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[Editor note: a small number of significant changes were made since this was faxed to you in November. Please use this copy as your editing baseline. Please contact me if you have any questions. -Randy Cassingham]

Last But not Least: the Trip to Pluto

by Robert L. Staehle[1], Randy Cassingham[1], John Carraway[1], Peggy Easter[1], Elaine Hansen[2], Paul K. Henry[1], S. Alan Stern[3], Richard Terrile[1], and Stacy Weinstein[1]

As a planetary system, Pluto is small in size but big in mystery. Pluto's neighbors, the gas giants, almost make it an insignificant speck in the outer Solar System. It wasn't even discovered until 1930, and its relatively huge moon Charon wasn't discovered until 1978. But this pint-sized binary planetary system has captured the popular imagination more than perhaps any other planet save Mars.

Its very remoteness has both fueled our imagination and made it a difficult place to visit. Known as the "farthest planet" from the Sun, its highly elliptical 248-year orbit is sometimes —

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as it is now — inside Neptune's, making it the "farthest planet. . . most of the time" . But in 1999, as it heads away from perihelion, Pluto will again cross outside Neptune's path, and will reign as the king of distance until 2227. And it is for this reason, its rapid departure from its relative closeness to the Sun, that gives urgency to the human probing of its secrets.

NASA's Jet Propulsion Laboratory has proposed a highly focused, low mass and low cost mission to Pluto by two spacecraft to perform the first reconnaissance of the only known planet left unexplored. Aiming for separate 1999-2000 launches, it is hoped both spacecraft will reach Pluto before its atmosphere freezes into a dusting of snow.

Exploring the Pluto/Charon System [II

Pluto's inclined and eccentric orbit. of the Sun carries it between about 30 and 50 AU, so Pluto exhibits a wide seasonal range. Pluto is known to have a thin atmosphere and quite a large moon, Charon[4], which orbits at a distance of about 20,000 km. Charon rotates around Pluto with a period of 6.39 days --- the same length as Pluto' s rotational period. Interest in Pluto and Charon has increased since the 1989 encounter with Neptune's moon Triton by Voyager 2. Triton is a near twin of Pluto in size and albedo, and has revealed an extremely complex geology, with active surface eruptions, polar ice caps, seasonal volatile changes, and limb hazes. These revelations fuel scientific imaginations about what might be found on Pluto and Charon. Only a spacecraft encounter can provide this kind of information.

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[4] "Charon" is pronounced with *Char* as in "shark" and *on* as in "on and off", with the accent on *Char*.

As Pluto has only recently passed perihelion, its surface is the warmest it will be for two centuries. It is essential that the system be explored before the 2020s; as the planet races from the Sun, its atmosphere will freeze and fall to the surface, where it will lay until evaporated by the next "close" encounter with the Sun.

The key questions to be answered about Pluto and Charon concern the origin of this "dual-planet" system and its relationship with the rest of the Solar System. Recent Hubble Space Telescope images were the first to distinctly resolve Pluto from Charon, revealing that they orbit a barycenter about 900 km above Pluto's surface. As suspected, Pluto's estimated density (~2.1 g/c^3) is higher than Charon's (~1.3 g/c^3) . Because of a greater uncertainty of Charon's diameter, its density estimate is less certain, but clearly it is different enough to indicate distinct compositional differences between the two. By its density, we can infer that Pluto has a substantial rocky component . A very tenuous atmosphere containing methane has been detected around Pluto using stellar occultation. There is also spectral confirmation of nitrogen, carbon dioxide, and methane ices on Pluto, and water ice on Charon. At surface temperatures of perhaps 40 K, 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. One awaits a spacecraft mission to learn if this is indeed the case" [1].

Ground-based measurements have shown that Pluto's surface reflectance varies, with some longitudinal variations and asymmetrical polar caps [2] . 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 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. Certainly, there is much to learn: each first planetary encounter has brought many complete surprises.

Primary Scientific Objectives

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, and are listed in Table 1. The three category "la" science objectives were identified as the highest priority required for this first mission, with the "lb" and "1c" category objectives considered desirable but non-essential. Note there is no ranking implied within the categories.

Table 1 -- Pluto Core Measurement Objectives

1a	Characterize Neutral Atmosphere Characterize Global Geology and Morphology Surface Composition Mapping
1b	Surface and Atmosphere Time Variability Stereo Imaging High Resolution Terminator Mapping Selected High Resolution Surface Composition Mapping Characterize Ionosphere and Solar Wind Interaction Search for Neutral Species Search for Charon's Atmosphere Determine Bolometric Bond Albedos Surface Temperature Mapping
1c	Characterize Energetic Particle Environment Refine Bulk Parameters (R, M, ρ) Search for Magnetic Field Search for Additional Satellites and Rings

The goal of an initial reconnaissance of the Pluto-Charon system is to understand the physical and geological processes on the surface, the surface composition, and the composition and nature of any atmosphere found on Pluto and Charon. We believe that these top-priority objectives can be met within the cost, size, and mission time constraints of a very small spacecraft mission, but to do so will require new developments in instrumentation (described below) . It is anticipated that the baselined spacecraft and instrument package will provide comparable or better scientific coverage of Pluto and Charon than was provided by *Voyager* at Triton.

To meet the category 1a science objectives, a series of measurement requirements were generated based on current knowledge of the Pluto-Charon system. These requirements were used to guide the design of the Pluto ' 'strawman' ' , or example, mission science payload. The specific measurement requirement.s for each of the Category la objectives are:

Geology and Geomorphology

Monochromatic Mapping: Obtain 1. km/lp (line pair) monochromatic global coverage of both Pluto and Charon. The resolution requirement is to be obtained at the sub-spacecraft point in each image; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the sub-spacecraft point.

Color Mapping: Obtain 3-10 km/lp global coverage of both Pluto and Charon in 3-5 color bands. The resolution requirement is to be obtained at the sub-spacecraft point in each image; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the sub-spacecraft point.

Phase Angle Coverage: Obtain sufficient imaging at moderate and high phase angles to specify the phase integrals of Pluto and Charon .

Image Dynamic Range and S/N: For all imaging, provide dynamic range to cover brightness contrasts of up to 30 (i.e. , normal albedo between 0.03 and 1) with an average S/N goal of about 100. 'l'he darkest portions are expected to produce a lower S/N.

Surface Composition Mapping

Mapping Coverage and Resolution: Obtain infrared spectroscopic maps of at least one hemisphere of Pluto and Charon with 5-10 km/pixel resolution. If payload accommodations permit, obtain this coverage globally. If payload accommodations do not. permit global coverage at this resolution, obtain infrared spectroscopy maps with a resolution of at least. 50–100 km/pixel on the non-closest approach hemispheres of each body.

Spectral Coverage and Resolution: For each spatial resolution element, obtain a spectral resolution of 300 over the entire region 1 .0-2.5 μm or a resolution of 400 over the entire region 1.5-2.5 μm.

Mapping S/N and Dynamic Range: Obtain S/N >100 everywhere, with sufficient dynamic range to meet this requirement.

Neutral Atmosphere Characterization

Composition: Determine the mole fraction of N_2, CO, CH_4, and Ar in Pluto's atmosphere to at least the 1% level. Minor constituent composition is a 1b objective.

Thermosphere Thermal Structure: Measure T and dT/dz at 100 km resolution to 10% accuracy at densities down to $10^9 cm^{-3}$.

Aerosols: Characterize the optical depth and distribution of near-surface haze layers over Pluto's limb at a vertical resolution of 5 km or better.

Lower Atmosphere Structure: Measure T and P at the base of the atmosphere to accuracies of 0.1 μbar and ±1 K.

It is required that these specific measurement requirements be obtained despite several constraints: a flight time of 7-10 years, a nominal flyby velocity of 12--18 km/see, use of two spacecraft, a technology freeze in 1995 for a fiscal 1996 new start, a payload mass allocation of 7 kg, a payload power allocation of 6 W, a Pointing stability of 10 prad/see, and a cost. allocation of '$30 M (of a total life cycle project cost of $450-750 M in FY 1993 dollars) . This is in addition to the givens of being at Pluto: very low photon flux (Pluto's distance from the Sun at encounter will be over 30 AU), and the extremely tenuous atmosphere to be measured.

"Strawman" Science Payload

To see if a set of instruments could be put together to meet the stated science requirements and still keep within the mandated spacecraft and mission constraints, a "strawman" payload was defined. The strawman instruments described below are not by any means final. descriptions; the instruments that will actually fly will be selected from proposals submitted in response to a future Announcement of Opportunity.

The concepts employ advanced materials and electronics, novel optical arrangements, shared optics, and highly integrated packages, some of which were developed for other projects (e.g. , the Strategic Defense Initiative) . Breadboards of critical items are due by the end of April, 1994. " Science requirements creep" will be avoided by issuing early, well-defined science measurement objectives and by making principal investigators responsible for accommodating the impacts of added requirements within their available resources.

Example Visible Imaging System

- **Visible Imaging System —** Telescope: Richey-Chretien optics (all reflecting); 750 mm focal length, 75 mm aperture.
- Visible **CCD Camera —** 1024×1024, **7.5** μm pixel Loral CCD; 10 μrad resolution; 0.6 deg. field of view; 4-8 position filter wheel and/or grism; shutter.

This example Visible Imaging System meets the geology and geomorphology objectives by providing the capability for subkilometer imaging resolution while the" spacecraft is inside of 100,000 km range. Complete color coverage will be obtained inside of 500,000 km. With the relatively short readout times, there will be sufficient time to carry out the observations. The data compression and encoding plan will allow all the data to fit within the spacecraft's memory.

Example Infrared Mapping Spectrometer

- **Telescope —** Same optics as CCD camera. 75 mm aperture for a 42 µrad resolution at 2.5 µm.
- **Focal Plane —** Mirrored slit alongside visible CCD at focus; grating spectrometer onto infrared detector.
- Infrared Detector — 256x256, 40 µm pixel NICMOS HgCdTe array; $\lambda/\Delta\lambda \sim 300$ over 1.0 to 2.5 µm; detector flight qualified by the Hubble Space Telescope; pixel field of view is 53 µrad; push-broom imaging.

The Infrared Mapping Spectrometer example shares the same foreoptics and some signal chain electronics with the example Visible Imaging System. A fixed grating would provide sufficient spectral resolution and S/N to meet the surface composition science objectives and allow the detection of condensed frosts of CO, CO_2, CH_4, etc. At a range of about 200,000 km, a complete map of Pluto can be measured in about 30 minutes with a spatial resolution of 10 km.

Example Ultraviolet Spectrometer

- Telescope — Separate UVS instrument; use one channel of the *Cassini*-developed ultraviolet spectrometer system to cover extreme ultraviolet.
- Instrument — Single channel covers 55-200 nm; single resolution mode $\Delta\lambda = 0.5$ nm.

The strawman UVS is a single channel, fixed resolution mode *Cassini*-based UVS. It provides a measurement of the composition of the neutral atmosphere by detecting spectral features during the solar occultation and by studying Pluto's airglow. It requires being pointed at the Sun during at least one Pluto occultation, ingress or egress. Additional measurements can be made in direct scanning modes of the surface. This will meet all the neutral atmosphere structure and composition objectives except the measurement of the surface temperature and pressure.

Example Uplink Radio Science Experiment

- **Hardware --** Combined with telecommunications subsystem; ultrastable oscillator (at least 10^{-14} stability over ~1 minute) .
- **Science Drivers –** Surface temperature and pressure profile; solar occultation and Earth occultation nearly simultaneous.

The example Uplink Radio Science Experiment is integrated into the RF telecommunications subsystem and includes several additional components such as an upconverter, mixer, phase detector, and an ultra-stable oscillator. *Mars Observer's* ultra-stable oscillator meets this stability requirement; a prototype is being built to demonstrate needed mass and power reductions. The Uplink Radio Science Experiment provides complementary data to the UVS and completes the temperature and pressure profile to the surface.

Spacecraft Subsystems

The Pluto mission spacecraft. has seven subsystems: Telecommunications (radio frequency) , Electrical Power and Pyrotechnics, Attitude Control, Spacecraft Data, Structure, Propulsion, and Thermal Control .

Spacecraft design has been driven" by three requirements embodying cost, schedule, and performance, in that order. cost is clearly the most important: if at any time during the course of the mission development it becomes apparent to NASA that the development cost cap is going to be exceeded, the Pluto mission team can expect the project to be canceled.

The second spacecraft driver is the need to get to Pluto as quickly as possible. This requisite stems from the Outer Planet Science Working Group science objectives and the implication of a short development cycle and cruise both contributing to lower cost .

The third spacecraft driver, completing the science 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, such as electrical power, 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.

From the fiscal 1992 baseline spacecraft wet mass of 1.65 kg, Advanced Technology Insertion (ATI) work (discussed below) has brought. the mass to <120 kg (wet) for the 1993 baseline design (Table 2). The selection of technologies for incorporation into each subsystem was driven by the desire to:

- reduce mass
- reduce power consumption
- reduce flight time
- keep cost and risk within the mission context.
  take advantage of existing activity in relevant technology areas

Telecommunications

The Telecommunications subsystem consists of a 1.5 m diameter high gain antenna and the RF electronics. In the 1992 baseline design, the mass of the subsystem is 25.2 kg, and power consumption is 28 W while transmitting. Both the transmit (downlink) and receive (uplink) signals operate at X-band (-8 GHz). The downlink rate is about 80 b/s at Pluto encounter range to a 34 m Deep Space Network station. A higher rate of '320 b/s 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 W while transmitting. In addition, a Ka-band (-32 GHz) option is in development, which could improve the data rate.

Advanced monolithic microwave integrated circuit and multi-chip module 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.

Power

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

The 1992 baseline design has a mass of 23.2 kg and generates 63.8 W of power after nine years of operation. Power is generated by a radioisotope thermoelectric generator, which uses five general purpose heat source modules. Power consumption of 64.4 W during the encounter mode includes a *20%* contingency for expected power growth as the design matures. Approximately 15 W is lost in DC-DC conversion and regulation inefficiency during the highest power modes. The current best estimate for power consumption during post-encounter downlinking (the highest power mode) is 52.31 W, plus contingency. 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 “]4 kg for the same power output. Technologies such as alkali metal thermoelectric converters (AMTEC) were considered to dramatically increase the efficiency of the subsystem, generating the same amount of electrical power using two general purpose heat source (GPHS) modules. A prototype AMTEC cell producing 3 W with 10% efficiency has been developed. Through additional development, a 3 W, 16% efficient cell is expected to be delivered soon. Other work is ongoing with thermophotovoltaic (TPV) converters which convert infrared radiation from the hot surfaces of two GPHS modules to electricity using low bandgap photovoltaics, but a number of lifetime and risk issues need to be resolved before their incorporation into the baseline.

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 1993 baseline, in spite of substantial Pluto ATI-funded progress. A more conservative application of unicouple converters, as on *Galileo* and Ulysses (and planned for *Cassini*), was selected, permitting a modest mass reduction from 23.2 to 19.4 kg.

Attitude Control

The Attitude Control subsystem includes Sun and star sensing devices, an inertial reference unit, 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 W of power.

New technology for a star tracker camera weighing <500 grams appears feasible by 1995. Related star camera activities are currently underway at the Lawrence Livermore National. Laboratory for the Clementine Project and it is hoped that lessons learned there can be applied to the Pluto mission. As a reserve against the possibility that micro star cameras may prove inadequate or difficult to qualify for Pluto, the 1993 baseline Attitude Control System mass rose to 6.65 kg.

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

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 W 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.

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 power system-induced radiation environment. The 1992 baseline featured 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 prototype composite bus structure weighing 5.7 kg, allowing the structure subsystem mass to drop from 20 to 14.6 kg in the 1.993 baseline. This structure is undergoing acoustic testing.

Propulsion

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.

Principal objectives for the Propulsion subsystem design are reductions in subsystem mass, gas leakage, and power consumption. The miniature cold-gas thruster approach meets the thrust, response time, and minimum impulse bit. requirements for the Pluto mission and the gaseous nitrogen exhaust minimizes potential spacecraft impingement problems.

From industry input, 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 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 (a 29,000-cycle 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 20.1 to 9.9 kg appears achievable.

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 from 24.6 to 6.9 kg is possible.

Thermal Control

This subsystem is basically passive, consisting of blankets, louvers, radiators, and other thermal paths and insulators. The radioisotope power source provides heat to the AV thrusters and is situated to help keep the spacecraft warm during cruise. Multi layer insulation blankets 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 power system, 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. The “thermal zoning” design of the spacecraft eliminates the need for small., separate radioisotope heater units, and minimizes the need for controllable electrical heaters.

In the 1992 baseline design, the mass of the subsystem is 4.o kg. Power consumption will not exceed 1 W 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 1992 baseline.

Table 2 — Spacecraft Baseline Mass Allocations

Subsystem	**1992 Baseline** (kg)	**Goal** (kg)	**1993 Design** (kg)
Telecommunications	25.2	16.8	12.75
Electrical Power	23.2	12.5	19.4
Attitude Control	2.7	2.1	6.65
Spacecraft Data	7.0	4.5	6.5
Structure	20.0	14.6	14.6
Propulsion	20.1	13.1	9.9
Thermal Control	4.0	3.5	3.7
Science Payload	9.0	7.0	7.0
Total	111.2	74.1	80.5
Contingency	29.5 (26.5%)	20.1	31.3 (38.9%)
Total Dry Spacecraft	140.7	94.2	111.8
Propellant (ΔV M/S)	24.6 (350)	16.1 (350)	6.9 (130)
Total Wet Spacecraft	165.3	110.3	118.7

Trajectory [3]

A wide range of trajectory types “to Pluto are available for missions using low-mass spacecraft in the late 1990s through the early 2000s. In order to minimize flight time, launch energy (C_3) and post-launch AV – while also providing desirable launch and backup opportunities – direct trajectories are preferable. Other trajectories, including Jupiter and Venus gravity-assist trajectories, have been considered. Currently, a direct trajectory is baselined [Editor: insert trajectory figure reference here] . With no gravity assist requirements, a direct launch to Pluto is possible every year; gravity assist trajectories offer more limited options, longer flight times, and higher operations costs.

Only ballistic (high thrust) trajectories were considered. These include: direct, Jupiter gravity assist (JGA), two- and three-year Earth Jupiter gravity assists (2,3-ΔVEJGAs), and combinations of Venus Earth Jupiter gravity assists (VEJGAs) . While low thrust (e.g., solar electric) trajectories appear attractive on paper, equipment of the capability required to perform this mission is unlikely to be available until well after *2000.*

Direct

Conceptually, the simplest trajectory goes direct from Earth to Pluto. Since no gravity assists are used, there is a yearly launch opportunity. The down side of direct trajectories is that they require large launch energies; few launch vehicles can inject mass to C_3s much over 110 km^2/s^2 (while ~>250 km^2/s^2 is required) , so additional upper stages are required. In order to have a fast flight time without augmenting the launch vehicle with upper stages, gravity assist trajectories must be used.

Direct with Jupiter Gravity Assist

Jupiter is the only outer planet with the proper orbital phasing and mass to provide a beneficial gravity assist to Pluto in the timeframe of interest. By launching to Jupiter enroute to Pluto instead of going to Pluto directly, the specific launch energy requirement is reduced to the 100-120 km^2/s^2 range. Relative motion of Jupiter and Pluto yields only three JGA launch years per Jupiter-Pluto synodic period (roughly 12.5 years); the next set occurs in 2003–2005, with 2004 being best as flight time, post-launch AV and specific launch energy are minimized for a conservative Jupiter flyby constraint.

Jupiter flyby distance is constrained because of its severe radiation environment. Accumulated electron and proton radiation doses can be quite high inside 14 R_J, risking damage to both the spacecraft and instruments. Increasing the radiation “hardness” (shielding, higher reliability components, etc.) of the spacecraft and instruments will decrease the risk, but with corresponding increases in cost and mass. The constraint on Jupiter flyby distance, then, includes consideration of shielding mass, cost of rad-hard parts, and flight time. In order to keep a low-mass, low-cost spacecraft, a Jupiter flyby constraint of 15 R_J has been used for trade-off analyses. If further analysis shows a closer flyby to be possible within cost and mass constraints, significant flight time reductions could be realized, but launch still. must wait for the appropriate alignment.

Two- and Three-Year AVEJGAS

Launch energies for the JGAs are still. quite high, requiring the use of more capable and more expensive launch vehicles. An Earth gravity assist can be added to the JGA to lower the C_3 at the expense of post-launch AV and flight time with a two- or three-year Earth return trajectory. The spacecraft then picks up a gravity assist and heads for Jupiter for another boost to direct it to Pluto. While this strategy adds two or three years to the overall flight time, the specific launch energies are significantly lower (25–30 km^2/s^2 with minimum post-launch **AVS of**

>1 km/s for the two-year option) , allowing the “use of lower-cost launchers such as the Delta II or Atlas IIAS.

Venus Gravity Assists

Venus gravity assists can also be added to an Earth boost flyby, as one was for Galileo on its VEEGA trajectory to Jupiter. The best opportunity identified so far in the timeframe of interest is a WEJ trajectory in 2000. But there are drawbacks to this trajectory as well. First, there is a deterministic post-launch AV requirement of >2 km/s for the lower flight times. Second, these trajectories require perihelia of 0.7 AU or less; since solar flux scales as the inverse of distance squared, the thermal environment for the spacecraft at Venus is twice as severe as the environment at 1 AU (Earth orbit) . Third, the Venus-Earth synodic period is roughly 1.5 years, which places Earth far from where it should be after only one synodic period. Therefore, launch can occur only every other synodic period, or once every three years, in order to go to Jupiter. While a VVVEGA opportunity has been identified (i.e., no flyby of Jupiter is required) , a very large post-launch AV is required to keep the total flight time under 15 years, making the option unattractive.

Advanced Technology Insertion [4]

NASA’s Office of Advanced Concepts and Technology 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 issued a request for information in November, 1992 and invited over]200 representatives from 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 for possible inclusion into the Pluto mission within the stated mission constraints.

Preliminary ATI work. has resulted in the delivery of the first breadboard products in August 1993, with subsequent deliveries due through June 1994. New technologies for the Pluto mission will be rigorously pursued until the 1995 technology freeze .

Breadboard to Flight Hardware

The introduction of new technology necessarily means flying components for the first time. To reduce risk, “breadboard” hardware has already been built [Editor: reference line drawings of spacecraft] . Many early problems will ‘be worked out at this level where components are inexpensive, different techniques may be easily tried, and reliability is not a concern. Delays introduced by problems discovered and worked out at this stage tend to be far less expensive than delays caused by problems discovered later. More than one breadboard version of a particular subsystem may be built where the benefits and risks of different implementations are uncertain. Much of the breadboard and subsequent equipment will be connected together and tested in JPL's new Flight System Testbed.

The next step is a "brassboard" spacecraft, having functional replicas of most subsystems built separately and then integrated into a partially functional spacecraft. Some subsystems (e.g. , power) will not be functional.; supporting lab equipment will act as surrogates. Other subsystems will be very close to flight functionality and configuration (e.g. , computer and memory equipment, which might differ from flight versions only in their lack of screened electronic parts and completeness and testing of software) . This brassboard will be used to work out nearly all subsystem interface details while there is still time to modify custom hardware and software.

Two flight qualified spacecraft will then be built. The first to be completed will be subjected to system-level flight qualification testing, and refurbished for the second launch. 'I'he other will be launched first. Spares will be built for a third spacecraft.

Students are providing significant support in the breadboard development. In fiscal year 1993, more than 50 students from 23 universities participated in a variety of areas, including a competition to design a prototype adapter between the spacecraft and the" launch vehicle's upper stage (see Table 3) . Students at the Georgia Institute of Technology won the competition; the goal was for the adapter to weigh "less than 12 kg". The students' final composite dodecahedral lattice cone adapter prototype, based on developments made by a researcher at Japan's Institute of Space and Aeronautical Sciences, weighed about 2 kg.

Table 3 — Student Participation in Pluto Mission

Subsystem	**University**	**Status**	**Project**
Tel ecom	U. of Michigan	complete	Build low-loss power divider
'Instruments/ spacecraft system	Caltech, Northern Arizona U.	complete	Payload design, spacecraft mockup
Structure/bus	Utah State U.	in progress	Build isogrid bus structure

End-to-end info system	Central State U.	in progress	Build data flow architecture simulator
Structure	Harvey Mudd	complete	Design and build stack adapters
Flight computing	U. of Baltimore	complete	Recommend data compression
Propulsion stack	Caltech	in progress	Build stack motor mockups
Flight computer	Stanford U.	in progress	Build low-power CMOS chip
'Trajectory/ science	Occidental	in progress	Animation of flyby
Trajectory	Purdue U.	complete	Pluto and follow-on trajectories
Mission	Southampton (UK)	complete	Pluto mission alternatives
Computer	UCLA	in progress	develop computer architecture
Spacecraft systems eng.	U. Texas (Austin)	in progress	Shuttle requirements
Spacecraft systems eng.	RPI	complete	telemetry requirements

End-to-end info system (EEIS)	Trinity	complete	EEIS/testbed architecture
EEIS	U. Colorado (Boulder)	in progress	Ground data system/EEIS
Adapter competition	see below	complete	Design and build vehicle/ spacecraft adapter
	U. W. Virginia		
	Manhattan College		
	Georgia Tech		(Winner)
	U. Naples (Italy)		
	Tuskegee U.		
	U. Central Florida		
	U. Maryland		

Mission Operations and Tracking

Students may also figure highly in mission operations. Lessons learned from using students at the University of Colorado in t-he operation of the Solar Mesosphere Explorer are being considered for achieving low cost, efficient operation of the Pluto mission [5] . Another operations option would integrate Pluto mission operations with t_he Voyager Interstellar Mission, operating all four (two *Voyager* plus two Pluto) spacecraft with a team only slightly larger than that required for *Voyager* alone.

Pluto mission design has considered operations from the outset. Features which contribute to low cost include:

a spacecraft design that permits long periods of unattended operations during cruise. This enables routine cruise operations to be built around a one or two brief weekly Deep Space Network tracking and data collection passes.
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 refined immediately before closest approach to allow for trajectory 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 (80 b/s over 34 m DSN stations; 320 b/s over 70 m DSN stations) via routine daily DSN passes for up to a year following encounter.

Accelerated Procurement

NASA Administrator Dan Goldin demands that NASA Centers do business “faster, better and cheaper”. And NASA is interested in showing the country that it is encouraging the use, and fostering the spread, of new technology. Consequently, JPL has emphasized new ideas such as the teaming with industry and universities to perform Advanced Technology Insertion (ATI) projects and mission operations, as discussed above. The Pluto Preproject is intended as a NASA showcase in the use of advanced technology. [Editor: see sidebar, attached at end of this document]

The Pluto Preproject's ATI effort needed to move quickly to meet schedule pressures and budget cycles, thus creating the need for significant acceleration of procurements. The most important factor in accelerating Pluto procurements was the Preproject manager's recruitment of a procurement representative from JPL's Procurement division, who became an active member of the Pluto team early in the development effort.. Additional negotiators from the Procurement division got involved as needed.

The procurement representative also became very involved in the ATI Request for Information, the first step in the ATI effort . The Preproject and the Procurement division had about a month to organize an industry briefing. Similarly short lead times were enabled for executing 16 ATI contracts by involving negotiators in early planning and training' cognizant engineers to work with them in navigating the complex procurement process.

NASA then issued a NASA Research Announcement for the ATI science instruments and JPL initiated contracts resulting from this process. JPL issued the requests for proposals for prototype spacecraft components and executed the resulting contracts . The Preproject manager specifically did not want any ''study'' contracts. Consequently, all these contracts specified breadboard hardware and software of the new components. Having the procurement representative assigned as a team member resulted in all contracts being let on schedule. With several contract deliveries already complete, all work is within fixed costs negotiated at the outset.

Conclusion

Pluto's distance makes any mission there a challenge. Once considered incredibly remote, Pluto is now clearly within reach, even with significant cost, mass and time constraints. Technologies pioneered for small Earth orbiters, and advanced technology development supported by NASA, universities, and industry, 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. As mission resource constraints grow tighter, recent work represents a head start toward reaching aggressive goals of life cycle cost and technology improvement within a first-class scientific mission.

Arguments for a visit to Pluto and Charon have become more compelling with *Voyager's successes* - and we *should* complete the initial reconnaissance of our Solar System. What measurements we have been able to make from Earth render Pluto and Charon an enigmatic pair, and there is no doubt. that additional important pieces to the puzzle of the Solar System's formation will be revealed with a successful mission to Pluto.

Acknowledgements

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[Sidebar]

Potential Commercial and Educational Benefits from the Pluto Mission

Advanced Technology Insertion contractors were asked to identify potential commercial and educational benefits from their participation in the Pluto mission. Excerpted comments from some of the responses include:

- *Our manufacturing processes are advancing to cope with the demands of the technology of our micropackaged computer. . . baselined for the Pluto flyby mission. This advance in technology may well prompt our next major commercial expansion.* —Richard A. Holloway, SCI Systems, Inc.

  Pluto Fast Flyby can be expected to enhance our industrial competitiveness. . . . The ability to produce miniaturized high technology systems at low cost and on a short time scale will lead to domestic jobs. . . .
  —Martin Goland, Southwest Research Institute

  The efficient, light weight, compact heat-to-electricity AMTEC generator will be attractive for many applications, such as residential natural gas furnace operation independent of the power grid. . . on-site power generation. . . residential cogeneration. . . (and) use in hybrid vehicles to reduce emissions. . . . (S)uccess with AMTEC development will put the U.S. in the forefront of a critical new technology.
  – Thomas K. Hunt, Environmental Research Institute of Michigan

- *The Isogrid structures. . . provide light, strong, high reliability aerospace structures for spacecraft, airplanes, automobiles, and many other products, and improves the* *quality, reliability, safety and "costs of these products. . . . (G)raduate students are doing most of the engineering and fabrication, (contributing) to their experience base, (giving) other students an example of how to be involved in "real" projects. . . (making) real contributions. . . (leading) to highly motivated and enthusiastic students, even among those not directly involved in the project.*

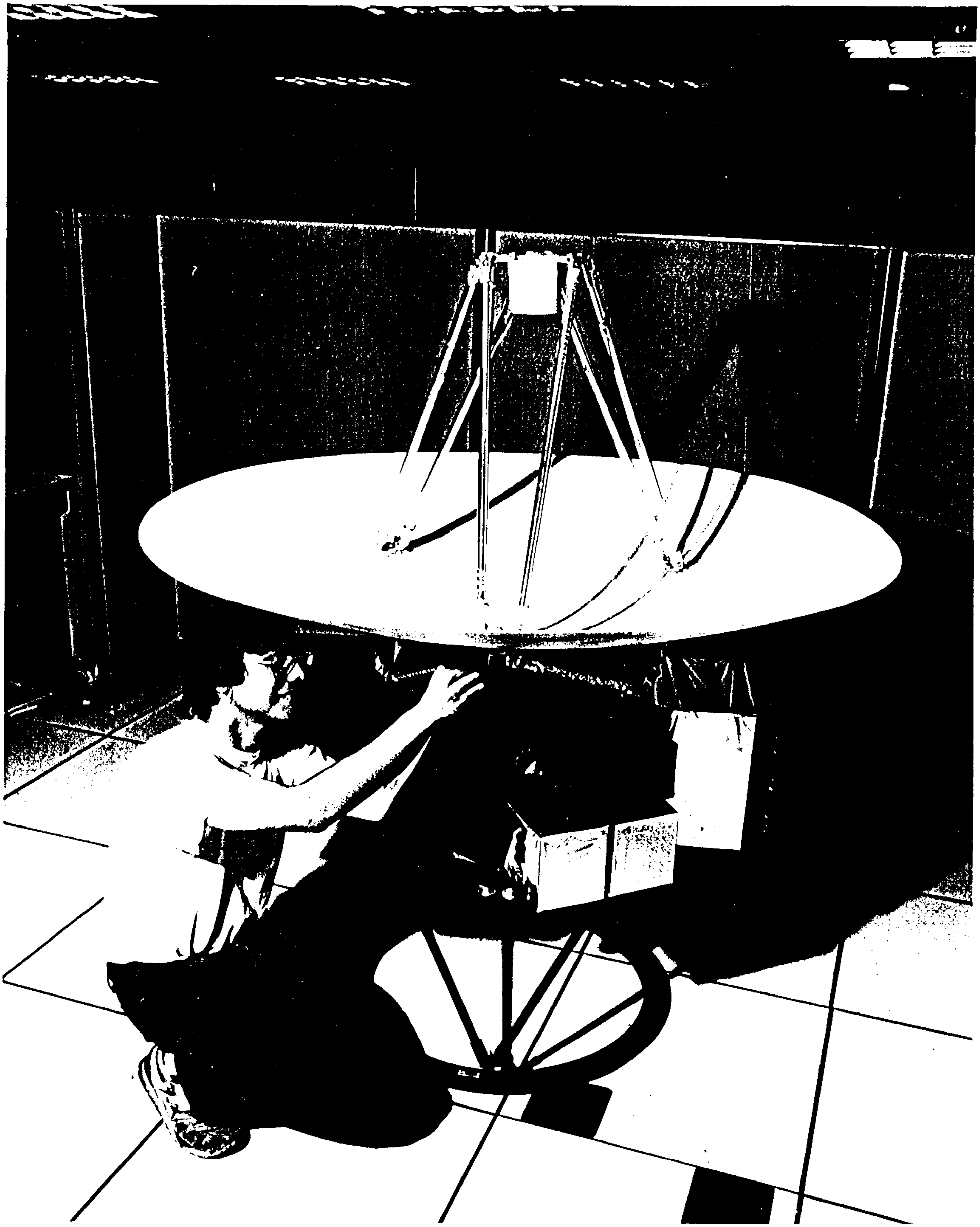
— Dr. Bartell Jensen, Space Dynamics Laboratory, Utah State University

- *The exploration of Pluto nourishes a tremendous national sense of accomplishment. The technical challenges cannot help but provide new technology for power generation, miniaturization, propulsion, and artificial intelligence. The project has already moved into the classrooms here, in astrophysics and critical thinking classes, (which) has already helped many students think on a grander scale.*

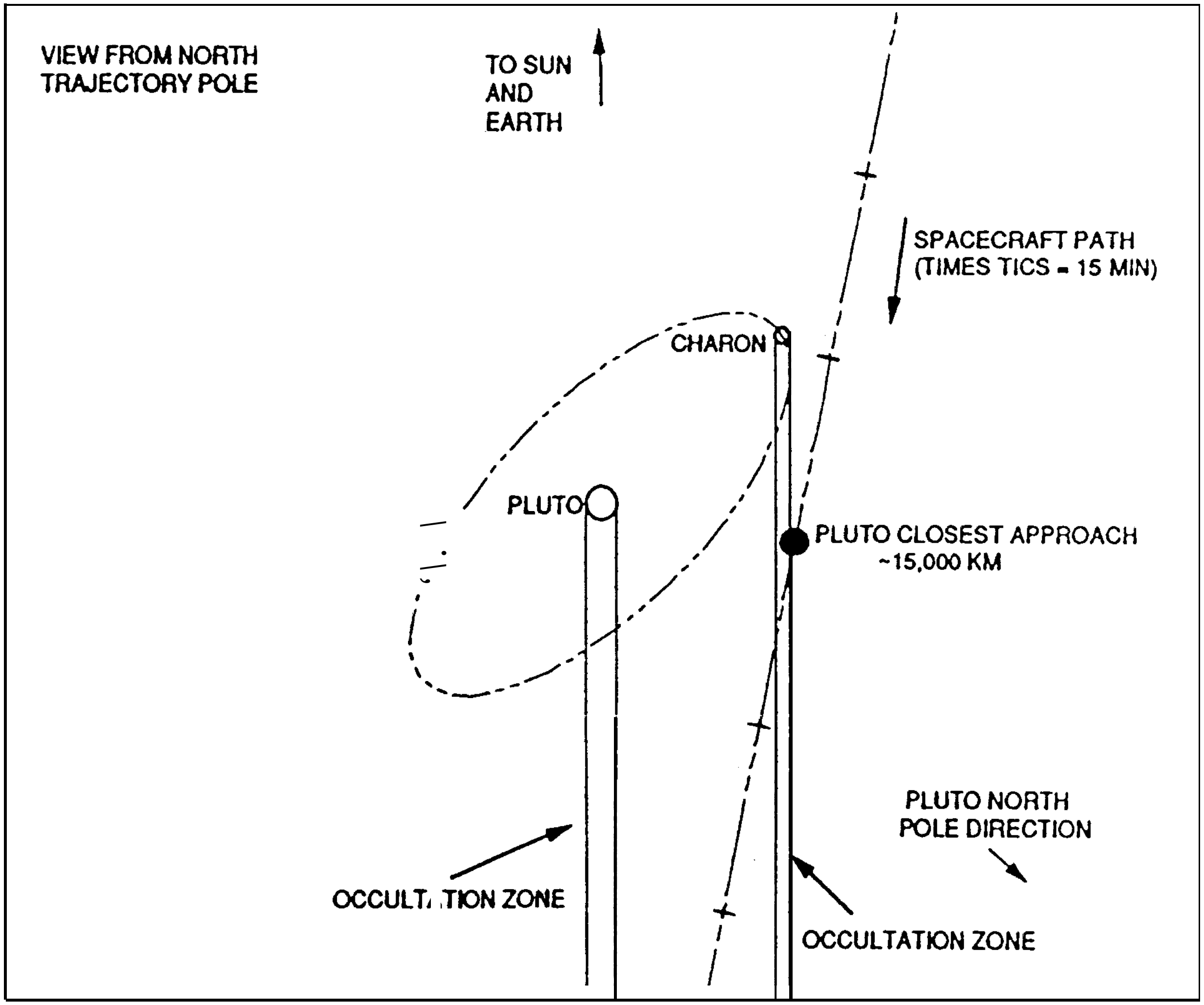
-- George M. Lawrence, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder

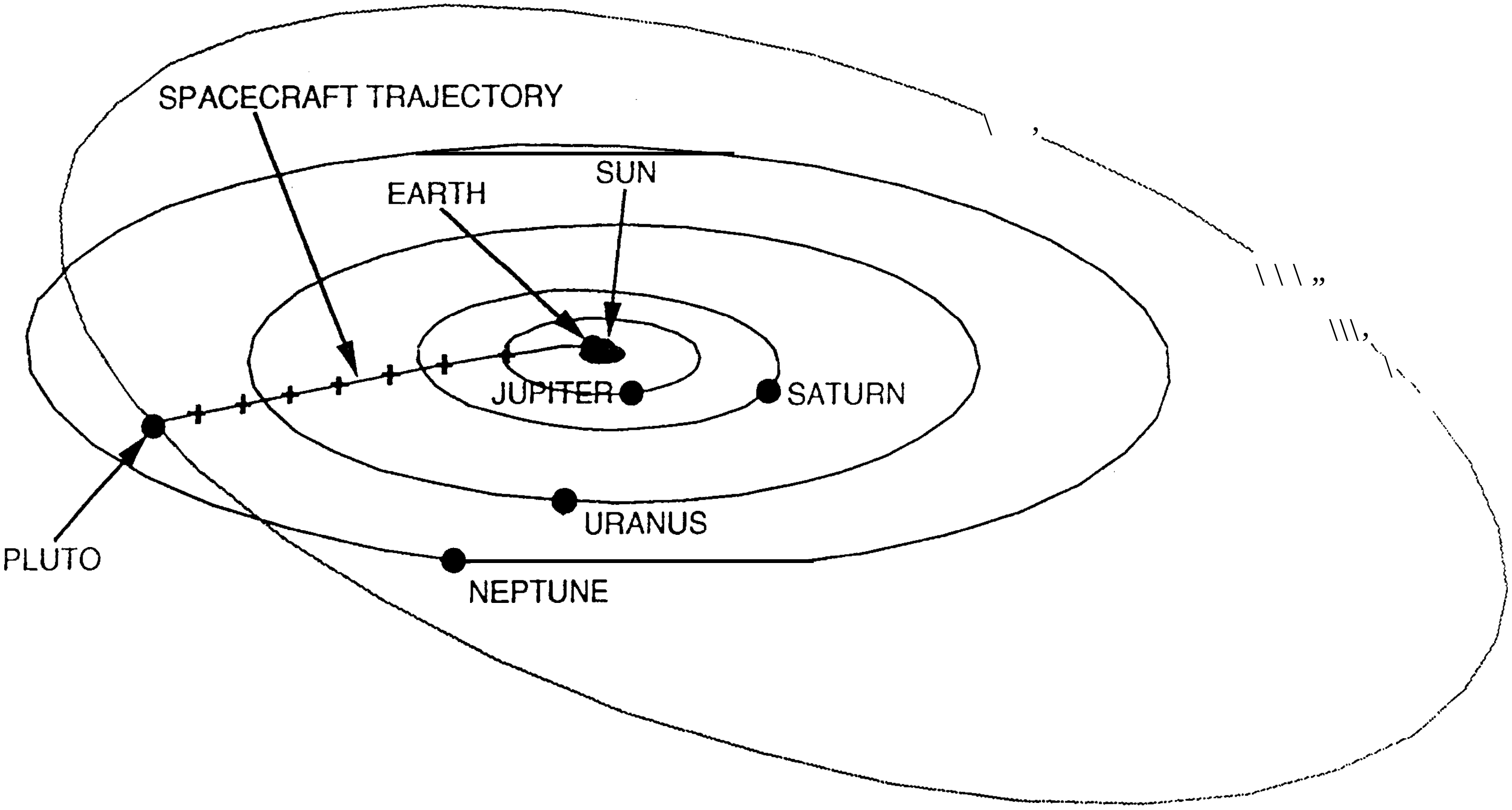
- *One of the biggest impacts. . . at Georgia Tech (has been) the educational opportunities. The six students that participated in the design, building and testing of the adapter learned more about engineering than in any single course that they took. . . . Certain aspects of the mission could be opened up to. . . international collaborative research projects, which benefit not only the countries involved, but also NASA and, most importantly, the students that would be involved in the research.*

— Kurt Gramoll, School of Aerospace Engineering, Georgia Institute of Technology



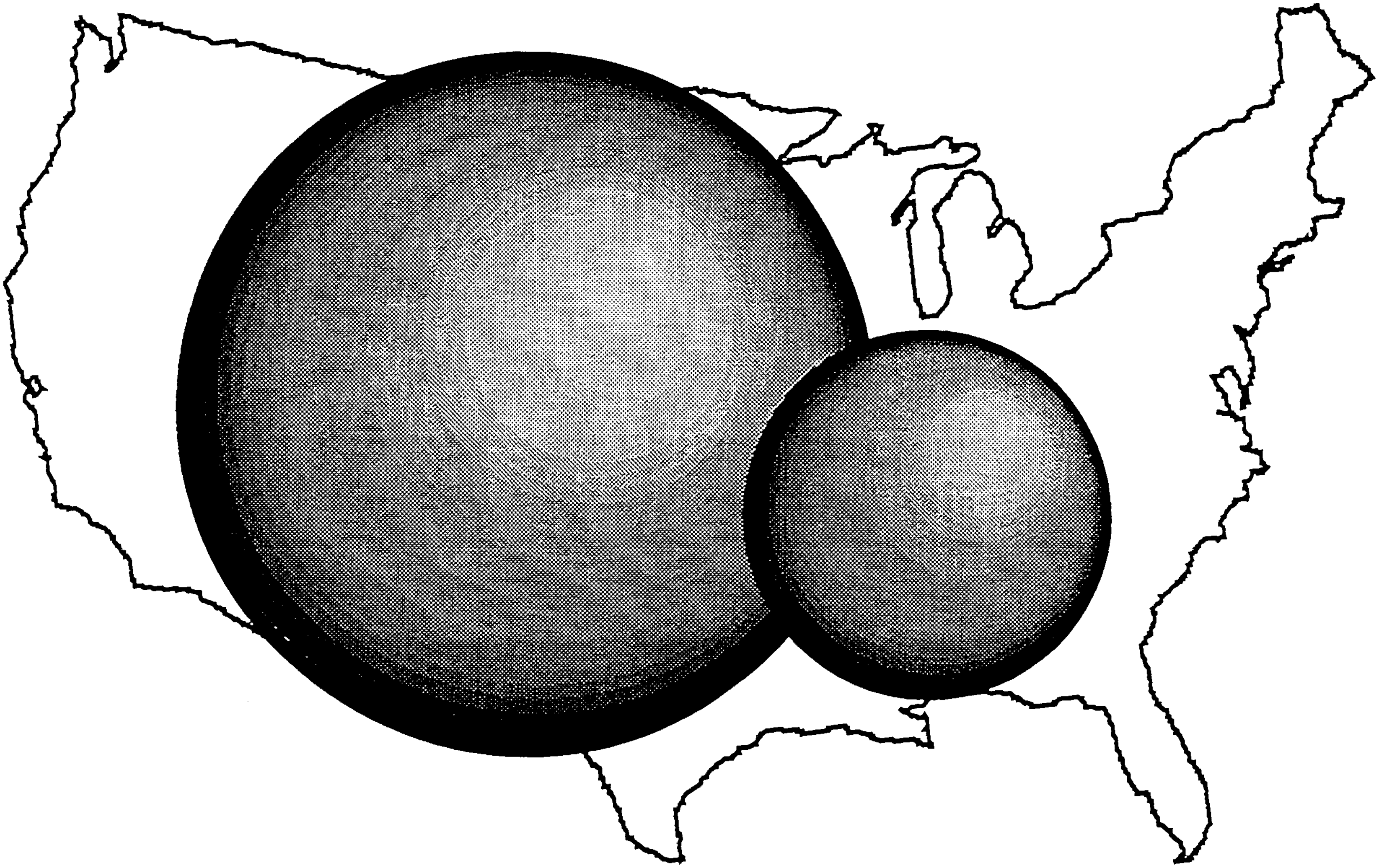
PLUTO VSS: PLUTO/ CHARON FLYBY





Pluto *Fast* Flyby

PLUTO and CHARON



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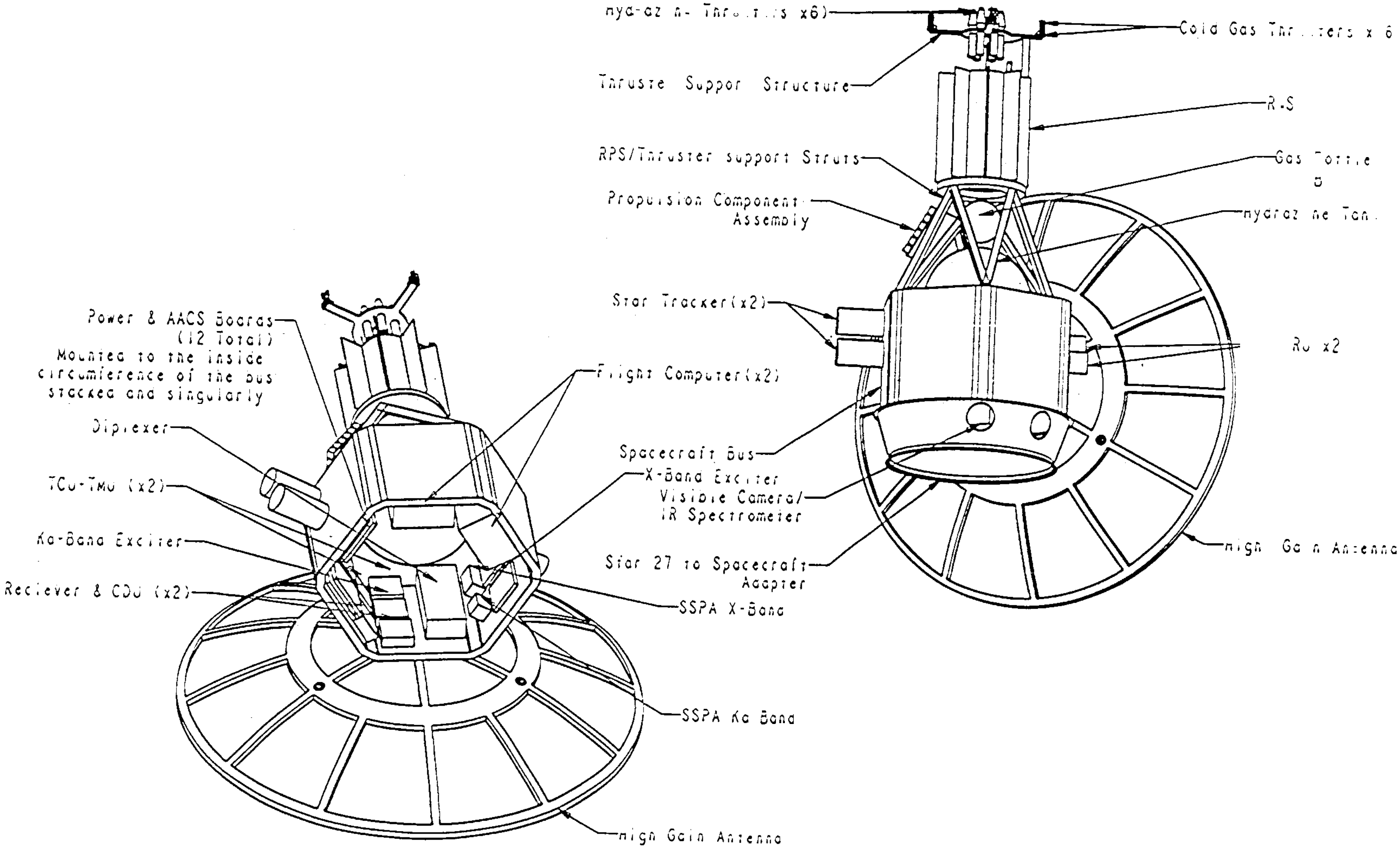
Hydrazine Thrusters x6)
Cold Gas Thrusters x 6
Thruster Support Structure
RPS
RPS/Thruster support Struts
Gas Bottle
Propulsion Component Assembly
Hydrazine Tank
Star Tracker(x2)
Ro x2
Spacecraft Bus
X-Band Exciter
Visible Camera/
IR Spectrometer
Star 27 to Spacecraft Adapter
High Gain Antenna
Power & AACS Boards (12 Total) Mounted to the inside circumference of the bus stacked and singularly
Flight Computer(x2)
Diplexer
TCU-TMU (x2)
Ka-Band Exciter
Reciever & CDU (x2)
SSPA X-Band
SSPA Ka Band
High Gain Antenna