

Pluto Fast Flyby: An Overview of the Mission and Spacecraft Design, Advanced Technology insertion Efforts, and Student Involvement Opportunities

by

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Abstract

In an effort to complete the initial reconnaissance of our solar system, the Jet Propulsion Laboratory (JPL) is designing a mission to send two very small spacecraft to explore Pluto and its moon, Charon. The two probes will each carry four science instruments designed to obtain information on both hemispheres of Pluto and Charon in the form of visual images, infrared and ultraviolet data, and radio science. Using this data, scientists will be able to characterize Pluto and Charon's global geology and geomorphology, perform surface composition mapping, and define the structure and composition of Pluto's neutral atmosphere -- feats not possible with the Hubble Space Telescope (even with the latest repairs). This paper provides a brief overview of the mission and spacecraft design, advanced technology insertion efforts, and student involvement needed to make these feats a reality. The cost-driven mission and spacecraft design focus on delivering two 120 kg spacecraft to the Pluto-Charon system for a development cost of under FY92\$400 million.

Time is also of the essence because Pluto's atmosphere is expected to condense and freeze out sometime after 2010 as Pluto moves toward the farthest reaches of its orbit. For this reason, a direct trajectory has been baselined that should enable arrival at Pluto in only 7 to 9 years from launch. A variety of advanced technology insertion efforts have been undertaken to reduce spacecraft mass and power requirements so as to facilitate the above cost and schedule goals. Results are reported for candidate scientific payload instruments, a composite structure, advanced antenna, significantly smaller electronics packaging, high efficiency thermal-to-electric converters, and other candidate areas. Students from more than 10 universities have played a key role in some of these advanced technology insertion efforts as well as in flight hardware mockup and prototyping activities. Plans to make spacecraft flight engineering data and compressed science data accessible by schools across the country render prospects for student participation in these areas bright as well.

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An Overview of the Mission and Spacecraft Design

Pluto is the least understood planet in the solar system. Discovered in 1930 by U.S. astronomer Clyde Tombaugh, Pluto's small size and vast distance from the Earth have impeded efforts to obtain clear telescopic images of the planet, even with the world's most powerful astronomical instruments. Pluto is the only known planet in the solar system not yet explored by spacecraft. With this absence of exploration in mind, artist Ron Miller created a postage stamp of Pluto for the U.S. Postal Service with the taunting caption, "PLUTO - NOT YET EXPLORED." This caption helped goad a small team of scientists and engineers at JPL into planning a dual Pluto flyby with very small spacecraft. Meanwhile, the Outer Planets Science Working Group (OPSWG), a charter group of leading planetary scientists, looked at small and large missions to Pluto and reported their findings to the National Aeronautics and Space Administration (NASA) in May, 1991. In subsequent meetings with NASA, OPSWG formally endorsed the JPL team's very small spacecraft mission.

The Mission Design [1, 2, 3]

With a diameter of about 2300 km (about the north-south span of the United States), Pluto is the smallest known planet in the solar system and is orbited by one large moon, Charon. Since it takes 248 Earth years for Pluto to travel once around the Sun, observers on Earth have seen only a fraction of the range of seasonal changes that occur over the course of a full Pluto year. However, the elliptical and tilted nature of Pluto's orbit has been found to bring about dramatic atmospheric change to the planet. Astronomers have observed that unlike any other planet, Pluto has an atmosphere for only part of the Pluto year. When closest to the Sun, surface frosts of methane, nitrogen and other ices on Pluto's rocky surface warm to a vapor state, creating a tenuous atmosphere. Later, as the planet moves farther away from the Sun, the atmospheric constituents condense and freeze back on the surface as icy frosts.

The Pluto Mission has been conceived to deliver two spacecraft to the Pluto system during the period in which the fullest range of atmospheric phenomena can be observed. Pluto has just passed perihelion (i.e., when it is closest to the Sun), an event that will not occur again until 2237. Since a large portion of the mission's scientific experiments require an atmosphere on Pluto, it is critical that the spacecraft reach Pluto

before atmospheric "collapse" begins. Scientists project that this collapse will begin sometime between 2010 and 2020. After atmospheric "collapse", the bulk of the atmosphere will have reverted to a frozen state of condensed frosts on Pluto's surface, thus impacting observations. In addition to the time-criticality for observations of Pluto's temporary atmosphere, there is a similar deadline for observations of the surfaces of Pluto and Charon. The spacecraft must arrive at Pluto before a significant portion of the planet has moved into semi-permanent seasonal shadow (Figure 1). This is critical since areas in shadow cannot be imaged or compositionally mapped. The shadowing begins around 2010-2020, which is the same time projected for atmospheric "collapse". After these two phenomena begin, the opportunities to study Pluto's atmosphere and globally map Pluto and Charon will be lost.

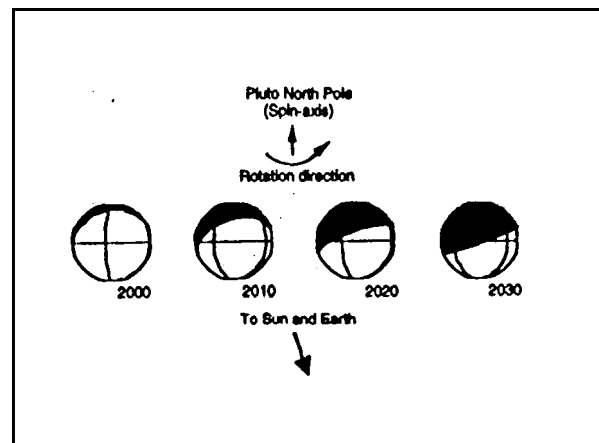


Figure 1. Pluto's Progression Into Semi-permanent, Seasonal Shadow

While there are many trajectory types and launch opportunities available for a Pluto/Charon flyby mission, the direct trajectory is preferable since it enables arrival at Pluto in the shortest period of time [4]. This minimal flight time not only provides for arrival at Pluto prior to the onset of atmospheric "collapse" and semi-permanent seasonal shadow, but also reduces mission operations costs. With this mind, JPL's mission plan calls for the launch of two spacecraft on a direct trajectory that will take them to within roughly 15,000 km of Pluto and Charon in 7 to 9 years (Figure 2).

Enabling a direct trajectory and associated flight time of 7 to 9 years necessitates huge launch energies. Only a few launch vehicles are capable of providing such energies and only if their upper stages are

supplemented with “kick” motors. Launch vehicles currently under consideration, include: the Space Shuttle, the Titan IV/Centaur, or the Russian Proton (in the event of a possible U.S.-Russian collaboration to explore Pluto). Two launches would be involved, one for each spacecraft.

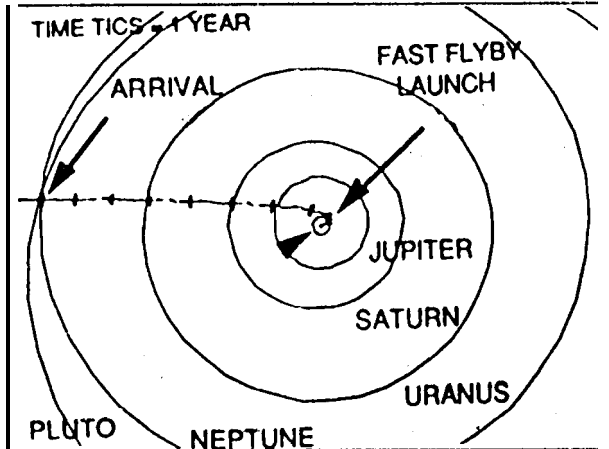


Figure 2. Pluto Fast Flyby Trajectory

Two spacecraft allow exploration of both sides of Pluto. Due to Pluto's orientation in the 2000 to 2020 time frame, its 6.4-day rotation period, its small size, and the spacecraft's encounter speed, high-resolution imaging will only be possible for part of the South polar region and a fraction of the North polar region. Therefore, a minimum of two spacecraft will be needed, one for each side of Pluto.

As the spacecraft flyby Pluto and Charon, they must accomplish a definite set of science objectives. The OPSWG developed science goals for the mission that fall into a couple of classes: the “must do” objectives (Category 1a) and the “if possible” objectives (Categories 1b and 1c). As shown in Table 1, the “must do” objectives include characterizing Pluto and Charon's global geology and morphology, surface composition mapping, and the characterization of Pluto's neutral atmosphere. The 1b and 1c objectives shown in Table 1 will only be attempted if they fit within project constraints and can be satisfied using the instruments carried to satisfy the 1a objectives. The “strawman” instrument payload currently under consideration consists of a visible imaging system, an infrared mapping spectrometer, and an ultraviolet spectrometer. The visible imaging system will meet the geology and geomorphology objectives by providing the capability to image at less than one kilometer resolution while the spacecraft arc within 100,000 km of the planet. The infrared mapping

spectrometer will allow detection and characterization of surface composition features such as condensed frosts. And, the ultraviolet spectrometer will allow measurement of Pluto's atmospheric composition by detecting spectral features during a solar occultation and by studying Pluto's airflow. An uplink radio science experiment will provide complementary data to the ultraviolet spectrometer, completing measurement of the temperature and pressure profile to Pluto's surface. The above instruments are only used as surrogates during preliminary design; actual flight instruments are to be selected by NASA through a formal announcement of opportunity.

PLUTO FAST FLYBY CORE SCIENCE OBJECTIVES

Category 1a

- Characterize Global Geology and Morphology
- Surface Composition Mapping
- Characterization of Neutral Atmosphere Structure and Composition

Category 1b

- Surface and Atmosphere Time Variability
- Stereo Imaging
- High Resolution Terminator Mapping
- Selected High Resolution Surface Composition Mapping
- Characterization of Pluto's Ionosphere and Solar Wind Interaction
- Search for Neutral Species Including: H, H₂, HCN, C_xH_y
- Hydrocarbons and Nitriles in Pluto's Upper Atmosphere
- Obtain Isotope Discrimination Where Possible
- Search for Charon's Atmosphere
- Determination of Bolometric and Albedos
- Surface Temperature Mapping

Category 1c

- Characterization of the Energetic Particle Environment
- Refinement of Bulk Parameters (Radii, Masses, Densities)
- Magnetic Field Search
- Additional Satellite and Ring Search

Table 1. Pluto Fast Flyby Core Science Objectives (No intended prioritization within categories)

The Spacecraft Design

In developing its spacecraft design for the Pluto Fast Flyby mission, JPL has broken with the requirements driven focus of the past, pursuing a cost-driven design philosophy instead. In this philosophy, all design decisions are first based on cost, then schedule, and then performance. Cost considerations focus on meeting a \$400 M (fiscal year 1992 dollars) cost cap on the development and launch of the two spacecraft as

well as on minimizing launch vehicle and post-launch mission operations costs. Such cost objectives differ significantly from past planetary missions in which spacecraft development costs alone sometimes ran as high as \$1 B or more. Schedule considerations relate to minimizing development and mission operations time, thereby reducing cost and minimizing spacecraft mass to facilitate spacecraft arrival at Pluto in time to satisfy the category 1a science objectives. Finally, performance considerations focus on providing the spacecraft data storage and transmission capability, pointing/slewing/attitude control capability, power, and reliability needed to fulfill all of the 1a science measurement objectives.

Pursuit of the above philosophy initially culminated in the spacecraft design shown in Figure 3 [1]. In this FY 92 baseline, the spacecraft was three-axis stabilized, using cold gas thrusters for pointing and turning. The spacecraft mass was 165.3 kg, counting propellant mass. Data storage capability was more than 800 Mbits with a data downlink rate of 40 bits/s. Main propulsion for changes in the spacecraft's speed, direction, and attitude control was supplied by two redundant sets of three 4.5 N, hydrazine-fueled thrusters. Additional attitude control was provided by two sets of twelve 0.009 N, cold-gas thrusters. The hydrazine was stored in a 42 cm diameter titanium tank located within the spacecraft bus. In view of the large range of thermal environments to which the spacecraft will be subjected during their journey to Pluto, the FY 92 baseline employed a combination of active and passive temperature control methods utilizing multilayer insulation, louvers, electric heaters, and small radioisotope heater units. For power, given the long flight time to Pluto and the planet's distance from the Sun at encounter (approximately 31 times the Earth's distance from the Sun or 2.9 billion miles), the baseline relied on a small, 70 W (end-of-mission) radioisotope power source.

Upon learning of the Pluto Fast Flyby mission, with its tiny spacecraft, fast trajectory and correspondingly attractive price tag, NASA Administrator, Daniel Goldin, gave it his enthusiastic endorsement but warned that the 165,3 kg spacecraft that the JPL team had envisioned would have to shed some kilograms in order to fly [5]. This admonition to reduce the spacecraft mass became the driver for developing new technologies that would enable a 100 kg-class spacecraft to do the same science as the more massive one and to do it for less cost to the tax payers.

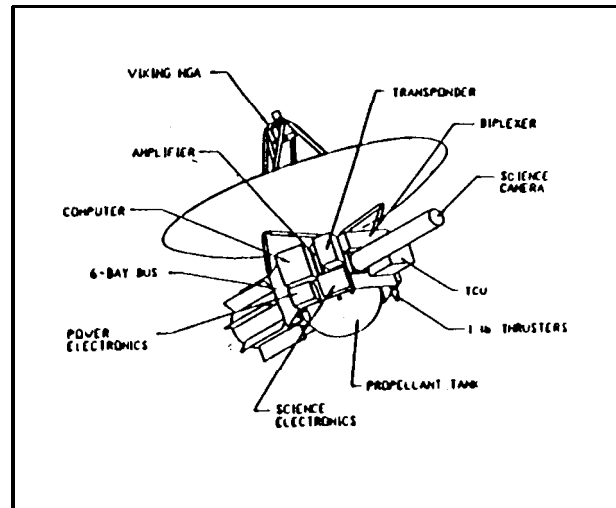


Figure 3. FY 92 Baseline Spacecraft

The advanced technology insertion efforts alluded to above culminated in the current spacecraft design shown in Figure 4.

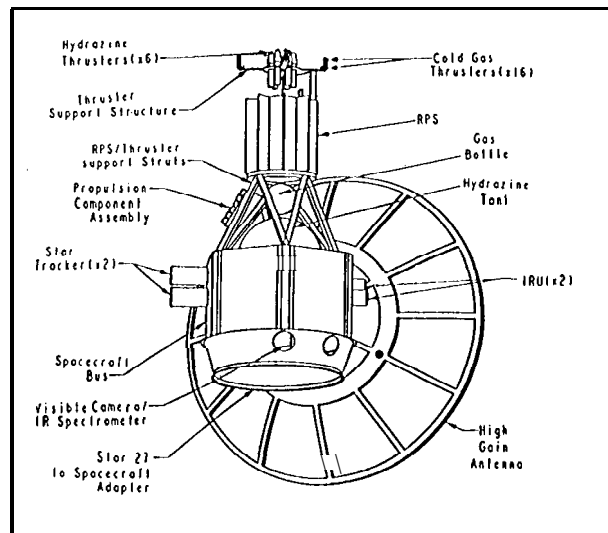


Figure 4. Current Baseline Spacecraft

The current spacecraft mass is only 80 kg without propellant and contingency, 118.7 kg with propellant and contingency -- 46.6 kg less than the FY 92 baseline. Several design changes account for this significant reduction in spacecraft mass. The aluminum bus structure has been replaced with a composite. The old Viking high gain antenna has been replaced with a new honeycomb, composite antenna. Similarly, the propellant tank has been replaced with composites. In the telecommunications subsystem, a

new, low-mass, micro-packaged digital receiver is being baselined; and, in the propulsion subsystem, new, smaller, low-leakage, cold-gas thrusters are being developed that significantly reduce the spacecraft mass. These and other new mass-reduction technologies, as well as the spacecraft subsystems to which they apply, are enumerated in Table 2 and will be discussed at length in the advanced technology insertion portion of this paper.

SYSTEM	TECHNOLOGY
Telecommunication	Micro-packaged digital receiver (MMIC, MCM), composite structure high gain antenna, high-efficiency SSPA(MMIC)
Electrical Power	High efficiency de-de conversion
Attitude Control	Miniature star camera, ring laser gyrodRU
Spacecraft Data	High density data storage,ASIC, MCM packaging
Structure	Composite spacecraft bus
Propulsion	Micro low-leakage cold gas thrusters, miniaturized components (valves, regulators)
Thermal Control	Light-weight ML1, louvers
Science	Integrated electronics,ASIC, MCM packaging, light-weight thermally stable materials

Table 2. Spacecraft Subsystems and Key Mass Reduction Technologies

In addition to the above mass reduction measures, the current design differs from the FY 92 baseline in several other important respects. Most obvious is the spacecraft configuration. The radioisotope power source has been repositioned so that its waste heat can be used in lieu of the radioisotope heater units for thermal control. And, the high-gain antenna has been relocated to the side of the spacecraft bus, allowing a better field of view for the science instruments. Other changes include an increase in the data storage capability to 2.0 Gbits, an increase in the downlink data rate to 80 bits/s, and smaller reaction control thrusters (appropriate to the reduced spacecraft mass) delivering 0.0045 N each.

The current baseline should not be considered fixed. As new cost, schedule, and performance opportunities and impediments come to light during the design

process, a new baseline will likely emerge -- a baseline that will serve as a benchmark against which to compare yet more alternatives as the design process focuses toward a final configuration.

Advanced Technology Insertion

Consistent with its charter, NASA's Office of Advanced Concepts and Technology (OACT) has been funding the development and demonstration of technologies that promise to enhance the Pluto mission's ability to achieve its cost, schedule, and performance goals. This Advanced Technology Insertion (ATI) effort began with JPL's Pluto team issuing a request for information (RFI) and inviting over 1200 contacts in industry, academia, and Federal laboratories to identify new technologies that would contribute to the type of spacecraft mass reduction directed by the NASA Administrator after his review of the FY 92 baseline. JPL's Pluto mission team leaders specifically made it clear to the contracting companies that paper studies were not the desired product. The team wanted proof-of-concept hardware or software showing that a particular technology could be developed for incorporation into the Pluto spacecraft in accordance with strict cost, schedule, and performance targets.

The resulting ATI contracts led to the delivery of breadboard products beginning in August of 1993, with subsequent deliveries scheduled through June of 1994. New technologies for the Pluto mission will be rigorously pursued to about mid-1995 when a technology freeze will be imposed. The remainder of this paper illustrates specific areas in the mission development where advanced technology is expected to show benefits. In some cases, technology demonstration work now under contract will not produce hardware of sufficient maturity to constitute an acceptable cost and schedule risk for the mission within available resources. In these cases, to be decided over the next several months, certain technologies may be left to others to bring to flight status [5].

Spacecraft Subsystem ATI Efforts

As alluded to in the discussion of the baseline spacecraft design, the Pluto Fast Flyby spacecraft has seven major subsystems: telecommunications (radio frequency), electrical power and pyrotechnics, attitude control, command and data, structures and

mechanisms, propulsion, and thermal control. The science instrument package is not referred to as a subsystem because it is being developed by a team different from the spacecraft team. The spacecraft team and the science instrument team coordinate to develop a complete spacecraft and instrument flight system.

As discussed earlier, the baseline spacecraft design for FY 92 indicated a wet spacecraft mass of 165.3 kg (with contingency). With the ATI work performed thus far, it was possible to reduce this mass to roughly 120 kg (118.7 kg wet with contingency) by the end of FY 93. Technologies selected for this work were driven by the following criteria:

- o mass reduction potential,
- o life-cycle cost reduction potential,
- o power consumption reduction potential,
- o flight time reduction potential,
- o cost and risk conformity to the mission context, and
- o the level of existing activity in the technology area.

Telecommunications [5]

Several areas in the telecommunications subsystem have been identified where significant mass and power savings can be achieved with the insertion of new technology. Design and fabrication of a low-mass, 1.5 meter parabolic antenna utilizing a new honeycomb hybrid reflector design will reduce the 5.8 kg mass associated with the spare Viking antenna to just 3.5 kg. The hybrid antenna will employ a dual X-band/Ka-band feed.

Attractive power and mass savings can be obtained for the Solid State Power Amplifiers (SSPA) utilizing pseudomorphic high electron mobility transistor (PHEMT) technology. Work is in progress to demonstrate a 1.5 W Ka-band output power module with 30% power added efficiency (PAE) and 6 dB of gain. Advanced 0.15 μm PHEMT devices will be utilized in this demonstration,

Advanced monolithic microwave integrated circuit (MMIC) and multi-chip module (MCM) packaging technologies will reduce the receiver portion of the transponder mass by 50% and increase functionality to include the Command Detector Unit (eliminating a separate physical module).

Power

The baseline Power and Pyrotechnics Subsystem consists of a radioisotope power source (RPS), power electronics for voltage conversion, regulation, transient peak power output, switching and fusing, and pyrotechnic device initiation (explosive bolts, pyro-valves, etc.) [5].

The FY 92 baseline design of this subsystem had a mass of 23.2 kg. Advanced technology insertion efforts focused on reducing this mass through the development of more efficient converter designs for the RPS. The FY 92 converter design relied on a smaller version of the thermocouple-based converters used for the Galileo and Ulysses power sources. Emerging thermal-to-electric conversion technologies such as alkali metal thermo-electric converters (AMTEC) and thermophotovoltaic (TPV) converters were investigated in hopes of developing a higher efficiency, lower mass converter for the RPS. While the technologies did not prove sufficiently far along to meet the 1995 technology freeze constraint for the Pluto mission, progress was made in pushing the technologies to a point where they might prove beneficial to some future mission. For instance, a prototype AMTEC cell that produced 2 W with 10% efficiency and a capacity to produce 3W with 16% efficiency at higher temperatures was developed and delivered to JPL's Pluto team. The development of this prototype set the stage for further development, testing, qualification, and incorporation into a system design prototype sometime in the indefinite future. In the TPV realm, the Pluto ATI program sponsored the first scale model demonstration of a simulated heat source/TPV system, again setting the stage for work that might be pertinent to some future mission.

In the current baseline, the power subsystem mass is being reduced through two new approaches: reduction of the structural mass associated with the current thermocouple-based converter and incorporation of advanced technologies in other areas of the power subsystem. Detailed structural analyses are in progress that promise to find methods of reducing the converter mass from 19.3 kg (o 15.4 kg. In other areas of the power subsystem, laser initiated pyrotechnics to reduce required power, a small solid state power switch to reduce mass, and a synchronous rectifier power

²Thermophotovoltaic converters transform infrared radiation from a heat source to electricity using low bandgap photovoltaics.

converter to improve de-to-de power conversion efficiency are all under investigation.

Attitude Control [5]

The attitude control subsystem (ACS) includes sun and star sensing devices, an inertial reference unit (IRU), electronics for interfacing with the central computer in the command and data subsystem, and electronics and switches to drive the thrusters in the propulsion subsystem. The star sensing device or star camera, with its software, can determine the spacecraft's three dimensional orientation by imaging star fields and comparing them with a catalog of stars in the computer's memory. The two Sun sensors are used to help recover orientation in the event of a star camera failure. By commanding the small cold gaseous nitrogen thrusters in the propulsion subsystem, the attitude control subsystem can change or maintain the spacecraft's orientation.

The primary focus of advanced technology insertion efforts in this subsystem centers on the star camera. New technology may provide a star camera with a mass of only 500 grams. Lawrence Livermore National Laboratory has been developing much of this technology for the star camera on its Clementine spacecraft -- a spacecraft that launched and operated successfully earlier this year. It is hoped that lessons learned from Clementine can be combined with new technology developments from industrial vendors to meet the Pluto mission's stringent 10-year lifetime and pointing requirements.

Additional savings in mass and power consumption are currently being investigated in the breadboard stage elsewhere for a low-mass IRU.

Command and Data [5]

The command and data subsystem includes the central computer and its memory, the mass storage memory, and the necessary input/output devices for gathering data from and commanding to other subsystems. The computer executes algorithms for attitude control, sequencing, propulsive maneuvers, fault protection, engineering data browse and reduction, and other data management functions. The mass memory is used to store all the near encounter science data for transmission to Earth post-encounter, and to store engineering data between ground communications cycles during the entire mission,

In the FY 92 baseline the subsystem had aggressive mass and power targets of 7.0 kg and 6.0 W during encounter. Total science data storage volume was 800 Mbits.

Use of advanced technology in electronics packaging and low power interface drivers is expected to achieve the mass and power targets for the current baseline design while increasing science data storage volume to 2 Gbits. The current design is based on an SCI FTP-3200 computer. The redundant electronics have a mass of 5.5 kg and will operate at 11 W during encounter. Development of low power I/O bus structures may reduce this power requirement.

Structure [5]

The structure subsystem includes the primary and secondary structure of the spacecraft and kick-stage adapter separation systems. It must support all of the spacecraft components during the vibration and acceleration of launch and injection by the upper stages. The structure helps shield the electronics from the natural and RPS-induced radiation environment. The FY 92 baseline featured an all aluminum primary structure with a mix of aluminum and graphite-epoxy composite members in the secondary structure utilizing procedures and processes proven in space applications.

In FY 93, an ATI contract was awarded for development of a composite bus structure, saving 5 kg for the structure subsystem by replacing the aluminum bus. Utilizing this new structure, the FY 92 baseline spacecraft was reconfigured to provide for more direct load paths, improved mass balance, and lower thermal impact from the RPS.

Propulsion [5]

The propulsion subsystem consists of a monopropellant hydrazine thruster set for providing the required trajectory corrections, plus cold-gas thruster attitude control equipment. A hybrid, blow-down system was adapted using a portion of the hydrazine tank pressurant gas as the working fluid for the cold-gas thrusters.

The principal objectives in the RFI were reductions in subsystem mass, gas leakage, and power consumption. Industry responses to the RFI indicated that reductions in mass of up to factor of five could be realized in several components. Cent ractor work focused on

miniaturizing the pressure regulators and valves (service and latch), developing a composite over-wrapped pressurant/propellant tank like that used in the fourth stage of the air-launched *Pegasus*, developing a surface tension propellant management device (PMD), and developing miniature (0.0045 N) cold-gas thrusters with improved internal leakage (factor of ten decrease), improved cycle life, and a broader operating temperature range. Coupled with 3-axis stabilization of the upper stages (that reduced the required mass of hydrazine monopropellant), these activities led to a 10 kg reduction in the mass of the propulsion subsystem relative to the FY 92 baseline.

Thermal Control [5]

The thermal control subsystem is basically passive, consisting of blankets, louvers, radiators, and other thermal control paths and insulators. Multi-layer insulation (MLI) blankets are used to minimize thermal energy transfer between elements of the spacecraft. Thermal conduction control (e.g., the thermal isolation between the spacecraft and the antenna) and thermal enhancements allowing more effective energy conduction from the electronics to radiators keep all the subsystems within tolerable temperatures. Mechanical louvers actuated by a hi-metallic device have good radiative properties in the open position and help to hold heat in when in the closed position.

In the FY 92 baseline, the mass of the subsystem was 4.0 kg. In the current baseline, this mass has been reduced to 3.7 kg through the application of new lighter-weight MLI blankets and louvers as well as a new spacecraft configuration that makes better use of the waste heat from the RPS, eliminating the need for any RHUs.

Science instrument ATI Efforts [5]

Because of the relatively short flight system development time, the science payload design must depend on technologies that are relatively mature. However, the mass and power allocations for the payload are very ambitious, 7 kg of payload and only 6 W of power. These constraints necessarily drive instrument design toward materials and architectures for which little or no flight experience exists. Achieving a balance between new technology application and acceptable risk is an ongoing challenge for the payload development team.

A NASA Research Announcement (NRA) was issued early in 1993 for Pluto instrument concepts, the purpose of which was to insert advanced technology into the Pluto payload design. In April 1994, contractors selected during this NRA process will deliver optical components, detectors, electronics and associated instrument designs to the JPL team for evaluation, comparison, and use in setting detailed interface specifications for a suite of flight instruments to be selected through a subsequent Announcement of Opportunity (AO).

The breadboard components to be delivered under this NRA process are being fabricated much earlier than usual in an effort to sort out the advantages and limitations of advanced technologies before the spacecraft design matures to the point where problems applying them could substantially increase programmatic risk. In the case of highly integrated packaging, for instance, the sharing of various structural, optical and electronic elements among the optical instruments would seem to be highly desirable to meet mass and power allocations. However, the successful adaptation of advanced materials and packaging techniques may compromise other factors such that it actually exacerbates mass, power, cost, schedule, or performance problems. For instance, use of lower mass structural materials than say, aluminum, may necessitate additional radiation shielding around sensitive electronic components, in turn, offsetting some of the mass advantages of the lighter-weight material. In the optics and electronics realms, a telescope is being investigated that has an aperture of about 7.5 cm to 12 cm and a focal ratio of f/10 to f/6.5, respectively. If development efforts are successful it will be capable of achieving a monochromatic resolution of 1 km/lp at a spacecraft range of 50,000 km [6]. By utilizing currently available CCDs with a 7.5 μm pixel dimension, this telescope will provide a resolution surpassing that of the Hubble Space Telescope while the spacecraft is still four to six months away from encounter. Investigators are also exploring multiple CCD arrays utilizing fixed filters or beam splitters that do not rely on mechanical devices like filter wheels to obtain color images.

Student Involvement Opportunities

University student involvement has been and will continue to be an enabling component of the Pluto Fast Flyby mission. Students have already made important contributions to the preproject development effort. For instance, students from Cal tech and other

institutions built the first full-scale mockup of the spacecraft and are presently building a new mockup to reflect the current baseline spacecraft configuration. Students at Georgia Tech recently won a competition for construction of a composite adapter that will unite the spacecraft to the upper stage solid rocket motors (SRMs). And, students are also in the process of building mockups of the upper stage SRMs and associated adapters. Several other examples of student involvement are enumerated below in Table 3. Similar opportunities for student involvement are expected to continue throughout the spacecraft design and development process.

SUBSYSTEM ELEMENT	UNIVERSITY	PROJECT
Telecom	Univ. of Michigan	Build low-loss power divider
Instruments/ SIC System	Caltech/N. Az. U. (MI)	Payload design, s/c mockup
Structure/ bus	Utah State U.	Build isoerid bus structure
End to End Info. System	Central State U. (HBCU)	Build data flow architecture simulation
Structure	Harvey Mudd	Design and build stack adapters
Flight Computing	U. of Baltimore	Recommend data compression
propulsion Stack	Caltech	Build stack motor mockups
Flight Computer	Stanford	Build low power CMOS chip
Trajectory/Science	occidental COJ lege	Animation of Pluto/Charon flyby

Table 3. Student Involvement in the Pluto Mission [5]

After the spacecraft have launched, Pluto mission operations are also expected to have an educational dimension. Students, advised by JPL/Pluto mission operations experts and supervised by experienced professionals, will staff some of the operational positions, as was the case during the Solar Mesosphere Explorer mission [7]. In addition, to encourage student participation and visibility, the operations workstations at JPL, universities, and science user sites will be linked through a distributed operations data system that utilizes international interfacing standards. As the spacecraft downlink engineering and compressed science data, these data will be made accessible to such workstations. Lessons learned at CU operating the Solar Mesosphere Explorer (SME) Mission [7] will be applied toward achieving this setup at low cost with a maximum of educational and scientific benefit.

Summary

By making spacecraft design trades on the basis of cost first, then schedule and performance, JPL is developing an affordable, scientifically exciting

mission to Pluto and its moon, Charon -- a mission that will complete mankind's initial reconnaissance of the Solar System. The scientific urgency of arriving at Pluto before atmospheric "collapse" in the 2010-2020 timeframe as well as the need to minimize mission costs necessitate arrival at Pluto as soon as possible. The faster flight times needed to achieve this rapid arrival require that the spacecraft mass be as low as possible. Technologies pioneered for small Earth orbiters and, in many cases, advanced further through NASA support for the Pluto advanced technology insertion efforts enable spacecraft mass and consequent operations cost reductions far below what was thought possible as little as three years ago. University students have played an integral role in these activities and are expected to continue to do so, not only during the spacecraft development phase but also after launch during the mission operations phase.

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References

1. R. I. Stachle, D.S. Abraham, J.B. Carraway, P.J. Esposito, E. Hansen, C.G. Salvo, R.J. Terrile, R.A. Wallace, S.S. Weinstein, "Exploration of Pluto," IAF-92-0558, 43rd Congress of the International Astronautical Federation, Washington, DC., August 28 -September 5, 1992.

PLUTO MISSION CONTRACTS & AGREEMENTS

INSTRUMENTS

- o Stanford University, Stanford, CA Len Tyler, PI, Uplink Radio Science Instrument
- o Johns Hopkins university/Applied Physics Laboratory, Laurel, MD; **Ultrastable** Oscillator
- o University of Colorado, Boulder, CO; George **Lawrence**, PI, Ultraviolet Spectrometer
- o Southwest Research Institute, San Antonio, TX; Alan Stern, PI, Integrated Pluto Payload System
- o Ball **Electro-Optics/Cryogenics** Division, Boulder, CO; Infrared and **Visible** Subsystems
- o Westinghouse Space Division, Baltimore, MD; Bruce Nichols, PI, Instrument Package Miniaturization Program
- o Goddard Space **Flight** Center, **Greenbelt**, MD; Don Jennings, PI, Linear Etalon Imaging **Spectral Array**
- o U.S. Geological Survey, Flagstaff, AZ; Larry **Soderblom**, PI, Integrated **UV/Vis/IR** Instrument
- o The Aerospace Corporation, Los Angeles, CA George **Rossano**, PI, Low-mass, low-power Visible Imaging System and IR Mapping Spectropheter
- o Washington University, **St. Louis**, MO; W. H. Smith, PI, Pluto Reflectance Imaging Mapping **Interferometric** Sensor

SUBSYSTEMS

- o Environmental Research Institute of Michigan, Ann Arbor, MI; Prototypic Alkali Metal Thermal-to-Electric Conversion (**AMTEC**) System Cells
- o Advanced Modular Power Systems, Ann Arbor, MI; Prototypic Alkali Metal Thermal-to-Electric Conversion (**AMTEC**) Cells
- o Boeing Defense and Space **Group**, Kent, WA **Thermophotovoltaic** Thermal-to-Electric Conversion Development
- o Martin Marietta **Astrospace**, King of Prussia, PA Ka-band Solid State Power Amplifier
- o **SCI** Systems, Inc., Huntsville, AL; Computer module
- o Composite Optics, Inc., San Diego, CA Bus Structure Engineering Development Model
- o Boeing Defense and Space Group, Kent, WA Telecommunications Antenna
- o **Futurecraft** Corporation, City of Industry, CA; Service Valves
- o **Moog**, Inc., East Aurora, NY; Cold-gas Thruster
- o Fairchild Space, Germantown, PA Advanced Radioisotope Thermoelectric Generator
- o Georgia Institute of Technology, Atlanta, GA Prototype Upper Stage Adapter
- o Northern **Arizona** University, Flagstaff, AZ; Spacecraft Mockup
- o California Institute of Technology, Pasadena, CA Spacecraft and SRM Stack Mockups
- o Harvey Mudd College, Claremont, CA SRM Stack Adapter
- o Utah State University, Logan, UT; Prototype **Isogrid** Bus Structure
- o Martin Marietta **Astrospace**, Denver, CO; Launch Vehicle - Upper Stages
- o University of Michigan, Ann Arbor, MI; Low-loss RF Power Divider
- o Lewis Research Center, Cleveland, OH; Launch Vehicle
- o Stanford University, Stanford, CA Low-power CMOS Chip
- o **Lawrence** Livermore National **Laboratory**, Livermore, CA Ballistic Missile Defense Office Technology Transfer (Star Camera)
- o TRW, Inc., Redondo Beach, CA Digital Receiver

OPERATIONS

- o University of Colorado/Colorado Space Grant Consortium, Boulder, CO; Mission Operations Concept and Development Software

OTHER CONTRACTS OR AGREEMENTS

- o **Altadena** Instruments, Pasadena, CA Instrument Data Architecture
- o JRF Engineering, La **Cañada**, CA Engineering and Rapid Development Consulting
- o **Central** State University, **Wilberforce**, OH; Data Flow **Architecture** Simulation
- o Occidental College, Los Angeles, CA; Video Animation of **Pluto-Charon** flyby
- o University of Baltimore, Baltimore, MD; Recommended Data **Compression** Scheme

Table 4. Pluto Mission Contracts and Agreements

2. S. Alan Stern, "The Pluto Reconnaissance Flyby Mission", *Eos, Transactions, American Geophysical Union*, Vol. 74, No. 07, February 16, 1993, pages 73 and 76-78.

3. Robert L. Stachle, Douglas S. Abraham, Roy R. Appleby, Stephen C. Brewster, Richard S. Caputo, John B. Carraway, Robert B. Crow, Margaret B. Easter, Paul K. Henry, Richard P. Rudd, Christopher G. Salvo, Michael D. Taylor, Richard J. Terrile, Stacy S. Weinstein, "Spacecraft Missions to Pluto and Sharon," *Pluto and Charon*, Space Science Series, University of Arizona Press, In press, 1993.

4. S. Weinstein, "Pluto Flyby Mission Design Concepts for Very Small and Moderate Spacecraft," **AIAA-92-4372**, **AIAA/AAS** Astrodynamics Conference, Hilton Head Island, South Carolina, August 10-12, 1992.

5. Robert L. Stachle, Stephen Brewster, Doug Caldwell, John Carraway, Paul Henry, Marty Herman, Glen Kissel, Shirley Peak, Vince Randolph, Chris Salvo, Leon Strand, Rich Terrile, Mark Underwood, Beth Wahl, Stacy Weinstein and Elaine Hansen. "Pluto Mission Progress: Incorporating Advanced Technology," Seventh Annual **AIAA/Utah State University Conference on Small Satellites**, Logan, Utah, September 13-16, 1993.

6. Robert L. Stachle, John B. Carraway, Christopher G. Salvo, Richard J. Terrile, Stacy S. Weinstein and Elaine Hansen, "Exploration of Pluto: Search for Applicable Satellite Technology," Sixth Annual **AIAA/Utah State University Conference on Small Satellites**, Logan, Utah, September 21-24, 1992.

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