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A description of the Pluto-bound New Horizons spacecraft

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Abstract

Pluto is the only planet in our solar system that has not yet been visited by a spacecraft from Earth. Beyond the orbit of Pluto lies the Kuiper-Belt: home to many primordial objects from the earliest days of the formation of the solar system, preserved in a cosmic deep freeze. The Johns Hopkins University/Applied Physics Laboratory (JHU/APL) is planning the mission for the Principal Investigator, Dr. S. Alan Stern of Southwest Research Institute. The planned design of the New Horizons spacecraft, along with a discussion of the design drivers, is presented. The design lifetime of the spacecraft would be 15.25 years. Measures taken to ensure the reliable operation of the spacecraft over the life of the planned mission are discussed.

1. Introduction

Pluto remains the only planet in our solar system that has never been visited by a spacecraft. The New Horizons (NH) mission would finally remedy this deficiency in our exploration of the outer planets by sending a spacecraft to rendezvous with Pluto, and its moon, Charon, as early as July 2015 after launching from Cape Canaveral Air Force Station in January 2006, using a Jupiter gravity assist trajectory. While New Horizons is planned as a flyby mission of Pluto, and not an orbiter, an intensive science campaign would begin approximately 5 months before closest approach and end 2 months after. The spacecraft would carry seven instruments to fulfill its scientific objectives. These instruments are provided by six institutions, and are supported by a world-class science team. After the Pluto–Charon encounter, in an extended mission phase, the spacecraft would proceed to rendezvous with at least one, and as many as three Kuiper Belt Objects. The Johns Hopkins University/Applied Physics Laboratory (JHU/APL) is planning the New Horizons mission for the Principal Investigator (PI), Dr. S. Alan Stern of the Southwest Research Institute (SwRI), and the National Aeronautics and Space Administration (NASA).

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2. Pluto–Charon background

The Pluto–Charon system is unique in the solar system. Pluto is neither a terrestrial world like the inner planets, nor is it a gas giant like the other outer planets. It is instead an ice dwarf, common to the deep outer solar system, and similar in many ways to the objects found in the Kuiper Belt. These worlds are primordial remnants from the earliest days of the formation of the solar system, which have been preserved in their pristine states in a cosmic deep freeze. By studying these bodies, we will advance our understanding of the fundamentals involved in the formation and evolution of the solar system.

Pluto and Charon are also the only example in our solar system of a true binary system; these two bodies orbit about the center of mass between them. Additionally, the atmosphere of Pluto is a transitional case between classical planetary and cometary atmospheres, and may also exhibit the phenomenon of hydrodynamic exchange, much as mass is exchanged between binary star systems. The New Horizons mission is in the best tradition of scientific exploration: a journey into the unknown [1].

3. New Horizons science

New Horizons would be the first spacecraft to provide reconnaissance of Pluto–Charon and a Kuiper Belt Object (KBO). Scientific questions regarding the surfaces, atmospheres, interiors, and space environments of Pluto and Charon would be investigated using imaging, visible and infrared spectral mapping, ultraviolet spectroscopy, radio science, and in situ plasma sensors. The science objectives for the mission have been prioritized into measurement groups as follows:

3.1. Group 1 objectives

- Characterize the global geology and morphology of Pluto and Charon.
- Map surface composition of Pluto and Charon.
- Characterize the neutral atmosphere of Pluto and its escape rate.

3.2. Group 2 objectives

- Characterize the time variability of Pluto's surface and atmosphere.
- Image Pluto and Charon in stereo.
- Map the terminators of Pluto and Charon with high resolution.
- Map the composition of selected areas of Pluto and Charon at high resolution.
- Characterize Pluto's ionosphere and solar wind interaction.
- Search for neutral species including H, H_2, HCN, and C_xH_y, and other hydrocarbons and nitriles in Pluto's upper atmosphere, and obtain isotopic discrimination where possible.
- Search for an atmosphere around Charon.
- Determine bolometric Bond albedos for Pluto and Charon.
- Map the surface temperatures of Pluto and Charon.

3.3. Group 3 objectives

- Characterize the energetic particle environment of Pluto and Charon.
- Refine bulk parameters (radii, masses, densities) and orbits of Pluto and Charon.
- Search for magnetic fields of Pluto and Charon.
- Search for additional satellites and rings.

The New Horizons mission plans to address all of these measurement objectives, with the exception of one Group 3 objective: the search for magnetic fields of Pluto and Charon. It is not expected that such magnetic fields exist. A magnetometer was not included in the New Horizons payload suite, thereby eliminating the requirement for a magnetically clean spacecraft. The presence of a magnetic field, should one exist, can be deduced from other instruments. As designed, the New Horizons payload suite consists of the following seven instruments:

- Alice: Ultraviolet mapping spectrometer (provided by SwRI).
- Ralph: Visible imager and infrared mapping spectrometer (provided by NASA's Goddard Space Flight Center and Ball Aerospace Corporation).

- LORRI: Panochromatic long-range imager (provided by JHU/APL).
- PEPSSI: Energetic particle spectrometer (provided by JHU/APL).
- SWAP: Solar wind analyzer (provided by SwRI).
- REX: Radio science experiment (provided by Stanford University).
- SDC: Student-built dust counter (provided by the Laboratory for Atmospheric and Space Physics).

4. Mission design and trajectory

The New Horizons spacecraft would be launched directly into an interplanetary trajectory (see Fig. 1) from Cape Canaveral Air Force Station, Florida, in January 2006 on a Lockheed Martin Atlas V 551 launch vehicle. A Boeing-supplied third stage is also required to achieve the launch energy C_3 of $164\,\mathrm{km}^2/\mathrm{s}^2$.

The spacecraft would then embark on an approximately 10-year journey that will bring it to Pluto and Charon, at the earliest, in July 2015 after a flyby of Jupiter in March 2007.The arrival date at Pluto is dependent on the launch date, as shown in Fig. 2. A Jupiter gravity assist, which enables earlier arrival dates at Pluto, is available only during the first 23 days of the 2006 launch window. A 14-day backup launch opportunity is available in February 2007. The trajectory design for this back-up opportunity does not use a Jupiter gravity assist [2,3].

The NH operational lifetime requirement is 15.25 years, beginning after launch and extending through the retrieval of all Pluto–Charon science data. The KBO encounters are not required to achieve full mission success but are part of an extended mission to be approved after launch. Therefore, the spacecraft design must not preclude operations for up to 18.35 years.

Science plans call for the first KBO rendezvous to occur by the time the spacecraft reaches a distance of 40 Astronomical Units (AU); the mission would end by the time the spacecraft reaches 50 AU.

The distance from Pluto to the Earth during the encounter is approximately 33 AU. The round-trip light time is about 9 h. At a downlink data rate of 600 bps, the encounter data would be transmitted to Earth over a 9-month period using NASA's Deep Space Network.

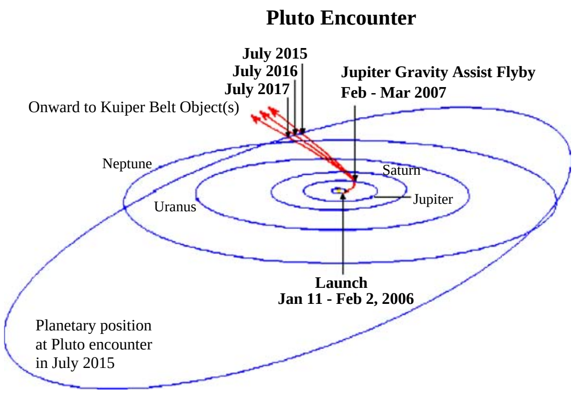

Fig. 1. New Horizons trajectory.

5. Spacecraft design drivers

Driver	Impact
Long Mission Life (15.25 years required/18.35 year goal)	Cross-strapped redundant avionics architecture; beacon-hibernation mode with cold sparing of redundant components; physics of failure analysis to validate processes and materials
Minimize mechanisms, scanning mechanisms, etc. for enhanced reliability	Thruster-only control, agile spacecraft, minimum impulse-bit thrusters for fine vehicle control
Limited power available from baselined Radioisotope Thermoelectric Generator power source	Duty cycling of science instruments required during encounter to ensure adequate power margins are maintained

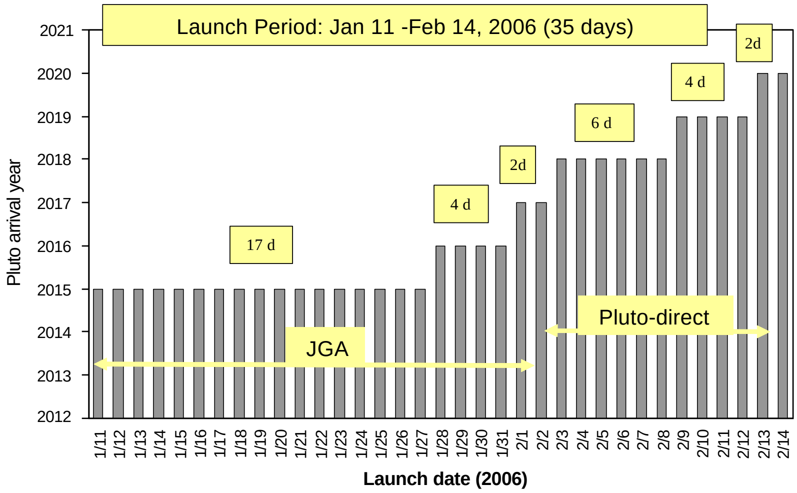

Fig. 2. New Horizons 2006 launch window.

Large spacecraft-to-Earth distance at Pluto encounter and long round-trip light travel time	Low downlink data rates (600 bps) for science data playback; robust spacecraft autonomy design
High launch energy requirement	Limits spacecraft launch mass to 465 kg (2006 launch opportunity)
NASA desire to minimize burden on heavily subscribed DSN	Use of beacon-hibernation mode for cruise between Jupiter and Pluto

The long mission lifetime requirement of 15.25 years is within the experience of long-life commercial communications satellites. Single-point failures are minimized. For example, as seen in the spacecraft block diagram (Fig. 3, found at the end of the paper), a hybrid coupler is designed to cross-strap the Radio Frequency (RF) Communications system. This coupler does represent a single point failure for the RF subsystem; however, it is a highly reliable passive device that has been used in previous deep space missions.

For New Horizons, as with many other JHU/APL-designed spacecraft, deployable mechanisms and scanning platforms are to be kept to a minimum. Several instruments would have protective covers that are deployed shortly after launch. One instrument would have an internal shutter to operate at the Pluto encounter. The Thermal control system would employ louvers. The spacecraft would have no scanning platforms or deployment mechanisms. The spacecraft would operate in a spin-stabilized mode (for launch, early operations, and cruise phases) and in a three-axis mode (for encounter phases). As planned, the spacecraft is required to be agile in the three-axis mode in order to provide the proper pointing for the science instruments. The propulsion system would use Cassini-heritage minimum impulse-bit thrusters for fine attitude control. There are no reaction wheels on board the spacecraft as designed.

Fig. 3 also shows that the spacecraft avionics are configured in a highly redundant cross-strapped architecture. The scientific payload design incorporates physical redundancy in some elements of the core payload, and functional redundancy among the instruments.

Limited spacecraft power from the baselined Radioisotope Thermoelectric Generator (RTG) would require that the science instruments be duty cycled throughout the encounter to maintain adequate power margins. The sensitivity of the RTG to power transients requires strict control of component turn-on transients; a large (33 mF) capacitor bank helps

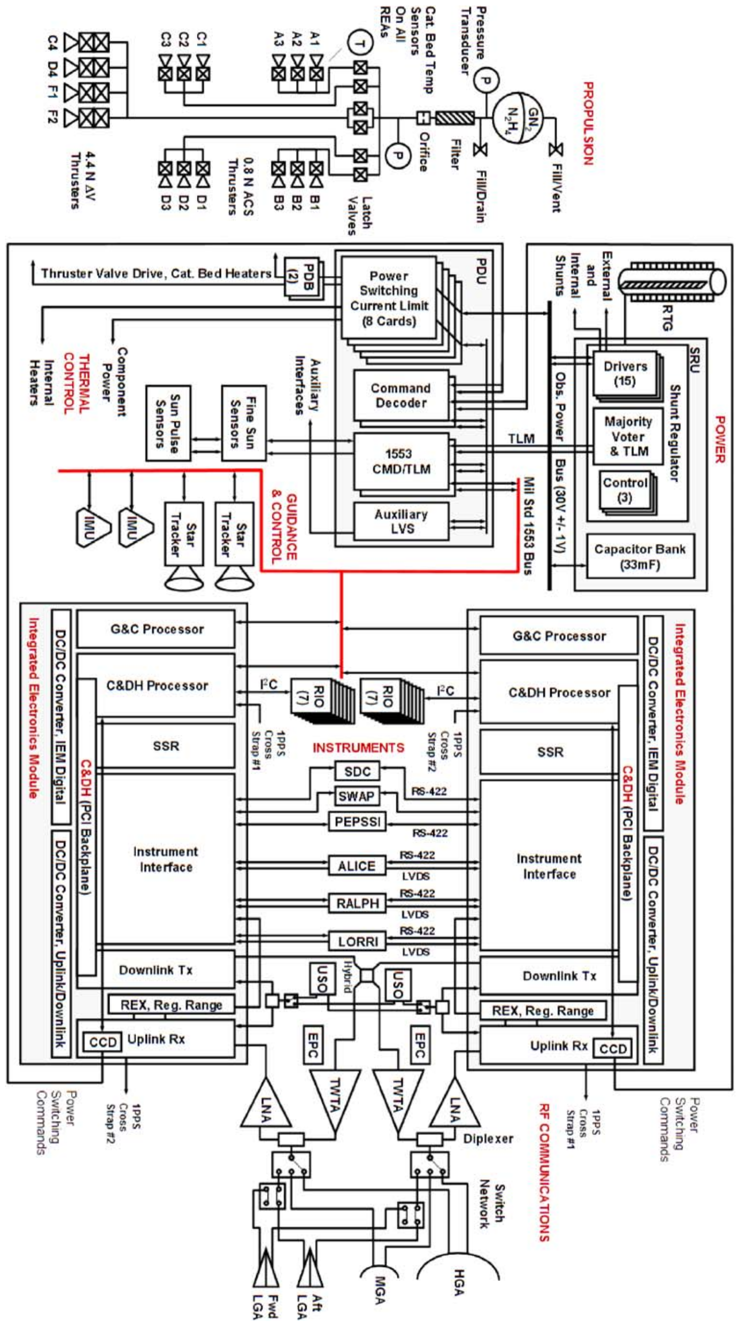

Fig. 3. New Horizons spacecraft block diagram.

source these transients, and fast-reacting solid-state circuit breakers provide further protection against RTG overloads. The spacecraft must also be able to autonomously recover from any power faults on the spacecraft bus. The spacecraft power system would not employ a battery.

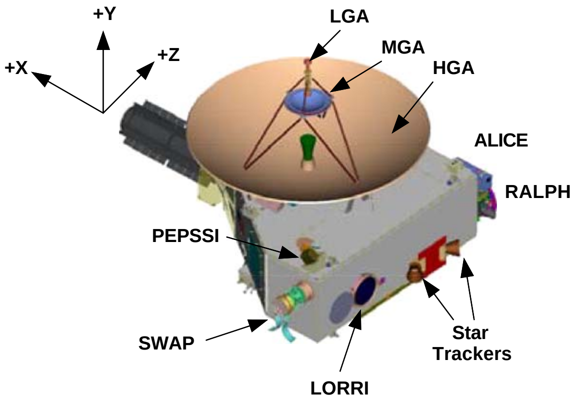

Fig. 4. New Horizons spacecraft.

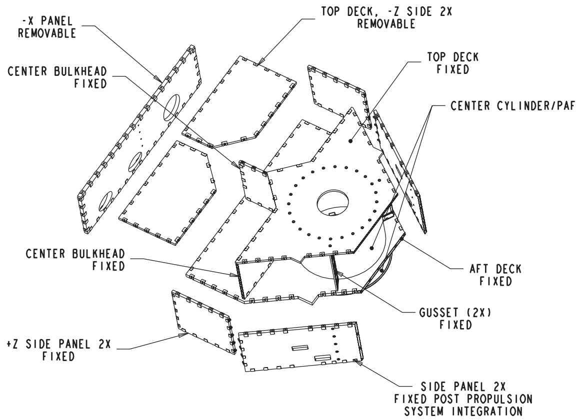

Fig. 5. Spacecraft primary structure.

For the planned mission, the high launch energy required from the launch vehicle and third stage limits available spacecraft mass to 465 kg for the 2006 launch opportunity. The even higher C_3 requirement of 166.2 km^2/s^2 for the 2007 launch opportunity limits spacecraft mass further to only 445 kg. This 20 kg reduction would be achieved by a reduction in the amount of fuel carried by the spacecraft propulsion system.

The long cruise period between Jupiter and Pluto would make use of a beacon-hibernation mode where the spacecraft is spin-stabilized with most of the avionics turned off to conserve operating life. According to mission plans, the axis of the high gain antenna is pointed towards the Earth (see Fig. 4). Spacecraft autonomy monitors the health of the spacecraft and broadcasts a "tone," rather than downlinking telemetry once per week. A "green tone" is broadcast if the spacecraft autonomy system has not detected any anomalies. A total of seven "red tones" may be broadcast if anomalies are detected, alerting ground controllers to take remedial action. This minimizes the burden on the DSN for spacecraft communications during the cruise period. New Horizons would be the first mission to make operational use of a beacon mode; Deep Space One, a NASA JPL mission implemented this feature as a technology demonstration [4,5].

6. Spacecraft overview

The New Horizons spacecraft (provided by JHU/APL) is a robust design featuring a heritage-based, highly redundant, fault-tolerant architecture allowing for a 31 kg science payload package, which requires 21 W of electrical power. The primary structure is composed of an aluminum central cylinder that supports surrounding honeycomb panels (Fig. 5). Power is baselined to be provided by an RTG of the same design as the Cassini RTGs, though with slightly different fuel characteristics. The communications system uses two low-gain antennas (LGA) for early communications and emergency uplinks to 5 AU, a medium-gain antenna (MGA) for uplink capability to 50 AU, and a high-gain antenna (HGA) to support 600 bps downlink at 36 AU. Thermal control is accomplished through use of electrical dissipation, RTG waste heat, and a "Thermos® bottle" design. The NH hydrazine monopropellant propulsion system is integrated into the spacecraft structure to make economical use of mass. The guidance and control functions are accomplished with various sensors and thruster actuators. Command and data handling is performed with two redundant Integrated Electronics Modules (IEMs) on a Mil-Std 1553 bus. The IEMs are embedded with many autonomy rules that enable them to handle anomalies without a ground contact.

The NH spacecraft is designed with a high degree of redundancy and cross strapping to deal with all credible single-point faults and some double-point faults. Some double-point faults (such as providing multiple clocks in hardware and command loss timers in both software and hardware) are addressed due to the long duration of this planned mission. All nonessential subsystems are powered off during the long cruise phase between Jupiter and Pluto/Charon, Pluto/Charon and the first KBO, and between subsequent KBOs, in order to increase reliability for the overall mission. Redundant units of essential components (command receivers, Power Distribution Unit (PDU) command decoders, Ultra-Stable Oscillators (USOs), Command & Data Handling (C&DH) processors, and PDU 1553s) can be switched off, but are automatically switched on in the event of a fault in the redundant unit or when spacecraft power is applied. At least one side of a redundant pair of essential components is always on.

As currently planned, the instruments are located on the spacecraft panels opposite the RTG, limiting radiation and thermal effects. Additionally, a thermal shield would prevent excess RTG waste heat from affecting the spacecraft thermal balance. The instruments are fixed-mounted, so coverage of Pluto–Charon is obtained by spacecraft maneuvers. Thus, deployable mechanisms are minimized, increasing overall mission reliability.

7. Structure

The spacecraft structure is designed to support the science instrument sensors, spacecraft subsystems, and electronic packages; maintain proper dimensional relationships, instrument alignments and clear fields of view (FOVs); and efficiently distribute loads associated with transportation, lifting, handling, launch, and flight operations.

The primary structure is composed of an aluminum 7075-T73 central cylinder that supports the surrounding honeycomb panels to complete the NH structure as shown in Fig. 5. The primary structure measures approximately $0.68\,\mathrm{m} \times 2.11\,\mathrm{m} \times 2.74\,\mathrm{m}$. The central cylinder serves as the payload adapter fitting (PAF), supports the RTG/SC interface, and houses the propellant tank. The panels surrounding the central cylinder have a core of aluminum honeycomb with aluminum face sheets.

In addition to the launch vehicle and instrument support stated above, the spacecraft structure also houses all the other subsystems of the spacecraft and provides the following:

- Suitable guidance and control sensor placements, with clear FOVs.
- Accessibility and flexibility for integration and test.
- Spin stabilization with correct inertia properties.
- High-gain antenna mounting support.
- Thruster mounting and operation support.
- Transportation and handling survival/stability.
- Launch survival/stability.

8. Power subsystem

The power subsystem is designed to provide the spacecraft with sufficient power throughout the mission. It provides 30 V (nominal) power to the spacecraft essential and nonessential loads. The spacecraft baselined power subsystem consists of the RTG, an internally redundant PDU with power transient management capabilities, a fault-tolerant, majority-voted Shunt Regulator Unit (SRU), and a bank of power bus capacitors. (The baseline design does not include batteries.)

To protect the power bus, the RTG and power bus are designed to be double insulated, all power-switching cards are fuse protected, and all individual switched loads have a circuit breaker function. The PDU has fully redundant power-switching and distribution electronics. The spacecraft SRU would be tied directly to the RTG, maintaining it at a regulated 29–31 V.

The RTG baselined for use on the NH mission is a General Purpose Heat Source RTG supplied by the Department of Energy (DOE) with support from Lockheed Martin. Because RTG-based power systems do not typically employ batteries, careful attention is paid to specifying maximum limits for transients due to the switching of loads, operational load transients, and fault conditions. The power bus response to these transients would be controlled by the combination of a bus capacitor bank, current limiters and electronic circuit breakers. Power consumed by the NH spacecraft would be managed so as not to exceed the steady-state output of the RTG, which will decrease over time. In vacuum, at the beginning of the mission, the RTG would supply approximately 253 (TBD) W at 30 VDC. It is expected that in July 2015, the earliest

Pluto encounter date, the RTG will supply approximately 202 (TBD) W at 30 VDC.

9. Thermal control subsystem

The electrical power limitations and the natural thermal leakage through the multi-layer insulation blankets and instrument/component apertures drive the New Horizons thermal design. The thermal design uses a “Thermos® bottle” approach, which balances the internal dissipation with the naturally occurring leaks. As designed, the spacecraft body is almost completely surrounded with thermal blankets. The design calls for utilization of some of the waste heat provided by the baselined RTG power source. Thermal louvers are included to provide additional thermal balance, if the spacecraft temperatures are too high. Power not dissipated inside the spacecraft bus would be dissipated on two external shunt plates. Each plate shares the total shunt current, and they are sized to reject the RTG maximum power while looking at the sun at 1 AU. As planned, the propulsion system components are thermally tied to the spacecraft bus and are kept warm through thermal contact with the structure. Heat leaks from the thruster modules and other penetrations through the thermal blankets are accounted for in the thermal design. Heat pipes are not used in the thermal control subsystem design.

10. RF communications subsystem

The RF communications subsystem is designed to provide the required science data return, a reliable command/telemetry link, precise radiometric tracking, and to be supported by four antennas. The radio science experiment (REX) would be integrated into the RF subsystem. The NASA Deep Space Network would transmit signals to the NH spacecraft for the radio science to achieve the required signal-to-noise ratio. The on-board RF receiver would be a new, low-power digital design, and an enabling technology for this mission.

The antennas are shown schematically in the block diagram of Fig. 3 and are depicted graphically in Fig. 4 (with the exception of the aft LGA, which is on the opposite side of the spacecraft). Switching between the four antennas is accomplished through an RF switching assembly controlled from the spacecraft Command and Data Handling (C&DH) subsystem. The entire communications system is redundant except for the antennas and the hybrid coupler in the downlink path. All antennas have Right Hand Circular (RHC) and Left Hand Circular (LHC) polarization feeds. To accommodate spin-stabilized attitude control, all antenna boresights are aligned with the spin axis ($+Y$) of the spacecraft.

Together the forward and aft LGAs (broad beam, $\pm 40°$ 3-dB beamwidth) provide spherical coverage. These LGAs are used during the early operations phase and any pre-Jupiter encounter emergency mode. The MGA (0.3 m dish, $\pm 5°$ 3-dB beamwidth) is focus-fed and can be used for commanding at 7.8 bps out to 50 AU using a pointing accuracy of $\pm 4°$. The HGA (2.1 m dish, $\pm 0.5°$ 3-dB beam width) is a dual reflector and is used in nominal mode for uplink and downlink. Uplink and downlink are accomplished by two sets of X-band (7/8 GHz) transceivers, two Ultra-Stable Oscillators (USOs), and two Traveling Wave Tube Amplifiers (TWTAs). The USOs and TWTAs are cross-strapped to the IEMs.

11. Propulsion subsystem

The New Horizons propulsion system would impart large velocity burns and fine attitude control as the spacecraft makes its way to Pluto–Charon. The 80 kg hydrazine fuel load provides 397 m/s delta-V for the 2006 launch mass of 465 kg. The use of a Jupiter gravity assist, along with the fact that NH would not enter orbit around Pluto, reduces the amount of propellant required for the mission.

As planned, the NH propulsion system is mounted directly to the structure. The system includes four monopropellant 4.4 N ΔV thrusters and 12 smaller monopropellant 0.8 N thrusters positioned around the spacecraft. The individual thrusters are mounted on the spacecraft in eight locations: four groupings (called Rocket Engine Modules) and four independent thrusters. The hydrazine would be stored in a titanium tank separated from the gaseous nitrogen pressurant by a girth-mounted diaphragm.

The propulsion system, which includes functional redundancy, would provide small minimum-impulse bit performance to achieve accurate three-axis attitude control for science imaging operations. The system would also support both three-axis and spinning ΔV maneuvers. Nitrogen would provide the pressure to ensure flow from the tank to the various thrusters.

Flow control and thruster firing are handled with in-line latch valves and thruster valves, respectively. The layout (shown in Fig. 3) is designed to improve system fault tolerance.

12. Guidance and Control subsystem

The Guidance and Control (G&C) subsystem is designed to determine and control the spacecraft's attitude. This system is responsible for de-spinning and de-tumbling the spacecraft following third-stage separation. It must provide for three-axis and spinning operational modes, and provide accurate and stable pointing for instrument observations and communications. The G&C subsystem also executes trajectory correction maneuvers, which impart translational ΔV for trajectory control.

G&C's sensor and actuator suite consists of two star trackers from Galileo Avionica; two Honeywell Inertial Measurement Units containing three gyros and three accelerometers each; two Adcole-developed sun sensors (Fine Sun Sensor and Sun Pulse Sensor); and the 16 propulsion system thrusters. There are no reaction wheels in the design; all spacecraft control is performed via thrusters. G&C would interface with the propulsion system thrusters through the PDU. G&C software resides redundantly in the two G&C (Mongoose V) Processors located in the IEMs.

The NH G&C software is designed to support three separate flight modes: passive spin, active spin, and three-axis. While in the spinning modes, the spacecraft would nominally spin at 5 rpm about the $+Y$ axis. In three-axis mode, the spacecraft would be commanded to track a celestial body at a parameterized rate or hold an inertial attitude.

13. Command and Data Handling subsystem

The functions provided by the C&DH subsystem are command management, telemetry management, time distribution, power/thermal management, and autonomy rule evaluation and execution.

On NH, resources within the IEMs would implement the C&DH functions. Of the nine cards in each IEM, the C&DH functions would be spread across five cards:

- C&DH Processor Card.
- Solid State Recorder (SSR) Card.
- Instrument Interface Card.
- Critical Command Decoder (CCD), on the Uplink Card.
- Downlink Formatter on the Downlink Card.

In addition to the cards in the IEM, the external Remote Input/Output (RIO) units would provide temperature and voltage measurements for monitoring the health and safety of the spacecraft.

Communication between cards within the C&DH section of the IEM would be over a Peripheral Component Interconnect (PCI) backplane. RIOs are designed to connect to the IEMs on an I^2C bus. A MIL-STD-1553 serial bus interface would be used between the IEMs to allow for redundancy and cross-strapping.

During normal operations, the C&DH section of one IEM would be fully powered and designated as prime. The prime C&DH processor would be the 1553 bus controller and is responsible for all spacecraft functions. The plan is to power the C&DH section of the second IEM, but in standby mode, during most operations.

During beacon-hibernation, however, the second C&DH section is planned to be powered off to increase the system reliability. If a failure in the prime IEM occurs, the second IEM is fully powered and designated as the new prime. As designed, full redundancy is provided for C&DH including data storage, RF communications, and G&C processing.

The C&DH processor distributes all non-critical commands to the addressed subsystem, collects and processes instrument data, sequences downlink telemetry, and performs advanced autonomy algorithms for operations. The C&DH processor evaluates the performance of the spacecraft by monitoring the data flow and content of the 1553 data bus. A low-power, 8-Gbyte SSR card, using Reed–Solomon error-correcting code, stores data between ground contacts. The instrument interface card provides RS-422 interfaces to six instruments, and high-speed LVDS interfaces for images and radio science data.

14. Conclusion

The New Horizons mission would complete our preliminary reconnaissance of the planets in our solar system by exploring Pluto, the farthest planet from the sun, and its moon, Charon. The New Horizons spacecraft and instrument suite is designed to fulfill the mission's scientific objectives by employing a robust architecture with considerable redundancy to ensure mission success at Pluto and beyond. Spacecraft and instrument development are on track for a January 2006 launch opportunity.

Acknowledgements

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