IAF-93-Q.5.41O

GRAZ AUSTRIA
1993

PLUTO MISSION PROGRESS REPORT: LOWER MASS AND FLIGHT TIME THROUGH ADVANCED TECHNOLOGY INSERTION

Robert L. Staehle, Stephen Brewster, Doug Caldwell, John Carraway, Paul Henry, Marty Herman, Glen Kissel, Shirley Peak, Chris Salvo, Leon Strand, Richard Terrile, Mark Underwood, Beth Wahl, Stacy Weinstein.

Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91109 USA

&

Elaine Hansen

Colorado Space Grant Consortium
University of Colorado
Boulder, CO 80309 USA

44th CONGRESS OF THE INTERNATIONAL ASTRONAUTICAL FEDERATION

October 16-22,1993 / Graz, Austria

IAF-93-Q.5.41O

PLUTO MISSION PROGRESS REPORT: LOWER MASS AND FLIGHT TIME THROUGH ADVANCED TECHNOLOGY INSERTION

Robert L. Staehle*, Stephen Brewster, Doug Caldwell, John Carraway, Paul Henry, Marty Herman, Glen Kissel, Shirley Peak, Chris Salvo, Leon Strand, Richard Terrile, Mark Underwood, Beth Wahl, Stacy Weinstein.

Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91109 USA

&

Elaine Hansen

Colorado Space Grant Consortium
University of Colorado
Boulder, CO 80309 USA

Abstract

A development team at the Jet Propulsion Laboratory (JPL) and other facilities is designing a mission to send two very small spacecraft to Pluto and Charon to complete the initial reconnaissance of our Solar System. The two probes, each carrying four science instruments, will obtain data on both hemispheres of Pluto and Charon in the form of visual images, infrared and ultraviolet data, and radio science. This paper briefly describes the mission design and spacecraft instrumentation and subsystems, and reports on the current progress to implement advanced technology in reducing spacecraft mass and power requirements. Cost, schedule and performance, in that priority, are the primary design drivers. The goal of the mission is to deliver two 120 kg class spacecraft costing less than $400M for both, on direct trajectories to the Pluto-Charon system taking approximately 7-10 years to arrive well before the collapse of Pluto's atmosphere and the impending polar shadow that will reduce the global science coverage. Contract and in-house work has been in progress to provide breadboard proof-of-concept hardware and software contributing toward the lower mass goal. Results are reported for candidate scientific payload instruments, a composite structure, advanced antenna, significantly smaller electronics packaging, high efficiency thermal-to-electric converters for the radioisotope power sources and other candidate areas for mass, power and size reduction within strict cost limits.

Mission Background

Referred to as the double-planet with its satellite Charon, Pluto is the only known planet in our Solar System that has yet to have a spacecraft encounter reveal some of its secrets.

In 1991, artist Ron Miller created a set of ten United States postage stamps commemorating spacecraft voyages to eight planets and Earth's

*Manager, Pluto Preproject

Moon. The tenth stamp in the set showed the artist's rendition of Pluto with the statement, – PLUTO – NOT YET EXPLORED. Sending a spacecraft to Pluto was not a new idea, but it was from this inauspicious reminder in October, 1991 that the current mission to Pluto was born.

There have been other attempts at designing missions to visit the outer planets including Pluto[1,2,3], so why hasn't Pluto been explored? The answer lies in the fact that Pluto is the "Mount Everest" of Solar System exploration. It is the farthest, coldest and hardest planet to get to. It was thought that with the present technology and economic environment, the end-to-end mission would take too long and cost too much to be successful. A mission of this scope indeed presents many challenges.

A proposal to investigate the mission concept was accepted and funded by NASA's Solar System Exploration Division in January, 1992.

The Outer Planets Science Working Group (OPSWG), a NASA chartered 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) as early as May, 1991. In subsequent meetings with NASA, OPSWG and NASA's Solar System Exploration Subcommittee (SSES) formally endorsed the JPL concept of a dual Pluto flyby with very small spacecraft.

In April, 1992, in response to increasing economic stresses and social concerns, Daniel S. Goldin, NASA's new administrator, asked its members to find faster, better and cheaper ways of doing the business of space science. NASA would need to find new ways to produce good science for fewer dollars. Upon learning of the exciting new Pluto mission with its tiny spacecraft, fast trajectory and attractive price tag, Goldin gave it his enthusiastic endorsement but warned that a spacecraft in the > 164 kg mass class would most likely not receive funding. This directive from NASA headquarters – to reduce spacecraft mass – would become the driver for adopting and developing new technologies that would enable a 100 kg class spacecraft to do the same science as a more massive one, and to do it for less cost to the tax payers. Some of the new technologies might then spin off into other space missions and into the private sector providing broader benefits. Deliveries of prototype hardware and software began in August 1993 for key spacecraft components to achieve mass reduction goals. This permits cruise to Pluto in less than 10 years using Titan, Proton, or the Shuttle with various upper stages.

FY92 Baseline and Beyond 4-9

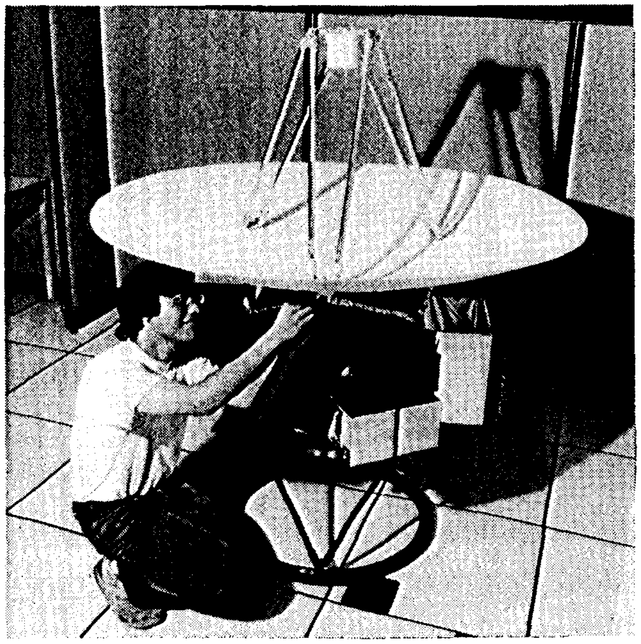

Fig.1 The FY92 baseline Pluto mission spacecraft carries a 1.5m *Viking* spare antenna, RTG, and other components mounted outside a small aluminum structure. Total design mass was 165 kg wet. Photo: JPL

The preliminary Fiscal Year 1992 baseline for the Pluto mission was designed to return valuable global scientific data from Pluto and Charon as soon as possible and to do it within a strict development cost cap. [1]

Plans are to launch two spacecraft on separate vehicles in 1999 and/or 2000 on direct trajectories to pass within -15,000 km of Pluto and Charon in 2007-2010, obtain scientific data and transmit that data to Earth following the encounter. The cost cap for this mission is $400 M(FY92) for the mission development.

Two spacecraft with their science payloads and mission operations from launch through 30 days after launch appear feasible. Cost caps for mission operations during the cruise and encounter stages have yet to be determined but will be kept down by limiting the size of the operations crew and by not performing cruise science.

Additional costs will be incurred for the launch vehicles, the radioisotope power source (RPS), mission operations, data analysis, and tracking by the Deep Space Net (DSN). All NASA-borne costs from the time NASA commits to the mission until the initial data analysis is complete comprise the life cycle cost (LCC). Prior planetary missions have typically been measured by their development cost, excluding the launch vehicle, some portions of the radioisotope thermoelectric generator (RTG – when flown), and all costs incurred after 30 days post-launch. These other substantial expenditures have typically been borne out of multiprogram accounts. *Voyager 1-2* and *Pioneer 10-11* development costs by the earlier accounting method were $7 16M and $342M, respectively, measured in FY92$US. This compares to the Pluto FY92$400M development cost cap, also for a two-spacecraft mission.

Pluto is to be among the first planetary missions to shift to a life cycle cost accounting method, where different phases and the total are expected to be capped. Development cost of the FY92 baseline was estimated at FY92$363M including 40°A reserves, and the FY93 baseline total was almost identical, in spite of changes in several amounts comprising the total.

Life cycle cost for the FY93 baseline was estimated at $1, 100M, which still compares favorably with *Voyager, Galileo,* and *Cassini*. Because of expected US Federal budget cuts to assist in deficit reduction, the challenge now is to bring life cycle cost substantially below FY93$1100M, while retaining the same science payload, increasing data return, and maintaining reliability suitable for a decade-long mission, In a mission redesign effort begun in September, all aspects of the mission are being reevaluated for possible savings and for possible consequences of changes in such areas as the need for early developmental funding, science yield, mission reliability, development costs and schedule risk, time. of flight, and value to industrial, educational, and government agency partners.

As part of this mission redesign, cost-saving partnerships will be considered with agencies in other countries for such mission elements as launch vehicles, science collaboration, instruments, subsystems, and tracking.

To come to fruition, the mission must maintain an exciting science content, early launch, and an attractive life cycle cost and cost profile during today's fiscally austere environment. This is the challenge of our present mission development activity, which remains funded at a level similar to the past year to permit substantial prototype hardware and software development, reducing cost and schedule risk when a final budgetary commitment must be made. Simply stated, if the costs exceed that amount which Congress initially approves, the entire effort can be expected to be canceled. NASA will choose when to submit the Pluto mission for a "new start" at which time it will be included as a line item in the Federal budget.

Advanced Technology Insertion[10]

The so-called FY92 Baseline Pluto spacecraft was designed at a mass of 165 kg, including reserves and propellant. It was felt that this relatively conservative design approach would benefit from more advanced technology to perform the same functions at lower mass, shortening trip time and stimulating new technology applications for deep space missions.

NASA's Office of Advanced Concepts and Technology (OACT) is funding research and demonstration of new technologies that will benefit the Pluto mission in meeting its goals. Within a process called Advanced Technology Insertion (ATI), the mission development team in November, 1992 issued a request for information (RFI) and invited over 1200 contacts in industry, academia, and Federal laboratories to look at the mission constraints of cost, schedule and reduced mass and to help identify

candidate new technologies that might be included in the conceptual design efforts. Team leaders 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 promise that a particular technology could be developed for incorporating into the Pluto mission within strict cost and performance goals. Preliminary ATI work has resulted in the delivery of the first breadboard products in August, with subsequent deliveries through June, 1994. New technologies for the Pluto mission will be rigorously pursued to about mid-1 995 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, as they may benefit later missions.

Science Instruments

In April, 1992 the OPSWG defined science goals for the mission, arranging and prioritizing them into three classes [Table 11. The first, class 1a, represents the "must do" science objectives for this mission. These include the characterization of Pluto's and Charon's global geology and morphology, surface compositional mapping, and the characterization of Pluto's neutral atmosphere. Class 1 b and 1 c objectives will be attempted if still within the project constraints.

The focused Class 1 a science objectives are a marked departure from the trend in planetary exploration over the past decades. Likewise, the science instrument complement for this mission reflects these limitations and has distinct similarities to earlier *Mariner* and *Pioneer* missions where the science payload was chosen to explore specific aspects of the planet in question. Later missions broadened the range of science addressed with a consequent sharp rise in development time, flight time, payload complexity and cost. The Pluto-Charon mission, with some degree of time urgency and a cost cap, has no such luxury; payload development will require both science teams and instrument designers to maintain a very strict discipline.

Table 1 PLUTO MISSION CORE SCIENCE OBJECTIVES
(no prioritization within categories)

<u>Category Ia</u>
- Characterize Global Geology and Morphology
- Surface Composition Mapping
- Characterization of Neutral Atmosphere Structure and Composition

<u>Category Ib</u>
- 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, H_2, HCN, C_xH_y, and other Hydrocarbons and Nitriles in Pluto's Upper Atmosphere.
- Obtain Isotope Discrimination Where Possible
- Search for Charon's Atmosphere
- Determination of Bolometric Bond Albedos
- Surface Temperature Mapping

<u>Category Ic</u>
- Characterisation of the Energetic Particle Environment
- Refinement of Bulk Parameters (Radii, Masses, Densities)
- Magnetic Field Search
- Additional Satellite and Ring Search

Because of the need to shorten flight system development time, the science payload design must depend on technologies that are relatively mature. However, the very ambitious mass and power allocations for the payload (7 kg, 6W) drive the design toward materials and architectures that have not been widely applied previously in planetary exploration and for which little or no flight experience exists.

Through a NASA Research Announcement and related Planetary Instrument Definition and Development Program (PIDDP), "strawman" instrument components are being developed by several teams as noted in Table 3. Achieving the delicate balance between bold application of new technology and acceptable risk will be a principle challenge of science payload development for the Pluto-Charon mission.

The breadboard hardware produced from the ATI effort will illustrate concepts that employ advanced materials and electronics, novel optical arrangements, shaped optics and highly integrated packaging,

To better understand the opportunities and implications of the adaptation of advanced materials and architectures for the Pluto mission, a NASA Research Announcement (NRA) was issued early in 1993 for Pluto instrument concepts, the purpose of which is to insert advanced technology into the Pluto instrument design process. The end result of the contracts issued under this NRA will be the mitigation of risk incurred later in the instrument development process by the inclusion of advanced technologies, and an increased confidence that the instrument complement necessary to achieve the science objectives can be accommodated within the constraints of the Pluto mission.

Table 2

PLUTO SPACECRAFT
BASELINE MASS COMPARISON

	FY92 (KG)	ATI QOAL (KG)	FY93 (KG)
TELECOM	25.2	16.8	12.75
ELECTRICAL POWER	22.2	12.5	19.4
ATTITUDE CONTROL	2.7	2.1	6.66
SPACECRAFT DATA	7.0	4.6	6.6
STRUCTURE	20.0	14.6	14.6
PROPULSION	20.1	13.1	9.6
THERMAL CONTROL	4.0	3.6	3.7
SCIENCE	9.0	7.0	7.0
TOTAL	111.2	74.1	80.5
CONTINGENCY	26.6 (26.6%)	20.1	31.3 (38.9%)
TOTAL DRY S/C	140.7	94.2	111.0
PROPELLANT (AV M/S)	24A (2S0)	16,1 (3S0)	6.6 [130)
TOTAL WET S/C	166.3	110.3	118.7

Breadboard hardware of critical instrument elements are being fabricated much earlier than usual in an effort to sort out the advantages and limitations of advanced materials and technologies for their application to deep-space planetary exploration. The experience gained will be available for application to the flight payload development.

The most demanding element of an IR system is the detector. The most mature detector technologies are iridium antimonide (InSb) and mercury cadmium telluride (HgCdTe or MCT). Either technology is applicable to this mission. However, recent advances in MCT focal plane arrays (FPA) show better operating characteristics at temperatures above those required for InSb (77 K). A higher operating temperature is desirable since it reduces the required size of the focal plane array cooling radiator and therefore reduces the mass. A 256 x 256 pixel MCT array with 40 micron pixel size has been developed for use on the Hubble telescope upgrade. This array, known as NICMOS III, would be suitable for a Pluto IR instrument, although other larger arrays may also be available in the timeframe required for the Pluto mission.

The degree to which all the science instruments on-board the spacecraft will need to be combined into a single, highly integrated payload package is a matter that should be resolved by the ATI investigations. On the one hand, the sharing of various structural, optical and electronic elements among the optical instruments would seem to be highly desirable to meet the mass and power allocations and several investigators are pursuing such highly integrated approaches. On the other hand, if the adaptation of advanced materials and packaging techniques prove successful, mass may become less of a problem than other factors such as compromised performance, schedule, and cost “ripple” effects likely to arise in a highly integrated payload. If the latter factors become the dominant consideration, then a more modular approach would be preferable. In some cases, the adoption of an advanced material or design in one area may result in an undesirable effect in another area. An example is that light-weight structural material provides less radiation shielding than say, aluminum, thereby requiring the possible addition of more shielding material around sensitive electronic components, in turn, off-setting some of the mass advantages of the lightweight material.

Spacecraft Subsystems

The Pluto mission spacecraft has seven subsystems: Telecommunications (Radio Frequency), Electrical Power and Pyrotechnics, Attitude Control, Spacecraft Data, Structures, Propulsion, and Thermal Control. The spacecraft team and the science instrument team coordinate to develop a complete spacecraft and instrument flight system.

The design of the spacecraft has been mainly driven by three requirements embodying cost, schedule; and performance, in that order. The first driver, cost, is clearly the most important. If at any time during the course of the mission development it becomes apparent to NASA that the $400M cost cap is going to be exceeded, the Pluto mission team can expect the project to be canceled. This not only means that the spacecraft designers must control the cost of the spacecraft development, but that they must also cooperate with the rest of the team to minimize the total cost. For example, it is necessary to consider ground operations impacts in the spacecraft design to ensure that decisions are made which reduce the combined cost of development and operations.

The second spacecraft driver is the need to get to Pluto as quickly as possible. This requisite stems from the OPSWG science objectives and the implication of a short development cycle and cruise both contributing to lower cost. Getting to Pluto faster impacts the spacecraft design in conflicting ways, The reduced development schedule limits the use of advanced technology, but advanced, lightweight technology could help to reduce the spacecraft mass and shorten the flight time. A balance must be struck between development cost and schedule, and operations cost and flight time.

The third spacecraft driver, obtaining the scientific objectives, defines the primary function of the spacecraft. The scientific objectives of the mission define what the spacecraft has to be capable of doing. From these objectives come performance requirements

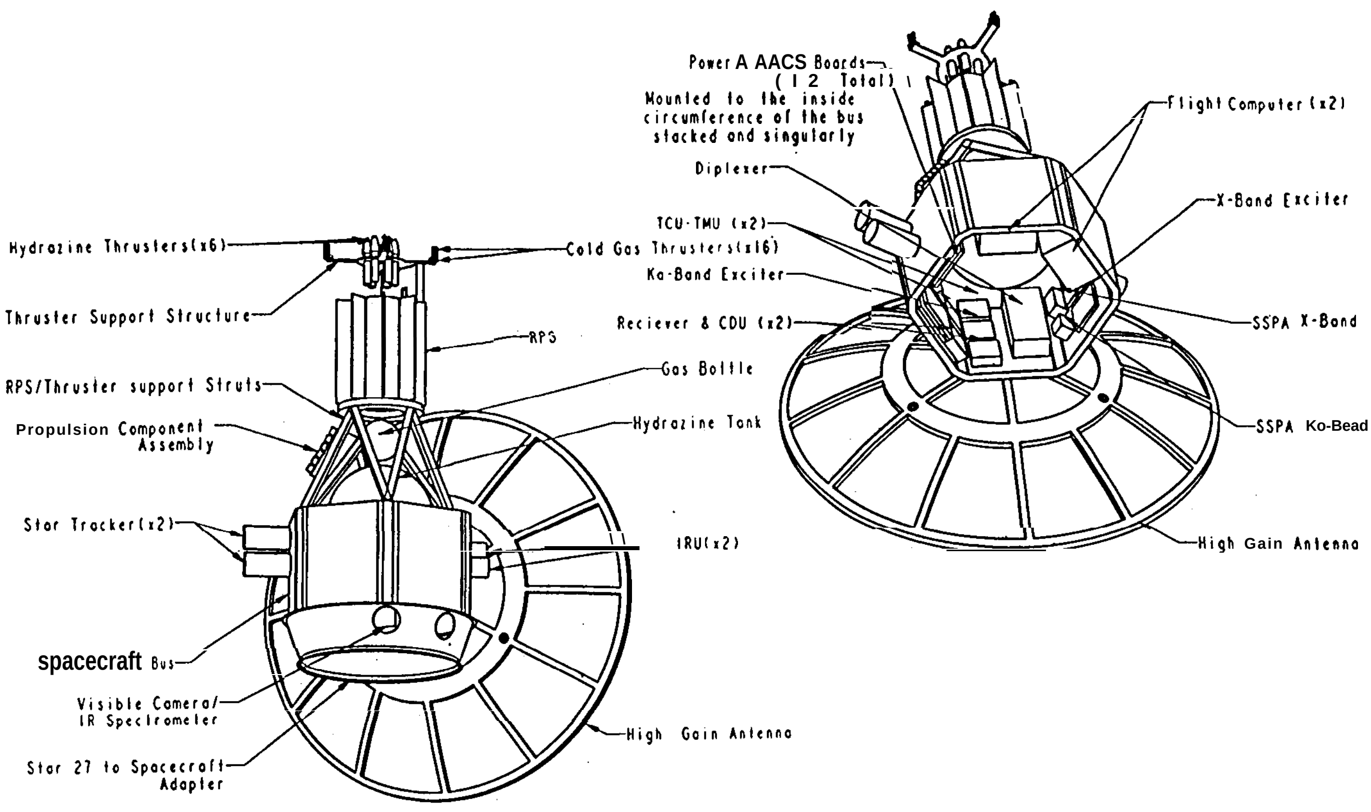

Figure 2 The FY93 Spacecraft configuration provides more direct loading paths, improved mass balance and lower thermal impact from the radioisotope power source (RPS).

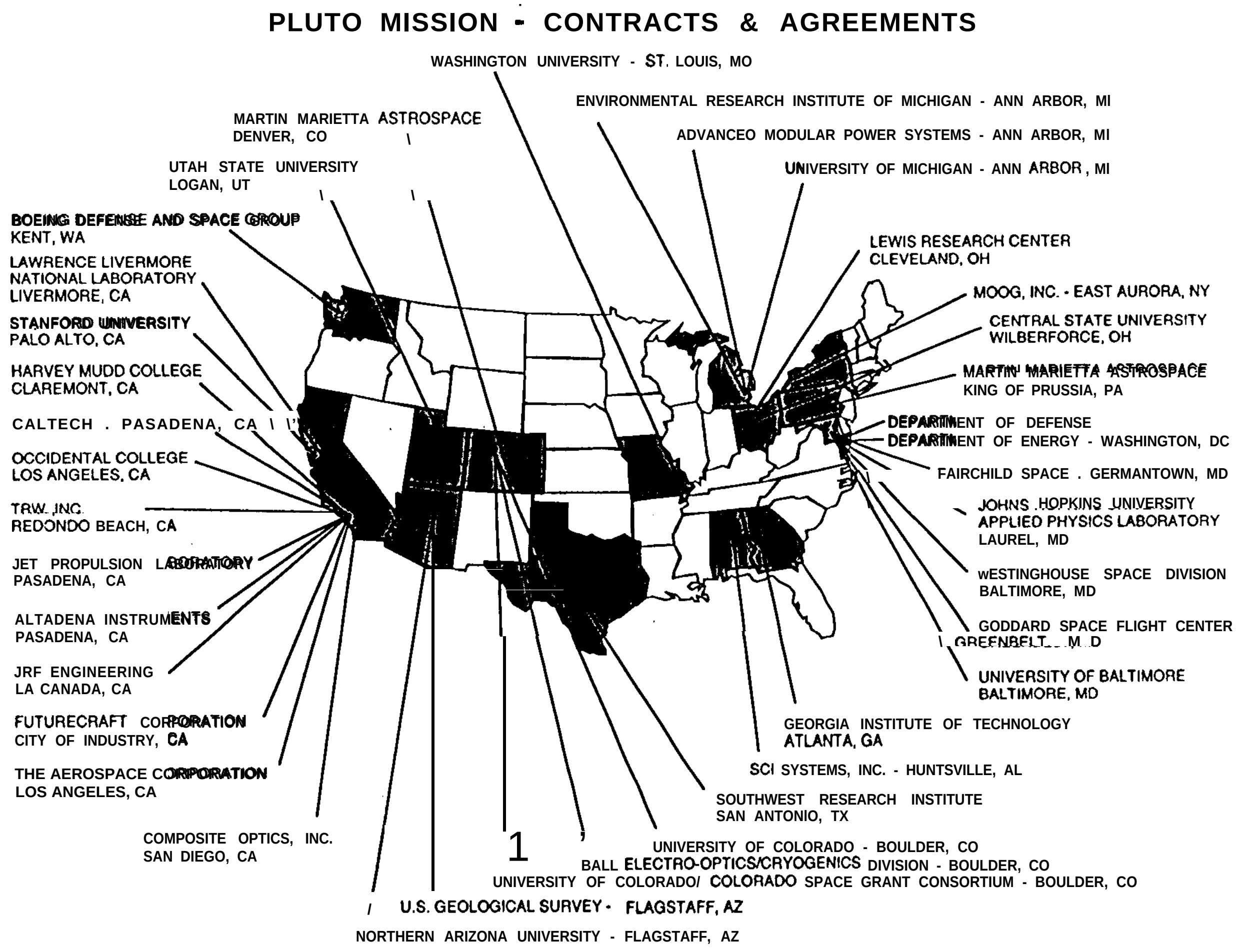

Figure 3 Contracts and agreements for advanced technology investigations will continue to be pursued aggressively until a technology freeze in mid-1 995.

on the spacecraft. These include electrical power generation, data storage, communications capability, propulsive capability, thermal control, pointing control, and a long list of other resources or capabilities which the spacecraft must provide to the instruments.

These three drivers (cost, schedule, performance) are not independent variables. Given the cost-schedule-performance priority for the Pluto spacecraft, the design approach must be very sensitive to cost, and allow capability within cost and schedule to define the performance, in this case the science return. Science requirements and cost-driven capabilities must find a sort of middle ground where adequate performance can be achieved for a reasonable cost. The objectives are focused and the resulting baseline science payload and spacecraft capability are modest; a result of cost-driven design.

From the FY92 baseline spacecraft wet mass of 164 kg, ATI work has brought the mass to <120 kg (wet) for the FY93 baseline (Table 2). Selection of technologies for incorporation into each subsystem was driven by the following criteria:

- Reduce mass
- Reduce power consumption
- Reduce flight time
- Keep cost and risk within the mission context
- Level of existing activity in a technology area

Telecommunications

The Telecommunications subsystem consists of a 1.5 m diameter high gain antenna (HGA), and the radio frequency (RF) electronics. In the 1992 baseline design the mass of the subsystem is 25.2 kg, and power consumption is 28 Watts while transmitting. Both the transmit (downlink) and receive (uplink) signals operate at X-band (-8 GHz). Nominal downlink rate is about 40 bits/second at Pluto encounter range to a 34 m Deep Space Network (DSN) station. A higher rate of -160 bits/second is possible using the larger 70 m antennas of the DSN. Advanced technology incorporated into the 1993 baseline includes a lighter composite structure antenna, high density electronics packaging, and higher efficiency RF amplifiers. These advances could reduce the mass of the subsystem to 12.75 kg and the power consumption to 22 Watts while transmitting. In addition, through the use of Ka-band (-32 GHz) some improvement in downlink rate may be achieved.

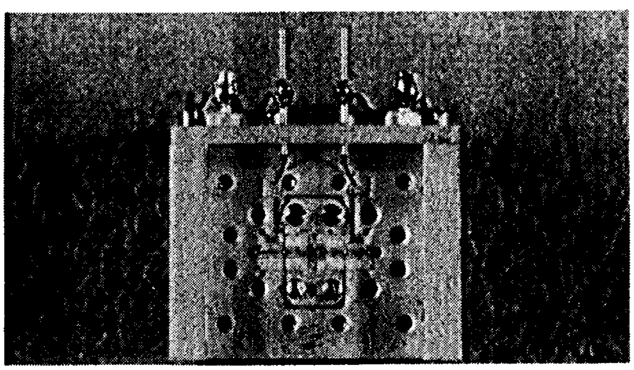

Figure 4. A Ka-band solid state PHEMT amplifier module was constructed by Martin Marietta Astro with substantially improved DC-to-RF efficiencies over current best practice, measured over operating temperature range. Ka-band could speed data return, reducing operating costs.
Photo: Martin Marietta Astro

Advanced monolithic microwave integrated circuit (MMIC) and multi-chip module (MCM) packaging technologies are the key to reducing the receiver portion of the transponder mass by 50% and increasing functionality to include the Command Detector Unit, eliminating a separate physical module. Prime power may be reduced by elimination of unnecessary functions, intelligent frequency planning, new device technology and the possibility of using a transceiver versus a transponder. The latter is a navigation issue being addressed where coherent, two-way ranging might be replaced with less precise ranging plus greater reliance on optical navigation.

Spacecraft Data

The Spacecraft 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 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 of 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 1992 baseline the subsystem had aggressive mass and power targets of 7.0 kg and 6.0 Watts during encounter. Total science data storage volume was 400 Mbits. Use of advanced technology in electronics packaging and low power interface drivers allowed a small mass reduction for the 1993 baseline design while increasing science data storage volume to as much as 2 Gbits.

Attitude Control

The Attitude Control subsystem includes sun and star sensing devices, an inertial reference unit (IRU), electronics for interfacing with the central computer in the Spacecraft 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 sun sensors are used to help determine 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 1992 baseline design has a mass of 2.7 kg and consumes 11.5

Watts of power.

New technology for a star tracker camera weighing <500 grams is feasible by May 1995 with a substantial development commitment now. Related star camera activities are currently underway at Lawrence Livermore National Laboratory for the Clementine Project and it is hoped that lessons learned there and technologies developed can be applied to the Pluto flyby. As a reserve against the possibility that micro star cameras may prove inadequate or difficult to qualify for Pluto, the FY93 baseline ACS mass rose to 6.65 kg.

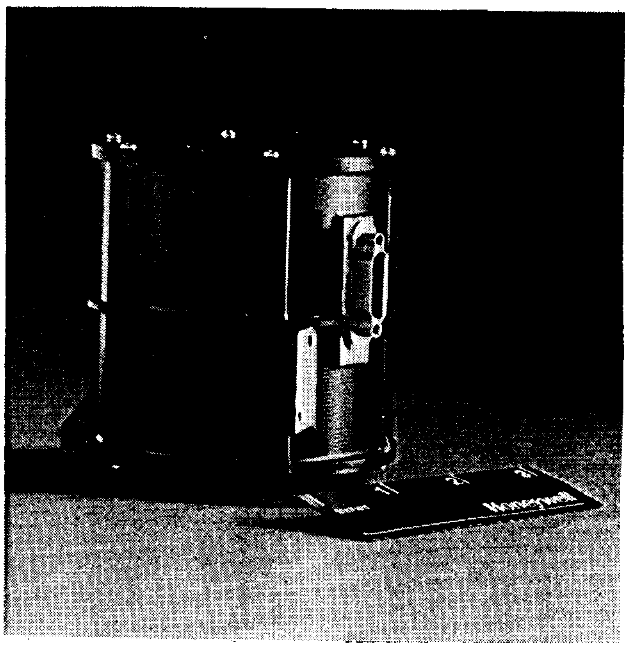

Figure 5. A Honeywell laser inertial reference unit (IRU), developed for ballistic missile intercept vehicles, is currently on loan by Lawrence Livermore National Laboratory to JPL for testing to Pluto mission parameters. Photo: Honeywell

Additional savings in mass and power consumption are currently being investigated in the breadboard stage elsewhere for a low-mass IRU, while test and design qualification activities are planned for the micro star camera.

Propulsion

The propulsion subsystem consists of a monopropellant hydrazine thruster set for providing the required trajectory corrections,

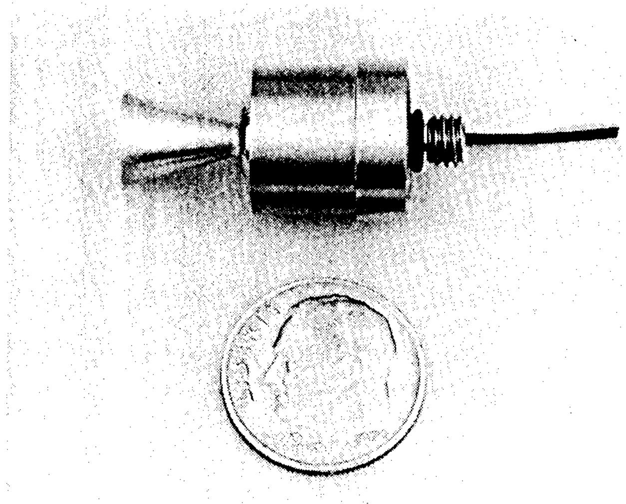

Figure 6. A tiny nitrogen gas thruster is in test to demonstrate 30,000 cycle life required for precise control of the Pluto spacecraft orientation over a long-term mission. 24 such 11 gm thrusters would be used, together using <1.5 kg of gas over the entire mission. Photo: Moog

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 ATI objectives in the RFI were reductions in subsystem mass, gas leakage, and power consumption. From industry responses to the Request for Information, it became apparent that reductions in mass up to factor of five could be realized in several components. Miniaturization of the pressure regulators and valves (service and latch), use of a composite over-wrapped pressurant/propellant tank as used in the fourth stage of the air-launched Pegasus, and a surface tension propellant management device (PMD) were identified as technologies of interest for the Pluto mission. Also identified was a miniature (0.0045 N) cold-gas thruster with improved internal leakage (factor of ten decrease) and cycle life (29,000 increase) specifications with a wider operating temperature range specification. Thruster valve actuation and holding power would also both be reduced. Based on prototype hardware completed for Pluto, a mass reduction from 20 to 9.9 kg appears achievable.

The miniature cold-gas thruster approach meets the thrust, response time, and minimum impulse bit requirements for the Pluto mission and the GN_2 exhaust minimizes potential spacecraft impingement problems. The ATI internal leakage and cycle life requirements will have to be further demonstrated for the approach to be considered a viable one.

With improvements in the injection accuracy, through 3-axis stabilization of the upper stages, plus reductions of the rest of the spacecraft mass, reduction in the mass of hydrazine monopropellant is possible from 24.6 to 6.9 kg.

Structure

The Structure subsystem includes the primary and secondary structure of the spacecraft, electrical and data busses, and separation systems. The structure 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 FY92 baseline features an all aluminum primary structure with a mix of aluminum and graphite-epoxy composite members in the secondary structure utilizing technologies with proven procedures and processes in space applications.

The ATI contractor delivered a composite bus structure weighing 5 kg, allowing the structure subsystem mass to drop from 20 to 14.6 kg.

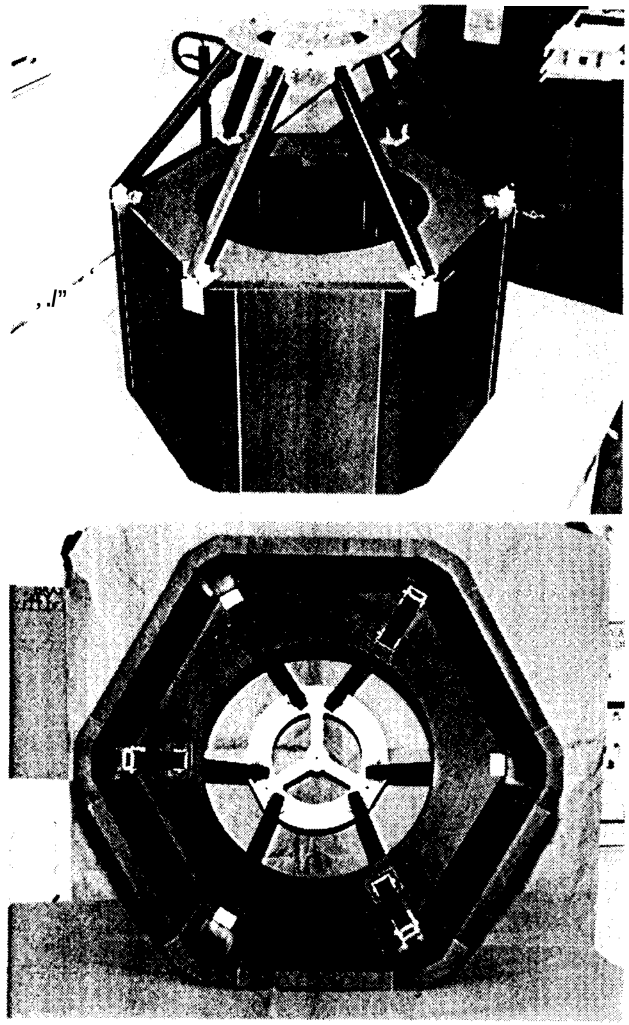

Figure 7. A composite prototype bus, designed at JPL and constructed at Composite Optics Inc., weighs less than the aluminum baseline, carries most components inside, and is designed in thermal zones to ease the radiation of waste RTG heat away from the spacecraft, keep hydrazine propellant above freezing, allow electronics to run cool, and keep sensitive detectors far enough from RTG radiation.
Photos: Composite Optics, Inc.

Thermal Control

This subsystem is basically passive, consisting of blankets, louvers, radiators, and other thermal control paths and insulators. The Radioisotope Power Source (RPS) provides heat to the ΔV thrusters and is situated to help keep the spacecraft warm during cruise. Multilayer insulation (MLI) blankets made from embossed Kapton® or Mylar® material will minimize undesirable thermal energy transfer between elements of the spacecraft. Thermal conduction control, such as the thermal isolation between the spacecraft and the antenna, and thermal enhancement allowing more effective energy conduction from the electronics to radiators that are designed to transfer excess heat from the RPS, keep all the subsystems within tolerable temperatures. Mechanical louvers actuated by a bimetallic device have good radiative properties in the open position and help to hold heat in when in the closed position. "Thermal zoning" design of the spacecraft eliminates the need for small, separate radioisotope heater units, and minimizes the need for controllable electrical heaters.

Kapton® and Mylar® ara registered trademarks of El. DuPont de Nemours & Co.

PLUTO MISSION CONTRACTS & AGREEMENTS

INSTRUMENTS

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

SUBSYSTEMS

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

OPERATIONS

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

OTHER CONTRACTS OR AGREEMENTS

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

TABLE 3

In the 1992 baseline design the mass of the subsystem is 4.0 kg. Power consumption will not exceed 1 Watt for heaters. The use of advanced technology, like high conductivity coatings and structural materials, may help to reduce the mass and decrease the temperature transients experienced by the subsystems. Subsystem mass has been reduced slightly, to 3.7 kg, from the FY92 baseline.

Power

The Electrical Power and Pyrotechnics subsystem consists of a radioisotope power source (RPS) to generate power, power electronics for voltage conversion, regulation, transient peak power output, switching and fusing, and pyrotechnic device initiation (explosive bolts, pyre-valves, etc.).

The 1992 baseline design has a mass of 25.2 kg and generates 63.8 Watts of power after 9 . years of operation. Power is generated by a radioisotope thermoelectric generator (RTG) which uses five general purpose heat source (GPHS) modules. Power consumption of 64.4 Watts during the encounter mode includes 20% contingency for expected power growth as the design matures. Approximately 15 Watts is lost in DC-DC conversion and regulation inefficiency during the highest power modes. The current best estimate for power consumption during downlinking post-encounter (the highest power mode) is 52.31 Watts leaving a meager 22% contingency and margin within the 63.8 Watts power capability. An additional 10% margin is needed in most modes to account for uncertainties in the design process, the decay of the power source and the aging of the spacecraft as a whole.

Advanced technology which was considered for the 1993 baseline design could reduce the mass of the subsystem to -14 kg for the same power output. Technologies such as alkali metal thermo-electric converters (AMTEC) were considered to dramatically increase the efficiency of the RPS, generating the same amount of electrical power using two (GPHS) modules. A prototype AMTEC cell producing 3W with 10% efficiency was developed and delivered to the Pluto team at JPL. Through additional development, a 3W, 16°A efficient cell is expected to be delivered by the end of fiscal 1993.

Other work is on-going with thermophotovoltaic (TPV) converters that convert infrared radiation from the hot surfaces of two GPHSS to electricity using low bandgap photovoltaics. A number of lifetime and risk issues need to be resolved with TPVS before incorporation into the baseline. To begin addressing these concerns, the Pluto ATI program is sponsoring the first scale model demonstration of a simulated GPHS/TPV system. Tests should be complete by the end of 1993. Both AMTEC and TPV systems require a substantial development commitment to be available for the Pluto project by the 1995 technology freeze date.

Because such a commitment was not possible within today's funding profile, neither AMTEC nor TPV were selected for the FY93 baseline, in spite of substantial Pluto ATI-funded progress. A more conservative application of unicouple 'converters, as on *Galileo, Ulysses* and planned for *Cassini*, was selected, permitting a modest mass reduction from 23.2 to 19.4 kg.

Mission Operations

Two possible low cost approaches to Pluto mission operations are being investigated during the ATI phase.

The first approach uses a migration of function approach by utilizing the *Voyager* flight team to fly the two Pluto spacecraft as well. The *Voyager* team has proven their ability to conduct successful planetary flyby operations and would be supplemented with selected Pluto specialists in the areas of mission planning, navigation, instruments, and spacecraft. This combined approach would draw heavily on JPL's Advanced Multimission Operations System (AMMOS) which is supporting current *Voyager* operations.

The second low cost operations approach being evaluated has been developed under a JPL contract at the University of Colorado (CU), Boulder based on experience with Solar Mesosphere Explorer. [11] In this approach, JPL would provide Deep Space Network (DSN) tracking and navigation, and CU would develop a simple and unified mission operations data system as a network of operations stations at JPL, universities, and science investigator facilities. Many routine operations would be accomplished by a remote-site operations team of students and professionals with JPL experts extending the operations team for critical or anomalous events and advising the university students. The primary, JPL-based, control center would direct the encounter and other critical events, and each site would serve as a backup to the other.

Additional reductions in operations costs can be realized by applying technological advances in the development phases of the strawman instrument package, spacecraft, mission and ground operations design that permits long periods of unattended operations during cruise. Eight hours of tracking and data collection per week would be made using the DSN to check up on the two spacecraft with the following attributes:

- a spacecraft engineering data return strategy that takes advantage of on-board data processing and analysis to minimize the amount of engineering data that needs to be downlinked and analyzed

- spacecraft command and control capabilities that allow cruise commands to be uplinked without simulations and elaborate 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

- capable on-board data management that permits capture and storage of all the science data collected during flyby and allows for on-board selection, compression, and return over a limited downlink (40 to 160 bps) via daily DSN passes for up to a year after the flyby

- early and continued interaction among the operations and data system design teams, the science investigator team, and the spacecraft design team to ensure that the Pluto mission operations and data system is specifically tailored, developed, and evolved to meet the needs of its users at lowest possible cost

- a progressive development philosophy where the basic mission operations and data system is developed at the start of the project; used to support prelaunch development, subsystem test, spacecraft test, calibration, and post-launch operations; and progressively grown 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 as part of the integrated end-to-end mission operations and data system.

Further developments of a single ground data system will allow using the same terminals and workstations which can be configured to operate either of the two spacecraft throughout their life cycle.

Student Involvement

University students have already been involved in the initial preproject development stages and will continue to be an important part of the Pluto team through to the end of the mission. Students from Caltech and other institutions built the first full-scale mockup of the spacecraft as the very first deliverable hardware. A competition among universities to design an adapter that unites the spacecraft to the upper stage solid rocket motors (SRMs) was recently concluded, with students at Georgia Institute of Technology providing the winning entry, based on Japanese/American developments of the Institute of Space and Aeronautical Sciences. Mockups of the upper stage SRMS with their adapters have also been delivered by students. Visualization tools from CU and Occidental College students are currently in production.

Other student activities are summarized on Table 4.

Summarv and Conclusions

A scientifically exciting initial reconnaissance of

Table 4 PLUTO MISSION STUDENT ACTIVITY STATUS 10/08/93

- **Allocations for FY93 student projects:**
  - **$100K from Code C funds**
  - **$57K from Code S funds**

- **The stats:**
  - **78% of the money went out to schools/ students**
    - **balance: 6% in-house testing, 3% reserve, 13% contractual overhead**
  - **18 schools involved**
  - **3 schools are minority institutions or HBCUs**
  - **over 40 students are significantly involved with Pluto Fast Flyby world-wide**

Subsystem	University	Current Status	Project
Telecom	U of Michigan	done 9/20/93	Build low-loss power divider
Instruments/ S/C-System	Caltech/ N. Az. U. (MI)	payload done	Payload design, s/c mockup
Structure/ bus	Utah State U	on contract	Build isogrid bus structure
End to End Info. System	Central State U (HBCU)	on contract	Build data flow architecture sire.
Structure	Harvey Mudd	finished	Design and build stack adapters
Flight Computing	U of Baltimore	have final report	Recommend data compression
Propulsion Stack	Caltech	in progress	Build stack motor mockups
Flight Computer	Stanford	on contract	Build low power CMOS chip
Trajectory Science	1Occidental College	in progress	Animation of Pluto/ Charon flyby
Trajectory	Purdue	Master's thesis	Pluto & Follow-on Trajectories
Mission	Southampton (UK)	Bachelor's Thesis	Pluto mission alternatives
Adapter Competition			Design and build S/C adapter
	-U West Virginia	-delivered report	
{These 7 universities	-Manhattan College	-delivered abstract	
participated,	-Georgia Inst. of Tech	-delivered h/w and report	Winner.
Abstracts delivered June 28.	-U of Naples (Italy)	-delivered abstract	
$ awarded 10/93}	-Tuskegee U (HBCU)	-delivered abstract	
	-U of Central Florida	-delivered abstract	
	-U of Maryland	-delivered abstract	

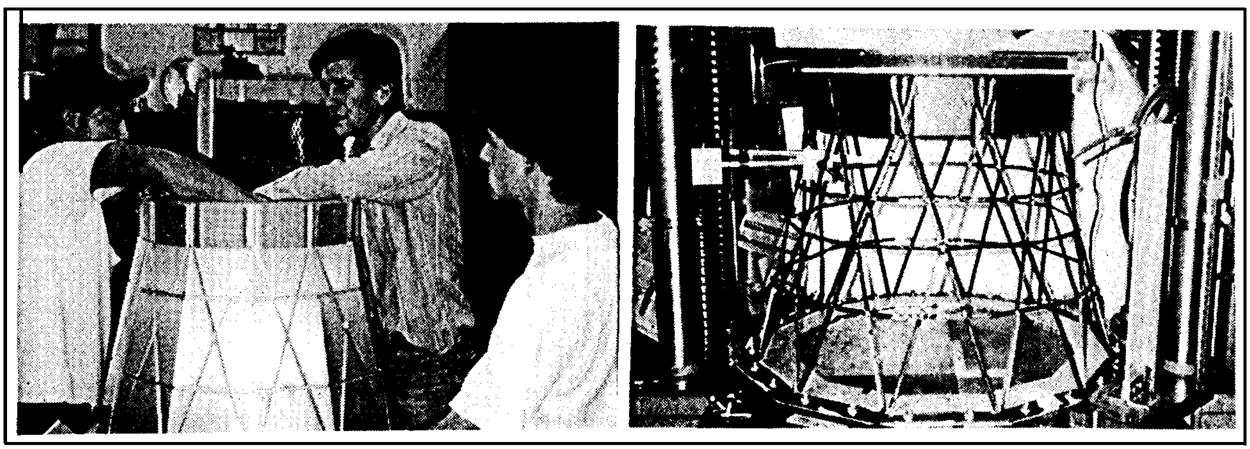

Figure 8. Responding to a challenge to deliver a prototype structure adapter between the baseline Thiokol Star 27 propulsion stage and the Pluto spacecraft, Georgia Tech students designed and built this composite dodecahedral lattice cone adapter weighing 2 kg, compared to a goal of "under 12 kg." "Further loading tests may show a need for greater mass. Larger prototype adapters for the lower stages were deliverad by students at Harvey Mudd College.
Photos: Georgia Institute of Technology

Pluto and Charon is possible within a strict cost cap. Technologies pioneered for small Earth orbiters, and in some cases advanced further through NASA support for the Pluto mission, enable spacecraft mass and operations cost reductions far below what was thought possible as little as two years ago. Present efforts are focused on demonstrating the viability of new subsystem and instrument components, and an innovative development, test and operations approach, through procurement and testing of proof-of-concept hardware and software. Mission resource constraints are being tightened even further, so recent work represents a head start toward reaching aggressive goals of life cycle cost and technology improvement within a first-class scientific mission to unexplored Pluto and Charon.

Acknowledgements

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under sponsorship of NASA's Office of Space Science and the Office of Advanced Concepts and Technology.

The authors are grateful to all the Pluto Team members and contributors, and for the considerable assistance from their respective institutions as noted on the map (Fig.3), including NASA Lewis Research Center, U.S. Department of Defense, U.S. Department of Energy, Southwest Research Institute, Martin Marietta Corporation, University of Colorado, Boulder, University of California, Los Angeles, University of Baltimore, University of Arizona, Occidental College, Harvey Mudd College, Utah State University and all the other organizations noted in Table 3, members of the Technology Challenge Team chaired by Dr. Lew Allen, and the Outer Planets Science Working Group, chaired by S. Alan Stern.

References

1. David H. Collins, "Pluto Flyby Study, " Presentation to the Discovery Program Science Working Group, (internal document), Washington, DC, 16 May 1990.

2. Robert Farquhar, S. Alan Stern, "Pushing Back the Frontier: A Mission to the Pluto-Charon System," The Planetary Report, July/August 1990.

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

4. R.L. Staehle, 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.

5. Robert L. Staehle, 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.

6. Robert L. Staehle, 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.

7. Glen J. Kissel, "Attitude Control for the Pluto Fast Flyby Spacecraft, " SPIE/International Symposium and Exhibition on Optical Engineering and Photonics in Aerospace and Remote Sensing, Orlando, Florida, April 12-16, 1993.

8. C.G. Salvo, "Small Spacecraft Conceptual Design for a Pluto Fast Flyby Mission, " AIAA-93-1003, AIAA/AHS/ASEE Aerospace Design Conference, Irvine, California, February 16-19, 1993.

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

10. Robert L. Staehle, 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, "Pluto Mission Progress: Incorporating Advanced Technology, " Seventh Annual AIAA/Utah State University Conference on Small Satellites, Logan, Utah, September 13-16, 1993.

11. 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.