

**Final Report**

**NASA/USRA  
University Advanced Design Program  
at the  
University of Illinois  
for the  
1989-1990 Academic Year**

**by**

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and**

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**Abstract**

This report reviews the participation of the University of Illinois at Urbana-Champaign in the NASA/USRA University Advanced Design Program for the 1989-1990 academic year. The University's design project was the Unmanned Probe to Pluto. Forty-two students divided into seven groups, participated in the Spring 1990 semester. A presentation, prepared by three students and a graduate teaching assistant for the program's summer conference, summarized the project results.

Teamed with the NASA Marshall Space Flight Center (MSFC), the University received support in the form of remote telecon lectures, reference material, and previously acquired applications software.

## Introduction

This is the fifth year that the University of Illinois has participated in the NASA/USRA University Advanced Design Program. This year, however, participation was as a Sustaining Member. Past projects, at the University, have included the Lunar Oxygen Transportation System (1985-86), the Two-bodied Comet Explorer (1986-87), the Manned Marsplane (1987-88), and the Logistics Resupply and Emergency Crew Return System for Space Station Freedom (1988-89). In keeping with the philosophy of studying a new project each year, an Unmanned Probe to Pluto was selected for this year's project.

The project concept was approved by Frank Swalley, the University's contact at MSFC, early in the Fall 1989 semester. Details of the interaction between MSFC personnel and the University were worked out generally in the Fall of 1989 and specifically during the Spring 1990 semester. A condensed calender of events is presented in Appendix A.

## Course Organization

The University's Flight Vehicle Design course, AAE 241, is comprised of two sections, one each for spacecraft and aircraft design. Based on individual interests and introductory information provided at the first class meeting, AAE 241 students choose one of the sections and are usually divided into two independent groups. Of the 87 students enrolled in AAE 241 in the spring of 1990, 45 selected the aircraft section and 42 selected the spacecraft section. The spacecraft section roster is given in Appendix B.

The Request for Proposal (RFP) given to the spacecraft section is presented in Appendix C. This document lists the mission design objectives and constraints and contain several requirement conflicts and ambiguities which had to be resolved by the students.

At the first meeting of the class, students were asked to fill out a questionnaire in order to identify courses they had taken and their preference of technical areas (at the spacecraft subsystem level). Based on these results, the

students were divided into seven competing design groups. Each group was responsible for a complete vehicle design.

The course was under the direction of Professor Kenneth Sivier. The spacecraft section teaching assistants were Andrew Koepke, Section Leader, and Albert Herman and Alan Hope.

Each project group selected its own project leader. The project leaders were responsible for group coordination and preparation of weekly status reports to the section staff.

Twelve homework assignments were assigned in the spacecraft section, exposing all the students to subsystem design analysis. Several of these assignments required the students to make use of software written by the teaching assistants and others and made available on twenty IBM ATs in an open computer laboratory. This software included:

CHEBY2 - low-thrust trajectory and mass optimization program.

MIND - Mechanically Intelligent Designer, an expert system shell for which the students generated design rules to perform conceptual spacecraft design. This program is also serving as an interim planning tool for strategic planning at OSSA under Joe Alexander.

MULIMP - multiple impulse trajectory and mass optimization program.

INERT - program for determining spacecraft composite inertia and mass properties.

SCSIM - scan platform dynamics and control simulation program.

Each student gave a five-minute, midterm, oral, viewgraph presentation representing an RFP response. Emphasis was placed on the identification of requirements and trade studies to be undertaken for the final design. At the end of the semester, a Final Design Report was submitted by each project group and

### NASA/MSFC Remote Lectures

Frank Swalley of MSFC provided reference contacts for University interactions with MSFC. As a result of these contacts, two Marshall engineers participated in remote telecon lectures. Each lecturer provided viewgraphs in advance of his presentation and copies were distributed to the students. A question and answer session followed each lecture, allowing the students to interact with the NASA professionals in a relaxed, albeit distant, manner. MSFC participants were:

Frank Swalley - systems engineering  
Robert Porter - structures

### Other Guest Lectures

In addition to the MSFC telecons, two guest lecturers delivered in-class presentations. Their affiliations and the topics they discussed were:

Mel DeSart - University of Illinois Library System; locating pertinent information from technical sources.

Michael Lembeck - Last year's lead TA; artificial intelligence.

### Results

The resulting designs were presented in the groups' Final Design Reports. Copies of these reports are included with this report. The project Abstract, submitted for inclusion in the Summer Conference agenda, is present as Appendix D. A summary report was filed with USRA on June 22. It is presented as Appendix E.

### Summer Program

Because of the limited funds available as a Sustaining Member, no summer intern assignment was possible this year.

Students, interested in attending the NASA/USRA University Advanced Design Program Summer Conference at NASA Lewis Research Center, were interviewed near the end of the semester. The three undergraduate students selected to attend the conference were George Gunning, Meredith Strinni and Shery Zimmerman. As a dress rehearsal for the summer conference, these three students, along with teaching assistant Alan Hope, made a presentation at a special evening meeting of the University's AIAA student branch on May 2, 1990. The presentation, repeated at NASA Lewis Research Center on June 14, 1990, summarized the class organization, design issues investigated, and results obtained by the design groups.

In addition to the three undergraduates and Hope, sufficient funds were available to allow Professor Ken Sivier and Teaching Assistants Andrew Koepke and Albert Herman also to attend the summer conference.

### Evaluation

One programmic item was still a problem; i.e., because of the geographic locations and a lack of travel funds, it was not possible for the students to visit MSFC or for MSFC personnel to visit the university campus. The quality of the program would have been improved by in-person interactions. If such a level of interaction had been possible, the impact of the program on the students would have been greater and more technically significant and applicable results would have been obtained from the program.

Resources provided by the Advanced Engineering Design Program add credibility and substance to the AAE 241 Flight Vehicle Design course at the University of Illinois. Contact with aerospace professionals working on real problems gives the students a point of reference, early in their careers. In conclusion, University participation in the Advanced Engineering Design Program has been beneficial for all involved organizations.

**Appendix A**  
**Condensed Calendar of Events**  
**AAE241**  
**Spacecraft Flight Vehicle Design Section**  
**Spring 1990**

January 11, 1990	first day of class
January 25, 1990	Mel DeSart, Guest lecture
February 8, 1990	Frank Swalley, teleconference
February 20, 1990	Robert Porter, teleconference
February 22, 1990	Mike Lembeck, guest lecture
March 6 and 8, 1990	oral reports (PDR's)
April 17, 1990	Tiger Team exercise
April 24, 1990	written final reports (FDR's) due
April 24, 26, and May 1	oral FDR's
May 2	Rehearsal for Summer Conference presentation

## Appendix B

### AAE 241, Flight Vehicle Design Spacecraft Design Section Class Roster, Spring 1990

#### Group 1

Fuehne, Douglas  
Herring, Jason  
Lemke, Gary  
Sharkey, Michael  
Sutton, Kevin  
Zayed, Husni

#### Group 2

Behling, Michael  
Buchman, Donald  
Marcus, Andres  
Procopis, Stephanie  
Wassgren, Carl  
Ziemer, Sarah

#### Group 3

Elbel, Jeff  
Hackett, Bruce  
Humphrey, Ted  
Kennedy, Ralph  
Leo, Donald  
Zimmerman, Sheryl

#### Group 4

Endre, Mark  
Hein, Randy  
Kelly, Jonathan  
Meyer, David  
Robinson, David  
Summers, Eric

#### Group 5

Dembowski, David  
Diekhaus, Stephan  
Konkolewski, Kimberly  
McLain, Marty  
Reynolds, Julie  
Treacy, Tim

#### Group 6

Barnstable, Robert  
Jacobs, Jeff  
Kepes, Paul  
Polte, Hans  
Walker, Kevin  
Williams, Stephen

#### Group 7

Eldred, James  
Gunning, George  
Labij, Denis  
Spapperi, Jeff  
Strinni, Meredith  
Wilkinson, Jeff



## **Appendix C**

**Request for Proposal  
for a  
Unmanned Probe to Pluto  
University of Illinois at Urbana-Champaign  
AAE 241, Flight Vehicle Design Course  
Spacecraft Section  
Spring 1990**

### **I. OPPORTUNITY DESCRIPTION**

Now that Voyager II has completed its grand tour of the solar system, all the planets in the solar system, save one, have been studied. This "planet" is Pluto. Even now, missions to return to Mercury, Venus, Mars, Jupiter, Saturn, and comets are planned or currently flying. However, a mission to Pluto is not planned until after 2010.

The first step in the exploration of Pluto will occur this year when Hubble Space Telescope becomes active. This mission should provide clearer pictures of Pluto and Charon than currently exist. Even this clarity will not be sufficient to perform the analyses necessary to answer the current questions about Pluto and Charon.

To give the scientists the data required to perform the analyses a mission to Pluto and Charon is necessary. There are three classes of missions which can be flown: 1) fly-by, 2) orbiter, and 3) lander.

Fly-by missions have an inherent limitation in the amount of time spent in the vicinity of the area of interest. However, they are the easiest to design and the least expensive to build and fly.

Orbiter missions are inherently more costly than fly-by missions because of the requirement to enter orbit about the body of interest. However, this type of mission provides more time to study the body of interest, thus allowing additional and more exact experiments to be performed. Because of the distance from the earth that the spacecraft

will be at the time of the encounter, this type of mission must be able to adapt to whatever environment the spacecraft may encounter.

The most costly mission is the lander. There exist two subclasses of landers; a "lander," which lands softly on the surface of the body in question and a "penetrator," which explores the area under the surface of the body. A lander mission provides the most accurate and largest quantity of data about another body. For this type of mission, an important question is which body to land on, Pluto or Charon?

## **II. PROJECT OBJECTIVE**

The project objective is to develop a conceptual design for a spacecraft to perform an unmanned scientific study of Plutoian space to be launched sometime in the first decade of the twenty-first century.

The spacecraft's performance, weight, and cost are very important to the acceptance of this type of mission, so approaches should be taken that optimize these parameters in design tradeoffs. The spacecraft should be reliable and easy to operate. It should use off-the-shelf hardware whenever available, but should not use materials or techniques expected to be available after 1999.

## **III. PROJECT GUIDELINES**

A thorough preliminary design study will be conducted to determine major design issues, establish the size of, define subsystems for, and describe the operation of the spacecraft that satisfies the following requirements:

- 1.) The amount of on-orbit assembly should be identified and minimized.
- 2.) The following subsystems are identified for the purposes of system integration:
  - a.) Structure (including materials, design, thermal control)
  - b.) Power and Propulsion
  - c.) Attitude and Articulation Control
  - d.) Command, Control, and Communication
  - e.) Science Instrumentation
  - f.) Mission Management, Planning and Costing

3.) The usage of the space shuttle should be identified. If the space shuttle is used for launch, the payload/shuttle interfaces must conform to NASA standards.

4.) Nothing in the spacecraft's design should preclude it from performing several possible missions.

5.) The spacecraft will have a design lifetime sufficient to carry out its mission plus a reasonable safety margin, but nothing in its design should preclude it from exceeding this lifetime.

6.) The vehicle will use the latest advances in artificial intelligence where applicable to enhance mission reliability and reduce mission costs.

7.) Mission science objectives must be described and justified.

8.) The design will stress reliability, simplicity, and low cost.

9.) For cost estimating and overall planning, it will be assumed that four spacecraft will be built. Three will be flight ready, while the fourth will be retained for use in an integrated ground test system.

#### **IV. ORAL MIDTERM PROPOSAL RESPONSE REQUIREMENTS**

The technical proposal is the most important factor in the award of a contract. As listed on the AAE 241 Schedule of Events, an oral midterm presentation is required. This presentation will serve as a proposal response outlining the approach to be taken and specific trade studies leading to the final design. While it is realized that all of the technical factors cannot be included in advance, the following should be included in the oral presentation:

1. Demonstrate a thorough understanding of the Request for Proposal (RFP) and Preliminary Design requirements.

2. Describe the proposed technical approaches to comply with each of the requirements specified in the RFP. Clarity, and completeness of the technical approach are primary factors in the evaluation of the proposals.

3. Particular emphasis should be directed towards identification of critical, technical problems. Descriptions, sketches, drawings, methods of attack, and discussions of new techniques should be presented.

## **V. FINAL DESIGN REPORT REQUIREMENTS**

The Final Design Report will contain all information obtained or developed for the design of an unmanned probe to Pluto. It should be specific and complete. While it is realized that all of the technical factors cannot be included in advance, the following should be included in the final design report:

1. Demonstrate a thorough understanding of the Request for Proposal (RFP) and Preliminary Design requirements.

2. Describe the technical approaches used to comply with each of the requirements specified in the RFP. Legibility, clarity, and completeness of the technical approach are primary factors in the evaluation of the final design. Spelling and proper use of the English language are also important.

3. Particular emphasis should be directed at identification of critical, technical problem areas. Descriptions, sketches, drawings, methods of attack, and discussions of new techniques should be presented in sufficient detail to permit engineering evaluation of the proposal. Exceptions to the proposed technical requirements should be identified and justified.

4. Include sensitivity analyses and tradeoff studies which were performed to arrive at the final design.

5. Provide an implementation plan for production of the final product.

## **VI. BASIS FOR EVALUATION**

### **1. Technical Content**

This concerns the correctness of theory, validity of reasoning used, apparent understanding of the subject, etc. Are all major factors considered and a reasonably accurate evaluation of these factors presented?

### **2. Organization and Presentation**

The effectiveness of the design report as an instrument of communication is a strong factor in the evaluation. Organization of the final design report, clarity, and inclusion of pertinent information are major factors.

### **3. Originality**

If possible, the design report should avoid standard textbook information and show independence of thought or a fresh approach to the project. Does the method and treatment of the problem show imagination?

### **4. Practical Application and Feasibility**

The group should present conclusions or recommendations that are feasible and practical, and which do not lead the evaluators into further difficult or "show-stopping" problems. Is the project realistic from a cost standpoint?

## **VII. FINAL DESIGN REPORT OUTPUT REQUIREMENTS**

Final design project summaries will be submitted to NASA as required by the University of Illinois - NASA Advanced Design program grant. Additionally, the results of AAE 241 projects will be documented in a paper to be submitted to an appropriate forum.

Group final design reports will consist of a clear, concise, and thorough description of the overall design, its major features, and operational capabilities. It will illustrate any special or unique features with clearly labeled diagrams inserted in the

text. It will explain and justify options selected to resolve the primary design issues. Students are encouraged to use original and innovative approaches so long as they meet or exceed the design requirements. The following are minimum output requirements:

1. One copy of the final design report will be submitted. It must bear the signatures, names, and student ID numbers of the project leader and design analysts within the group. Designs that are submitted must be the work of the students, but guidance and information may come from outside sources and should be accurately referenced and acknowledged.

2. Final design reports should be no more than 100 double-spaced typewritten pages (including graphs, drawings, photographs, and appendices). Equations related to the final design analysis shall be placed in an appendix at the end of each subsystem section.

3. Outline of the mission sequence of events, including, but not limited to:

- a.) Launch date.
- b.) Significant intermediate events
- c.) Encounter date.
- d.) Proposed end of mission date.

4.) A table correlating the primary design issues, related design requirements, options considered, preferred option, and rationale for the option selected. This will not supplant, but summarize, the discussion of trade studies in the text.

5.) Design concepts, including comparison of options considered, major component weights, and total subsystem weights, for the subsystems identified above (where applicable).

6.) Overall drawings showing the layout of the system and its component subsystems. The drawings should be to scale and show major dimensions, the location of major elements of each of the subsystems, and be clearly labeled.

7.) Top-level program cost estimates and schedule including major milestones for development, testing, and engineering activities.

8.) A scale model of the major system components will be built and displayed during the final report. These models will also serve as the centerpiece of the University of Illinois' static display at the NASA/USRA 1989 Summer Conference.

## **VIII. SOURCES OF REFERENCE MATERIALS**

Some reference material required to carry out the design will be provided in the form of paper hardcopy, lectures, and electronic media where applicable.

## **Appendix D**

### **An Unmanned Probe to Pluto**

**University of Illinois at Urbana-Champaign  
Flight Vehicle Design Course  
Spring 1990**

#### **ABSTRACT**

Now that Voyager II has completed its grand tour of the solar system, all the planets in the solar system, with the exception of Pluto, have been studied. Even now, missions to return to Mercury, Venus, Mars, Jupiter, and Saturn are currently flying or are planned. However, a mission to explore Pluto is not, at the present time, being considered seriously.

The design problem presented to the students was very general, i.e., design an unmanned mission to Pluto with a launch window constraint of the years 2000-2010. All other characteristics of the mission, such as mission type (flyby, orbiter, lander, penetrator), scientific objectives and payload, and the propulsion system, were to be determined by the design teams.

The design studies exposed several general problems to be solved. Due to the extreme distance of Pluto (and a corresponding travel time in the range of 10 to 25 years), the spacecraft had to be lighter and more robust than current spacecraft designs. In addition, advanced propulsion concepts had to be considered. These included the new generation of launch vehicles and upper stages and nuclear electric propulsion.

The probe design offered an abundance of synthesis and analysis problems. These included sizing trade studies, selection of subsystem components, analysis of spacecraft dynamics, stability and control, structural design and material selection, trajectory design, and selection of scientific equipment. Since the characteristics of the mission, excluding the launch window, were to be determined by the design teams, all the solutions varied widely.



## **Appendix E**

### **An Unmanned Probe to Pluto**

**University of Illinois at Urbana-Champaign  
Flight Vehicle Design Course, Spacecraft Section  
Spring 1990**

#### **ABSTRACT**

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## INTRODUCTION

Although missions to return to Mercury, Venus, Mars, Jupiter, Saturn, and comets are planned or currently flying, a mission to Pluto is not planned until after 2010. The first step in the exploration of Pluto will occur this year when Hubble Space Telescope becomes active. This instrument should provide clearer pictures of Pluto and Charon than currently exist. However, even this clarity will not be sufficient to perform the analyses necessary to answer the current questions about Pluto and Charon.

To provide scientists with the data required to perform those analyses, a mission to Pluto and Charon is necessary. There are three classes of missions which can be flown: 1) flyby, 2) orbiter, and 3) lander. Flyby missions have an inherent limitation in the amount of time spent in the vicinity of the area of interest. However, they are the easiest to design and the least expensive to build and fly.

Orbiter missions are inherently more costly than flyby missions because of the requirement to enter orbit about the body of interest. However, this type of mission provides more time to study the body of interest, allowing additional and more exact experiments to be performed. Because of the distance from Earth to Pluto, this type of mission must be able to adapt to the environment the spacecraft encounters.

The most costly mission class is the lander. There exist two subclasses of landers; a lander, which lands softly on the surface of the body in question and a penetrator, which explores the area under the surface of the body. A lander mission provides the most accurate and largest quantity of data about another body. For this type of mission, an important question is which body to land on, Pluto or Charon?

## PROJECT BACKGROUND

Forty-two undergraduate students, divided into seven groups, were enrolled in the spacecraft section of Aeronautical and Astronautical Engineering (AAE) 241, Flight Vehicle Design, in the spring 1990 semester. This paper summarizes the work of those student groups as submitted in their final design reports.

Today, little is known about Plutonian space and current discoveries raise more questions than they answer. The Hubble Space Telescope should be able to

answer some of the questions, but the only way to answer most of the questions is to send a spacecraft to Pluto to take data first hand.

Pluto, the ninth planet in our solar system, was discovered in March of 1930, using photographic plates taken in January of that year. Charon, Pluto's only known satellite, was discovered in July 1978 but not recognized until 1985. With an eccentricity of 0.25 and a perihelion of 29.6 Astronomical Units, Pluto has an orbital period of 248 years.

Pluto itself is estimated to weigh about 1/400 of the mass of the Earth, with a diameter of approximately 2300 km. The composition of the planet is estimated to be about 70% rock and 30% water ice and methane ice. The atmosphere is believed to be composed mostly of methane, which is sublimating from the surface, with traces of heavier gases such as argon, neon and nitrogen. Due to the large eccentricity of the orbit and the distance from the sun, the atmosphere of Pluto is thought to form and collapse cyclically as a function of the orbital period. The next collapse is expected to occur around 2025.

## PROJECT OBJECTIVE

The project objective was to develop a conceptual design for a spacecraft to perform an unmanned scientific study of Plutonian space to be launched sometime in the first decade of the twenty-first century.

Performance, weight, and cost are very important to the acceptance of this type of mission, so approaches were taken that optimize these parameters in design tradeoffs. The spacecraft had to be reliable and use off-the-shelf hardware whenever available. The use of materials or techniques expected to be available after 1999 was prohibited.

## SYSTEM REQUIREMENTS

A thorough preliminary design study was conducted by the students to determine major design issues, establish the size of, define subsystems for, and describe the operation of the spacecraft that satisfies the following requirements:

- 1.) The amount of on-orbit assembly should be identified and minimized.
- 2.) The following subsystems are identified for the purposes of system integration:

- a.) Science Instrumentation
  - b.) Mission Management, Planning and Costing
  - c.) Attitude and Articulation Control
  - d.) Command, Control, and Communication
  - e.) Power and Propulsion
  - f.) Structure (including materials and thermal control)
- 3.) The usage of the space shuttle should be identified. If the space shuttle is used for launch, the payload/shuttle interfaces must conform to NASA standards.
  - 4.) Nothing in the spacecraft's design should preclude it from performing several possible missions.
  - 5.) The spacecraft should have a design lifetime sufficient to carry out its mission plus a reasonable safety margin, but nothing in its design should preclude it from exceeding this lifetime.
  - 6.) The vehicle should use the latest advances in artificial intelligence where applicable to enhance mission reliability and reduce mission costs.
  - 7.) Mission science objectives must be described and justified.
  - 8.) The design should stress reliability, simplicity, and low cost.
  - 9.) For cost estimating and overall planning, it should be assumed that four spacecraft will be built. Three will be flight ready, while the fourth will be retained for use in an integrated ground test system.

## SCIENCE INSTRUMENTATION

The students working in this area were to determine the science objectives for the mission. In addition, they were to select the instruments necessary to fulfill these objectives. Some of the selected objectives were:

- Determine the composition and structure of Pluto's atmosphere
- Study the dynamics of the Pluto/Charon system
- Determine the mass, composition, and structure of Pluto
- Determine the mass, composition, and structure of Charon
- Determine the surface characteristics of Pluto
- Determine the existence and structure of the magnetic field of Pluto
- Study Jupiter (during a gravity assist maneuver)
- Search for other satellites in the Pluto/Charon system

The instruments chosen to meet these objectives can be divided into two major groups, remote sensing and fields and particles. The remote sensing instruments were determined to be the most important with all seven groups selecting both narrow and wide angle cameras and ultraviolet spectrometers. These instruments provide information to help determine the composition and structure of the bodies and the atmosphere and provide for the search for additional satellites in the Pluto/Charon system. Pictures of the system taken by the cameras will help determine its dynamics.

The fields and particles instruments will be used for interplanetary science experiments during the voyage to Pluto and will be used to study the magnetic field of Pluto, if one exists. The instruments selected include magnetometers, selected by 6 groups, and plasma particle detectors, selected by 6 groups. Figure 1 shows the layout of a representative science platform.

## MISSION MANAGEMENT, PLANNING AND COSTING

Mission management was responsible for the selection of a trajectory to Pluto and a launch vehicle for the spacecraft. Table 1 shows the types of missions chosen and the duration of the missions. Five of the seven groups selected a flyby mission, like Voyager, whereas the other two felt the additional data gathering capabilities provided by the orbiter were important. The duration for the flyby missions ranged from 13 to 19 years, while the orbiter missions were 22 and 15 years respectively. Note that Group 7 utilized a nuclear electric propulsion system. Note also that all seven spacecraft are expected to arrive in Plutonian space prior to the predicted collapse of the atmosphere of Pluto.

**Table 1 - Mission Type and Duration Summary**

<b>Group</b>	<b>Mission Type</b>	<b>Launch Date</b>	<b>Arrival Date</b>	<b>Mission Time (yrs)</b>
1	Flyby	09/2000	05/2018	18
2	Flyby	02/2002	02/2017	15
3	Flyby	01/2002	09/2020	19
4	Orbiter	12/2004	01/2025	22
5	Flyby	01/2003	02/2019	16
6	Flyby	05/2009	12/2021	13
7	Orbiter	04/2004	04/2019	15

For the six groups using the classical chemical propulsion systems, a tool call MULIMP was utilized to help determine a trajectory for the spacecraft. As shown in Table 2, a variety of trajectories were selected. These include a Jupiter Gravity Assist (JGA), where the spacecraft leaves the Earth and performs a gravity assist maneuver at Jupiter in order to increase the speed of the spacecraft and shorten the trip time. Another trajectory was the Earth-Jupiter Gravity Assist (EJGA) where the spacecraft leaves Earth's sphere of influence, performs a gravity assist maneuver at Earth, and then performs another gravity assist maneuver at Jupiter before proceeding on to Pluto. One group chose to fly directly to Pluto without any interplanetary flybys or gravity assists in order to get to Pluto before the atmosphere collapsed. The final chemical trajectory performed gravity assist maneuvers at both Jupiter and Saturn on the way to Pluto (JSGA).

Table 2 - Trajectory and Launch Vehicle Summary

Group	Launch Vehicle	Trajectory	Delta V (km/s)	Propulsion Type
1	Titan IV/Centaur	JGA	11.2	Chemical
2	Titan IIID/Centaur	EJGA	7.5	Chemical
3	Titan Commercial/TOS	EJGA	5.9	Chemical
4	Shuttle C/STV	JGA	12.1	Chemical
5	Ariane IV	DIRECT	8.6	Chemical
6	Titan T-34D/Centaur	JSGA	12.4	Chemical
7	Shuttle C	JGA	N/A	Nuclear Electric

N/A - Not Available

E - Earth

J - Jupiter

S - Saturn

GA - Gravity Assist

Group 7 uses a nuclear electric propulsion system. The analysis of this trajectory was performed using a tool called CHEBY2. However, this program does not provide for gravity assist maneuvers. This spacecraft spirals out of Earth's sphere-of-influence beginning in Nuclear Safe Orbit. The spacecraft performs a gravity assist maneuver at Jupiter and finally spirals into an orbit about Pluto.

The total costs of the missions were determined using the Science Applications International Corp. Planetary Cost Model. This model includes design, development, testing and evaluation, the four flight vehicles required by the RFP and the ground support personnel required during the entire mission. For the chemical systems, the estimated costs range from 1.03 billion to 2.11 billion in 1990 dollars while the nuclear electric orbiter's estimated cost is 4.21 billion.

## ATTITUDE AND ARTICULATION CONTROL

For attitude determination, all seven groups chose to use a sun sensor and the ASTROS star sensor for determining attitude. Also, all the groups used the Fiber Optic Rotational Sensor (FORS) as the gyroscope to be used most of the time.

For control, all groups selected a 3-axis active control system over spin stabilized or dual-spin configurations. All seven groups chose to use thrusters as the method of attitude correction, with the electric propulsion group using reactions wheels, as well, for stability. For the attitude control thrusters, the six chemical groups used mono-propellant hydrazine as the propellant, while the electric propulsion group used ionic mercury as the propellant.

In order to isolate the motion of the science instruments from the rest of the spacecraft, all seven groups chose to put the instruments requiring pointing on a scan platform. This scan platform was gimballed in two axes in order to provide the equipment with the widest field of view. The most common scan platform selected was the High Performance Scan Platform (HPSP).

## COMMAND, CONTROL, AND COMMUNICATION

This subsystem is responsible for selecting the communications equipment as well as the "brains" of the spacecraft.

For the communications portion, a large antenna is required in order to communicate over such a large distance. In addition, a large power is also required for the same reason. Also, adequate storage for the scientific data obtained is required when the spacecraft is unable to communicate with Earth, or when the data input is greater than the communications rate.



As shown in Table 3, the antenna sizes ranged from 1.5 meters to 4.8 meters with 4.8 meters used most frequently. Also, most groups utilized the proposed upgrades in the deep space network (DSN) in order to improve communications capability. These upgrades included increasing the size of the primary receiver to 70 meters and making the antennas Ka band capable. For communications, the data rates ranged from 300 bits per seconds to 388000 bits per second. Powers ranged from 6.3 watts to 25 watts, except for the nuclear electric orbiter which used a power of 1,000 watts.

Table 3 - Antenna Sizing Summary

Group	Size (m)	Band	Transmitted Power (W)	DSN Receiver Size (m)	Data Rates (bps)
1	4.8	Ka	20	70	316891
2	1.5	X	13	64	300
3	4.8	Ka	10	70	145500
4	4.8	Ka	6.3	70	388000
5	2.5	X	20	70	N/A
6	3.7	X	25	64	N/A
7	4.8	Ka	1000	70	N/A

## POWER AND PROPULSION

The selection of the method for supplying electric power to the spacecraft was based on a combination of the mission length, the distance from the sun, and the peak power loads. For the power supply, Pluto is too far from the sun for practical use of solar radiation. The mission times are too long for batteries to be able to store energy for the entire voyage. This leaves a nuclear power supply as the only viable option. Of the different types of nuclear power sources, five groups chose the Modular Isotopic Thermoelectric Generator (MITG), one group chose a type of Radio-isotope Thermoelectric Generator (RTG), and one group chose a nuclear reactor.

Once the power supply has been selected, the size of the power supply must be determined. This is a function of the peak power required, and the duration of

the mission. The power selections are summarized in Table 4. Again, the group using the electric propulsion has a vastly different power supply. They plan to carry two SP-100 nuclear reactors to supply all the power needs of the spacecraft.

Table 4 - Power Supply Summary

Group	Mission	Mission Duration (yrs)	Peak Power (W)	Power Supply	Number of Slices	Mass (kg)
1	Flyby	18	297	MITG	13	29.1
2	Flyby	15	256	MITG	15	34.0
3	Flyby	19	165	MITG	2 x 11	49.9
4	Orbiter	22	237	RTG	1*	26.0
5	Flyby	16	373	MITG	23	44.4
6	Flyby	13	290	MITG	13	60.0
7	Orbiter	15	80500	Reactor	2*	4600.0

MITG - Modular Isotopic Thermoelectric Generator

RTG - Radio Isotope Thermoelectric Generator

\* indicates the number of power units where slices are not applicable

The responsibilities in the propulsion area were propellant selection, propellant tank sizing, and orbit insertion propulsion for the two orbiters. For this mission, four chemical propulsion options were considered; cold gas, solids, monopropellants and bipropellants. Cold gas and solids are not applicable to the mission. Three groups selected the monopropellant hydrazine because it is simple, reliable, storable, and has relatively low cost. The other three chemical groups chose the more complex, but higher Isp bipropellant, hydrazine and nitrogen tetroxide.

The nuclear electric propulsion system is different. The propellant options investigated for this system include Cesium, Xenon, Argon, and Mercury. Of the four options, Mercury was selected because it provides the best trade-off between cost, storability, and Isp.

For the chemical systems, the propellant mass ranged from 473 kg to 2000 kg for the flyby missions and 3120 kg for the orbiter. The nuclear electric mission had a propellant mass of 12,000 kg.

## STRUCTURES

This subsystem was responsible for locating the components, determining the mass properties, and thermal control. Figures 2 through 4 show the layout of three representative spacecraft; Figure 2 is a flyby, Figure 3 is an orbiter and Figure 4 is the nuclear-electric propulsion orbiter.

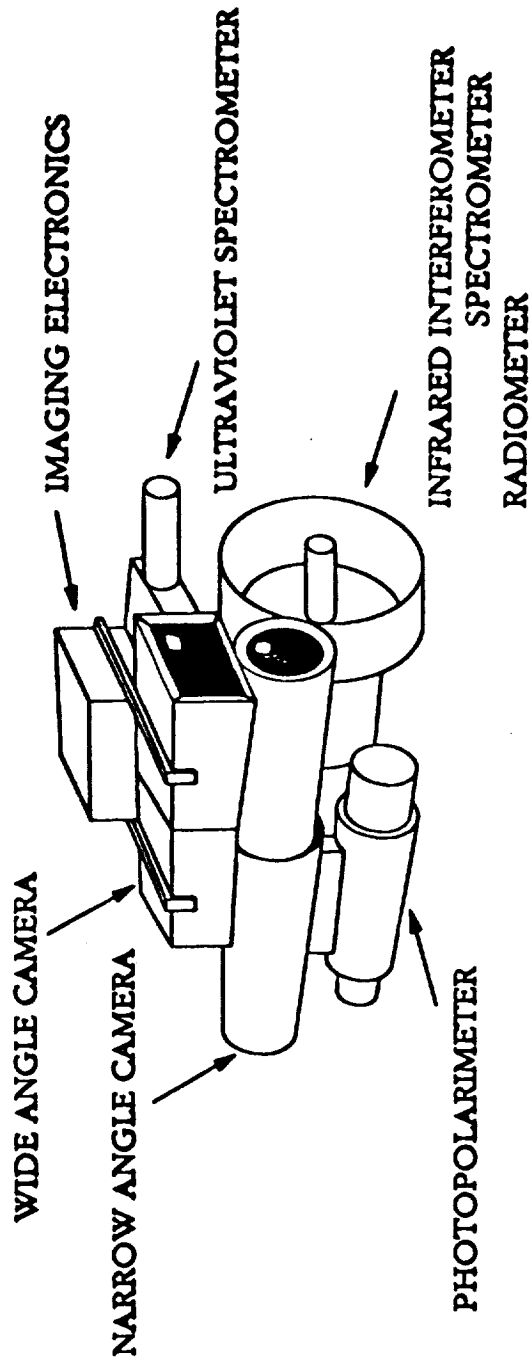
Locating the components and determining the mass properties must be performed together. The components should be arranged on the spacecraft to minimize the cross product of inertia about the axes of the thrusters. This is the principle reason for the arrangements shown in Figures 2 through 4.

Thermal control is required in order to maintain the temperature within acceptable limits for all components within the spacecraft. Various methods were employed by the groups. The most widely selected method was the placement of thermal heaters throughout the interior of the spacecraft. Radio isotope heating units, where the energy from nuclear decay is used to heat nearby components, were also common. The nuclear electric orbiter used high temperature radiators to remove the waste heat from the nuclear reactor.

For the chemical flyby missions the structure (dry) masses range from 445 kg to 756 kg with the total masses ranging from 1093 kg to 2500 kg. The chemical orbiter has a dry mass of 3243 kg and a total mass of 6363 kg. The nuclear electric orbiter has a dry mass of 8914 kg and a total mass of 20914.

**Figure 1. Example Science Scan Platform**

- **Mounted on a Two Degree-of-freedom Actuator**
- **Aimed with the Narrow Field-of-view Camera**
- **Deployed on an Extendable Boom**



**Figure 2. Bottom View of an Example Flyby Spacecraft**

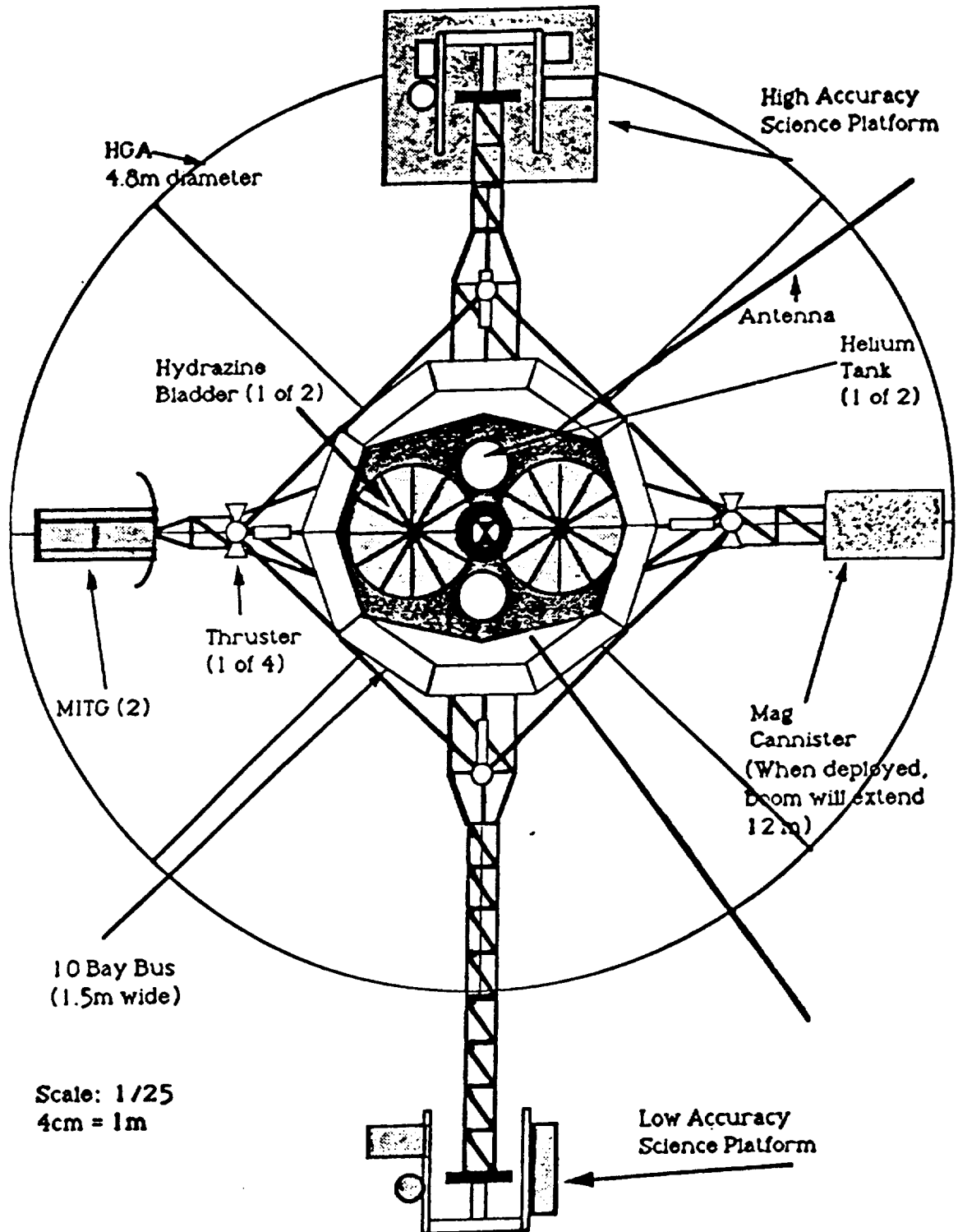
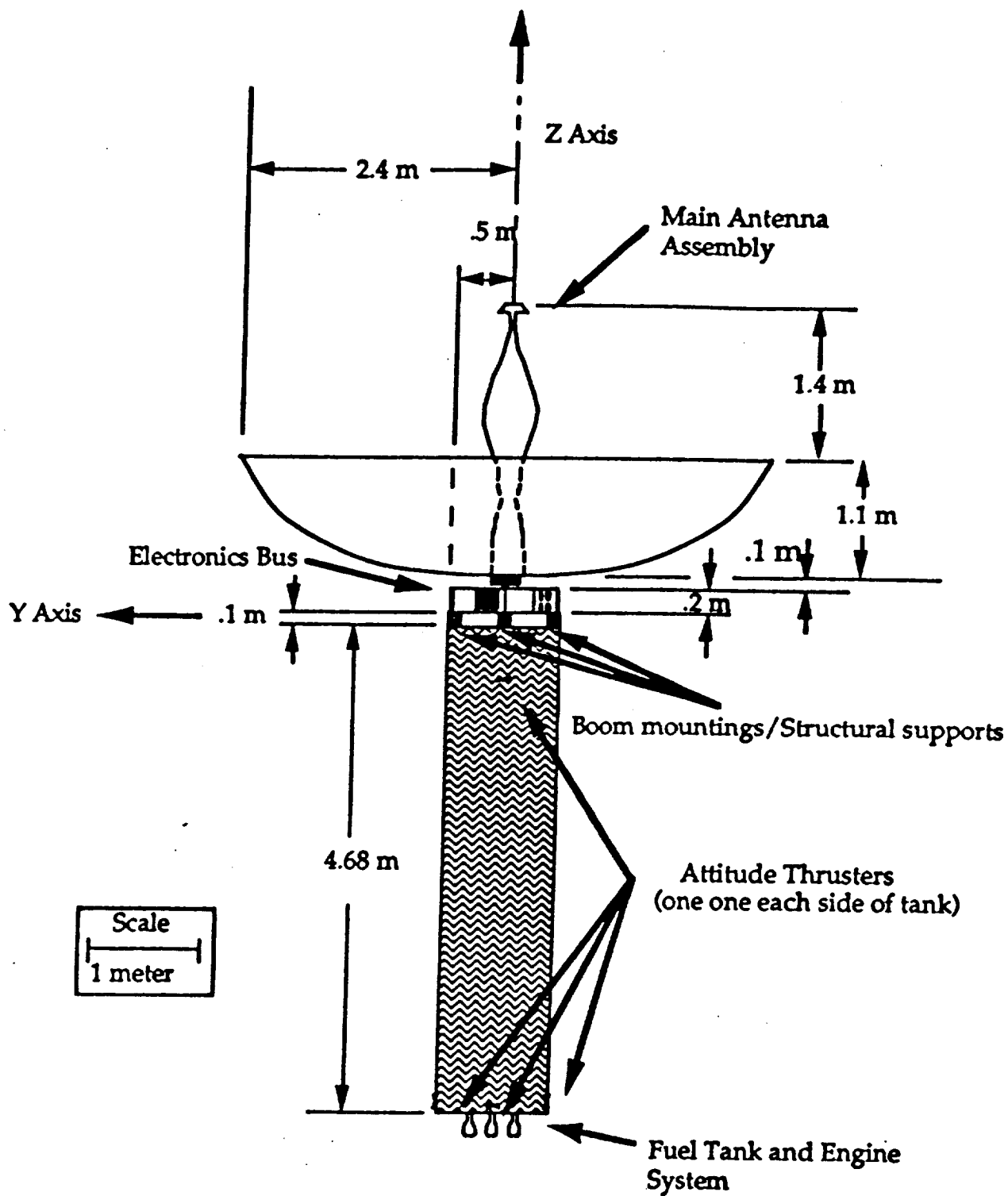


Figure 3. Side View of an Example Orbiter Spacecraft



**Figure 4. Side View of the Nuclear Electric Orbiter Spacecraft**

