Exploration of Pluto:
Search for Applicable
Satellite Technology

Robert L. Staehle*, John B. Carraway, Christopher G. Salvo, Richard J. Terrile, and Stacy S. Weinstein
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109 USA

and

Elaine Hansen
Colorado Space Grant Consortium, University of Colorado, Boulder, Colorado 80309 USA

*   Contact Address:
    Jet Propulsion Laboratory, Mail Stop 601-237
    4800 Oak Grove Drive
    Pasadena, Calif., 91109, USA

Exploration of Pluto:
Search for Applicable Small Satellite Technology

Robert L. Staehle, John B. Carraway, Christopher G. Salvo,
Richard J. Terrile, and Stacy S. Weinstein
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, California 91109 USA, and

Elaine Hansen, Colorado Space Grant Consortium
University of Colorado, Boulder, Colorado 80309 USA

Abstract

Pluto is the last known planet in our Solar System awaiting spacecraft reconnaissance. In its eccentric orbit taking it 50 AU from the Sun, Pluto presently has a thin atmosphere containing methane, which is projected to "collapse" back to the icy planet's surface in about three decades, following Pluto's 1989 perihelion pass at 30 AU. Based on ground- and Earth-orbit-based observing capabilities limited by Pluto's small size and extreme distance, present top-priority scientific questions for the first mission concern Pluto and Charon's surface geology, morphology and composition, and Pluto's neutral atmosphere composition.

Budgetary realities preclude a large, many-instrument flyby spacecraft, while distance and launch energy requirements preclude any but the smallest orbiter using presently available launch vehicles and propulsion techniques. A NASA-sponsored Pluto Mission Development activity began this year at the Jet Propulsion Laboratory. The Pluto Fast Flyby (PFF) tentative mission baseline utilizes two 125-160 kg spacecraft launched in 1998-99 aboard Titan IV(SRMU)/ Centaurs or Protons on 7-10 year direct trajectories to Pluto. Instruments are likely to include a CCD imaging camera combined with an infrared spectrometer, plus an ultraviolet spectrometer. An ultra-stable oscillator is to be added to the telecommunications subsystem for radio occultation measurements.

Solid state memory stores data during the brief encounter, to be played back over several months. Cost is the primary design driver with major tradeoffs between spacecraft development, launch services, radioisotope thermoelectric generator procurement and launch approval, and mission operations. Significant benefits are apparent from incorporating "small satellite" technologies from Earth orbiters, with a primary challenge to upgrade component lifetimes consistent with mission duration.

The Pluto Team is presently identifying hardware, software and experience from the small satellite community and elsewhere which will be helpful in implementing the Pluto Fast Flyby mission within stringent cost, lifetime and performance constraints. The desired technology flight qualification date is 1994.

Overview

At 4.5 billion kilometers' distance, reaching Pluto in a relatively short time can only be achieved with a small spacecraft using a large launch vehicle and appropriate upper stages.[1] At the dawn of the space age, Pluto seemed unimaginably far away as a target for space probes. Now, as the last known planet not yet visited by a spacecraft, Pluto is the obvious target for a reconnaissance mission which could unlock many secrets about the formation of our Solar System. Within 20-30 years, the small planet's tenuous atmosphere is forecast to condense out as surface frost while Pluto recedes from the Sun in its 248 year eccentric orbit. If we are to learn what Pluto has to offer during its present visit "close" to the Sun, many techniques we have learned with small spacecraft closer to home will play a pivotal role.[2]

A NASA-sponsored mission development activity was begun in January to define and prepare for an "intermediate class" mission to Pluto, which could be launched before the end of the decade.[3] Balance must be struck between moderate cost and achieving sufficient scientific objectives to justify a mission which, by any accounting, is still costly. New approaches have been introduced for the Pluto mission development to reduce the time, staffing levels and cost associated with more complex missions whose goals necessarily reach beyond initial reconnaissance for targets already visited.

Under development is a two-spacecraft mission to carry out observations during high-speed flybys to learn about Pluto and Charon's surface geology and composition and the structure and composition of Pluto's atmosphere. In the present concept, an imaging camera, infrared imaging spectrometer, ultraviolet occultation

spectrometer and radio science experiment are to be carried aboard two 157 kg spacecraft launched using Titan or Proton boosters with upper stages. The spacecraft are to fly direct trajectories from Earth to Pluto, arriving a few months apart timed so that each spacecraft flies by the opposing faces of both Pluto and Charon. This paper reports on development status as of mid-August. Changes in the baseline are likely as the mission concept matures.

Plans are to incorporate recent technological developments which can be flight qualified by 1994 in portions of the spacecraft where significant mass and/or cost savings are possible. Instrumentation, telecommunications, command and data handling, and attitude control are areas where significant gains appear possible when compared with other interplanetary spacecraft. Members of the Pluto Team are interested in learning more about the experience and availability of components from the Earth-orbiting small satellite world. Key challenges are meeting cost goals and ensuring reliability over a mission life of approximately ten years.

Science Goals and Instrumentation Needs

Since Clyde Tombaugh's discovery of Pluto in 1930, very little has been learned about its nature. Pluto's inclined and eccentric orbit of the Sun carries it between 30 and 50 AU. Since its orbital period is 248 years, only a short portion of Pluto's year has been sampled. An excellent summary of present-day knowledge and uncertainties about Pluto is contained in the review paper by S. A. Stern,[4] from which much of what follows is drawn. Pluto is known to have a thin atmosphere and a relatively large moon, Charon, orbiting at a distance of about 20,000 km. Methane is a constituent of the surface and atmosphere but little else is known about other components. Interest in Pluto has increased since the 1989 2 encounter with Neptune's moon Triton. Triton is a near twin of Pluto in size and albedo and has revealed an extremely complex geology, active surface eruptions, polar ice caps, seasonal volatile changes and limb hazes. Only a spacecraft encounter can provide this kind of information. Pluto is now just past perihelion; as it moves away from the Sun its atmosphere is condensing. It is essential that Pluto be explored before the 2020s when its atmosphere will be frozen onto its surface for the next two centuries.

Key questions about Pluto and Charon concern the origin of this "dual-planet" system and its relationship to the rest of the Solar System. While reasonable theoretical limits have been proposed, it is impossible to resolve the mass and density of either body separately— only the aggregate is known. The radii of the two bodies are reasonably well estimated based on the mutual occultation events measured during the 1980s. From the combined system mass we can infer that Pluto has a substantial rocky component. A very tenuous atmosphere containing methane has been detected around Pluto using a stellar occultation, while water ice is indicated on Charon and methane ice on Pluto. At surface temperatures of perhaps 40K, methane ice relaxes over geologic time scales for larger topographic features, while water ice behaves more like terrestrial rock. Thus, there is "the speculative but interesting possibility that Pluto's surface may harbor only the record of more recent impacts, while Charon's harbors a long-term integrated flux."[4]

Ground-based measurements have shown that Pluto's surface reflectance varies, with some longitudinal variations and asymmetrical polar caps.[5] Charon is also thought to have at least subtle surface markings. With at least a transient atmosphere, there is a mechanism on Pluto for material transport, such as by frost sublimation. On both bodies, radiation effects may cause surface chemistry changes resulting in color and brightness variations beyond what would be caused by impacts alone. No doubt there is much to learn, just as with every other first planetary encounter!

The science goals and measurement objectives for a first reconnaissance mission to Pluto were formulated and prioritized by NASA's Outer Planet Science Working Group (OPSWG), as noted in Table 1. The three category "1a" science objectives were identified as the highest priority required for this first mission, with the "1b" and "1c" category objectives considered desirable but non-essential.

Table 1. Pluto Core Measurement Objectives (no ranking intended within categories).

Neutral Atmosphere	1a
Geology & Morphology	1a
Surface Composition Mapping	1a
Ionosphere	1b
Bolometric Bond Albedo	1b
Surface Temperature Mapping	1b
Energetic Particles	1c
Bulk Parameters (R, M, ρ)	1c
Magnetic Field	1c
Additional Satellites	1c

Within a science allocation of 7 kg and 6 W, a set of four "strawman" instruments is proposed to provide comparable or better scientific coverage of Pluto and Charon than was provided by *Voyager* at Triton. A combined visible imaging/infrared imaging spectrometer

can begin taking data a few weeks before closest approach with better resolution than Hubble Space Telescope. Within 100,000 km, reached ~1.7 hr before closest approach, imaging pixel size is 1 km or smaller on the surface at the sub-spacecraft point and monochromatic global mapping can take place, to be combined with color images taken at slightly lower resolution. While visible imaging pictures are being taken, infrared spectra of larger resolution elements can be acquired to infer the composition of surface ices, some organics, or other materials which may be exposed.

Because the approach is from almost precisely the direction of the Sun, views of the terminator and at middle phase angles are possible for only a few minutes around closest approach, necessitating a fairly rapid, 2.5 second readout rate of the camera CCD detector. With all instruments fixed to the body of the 3-axis stabilized spacecraft, rapid reorientations of the spacecraft are required, with short settling times. In the dim light at 31 AU, the camera optics are sized to provide adequate exposures of about 1 sec.

Shortly after closest approach, the encounter will be targeted to fly through Pluto's shadow. Entering the shadow, the ultraviolet occultation spectrometer will observe the atmosphere in the direction of the Sun to map the spectral signature of N_2, CO, CO_2, Ar, or other gasses difficult to detect from Earth. Such buffer gasses could make up the bulk of Pluto's atmosphere. Exiting Pluto's radio shadow as seen from Earth, an ultrastable oscillator in the transponder is to be used to measure the phase shift in a strong radio signal from Earth to infer the temperature and pressure profile of the atmosphere from the surface up to the ionosphere.

All data within a few days of the encounter will be stored in a solid state memory for playback to Earth over subsequent months. While data rates of 25-40 b/s seem low by today's standards, the Mariner 4 mission to Mars beamed back its revolutionary images at 8¼ b/s.

While there are encouraging results from other space missions, getting the integrated science payload within the 7 kg/6 W mass and power budget with funding very tight is a principle challenge for the mission development.

Trajectory and Launch Vehicle

<u>General Discussion</u>

<u>Trajectory</u>

A wide range of trajectory types are available to launch a Pluto flyby mission in the 1995-2005 time frame (see Figure 1). Most of these opportunities involve

Jupiter gravity-assists. While Jupiter (and other planetary) gravity assists can significantly lower the launch energy required, thus increasing the payload mass, the first beneficial launch to Jupiter does not occur until 2004.[6] If maximizing performance were the primary design parameter of this mission, it would be very tempting to wait until 2004 to launch and possibly achieve flight times of 6-8 years with a larger spacecraft. However, since minimization and control of cost is the main mission design parameter, the key is to launch as early as possible with as simple a trajectory as possible in order to freeze technology early and reduce design requirements. Also, Jupiter flybys with low trip times require significant radiation exposure at Jupiter, increasing cost and mass while lowering reliability. Of course, the scientists and engineers also want the fastest flight time possible (certainly under ten years), and it is one of the mission's programmatic goals to return the science data as soon as possible.
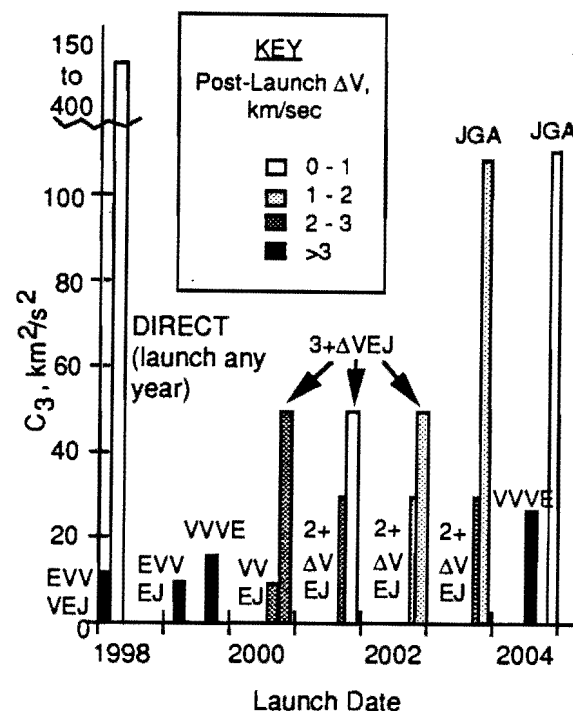

Figure 1. Pluto Flyby: Trajectory Types

Thus, an ideal trajectory is one which goes directly to Pluto without gravity assists.[7] A direct trajectory has a launch opportunity once per year, so there are automatic backups in case of a launch slip. Since another programmatic goal is to image both sides of Pluto, meaning two spacecraft are needed,[8] direct trajectories offer the possibility of launching in consecutive years with a near-negligible difference in flight time.

3

The disadvantage of direct trajectories is the high launch energy. For instance, a seven-year flight time to Pluto requires a launch energy (or C_3) of 305 km²/sec² (see Figure 2), or the equivalent of 12.9 km/sec out of low Earth orbit! This launch energy is significantly higher than that of any mission launched before. No existing launch vehicle is capable of supplying that kind of energy on its own, much less with any payload capability. Therefore, solid rocket motors are added as kickstages to the launch vehicle in order to provide more ΔV. However, this approach only works as long as the spacecraft wet mass is low (<200-300 kg); otherwise, the flight times become very long (see Figure 3).
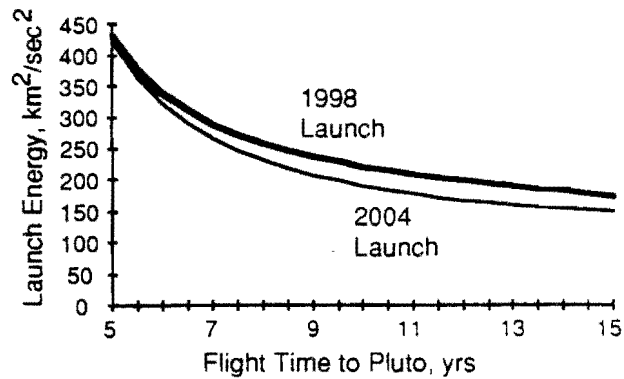

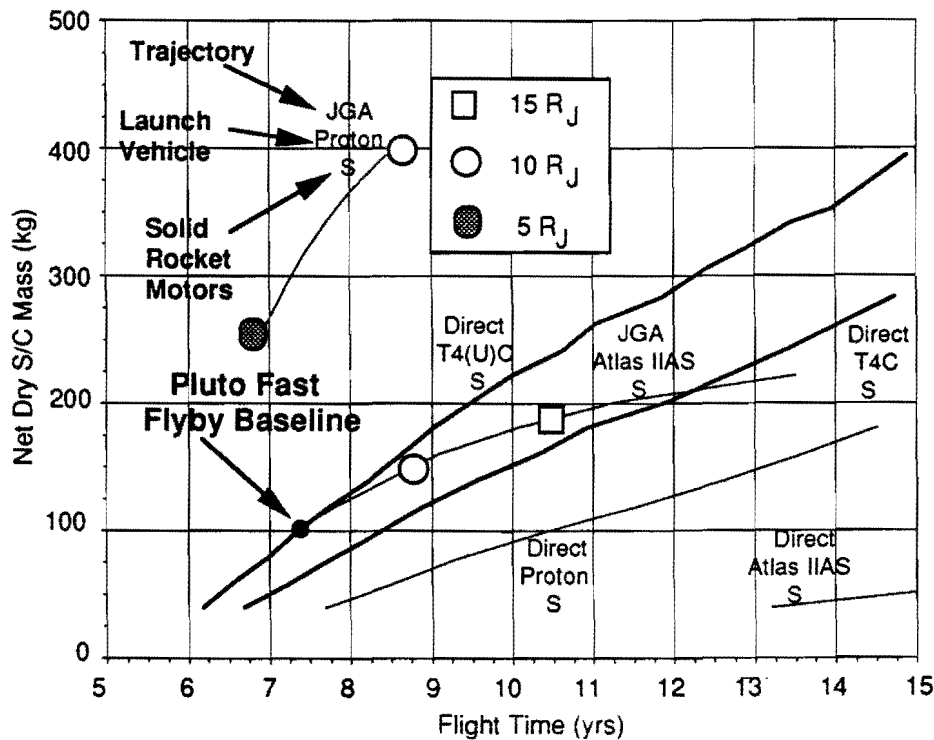Figure 2. Launch Energy vs. Flight Time for Direct Trajectories to Pluto

Figure 3. Pluto Fast Flyby Trade-space: Net spacecraft mass vs. flight time. Note: (Net dry spacecraft mass) = (dry spacecraft mass) minus (propellant tankage).

Launch Vehicle

In order to obtain the fastest flight time possible, it is necessary to use the most powerful combination of upper stages possible. Unfortunately, there are a finite number of solid rocket motors and launch vehicle upper stages available, making optimization difficult since design and qualification of the optimal upper stage "stack" cannot be achieved in a cost- and schedule-constrained environment. However, there are some very capable propulsion "stack" combinations. Using the Centaur as the first upper stage and the Thiokol Star 48B and Star 27 motors as the second and third stages proves to be an extremely powerful combination.

While the Atlas IIAS and the Titan IV launch vehicles are both designed to accommodate Centaurs, the Atlas IIAS is not capable of handling this particular staging combination. Using lighter solid rocket motors is an option which is very costly in flight time. 0Therefore, the Titan appears to be the best launch vehicle for the performance trade. However, the main design driver is cost. The Titan IV/Centaur is currently estimated to cost 2-4 times the price of an Atlas IIAS.

4

While launch vehicle costs are not included in the JPL cost to NASA's Solar System Exploration Division, NASA still has to pay for the vehicles, so it is desirable to keep the price of the launch vehicle down.

Recent events in the former Soviet Union have made the idea of using the Proton an option. Initial studies performed at NASA's Lewis Research Center indicate that the combination of the three-stage Proton, the Atlas version of the Centaur, plus the Thiokol Star 48B and Star 27 may perform better than the Titan IV/Centaur with the same kickstages. The difference is that the Proton is currently considerably cheaper than even the Atlas IIAS; Proton recently submitted a bid of $35M for an Inmarsat launch. Of course, integrating the Centaur onto a foreign vehicle which is integrated horizontally is no trivial matter, and there still is a lot to learn about the Proton, but it looks like it could be a beneficial trade of cost and performance.

Mission Description

With an aggressive design/test schedule and proper funding levels, the earliest launch date is February 1998. The spacecraft includes 350 m/sec of onboard hydrazine propellant to perform clean-up maneuvers from the solid rocket motors as well as trajectory corrections and re-targeting. Flight time is then around 7.5-8.2 years on a direct trajectory (see Figure 4) depending on the launch period duration. At encounter, using the 7.5-year flight time, Pluto is 30.9 AU from the Sun and 30.2 AU from the Earth. The encounter sequence will be designed to achieve Earth and Sun occultations of both Pluto and Charon. As shown in Figure 5, the spacecraft will move quickly through the system with a velocity of around 16.5 km/sec relative to Pluto.
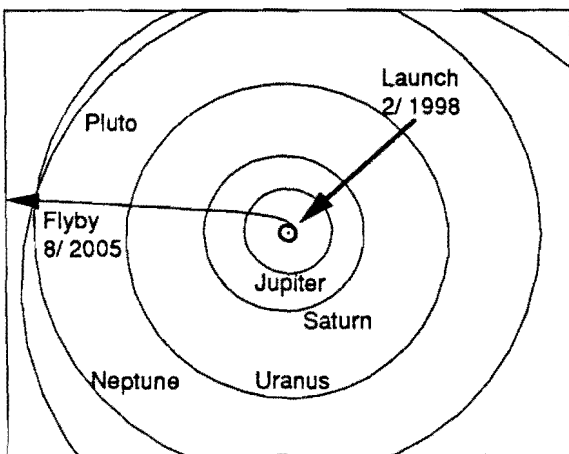

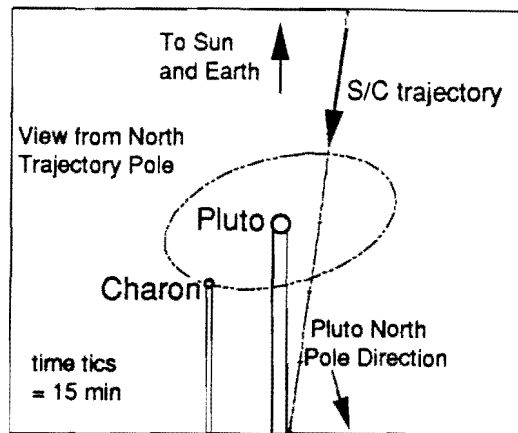Figure 4. Pluto Fast Flyby Direct Trajectory

Figure 5. Pluto/Charon Flyby

Conceptual Flight System

The flight system consists of the spacecraft, the solid kickstages, and all structural adapters above the separation plane of the Titan IV/Centaur (or Proton). Included with the Star 48B kickstage is a chemical rocket spin-up system similar to that used on PAM-S. The Star 27 has attached to it a nutation control system similar to that used on PAM-D, yo-yo's for despinning the empty Star 27 case and the spacecraft, and a sequencer to initiate stage ignitions, separations, spin/despin, etc. The spacecraft has been conceived as a high reliability, fault tolerant system. A large amount of component internal fault tolerance has been used to achieve high reliability. Block redundancy is used where internal redundancy was inappropriate.

The Pluto Fast Flyby (PFF) spacecraft is three-axis stabilized utilizing cold gas attitude control. It is powered by a small radioisotope thermoelectric generator (RTG) augmented with capacitors for short peak loads. Telecommunications are X-band uplink and downlink with a maximum downlink rate of about 40 b/s at encounter range to a 34 m DSN station. The Command and Data Subsystem has a central computer for all commanding, sequencing, and computations and can store 400 Mbits of science data. A blowdown monopropellant hydrazine propulsion subsystem is included to perform maneuvers. Attitude control uses nitrogen pressurant from the monopropellant tank.

Figures 6 and 7 show isometric views of the Pluto spacecraft. The high gain antenna (HGA) shown is about 1.5 m in diameter. Overall spacecraft dimensions are ~1.6 m maximum width and ~1.2 m height. The bus has a 0.5 m maximum diam-eter. Dry spacecraft mass is 131.1 kg including 26.5 kg contingency for mass growth during detailed design. The spacecraft is loaded

with 25.9 kg of monopropellant hydrazine to perform 400 m/s delta-V, resulting in a total wet spacecraft mass of 157 kg. Additional mass margin exists in the form of increased flight time with increased system mass. Table 2 presents a subsystem mass summary for the spacecraft.
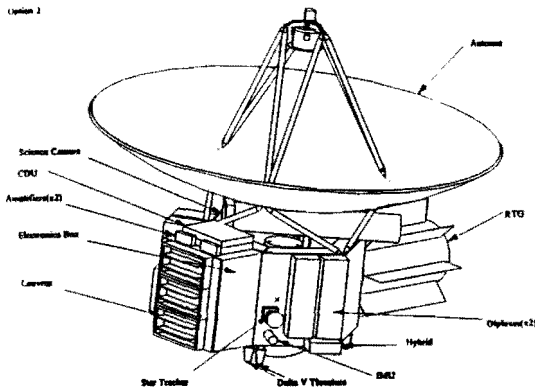

Figure 6. Spacecraft Cruise/Encounter Configuration (+Z Isometric View)
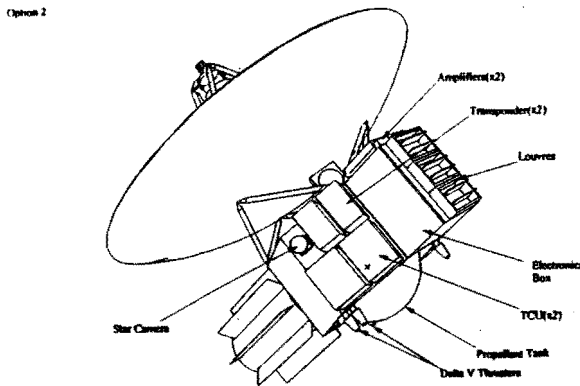

Figure 7. Spacecraft Cruixe/Encounter Configuration (-Z Isometric View)

Table 2. Subsystem Mass Summary

Telecommunications	25.8
Electrical Power	23.2
Attitude Control	1.3
Command and Data Handling	7.0
Structure	20.0
Propulsion	17.1
Thermal Control	3.2
Science Instruments	7.0
Total Mass (kg)	104.6
Contingency (25%)	26.5
Monopropellant (400 m/s)	25.9
Total Wet Spacecraft (kg)	157.0

Power output from the RTG is 65 Watts at encounter and 63.8 Watts the end of the mission ~10 years after launch. Power consumption of 60.8 Watts during the encounter mode includes 30% contingency and is summarized in Table 3. Losses for voltage conversion and regulation are included in the Electrical Power Subsystem. The current best estimate for power consumption during downlinking post-encounter is 49.3 Watts leaving a 29.5% contingency and margin for the RTG power of 63.8 Watts.

Table 3. Subsystem Power Summary

Telecommunications	15.0 Watts
Electrical Power	11.0
Attitude Control	6.2
Command and Data Handling	6.0
Structure	0.0
Propulsion	1.5
Thermal Control	1.0
Science Instruments	6.0
Total Power	46.8 Watts
Contingency (30.0%)	14.0 Watts
Total Power	60.8 Watts

The flight system has been designed to execute the following mission scenario. The Centaur spins the flight system up to ~10 rpm prior to separation. Additional spin-up to ~60 rpm, kickstage burns and separations, nutation control, and yo-yo spin-down are sequenced by the propulsion stack sequencer on the Star 27. After release from the Star 27, the spacecraft acquires an inertial star reference, turns the HGA to Earth point and establishes communications. After performing an injection error correction maneuver, the spacecraft cruises with the HGA Earth-pointed and uses one 8-hour DSN pass per week. At distant encounter optical navigation images are taken by the science camera and returned to the ground for processing. Near encounter science is stored in solid-state memory for post-encounter playback at 25-40 b/s. During post-encounter cruise the spacecraft uses one 8 hour DSN pass per day to downlink 400 Mbits of science data in less than 6 months.

Many features of this conceptual design contribute to lower cost. The overall spacecraft concept has been kept simple. There are no articulations or deployments. A cold gas thruster attitude control scheme was chosen over the complexity of reaction wheels or stable platforms/secondary mirrors. The spacecraft also uses components that will be qualified by 1994 (with some exceptions). The RTG is derived from a standard General Purpose Heat Source (GPHS) device, the

propulsion subsystem is entirely off-the-shelf, and the HGA could be residual *Viking* hardware. Also contributing to lower cost is the minimal performance of the spacecraft. The low data rate, modest data storage, ΔV, and minimal power level are all the result of an effort to hold capabilities to the level required to meet top priority science objectives.

The Telecommunications Subsystem is an X-band uplink and downlink system. It uses a *Viking* residual 1.47 m high gain antenna as its only antenna. A safe mode in the Attitude Control Subsystem commands Earth pointing of the HGA in the event of an attitude anomaly. The components are largely of *Cassini* inheritance with the exception of the Solid State Power Amplifier (SSPA) and the Telemetry Control Unit (TCU). The SSPA is based on commercially available parts in a new component design. The TCU is a reduced function device using *Cassini* pieces repackaged in a smaller form. Both of these components are relatively low risk developments. All components are block redundant and cross-strapped.

The Electrical Power Subsystem is based on a 5 brick RTG derived from the standard GPHS. It generates 65 Watts at encounter and 63.8 Watts 10 years after launch, at 14 volts. Power is upconverted to 28 volts and distributed on two busses at 14 and 28 volts. A discharge controller using capacitor banks is used to accommodate short duration spike loads (ACS thruster pulses, switch transients, etc.). All other power demands are met by the RTG. Excess RTG power is shunted to a radiator. Power electronics are internally redundant.

The Attitude Control Subsystem uses a wide field of view miniature star camera for its inertial sensor. Star matching is done using the processor in the Command and Data Subsystem. Three solid state rate sensors are used to maintain attitude reference between star updates. Control is via cold gas thruster couples about all three spacecraft axes. Pointing knowledge is 1.5 mrad, and stability is 10 microrad over one second. Fast slews of 90 degrees require 2.7 minutes, zero rate to zero rate, plus settling time. The star camera and the rate sensors are block redundant.

The Command and Data Subsystem (CDS) uses a 1.5 Mips single-board computer with rad hard parts (25 krad). The particular processor has not been chosen. Candidates include the IBM RAD6000, and 1750A computers from various vendors. VLSI (Very Large Scale Integration) ASIC (Application Specific Integrated Circuit) and surface mount packaging technology are used for reduced mass, and power strobing is used to minimize power. Input/output is via direct lines, serial

interfaces, and a high rate science interface (5 Mb/s). The 400+ Mb solid state memory uses high density packaging and includes an error detection and correction capability. A data compression chip may be used to loosely compress the science data before storing it in memory. Other data compression schemes are also being evaluated. The CDS is internally redundant with all of the boards block redundant.

The main structure of the spacecraft is an aluminum hexagonal bus. The propellant tank is held within this structure by three brackets to its equatorial plane. Truss structures are used for the adapter to the injection stages and to mount the antenna to the bus. There are no articulated or deployed mechanisms.

The Propulsion Subsystem is a blowdown monopropellant system using only off-the-shelf components. The tank has a maximum capacity of ~23 kg of propellant. The remaining volume contains nitrogen pressurant which is regulated down to 5 psi for use in a cold gas reaction control system. The large tank size ensures that the pressure load is sufficient to maintain acceptable monopropellant feed pressure as monopropellant and cold gas are expended.

The Thermal Control Subsystem utilizes the excess heat from the RTG to keep the propellant tank and the bus of the spacecraft warm. RHU's (Radioisotope Heater Units) are also used to heat the thrusters. The high gain antenna and the RTG shadow the bus from the Sun in nominal Earth-point attitude removing the need for a low-gain antenna. Multi-layer insulation (MLI), small heaters, and louvers regulate component temperatures during power fluctuations.

There are some areas where mass reductions may be possible. Some reductions would be the result of trading capabilities (bit rate for amplifier power or antenna mass) and may or may not affect cost. Further reductions could be made through the aggressive use of microspacecraft technology (advanced electronics packaging, composite propellant tanks), but this would certainly increase cost. More design trades are currently being conducted to reduce mass and increase design maturity.

Mission Operations and Tracking

Personnel at JPL and the University of Colorado (CU) at Boulder have developed a cooperative concept for low cost mission operations. The present plan is that JPL will provide Deep Space Network (DSN) tracking and navigation and CU will develop a single, simple mission operations data system that will have versions located in operations nodes at both Boulder

and JPL. Routine operations are planned to be done out of Boulder with planned JPL support for critical events and as required for spacecraft anomaly analysis.

Operations at CU will have an educational dimension. Students, supervised by experienced professionals, will staff many of the operational positions. Science and engineering data will be accessible to schools. The operations nodes at both JPL and CU will be set up to allow student participation and visibility. This distributed operations system will exploit international standards for the interfaces between nodes and therefore will offer the opportunity for cooperation with other institutions, nations, and schools. Lessons learned at CU operating Solar Mesosphere Explorer (SME)[9] will be applied toward achieving educational, low cost, and efficient operations for the Pluto mission.

Mission and spacecraft design features are key to enabling small team operations and a relatively simple ground data system. Pluto Mission Development management is strongly committed to engineering participation by the mission operations team in the spacecraft, instrument, and mission design process. Current design features that are important to enabling low cost operations include:

- a spacecraft design that permits long periods of unattended operations during cruise. This enables routine cruise operations to be built around a single weekly DSN tracking and data collection pass;

- a spacecraft engineering data return strategy that exploits on-board data processing and analysis to minimize the amount of engineering data that must be downlinked and analyzed;

- spacecraft command and control capabilities that allow cruise commands to be uplinked without elaborate simulation and constraint checking;

- an encounter/flyby command sequence that is pre-planned and tested during cruise and is only "tweaked" immediately before closest approach to allow for mosaic retargeting and arrival time uncertainties;

- a large on-board memory that permits capture and storage of all the science data collected during flyby and allows its subsequent return over a limited downlink (25-40 bps) via routine daily DSN passes for up to a year following encounter;

- a progressive development philosophy where the basic mission operations system is devel-oped at the start of the project; used to support prelaunch development, subsystems test, space-craft test, calibration, and post-launch operations; and progressively enhanced to meet the needs of these project phases and users; and

- a unified operations system architecture that facilitates the migration of functions from the ground to space and enables trades between flight- and ground-based functions by including both flight and ground data systems in one mission operations system.

The challenges in building a mission operations system that is both low in cost and able to support the ~10 year Pluto mission are many. These challenges include the selection of appropriate standards; development of a system that can continue to evolve through the long mission; data compression technologies; and techniques to enable unattended spacecraft operations. We are confident that these challenges can and will be met through the ingenuity of NASA, industry, and academia.

Conclusion

Having only begun in January, and existing in a tenuous budgetary environment for planetary exploration, the Pluto Fast Flyby mission will no doubt change to some degree during its development. NASA sponsors of the present mission development activity have been very encouraging of a rapid development schedule, focus on the highest priority objectives, and the absolute necessity of containing costs. Work to date indicates that there is a scientifically valuable mission possible within "intermediate" cost limitations.

A "hardware rich" development environment is planned where key subsystems are to be breadboarded beginning in FY93, followed by brassboard development leading to a system-level brassboard of most of the spacecraft (RTGs and loaded propulsion equipment excluded). The present plan is for a prototype to be built and subjected to thorough qualification testing, then refurbished to serve as a flyable spare. Two flight spacecraft will be built, virtually identical to the prototype, and environmentally tested at the system level to verify integrity.

Considerable use of small spacecraft technology and components is necessary to meet cost and mass goals, which in turn govern the mission's programmatic viability and flight time. Reliability requirements are

8

higher than for typical Earth orbiters, though the thermal and radiation environment is in many ways more benign on the way to Pluto. Information is solicited from vendors and institutions having relevant hardware and mission experience, so that the most appropriate components, subsystems and procedures are made available for flight system and instrument development.[10]

Acknowledgements

The authors wish to thank the many members of the Pluto Team and their institutions, including NASA, the Jet Propulsion Laboratory, California Institute of Technology, University of Colorado, Southwest Research Institute, University of California at Los Angeles, Occidental College, and Science Applications International Corporation.

Work described here was carried out at the California Institute of Technology's Jet Propulsion Laboratory under contract to the National Aeronautics and Space Administration, sponsored by the Solar System Exploration Division.

References

1. Nuclear electric propulsion may be able to provide short trip times, as well, but is not a presently available technology.

2. Ross M. Jones, "Small Spacecraft Activities at JPL," Utah State University Conference on Small Satellites, Logan, Utah, August 26, 1991.

3. Robert L. Staehle, Douglas S. Abraham, John B. Carraway, Paul J. Esposito, Elaine Hansen, Christopher G. Salvo, Richard J. Terrile, Richard A. Wallace and Stacy S. Weinstein, "Exploration of Pluto," 43rd Congress of the International Astronautical Federation, Washington, DC 1992 September 4. (Portions of this reference are reproduced in the present paper.)

4. S. A. Stern, "The Pluto-Charon system," in G. Burbidge, D. Layzer and J.G. Phillips, eds., *The Annual Review of Astronomy and Astrophysics (1992)*, Annual Reviews, Inc., Palo Alto, CA, 1992, in press.

5. E. F. Young and R. P. Binzell, "Comparative Mapping of Pluto's Sub-Charon Hemisphere: Three Least-squares Models Based on Mutual Event Light Curves," AGU/Montreal, and *Icarus*, 1992, in preparation.

6. While it is possible to "tack-on" combinations of Earth and Venus gravity assists in order to launch early, further minimize launch energy, and still hook in with the Jupiter gravity assist opportunity, the post-launch ΔV (which translates into the amount of propellant carried on board the spacecraft) generally increases along with the interplanetary flight time, thus driving key requirements such as lifetime, propulsion, attitude control, and thermal control.

7. S. S. Weinstein, "Pluto Flyby Mission Design Concepts for Very Small and Moderate Spacecraft," AIAA Paper 92-4372, AIAA/AAS Astrodynamics Meeting, Hilton Head, S.C., August 10-12 1992.

8. Other schemes are possible with larger spacecraft: using a much larger telescope to get 1 km surface resolution one-half rotation period before closest approach is one method, while using a smaller daughter spacecraft is another.

9. Elaine Hansen, "Lowering the Costs of Satellite Operations: Lessons Learned from the Solar Mesosphere Explorer (SME) Mission," Paper AIAA-88-0549, AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1988.

10. Contacts: Spacecraft Subsystems—Chris Salvo, 818/354-1772, Science Instruments—Richard Terrile, 818/354-6158, Programmatic—Robert Staehle, 818/354-1176.