch, and is monotonically increasing over the course of the entire mission with no rollovers. MET is also used in onboard command sequences to execute time-tagged commands and on-board macros. A second time, based upon MET, is used by the G&C processors in conjunction with onboard ephemerides. The spacecraft produces a Terrestrial Dynamical Time (TDT) using the following equation:

$$TDT(t) = (MET(t)-MET_o)\cdot\Delta rate + TDT_o \tag{1}$$

where TDT_o, MET_o, and $\Delta rate$ are parameters that are periodically loaded to the spacecraft as needed. The $\Delta rate$ is the drift rate between the USO onboard New Horizons and clocks on the Earth which compute TDT time. Ground software compares the onboard TDT to ground based TDT to ensure time accuracy requirements are met [2]. Having an accurate reconstruction of an observation's TDT time is critical when performing optical navigation observations.

The C&DH system has 0.75 Mbytes of storage for command macros. These macros can consist of a single action (such as powering an instrument) or a string of commands (such as reconfiguring the communications system). Unique macros are loaded for each command sequence. A command sequence consists of a set of up to 512 time-tagged rules which trigger and execute one or more of the command macros when the value of MET is greater than or equal to the value of the MET specified in the rule. There is also an onboard CD&H parameter called the "MET time shift register". This parameter can universally adjust the time that sequenced commands will execute on the spacecraft by an integer number of seconds (either positive or negative). This was designed to account for large uncertainties in the time of closest approach. Shifting when commands execute will allow for the sequence timing to be updated shortly before closest approach to maintain the designed geometry of the science observations. The MET time shift register is saved to non-volatile RAM on both C&DH processors which protects against resets or bus controller switches.

3. Encounter Profile

Though science has been collected periodically throughout the cruise from Jupiter, formal Pluto science collection starts in January of 2015 and concludes at the end of July. Figure 4 presents the spacecraft's distance from Pluto during this 3-axis mode timeframe with some key events called out. During the early approach period (AP), in addition to non-pointed plasma, dust, and solar wind science the spacecraft will collect optical navigation (OpNav) images and perform periodic TCMs to correct the trajectory. The quality of the science data improves as the spacecraft approaches Pluto, and LORRI images exceed the best resolution ever achieved by the Hubble telescope about 50 days prior to closest approach. During this time the spacecraft is increasingly busy, with the exception of a 2 week period in spin mode when the spacecraft will downlink as much data as possible before final approach. The best science is collected in the single CORE command sequence. The CORE sequence starts 7 days before closest approach and ends 2 days after closest approach. During the 9 day period the spacecraft will be placed into Encounter State, and special autonomy rules and macros will protect science collection activities. The command sequence is burned to flash memory on both C&DH processors to protect against a C&DH processor reset or bus controller failure. After closest approach the spacecraft will continue to collect 3-axis science data for a few weeks during the departure phase (DP) before beginning a more than yearlong playback of science data.

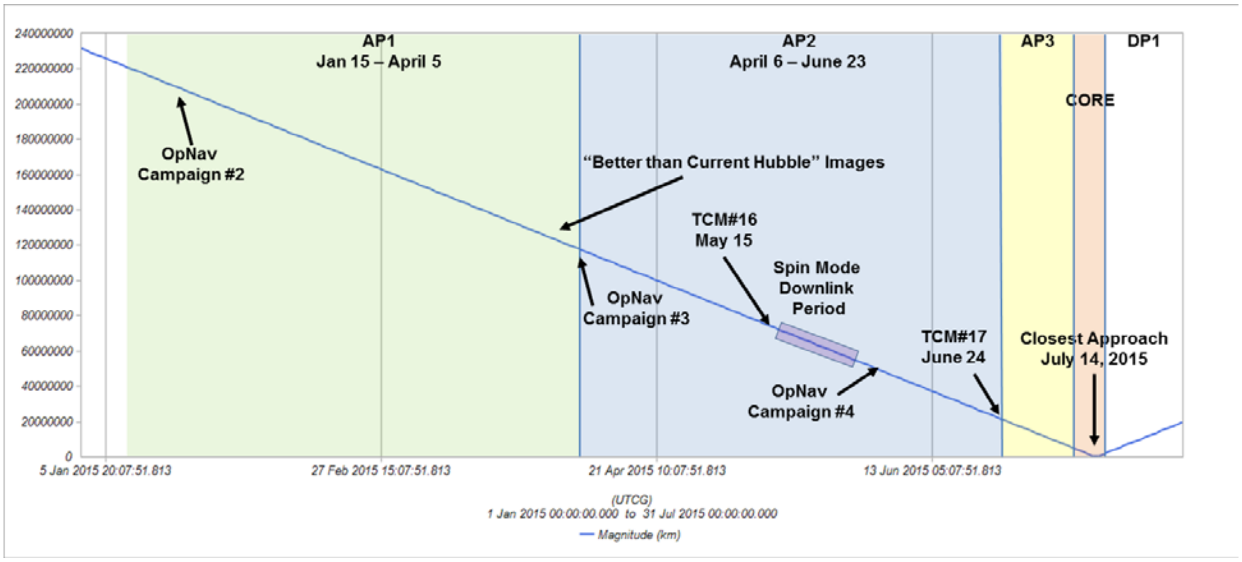

Figure 4. Distance from Pluto in Kilometers Versus Time with Some Key 2015 Events.

During the CORE period, 70 Gbits of science and spacecraft housekeeping data will be recorded to the two SSRs. A subset of this data is redundantly recorded to both SSRs, but 59 Gbits is unique and planned to be downlinked to the ground over a period of more than one year. Since all instruments are body-fixed the spacecraft must reorient itself to collect data. Over the 9 day CORE period the spacecraft will consume roughly 6 kg of propellant while performing 371 re-targeting slews, 92 scans, and 36 mosaic sequences, making this time frame by far the most stressing period since launch.

Prior to loading the CORE sequence to the spacecraft several key events must occur such that New Horizons reaches Pluto at the correct time and B-plane crossing. Two time critical observations following closest approach in the CORE period are occultations of the Sun and Earth by Pluto and Charon. Figure 5 presents the nominal design trajectory around the occultations. If the spacecraft's trajectory is too far from the nominal design then these occulations may not happen. To ensure the spacecraft is on the correct trajectory the navigation team will perform OpNav sequences in the months leading up to encounter. Each group of OpNav images should improve the spacecraft's trajectory knowledge with respect to the Pluto system. TCMs are then scheduled periodically to correct any trajectory errors. Each TCM has multiple back-up opportunities to protect against any faults. The final nominal TCM is currently scheduled for 20 days prior to closest approach, with back-up opportunities 14 days and 10 days prior to closest approach in the event of an anomaly.

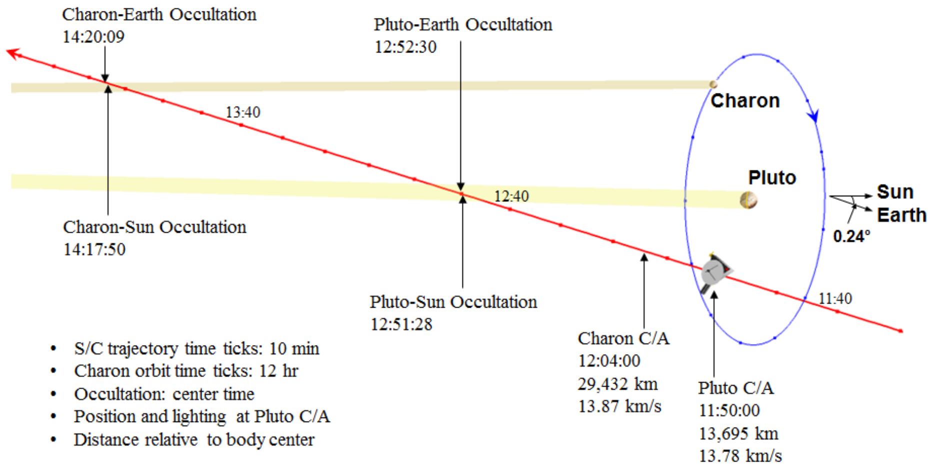

Figure 5. Nominal Pluto-Charon Encounter Geometry (UTC).

In addition to the OpNavs and standard science observations New Horizons will be looking for any debris or hazards which may pose a threat to the spacecraft. If any hazards are detected then the spacecraft trajectory could be slightly modified at any of the pre-scheduled TCM opportunities to divert to a "safe haven by other trajectory" (SHBOT) which would decrease the risk of an impact. A different pre-designed CORE command sequence would then be loaded to the spacecraft in the place of the nominal CORE sequence. This SHBOT sequence places the high gain antenna towards the velocity vector (RAM) during closest approach so that any particles impacting the spacecraft would first hit the HGA, which provides extra protection for the rest of the bus and exposed cables. Limited science observations during the antenna-to-RAM period will be conducted, and are designed to be valid for any of the potential SHBOT trajectories chosen. Outside of the closest approach activities the SHBOT sequence is identical to the nominal CORE sequence. Figure 6 presents some of these potential trajectories.

Science during the CORE period is grouped into three categories: groups 1, 2, and 3. All group 1 science objectives are required for the mission to be considered a success, and include requirements like mapping the surface of Pluto and Charon and characterizing the atmosphere. Group 2 science contains the very important, highly desirable, but not required science observations. These goals include imaging Pluto and Charon in stereo, characterizing the ionosphere and solar wind interaction, and mapping surface temperatures. Group 3 science is desired and includes goals such as performing satellite searches and refining the density of Pluto and Charon. The CORE sequence is designed such that all group 1 science has multiple observations spread over time with multiple or redundant instruments to insure any single spacecraft fault or instrument failure will not endanger science collection. Group 2 science will have backup observations as time and data resources permit, and group 3 science fills in the remainder of the timeline. Because virtually all of the group 1 science (with the exception of plasma observations) takes place within a few days of closest approach the start and end of the CORE sequence was designed such that any potential fault just prior to entering Encounter State which places the spacecraft into safe mode will not prevent the spacecraft team from analyzing the fault, proposing a fix, and reentering the CORE sequence prior to the collection of group 1 science.

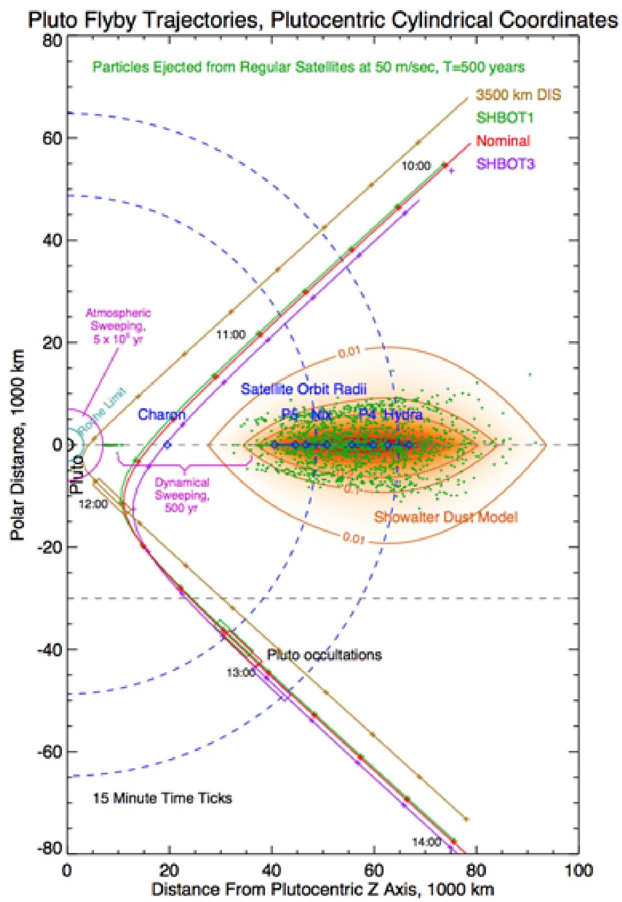

Figure 6. Potential Hazards and Various SHBOT Trajectories. Predictive Models from Mark Showalter.

4. Ephemeris Management

New Horizons G&C flight software has seven onboard, uploadable trajectories which define the spacecraft's state with respect to the rest of the solar system. In addition to the seven uploadable trajectories, the Earth's position with respect to the Sun is modeled using a set of Keplerian parameters that are valid for the entire mission and are not intended to be changed. The seven aforementioned trajectories include two spacecraft trajectories used exclusively in spin mode (nominal and coarse), two spacecraft trajectories used exclusively in 3-axis mode (nominal and coarse), Central Body (CB) 1, Central Body 2, and Central Body 3 which are exclusively used in 3-axis mode. The CB trajectories are typically loaded with celestial, moving targets such as Pluto, Charon, etc. CB1, the spacecraft's spin mode trajectories, and the spacecraft's 3-axis coarse trajectory can only be referenced with respect to the Sun's position. CB2, CB3, and the spacecraft's 3-axis nominal trajectory can be referenced with respect to either the Sun's position or whatever trajectory is defined in CB1. Prior to 3-axis entry in 2015 Pluto's Barycenter will be loaded to CB1 and the New Horizons trajectory, Pluto system CB2 targets (e.g. Pluto, Charon, Hydra, etc.), and CB3 targets will be referenced to the Barycenter.

The New Horizons navigation team will periodically deliver an orbit determination (OD) trajectory solution set consisting of a development ephemeris (DE) file containing the solar system body Barycenters (including the Sun and the Pluto System Barycenter), celestial body files which contain the planetary positions about Pluto's Barycenter (e.g. Pluto, Charon, Styx, Nix, Kerberos, and Hydra), and the New Horizons trajectory (both reconstructed and predicted) with respect to the Sun. These trajectories are delivered as SPICE files, and contain each object's position as a function of Barycentric Dynamical Time (TDB). These SPICE files are then processed by ground software to create 12th order Chebyshev polynomial fits of the trajectories in TDT. Since TDB varies from TDT by a maximum of less than 2 msec over the course of a year this is a reasonable approximation.

The residual fit errors of the Chebyshev polynomials vary as a function of span duration and any external disturbances such as a TCM or close flyby of a planet whose gravity disturbs the trajectory. The larger the disturbance or the longer the span, the worse the residual fit. Thus to get the best fit onboard the spacecraft the nominal spacecraft trajectories contain three Chebyshev spans, with the middle span intended to straddle any event that would cause large residual errors. The coarse trajectories consist of a single span which has larger residual errors but also a larger span duration. In the event the spacecraft runs off the end of a nominal span the G&C software will use the coarse span to determine its position with respect to the Earth and signal autonomy to demote the spacecraft into Earth Acquisition state to allow for new ephemerides to be uploaded to the spacecraft. In the event all ephemerides are invalid New Horizons can use the Sun sensor in Sun Acquisition state to orient its MGA to receive commands from the ground.

Normally during a command sequence any updates to the target (CB2 or CB3) ephemerides are loaded as part of the command sequence. However, because the OpNav images also refine the positions of the celestial bodies around Pluto's Barycenter the CORE sequence has been designed to load the CB2 targets from on-board macros that are stored in C&DH flash and RAM memory. Thus the on-board blocks can be updated to RAM without altering the CORE sequence. The exceptions are any CB3 ephemerides around closet approach. CB3 trajectories during the CORE will consist of imaginary aimpoints that will allow the spacecraft instruments to scan across the large target uncertainty ellipsoids while attempting to minimize smear near closest approach. During the encounter any CB3 trajectories are loaded by the command sequence. Because these parameters are loaded as part of the CORE sequence (which is burned to flash memory several days before the start of the CORE period) the spans cannot be changed once the sequence has been designed. Thus for any non-zero MET time shift register the TDT time used by the CB3 algorithms must be shifted by an identical number of seconds to maintain the designed geometry and validity of the trajectories. This is accomplished during a Knowledge Update, where CB3 time shift parameters are loaded to both G&C processors and then burned to flash memory when the C&DH time shift is loaded.

5. Rehearsal Concept

The primary goal of the two rehearsals was to test the CORE sequence as much as safely feasible while still protecting the spacecraft. A secondary goal was to alter as few of the onboard commands, onboard autonomy, ground software, or operational processes as possible. It was decided that a rehearsal in 2012 would test the 22 hours around closest approach which contain the most stressful observations. This "stress test" would use less consumables than a full rehearsal, but would allow mission engineers and scientists to verify the spacecraft hardware and instruments were performing as expected. If no major issues were detected then a more complete rehearsal would be conducted the following year. In order to ensure the science instruments were never pointed close to the Sun, which could potentially cause damage or degrade their future performance, it was determined that all pointed activities following the Charon occultation commands would not be tested onboard the spacecraft during either rehearsal. Additional adjustments to the command sequence were made to protect instruments from potential degradation due to designed Sun exposure, such as disabling the Alice instrument's high voltage when the Sun was in the solar occultation channel (SOC) field of view.

When conceiving the rehearsal concept of operations, the decision was made to replicate the inertial orientations and maneuvers of the CORE sequence. Inertial sensors and instruments like the star trackers and LORRI imager would see the same star fields they would in 2015. Maintaining the same inertial pointing also verified there is adequate time allocated between observations to re-orient the spacecraft and settle into the required pointing deadbands before collecting data. Maintaining identical Earth and Sun angles was deemed less important except during DSN contacts when the HGA would need to be oriented towards the real Earth for telemetry. Maintaining proper Earth angles during REX observations and plasma rolls was not required. There were several proposals for accomplishing these requirements, including modifying onboard ephemerides using specialized ground software. These ephemerides would preserve the inertial geometry of the CORE sequence but would be valid for the rehearsal time. However, this would require changes and recertification of many of the ground tools and processes that the team wanted to test. There was also a brief discussion to temporarily alter MET to 2015, but this would be logistically very difficult from a data archiving standpoint, and add risk if the spacecraft entered a safe state, and thus was quickly abandoned. It was deemed a simpler and safer way to enter a "rehearsal state" was to adjust the spacecraft's onboard MET/TDT parameters such that the G&C flight software thought it was 2015. Thus 2012 MET values would be associated with 2015 TDT values. In this way the spacecraft ephemerides, and the ground software that generates them, would not need to be specially modified for the rehearsals. The rehearsal MET times of the simulated closest approach were aligned with the TDT time of the real closest approach, and this preserved the designed geometries of the flyby. This also allowed the epoch of the rehearsal quaternions to easily be adjusted for data analysis using visualizer tools such as Satellite Tool Kit.

The decision was made to keep the wall clock time of the nominal 2012 simulated closest approach the same as it will be in 2015, to make reviewing the command sequence easier. However, the day of closest approach was shifted to keep the Earth-Probe-Sun angle as similar to the real encounter as feasible. This meant the day of simulated nominal closest approach date was changed to May 30, 2012. For the 2013 rehearsal the REX uplink observations took precedence to maintaining the same wall clock time. Thus all commands were shifted by the difference in one way light time between 2013 and 2015 to allow the same ground stations to send the uplink signals at the same wall clock time as they would during the real encounter. Again, the rehearsal date was designed to maintain similar Earth-Probe-Sun angles, and was selected to be July 12, 2013. Table 1 presents the nominal MET/TDT parameters used by New Horizons and the modifications made for the 2012 and 2013 rehearsals.

Table 1. Change to MET/TDT Parameters to allow G&C Flight Software to use 2015 Trajectories.

MET/TDT parameters	*MET_0*	*TDT_0*	*$\Delta rate$*	*Time of Closest Approach (TDT)*
Nominal	167852553	358818701.53457099199	1.0000000108200000071	2015-195T11:51:06
2012 Rehearsal	200684517	490146666.184	1.0	2012-151T11:51:06
2013 Rehearsal	235938784	490146666.184	1.0	2013-193T12:41:06

During the 2012 rehearsal there was only a single, short downlink-only track contained in the 22 hours around closest approach. However, in 2013 the entire CORE period was to be tested, including the Knowledge Updates. This required pointing the HGA towards Earth for uplink and downlink passes. Since changing the MET/TDT parameters shifted where the spacecraft thought it was in inertial space, when commanded to point to the Earth it would actually be pointed incorrectly, by about 2 degrees. This required a small modification to the CORE sequence to use a modified HGA boresight in the guidance algorithms when pointing towards Earth during DSN passes. This did not change the number of commands in the sequence, just the value in a sequenced G&C parameter load.

There was also the desire to test the MET time shift register in conjunction with the CB3 time shift by the 3-σ delivery uncertainties. To test both the positive and negative cases, it was determined to load (-450) in 2012, and +450 seconds in 2013. This had the added benefit of acting as perturbed trajectory testing, since the motion of the targets about their orbits could change the slew durations during time-critical events. In 2012 the time shift was part of the rehearsal entry macro in the command sequence. In 2013 the time shift was accomplished in conjunction with real-time Knowledge Updates and simulated OpNav imaging sequences.

To protect the health and safety of the spacecraft several key changes to autonomy and the CORE command sequence were made for the rehearsals. The first change was that a non-encounter version of autonomy would be used to allow the spacecraft to enter safe mode in the event of a serious fault. Unlike the real encounter, where autonomy would take action to preserve science observations, it was decided if there was a major anomaly like a C&DH reset the best recourse would be to end the rehearsal and transition the spacecraft to Earth Acquisition state. However, because the spacecraft was in rehearsal mode and modified MET/TDT parameters were being used by the G&C processors additional actions would be needed by autonomy to allow the spacecraft to point to Earth in spin mode. The safe mode transition macros were updated prior to the rehearsal to reset the G&C processor during the safing event. This would clear out any parameters which were loaded as part of the rehearsal, including encounter ephemerides and the rehearsal MET/TDT parameters. An additional "red tag" autonomy rule was also loaded to C&DH RAM to safe the spacecraft in the event of a G&C reset. Normally a G&C reset is not an anomaly that safes the spacecraft. However, if the G&C processor was reset during the rehearsal period then all the G&C parameters would have been cleared out of RAM memory, and the G&C would again be using 2012 MET/TDT and ephemerides. This would cause numerous faults and alarms, and would unnecessarily waste propellant for a rehearsal that would need to be repeated. Also because the commanded geometries would be different than the design, instruments could potentially be placed at risk.

An additional change was to make sure all G&C parameter loads were to RAM only. Normally during the encounter, Knowledge Updates to the spacecraft trajectory are burned to G&C flash as part of the Knowledge Update process to protect against a G&C reset. However, it was decided that no rehearsal parameters should be burned to flash. This would protect the spacecraft from using these values in the event of an anomaly which places the spacecraft into safe mode.

6. 2012 Rehearsal Lessons Learned

The 2012 rehearsal was a great success. However, as with all first time events there were many lessons learned during the rehearsal; some dealing with the spacecraft commanding or data compression, and others with ground operations and sequence planning. Some, such as detecting a small boresight misalignment in the ALICE instrument, required changes to instrument kernels and the command sequence. Others, such as the generation of uplink predicts used for the REX radio experiment, required interaction with the DSN stations and network operations engineers to update the delivery process. Despite any discrepancies, the rehearsal met its goals. It proved that the spacecraft could perform the maneuvers and observations required during the most stressing part of the CORE period in the time allocated. Any abnormalities were documented and corrected in the command sequence, ground software, or autonomy. Updates to tools such as the hardware-in-the loop simulators and the small forces file generator were made. The rehearsal demonstrated that the method of entry into a rehearsal mode worked as planned, and could be replicated for the more complicated 2013 rehearsal. The use of a modified HGA boresight parameter to properly orient the real HGA towards the Earth during the rehearsal DSN passes performed as designed. The command sequence had been properly time shifted by (-450) seconds, which verified the MET time shift register and CB3 times shifts performed as expected. Finally, a brief real-time telemetry contact during the rehearsal assured the team the spacecraft was healthy and performing as designed.

Though the total number of lessons learned for the mission are too numerous to document here (most positive confirmations of the design and processes), some of the more critical lessons learned that required changes are presented. For G&C there were two key findings during the 2012 rehearsal that led to changes to the CORE sequence. The first, and most significant, was that dynamic IMU bias estimation performed by the attitude estimator had to be disabled during any science observations. This was due to small misalignments of the IMU resulting in incorrectly estimated gyro biases during the fast (> 1º/sec) spacecraft slews between observations. These false biases were then used by the attitude estimator's Kalman filter algorithms, which corrupted the calculations and manifested as large residual errors between the star tracker measurements and the attitude estimator solution. While these residual errors would slowly converge once the body rates dropped, they still exceeded requirements during the observations. Figure 7 presents the residual errors measured by the flight software during the 2012 rehearsal. Figure 8 presents the incorrect gyro biases computed by the attitude estimator during the fast scans and slews of the 2012 rehearsal. The true biases have been measured during quiescent periods and are currently less than 1 µrad/sec. By disabling the dynamic computation of these biases during science collection the residual errors are not as large, converge much faster (within seconds of the end of a slew), and the spacecraft attitude estimates meet requirements during observations.

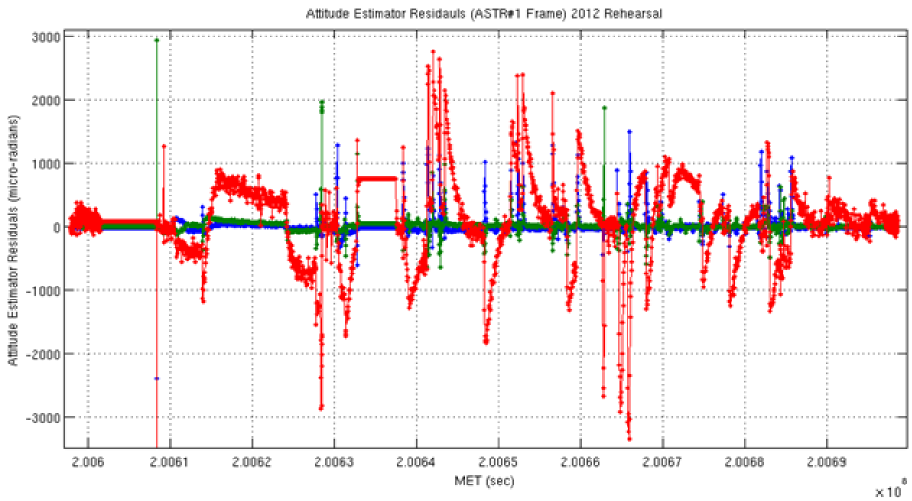

Figure 7. Attitude Estimator Residual Errors in Star Tracker #1 frame when Dynamic IMU Bias Estimation is Enabled. The red line is the about the star trackers Z-axis (sensor boresight).

It should be noted that during the Jupiter flyby, which also had fast slew rates, this dynamic IMU bias estimation was disabled due to a flight software bug that was fixed after the flyby. Dynamic bias estimation had been used in previous 3-axis periods since the flight software fix, but the slews and scans were much slower during those observations so the residual errors were much smaller and would converge well before science imaging. The fast slew rates of the CORE period combined with the short settle times uncovered the issue. Models on the ground were updated which confirmed the behavior, and changes to how the spacecraft is operated were made.

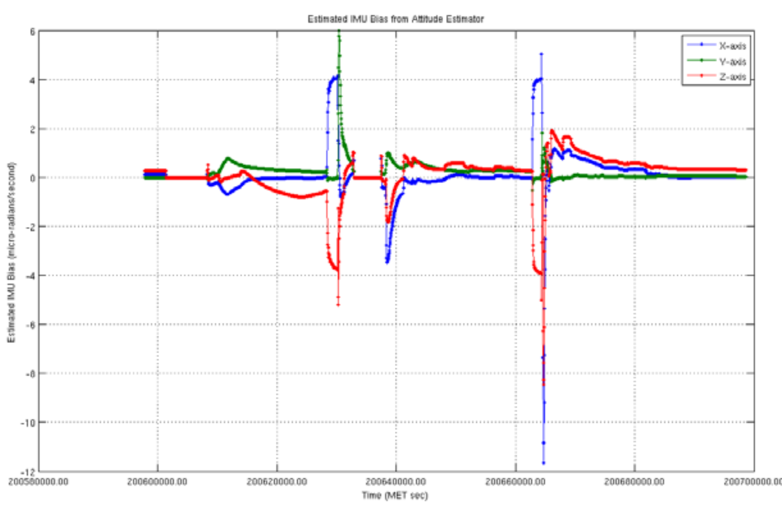

Figure 8. Estimated IMU Biases in Spacecraft Body Frame in μ/sec when Dynamic IMU Bias Estimation is Enabled.

A second discrepancy occurred during events called "plasma rolls". During these observations the spacecraft HGA axis (which is slightly misaligned from the spacecraft principal axis) was pointed to Earth in the tightest attitude deadband and the spacecraft was commanded to scan about the HGA axis by 1.2 deg/sec for 30 minutes. It should be noted that this was the fastest and longest science scan ever attempted on the spacecraft. It was also complicated by the fact that scans rates were not about a spacecraft principal axis, but about a mechanical axis, which led to larger kinematic torques. It was found that this type of scan at the very fast scan rates causes “chattering” in the scan axis thrusters due to excessive rate noise about the scan axis. While the scarcity of data made it unclear why there was an increase in scan axis rate noise, the solution was to slow the scan down, spin about the principal axis instead of the mechanical HGA axis, and loosen the rate deadbands. Since there were 40 plasma rolls originally planned during the approach phase these changes saved a significant number of thruster cycles.

Following the 2012 rehearsal it was also found that the values reported in the small forces file, which is generated by JHU/APL for the navigation teams, were different than the values observed by the navigation teams in their tracking data. The small forces file uses spacecraft attitude and thruster firings and attempts to model what the residual ΔV should be. However, the real small forces due to thruster misalignments, over/underperformance of each thruster, non-repeatability of small 5 msec thruster pules, and impingement are slightly different than those modeled, so updates were made to the model to better match the observations. The observed residual ΔV vector in EME J2000 was [0.37 43.37 -16.44] mm/sec. Thruster gains in the model were modified to remove the majority of the discrepancy.

Instrument team lessons learned that required changes were largely focused on data compression and data allocation. All instruments performed as expected. One additional change to the CORE command sequence was made after the 2012 rehearsal that was not directly related to the rehearsal itself. On July 20, 2011 an additional moon of Pluto (Kerberos) was announced in Central Bureau Electronic Telegram (CBET) 2769. Then, on July 12, 2012 another moon (Styx) was announced in CBET 9253, bringing the total known bodies in the Pluto-Charon system to six. Some observations, termed retargetables, were adjusted after the discoveries to observe the newly discovered moons. Ephemerides for the new targets were generated and will be loaded as onboard blocks using the same method as the other targetable bodies. After all of the updates to the command sequence and ground observations were made, the operations team and spacecraft prepared for the full 2013 encounter rehearsal, including conducting operational readiness tests for all expected ground operations, such as updating the spacecraft’s trajectory in the days leading up to closest approach.

7. Knowledge Updates

Periodically during the CORE sequence several C&DH and G&C parameters need to be updated together based upon the most recent navigation OD solution set. This process is called a Knowledge Update, and can occur once a day up to 2 days prior to closest approach. This cadence allows for multiple uplink opportunities for a given solution set. Traditionally ephemerides are uploaded to G&C flash memory as part of a command sequence. This protects against any corruption of the parameters during uplink that would result in the flight software rejecting the commands. However, since the Pluto encounter sequences are developed weeks to months before they are loaded it is not feasible to load ephemerides in this way near closest approach. This includes not only the spacecraft trajectory, but also planetary ephemerides that have been refined due to OpNav imaging. Thus, these ephemerides must be loaded via real time commands, and subsequently burned to G&C flash.

The concept of operations is to load the MET time shift register, the CB3 time shift, CB1, and the spacecraft 3-axis nominal trajectory in real time to the spacecraft inside a single macro to both C&DH and G&C processors. A cyclic redundancy check is performed by the spacecraft upon receipt, thus if any corruption occurred the macro would not be executed. The G&C parameters will be burned to flash on both processors to protect against a G&C reset or switch, and the MET time shift register is located in non-volatile C&DH RAM on both processors so it is protected against a C&DH reset or switch. In addition, onboard C&DH blocks containing the CB2 targets for Nix, Hydra, Kerberos, and Styx will also be updated in RAM in a separate real-time loaded macro. Pluto and Charon ephemerides are not planned to be updated during the CORE period because their a priori knowledge with respect to the Pluto Barycenter is known better than any OpNav images will provide. There is a risk that a C&DH reset could erase the updated CB2 trajectories, so the observations were designed using larger a priori target uncertainties. The CB2 loads will improve the performance of the system, but are not required for mission success.

The first step of any Knowledge Update is to have the spacecraft perform a sequence of OpNav images, and then downlink those images to the ground. Each sequence contains at least five images of Pluto, Charon, and/or potentially Hydra, as well as several guide stars. These images, along with estimated attitude data, are processed by two independent navigation teams to compute the spacecraft and planetary body ephemerides with respect to each other. Each navigation team uses their own tools, and when the two team's solutions agree with one-another these trajectories and an updated estimated time of closest approach are delivered to the mission operations center as an OD trajectory solution set. These files are then processed and analyzed by the mission design, mission operations, science operations planning, and G&C teams. Differences with the OD solution set onboard the spacecraft are compared, and if these differences are large enough the teams give the go ahead to load the new solution set. It should be noted that because every Knowledge Update is performed via real-time commands there is an associated risk with loading a new set. For this reason a lot of time and effort are put into the vetting and approval process before commands are sent to the spacecraft.

Because 2012 was only a 22 hour test near closest approach there were no real-time updates to onboard ephemerides during the rehearsal. The modified OD solution set with a time of closest approach 450 seconds earlier than the nominal design was loaded as part of the rehearsal entry macro in the command sequence. However, the program wanted to test the mechanism for loading Knowledge Updates during the days leading up to simulated closest approach in the 2013 rehearsal. Thus over the intervening year between the 2012 and 2013 rehearsals many operational readiness tests (ORTs) were conducted to develop and refine the tools and methodologies to successfully load updated parameters to the spacecraft.

During the 2013 rehearsal the Knowledge Update process was exercised six times over five days. Each process takes about eighteen hours from the receipt of images on the ground to uploading new parameters to the spacecraft. Simulated OpNav images were used in place of spacecraft images (since there were no targets in the real images); however actual images were downlinked for processing and transmission by ground software tools. The full process was tested end-to-end, from downlink and transmission of spacecraft images, to processing and delivery of new spacecraft trajectories by the navigation teams, to the validation of those files by the mission operations and the spacecraft teams, to the approval process by program management. Even the daily cadence based upon wall clock time was maintained, which led to many overnight activities. Of the six updates two were loaded to the spacecraft during the rehearsal. The first Knowledge Update shifted the time of closest approach by +423 seconds, and the second by +450 seconds. The sign of these shifts represented the spacecraft arriving later than designed. One key difference were neither the trajectories nor CB3 time shift were burned to flash on the G&C processors for safety reasons, whereas as they will be in 2015.

8. 2013 Rehearsal Lessons Learned

As with the 2012 rehearsal, the full rehearsal was a great success. The changes made based upon 2012 lessons learned properly addressed the issues identified, and while there were more lessons learned over the 9 day period it was determined that an additional rehearsal was not needed. Most of the new findings were related to ground operations, logistics, and interactions with the DSN teams. Any issues that required a command sequence change will be made during the final sequence development phase in 2015.

The key finding in 2013 was not related to the spacecraft, but to the workload on the ground operations teams. The cadence of the Knowledge Updates was very stressful. As mentioned, the full process was exercised six times over five days and each Knowledge Update takes about 12 hours of ground processing to complete from start to finish. The daily cadence of the Knowledge Update process also shifts from day-to-day. The update process six days before closest approach starts at 7:30 AM and ends at approximately 7:30 PM, whereas the following day starts at 3:30 PM and ends at 3:30 AM, leaving about 4 hours until the start of the next update process. This near constant processing, simulation, and review for the updates, coupled with the regular health and safety monitoring as well as planning for future command sequences and attending spacecraft daily status reviews quickly fatigued the teams. This aspect of the operations may not have become evident without the rehearsal, and programmatic steps to mitigate the workload on the team are in development, including training additional personnel for the encounter.

The changes to the spacecraft configuration and the command sequence during the rehearsal performed exactly as expected. As Fig. 9 presents, the residual errors seen in G&C attitude estimator in 2012 were greatly reduced over the same time range. Modifications to the plasma rolls also had the intended result. The thruster chattering went away, and the propellant usage match predicted levels. The only “surprise” seen by the autonomy and G&C teams was that the star tracker demoted due to Sun blinding during a slew back to Earth for the Pluto occultation that did not occur during a similar slew in 2012. Review of the attitude data determined the slew path for the maneuver in 2012 should not have blinded the star tracker, but the path in 2013 was different enough that blinding should have occurred. This small difference in slew paths is an inherent feature of the G&C attitude control logic, and in 2015 occasional blinding of the star trackers may or may not occur. However, autonomy performed exactly as designed and the observation met all requirements.

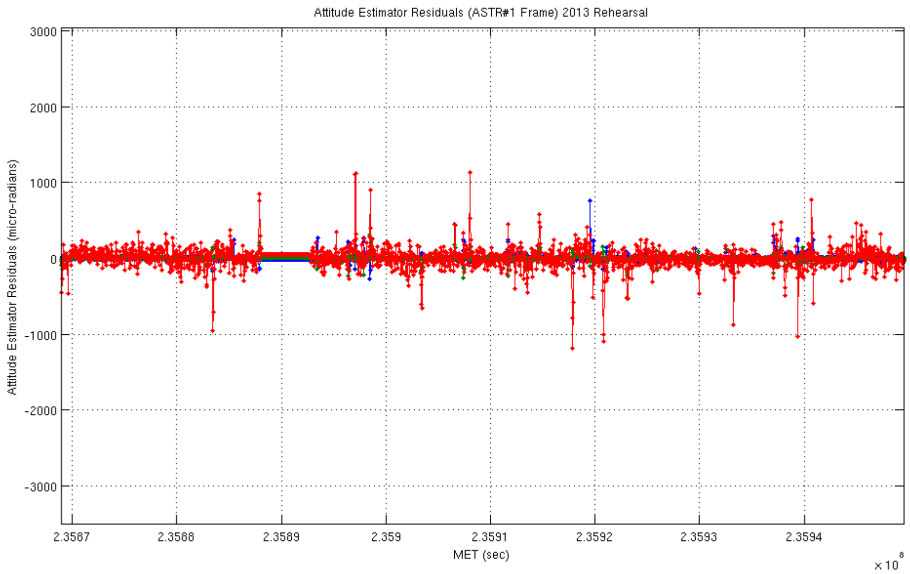

Figure 9. Attitude Estimator Residual Errors in Star Tracker #1 frame when Dynamic IMU Bias Estimation is Disabled. Same Rehearsal Time Region and Scale as Figure 7.

As with 2012, refinements were made to how the small forces were modeled for delivery to the navigation team. One advantage of the rehearsals was that the large amount of propellant used over a short timeframe allowed the navigation team to measure the residual ΔV from DSN track to track. Figure 10 shows the difference between the post-2012 calibrated small forces estimated by the ground software, and those observed by the navigation team. One can notice that while the X-axis was flat in 2012, there was a large increase of almost -25 mm/sec in 2013. The direction of the discrepancies could be mostly compensated for by realigning the thrusters by 0.1 degrees towards the +Y axis in the model. This simulates impingement on the underside of the HGA or spacecraft bus. The current model now splits the difference between the small forces measured from the two rehearsals, and any residual errors will be treated as uncertainty by the navigation team.

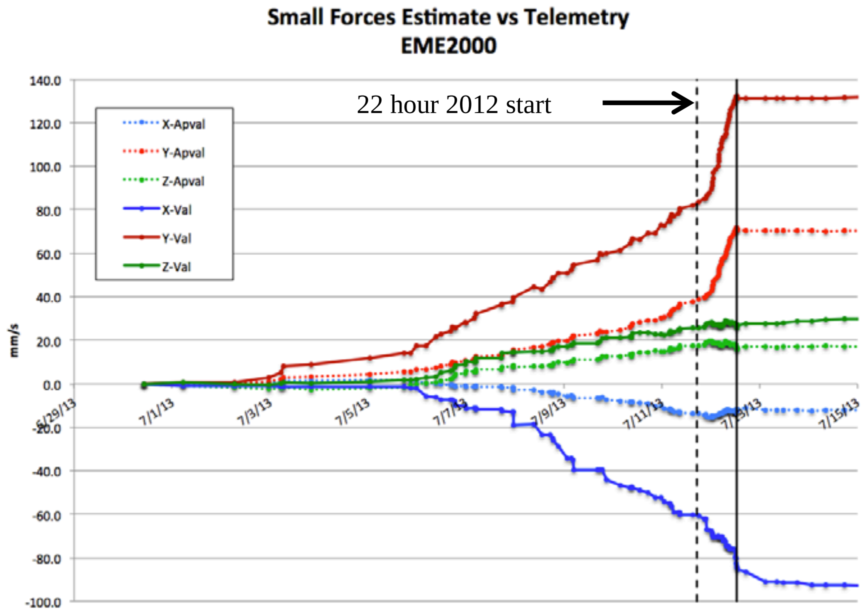

Figure 10. Observed (Solid Line) Versus Modeled (Dashed) during 2013 rehearsal.

The observed performance matched very closely with the simulations, even with the +450 second adjusted trajectory. All slews completed before a given observation would begin. Propellant usage was monitored, and it was demonstrated that the thrusters were performing more efficiently than the spacecraft models. The analysis also showed that the mass flow rates of the thrusters were slightly smaller than the models. Both of these observations had a positive impact on the propellant budgets used by the mission.

9. Data Analysis

Analysis of spacecraft telemetry was conducted by the various spacecraft and instrument teams over an extended period of time. It took over a month of dedicated DSN downlink passes to collect enough data for the teams to begin to make a detailed assessment, as at best the downlink rates were 5600 bps or less. Approximately 1.4 Gbits of data was eventually played back for analysis. Instrument health and safety, OpNav images, and limited science data were played back over the 9 day encounter period, but no attitude data nor spacecraft housekeeping during science activities were downlinked at that time. The only indication that the spacecraft was performing as expected during the rehearsal was the limited real-time housekeeping data received during DSN downlinks. Telemetry indicated that no autonomy rules were firing. The mission operations team was able to verify that the amount of data being recorded to the SSRs matched predictions and the G&C and propulsion teams monitored thruster usage and tank pressure to verify they were trending with models.

Once the data was on the ground, the primary analysis by the G&C team was to look at the spacecraft attitude, body rates, propellant usage, and attitude estimator residual errors to ensure the system was meeting its performance requirements. An extremely detailed analysis of every maneuver was performed and the time margins required to slew and settle between observations were documented. As previously explained, looking at residual errors between the star tracker quaternions and the attitude estimator quaternions was important in determining if the attitude solution converged in time. The time margin between when the G&C system met its designed requirements and the start of a particular observation was presented to the larger team. The mission team agreed there was sufficient margin throughout the sequence. The team performed the additional step to look at images from LORRI and compare the observed star fields with G&C estimated star fields to provide an independent check on performance.

Another analysis tool used throughout the rehearsals was Satellite Tool Kit. A very detailed scenario file has been created and was validated during the Jupiter flyby. The scenario contains the spacecraft instrument fields of view, celestial body positions, spacecraft position and attitude, and Tycho-2 star catalog, which contains over 2.5 million stars. The quaternions from the rehearsal were shifted in time and ingested into the scenario, along with the updated navigation OD team solution set generated during the Knowledge Update process. This allowed the review teams to walk through the CORE sequence to make sure for each observation the intended instrument field of view was pointed at the desired target. Figure 11 presents an example of one of the visualization windows used for this analysis during a LORRI observation of Pluto.

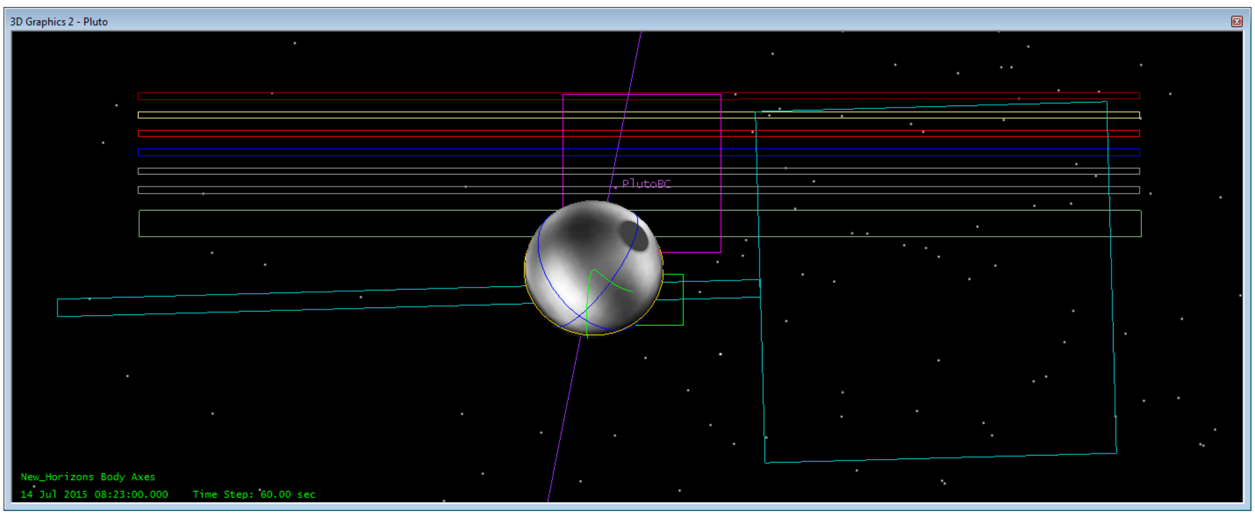

Figure 11. Instrument Fields of View with Respect to Pluto During P_LORRI Observation. LORRI is the Green Square Near Image Center.

10. Conclusion

During the first two weeks of September, 2013 during several all-day meetings, the instrument and subsystem teams presented to program management and the NASA sponsors the results of the 2013 rehearsal. NASA and the New Horizons project management team declared the rehearsal a success. Ultimately both rehearsals accomplished their goals; to successfully rehearse the key portions of the CORE encounter sequence as safely, but as realistically as possible. The lessons learned from the 22 hour stress test rehearsal were successfully incorporated into the full rehearsal the following year. Lessons learned from that rehearsal, which primarily dealt with changes to ground operations, will be practiced on the ground in ORTs during the time leading up to the real encounter. All remaining liens on the sequence will be incorporated in 2015 during final sequence testing.

Onboard flight rehearsals are vital for any spacecraft mission with critical, one-time events. Mission simulations, no matter how complex, cannot fully replicate all of the multi-agency intricacies of a real encounter. Even the best spacecraft models and hardware-in-the-loop simulators are unable to perfectly replicate all of the conditions onboard the spacecraft. Rehearsals also demonstrate where there are vulnerabilities with ground software, personnel, and processes. They provide vital training for the operations and science teams, and will make the actual encounters run smoother. Ideally any flight rehearsal should be conducted far enough in advance that action can be taken to remedy any issues seen, but close enough to be useful to the team as training. The New Horizons rehearsals greatly reduced the risk associated with the extremely busy yet critical 2015 mission operations schedule.

11. Acknowledgements

Special thanks to the flight operations team at JHU/APL, the science operations planning team at Southwest Research Institute and at Cornell University, the navigation teams at KinetX and JPL, and the New Horizons science team members around the country who have be working diligently to shepherd our spacecraft safely across the solar system. The success of the rehearsals was due to their hard work and diligence over the past 8+ years.

12. References

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