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# NEW HORIZONS MISSION TO PLUTO/CHARON: REDUCING COSTS OF A LONG-DURATION MISSION

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## ABSTRACT

The long-duration and long light-time delay of NASA's planned New Horizons mission to Pluto, its moon Charon, and the extended mission to one or more Kuiper Belt Objects poses unique challenges to mission operations, especially in this time of limited space exploration budgets. A number of courses of action can be followed to reduce wear on Observatory hardware, reduce operations staffing costs, and reduce Deep Space Network usage and costs without sacrificing the health and safety of the Observatory or risking the successful completion of the primary mission. Major components in this system are an autonomy subsystem that can react quickly enough to safe the Observatory when it is out of contact with the ground station; the use of a beacon to indicate the health of the Observatory during the dormant phases of the mission; command loading and verification strategies to accommodate the long light-time delays; and the combining of operations personnel to take advantage of similarities of Observatories, supporting ground station setup, and procedures. When planned early in the mission development phase, these components are easily integrated into the operations concept and Observatory hardware to form a cohesive plan to mitigate cost and risk. Cost reduction measures for long-duration missions, such as those planned for New Horizons, enable funding for a greater number of equally important space exploration missions from a limited space exploration budget.

## 1. BACKGROUND

The New Horizons (NH) mission is part of NASA's New Frontiers Program. It was awarded in the fall of 2001, with a start date of January 2002 at a cost of less than \$600M. Dr. S. Alan Stern of Southwest Research Institute (SwRI) in Boulder, CO, USA, is the mission's Principal Investigator (PI) and is responsible for the overall NH mission. Responsibilities of Observatory

design, development, and mission operations are delegated to the Johns Hopkins University/Applied Physics Laboratory (JHU/APL) in Laurel, MD, USA. The Tombaugh Science Operations Center (TSOC), named for the discoverer of Pluto, would serve as the center of scientific research and data repository for this mission. Throughout this paper, the term "Observatory" is defined as the integrated spacecraft and science instrument payloads.

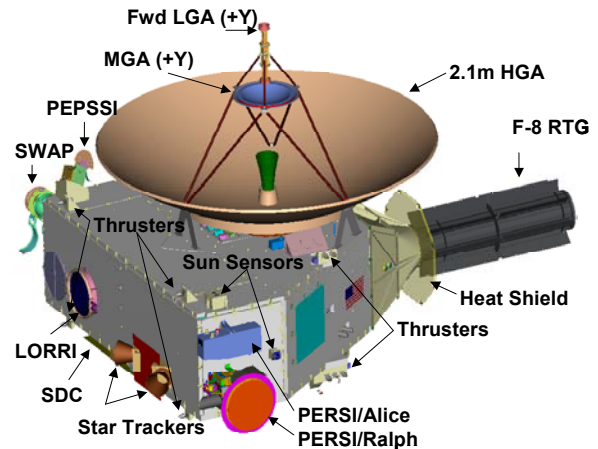
The primary mission would be to conduct a detailed first reconnaissance flyby of the Pluto/Charon system, with observations planned to begin 150 days prior to and 60 days after closest approach (C/A). The extended mission would be to conduct a flyby of one or more Kuiper Belt Objects (KBOs). The NASA decision to fund the extended mission would be made sometime after launch of the NH Observatory. Table 1 gives an overview of the currently planned NH mission phases.

The NH Observatory primary launch window would span 35 days from January 11 to February 14, 2006, giving C/A arrivals from July 2015 to July 2020. If launched in the first 23 days of the launch window, a Jupiter Gravity Assist (JGA) would be used to reduce flight time to Pluto/Charon by as much as 5 years; if launched in the last 12 days, the trajectory would be a direct flight to Pluto/Charon. Launch would be from Cape Canaveral, FL, USA, using an Atlas 551 with a Star 48B upper stage. Figure 1 depicts the current configuration of the NH Observatory.

**Table 1 NH Mission Phase Overview**

MISSION PHASE	TIMEFRAME (nominal-planned)	OBJECTIVE
Launch & Early Operations (LEOps)	Launch + 60 days (Jan–Mar 2006)	Observatory (Obs.) Checkout, Navigation & Targeting
Cruise 1	Cruise following LEOps to 61 days before Jupiter C/A (Mar–Dec 2006)	Instrument Commissioning, Flight Tests, Navigation & Targeting, etc.
Jupiter	60 days pre to 40 days post JGA (Jan–Apr 2007)	JGA, Navigation & Targeting, Jupiter Science
Cruise 2	41 days post JGA to 201 days pre Pluto/Charon C/A (Apr 2007–Jan 2015)	Beacon-Hibernation, Annual Checkouts, Precession Maneuvers, Navigation & Targeting, Rehearsal
Pluto/Charon	200 days pre to 14 days post Pluto/Charon C/A (Jan–Jul 2015)	Science Observation Final Rehearsals, Navigation & Targeting, Science Collection, First-Look Data Return
Pluto/Charon Data Retrieval	15 days to 270 days post Pluto/Charon C/A (Aug 2015–Apr 2016)	Return of Pluto/Charon Science Data, Navigation & Targeting
Cruise 3 (extended mission)	271 days post Pluto/Charon C/A to 81 days pre KBO 1 C/A	Beacon-Hibernation, Annual Checkouts, Precession maneuvers, Navigation & Targeting

MISSION PHASE	TIMEFRAME (nominal-planned)	OBJECTIVE
KBO 1 (extended mission)	80 days pre and 90 days post KBO 1 C/A	Science Observation Final Rehearsals, Navigation & Targeting, Science Collection, Data Return
Cruise 4 (extended mission)	91 days post KBO 1 C/A to 81 days pre KBO 2	Beacon-Hibernation, Annual Checkouts, Precession Maneuvers, Navigation & Targeting
KBO 2 (extended mission)	80 days pre and 90 days post KBO 2 C/A	Science Observation Final Rehearsals, Navigation & Targeting, Science Collection, Data Return



**Figure 1 NH Observatory Current Configuration**

## 2. INTRODUCTION

The NH mission operations team (MOps) is expected to face a number of unique operational challenges as a result of the long-duration and light-time delay of this mission. Recognition and mitigation of these challenges began from the onset. To help address the long duration and the subsequent Deep Space Network (DSN) usage and costs, a beacon-hibernation phase would be implemented for the cruise between JGA and Pluto/Charon C/A denoted as Cruise 2.

To address the long light-time delay that will reach approximately 4.5 hours one way at Pluto/Charon, an autonomy safing strategy and a modification to nominal command load and verification would be implemented. Both of these mitigations would result in changes to the standard staffing concept of the mission operations team and would be done with minimal risk to the primary mission objectives occurring, at the earliest, 9.5 years after launch.

### **3. MISSION DURATION**

Because of the long duration of this mission and the resulting relative cost of DSN support as compared with the total mission cost, as well as the number of spacecraft competing for the DSN stations, it was decided during the concept study phase that DSN costs and usage would be minimized in order for the proposal to be considered by NASA. One way of reducing costs is to reduce the number of required DSN passes by placing the Observatory into a beacon-hibernation mode. Deep Space 1 first demonstrated the feasibility of using a set of beacon tones to indicate a spacecraft's health.<sup>1</sup> During the Deep Space 1 technical demonstration, one of four beacon tones was transmitted for the short periods between telemetry contacts. Based on these results, a beacon-hibernation concept was developed for the NH mission, utilizing eight beacon tones (four each on two carriers), with one "green" and seven "red" tones, each indicating a specific Observatory state of health.

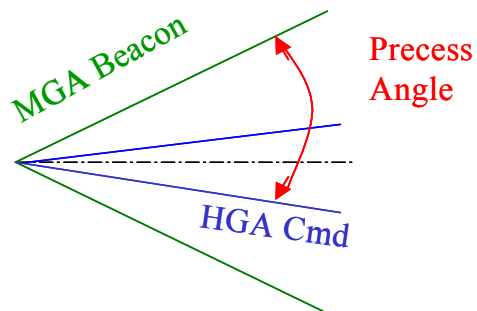
#### **3.1 Cruise 2**

The mission operational concept for Cruise 2 (the phase between Jupiter and Pluto/Charon) is to have "active periods" and "dormant periods". Active periods would be when the Observatory is in either an active spin or a three-axis stabilized state, meaning that Guidance and Control (G&C) is controlling the Observatory attitude. (See the Appendix for a discussion of NH Observatory modes and states.) The active periods would include planned precession maneuvers to orient the medium gain antenna (MGA) to Earth, trajectory correction maneuvers (TCMs), annual checkouts, and response to "red" beacon tones or emer-

gency telemetry. Dormant periods would be when the Observatory is in a passive spin-hibernation (PS-H) state with no active G&C control. The majority of time during Cruise 2 would be spent in PS-H with the operations team relying upon the beacon tone to indicate the health of the Observatory. In the current concept, the Observatory could be placed in PS-H for up to 11 months at a time. Cruise 2 would last approximately 7.5 years, assuming a 2015 Pluto/Charon arrival.

#### **3.1.1 Active Periods**

Active periods would comprise about 2 months of each year. Planned periods of Observatory activity would include precession maneuvers, TCMs, and annual checkouts. Precession maneuvers would be conducted to maintain MGA pointing to Earth for beacon tone transmission/reception and emergency commanding at 7.8 bps. The high gain antenna (HGA), MGA, and forward low gain antenna (LGA) would be co-aligned (Figure 1). Another precess to the edge of the MGA would be conducted before the pointing drifts outside of the HGA deadband, (Figure 2). These maneuvers would require DSN 70-m antenna support of one 8-hour pass per day for a week, for a total of approximately 504 hours of 70-m antenna time. Preliminary analysis indicates that approximately nine precession maneuvers would be required outside of the annual checkout periods. While TCMs require DSN support of one 8-hour pass per day for a week, all needed TCMs would be planned to occur during the annual checkout periods.



**Figure 2 NH Precession Angles**

The annual checkout period would be devoted to accessing the NH Observatory subsystem and instrument states of health, obtaining navigation data to support any needed TCMs and the next period of PS-H, and performing routine maintenance on designated subsystems and instruments. The first annual checkout period would occur within 6 months after the end of the Jupiter phase. Each of the eight planned checkouts spans 50 days. DSN contacts would vary from two to three 8-hour passes per week except for the one annual checkout that includes the Pluto/Charon rehearsal. At the end of the checkout period, the MGA-to-Earth pointing would be precessed to the edge of the pointing deadband. The mission operations team would load the time tag commands to broadcast the weekly “green” beacon tone corresponding to the already scheduled weekly DSN beacon contacts and the time tag commands to “wake up” the Observatory for precession maneuvers, TCMs, and annual checkout periods. Each nominal annual checkout period would utilize approximately sixteen 8-hour 70-m DSN passes (or 128 hours), while the one annual checkout period that contains the first Pluto/Charon rehearsal is currently estimated to require 392 hours of 70-m DSN support time. This gives a total of 1288 hours of 70-m support over Cruise 2 to support all annual checkouts.

### **3.1.2 Dormant Periods**

During the beacon-hibernation phase of Cruise 2, the Observatory would be placed in PS-H with the “green” beacon tone broadcast weekly for a 24-hour period centered around the planned DSN contact. Each weekly DSN beacon contact would be scheduled for 1.5 hours, although it is expected to take much less time for the DSN to receive and analyze the tone (less than 45 minutes). These measures would be taken to cover any DSN or operations contingency that might arise. For distances of less than 25 AU, the 34-m stations would be used to support beacon contacts. At distances of 25 AU and beyond, use of the 70-m stations would be necessary to detect the beacon tone. The “green” tone will not be broadcast continuously to maximize the life-time of the traveling wave tube’s cathode filament. In the case of an onboard failure

requiring attention, the autonomy rule facility (ARF) would initiate one of seven “red” beacon tones, disable the preloaded weekly “green” tone, and broadcast the “red” tone continuously. In certain cases, the ARF would command the Observatory to go the Active Spin-Earth Acquisition (AS-EA) safe state, in which case telemetry would be broadcast at the emergency rate (10 bps) instead of a “red” beacon tone, and a 14-day “demote to Active Spin–Sun Acquisition (AS-SA) state” timer would be initiated. Dormant periods will comprise on average approximately 10 months each year and require 281 hours of 34-m and 182 hours of 70-m DSN beacon support over the 7.5-year period of Cruise 2.

## **4. LONG LIGHT-TIME DELAY**

The NH mission end of life would be realized at a solar distance of 50 AU. Analysis early in the concept study phase determined that probability was high that two KBOs with diameters greater than 50 km could be encountered within 50 AU.<sup>2</sup> As a result, the MGA is being sized to provide emergency commanding out to 50 AU. Primary mission objectives would occur at approximately 32 AU, with the extended mission objectives (first KBO encounter) predicted at 40 AU. One Way Light Time (OWLT) delays would be 4.3 hours and 5.3 hours respectively. Due to these long OWLT, Observatory safing and command loading and verification concepts would be modified from missions with shorter OWLTs.

### **4.1 Observatory Safing**

During all cruise phases of this mission except for the cruise from Earth to Jupiter (Cruise 1), the Observatory would be placed in a PS-H state for long periods, relying upon the ARF to determine the state of health and report this state to the NH mission operations center (MOC) via a beacon or telemetry. The ARF would report in three different ways, “green” beacon tone, “red” beacon tone, or emergency telemetry by commanding the Observatory to AS-EA. Many components would be turned off during this phase, partly to reduce wear and partly to reduce risk.

Within the ARF, conditions would be defined that merit a “red” beacon tone. Definition of the conditions triggering a “red” beacon tone will be chosen carefully to maximize safety and minimize false or non-mission threatening conditions that do not require operations intervention. Because there are seven “red” beacon tones, if a “red” tone were received, the mission operations team would have a good indication of the type of onboard anomaly just from the particular tone received.

Because DSN telemetry contacts would not be scheduled during the dormant periods of the cruise phases, it will be imperative that the ARF request for a telemetry contact be done only when needed to avoid impacting the DSN schedule. The seven “red” tones would be divided into priority categories, with not all “red” tones requiring immediate ground intervention. When ARF places the Observatory in AS-EA, ground intervention must occur within 14 days or the ARF would command the Observatory to AS-SA and broadcast the highest priority “red” tones.

## **4.2 Command Loading and Verification**

The nominal uplink rate for the NH Observatory will be 500 bps, with the capability of a 2000-bps rate when needed. It is expected that at 2000 bps, the longest command load would take 15 minutes to radiate. 70-m downlink rates for the Observatory would be variable, ranging from about 37 kbps at Jupiter to about 1000 bps at Pluto/Charon. While these downlink rates limit telemetry data return, especially at Pluto/Charon and beyond, the largest telemetry delay would be due to the OWLT. For this reason, ways to decrease the number of OWLTs required for loading commands on the Observatory were explored.

Nominally, the operations center ground station would send each telecommand transfer frame (TCTF) once to the DSN for upload to the Observatory. Each TCTF would contain command or time tag macros. Command macros contain individual commands; time tag macros contain the execution time for each command macro. NH would implement a modified version of the

Consultative Committee for Space Data Systems (CCSDS) Command Operations Procedure 1 (COP 1) protocol for TCTF uplink verification. The Observatory Command and Data Handling subsystem (C&DH) will accept the TCTF and its command contents after performing validity checks that include a check of the TCTF sequence number. The entire TCTF would be rejected if any frame/command check fails or the sequence number is not the one expected. The failure of one telemetry frame would cause a re-transmit request to be sent to the ground and all subsequent telemetry frames to fail until the expected sequence number is received. To mitigate this potential failure and to increase the chances that the first attempt to transmit the TCTFs to the NH Observatory is successful, the ground station software would be modified to include the ability to send each TCTF up to “n” times. The NH Observatory C&DH would accept only the first valid expected TCTF and would ignore other TCTFs with the same sequence number. When OWLTs are short, TCTFs will routinely be sent one time. As the OWLTs increase, the mission operations team would have the ability to increase the number of times the TCTFs are sent. It is expected that no more than  $n = 3$  will be used operationally. Early in the mission, tests would be performed to verify the sending and receipt of TCTFs at  $n > 1$ .

Command load verification will be accomplished by loading the command and time tag macros in a disabled state, commanding a dump of the onboard memory containing the load and verifying the dump against the expected image on the ground. After ground verification, commands would be sent to enable the macros and to enable the load transition autonomy rule, which would allow activation of the new load when the current load completes. This process requires a delay of three OWLTs plus an OWLT to verify the “command load enable” status. When OWLTs reach a pre-determined duration, the command loading and verification strategy would be modified so that the command load, verification, and enabling time is decreased to one OWLT plus an OWLT to verify the “command load enable” status, and optimally would not span more than one 8-hour DSN pass.

With the modified strategy, the command and time tag macros would be loaded with a ground-calculated checksum. As part of the C&DH acceptance of the command macro, an onboard checksum would be performed and compared to the ground-calculated checksum uploaded with command macro. Only if the checksums match would the command macro be enabled. Furthermore, the load transition autonomy rule would allow activation of the new load only if all macros in the loaded range were reporting "enabled" (i.e., they have all passed the checksum compare.) At the end of the DSN pass or the beginning of the next pass, the command load "enabled" status is verified via telemetry. The mission operations team also would have the ability to delay the dump of the on-board memory containing the command load so that it corresponds to the next scheduled DSN pass. When this strategy is followed, the dump would be compared with the expected ground image, and the command to enable the transitional autonomy rule would be sent during this second pass. This would result in the mission operations team having three strategies to perform a command load and verification choosing the strategy that best fits the OWLT delay and mission phase.

## **5. MISSION OPERATIONS CENTER STAFFING**

The lengthy periods spent with the Observatory in PS-H during Cruise 2 would allow for a reduction in mission operations center staffing. An average of 5 operations center staff per month would be needed to support operations for the first 2 years after Jupiter and then would decrease to 3.5 operations center staff per month to support the remaining years of Cruise 2 before the Pluto/Charon phase begins. This translates into significant savings compared with an average of about 9.5 operations center staff per month needed to support a more traditional mission concept.

Additionally, a staffing concept would be developed to allow sharing of staff among Observatories with common onboard hardware and ground systems. This allows a pool of staff equally well versed in operations to move between Observatories de-

pending on the current staffing need and Observatory events. In some cases this is problematic and results in the requirement that staff be experts in more than a few disciplines in order to minimize staffing cost.

## **6. DSN USAGE AND COST SAVINGS**

Both the 34-m and the 70-m DSN antenna resources are heavily subscribed, and any reduction in use would help ease this strain. This is especially true of the 70-m antenna resources. Unfortunately, the distances of this mission require heavy reliance on the 70-m resources to get the downlink rates to support telemetry and data retrieval in a timely manner. After Jupiter, all DSN telemetry passes would be run with the 70-m antennas. By incorporating a beacon, the mission operations team would not have to rely upon a DSN telemetry pass to ascertain the health of the Observatory; the receipt of a beacon tone via a DSN beacon pass would give this information. Also, these DSN beacon passes would make use of the 34-m antennas out to 25 AU, thereby reducing this mission's 70-m antenna requirements. Couple these 70-m resource savings with the fact that a DSN beacon pass would take much less time (conservatively estimated at 1.5 hours) than scheduling one or more weekly 8-hour DSN telemetry pass, and the DSN 70-m antenna usage would be decreased by approximately 2274 hours.

## **7. SUMMARY**

As currently planned, the NH mission would be a long-duration mission with long OWLTs, both of which pose challenges to the project budget and mission operations team. Developing a concept of operations that meets these challenges early in the life of the project would allow hardware and software to be developed to support these concepts from the very beginning, saving cost. Use of a beacon-hibernation mode supported by an autonomy system with emphasis on simplicity and safing the Observatory for long periods of time would save in DSN usage, cost, and staffing. Co-locating mission operations centers for Observatories with common onboard hardware and

common ground systems would allow staff sharing between missions, decreasing costs for both projects. Developing a strategy for command load verification that minimizes OWLTs would decrease DSN usage and time devoted to command loading. In addition, the ability of the ground station to send telemetry frames more than once and the Observatory to accept the first valid frame and wait for the next expected frame would add additional robustness to Observatory command loads.

Many of the cost reductions would also add robustness and lessen risk to the mission. Incorporating the beacon to support the beacon-hibernation concept and the ARF to trigger the appropriate beacon tone when in PS-H would reduce DSN usage and operations center staff. It also would reduce risk to the mission, as it would not be possible to maintain real-time contact with the Observatory given the long light-time delays. Using shared staff between common Observatories and ground stations also would lessen risk, as it would allow a larger pool of staff during inactive periods on both Observatories, increasing team depth more than would normally be possible.

## **8. APPENDIX**

A brief description of the NH Observatory modes and states is provided for clarification.

The NH Observatory would have three modes of operation (three axis [3A], active spin [AS], and passive spin [PS]) and six states (trajectory correction maneuver [TCM], normal [N], hibernation [H], encounter [E], Earth acquisition [EA], and Sun acquisition [SA]). There would be a total of ten mode/state combinations, since not all states are allowed in every mode, as shown in Table 2.

**3A-E mode/state** would be used for instrument pointing and scanning for science observations. Autonomous exiting of this state is allowed only with the expiration of a long-term backup timer (currently envisioned to be 14 days). Due to the propellant required to maintain this state, it is used only when required.

**3A-N mode/state** would be the typical configuration of the Observatory when in 3A mode. It would be used for instrument commissioning and calibration, selected encounter science observations, and optical navigation.

**3A-TCM mode/state** would be entered via MOps ground command for G&C controlled TCMs and would be maintained only long enough to complete the TCM.

**AS-N mode/state** would be the typical state of the Observatory when in AS mode. Examples of its planned use are science observations not requiring 3A mode, checkout activities not requiring 3A mode, and precessions to maintain the HGA to Earth.

**AS-TCM mode/state** would be entered via MOps ground command for G&C controlled TCMs and would be maintained only long enough to complete the TCM.

**AS-EA mode/state** would be entered after the occurrence of Observatory faults such as low voltage sensing (LVS) or a loss of communications. After 14 days, if no contact has been made with the Observatory or if internal reference is lost for 24 hours, the autonomy rule facility (ARF) would time out and would command the Observatory to AS-SA mode/state.

**AS-SA mode/state** would be entered only when the Observatory cannot point to Earth (loss of inertial reference capability) or after an extended loss of communications (14 day in AS-EA mode).

**PS-N mode/state** would be the typical state of the Observatory while in PS mode. This mode/state would be used to transition the Observatory out of PS-H and verify that the Observatory subsystems are nominal before transitioning to PS-TCM or an AS mode. In PS-N, G&C would be on and operating in a passive state, i.e., not actively controlling the spin axis. It also would be used during non-active periods in Cruise 1 to save propellant.

**PS-TCM mode/state** would be entered via MOps ground command and would be used for MOps initiated and controlled TCMs, spin-ups, and spin-downs. This mode/state

would be maintained only long enough for the completion of these activities.

**PS-H mode/state** would be the mode/state used for journeys from Jupiter to Pluto (if on a JGA trajectory) or from Launch + 1 year to Pluto (if on the Pluto-direct trajectory), from Pluto to KBO 1, and from KBO 1 to KBO 2. Most subsystems would be powered off (including the G&C subsystem), and the propulsion system latch valves would be closed. The Observatory would remain in PS-H mode/state except during the annual checkout periods and for those precession maneuvers occurring outside of the annual checkout period.

**Table 2 NH Observatory Modes and States**

State	Mode		
	3-Axis	Active Spin	Passive Spin
TCM	3A-TCM	AS-TCM	PS-TCM
Normal	3A-N	AS-N	PS-N
Hibernation	Not allowed	Not allowed	PS-H
Encounter	3A-E	Not allowed	Not allowed
Earth Acquisition	Not allowed	AS-EA	Not allowed
Sun Acquisition	Not allowed	AS-SA	Not allowed

## **9. ACKNOWLEDGMENTS**

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## **10. REFERENCES**

1. DeCoste et al., "Deep Space 1 Technology Validation Report – Beacon Monitor Operations Experiment," Jet Propulsion Laboratory, California Institute of Technology. February 2000.
2. J. Spencer, M. Buie, L. Young, Y. Guo, and A. Stern 2003. "Finding KBO Flyby Targets for New Horizons," *Earth, Moon and Planets* **92**, 483-491.