MESSENGER

MErcury: Surface, Space ENvironment, GEochemistry, Rang

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THE JOHNS HOPKINS UNIVERSITY

A Discovery Mission Concept Study in Response to NASA AO 98-OSS-(

CARNEGIE INSTITUTION OF WASHINGTON

DEPARTMENT OF TERRESTRIAL MAGNETISM
5241 BROAD BRANCH ROAD, N.W.
WASHINGTON, D.C. 20015

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EXTENSION

23 March 1999

Discovery Science Peer Review Panel
Lunar and Planetary Institute
3600 Bay Area Boulevard
Houston, TX 77058-1113

Dear Discovery Panel:

I am pleased to submit an original and 35 copies of the Concept Study report for the proposed Discovery Program mission entitled "MESSENGER: A Mission to Orbit and Explore the Planet Mercury," in response to NASA's Discovery Program Announcement of Opportunity AO 98-OSS-04.

The MESSENGER team offers an outstanding partnership that includes, in addition to the Carnegie Institution, The Johns Hopkins University Applied Physics Laboratory (JHU/APL), GenCorp Aerojet, and Composite Optics, Inc., as well as a Science Team of extraordinary breadth and experience with representatives from twelve academic and research institutions. The mission is scientifically and technically ambitious, with no less a goal than a full exploration of the least-studied terrestrial planet and of the key answers it can provide to fundamental questions regarding the formation and evolution of the inner solar system.

Five years from today the launch window for MESSENGER opens. The mission is scientifically compelling and technically ready. The planet Mercury awaits our return.

Sincerely,

Sean C. Solomon
Director

JOHNS HOPKINS
UNIVERSITY

Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel MD 20723-6099
240-228-5000 / Washington
443-778-5000 / Baltimore

Please refer to:
AD-17989
March 23, 1999

Carnegie Institution of Washington
Department of Terrestrial Magnetism
5241 Broad Branch Road, NW
Washington, DC 20015

Attention: Dr. Sean C. Solomon, Director

Subject: Transmittal of MESSENGER Discovery Concept Study

Reference: NASA AO 98-OSS-04

Enclosure: Proposal entitled "MESSENGER, MErcury: Surface, Space ENvironment, GEochemistry, Ranging; A Mission to Orbit and Explore the Planet Mercury", dated March 1999

Dear Dr. Solomon:

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is pleased to submit this Concept Study entitled "MESSENGER, MErcury: Surface, Space ENvironment, GEochemistry, Ranging; A Mission to Orbit and Explore the Planet Mercury" for consideration by NASA in Reference to AO 98-OSS-04. This Concept Study includes data that shall not be disclosed outside the Carnegie Institution of Washington or the Government, and shall not be duplicated, used, or disclosed in whole or in part, for any purpose other than in connection with the evaluation of this proposal. If this Concept Study is selected for implementation, it is understood that separate contracts will be issued by NASA to the Carnegie Institution of Washington and to JHU/APL. According to NASA's final delivery instructions, MESSENGER will be submitted as follows: Original proposal and 35 copies to the Discovery Science Peer Review Panel, Lunar and Planetary Institute in Houston, Texas.

Should you have any questions, require additional information, or wish to schedule personal discussions, please contact Mr. Max R. Peterson at (240) 228-5832.

Very truly yours,

S. M. Krimigis

S. M. Krimigis
Head, Space Department

G. L. Smith
Director

GLS/SMK/TBC/MRP/BAN/JEF/jef

SECTION B

TABLE OF CONTENTS

MESSENGER

*ME*rcury: *S*urface, *S*pace *EN*vironment, *GE*ochemistry, *R*anging

A Mission to Orbit and Explore the Planet Mercury

A Discovery Mission Concept Study

March 1999

C EXECUTIVE SUMMARY

MESSENGER is a scientific mission to Mercury. Understanding this extraordinary planet and the forces that have shaped it is fundamental to understanding the processes that have governed the formation, evolution, and dynamics of the terrestrial planets.

MESSENGER is a *ME*rcury *S*urface, *S*pace *EN*vironment, *GE*ochemistry and *R*anging mission to orbit Mercury for one Earth year after completing two flybys of that planet following two flybys of Venus. The necessary flybys return significant new data early in the mission, while the orbital phase, guided by the flyby data, enables a focused scientific investigation of this least-studied terrestrial planet. Answers to key questions about Mercury's high density, crustal composition and structure, volcanic history, core structure, magnetic field generation, polar deposits, exosphere, overall volatile inventory, and magnetosphere are provided by an optimized set of miniaturized space instruments.

Our goal is to gain new insight into the formation and evolution of the solar system, including Earth. By traveling to the inner edge of the solar system and exploring a poorly-known world, MESSENGER fulfills this quest.

On the basis of detailed engineering and trade-off studies of alternative solar electric propulsion and (chemical) ballistic missions, we have designed an advanced bipropellant spacecraft and multiple-planetary flyby mission. This design combines generous margins with appropriate technologies to define the mission best able to address the key science questions at minimum cost and low risk.

To implement the mission, the Principal Investigator, Dr. Sean C. Solomon, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (CIW), and The Johns Hopkins University Applied Physics Laboratory (hereinafter referred to as APL) head a consortium to provide the spacecraft and instrumentation. Consortium team members include Composite Optics, Inc., a leader in light-weight spacecraft structures, GenCorp Aerojet, a leader in spacecraft propulsion systems, Goddard Space Flight Center, the University of Colorado, and the University of Michigan. Co-engineered with planetary and space scientists from twelve institutions, MESSENGER has been designed to accommodate the severe near-Sun thermal environment and supply the required large spacecraft velocity change while enabling all science observations. The integrated structure, propulsion system, and thermal design; fully-redundant integrated electronics module for avionics functions; dual phased-array antennas; radiation-hardened, high-temperature solar panels; and high level of spacecraft autonomy provide robust margins. Extensive analysis and testing to date ensure that mission and spacecraft designs are unusually mature for a proposed Discovery mission.

To engage students and the public, the MESSENGER Education and Public Outreach (E/PO) Plan, coordinated by the American Association for the Advancement of Science, targets segments of the population at all levels of education and privilege. The education component of the plan is designed to meet or exceed the National Science Education Standards as well as NASA education goals. Through the public awareness component of the program, all Americans and the greater world community have the opportunity to share in the technical challenges faced by the MESSENGER mission and the renewed exploration of Mercury and the inner solar system.

Mercury is a planet of many mysteries. The closest planet to the Sun, Mercury has the largest diurnal range in surface temperature yet has polar deposits thought to consist of water ice. Mercury is the only planet locked in a spin-orbit resonance, an important though poorly understood constraint on dynamical and internal evolution. It has the largest uncompressed density and, by inference, the greatest mass fraction of iron-nickel of any planet or satellite, a compositional anomaly that is a critical clue, not yet deciphered, to the processes by which the inner planets formed. Mercury has a strong internal magnetic field and presumably a hydromagnetic dynamo in a fluid outer core, yet the known portion of the surface has a density of impact craters indicating that geological activity largely ceased early in the planet's history. Mercury's magnetic field gives rise to a small magnetosphere with many similarities to that of the Earth, yet the presence of only a tenuous atmosphere and ionosphere and the greater proximity to the Sun affect the nature of solar wind interaction with the planet in ways still poorly discerned.

Mercury is also the least explored planet save Pluto. Most of what is known comes from the three flybys of Mercury by Mariner 10 in 1974 and 1975. In the decade following the Mariner 10 mission, it was generally thought that insertion of a spacecraft into orbit around Mercury could not be achieved by a conventional propulsion system, a view that colored the priority placed on further exploration of the planet. Nonetheless, the Committee on Planetary and Lunar Exploration of the Space Studies Board has consistently recommended for two decades that a means be found to explore this little-known world to a level of detail not possible with the brief Mariner 10 flybys of the mid-1970s.

With the recognition that gravity-assisted trajectories, using the launch systems available in the Discovery Program, now permit the insertion of a spacecraft into Mercury orbit, the need for the intensive exploration of the innermost planet has again been recognized in NASA plans. A Mercury orbiter is central, for instance, to two of the campaigns described in the recent Solar System Exploration Roadmap (Formation and Dynamics of Earth-Like Planets, and Astrophysical Analogs in the Solar System). Such a mission has also been recognized as important in NASA's most recent Space Science Enterprise Strategic Plan.

A substantially improved knowledge of the planet Mercury will add critical new insight into how terrestrial planets formed and evolved. Determining the composition of Mercury, with its anomalously high ratio of metal to silicate, will provide a unique window on the processes by which planetesimals in the primitive solar nebula accreted to form planets. Documenting the global geological history will elucidate the role of planet size as a governor of magmatic and tectonic history for a terrestrial planet. Characterizing the nature of the magnetic field of Mercury and the size and state of Mercury's core will allow us to generalize our understanding of the energetics and lifetimes of magnetic dynamos in solid planets and satellites. Determining the nature of volatile species in Mercury's polar deposits, exosphere, and magnetosphere will provide critical insight into volatile inventories, sources and sinks in the inner solar system.

Key questions addressed by the MESSENGER mission include:

What planetary formational processes led to the high metal/silicate ratio in Mercury?

What is the geological history of Mercury?

What is the nature and origin of Mercury's magnetic field?

What is the structure and state of Mercury's core?

What are the radar-reflective materials at Mercury's poles?

What are the important volatile species and their sources and sinks on and near Mercury?

MESSENGER will answer these questions, all of central importance for improving our general understanding of the origin and evolution of the inner solar system.

The rationale linking these questions to the mission instrument suite and measurement strategy begins with the scientific objectives, which are, in order of priority, to determine (1) the chemical composition of Mercury's surface, (2) the planet's geological history, (3) the nature of Mercury's magnetic field, (4) the size and state of the core, (5) the volatile inventory at Mercury's poles, and (6) the nature of Mercury's exosphere and magnetosphere. Objective (1) leads to a measurement requirement for global maps of elemental composition at a resolution sufficient to discern major units and to distinguish material excavated and ejected from young impact craters from a possible veneer of cometary and meteoritic material; information on surface mineralogy is also important. Objective (2) leads to the measurement requirement for global monochrome imaging at a resolution of hundreds of meters or better, for topographic profiles across key geological features from altimetry or stereo, and for spectral measurements of major geologic units at spatial resolutions of several kilometers or better. Objective (3) leads to a requirement for magnetometry, both near the planet and throughout the magnetosphere, as well as for energetic particle and plasma measurements so as to isolate external from internal fields. Objective (4) can be met by altimetric measurement of the amplitude of Mercury's physical libration as well as determination of the planet's obliquity and low-degree gravitational field. Objective (5) can be met by remote and in situ identification of neutral and charged species in the polar atmosphere, remote assessment of surface composition, particularly hydrogen content, and imaging and altimetry of polar-region craters. Objective (6) leads to measurement requirements for the identification of all major neutral species in the exosphere and all charged species in the magnetosphere.

This set of measurement requirements demands a Mercury orbiter. Characterizing the planetary magnetic and gravitational fields and measuring the amplitude of Mercury's physical libration can be accomplished only from orbit. An orbiter enables multiple cuts through the magnetosphere and exosphere. Only an orbiter can provide sufficient integration time to produce elemental and mineralogical maps of the planet at the resolution necessary to distinguish among hypotheses for planet formation or to discern geological history. For these reasons, and given the limitations of the Mariner 10 results, we believe that yet another flyby-only mission to Mercury is neither warranted nor cost-effective.

The measurement requirements (keyed by number) for MESSENGER are met by a suite of seven scientific instruments plus the spacecraft communication system. There is a dual imaging system (1,2) for wide and narrow fields-of-view, monochrome and color imaging, and stereo; gamma-ray and neutron (1,2,5,6) and X-ray (1,2,6) spectrometers for surface chemical mapping; a magnetometer (3); a laser altimeter (2,4,5) and radio science (2,4); a combined UV-visible (5,6) and visible-near-infrared (1,2) spectrometer to survey both exospheric species and surface mineralogy; and an energetic particle and plasma spectrometer (3,5,6) to sample charged species in the magnetosphere.

The payload instrumentation has been selected to provide functional redundancy across scientific objectives and to give complementarity of observations in case of problems. Such redundancy also provides for important consistency checks of results obtained with more than one instrument.

The baseline MESSENGER mission employs state-of-the-art chemical propulsion and multiple gravitational flybys to reach Mercury orbit. Both the flybys and the orbit have been optimized to satisfy all scientific measurement requirements while meeting the constraints of the Discovery Program. The mission profile has also been carefully tailored to include prudent schedule and mass margins and reserves. Fuel reserves and maneuver schedule margins are included to provide resiliency and to minimize risk in mission implementation. Additional mass margin can be gained by an additional Mercury flyby, if required, yielding an extraordinarily robust mission design. There are no other mission designs for the coming decade that can reach Mercury orbit with this level of redundancy using tried-and-tested technology.

After launch by a Delta II 7925H, an Earth flyby, two flybys of Venus, and two flybys of Mercury are needed before orbit insertion at the third Mercury encounter. Orbital science observations are then carried out for one Earth year. An additional year of analysis provides a full suite of results conveyed to the science community, public, and Planetary Data System (PDS).

The periapsis altitude and orbit phasing for MESSENGER are optimized to balance thermal constraints against science requirements. The inclination and latitude of periapsis result from a complex set of trade-space optimizations driven by imaging and altimetry coverage requirements as well as thermal input and spacecraft mass. Solar perturbations impose changes in the periapsis altitude and latitude that are corrected periodically in accord with science measurement requirements.

Significant scientific return can be expected from each flyby, and the orbital phase of the mission achieves all principal scientific objectives. During the flybys of Mercury, regions unexplored by Mariner 10 are seen for the first time. New data are gathered on Mercury's exosphere and magnetosphere as will the first information on surface composition. Approach and departure movies as well as high-resolution imagery bring the mission alive to both the scientific community and the public at large.

During the orbital phase of the mission, MESSENGER's science strategy shifts to detailed global mapping, characterization of the exosphere, magnetosphere, and polar deposits, acquisition of gravity field and topographic data for geophysical studies, and focused study of high-priority targets identified during the flyby phase. Details of the observations follow from the key science questions.

Bonus science accrues as well during the cruise to Mercury. The gamma-ray and neutron spectrometer have sufficient timing resolution to contribute to gamma-ray burst localization. The spectral and imaging instruments will look for temporal changes at Venus since the demise of the Pioneer Venus Orbiter, including changes in atmospheric sulfur dioxide abundance and cloud structure and evidence for lightning and for X-ray emission similar to that observed recently from comets. The fields-and-particles instrument complement contribute another vantage point from which to observe the three-dimensional structure and evolution of coronal mass ejections on their way from the Sun to the Earth and outer heliosphere.

The MESSENGER team is committed to providing all mission data to the scientific community as soon as processing and validation are completed. All validated mission data will be archived with the PDS. In parallel with this archiving, scientific results will be shared with the science community via scientific meetings and peer-reviewed publications. Public dissemination of images and data will start immediately following their receipt. Additional data products of scientific interest will be disseminated in electronic and printed formats. Optimal use will be made of the World Wide Web to provide results to the scientific community, to mission educational and outreach endeavors, and to the general public.

The MESSENGER Science Team consists of 21 highly qualified individuals who collectively contribute an extraordinary range of technical and scientific expertise. To facilitate the design, development, and testing of instrumentation, and to carry out the analysis of mission data in an effective manner, the Science Team is divided into four broad groups with distinct but complementary interests in geology, geochemistry, geophysics, and atmospheric and magnetospheric physics. A Science Steering Committee ensures interdisciplinary synthesis of all data sets.

The MESSENGER E/PO program focuses on high-leverage opportunities; builds on and coordinates with existing educational programs, institutions, and infrastructure; and collaborates with science museums and other outreach partners. The educational component achieves extensive student involvement through a series of workshops for NASA educators, regional K-12 teachers, and educators in the disadvantaged sectors. The outreach component maximizes the dissemination of information through the Web, radio segments, exhibits in high-traffic science museums, general audience books, and a documentary film. The E/PO program targets historically underrepresented minorities and those who have little or no Internet access and coordinates worldwide observations of Mercury by amateur and professional astronomers.

MESSENGER employs a prudent combination of cutting-edge technologies and established approaches to both spacecraft and instrumentation design in order to accomplish its challenging mission. Several of these new technologies have been developed under competed, peer-reviewed NASA grants funded through the Planetary Instrument Definition and Development Program. By engaging a technology transfer agent, MESSENGER maximizes the development and application of new technology by the commercial sector.

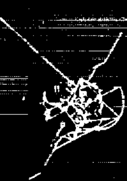
The MESSENGER project has adopted a proactive position for engaging participation by small disadvantaged and women-owned businesses. Preliminary implementation plans already include significant participation by such entities, particularly in enabling high-level scientific data products and guaranteeing their archiving in the Planteary Data System.

We have completed a discrete-element cost estimate for the entire MESSENGER mission within the guidelines specified in the Discovery Program. Costs are based on contractor and supplier quotes and on actual costs incurred during the design, development, production, integration, test, launch, and operations of the Near Earth Asteroid Rendezvous mission, now being conducted by APL for NASA.

There are no "show stoppers." MESSENGER is ready for development. Mercury awaits.

MErcury: Surface, Space ENvironment, GEochemistry and Ranging

A Discovery Mission Concept Study in Response to NASA AO 98-OSS-04



GenCorp Aerojet

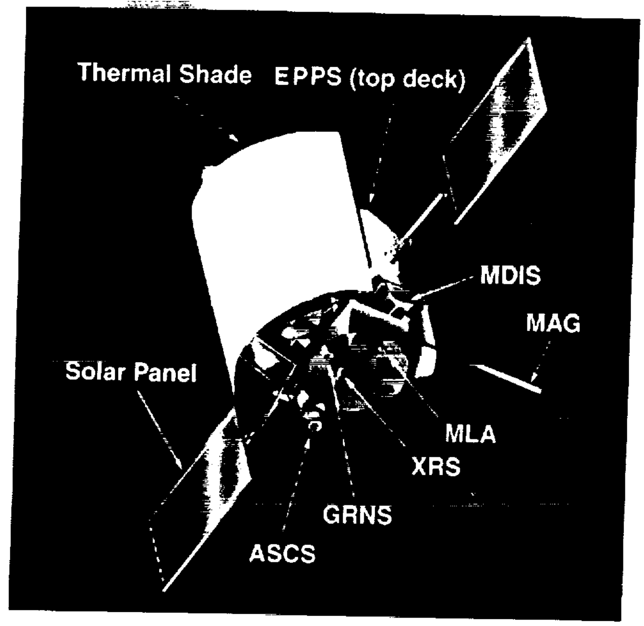
Mission Overview

MESSENGER is a scientific investigation of the planet Mercury. Understanding Mercury, and the forces that have shaped it, is fundamental to understanding the terrestrial planets and their evolution.

MESSENGER is a MErcury: Surface, Space ENvironment, GEochemistry and Ranging mission to orbit Mercury following two flybys of that planet. The orbital phase will use the flyby data as an initial guide to perform a focused scientific investigation of this enigmatic world.

MESSENGER will investigate key scientific questions regarding Mercury's characteristics and environment during these two complementary mission phases. Data are provided by an optimized set of miniaturized space instruments and the spacecraft telecommunications system.

MESSENGER will enter Mercury orbit in September 2009 and carry out comprehensive measurements for one Earth year. Orbital data collection concludes in September 2010.



Mission Management

Principal Investigator:	Dr. Sean C. Solomon Carnegie Inst. of Washington
Project Management:	JHU/APL
Spacecraft Integration:	JHU/APL
Instruments:	JHU/APL, GSFC, Univ. Colorado, Univ. Michigan
Structure:	Composite Optics, Inc.
Propulsion:	GenCorp Aerojet
Navigation:	Jet Propulsion Laboratory

Mission Summary

Launch dates:	March 23→April 6, 2004 (15 days) August 2→16, 2004 (15 days)
Launch vehicle:	Delta II 7925H
Venus flybys (2):	October 25, 2006 June 6, 2007
Mercury flybys (2):	January 15, 2008 October 6, 2008
Mercury orbit insertion:	September 30, 2009

Schedule and Cost Summary

16 weeks schedule reserve
$26 M (Real FY) cost reserve

Phase	Date	Duration	Real FY $M	FY 99 $M
A/B	1 Jan 00	18 months	31	29
C/D	1 Jul 01	34 months	163	143
E	23 Apr 04	89 months	81	57
ELV			64	57
		Total	339	286

http://sd-www.jhuapl.edu/sdhome/Discovery/messenger/

Science Payload

Mercury Dual Imaging System (MDIS)
Gamma-Ray and Neutron Spectrometer (GRNS)
Magnetometer (MAG)
Mercury Laser Altimeter (MLA)
Atmospheric and Surface Composition Spectrometer (ASCS)
Energetic Particle and Plasma Spectrometer (EPPS)
X-ray Spectrometer (XRS)
Radio Science (RS) uses telecommunication system

Key Spacecraft Characteristics

Power and mass margins >20%
All major systems redundant
System uses off-the-shelf components and standard data interfaces
Subsystem heritage from NEAR and TIMED
Life-cycle costs minimized through advanced on-board autonomy
Passive thermal design requires no high-temperature electronics
Fixed phased-array antennas replace a deployable-high-gain antenna
Dual-sided solar array reduces cell temperatures

Mission Benefits

Technology transfer to robotics, medicine, oil-exploration, industrial laboratory instrumentation, aircraft communications
Small disadvantaged businesses targeted in six specific areas
Comprehensive Education/Public Outreach program

MESSENGER– to Mercury, the last frontier of the terrestrial planets

Understanding Mercury is fundamental to understanding terrestrial planet evolution

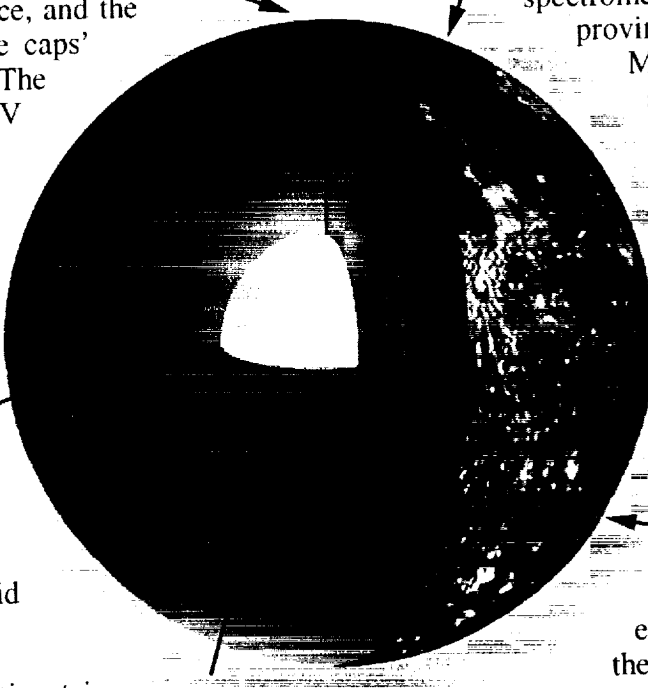
- *Key questions: What is the origin of Mercury's high density? What are the composition and structure of its crust? Has Mercury experienced volcanism? What are the nature and dynamics of its thin atmosphere and Earth-like magnetosphere? What is the nature of its mysterious polar caps? Is a liquid outer core responsible for generating its magnetic field?*

MESSENGER provides:

- *Multiple flybys for global mapping, detailed study of high-priority targets, and probing of the atmosphere and magnetosphere*
- *An orbiter for detailed characterization of the surface, interior, atmosphere, and magnetosphere*
- *Aggressive education and public outreach program (four educational and five outreach programs to produce exhibits, a documentary, plain-language books, educational modules, and teacher training)*

MESSENGER Science Objectives:

Polar cap volatiles – The gamma-ray and neutron spectrometer will determine if Mercury's polar caps contain hydrogen in water ice, and the laser altimeter will map the caps' topography and thickness. The particle and plasma and UV spectrometers will detect effluent from the frozen volatiles, even if the cap is formed of elemental sulfur.



Core and magnetic dynamo – Accurate measurement of Mercury's libration by the laser altimeter and radio science experiments will reveal whether or not Mercury still possesses a liquid outer core.

Crust and mantle – Altimetric mapping by the laser altimeter and gravity mapping by the radio science experiment will probe for spatial variations in the structure of the lithosphere, evidence for early impact stripping of the crust, and evidence for ongoing mantle convection.

Magnetosphere – While the magnetometer maps the configuration and time-variability of Mercury's magnetic field, the combined plasma- and energetic-particle spectrometer will determine the types, abundances, and energetics and dynamical characteristics of ions trapped within it.

Crustal composition – Global elemental abundance mapping by the X-ray and gamma-ray and neutron spectrometers will reveal the chemical provinces within Mercury's crust. Multicolor imaging and IR spectroscopy will detect and map variations in mineral abundances to scales of 1 km or less. These data will allow determination of the abundance and distribution of volcanic materials and the testing of models for the origin of Mercury's high bulk density.

Geologic evolution – Global imaging coverage at 250 m/pixel, acquired at stereo geometries and with elevation "ground truth" from the laser altimeter, will provide morphologic information critical to understanding the sequence of tectonic deformation, volcanism, and cratering that shaped Mercury's surface.

Exosphere – The UV spectrometer will measure the composition and structure of Mercury's tenuous atmosphere and determine how it varies with local solar time, solar activity, and the planet's distance from the Sun. The energetic-particle spectrometer will measure the exchange of species between the exosphere and magnetosphere, and the plasma spectrometer will observe pick-up ions in the solar wind.

98-0112 03/17/99

Section D is an exact duplicate of the Phase-One MESSENGER Science Investigation (formerly Section E), with the following exceptions:

(1) All section notations have been changed from E to D to agree with the required contents for this Concept Study; such changes are not shown with underlining.

(2) All other changes are noted with underlining.

(3) Changes on color pages are noted with red lettering and underlining.

D SCIENCE INVESTIGATION

D.1 Scientific Goals and Objectives

D.1.1 Science Rationale

Mercury is the least studied planet save Pluto. Much of what is known (Chapman, 1988; Vilas et al., 1988) comes from the three flybys of Mercury by Mariner 10 in 1974 and 1975. Mariner 10 imaged only about 45% of the surface at an average resolution of about 1 km and less than 1% of the surface at better than 500 m resolution. Further, Mariner 10 discovered the planet's internal magnetic field; measured the ultraviolet signatures of H, He, and O in Mercury's atmosphere; documented the time-variable nature of Mercury's magnetosphere; and determined some of the physical characteristics of Mercury's surface materials. Important subsequent ground-based discoveries include the Na and K components of the atmosphere (Potter and Morgan, 1985, 1986) and the radar-reflective polar deposits (Slade et al., 1992; Harmon and Slade, 1992).

In the decade following Mariner 10, it was generally thought that insertion of a spacecraft into orbit around Mercury could not be achieved by a conventional propulsion system, a view that colored the priority placed on further exploration of the planet. The Committee on Planetary and Lunar Exploration (COMPLEX) of the Space Science Board (now the Space Studies Board) recommended in 1978 that "steps should be made to prepare for the investigation of Mercury after definition of an adequate propulsion capability" and that the primary objectives in the next stage of exploration of Mercury should be "to determine the chemical composition of the planet's surface on both a global and regional scale, to determine the structure and state of the planet's interior,...to extend the coverage and improve the resolution of orbital imaging" (COMPLEX, 1978) and "characterization of Mercury's magnetic field" (COMPLEX, 1990). With the recognition that gravity-assisted trajectories permit, with current launch systems, the insertion of a spacecraft into Mercury orbit (Yen, 1985, 1989), COMPLEX (1990) concluded that "A Mercury mission is a possible near-term activity, and justification of such a mission should rest on the important role of Mercury in understanding the origin and evolution of all of the terrestrial planets." We concur with this assessment, and we provide a clear justification in the following section. We note also that a Mercury orbiter mission is featured prominently in two of the "campaigns" (Formation and Dynamics of Earth-Like Planets, and Astrophysical Analogs in the Solar System) described in the recent *Solar System Exploration Roadmap* (Roadmap Development Team, 1998) as well as in *The Space Science Enterprise Strategic Plan* (NASA, 1997).

Mercury:
A Key to Terrestrial Planet Evolution

A substantially improved knowledge of the planet Mercury is critical to our understanding of how terrestrial planets formed and evolved. Determining the composition of Mercury, with a ratio of metal to silicate higher than any other planet or satellite, will provide a unique window on the processes by which planetesimals in the primitive solar nebula accreted to form planets. Documenting the global geological history will elucidate the role of planet size as a governor of magmatic and tectonic history for a terrestrial planet. Characterizing the nature of the magnetic field of Mercury and the size and state of Mercury's core will allow us to generalize our understanding of the energetics and lifetimes of magnetic dynamos in solid planets and satellites. Determining the nature of volatile species in Mercury's polar deposits, atmosphere and magnetosphere will provide critical insight into volatile inventories, sources, and sinks in the inner solar system. The following key questions, in order of priority, can be addressed by a spacecraft in Mercury orbit.

What planetary formational processes led to the high metal/silicate ratio in Mercury?

Perhaps the question of greatest importance for our understanding of terrestrial planet formation is the origin of Mercury's high uncompressed density (about 5.3 Mg/m^3). Interior structure models in which a dominantly iron core has fully differentiated from the overlying silicate mantle indicate that the core radius is approximately 75% of the planetary radius and the fractional core mass about 65% (Siegfried and Solomon, 1974). This metallic mass fraction is more than twice that of the Earth, Venus, or Mars. At one time, the high density was attributed (Lewis, 1972) to the slightly higher condensation temperature of iron compared with magnesian silicates in the cooling solar nebula, such that at Mercury's distance from the protosun the ratio of solid metal to silicate was much higher than in the formation zones of the other terrestrial planets. Subsequent calculations of dynamically plausible accretion scenarios, however, have shown that the terrestrial planets probably formed from material originally occupying a wide range in solar distance (Wetherill, 1988, 1994). In particular, Mercury-size bodies can experience wide migrations of their semimajor axes during their growth (Wetherill, 1988). Given such scenarios, equilibrium condensation models cannot account for the high metal/silicate ratio in Mercury (Goettel and Barshay, 1978; Lewis, 1988).

There are currently three classes of explanations for the high metal fraction of Mercury. One class invokes differences in the response of iron and silicates to impact fragmentation and aerodynamic sorting in the presence of gas to achieve fractionation during accretion (Weidenschilling, 1978). A second class attributes the high metal content of Mercury to preferential vaporization of silicates by solar radiation early in the Sun's evolution (Cameron, 1985; Fegley and Cameron, 1987). In the third class, selective removal of silicate occurred as a result of a giant impact on a previously differentiated protoplanet (Wetherill, 1988; Benz et al., 1988).

These three hypotheses lead to different predictions for the bulk chemistry of the silicate fraction of Mercury (Lewis, 1988). Under the impact hypothesis, the residual silicate material on Mercury would be dominantly of mantle composition. The FeO content would reflect the oxidation state of the material from which the protoplanet accreted, but the loss of much of the original crust would deplete Ca, Al and alkali metals without enriching refractory elements. The vaporization model, in contrast, predicts strong enrichment of refractories and depletion of alkalis and FeO (Fegley and Cameron, 1987). Under both of these models, the present crust should represent primarily the integrated volume of magma produced by partial melting of the relic mantle. Under the selective accretion model (Weidenschilling, 1978) the core and silicate portions of Mercury may be adequately described by condensation models, suitably weighted by solar distance, except that the ratio of metal to silicate is much larger (Lewis, 1988). This model permits a thick primordial crust, i.e., one produced by crystal-liquid fractionation of a silicate magma ocean. With any of the three models, late infall of cometary and asteroidal material may have influenced surface and near-surface chemistry.

Thus determining the bulk chemistry of the silicate portion of Mercury offers the unique opportunity to learn which of the mechanisms operating during the formation of the inner solar system had the greatest influence on the bulk composition of the inner planets. Present information on the chemistry and mineralogy of the surface of Mercury, however, is far too limited to distinguish clearly among the competing hypotheses. Ground-based reflectance spectra at visible, infrared, and millimeter wavelengths suggest generally low FeO and high alkali feldspar contents (Vilas, 1988; Sprague et al., 1994; 1997; Jeanloz et al., 1995; Blewett et al., 1997), and the observations of K and Na in Mercury's tenuous atmosphere favor significant alkali contents, although whether the source for these species is a surficial veneer of meteoritic material or deeper regions of the Mercury crust is not known (Hunten et al., 1988). An important adjunct to direct determination of the chemistry of surface materials, including those ejected by large impacts from some depth, would be an estimate of the thickness of Mercury's crust. The thickness can be estimated by a combined analysis of gravity and topography measurements if such data are sensitive to variations on horizontal scales of several hundred kilometers and greater (Zuber et al., 1994; Simons et al., 1997).

What is the geological history of Mercury?

Because of Mercury's size, intermediate between the Moon and Mars, as well as its high metal-to-silicate ratio, documenting the geological history of Mercury is crucial to understanding how terrestrial planet evolution depends on planet size and initial conditions. A generalized geological history of Mercury has been developed from Mariner 10 images (e.g., Strom, 1979, 1997; Spudis and Guest, 1988), but the limited coverage and resolution of those images render that history uncertain.

Most of the 45% of Mercury imaged by Mariner 10 can be divided into four major terrains. Heavily cratered regions have an impact crater density suggesting that this terrain records the period of heavy bombardment that ended about 3.8 billion years ago on the Moon. Intercrater plains, the most extensive terrain type, were emplaced over a range of ages during the period of heavy bombardment. Intercrater plains may be of either volcanic or impact origin, but there are no diagnostic morphological features to distinguish between these two possibilities visible at Mariner 10 resolution. Hilly and lineated terrain occurs antipodal to the Caloris basin, at 1300-km diameter the largest known impact structure on Mercury, and is thought to have originated at the time of the Caloris impact by the focusing of impact-generated shock waves (Gault et al., 1975). Smooth plains, the youngest terrain type, cover 40% of the area imaged by Mariner 10 and are mostly associated with large impact basins. In a stratigraphic position similar to that of the lunar maria, they are thought to be volcanic deposits on the basis of their relative age, visible color properties (Robinson and Lucey, 1997), and areal extent, but no volcanic morphological features are evident in Mariner 10 images.

The volcanic history of Mercury is thus quite uncertain. Ground-based infrared and millimeter observations of Mercury have been interpreted as indicating a generally basalt-free surface, and thus a magmatic history governed primarily by intrusions rather than surficial eruptions of magma (Jeanloz et al., 1995). If this inference is correct, Mercury would have experienced less volcanism than any other terrestrial planet.

Correlated with the volcanic history of a planet is its thermal history, particularly the evolution of the thermal structure of the outer few tens of kilometers of the planet. Important constraints on that thermal evolution can come from observations of topography and gravity, because of the strong temperature dependence of the elastic and ductile strengths of crustal and mantle materials. For instance, the thermal gradient may be estimated from the flexural response of the planet's lithosphere to vertical loading by volcanic deposits or edifices (Solomon and Head, 1990). The pattern of tectonic features associated with the Caloris basin has been interpreted as evidence that smooth plains deposits surrounding the basin loaded a lithosphere 75-125 km thick at the time of plains emplacement (Melosh and McKinnon, 1988), but gravity data are lacking to test this hypothesis. Additional constraints can come from gravity and topographic measurements across impact structures, because the original topographic relief at the surface and at the crust-mantle boundary beneath such features may have been subject to viscoelastic relaxation of stress to a degree determined by feature age and the thermal evolution of the surrounding crust (Solomon et al., 1982).

The most important tectonic features on Mercury are the lobate scarps, 20 to 500 km in length and hundreds of meters or more in height (Melosh and McKinnon, 1988; Watters et al., 1998). These scarps appear to be great thrust faults (Strom et al., 1975), although this interpretation should be tested with higher resolution images and topography. On the basis of their apparently random spatial and azimuthal distribution over the imaged fraction of the surface, Strom et al. (1975) surmised that the scarps record global contraction. From the number and height of the scarps, a total contraction of 1-2 km in radius was derived (Strom et al., 1975), a figure consistent with global cooling of the outer lithosphere or with partial solidification of a fluid metallic core (Solomon, 1976), although reconsiderations of both the geologically inferred (Watters et al., 1998) and geophysically predicted (Phillips and Solomon, 1997) magnitude of global contraction have called this agreement into question.

The geologic history of the planet may require considerable revision once global imaging coverage is available. Improved image resolution will permit the identification of key features diagnostic of plains emplacement mechanisms. Global stratigraphic and tectonic scenarios will be testable over the 55% of the surface yet unseen, and important new classes of landforms may be found. Earth-based radar observations of the portion of Mercury not seen by Mariner 10, for instance, show a radar-bright feature similar to large and relatively young shield volcanoes on Mars and Venus (Harmon, 1997). Such an identification, if verified by spacecraft observation, would demand models for interior thermal evolution different from those considered to date.

What is the nature and origin of Mercury's magnetic field?

Mercury's intrinsic magnetic field, discovered by Mariner 10, has a dipole component nearly aligned with the ecliptic normal and a moment of about 300 nT-R_M^3 (Connerney and Ness, 1988). This magnetic field is sufficient to stand off the average solar wind at an altitude of about 1 R_M (Russell et al., 1988). The compression or erosion of the dayside magnetosphere to the point where solar wind ions can directly impact the surface remains a topic of controversy (Siscoe and Christopher, 1975; Slavin and Holzer, 1979a; Hood and Schubert, 1979; Goldstein et al., 1981).

The origin of Mercury's internal magnetic field is not well understood, yet the recent discoveries of a field at Ganymede (Kivelson et al., 1996) and no global field on Mars (Acuña et al., 1998) heighten the importance of this question. Mercury's magnetic field cannot be externally induced (Connerney and Ness, 1988). The possibility that the dipole field is a remanent field acquired during lithospheric cooling in the presence of an internal or external field has been suggested (Stephenson, 1976; Srnka, 1976), but such severe constraints on the timing and geometry of the remanence are required as to render the suggestion unlikely (Schubert et al., 1988). Short-wavelength magnetic field anomalies arising from regionally coherent remanent magnetization of crustal rocks remain a strong possibility, however. A hydromagnetic dynamo in a liquid, metallic outer core is generally viewed as the most likely explanation of the dipole field (Schubert et al., 1988), although such other possibilities as a thermoelectric dynamo have been postulated (Stevenson, 1987). A better knowledge of the geometry of the magnetic field is needed to distinguish among these hypotheses.

Depending on the trajectory of the observing spacecraft, external sources can in fact dominate the total measured field, as was the situation for Mariner 10 (Ness et al., 1975, 1976). Errors from external fields were such that the uncertainty in Mercury's dipole moment is a factor of 2 (Slavin and Holzer, 1979b), and higher order terms are linearly dependent (Connerney and Ness, 1988). For these reasons, determining the structure of the magnetic field of Mercury must be carried out by an orbiting spacecraft that will accumulate long-term averages and remove the dynamics of the solar wind and Mercury's magnetosphere, which are readily identifiable by measuring simultaneously the plasma distribution, as well as the magnetic field.

Mercury has a small magnetosphere with similarities to that of the Earth. Despite the limited duration of the two Mariner 10 flybys, which passed through the nightside magnetosphere for a total of only about 1 hour, much was learned about its dynamics. Evidence of substorm activity was obtained in the form of intense energetic particle injections and dipolarizations of the magnetic field, similar to those observed in the near-tail region at Earth (Siscoe et al., 1975; Baker et al., 1986; Eraker and Simpson, 1986; Christon et al., 1987). Although the substorm interpretation has been questioned (Luhmann et al., 1998), compelling evidence was found for intense perturbation of the magnetic field due to field-aligned currents following substorm events (Slavin et al., 1997), in spite of the tenuous nature of Mercury's atmosphere and the high resistivity of the planet's regolith. These magnetospheric dynamics are important in their own right and for comparison to those of the Earth, since reconnection rates relative to 1 AU should be larger by a factor of three due to lower Alfvénic Mach numbers and a more intense interplanetary magnetic field.

What is the structure and state of Mercury's core?

The hypothesis that Mercury's internal magnetic field arises from a core dynamo requires that Mercury have a metallic core that is at least partially molten. The presence of a fluid core during the time of Mercury's capture into its 3:2 spin-orbit resonance enhances the capture probability (Peale, 1988). However, different thermal history models of the planet lead to different predictions regarding the evolution and current state of the core. For most models in which core-mantle differentiation occurs early and the core is either pure iron or iron-nickel, an initially molten core should have cooled and solidified by now (e.g., Siegfried and Solomon, 1974; Fricker et al., 1976; Cassen et al., 1976). Schubert et al. (1988) show that an outer fluid core can be maintained to the present if a lighter element such as sulfur is mixed into the core to reduce the melting temperature.

A direct observation that yields an unambiguous determination of the existence and extent of a liquid core would have profound effects on theories for magnetic field generation and thermal history in terrestrial planets and icy satellites (Schubert et al., 1996), as well as for inferences on Mercury's rotational history. Such an observation, described by Peale (1976, 1981, 1988), is measurement of the amplitude of Mercury's libration. For the experiment to work, the fluid outer core must not follow the 88-day physical librations of the mantle, but the core must follow the mantle on the time scale of the 250,000-year precession of the spin. These constraints lead to bounds on outer core viscosity, but the bounds are so broad as to be readily satisfied (a result robust with respect to the possible effects of topographic, gravitational, or magnetic coupling between core and mantle).

The physical libration of the mantle about the mean resonant angular velocity arises from the periodically reversing torque on the planet as Mercury rotates relative to the Sun. The amplitude of this libration ϕ_0 is approximately equal to $(B-A)/C_m$, where A and B are the two equatorial principal moments of inertia of the planet and C_m is the moment of inertia of the solid outer parts of the planet about the rotation axis (Peale, 1972). Dissipative processes will carry Mercury to rotational Cassini state 1 with an obliquity θ close to 0° (Peale, 1988), which yields a relationship between θ and the differences in the moments of inertia and other orbital parameters. The moment differences also appear in expressions for the second-degree coefficients of the planetary gravity field C_{20} and C_{22}.

These relations give a strategy for determining the presence of a fluid outer core and its outer radius by measurement of the second-degree gravity field, the obliquity θ, and the physical libration amplitude ϕ_0: $C_m/C = [C_m/(B-A)]\,[(B-A)/MR^2]\,[MR^2/C] \leq 1$. The first quantity in brackets follows from ϕ_0; the second is equal to C_{22}; and the third can be obtained from the relation between θ and the second-degree gravity field coefficients. Thus C/MR^2 can be derived to an accuracy limited by the uncertainty in θ, and C_m/C can be obtained to an accuracy limited principally by the uncertainties in ϕ_0 and θ (Peale, 1997). If $C_m/C = 1$, then the core of Mercury is solid; from a value for $C_m/C < 1$ follows the radius R_C of the fluid outer core ($C_m/C = 0.5$ for $R_C/R = 0.75$), and from C/MR^2 the radius of any solid inner core may be estimated or bounded.

What are the radar-reflective materials at Mercury's poles?

Radar images of Mercury obtained in 1991 revealed regions of high reflectivity and high polarization ratios in Mercury's polar regions (Slade et al., 1992; Harmon and Slade, 1992). Because the high polarization ratios are similar to those of outer planet icy satellites and the residual polar caps of Mars, they are widely thought to indicate surface or near-surface water ice. A lower absolute radar reflectance than the Martian polar cap can be the result of incomplete areal coverage by ice units or a thin cover of dust or soil (Butler et al., 1993).

Because of the near-zero obliquity of the planet, the permanently shadowed floors of impact craters near the poles are sufficiently cold to preserve water ice for billions of years, assuming that Mercury has been in its current Cassini state for such a time (Paige et al., 1992; Ingersoll et al., 1992; Butler et al., 1993). Indeed, many of the areas of highest backscatter coincide with known impact structures imaged by Mariner 10 (Harmon et al., 1994). The source of water ice is not known, but impact volatilization of cometary and meteoritic material followed by random-walk transport to the poles is a possibility.

Sprague et al. (1995) proposed an alternative hypothesis that the polar deposits are composed of elemental sulfur. Their rationale includes thermodynamic properties suitable for long-term stability in polar cold traps and several arguments for the presence of abundant sulfides in the regolith and interior of the planet. Sulfur could be injected into the atmosphere by sputtering, volatilization, or interior degassing and then redeposited in polar cold traps. Distinguishing between water ice and sulfur, an important step toward understanding volatile inventories in the inner solar system, can be accomplished through UV observations of the polar atmosphere and γ-ray spectra and neutron fluxes from the polar surface.

What are the important volatile species and their sources and sinks on and near Mercury?

Mercury's atmosphere is a surface-boundary exosphere whose composition and behavior are controlled by interactions with the magnetosphere and the surface. The atmosphere is known to contain five elements (H, He, O, Na, and K), which together have a surface density at the sub-solar point of 10^4 atoms cm^{-3} (Hunten et al., 1988). The Mariner 10 airglow spectrometer detected H, He, and O (Broadfoot et al., 1974, 1976), while ground-based spectroscopy revealed Na and K (Potter and Morgan, 1985, 1986). Searches for additional constituents (e.g., Ca and Li, Sprague et al., 1993, 1996) have not succeeded. Ground-based studies of Na indicate that the atmosphere is spatially and temporally variable. Orderly changes in Na surface density are related to changes in solar radiation pressure (Smythe and Marconi, 1995), but atmospheric chaotic variations also occur (Killen et al., 1990).

Our inventory of Mercury's atmospheric composition is incomplete. Current understanding of source processes suggest the presence of yet undetected species, including Ar, Si, Ca, Al, Mg, Fe, S, and OH. With the exception of Ar, all these species have strong ground-state emission lines (e.g., Morgan and Killen, 1997) in the spectral range 0.13-0.43 µm. To date, observational constraints have prevented these species from being seen from the ground or Earth orbit.

The processes which supply and remove atmospheric material are poorly understood. Hydrogen and helium are thought to be primarily derived from neutralized solar wind ions, although photodissociation of meteoritic water yields some H and crustal outgassing should supply some He. Proposed sources for Na, K, and O include impact vaporization, ion sputtering, photon stimulated desorption, and crustal degassing. There is strong disagreement about the relative importance of these four mechanisms (McGrath et al., 1986; Cheng et al., 1987; Sprague, 1990; Morgan and Killen, 1997). The principal loss mechanisms are thermal escape and photoionization with subsequent loss through transport along open magnetic field lines. Although thermal escape appears to be the dominant loss mechanism for both H and He, it is probably unimportant for Na and K (Hunten et al., 1988). Magnetospheric processes, including ion precipitation onto Mercury's surface and pickup of photo-ions, may help control atmospheric sources and losses.

Determining a comprehensive inventory of atmospheric and magnetospheric species and measuring their spatial and temporal distributions will allow us to quantify the dominant source mechanisms for the various atmospheric species and will provide additional insight into upper crustal composition. Sputtering, for instance, can yield all the common regolith species in the atmosphere (O, Si, Ca, Al, Mg, and Fe). Impact vaporization preferentially supplies volatiles (S, H_2O, and OH; e.g., Killen et al., 1997) in addition to regolith species. Crustal diffusion is also predicted to contribute regolith-derived species to the atmosphere (Sprague, 1990). Plasma composition is important because of the close coupling among Mercury's surface, atmosphere, and magnetosphere. Both planetary and solar wind ions must be present at the bow shock, magnetopause, and cusps, and in the plasma sheet.

D.1.2 Prioritized Scientific Objectives and Measurement Requirements

To answer the key questions discussed above, of central importance for improving our general understanding of the formation and evolution of terrestrial planets, we propose MESSENGER, a MErcury Surface, Space ENvironment, GEochemistry and Ranging mission to fly by and orbit the planet Mercury.

Science-Instrument Traceability. A clear rationale linking the above questions to the instrument suite and measurement strategy for MESSENGER is given in Table D-1-1. The scientific objectives, in order of priority, are to determine (1) the chemical composition of Mercury's surface, (2) the planet's geological history, (3) the nature of Mercury's magnetic field, (4) the size and state of the core, (5) the volatile inventory at Mercury's poles, and (6) the nature of Mercury's exosphere and magnetosphere. These objectives are coded by color across the table. The first objective leads

Table D-1-1 MESSENGER Science Traceability

Science Questions	MESSENGER Objectives	Science Measurement Objectives
What planetary formational processes led to the high metal/silicate ratio in Mercury?	Map the elemental and mineralogical composition of Mercury's surface	**Surface elemental abundances** **GRNS**: Fe, Si, alkali depletion from K/U and K/Th, H
		Surface elemental abundances **XRS**: Fe, Mg, Ca, Al, Si, Ti,S
		Spectral measurements of surface Surface mineralogy: Fe, Ti; spectral units **ASCS/VIRS**: Visible and near IR absorption bands
What is the geological history of Mercury?	Image globally the surface at a resolution of hundreds of meters or better	
		Elemental abundances of major units **XRS**: Abundances of Fe, Mg, Ca, Al, Si, Ti,S **GRNS**: K, U, Th, Fe, Si, O, H
		Global imaging 100's-m resolution; fill in missing Mariner 10 areas **Global multispectral mapping** km resolution; mafic mineralogy and spectral unit maps **High-resolution multispectral imaging** Crustal stratigraphy from crater ejecta, volcanic flow units **High-resolution monochrome imaging** Volcanic landforms, tectonic features, plains emplacement mechanisms **MDIS**: Global stereo @ 250 m/pixel; global multispectral map @ 1 km/pixel, selected areas @ 10 m/pixel
		Altimetry Crustal structure, volcanic morphology, tectonic structures **MLA**: N-hemisphere topography, ground truth to stereo
What is the nature and origin of Mercury's magnetic field?	Determine the structure of the planet's magnetic field	**Comprehensive magnetic field measurements** Strength, configuration, moments of internal field. Deformation by solar wind, substorm events, time variability **MAG**
		Magnetospheric species Solar vs. planetary source **EPPS**
What is the structure and state of Mercury's core?	Measure the libration amplitude and gravitational field structure	**Gravity field, occultation radii, libration amplitude, and pole position** **RS + MLA**
What are the radar-reflective materials at Mercury's poles?	Determine the composition of the radar-reflective materials at Mercury's poles	**Detection of H at poles if present** **GRNS**: H, S (if present)
		Topographic profiles over craters containing frozen volatiles **MLA**
		Atmospheric composition over polar regions **ASCS/UVVS**
		Detection of H or S enrichment over polar regions **EPPS**
		Spectral measurements of atmosphere Composition and density at different latitudes, times of solar day, times of solar year **ASCS/UVVS**
What are the important volatile species and their sources and sinks on and near Mercury?	Characterize exosphere neutrals and accelerated magnetosphere ions.	
		Elemental composition of surface **GRNS, XRS**
		Composition of magnetospheric ions and pickup ions in the solar wind from sputtered neutrals **EPPS**

Instrument Requirements	Mission and Spacecraft Requirements	Data Product
MDIS Dual imagers: wide angle imager with 25° FOV, eight filters; narrow-angle imager with 1.5° FOV; thermoelectric coolers; common scan mirror for flyby imaging	Clear FOV for entire scan range of mirror Observe over two Mercury solar days at two geometries for stereo image of entire planet	Catalogued images
GRNS γ-ray detector: 0.1 to 10 MeV range; active shield; CsI detector and photodiodes with anti-coincidence; neutron detector, 2 channels: thermal + epithermal, thermal < 0.5 eV; discrimination against cosmic rays	Maximize time at lowest altitudes; 45° FOV	γ-ray spectra ordered by latitude and longitude; thermal and epithermal neutron fluxes ordered by latitude and longitude
MAG Three-axis fluxgate magnetometer; dual range; 0.03 nT precision; 40 Hz sampling; selectable averaging 0.025 s to 300 s	Minimize magnetic interference, 3.6-m boom. Minimize periapsis elevation; maximize range, coverage	B-field vectors
MLA Positive link margin @ 1000 km range, worst case; along-track resolution of ~1 km. Cr:Nd:YAG xmit at 20 mJ and 5 Hz rep rate; 25-cm-dia Be telescope	Operate for four Mercury years; inclination 80°, latitude of periapsis maintained to ~ 60° N latitude; minimize periapsis altitude	Mercury range profiles and radiometry
ASCS/UVVS Atmos. comp. from UV emission; altitude profiles of H, O, Na, and K; search for other species: 0.115 to 0.6 μm; 1 nm spectral and 25 km spatial res.; < 20° lat/lon res.; 1 Rayleigh in 10^4 s	Co-align with MLA, XRS and GRNS Execute limb scans by nodding S/C to obtain altitude profiles	Spectra, tangent height
ASCS/VIRS Surface mineralogy from absorption bands; ferrous-bearing minerals, glasses and iron: 0.3 - 1.45 μm; 4 nm spectral and 5 km spatial res.; SNR>200	Co-align with MLA, GRNS and XRS	Spectra by latitude and longitude
EPPS *EPS*: Differential flux, spectra, compositional separation: six angular channels; four species channels; six energy channels, ≥ 10 keV/nuc to ~ 5 MeV; miniaturized TOF sensor with solid state detectors; *FIPS*: Thermal plasma ion distribution function and composition over 2π ster; up to ~ 10 keV/charge; Electrostatic filter + TOF with MCP detectors	Minimize thermal input to front foil while maintaining 160° x 12° FOV for EPS head; 2π ster FOV for FIPS head with allowance for view of aberrated solar wind flow and pickup ions	Particle differential intensity spectra and composition, pulse height events Particle 3-D distribution functions and composition
XRS K_α X-ray detection, 1 to 10 keV; Si-PIN detectors with Mg and Al filter for element separation at < 2 keV; Be-Cu collimator w/400 km x 20 km max spatial resolution; Si-PIN solar monitor w/pinhole	Maximize time at lowest altitudes; 6° clear FOV; provide pinhole in thermal shade for solar monitor	X-ray spectra ordered by latitude and longitude
RS X-band transponder implemented for S/C downlink; ≤1 mm/s quality data from single DSN station for each mission day except solar conjunction	Symmetric S/C thermal design to simplify radiation-pressure model, Minimize active momentum dumping	Doppler data, ranging data, occultation times

Analysis Product	Science Results
Global maps by element - low spatial resolution **GRNS**	Mechanism for loss of silicates/ enrichment of metals from predictions of different planet-formation models
Global maps by element - high spatial resolution **XRS**	
Spectral unit maps - **MDIS, ASCS/VIRS**	
	Composition of major rock units Compositional layering from exposures in impact basins of deeper crust Identification of volcanic units
Global maps by element- **XRS, GRNS**	
Global monochrome maps Stereo maps Multispectral image catalog **MDIS**	Global geologic history Distribution, compositions, ages of volcanic structures
North-hemisphere topographic map, altimetric profiles **MLA**	Type, amount, timing of tectonic deformation
North-hemisphere gravity model **RS**	Lithospheric and crustal thicknesses from tectonics, topography-gravity relations
Multipole internal magnetic field model **MAG**	Structure and time-variability of internal magnetic field
Time-dependent magnetosphere model **MAG, EPPS**	Interactions with atmosphere, surface, and solar wind
Libration amplitude; RA and DEC of Mercury's rotational pole **MLA+RS**	Presence and radius of liquid outer core
Spherical harmonic gravity field Low-degree global shape **RS**	
Global maps by element - low spatial resolution **GRNS**	Confirmation of H-containing material if present
North-hemisphere topographic profiles **MLA**	Thickness and amount of frozen volatiles
Time-dependent magnetosphere model **MAG, EPPS**	Detection of other volatiles
Exosphere model **ASCS/UVVS**	
	Atmospheric composition and variation with local solar time, solar activity, distance from the Sun
Volatile species and sources **ASCS/UVVS, EPPS, GRNS, XRS**	Evaluation of candidate sources and sinks

LEGEND

Each color indicates the science flow:

Science Question → Instrumentation Requirement → Science Result

Individual boxes delineate payload instruments.

Most instruments address multiple science questions.

to a measurement requirement for global maps of elemental composition at a resolution sufficient to discern major units and to distinguish material excavated and ejected by young impact craters from a possible veneer of cometary and meteoritic material; information on surface mineralogy would also be important. The second objective leads to the requirement for global monochrome imaging at hundreds of meters or better, for topographic profiles across key geological features from altimetry or stereo, and for spectral measurements of major geologic units at spatial resolutions of several kilometers or better. The third objective leads to a requirement for magnetometry, both near the planet and throughout the magnetosphere, as well as for energetic particle and plasma measurements so as to isolate external from internal fields. The fourth objective can be met by altimetric measurement of the amplitude of Mercury's physical libration as well as determination of the planet's obliquity and low-degree gravitational field. The fifth objective can be met by UV spectrometry of the polar atmosphere and by γ-ray and neutron spectrometry, imaging, and altimetry of polar-region craters. The sixth objective leads to measurement requirements for the identification of all major neutral species in the exosphere and all charged species in the magnetosphere.

These measurement requirements are met by a suite of seven scientific instruments plus the spacecraft communication system. There is a dual imaging system for wide and narrow fields-of-view, monochrome and color imaging, and stereo; γ-ray, neutron, and X-ray spectrometers for surface chemical mapping; a magnetometer; a laser altimeter; a combined UV-visible and visible-near-infrared spectrometer to survey both exospheric species and surface mineralogy; and a combined energetic particle and plasma spectrometer to sample charged species in the magnetosphere. The extent to which each instrument contributes toward each scientific objective is shown by the mapping of the color code into the central column of Table D-1-1.

Orbital Mission Rationale. Answering all of the key science questions demands a Mercury orbiter. Characterizing the global planetary magnetic and gravitational fields and measuring the amplitude of Mercury's physical libration can be accomplished only from orbit. An orbiter enables multiple cuts through the magnetosphere and exosphere. Only an orbiter can provide sufficient integration time to produce elemental and mineralogical maps of the planet at the resolution necessary to distinguish among hypotheses for planet formation or to discern geological history. For these reasons, and given the limitations of the Mariner 10 results, we believe that yet another flyby-only mission to Mercury is neither warranted nor cost-effective.

D.1.3 Baseline Mission

The baseline MESSENGER mission employs state-of-the-art chemical propulsion and multiple gravitational flybys to reach Mercury orbit. Both the flybys and the orbit have been optimized to satisfy all scientific measurement requirements while meeting the constraints of the Discovery program. In particular, we have examined in detail all launch possibilities for ballistic missions through 2010. The selected baseline is the only scenario that combines the highest mass margin with schedule resiliency; this combination will not recur in the next selection round for Discovery missions.

Launched in March 2004 on a Delta II 7925H (the first of two 15-day launch windows separated by four and a half months), MESSENGER executes two gravity assists at Venus and two at Mercury. Orbit insertion is accomplished at the third Mercury encounter. The orbit has an initial periapsis of 200 km and initial latitude of periapsis of 60°N; the orbit is inclined 80° to the equatorial plane of the planet and has a 12-hour period. The periapsis altitude and orbit phasing are optimized to balance thermal constraints against science requirements. The inclination and latitude of periapsis result from a complex set of trade-space optimizations driven by imaging and altimetry coverage requirements traded off against thermal input and mass (Sec. D.2.2). Solar perturbations impose changes in the periapsis altitude and latitude that are corrected periodically in accord with science measurement requirements.

D.1.4 Science Strategy

The MESSENGER mission is designed so that significant scientific return can be expected from each flyby and the orbital phase of the mission will achieve all principal scientific objectives.

During the first flyby, roughly half of the hemisphere not observed by Mariner 10 is illuminated; the first data return from MESSENGER will thus observe new terrain, including the previously unseen half of Caloris basin and its ejecta. During the second flyby, illumination is centered on the eastern edge of the Mariner 10 hemisphere, including the site of the possible shield volcano imaged by radar (58°N, 345°W). Total flyby coverage excludes only the polar regions and two ~20° longitudinal bands, one ~120° west of Caloris and the other centered at ~140° W longitude in the Mariner 10 hemisphere (Fig. D-1-1). These gaps will be filled during the orbital phase of the mission. Each of the two flybys have similar geometries (Table D-1-2), and similar observation strategies will be used for each (Table D-1-3).

During the flyby phase, 85% of the planet is imaged in monochrome averaging ~500 m/pixel, and in color at ~8 km/pixel. 50% is covered in color at ~4 km/pixel. The high-resolution data swaths contain monochrome images at better than 125 m/pixel, color at ~2 km/pixel, and IR and X-ray spectrometer transects with spot sizes of 700 m and 200 km, respectively. MESSENGER will also probe the atmosphere over two different regions and the magnetosphere along two different trajectories.

Important science investigations can be also be carried out at the Venus flybys during the early part of the mission. For example, the imager will observe cloud layers at 415 and 950 nm to compare with the Galileo results (Belton et al., 1991), fields-and-particles instruments will observe pick-up particles (Williams et al., 1991), and the UV spectrometer will look for changes in the composition of the upper atmosphere (Esposito, 1984). New science possibilities include a search for lightning on the nightside, altimetric probing of the Venus cloud deck, and a search for Venus's signature in X-rays, similar to that observed recently at comets (Lisse et al., 1996). The Venus flybys will also provide in-flight calibrations.

During the Mercury orbital phase of the mission, MESSENGER's science strategy shifts to detailed global mapping, characterization of the atmosphere, magnetosphere, and polar deposits, geophysical studies, and focused study of high-priority targets identified during the flyby phase. Details of the observations given in the investigation plans below follow from the key science questions (Table D-1-1).

Imaging Investigation Plan. The three major objectives of orbital imaging (Table D-1-4) are filling gaps in flyby color coverage (Fig. D-1-2), high-resolution targeted coverage (Fig. D-1-3), and global stereo imaging for high-resolution topography (Fig. D-1-4). Filling gaps in color coverage is relatively simple except at low altitudes over high northern latitudes (Fig. D-1-5), when limiting smear requires short 30-50 ms exposure times. The impact on signal-to-noise ratio (SNR) can be offset by pixel averaging, because full spatial resolution is ~120 m/pixel compared with the 1-2 km/pixel required to fill the gaps. High-resolution narrow-angle panchromatic images require ~2 ms exposure times to limit smear at periapse, which is easily attained with good SNR.

Global monochrome image mosaics averaging 250 m/pixel will be built up using the narrow-angle imager for southern latitudes when altitude is high, and the wide-angle imager with its broadband filter for the northern hemisphere (Fig. D-1-6 and Table D-1-5); at periapse the desired resolution is exceeded by a factor of ~2. The one-year orbital mission encompasses two Mercurian solar days. A full global mosaic will be built up during the first six months of the mission. In the second six months, the operation will be repeated with different scan mirror positioning to yield global stereo coverage (at ~250 m/pixel).

Elemental and Mineralogical Investigation Plan. A γ-ray and neutron spectrometer remotely senses characteristic γ-ray emissions and neutrons and will yield global maps of Mercury's elemental composition. The γ-ray spectrometer detects discrete-line γ-ray emissions and will be used to measure galactic-cosmic-ray excited elements O, Si, S, Fe, and H and naturally radioactive elements K, Th, and U to a depth of about 10 cm (Trombka et al., 1997). The neutron spectrometer component detects low-energy neutrons produced by cosmic-ray bombardment and moderated by

Fig. D-1-4 Image of the Discovery Rupes Scarp (~240 m/pixel). MESSENGER will provide global stereo monochromic imaging at ~250 m/pixel.

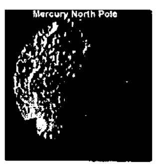


Fig. D-1-5 Shadowed craters associated with anomalous radar reflectivity (Harmon et al., 1994) are clearly visible. MESSENGER will assay all craters that display radar-bright deposits near the north pole.

Table D-1-2 Flyby Imaging Summary

Flyby	Phase Angle In/Out-Bound	Flyby Lat, Lon	Illuminated Longitudes	Coverage	High-Res. Imaging, XRS, NS, VIRS Targets
#1	120°, 54°	-12°, 323°	86° - 266°	Inbound: Similar to Mariner 10 Outbound: Caloris region, plains, highlands	Tolstoj-Beethoven basins and surrounding highlands
#2	130°, 40°	-1°, 132°	268° - 88°	Inbound: Terra Incognita Outbound: Fill most of Mariner 10 gore	Terra Incognita, Caloris antipode

Table D-1-3 Flyby Observation Strategy and Data Volume

Instrument	Data Coverage, Compression	Phase Angle		Mbit per Flyby	
Flyby Approach		1	2	Raw	Compress
WA approach movie	30 1-frame, 3-color images to 4 R_M, every 2 min, 8:1 compression	115°	125°	377	47
NA monochrome map to ±80° lat	40 frame (5 x 8) mosaic from 9 R_M, 550 m/pixel, 6:1 compression	115°	125°	503	84
WA color map to ±80° lat	1-frame, 7-color image from 8 R_M, 8.9 m/pixel, 6:1 compression	120°	130°	88	14
WA color map to ±70° lat	2-frame, 7-color mosaic from 3 R_M, 3.3 km/pixel, 6:1 compression	130°	—	125	21
MLA	(Cannot view surface due to geometry)	—	—	—	—
EPPS and MAG	Magnetospheric survey, high-resolution starting at 12 R_M	—	—	3	3
Flyby Departure		1	2		
ASCS	~70 spectra as atmosphere profiles, surface swaths	90°	90°	30	30
XRS	Integrate over steps on swath	90°	90°	9	9
NA monochrome strip across region of interest at high resolution	40-frame (20 x 2) mosaic from 0.6 R_M, 125 m/pixel, binned, 6:1 compression	80-90°	80-90°	503	84
WA color from 1 R_M covering region of interest	4-frame (2 x 2) 7-color mosaic from 1 R_M, 1.1 km/pixel, 6:1 compression	78°	80°	352	58
NA monochrome from 2 to 4 R_M - complete global coverage	2 50-frame (5 x 10) mosaics from 2 R_M, 250 m/pixel, 6:1 compression	60-75°	53-60°	1258	210
WA departure movie	30 1-frame, 3-color images, 4 to 16 R_M, 4.4-18 km/pixel, 8:1 compression	49°	35°	377	47
NA monochrome map to ±80° lat	50 frame (5 x 8) mosaic from 9 R_M, 550 m/pixel, 6:1 compression	49°	35°	503	84
WA color map to ±80° lat	1-frame, 7-color image from 8 R_M, 8.9 km/pixel, 6:1 compression	54°	40°	88	15
MLA	Surface swath, 2.5 samples/s for 360 s	—	—	0.07	0.07
EPPS and MAG	Magnetospheric survey, high-resolution ending at 12 R_M	—	—	3	3
Totals		—	—	4219	709

Notes: (1) All images are 12 bits/pixel. (2) Downlink assumes 70% data recovery, one 8 hr pass/day, 70-m DSN site. (3) Each DSN pass assumes 1 hr unused (setup time, signal acquisition, etc.). (4) Final data volume adds 12.5% for housekeeping, headers, etc. (5) Downlink flyby 1 takes 3 passes, flyby 2 takes 5 passes (greater S/C distance).

MESSENGER

Observing Strategy and Performance: Flybys and Orbital Operations

- Global coverage at high spatial resolution (~250 m/pixel)
- Stereo viewing for global topography
- Global multicolor imaging at moderate spatial resolution (~1-3 km/pixel)
- High-resolution coverage of critical targets

Fig. D-1-2 (left) Mariner 10 mosaic of Mercury color differences suggests that some plains units were formed as volcanic flows (orange) and pyroclastic eruptions may have formed dark mantling deposits (blue). Isolated red units are consistent with a low opaque mineral content (Robinson and Lucey, 1997).
Fig. D-1-3 (right) One of the highest resolution Mariner 10 images (~ 90 m/pixel). MESSENGER will acquire images at higher resolutions, up to ~ 6 m/pixel.

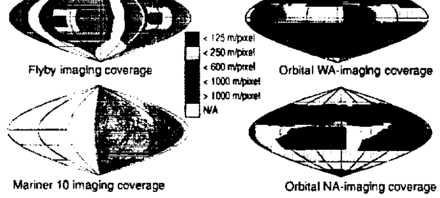


Fig. D-1-1 MESSENGER imaging coverage during the flybys and orbital phase compared with the Mariner 10 coverage.

Table D-1-4 Orbital Imaging Coverage and Data Volume Summary

Instrument	Data Coverage and Compression	Gb
MDIS WA + NA	Global monochrome map, 12 bits, ~250 m/pixel, stereo, 10% frame overlap, 6:1 compression	4.7
WA imager	Color in polar regions and flyby mosaic gaps (~ 40% planet), 7 filters, 12 bits, 1.1 km/pixel, 6:1 comp.	0.3
WA imager	1% coverage, 7 filters, 12 bits, 300 m/pixel or better, 6:1 compression	0.1
NA imager	Targeted high-resolution monochrome, 12 bits, 6-80 m/pixel, ~6:1 compression (~500 frames)	0.5
Total downlink data (Gbits)		5.6

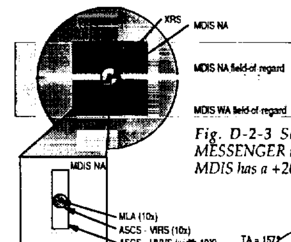


Fig. D-2-3 Scale and alignment of MESSENGER instrument fields-of-view. MDIS has a +20°, -50° field of regard.

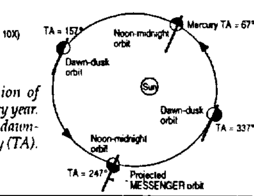


Fig. D-2-2 Ecliptic projection of orbital geometry over a Mercury year. MESSENGER injects into a dawn-dusk orbit at 337° true anomaly (TA).

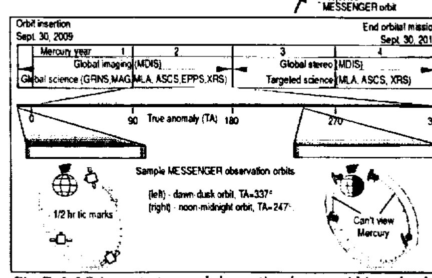


Fig. D-1-6 Science strategy and observational zones within each orbit.

Table D-1-5 Orbital Observation Strategy (colors refer to Fig. E-1-6)

Instrument		Northern Polar Zone	Mid Zone	Far Zone
MDIS	NA	-	Mapping, < 125 m/pixel	Mapping, < 500 m/pixel
	WA	Mapping, < 125 m/pixel	Mapping, < 500 m/pixel	Mapping, < 1000 m/pixel
GRNS		300 s integration time	500 s integration time	1800 s integration time
MAG		10 Hz sampling	1 Hz sampling	0.1 Hz sampling
MLA		2.5 Hz ranging (up to 1000 km altitude)		Standby
ASCS	VIRS	~ 1 s integration surface observations		
	UVVS	-	< 100 s integration limb scans, ~ 1 s surface observations	
EPPS		EPS - 36 s integration time; FIPS - 1 min scan time		
XRS		100 s integration time	300 s integration time	2000 s integration time
RS		Radiometric data 8 hrs/day over various portions of orbit		

collisions with near-surface (~40 cm), H-rich material (Feldman et al., 1997). Since solar illumination does not significantly affect γ-ray or neutron coverage, observations over the north pole will detect any concentrated water ice (H and O) or sulfur (S) deposits in the permanently shadowed regions. For example, H can be detected by the 2.223 MeV γ-ray line and by study of line strengths due to capture and inelastic scattering of neutrons (Evans and Squyres, 1987). Simultaneous measurement of the thermal and epithermal neutron flux yields strong constraints on the hydrogen content of the regolith. The best determination of the amount of hydrogen present can be made by a self-consistent unfolding of both a γ-ray spectrum and neutron-flux measurements (Haines and Metzger, 1984a,b). For an assumed composition, we have calculated (Table D-1-6) required counting times to determine the composition to a precision level of 20% for the instrument described in Sec. D.2.1. MESSENGER will be able to discern a high sulfur content, if present. The spatial resolution will be about 170 km from 200 km altitude, and the spacecraft will be over the polar region for ~15 min every orbit (once every 12 hours).

Table D-1-6
Compositional Uncertainty for Given γ-Ray Observation Times

Element	Assumed Composition (%)	1 Hour Relative Uncertainty (%)	8 Hours Relative Uncertainty (%)
Si	20	23	8.3
Al	11	52	18
Mg	4	92	32
Ca	10	**	92
Ti	1.4	**	78
Fe	9	24	8.6
K	0.12	25	8.8
Th	1.9 ppm	31	11
U	0.5 ppm	45	16
S	0.07	**	**
H	0.004	**	**
S	10	**	44
H	1	41	15

Uncertainties quoted are at the 3σ level; uncertainties greater than 100% are listed as "**."

Visible and near-infrared spectrometry will be used to search for ferrous bearing minerals (spectral signatures near 1 μm), Fe-Ti bearing glasses (spectral signatures near 0.34 μm), and ferrous iron (strong band near 0.25 μm) on the planet's surface. These measurements will be made with a spatial resolution of 5 km or better. Measurements during imaging sequences will provide absorption line data across the spectrum for mineralogical identification.

X-ray spectrometry remotely senses characteristic X-ray emissions, which are diagnostic of elemental composition within 1 mm of the surface. With a planet-pointing X-ray spectrometer, we will detect characteristic X-rays to measure globally the surface abundances of elements Mg, Al, Si, Ca, S, and Fe with spatial resolution down to ~20 km. To ensure a proper quantitative analysis, a sunward-pointing X-ray detector will measure the time-variable incident solar flux.

The X-ray measurements complement those from γ-ray and neutron spectrometry. For the same element, differences in measured concentrations should reveal the extent of a dust layer on the surface and allow comparison with elements sputtered from the surface. X-ray, neutron, and γ-ray measurements also provide a cross-check on the mineralogical identifications made from absorption bands, allowing for resolution of any ambiguities. Table D-1-7 lists required integration times for identifying the listed elements at the 10% and 30% uncertainty levels for different solar conditions for the instrument configuration in Sec. D.2.1. At 15 minutes per orbit spent over the polar region and one orbit every 12 hours, the one-Earth-year nominal mission will provide ~180 hr (7.6 d) of high-resolution X-ray measurements.

Magnetic Field Investigation Plan. To characterize Mercury's magnetic field, emphasis early in the mission will be on periapsis passes (<1000 km altitude), where the planetary contribution to the ambient field is greatest. These measurements will remove the present ambiguity in the multipole parameters (Connerney and Ness, 1988).

To produce a three-dimensional model of Mercury's magnetosphere, magnetic field measurements will be taken at low sample rate over the entire magnetospheric fraction of the orbit (Table D-1-5), with high-rate samples at the magnetopause, cross-tail, and field-aligned external current regions. These observations will be combined with charged particle observations to investigate such dynamic processes as

Table D-1-7 Required X-ray Integration Times for Determination of Elemental Compositions

	Relative Uncertainties	Anorthosite		Basalt	
		Normal	Flare	Normal	Flare
Fe	10%	23 d	2 hr	33 hr	5 min
	30%	2 d	15 min	3 hr	48 s
Ti	10%	97 d	3 min	35 hr	3 min
	30%	12 d	23 s	3 hr	23 s
Ca	10%	81 min	2 min	3 hr	3 min
	30%	8 min	12 s	15 min	32 s
S	10%	—	—	—	—
	30%	—	—	—	—
Si	10%	10 min	3 min	10 min	2 min
	30%	1 min	20 s	1 min	13 s
Al	10%	8 min	50 s	33 min	5 min
	30%	50 s	17 s	3 min	50 s
Mg	10%	5 d	20 hr	40 min	13 min
	30%	13 hr	2 hr	5 min	2 min

Times listed are those required to achieve 10% and 30% uncertainty levels, respectively, for the assumed compositions and levels of solar activity (45° solar incidence angle; 3x0.25 + 2x1 cm² Si-PIN detectors, filled FOV; following Clark and Trombka, 1997, but with smaller areas).

substorms and magnetic reconnection at the magnetopause. With apparent substorm durations of only about 1 min at Mercury, it should be possible to gather definitive substorm statistics at a variety of locations throughout the magnetosphere without the motion of the spacecraft aliasing measurements.

Mercury's magnetosphere contains a charged particle population that varies significantly on short temporal (~10 s) and spatial scales. Nothing is known from the Mariner 10 flybys regarding the composition, and there remains controversy about interpretation of Mariner 10 data (Armstrong et al., 1975). To answer these questions, an energetic particle and plasma spectrometer will be operated continuously in concert with the magnetometer. Representative samples of the global particle distribution in the magnetosphere will be obtained during each Mercury year. We will also monitor background penetrating particles to provide a measure of radiation dosage for spacecraft and instrument electronic subsystems.

Libration Amplitude, Altimetry, and Gravity Investigation Plan. Topographic Mapping. The laser altimeter will measure the range to the surface of Mercury at spacecraft elevations of 1000 km or less with 90% probability of detection and lower detection rates at higher altitudes. To determine range, the spacecraft orbital trajectory will be interpolated to times of measurement, correcting for spacecraft pointing. Ranges will be converted to planetary radii with respect to Mercury's center of mass. Profiles will have an along-track resolution of 0.8-1 km. The MESSENGER orbit will enable altimetric mapping of nearly the entire northern hemisphere. Topographic profiles will be assembled into regional grids with resolution dictated by ground track spacing. Radii obtained from altimetry in the northern hemisphere and radio occultations in the northern and southern hemispheres (Fig. D-1-7) will be combined to produce a model of Mercury's global shape. The combination of topography with gravity and compositional information will be used to model interior density variations, particularly the distribution of crustal thickness.

Measurement of Physical Libration. Mercury's forced physical libration will be manifest as an irregular rotation of the planet, i.e., a 350-m half-amplitude oscillation in longitude with a period of 88 days (one Mercury year). We will extract the libration from the rotation using the planetary shape (Zuber and Smith, 1997). Others have proposed recovering this signal using short-wavelength horizontal offsets measured with an orbital camera (Wu et al., 1995, 1997). The MESSENGER method offers a similar level of predicted recoverability with a much lower data rate, less stringent spacecraft pointing requirements, and simple data processing.

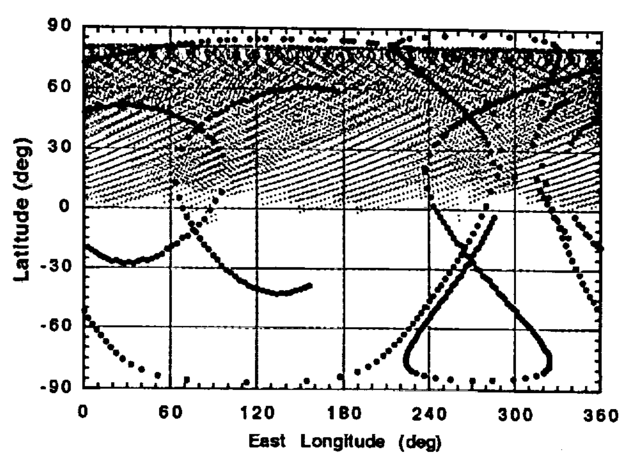


Figure D-1-7 Potential occultation locations (large dots) and altimetry footprints (small dots).

Libration recovery from topography requires knowledge of the longest wavelength longitudinal terms (say, spherical-harmonic orders 1-4) referenced to the planetary center of mass. In addition, we must determine the precise position of the planetary rotation pole. Our approach will be to use altimetry, occultation, and gravity data to solve for the libration's amplitude and phase, the direction of the spin axis (obliquity), and the low-degree planetary altimetric and gravitational shapes. Because knowledge of only the global-scale shape is required, the sparse data distribution in the southern hemisphere provided by the occultations will be adequate.

To demonstrate that MESSENGER can measure the libration to the required accuracy, we have simulated recovery of the signal for the proposed mission scenario. Altimeter data were simulated at 1-min intervals (the actual data rate will be 2.5 Hz). We assumed 10-m radial noise due to altimeter measurement and orbit errors and 0.1° noise from spacecraft pointing error. Normal equations were developed from the simulated data, and we solved for the libration, spin-axis direction, and a 16x16 topographic model. Free adjustments were permitted for the libration and the spin axis, but a σ of 100 m was applied to each coefficient of the 16x16 topography. We recovered the libration amplitude to 9% (1 σ) and the pole position to (1-2)x10^{-5} rad. The simulation demonstrates the ability to recover the libration and obliquity to a 10% level, sufficient for discrimination of a liquid from a solid core. An independent estimate of libration amplitude can be obtained from the gravity field.

Geodetic Control Network. Combined altimetry and radio tracking data will provide the basis for a global geodetic control network with which to reference other data sets, particularly imaging. The network will have a precision of ~50 m horizontally and 20-30 m radially in the mid to high northern latitudes. Poorer quality areas in the southern hemisphere where altimetry is lacking will be filled in with the global image-based control network.

The Gravity Field. The X-band transponder on the spacecraft will provide range-rate data between the spacecraft and a Deep Space Network (DSN) ground station and will be used to define a spherical harmonic expansion of Mercury's gravity field. From a simulation of the spacecraft orbital evolution over the mission life we estimate that a gravity model to degree and order 16 will be recoverable with an average resolution of ~400 km in the northern hemisphere and about 1500 km in the southern hemisphere. The principal perturbations over one Earth year of the node of the spacecraft orbit are given in Table D-1-8. Particularly important are the very low-degree terms because of their relationship to the librations. Table D-1-9 shows the ability to estimate the second-degree terms and the direction of the rotation pole from tracking the orbiting spacecraft over one Earth year.

Occultations. For a period during most orbits the spacecraft will be occulted from Earth. If the spacecraft is tracked into, or as it emerges from, occultation, the time of the occultation can be used to estimate the planetary radius at the grazing ray location (Kliore et al., 1972; Lindal et al., 1979). Since the orbital position will be known to a few tens of meters we can derive occultation radii to a similar level. Measurements will be particularly important in the southern hemisphere, which will lack altimetric coverage (Fig. D-1-7). These observations will be very important in constraining the global shape of the planet (e.g., Smith and Zuber, 1996) and will significantly improve our knowledge of the offset between centers of figure and mass for Mercury (Anderson et al., 1996).

Exosphere, Magnetosphere, and Polar Volatiles Investigation Plan. Spectrometry from 0.115-0.600 µm (at a 1 nm resolution) will be used to measure altitude profiles of known species (H,

Table D-1-8 Principal Perturbations to Node of Spacecraft Orbit

Source of Perturbation	Type	Magnitude
Mercury gravity		
$C_{2,0} = -2.7 \times 10^{-5}$	Secular	34 km
$C_{2,1} = 1.0 \times 10^{-7}$	Periodic, 59 days	10 m
$C_{2,2} = 1.6 \times 10^{-5}$	Periodic, 30 days	210 m
Solar radiation pressure	Secular	200 m
	Periodic, 88 days	400 m
Physical libration	Periodic, 88 days	<350 m

Assumes 1 mm/s quality data from a single DSN tracking station each day of the mission year, except during solar conjunctions. The error model for the gravity field was 10% in degrees 9 and 10, all orders, and 20% in degrees 11 and 12, all orders, and an error of 10% in the radiation pressure model was included. Thirty-six 10-day orbital arcs were created and analyzed. Six orbit parameters per arc, an 8x8 gravity field, and three planetary rotation parameters were adjusted in the analysis.

Table D-1-9 Expected Accuracies for Second Degree Gravity Field Coefficients and Rotation Pole Position

Gravity Field:	Complete to degree 16 $\sigma(C_{2,0}) < 0.4\%$, assuming $C_{2,0} = -2.7 \times 10^{-5}$ $\sigma(C_{2,2}) < 1\%$, each coefficient, assuming $C_{2,2} = 1.6 \times 10^{-5}$	
Pole Location:	RA of the pole Dec of the pole	$<1.4 \times 10^{-4}$ rad $<1.8 \times 10^{-4}$ rad
Spacecraft orbit:	Along-track error Across-track error Radial error	~50 m ~20 m ~5 m

O, Na, and K) and to search for predicted species not previously detected (Si, Ca, Al, Mg, Fe, S, OH) as well as new species. Limb scans will be made by "nodding" the spacecraft to provide altitude profiles of emission lines. Ground-based studies indicate that an altitude resolution of 25 km and a latitude resolution of better than 20° are required to characterize the exosphere adequately.

The exosphere-magnetosphere system is diagnostic of volatiles present on the surface (Cheng et al., 1987). Surface sources of exospheric materials will be mapped with the X-ray, γ-ray, and neutron spectrometers, and the magnetospheric connection will be made with measurements of energetic ions, electrons, and thermal plasma ions. In addition to magnetospheric ions, solar-wind pick-up ions, e.g., Na^+ and K^+, that originate as neutral atoms at Mercury and are ionized locally will be measured. The γ-ray and neutron spectrometer in concert with laser altimetry will be used to characterize the composition and thickness of any frozen volatiles in permanently-shadowed craters near Mercury's poles that may be responsible for the anomalous radar returns from those regions (Slade et al., 1992; Harmon et al., 1994).

D.1.5 Instrument Suite

The challenge of providing the full set of measurements required to satisfy the MESSENGER science objectives (Sec. D.1.2 and Table D-1-1) is met with a suite of seven instruments, along with the spacecraft telecommunications system, with characteristics listed in Table D-1-10: Mercury Dual Imaging System (MDIS), Gamma-Ray and Neutron Spectrometer (GRNS), Magnetometer (MAG), Mercury Laser Altimeter (MLA), Radio Science (RS), Atmospheric and Surface Composition Spectrometer (ASCS), Energetic Particle and Plasma Spectrometer (EPPS), X-Ray Spectrometer (XRS), and a data processing unit (DPU). The ASCS includes both an Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS). These instruments capitalize on emerging technologies developed over several years at the Applied Physics Laboratory (APL), Goddard Space Flight Center (GSFC), U. Colo., and U. Md. (the latter effort recently moved to U. Mich.). The selected instruments accomplish the required observations at low cost with the low masses necessary for implementing this mission. The instruments are all modified or different in some way from those that have flown before. The technical readiness levels (TRL) in Table D-1-10 represent averages for the technologies used in the subsystems and assemblies within each instrument, not necessarily the MESSENGER configuration.

All except MAG are fixed and body mounted for high reliability and low cost. Aperture heat-rejection filtering is required only for MDIS and MLA (but not ASCS), since the internal

Table D-1-10 MESSENGER Scientific Payload and Characteristics

	Mass (kg)	Power (W)	Data Rate, Vol	Design Heritage	TRL
MDIS Dual imagers, 1024x1024 Narrow: 1.5° fov, b&w Wide: 25° fov, 8-filter wheel Scanning mirror and controls	 2.0 2.5 1.0	 10.0	 178 b/s, 15 Mb/d	 EISAT Imager, PIDDP	6
GRNS CsI γ-ray + Li n^0 spectrometer	6.0	1.0	80 b/s, 6.9 Mb/d	NEAR	6
MAG Flux gate magnetometer 3.6 m boom	 1.0 2.0	1.0	6 b/s, 0.5 Mb/d	NEAR, Lunar Prospector	7
MLA Laser altimeter, 1000-km range	5.0	20.0	32 b/s, 2.7 Mb/d	NEAR, MGS, GLAS	5
RS X-band transponder	[Included as S/C Telecomm System]			DS-1	9
DPU Integrated electronics, power processing for all instruments	3.0	12.0	3 b/s 0.3 Mb/d	NEAR, Cassini	8
MINIMUM SCIENCE FLOOR	**22.5**	**44.0**	**25 Mb/d**		
ASCS UV/Visible spectrometer Visible/IR spectrometer	 1.5 1.0	 1.5 1.5	64 b/s, 5.4 Mb/d	Galileo UVS	8
EPPS Energetic particle spectr. Fast imaging plasma spectr.	1.3	2.0	80 b/s, 6.8 Mb/d	PIDDP ACE,SAMPEX	6
XRS X-ray spectrometer, 1-10 keV	4.0	8.0	40 b/s, 3.4 Mb/d	NEAR, Mars Pathfinder	7
DPU additions for ASCS, EPPS, XRS	2.0	6.0	3 b/s, 0.3 Mb/d	NEAR, Cassini	8
MISSION BASELINE	**32.3**	**63.0**	**41 Mb/d**		

TRL = Technology readiness level (Bearden et al., 1996)

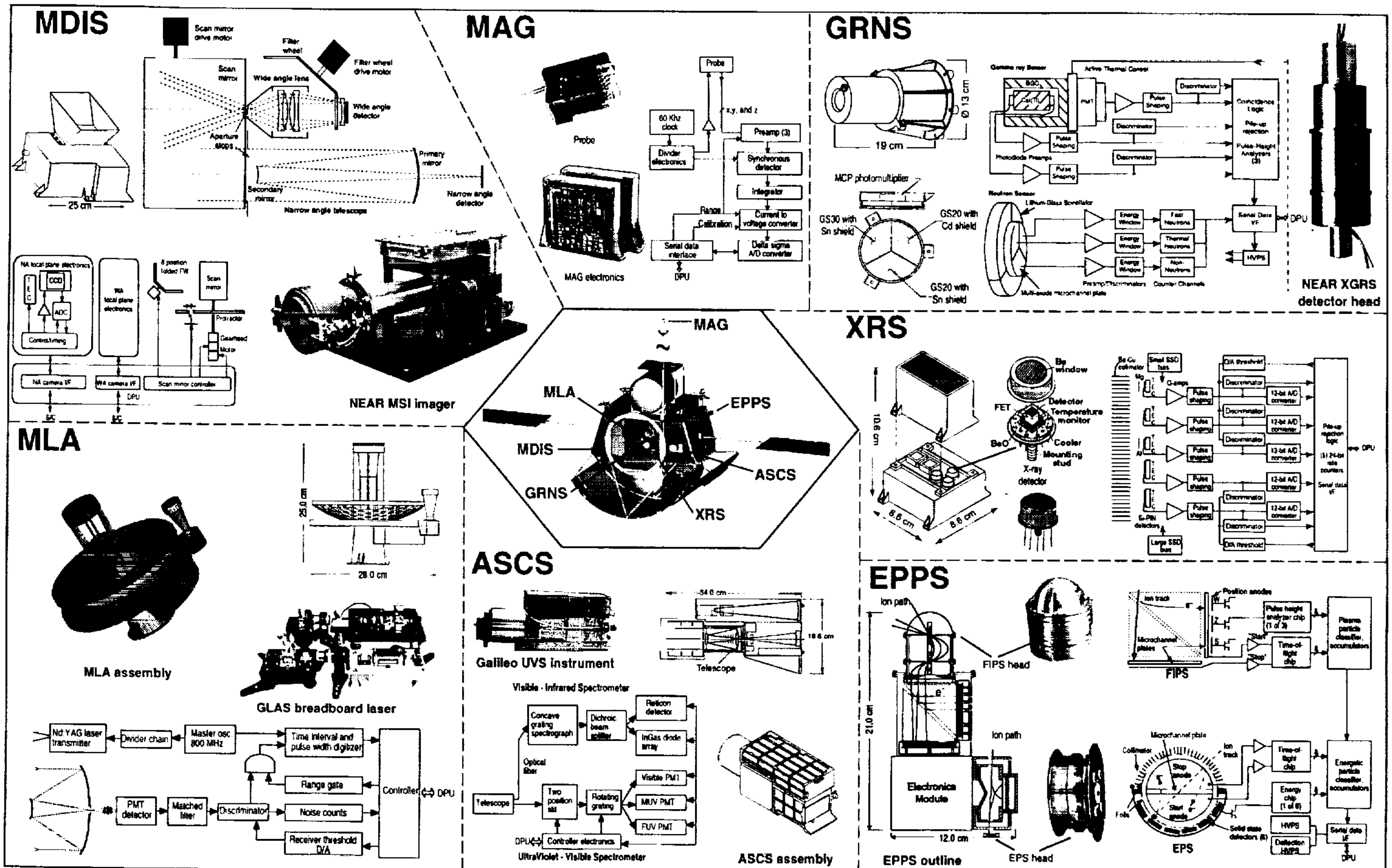


Fig. D-2-1 Revised *MESSENGER instrumentation.* *Instrument layouts and block diagrams are unchanged; dimensions and other instrument details added.*

spacecraft thermal environment is benign by design. A compact, shared DPU includes high-level electronics, power converters, power switching, and data processing for instruments to reduce mass and power. An internal scan mirror in MDIS provides for full coverage of Mercury during flybys.

D.1.6 Descope Options and Performance Floor

The minimum acceptable scientific return from the MESSENGER mission includes a full map of the planet at visible wavelengths, information on global surface chemistry, characterization of the internal magnetic field, and limits on the extent of the liquid core. This performance floor can be achieved only if the spacecraft reaches Mercury orbit and operates at least six months.

To provide this minimum science return, the minimum complement of instruments is an imaging system (MDIS), a γ-ray and neutron spectrometer (GRNS), a magnetometer (MAG), a laser altimeter (MLA), and radio science (RS). Such an instrument suite will provide:

- Global monochrome map at 500 m/pixel
- Global color at 2 km/pixel
- Surface elemental composition, including one pole, to an uncertainty < 10%
- Magnetic field strength and configuration
- Altimetry, gravity of northern hemisphere
- Distinguish liquid from solid core.

While we do not anticipate problems during the spacecraft and instrument development, problems can arise in any project, affecting baseline plans. The minimum science floor provides significant, yet simple, descope options that mitigate cost and /or mass problems (Table D-1-10). The scientific costs of descoping the instruments, in priority order are: (1) XRS – loss of spatial resolution of elemental composition, (2) EPPS – loss of magnetospheric energetic particle and thermal plasma information, (3) ASCS/VIRS – loss of information on surface mineralogy, and (4) ASCS/UVVS – loss of information on atmospheric composition.

D.2 Science Implementation

D.2.1 Instrumentation

The MESSENGER science payload is listed in the central column in Table D-1-1. The color coding schematically illustrates how each instrument and its capabilities are traced from the science measurement objectives to the instrument requirements. The basic characteristics of the instruments are shown in Table D-1-10. Block diagrams and mounting locations on the spacecraft are shown in Fig. D-2-1.

Mercury Dual Imaging System (MDIS) (Table D-2-1) meets all of the imaging requirements by combining an 8-filter (clear plus 7 colors) wide-angle (WA) imager with a high-resolution, narrow-angle (NA) imager into a single unit. This design permits a common scan mirror and dichroic heat-rejection filter. The camera uses the core electronics of APL's 500-g imager as originally built for the Air Force Jawsat satellite and continuing development in an ongoing Planetary Instrument Definition and Development Program (PIDDP) project for light-weight space imagers. The wide-field, refractive and narrow-field, reflective imagers are coaligned. Locating their apertures close to the scan mirror minimizes the size of both the mirror and the heat rejection filter. A thermally isolated baffle reduces stray light and heat from outside the imager field of view.

Wide-Angle Imager. Spectral information is provided by the wide-angle imager. A reversed Ploessl "eyepiece" lens has a small entrance pupil placed close to the scan mirror. A small field-flattening lens assures excellent image quality over the full wavelength range. Radiation resistant glasses are used throughout. The lens is achromatic, and the spot size is smaller than the 14 µm pixels over 24°. The optics are inherently small due to the short focal length. The lenses are 30 mm in diameter, and the distance from the aperture stop to the image is only 79 mm.

Table D-2-1 MDIS Characteristics

	Narrow Angle	Wide Angle
Scan range	+50° to -20°	
Field of view	1.5°	25°
Spectral filtering	None	8 filter positions
Focal length	550 mm	35 mm
Focal ratio	18	5
Detector	CCD 1024 x 1024, 14 µm pixels	
Pixel field of view	5.2 m @ 200 km alt., 390 m @ 15,000 km	172 m @ 200 km alt. 12.9 km @15,000 km
Signal-to-noise ratio	> 200:1	
Quantization	12 bits/pixel	
Compression	Lossless, multi-resolution lossy, 12-to-n bit	

The 7 color filters are 415 nm center x 40 nm wide for titanium (Ti); 560 x 10 nm for Ti and continuum; 650 x 10 nm for glass; 750 x 10, 900 x 10, 950 x 20, and 1020 x 40 nm for olivine to pyroxene ratio and glass. The clear filter is centered on 750 nm and is 300 nm wide.

Narrow Angle Imager. The narrow FOV of 1.5° requires a focal length of 550 mm. A compact, off-axis section of a Ritchey-Chretien reflective telescope is utilized. The mirrors correct spherical aberration and coma. Focal-plane curvature and astigmatism are small, and a correction lens is not necessary. Performance at 0.4° off axis is diffraction limited, and the spot size is smaller than a pixel over 80% of the FOV. An aperture stop minimizes stray light.

Camera Heads. Both imagers use two custom VLSI chips and a gate array for all clocking, control, and readout of the CCD. Each 1024x1024 frame-transfer CCD has manual and automatic exposure control for 0.1-ms to 10-s exposures with no need of a shutter. On-chip summing of 2x2 pixels can be commanded for 512x512 images as required. Both CCDs have thermoelectric coolers for low dark current. Images can be taken as often as every second, with an average spacing of 4.1 s, and fed to the MESSENGER solid state recorder. They can be recalled later for processing and compression. Three image-compression techniques are available and may be used singly or in combination, as listed in Table D-2-2.

Scan Mirror and Heat Rejection Filter. The scan mirror is required for mapping the planet during the flybys and for full resolution global coverage during the orbital phase, although the mirror is usually fixed. It is driven by a small stepper motor with redundant windings (a scan mirror of this design has been under test at APL continuously stepping in a hard vacuum for >2 yr). The mirror is only 65 mm square and made of light-weighted beryllium. The entrance window rejects the infrared thermal radiation from the surface of the planet but transmits the visible and near infrared up to 1100 nm. To ensure that scattered light will not be a problem, MDIS will be constructed with low-reflectivity coatings, internal baffles, and a high-quality surface on the heat-rejection filter. Assembly will be done in a class-100 clean room. Detailed MDIS performance will be characterized during the Earth and Venus flybys.

Table D-2-2 Data Compression

Compression Type	Compression Ratio
Lossless - Fast and Rice algorithms	~2:1
Lossy - Wavelet based multiresolution algorithm	2:1 to 10:1
Lossy - 12 to n-bit table lookup (8 tables available)	1.5:1 to 2:1

Calibration. Complete calibrations will be conducted at the APL Optical Calibration Facility and will include measurement of point-spread, geometric distortion, flat field, dark current, radiometric response, wavelength calibration, scattered light, and detector alignment. Inflight calibrations will verify these measurements. MDIS will be turned on for the Venus flybys for flat-field calibration using the Venus disk.

Gamma-Ray and Neutron Spectrometer (GRNS) (Table D-2-3) has an active shielded scintillator that measures a wide range of elemental abundances (O, Si, S, Fe, H, K, Th, U) and a neutron spectrometer to provide high sensitivity to possible H_2O at the poles. Like the Near Earth Asteroid Rendezvous (NEAR) γ-ray detector, the γ-ray spectrometer (GRS) subsystem scintillator is mounted in a thick cup-shaped active shield of bismuth germanate (BGO) 1.25 cm thick. The shield defines a ~45° FOV, protects the central scintillator from locally generated backgrounds, and reduces the Compton and pair-production contributions to the background. NEAR has demonstrated three orders of magnitude background suppression with this type of detector mounted directly to the spacecraft, i.e., without a long, heavy boom.

The primary GRS detector is a 25 x 60 mm CsI scintillator directly coupled to photodiodes. The higher quantum efficiency of the photodiodes results in improved energy resolution (8.0% vs. 8.7% on NEAR) and eliminates a heavy photo-multiplier tube (PMT). CsI works near room temperature, so cryogenic coolers are not required, and it is nearly immune to radiation damage, important for this long-duration mission. The complex geometry of the GRS shield requires a PMT for light collection; the scintillators and PMT are thermally controlled for gain stability, and the overall assembly is thermally isolated from the deck.

The Neutron Spectrometer (NS) subsystem uses three lithium glass scintillators in the form of equal ~120° segments of a disc, each ~25 cm^2 x 6.35 mm thick, coupled to a 25-mm diameter

Table D-2-3 GRNS Characteristics

GRS	
Measured elements	O, Si, S, Fe, H, K, U, Th
Central detector	CsI(Tl) 25 mm dia. x 60 mm
Resolution	8% fwhm @ 662 keV
Readout	2 enhanced Si-PIN
Energy range	0.3 — 10 MeV
Field of view	~45°
Shield detector	BGO cup 6.0 cm dia.x 8.5 cm
Energy range	0.1 — 10 MeV
Resolution	14% fwhm @ 662 keV
Escape recovery	60% @ 511 keV
Readout	Photomultiplier
Integration period	300 s @ periapsis; 1800 s @ apoapsis
NS	
Measured quantities	Thermal and epithermal neutrons
Epithermal neutrons (E > 0.5 eV) + CRs	26 cm², 6.35 mm thick ^{6}Li scintillator (GS20); 750 µm Cd shielding
Thermals + epithermals + CRs	26 cm², 6.35 mm thick ^{6}Li scintillator (GS20); 750 µm Sn shielding
Cosmic rays (CRs)	26 cm², 6.35 mm thick ^{7}Li scintillator (GS30); 750 µm Sn shielding
Detector	Triple-split anode MCP photomultiplier, 25 mm dia.
Field of view	~ 4π ster
Rejection ratio	99.9% rejection of thermals in Cd shield; 99.99% rejection of neutrons in ^{7}Li
Integration period	300 s @ periapsis; 3600 s @ apoapsis

microchannel plate (MCP) PMT with a triple-split anode. Two segments are GS20 (95% ^{6}Li glass), one wrapped with 750 µm of tin and the other with 750 µm of cadmium; the Sn segment allows detection of all neutrons, while the Cd side rejects all neutrons below ~0.5 eV, above the gravitational escape energy of ~0.1 eV. The third segment of GS30 (99.99% ^{7}Li glass) has no response to neutrons and monitors the cosmic ray background rate in each segment.

Ground calibrations will be performed on the GRNS using γ and neutron sources (Evans et al., 1996). Infight calibration will rely on prominent spectral lines, e.g., the 0.511-MeV annihilation line. Activation will be monitored over time to characterize fully the buildup of the background. The NEAR GRS confirms the efficacy of this approach.

Magnetometer (MAG) is a miniature three-axis ring-core fluxgate magnetometer with low-noise electronics. It is mounted on a 3.6-m boom in the anti-sunward direction. MAG has ±4096 and ±65536 nT ranges with 20-bit quantization, which provides up to 0.03 nT resolution even on the high range. The detector samples at a 40-Hz rate. Hardware anti-aliasing filters and digital filtering in the DPU provide selectable averaging intervals from 0.025 s to 1 s and 0.5-s-average samples for intervals of 1 s to 100 s. Nominal 0.1 Hz sampling of the field will be increased to a maximum of 10 Hz near periapses and 40 Hz at modeled magnetospheric boundary crossings. Digital filters also provide selectable bandpassed channels of magnetic field variations. The MAG sensor (GSFC) and processing electronics (APL) are almost exact copies of the NEAR design, using miniaturized surface-mount electronics packaging.

The magnetometer and spacecraft teams will work to minimize stray spacecraft magnetic fields, as was done with the Advanced Composition Explorer (ACE). MAG will undergo extensive calibrations at GSFC and APL prior to integration. Calibrations will be refined in flight. Statistical variance techniques (Davis and Smith, 1968; Belcher, 1973) will be used in the solar wind to determine the spacecraft fields. The same method can be used at the high Mercury orbit apoapsis.

Mercury Laser Altimeter (MLA) (Table D-2-4) is based on the instruments flown on Mars Global Surveyor (MGS) and being designed by our team members for the Geoscience Laser Altimeter System (GLAS) to be flown on the Ice, Cloud, and land Elevation Satellite (ICESat). Modifications to the design provide lower mass and longer range while accommodating the thermal loads. MLA consists of a Q-switched, diode-pumped Cr:Nd:YAG laser transmitter operating at 532 nm, a 25-cm-diameter beryllium telescope, a PMT, and a photon-counting time interval unit (TIU).

Measurements start with the laser firing. A small fraction of the laser beam is sampled by an optical fiber and relayed onto the start detector, which initiates the timing process in the TIU. A light-weight beam expander, with a heat rejection filter at its base, achieves a beam divergence of ≤ 50 µrad.

The receiver telescope collects the back-scattered laser echo pulses and passes them through a heat rejection filter and an optical bandpass filter to reject solar background. The pulse is detected with a small, rugged hybrid PMT.

The receiver electronics are based on recording the arrival time of individually reflected

Table D-2-4 MLA Characteristics

Laser pulse rate	5 measurements/s
Detection probability	90% @ 1000 km range
Spot diameter	10-50 m full width
Spot spacing	100-300 m along track
Ranging precision	0.75 m
Energy resolution	5%, transmit and echo
Laser	Cr:Nd:YAG, passive Q-switched, diode pumped
Wavelength	532 nm
Pulse	20 mJ, 5 ns fwhm
Beam divergence	≤ 50 μrad
Lifetime	> $5x10^7$ pulses (> 1 year)
Receiver telescope	0.25 m beryllium Cassegrain
Detector	Hybrid photomultiplier (photon counting)
Sensitivity	10 photons/pulse

photons. The photon-counting timer measures the laser transit time with 75-cm (5-ns) range resolution. After detection, the measured width of the echo pulse is used to adjust the timing estimate to the pulse center.

The surface-lidar link margin quantifies the transmitted laser energy just above the minimum needed to achieve the required instrument performance based on the expected signal and noise levels. Under worst-case conditions (daytime, 6% surface reflectivity, 5° slopes), MLA has a ranging probability of 90% at a 1000-km slant range. Surface roughness, surface slopes, and spacecraft-pointing effects are the major sources of error in the determination of range.

Pre-flight measurements with a variety of simulated echoes and backgrounds at various distances and return signals will be used to characterize performance. MLA will be active during the second Mercury flyby to characterize performance prior to the orbital tour so that accumulation time of libration data will be maximized.

Atmospheric and Surface Composition Spectrometer (ASCS) (Table D-2-5) is derived from the Galileo Ultraviolet Spectrometer (Hord et al., 1992). A well baffled telescope simultaneously feeds both an Ultraviolet-Visible Spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS), indicated separately in Table D-1-1. UVVS is optimized for measuring the composition and structure of the atmosphere and surface reflectance. VIRS is optimized for measuring visible and near-infrared surface reflectance. VIRS is mounted on top of the UVVS and is coupled to the telescope focal plane with a short fiber optic bundle. Internal electronics manage instrument configuration, control spectral scanning, and provide communications to the DPU. ASCS is identical to Galileo UVS except for three minor modifications. The aperture has been modified to accommodate the Mercury thermal input, the grating is different, and there is a mask at the spectrometer entrance slit. UVVS has 25 km resolution at the limb; VIRS has 100 m to 7.5 km resolution depending on altitude.

Table D-2-5 ASCS Characteristics

	UVVS	VIRS
Telescope	250 mm, f/5	
Focal length	125 mm	210 mm
Spatial resolution	25 km on limb	100 m to 7.5 km
Grating	1800 lines/mm	120 lines/mm
Spectral resolution	0.5 nm FUV 1.0 nm MUV, VIS	4 nm
Wavelength range	FUV 115-190 nm MUV 160-320 nm VIS 250-600 nm	VIS 0.300-1.025 μm IR 0.95-1.45 μm
Detector	3 PMT: CsI, CsTe, Bi-Alkali	512 x 1, Si, 256 x 1, InGaAs
FOV	1° x 0.05° Atmosphere 0.023° x 0.023° Surface	0.023° x 0.023°
Sensitivity	10 R in 100 s (5σ)	SNR > 200

Ultraviolet-Visible Spectrometer (UVVS). UVVS consists of a Cassegrain telescope and an Ebert-Fastie diffraction grating spectrometer. The thermally isolated external light shade and the extensive baffle system have demonstrated off-axis scattered light rejection greater than 10^5 for point sources ≥ 1° from the field of view (Hord et al., 1992).

An 1800-groove/mm grating provides an average spectral resolution of 1.0 nm. The spectrum is scanned by rotating the grating in 0.25 nm steps, providing a factor of 4 oversampling. Three PMTs, behind separate slits, are used in pulse-counting mode for the atmospheric observations where high sensitivity is required. The PMTs cover the Far Ultraviolet (FUV), Middle Ultraviolet (MUV), and Visible (VIS). Both FUV and MUV may be used for surface reflectance measurements. The VIS detector is protected from damage by a limb sensor that disables its high voltage before the field of view intercepts the sunlit disk of the planet. UVVS is optimized to observe weak atmospheric emission from both atoms and molecules. Expected atmospheric limb emission rates range from 10 Rayleighs (R) to a few kR.

Over the range 0.190-0.45 μm, 100-s integration times give a SNR of 10 for emissions as weak as 10 R.

A mature, scanning spectrometer design is most appropriate for MESSENGER, which requires low mass, moderate resolution, and very high sensitivity, for a small number (10-20) of isolated emissions at known wavelengths within a very broad range (0.115–0.60 μm). It will give greater sensitivity and resolution for the widely-separated weak lines than a spectrograph with a line-array detector. There is ample time in the orbital phase to make a thorough search for unsuspected emissions over the entire spectral range.

Visible-Infrared Spectrograph (VIRS). The VIRS measures surface reflectance (0.3-1.45 μm). Light is fed to the VIRS through a fused silica fiber-optic bundle. The concave holographic diffraction grating images onto two semiconductor detectors. A dichroic beam splitter separates visible (300-1025 nm) and infrared (0.95-1.45 μm). The visible, Reticon 512-element line array has a high-pass absorption filter in front of the long-wavelength half to eliminate the second-order spectrum (Maymon et al., 1988). The IR detector is a 256-element InGaAs array, which does not require cooling. Both detectors are digitized to 12 bits. A 1-s integration will provide SNR > 200. The 1.45-μm long-wavelength cutoff for VIRS was chosen because beyond that wavelength thermal emission from Mercury's surface is comparable to the solar reflectance.

In addition to standard laboratory calibrations, the UVVS and VIRS will be active during the two Venus flybys to acquire spectra that can be compared with previous Venus spectral results.

Energetic Particle and Plasma Spectrometer (EPPS) (Table D-2-6) measures ions from thermal plasmas through ~5 MeV and electrons from ~20 keV to 400 keV. EPPS combines a Fast Imaging Plasma Spectrometer (FIPS) head for thermal plasmas, and an Energetic Particle Spectrometer (EPS) head for energetic ions and electrons, with common electronics in a compact and low-mass instrument. EPPS is mounted on the side of the top deck of the spacecraft, near the edge of the thermal shade shadow, to observe the solar wind and pickup ions from the surface of the planet. This mounting also minimizes the thermal input from the planet onto the EPS entrance foil. Both EPS and FIPS use a time-of-flight (TOF) system to determine the velocity (energy/mass) of the detected ions.

Table D-2-6 EPPS Characteristics

FIPS Thermal Plasma Head	
Measured species	H, ^{3}He, ^{4}He, O, Ne, Na, K, S, Ar, Fe
Field of view	360° azimuth x 75° elevation
Geometrical factor	~ 0.05 cm² sr
Entrance foil	~1.0 μg/cm² carbon
TOF range	50 ns-500 ns
Deflection voltage	0.05-8.0 kV
Energy/charge range	0.05-10.0 keV/q
Voltage scan period	1 min
EPS Energetic Particles Head	
Measured species	H, He, CNO, Fe, electrons
Field of view	160° x 12°
Geometrical factor	~ 0.1 cm² sr
Foils	Polyimide, aluminum; 9 μg/cm²
TOF range	0-200 ns, ± 200 ps (1σ)
Peak input rate	1 MHz
Detectors	6 Si 500 μm thickness, 2 cm² each
Energy range	10 keV/nuc-5 MeV total energy
Integration period	Fixed, 36 s

Energetic Particle Spectrometer (EPS) is a hockey-puck-sized, TOF spectrometer that measures the energy spectra, atomic composition, and pitch angle distributions of energetic ions from ~10 keV/nuc to ~5 MeV/nuc energy and electrons from ~20 keV to 400 keV. EPS is based on an ongoing NASA PIDDP grant development. An engineering model has operated well at the accelerator facility at GSFC.

EPS measures the ion TOF using secondary electrons generated as the ion passes through the entrance and exit foils in the spectrometer. Total energy is measured by a silicon detector. A collimator, not shown in the Fig. D-1-2, defines the acceptance angles for the six segments. The FOV is 160° by 12° with six segments of 25° each; the geometric factor is ~0.1 cm^{2}sr.

The 'start' and 'stop' signals for the TOF measurements (from 100 ps to 200 ns) are detected by an MCP electron multiplier. Timing, energy, and event-classification chips produce an eight-point energy spectrum for each of four species, and all directions are read out every 36 s. Electrons are recognized by a foil that covers one of the solid state detectors.

EPS will be fully calibrated using α-particle and accelerator sources prior to integration with the spacecraft. Flight experience with similar instrumentation built by APL for Voyager, Active Magnetospheric Particle Tracer Explorers (AMPTE), Galileo, ACE, and Cassini shows that no in-flight calibration is required.

Fast Imaging Plasma Spectrometer (FIPS) measures low energy plasmas in the Mercury environment from ~10 keV/q down to the spacecraft potential.

FIPS has nearly full hemispherical coverage with its aperture dome and cylindrical electrostatic analyzer (Zurbuchen and Gloeckler, 1998). A particle passes through one of ~128 holes in the dome, a simple electrostatic deflection system, and a position-sensing TOF telescope. For a given incidence angle (and incident azimuth), a setting of the deflection voltage allows only ions within a narrow energy/charge (E/q) range to pass through the deflection system. The ions are then post-accelerated by a fixed voltage before passing through a very thin (~1 $\mu g/cm^2$) carbon foil. The ions travel a known distance and hit the stop MCP assembly, while the forward-scattered electrons from the carbon foil are focused onto the start MCP. Position sensing of the start electrons with a wedge-and-strip anode in the MCP assembly determines the initial incidence angle. The mass per charge of a given ion follows from E/q and the TOF, allowing reconstruction of distribution functions for different mass/charge species. The deflection voltage steps from 0.05 kV to 8 kV over 1 minute and covers an E/q range of 0.05 to ~10.0 keV/q. A prototype of the electrostatic analyzer has been successfully tested in the accelerator facility at GSFC.

The signal processing of EPS and FIPS share common electronics using rad-hard application-specific integrated circuits (ASICs) that combine analog and digital electronics on the same chip. Also included are the MCP high-voltage supplies and the FIPS deflection high-voltage supply.

X-Ray Spectrometer (XRS) (Table D-2-7) consists of five state-of-the-art Si-PIN detectors mounted on miniature thermoelectric coolers. Thin absorption filters on two of the detectors differentially separate the lower energy lines (Al, Mg, Si). This balanced filter technique is used on NEAR. A Be-Cu honeycomb collimator provides a 6° FOV, which is smaller than the planet at apoapsis and eliminates the X-ray sky background. At intermediate altitudes, spatial resolution improves greatly. A small (0.1 mm^2) solar flux monitor looks through the antenna radome and tracks the solar X-ray input to the planet. Energy spectra are accumulated from 1 to 10 keV, which covers the elements Mg, Al, Si, S, Ca, Ti, and Fe. Resolution is 350 eV.

The NEAR mission was the first to fly this new high-resolution X-ray detector technology (as a solar flux monitor). The XRS is based on an improved design with better energy resolution subsequently flown on the Mars Pathfinder rover. This design, using discrete reset, rather than resistive feedback, not only gives better resolution, it is also less susceptible to energetic electrons which can build up a space charge in the photodiode and require temporary shut downs to discharge the circuit.

Extensive ground calibrations will be performed on the XRS using both pure elemental samples and assayed samples prepared by the US Geological Survey. Experience with NEAR shows no onboard calibration sources are required.

Radio Science (RS) observations are required for gravity measurements and support of the laser altimetry investigation. In particular, accurate knowledge of spacecraft location is required to recover the magnitude of the physical libration, a key mission objective. The performance requirements are met by the telecommunications subsystem and DSN with standard operations at existing facilities.

Data Processing Unit (DPU) provides all of the instrument processing, high-level electronics,

Table D-2-7 XRS Characteristics

Measured elements	Mg, Al, Si, S, Ca, Ti, Fe
Detector	Si-PIN, 300 μm thick
Active area	5 detectors; 2.75 cm^2 total + solar monitor; 0.12 mm^2
Field of view	6°, Be-Cu honeycomb
Window	Beryllium 25 μm
Balanced filters	8.5 μm Mg; 8.5 μm Al
Energy range	0.7 to 10 keV
Energy resolution	350 eV fwhm, small det.; 700 eV fwhm, large det.
Maximum input rate	20 kHz
Integration period	100 s @ periapsis; 2000 s @ apoapsis

and power converters or power switching. Dual processors are fully redundant and cross-strapped. No single-point failure will disable the instrument suite. The DPU core is flying on the Cassini Magnetospheric Imaging Instrument (MIMI). Instrument-specific interface cards connect the payload to the DPU core. Processor and bus margins are sufficient to allow full instrument operation with any single redundant component failure. The software for MDIS, GRNS, MAG, EPPS, and XRS is nearly identical to that of similar instruments currently flying on Cassini, ACE, and NEAR. MLA and ASCS software, while new, only requires simple serial data and command passing.

Functional Redundancy. The payload instrumentation has been selected to provide functional redundancy across scientific objectives to give complementarity of observations in case of problems. Such redundancy also provides for important consistency checks of results obtained with more than one instrument. The redundancies include:

- Surface chemistry (GRNS, XRS, VIRS)
- Morphology (NA imager, WA imager)
- Surface spectral properties (WA imager; UVVS, VIRS)
- Altimetry (MLA, stereo imaging)
- Atmospheric properties (UVVS, EPPS)
- Polar cap composition (GRNS, EPPS)

D.2.2 Mission Observing Profile

The observing profile for the MESSENGER mission is driven by tradeoffs among required observations, thermal constraints, and mass constraints. Investigation plans that link the science measurement objectives to the instrument requirements (Table D-1-1) are given in Sec. D.1.4; characteristics of the spacecraft trajectory and orbit are discussed under mission design (Sec. F.1).

Orbital operations at Mercury extend for one year, four Mercury revolutions about the Sun. Four Mercury years are required for measuring the planetary libration, and the planet's 3:2 spin resonance means MESSENGER's mission extends for two solar days at the planet (Fig. D-2-2). This duration allows for global surveying during the first six months followed by stereo coverage, concentrated observations of targets of interest, and repeat coverage as required. A one-Earth-year orbit phase also improves the accuracy of surface composition measurements (Sec. D.1.4). The manner in which investigation objectives (Table D-1-1) drive mission design (Table F-1-3 and Fig. F-1-2) and operations is given in Table D-2-8.

MESSENGER enters its orbit over the planet's terminator at a Mercury true anomaly (TA) of 337°. The orbit remains fixed in inertial space due to Mercury's small oblateness. Thus, with no additional use of fuel, this orbit minimizes the thermal stresses experienced by the spacecraft (Sec. F.2.3). Fig. D-2-2 shows the evolution of MESSENGER's observing geometry during the second Mercury year of operations (Dec. 27, 2009 – Mar. 25, 2010). Color coding indicates the various observing zones and instrument operation plans for the two extreme cases: near-terminator orbit (TA 337°) and near-noon-midnight orbit (TA 247°). Thermal stresses for TA 67° are less than for TA 247°, as MESSENGER's altitude over the sub-solar point is higher in the TA 67° case.

MESSENGER orbits Mercury twice a day. Science observations (shown in Fig. D-1-6) are made during the first 12-hr orbit; for eight hours of every second 12-hr orbit (not shown) the spacecraft is oriented for data downlink to Earth and acquisition of ranging data (Sec. F.2.4).

Table D-2-8 Mission Drivers

Required Meas.	Drivers(s)	Selected Parameter(s)
Use remote-sensing instruments	Worst thermal case: spacecraft periapse near local noon	3-axis stabilized spacecraft; thermal shade allows pitch ±12.7°, yaw ±15°
Global imaging at ~250 m/pixel (MDIS)	Available downlink rate; view of planet; body-fixed instruments	Utilize flyby imaging, scan mirror, pixel summing, and data compression
Libration and obliquity to 10% level (MLA+RS)	Periapse > 10° off pole	Orbital inclination of 80°
	Maximum eclipse time drives battery mass	Initial latitude of periapse 60°N
	Radiation pressure on thermal shade and solar arrays	Symmetric spacecraft; minimize thrusting events for momentum dumps
Elemental changes across pole (GRNS)	Altitude; thermal input from planet	Initial 200 km altitude at periapsis; adjust for solar perturbations during year
Determine ranging to surface features (MLA)	Lidar range of 1000 km	
Global coverage of B-field (MAG+EPPS)	Simple mission ops; low fuel usage	12-hr elliptic orbit fixed in inertial space
Exosphere at 25 km res. (ASCS/UVVS)	Body-fixed instruments	Limb drift through FOV + pitch as needed

When in near-terminator orbits (Fig. D-1-6), the spacecraft continuously rolls about the sun line to keep the planet in nadir view. In near-noon-midnight orbits, the spacecraft maneuvers to the extent possible to maximize the coverage of the planet while maintaining the spacecraft bus behind the thermal shade.

The power system (Sec. F.2.5) is sized to accommodate full operation of all instruments simultaneously over > 99.5% of the orbital phase of the mission. The exceptions are ~15 min each orbit during ~1 week each Mercury year, centered near TA 270°, when the solar panels must be turned edge on to the Sun due to thermal input from the planet (Sec. F.2.1).

Fields of view of the remote-sensing instruments (Fig. D-2-3) are co-aligned; the MDIS scan mirror increases the field of regard to allow imaging of the entire planet (Fig. D-1-1). The mounting of the MAG minimizes electromagnetic interference from the spacecraft while maintaining a benign thermal environment; the mounting of EPPS allows for the observation of targeted plasma and particles while thermally shielding the instrument. Instrument observing sequences commensurate with the average allowable data rates (Table D-1-10 and Sec. F.2.11) will be determined at the bi-monthly Science Team meetings (Sec. G.2).

The Mercury flybys will be used to obtain imaging difficult to achieve during the orbital phase (Fig. D-1-1; Sec. D.1.4). The flyby observation strategy and data downlink plan (Table D-1-3; Sec. F.2.11; Table F-6-1) are driven by the flyby geometry (Table D-1-2).

Science and calibration data from the Earth and Venus flybys and cruise use low data rates and will be accommodated within the usage shown in Table F-6-1. MDIS performance measurements, spacecraft radioisotope buildup by cosmic rays (GRNS), and spacecraft magnetic field data (MAG) are the only required data prior to first Mercury flyby; other science data will be collected as resources permit.

Deep Space Maneuvers (DSMs) and the planetary injection maneuver are the only time-critical events; the DSMs establish the planetary flyby times. Allowance has been made for clean-up maneuvers (Sec. F.1 and Table F-1-4) and possible DSM execution delays of 2 to 12 days.

Maneuvers are planned outside of solar conjunctions so that real-time communications are maintained with the spacecraft.

D.2.3 Data Analysis and Archiving

All relevant mission data will be validated by the project and archived to the Planetary Data System (PDS). Software code and design will be reused from previous programs, in particular NEAR, but will be retested and validated by the project. Any new software for MESSENGER will be developed and tested using formal software development methods and will be overseen by the project.

All MESSENGER data are downlinked to the DSN and forwarded to the Mission Operations Center (MOC) at APL. Telemetry data flow from the MOC to the Science Operations Center (SOC), for low-level data processing, data distribution, and archiving (Fig. D-2-4). The SOC creates and maintains a Science Archive, the central repository for science data products; it maintains a telemetry archive, a record of instrument and spacecraft commands, and records of science sequences; it cleans, merges, and time-orders science telemetry and separates it by instrument; and it develops and maintains a Science Data Catalog, to enable easy access to science data files, to support creation of data products, and to facilitate data searching. The SOC also performs preliminary data calibrations, using algorithms developed by the Science Team.

Recognition by the MESSENGER Project of the crucial need to allocate adequate resources for analysis, interpretation, and archiving of all scientific data has been folded into overall mission planning. Time phasing of analysis is coordinated with events such as planetary

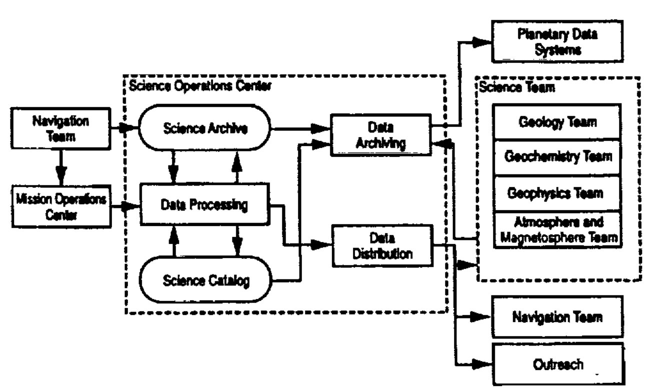


Figure D-2-4 MESSENGER science data flow.

flybys in addition to the orbital tour of Mercury itself. All science Co-Is are funded for a full calendar year following the end of mission operations in order to allow for the final analysis, detailed interpretation, and full archiving of the data. Applied Coherent Technology (ACT), a Small Disadvantaged Business (SDB)with experience in similar archiving activities, has been engaged by the MESSENGER Project to ensure that all science data processing requirements are met. Details of the resource allocations to these tasks are given in Section F.6.3.

Data Products. Table D-2-9 illustrates the MESSENGER data products and the teams responsible for producing them; the first two columns duplicate entries in the second large column of Table D-1-1 showing traceability back to the science questions. EPPS and MAG products will be in the form of time-series. Spectra from GRNS, ASCS, and XRS will be organized by latitude and longitude. Preliminary data will be released on a public web site within ~72 hours of downlink. All data, applicable housekeeping, and calibration algorithms will be released to the PDS after the second flyby and within six months of the end of mission. The Science Team (Sec. D.2.4) will be responsible for determining the general layout of the archive, the SOC is responsible for producing original media for the PDS, and the PDS is responsible for making copies and distributing the archive. Public dissemination of selected images and data will occur immediately following calibration with the best currently available calibration algorithms.

Table D-2-9 Data Products

System	Data Product	Team	Lead
Spacecraft	Uncalibrated telemetry	SOC	-
Spacecraft	Command history	MOC	-
Instruments	Calibrated instrument data	SOC	-
MDIS	Catalogued images	GG	Murchie
GRNS	γ-ray spectra, neutron flux	GC	Boynton
MAG	B-field vectors	AM	Slavin
MLA	Range profiles, radiometry	GP	Zuber
ASCS	Spectra, tangent height	AM	McClintock
EPPS	Energy spectra, composition, and distribution functions	AM	Gold
XRS	X-ray spectra	GC	Trombka
RS	Doppler data, ranging data, occultation times	GP	Smith

Selected additional data products of scientific interest will be disseminated in electronic and printed formats.

A Data Working Group (DWG) consisting of the PI, Project Scientist, and Science Group Chairs will oversee calibration and data product software development. The DWG will provide configuration oversight of all software implementations to ensure that data delivered to the PDS are produced using project approved software.

Science Data Processing Facilities. The science data processing facilities will be developed by the Data System Coordinator in cooperation with the Science Team. The facilities will share a common architecture and will be at APL and operated by ACT, an SDB; see Secs. E.2 and F.6.7. The SOC is designed to ingest the total science and housekeeping stream from the DSN on a daily basis during MESSENGER orbital operations, produce data for the data analysis facilities, and produce products for archiving with the PDS.

Publications. In parallel with final archiving at the PDS, scientific results will be shared with the science community via scientific meetings and peer-reviewed publications. None of the data will be treated as proprietary. We recognize the necessity and responsibility for providing fully documented data sets in a timely manner to maximize the science return from the mission. Optimal use will be made of the PDS and the World Wide Web to provide results to the scientific community as well as to associated educational and outreach endeavors. Final results, detailed in the third major column of Table D-1-1, provide closure with respect to the key scientific questions posed in Sec. D.1.1. The science team is funded for one full year of data validation, analysis, and archiving to assure that all scientific responsibilities will be met.

D.2.4 Science Team

The MESSENGER Science Team consists of highly qualified individuals who collectively bring an extraordinary range of technical and scientific expertise. To facilitate the design, development, and testing of instrumentation, and to carry out the analysis of mission data in an effective manner, the science team, led by the Principal Investigator (PI) Sean C.

Solomon, will be divided into four broad groups with different but complementary interests. A Geology Group (GG), chaired by James W. Head III, will oversee development of the imaging system and will lead the scientific interpretation of the data pertinent to the geological history of Mercury. A Geochemistry Group (GC), chaired by William V. Boynton, will oversee development of the γ-ray, neutron, and X-ray spectrometers and the VIRS spectrometer and will lead the scientific interpretation of the measurements on the surface composition of the planet. A Geophysics Group (GP), chaired by Maria T. Zuber, will oversee development of the altimeter and the spacecraft transponder system, and will lead the scientific interpretation of altimetry and gravity measurements, including the measurement of Mercury's physical libration and its relation to the state of the core and the origin of the magnetic field. An Atmosphere and Magnetosphere Group (AM), chaired by Stamatios M. Krimigis, will oversee development of the magnetometer, UVVS spectrometer, and EPPS, and will carry out the scientific analysis of magnetic field structure, neutral atmosphere, and energetic particle and thermal plasma characteristics.

These Chairs, together with the Project Scientist, R. L. McNutt, Jr., the Science Payload Manager, Robert E. Gold, and the Project Manager, Max R. Peterson, constitute the Science Steering Committee (SSC). The PI leads the SSC in overseeing the entire MESSENGER mission science implementation, from instrument development through the interdisciplinary synthesis of all data sets.

The particular contributions expected of each Science Team member (Table D-2-10) illustrate the rationale for their inclusion on the team. The range of expertise each member brings to the team is best documented by their vitae (Appendix A).

Table D-2-10 Roles and Responsibilities of Science Team Members

Team Member	Group(s)	Role and Responsibility
Sean C. Solomon	PI	Leads MESSENGER effort with responsibility for design, execution, and success of the mission; reports on project progress and status to NASA. Co-chairs all Science Team meetings. Ex-officio member of each Science Team group. Leads overall scientific analysis effort and participates in interpretation of imaging, geochemical, and geophysical measurements.
Mario H. Acuña	AM	Shares in development of MAG. Participates in the analysis of magnetometer data.
Daniel N. Baker	AM	Participates in the analysis of MAG, EPPS and UVVS data. Leads efforts to characterize magnetospheric processes.
William V. Boynton	GC Chair	Participates in the development of GRNS and XRS. Leads the analysis of γ-ray, neutron, and X-ray measurements.
Clark R. Chapman	GG	Participates in the analysis of imaging and IR spectral measurements. Leads the interpretation of the impact cratering record.
Andrew F. Cheng	AM	Leads the analysis of MAG, EPPS, and UVVS data for study of interaction of the magnetosphere and the planetary surface.
George Gloeckler	AM	Oversees development of FIPS subsystem of EPPS. Leads the interpretation of thermal plasma data.
Robert E. Gold	AM	Implements science payload. Oversees the development of EPPS. Participates in analysis of energetic particle data.
James W. Head III	GG Chair	Leads the analysis of imaging data for the identification of volcanic features and the stratigraphic analysis of geologic units.
Stamatios M. Krimigis	AM Chair	Leads the analysis of EPPS data to characterize the magnetosphere and interplanetary medium.
William McClintock	GC and AM	Oversees development of of ASCS. Leads the interpretation of UV spectra. Participates in the interpretation of IR spectra.
Ralph L. McNutt, Jr.	GC and AM	Project Scientist; assists PI. Oversees development of GRNS and XRS. Participates in analysis of surface composition.
Scott L. Murchie	GG and GC	Oversees MDIS development. Leads development of observing sequences and interpretation of imaging and spectral data.
Stanton J. Peale	GP	Leads strategy for and interpretation of measurements of planetary orientation and physical libration.
Roger J. Phillips	GP	Leads the analysis of topography and gravity data for regional tectonics and interior dynamics.
Mark S. Robinson	GG and GC	Leads development of mosaicking and geometrical corrections for MDIS. Leads the analysis of imaging and spectral data.
James A. Slavin	AM	Participates in development of MAG. Leads the analysis of magnetometer data for magnetic field structure.
David E. Smith	GP	Oversees design, fabrication, and testing of MLA. Leads investigation of radio science. Participates in analysis of MLA data.
Robert G. Strom	GG	Participates in analysis of imaging and IR spectral measurements. Leads the interpretation of volcanic and tectonic history.
Jacob I. Trombka	GC	Oversees selection of GRNS and XRS detectors. Participates in the analysis of γ-ray, neutron, and X-ray measurements.
Maria T. Zuber	GP Chair	Leads analysis of MLA data. Participates in the analysis of occultation, radio science, and gravity/topography data.

E EDUCATION, OUTREACH, TECHNOLOGY, AND SMALL DISADVANTAGED BUSINESS PLAN

E.1 Education and Public Outreach Plan

MESSENGER's mission to Mercury presents a first-class opportunity to involve the lay public and students throughout America in the excitement of planetary exploration. Mercury's unseen face is one of the last easily comprehended terra incognita in the solar system, analogous to the western hemisphere of our own planet during the 15th and 16th centuries. Moreover, Mercury is a linchpin for comparative studies of rocky planets, in both our own and, perhaps, other solar systems.

In addition to traditional training of undergraduate, graduate, and post-doctoral students at the various Co-I institutions, the MESSENGER mission provides a wealth of "events" to anchor Education and Public Outreach (E/PO) programs: launch, two Venus flybys, two Mercury flybys, then a year-long orbit, followed by reporting of the final scientific discoveries. These events and activities will be a springboard for education at all levels - whether through a child's introduction to the planets, a freshman-level course in the Earth sciences, or a general-interest museum/planetarium program.

MESSENGER's E/PO program:

(1) Reflects NASA's evolving visions and goals while meeting or exceeding national educational standards;
(2) Creates and maintains strong working partnerships with capable groups;
(3) Proactively finds opportunities to catch public attention;
(4) Is run by qualified, knowledgeable professionals; and,
(5) Contains programs and activities to reach all levels of age, education, and privilege.

Working in close coordination with the Science Team, a carefully selected group of E/PO professionals has been engaged to design a comprehensive set of activities coordinated with MESSENGER events to enliven education from kindergarten through college and to excite the public. These activities include teacher training, curriculum development, student experiments with MESSENGER, a television documentary, museum displays, and special outreach to underserved and minority students. The full multi-faceted E/PO program is carried out with an extensive network of individual and institutional partners throughout the country under the supervision of the MESSENGER Education and Outreach Directors and with the active participation of the entire Science Team and key technical leaders (Table E-1).

Lead organizations include (1) the American Association for the Advancement of Science (AAAS), (2) the Challenger Center for Space Science Education (CCSSE), (3) the Carnegie Academy for Science Education (CASE), (4) Proxemy Research, Inc. (PRI), educational consultants, (5) the Center for Educational Resources (CERES) at Montana State University (MSU)-Bozeman, (6) Minority University-SPace Interdisciplinary Network (MU-SPIN, located at GSFC), (7) the National Air and Space Museum (NASM), (8) the American Museum of Natural History (AMNH - New York City) and (9) an independent television Producer/ Director team.

Concordance with NASA Vision, Goals and Strategy. The MESSENGER Project is committed to the NASA vision of developing activities to enhance science, mathematics, and technology education and literacy. MESSENGER breaks new scientific, engineering, and technology ground and will promote the education mission of NASA's Office of Space Science (OSS) by inspiring and educating students and the public about the wonders and realities of human accomplishment as we reach beyond our home planet. By building upon the OSS operating principles and strategy (*Partners in Education*, 1995; *Implementing the Office of Space Science (OSS) Education/Public Outreach Strategy*, 1996), MESSENGER fulfills these goals in a timely and cost-effective manner.

Key Personnel. Working in close coordination with MESSENGER's Science Team, the E/PO team is led by Dr. Shirley M. Malcom and Dr. George "Pinky" D. Nelson, both with the American Association for the Advancement of Science (AAAS). Dr. Malcom is a member of the President's Committee of Advisors on Science and Technology and Director of Education and Human Resources for AAAS. Dr. Nelson is an astrophysicist, astronaut, educator, and the Director of Project 2061, the AAAS long-term educational reform effort. They are implementing the MESSENGER Education and Public Outreach Strategy, assuring compliance with the criteria contained in the national mathematics, science, and technology education standards and evaluating products and activities against these standards for quality, impact, effectiveness, and equity. They are assisted by Ms. Judy Kass, Director of Outreach Programs within the Education and Human Resources (EHR) Directorate of AAAS, who is responsible for development of "plain language books" to explain MESSENGER, orchestrating the coaching of Science Team members on communicating with the general public, and leveraging the use of AAAS radio program facilities in publicizing the mission. AAAS is also the principal dissemination avenue for targeted print media and radio programming.

The principal liaison with the Science Team is Dr. Clark R. Chapman, a MESSENGER Co-Investigator, well-known popularizer of planetary science, and 1999 Sagan Medalist of the American Astronomical Society. Everything presented to students and the public is vetted for scientific accuracy by the Science Team; moreover, each Science Team member is responsible for a local E/PO program in his or her own community and for mentoring students and teachers in our national effort.

Curriculum development and dissemination efforts are coordinated by Ms. Stephanie A. Stockman (of PRI), director of the educational outreach effort at the Laboratory for Terrestrial Physics at GSFC. With a background in both geology and K-12 educational curriculum development, Ms. Stockman is well situated to direct the overall education component and to maximize use of NASA/Central Operation of Resources for Educators (CORE), the NASA Educational Resource Centers, and Spacelink.

Outreach efforts are coordinated by Dr. Jeffrey J. Goldstein, planetary astronomer and Director of Space Science Research at CCSSE. He is working with Drs. Malcom and Nelson and Ms. Stockman to fold Challenger Center efforts and infrastructure efficiently into the overall program. All E/PO staff and scientists will participate in Project 2061 workshops to ensure that educational goals are clear, consistent, and aligned with standards. Web sites are to be developed by the E/PO team and maintained by the MESSENGER Project at CIW.

The total expenditure for Education and Public Awareness is $ 4,474,579, equal to 1.32% of the total mission cost including the Delta launch vehicle or 1.63% excluding the launch vehicle (with all costs in real-year dollars). MESSENGER thus helps OSS fulfill the recommended goal of 1 to 2% established by the Education/Public Outreach Task force. Time-phasing of the expenditures is indicated in Table E-1.

E.1.1 Educational Program Activities and Products

The educational program component builds on significant partnerships with professional educators. MESSENGER's education program:

(1) Maps the mission science into the National Science Education Standards (NSES) developed by the National Research Council and Benchmarks for Science Literacy developed by AAAS Project 2061;

(2) Develops good examples and targeted implementation plans, including how teachers can incorporate MESSENGER science instruction into their classrooms;

(3) Disseminates these materials and models via both traditional routes (print media and workshops) and through new communications-technology routes;

(4) Uses MESSENGER Student Investigator programs to involve students and their teachers with Science Team Mentors; and

(5) Updates the education program and its content through an ongoing assessment of the impact and effectiveness of these efforts.

Products will include maps or guides linking NSES Project 2061 Benchmark and MESSENGER components, MESSENGER Educational Modules for workshop use, a set of Student Investigations (MESSENGER Trans-Missions), an interactive Web-based exploration scenario (MESSENGERlink), and a nationally distributed Web-and-CD-ROM archive of these materials.

Mapping to Standards and Benchmarks - The MESSENGER Guide. Virtually all states and many localities are involved in developing

Table E-1 MESSENGER Time-phased Education, Public Awareness Activities, and Traceability

				2000-2001	2002-2003	2004-2005	2006-2007	2008-2009	2010-2011	
Funding Profile (Real-Year k$), by fiscal year			4,475 TOTAL	473	987	938	691	816	571	
Activity			*Target*	*Development*		*Launch/Earth Flyby*	*Venus Flybys (10/06, 6/07)*	*Mercury Flybys (1/08,10/08) Orbit (9/09)*	*Analysis/Closure*	*Leads (Lead Org.) Partner Orgs*
Education										
The MESSENGER Guide[1,2,8]			Professional educators	Create scientist-teacher teams; identify content/skills; map to standards		Ongoing development/review of products and using Project 2061 methods; assess efficacy and input to module development and testbed activities				G. Nelson (AAAS)[¶] CCSSE, CASE
The MESSENGER Classroom[1,3,5,6]	MESSENGER Education Modules and supporting materials		K-13		Start MEMs development	Launch items, launch video	Flyby items, imaging activity	Orbit-insertion items; data analysis activities	Results items, new knowledge about Mercury from MESSENGER	J. Goldstein (CCSSE)[¶]
	MESSENGER Fellows		K-13		Start Fellowship program	MESSENGER Fellows program				J. Goldstein (CCSSE)[¶]
	MESSENGER CASE Curriculum		K-6	Develop basic curriculum support materials; field test materials in classrooms; finalize		Implement curriculum; develop as mission progresses				C. James (CASE)[¶] AAAS
	MESSENGER Internships		7-12		Prepare internships; recruit women and minorities vigorously	Provide student internships at Science Team member institutions				Science Team Co-I institutions
	MESSENGER Student Investigations and "Trans-Missions"		9-12 (K-8 remote)	Set requirements and procedures for competitions; establish remote projects		Student investigator competitions	Investigations begin with cruise phase. Flyby 2 competition	Trans-Mission writeups, presentations	Late-mission opportunities	G. Nelson (AAAS)[¶] CCSSE, CASE, Science Team
The MESSENGER Educator[4,5,6]	MESSENGER Educator Workshops	1 Regional Workshops	K-13 teachers		Begin Fellowship workshops	Regional workshops for educators				J. Goldstein (CCSSE)[¶] Science Team
		2 "Train the Trainer"	NASA educators	Preparation	"Train the Trainer" workshops	Ongoing training				S. Stockman (GSFC)[¶]
		3 MU-SPIN/NRTS Workshops	Educators of underserved, underutilized, minority sectors	Preparation	Begin workshops	Develop new materials as needed; provide training through MU-SPIN and MSU CERES to reach underserved and underrepresented groups				J. Harrington Jr. (MU-SPIN)[¶] MSU
	MESSENGER Online	1 CERES Projects	K-12 teachers	Initiate Website development, online courses, and projects	<------------------	Expand MESSENGER Website; establish links with multiple partners; adapt materials for Website delivery throughout project				G. Tuthill (MSU)[¶], CASE
		2 MESSENGERlink	All students, teachers	Develop MESSENGERlink		Implement MESSENGER link; students analyze real data, file reports, interact with mission scientists				T. Dutter (SEI)[¶]
MESSENGER Feedback[2,3,7]			All	Perform quality control and assessment for products and developing projects		Ongoing quality control with significant inputs from user (student/teacher/lay person) feedback				S. Malcolm (AAAS)[¶] CCSSE, CASE, Science Team
Public Awareness										
The Eye of MESSENGER[1,5]			Amateur, professional observing community		Groundwork	Observation campaigns to tie into mission cruise and events; discussion forums				C. Chapman (Science Team)
MESSENGER Extended Family[5]			Disadvantaged public		Start WolU program infusion	Utilize AAAS networks for distribution of information about mission into target communities, e.g., HBCUs, MEIs, Society of Women Engineers				J. Kass (AAAS)[¶] MU-SPIN, CCSSE
MESSENGER: The Movie[1,6]			National television audiences	Develop proposal for documentary; secure broadcaster partners for external funding support. Begin filming.		Air major TV special after launch	Revise/retell developing mission story in series of programs with different formats	Air second major TV special near end of mission		N. Parmee[¶], E. Weinreich[¶] (Independents)
The Voice of MESSENGER[1,4,5,6]			Professional and general public	Prepare MESSENGER team for interactions associated with major events.		Provide media training for team; prepare articles for publications; develop radio segments and materials for Website distribution; participate in briefings at news outlet associations				J. Kass (AAAS)[¶] APL, CCSSE
The MESSENGER Broadside[1,5]	Museum Displays	1 NASM	Develop display materials	Exhibition: NASM Planetary Gallery, Washington, D.C. ------>			Evolve exhibits with mission to include computer feeds with spacecraft status and "real time" science data			T. Watters (NASM)[¶]
		2 AMNH		Exhibition: AMNH (New York, N.Y.) ------>						N. Hechinger (AMNH)[¶]
	General Audience Books		General public			Develop "plain language book" on exploration of solar system (to include MESSENGER); focus on disadvantaged community outreach		Followup book on development and launch of spacecraft, the science mission and technology challenges, and initial science results		J. Kass (AAAS)[¶]

NASA Guidelines:

[1] Involve scientists and engineers in education and outreach to ehance core OSS research goals
[2] Support local, state, and national efforts directed towards systemic reform of science, mathematics, and technology education
[3] OSS-developed educational products and activities driven by National Math, Science, and Technology Education Standards
[4] Provide meaningful opportunities for underserved and underutilized groups
[5] Enhance the breadth and effectiveness of partnerships by:
- a) Focusing on high leverage opportunities
- b) Building on existing programs, institutions, and infrastructure
- c) Emphasizing collaboration with planetariums and science museums
- d) Coordinating with ongoing education and outreach efforts

[6] Make materials available and accessible using modern technology
[7] Evaluate for quality, impact, and effectiveness

[¶] Letter of Endorsement to collaborate with MESSENGER has been received and is included in Appendix B

curriculum standards and frameworks using the National Education Standards and Benchmarks as a template. Resources being developed by AAAS Project 2061 permit a user to map a concept between national standards and state or local frameworks. We will provide such a mapping customized for MESSENGER. This effort is led by Dr. G. Nelson of AAAS.

Developing Quality Classroom Materials - The MESSENGER Classroom. While frameworks and standards are used to anchor MESSENGER science within the curriculum, their ultimate use depends on the quality of the materials, lessons, or modules produced for different school levels, the development of effective in-service teacher training models, and the formation of a leadership group of educators capable of carrying the materials into school systems.

MESSENGER Education Modules (MEMs)(K-13). MEMs will be developed by CCSSE for national use. MEMs are a standardized presenter's package that can be used by teacher trainers and presenters and consist of a diverse mix of educational materials and multimedia resources. A MEM is developed for each of three grade levels: elementary (grades K-4), middle (5-8), and secondary (9-13).

The MEMs equip the presenter to train educators who teach science in both formal (classroom-based) and informal (museum/ science-center-based) settings. MEMs are centered on mission-related educational topics, providing a solid grade-appropriate overview of the MESSENGER mission and its science objectives within the context of the curriculum. MEMs provide a window on the research experience, the breadth of planetary science exploration, and concepts/content relevant to the national science and mathematics standards. MEMs are updated throughout the mission and include components that can be made available over the Internet

MESSENGER Fellows. Thirty Fellows will be sponsored by MESSENGER to participate in CCSSE's nationwide teacher-training and education-module program. Fellows sign up for a minimum of three years and conduct three educator workshops per year for an average of at least 40 educators per workshop. Over the eight years (FY03-10) of Fellow-conducted workshops, at least 28,800 educators are trained in science and educational aspects necessary to present effectively MESSENGER-related topics: Mercury, its terrain and composition, its magnetosphere and exosphere. Working in concert with the MESSENGER E&PO Team, Fellows are trained at a four-day workshop held at an appropriate MESSENGER site, e.g., APL. Training takes place once every two years starting in FY03, providing for four training workshops. MESSENGER funds all travel expenses for these workshops. In the intervening years, Fellows will be encouraged to attend the National Science Teachers Association (NSTA) National conference where Challenger Center holds a one-day MESSENGER update session. All 30 Fellows are given the latest MESSENGER Education Modules (MEMs) kit during the training workshop, and would be given a kit supplement at the NSTA update session.

While a variety of factors are used in the final selection, the ideal MESSENGER Fellow would be actively teaching or conducting teacher training in a formal or informal science environment (e.g., school district, science center, museum, educational organization); be willing to conduct the required Teacher Training Workshops during each year they are involved with the program; and have a written commitment from their host institution (current employer or sponsoring organization) providing release time for the Teacher Training and committing to support the candidate's workshop initiatives. Fellows will be chosen from extensive networks of classroom teachers, curriculum specialists, and museum/science center educators. This effort will be led by Dr. J. Goldstein of CCSSE.

MESSENGER CASE Curriculum (K-6). The Carnegie Academy for Science Education (CASE), an affiliate of the home institution of the Principal Investigator, Dr. Sean C. Solomon, will develop lessons that respond to the realities of teaching science at K-6 grade levels. Models developed for this level will be interdisciplinary, in keeping with general teaching methods at this level (i.e., incorporating measurement concepts into mathematics and the stories, myths, and legends of Mercury into language arts). We plan to model the lesson structure and implementation methods for elementary classes on the successful program at CASE that increases District of Columbia Public School teachers' knowledge of science and instructional methods for bringing science to their inner-city students. The Summer Institute at CASE, currently in its fifth year, exposes teachers to new ways to teach math as well as science, making use of current software and materials. Teachers spend their days engaged in hands-on, minds-on activities that their students will use. This strategy leads to implementations that engage the attention of both students and teachers, an element critical to the actual use of materials developed. Dr. Solomon will be a mentor to the teachers involved with this project, which will be led by Mr. Charles James of CASE.

MESSENGER Internships (7-12). Local middle- and high-school students will participate in summer internships at the home institutions of the science and engineering team members. Students become directly involved in mission and data analysis support and work under the close supervision of members of the science and technical teams. Women and minority students will be vigorously recruited. This effort is coordinated by Ms. S. A. Stockman with assistance from the MESSENGER Project Office at APL.

Student Investigators and MESSENGER "Trans-Missions" (Advanced 9-12). From the initial cruise phase through the second Mercury flyby, there are opportunities for an interactive program to promote the involvement of K-12 students in the scientific study of space, the solar system, and the planets. On the basis of a national competition involving student-initiated proposals, selected Student Investigators (grades 9-12) will be brought to MESSENGER team institutions for collaborations at an intensive level. These Student Investigators will help plan, execute, and analyze observation sequences using the MESSENGER spacecraft and its instrumentation and convey their results to a larger community.

In parallel, a remotely accessible activity set will be open to a broader K-12 student audience. Remote participation will be channeled through the MESSENGER Web page and the Educational Coordinator, Ms. Stockman. The Web page will list several possibilities for "Trans-Missions," miniature scientific missions done en route to Mercury, along with background information and procedures for proposing studies. MESSENGER has the advantages of a long cruise phase, the ability to view the entire sky over one solar orbit, and close approaches to Venus and Mercury, but has limited downlink capacity for student projects. Over five years of cruise (with assorted flybys) 10-20 projects can be proposed, accepted, and conducted, but each "Trans-mission" can involve multiple and geographically widely distributed student participants. Science Team members will take on mentoring roles for individual projects, with the lead for organization of this effort provided by Science Team Co-Is Drs. Scott L. Murchie and Mark S. Robinson. Possible projects that have the potential for new scientific findings are a search for Trojan objects in the orbits of Venus and Mercury and targeted science, as proposed by one or more students, for the second Mercury flyby.

Dissemination Mechanisms-The MESSENGER Educator. Once curriculum support materials and in-service training are sufficiently tested and refined, teacher workshops, and "train the trainers" workshops will be offered extensively. Teacher training is the preferred avenue for dissemination of materials, because teachers who immerse themselves in activities are more likely to use the materials in their classrooms than teachers who receive materials through other routes.

Workshops. 1. Challenger Center for Space Science Education (CCSSE). Challenger Center's focus is on training and equipping MESSENGER Fellows with the knowledge, materials, and support to conduct a variety of workshop models targeting at least 40 teachers at a time. While Challenger Center defines a standard presentation to help maintain quality and accuracy, it plans to give presenters the flexibility to provide a half-day inservice in a school district, a full-day workshop at a museum or science center, or a one-hour presentation at a conference. The focus is not so much on the workshop as on empowering the presenter. Challenger Center manages the activities of the MESSENGER Fellows and ensures the implementation of a minimum of 90 MESSENGER educator workshops per year (three per Fellow) at sites across the nation.

Challenger Center also works to facilitate presentations by Fellows at regional and national educational conferences such as NSTA, National Middle School Association (NMSA), and other appropriate venues.

Efforts will be made to have the MESSENGER teacher workshops sponsored by a coalition of community organizations. Opportunities for participants to earn inservice credit or professional development credit will be fully explored.

Workshops. 2. NASA Resources for MESSENGER. "Train the trainer" workshops will focus on NASA's education community, the Educators' Resource Center Network (ERCN), and NASA Aerospace Education Services Program (AESP) personnel. These workshops, at least one per year, are conducted by Ms. S. Stockman and modeled after the Mission to Planet Earth Education Products Workshop. Participants are expected to conduct at least three teacher training programs using MESSENGER Project materials in their home areas.

Workshops. 3. Minority University-SPace Interdisciplinary Network. Minority groups will be reached via "trainer workshops" through NASA/GSFC's MU-SPIN, a comprehensive educational initiative for Historically Black Colleges and Universities (HBCUs) and Minority Institutions (MIs). These workshops will be offered in conjunction with MU-SPIN's Network Resources and Training Sites (NRTS). Each NRTS consortium consists of at least four minority-institutions (community college to graduate level schools) and at least one predominantly minority-attended K-12 institution. There are 75 core partners in MU-SPIN at all educational levels, with emphasis on high school and college. Funded by NASA, this effort is led by Dr. James L. Harrington, Jr., MU-SPIN Project Director, and coordinated with other MESSENGER efforts by Ms. S. Stockman.

MESSENGER On-Line. 1. Montana State University (MSU)-Bozeman. MSU-Bozeman has assumed a leadership role in the development of on-line science courses and classroom materials for K-12 teachers. Through its Burns Telecommunications Center (BTC), MSU reaches science teachers nationwide with these products. The MSU Center for Educational Resources (CERES), a NASA-funded program developing on-line credit courses in space science for K-12 teachers, is working with the MESSENGER E/PO team to (1) adapt curricular materials from the MESSENGER project to the Internet and other interactive media; (2) prepare CD-ROMs for storage and distribution of materials; (3) provide access to learning technologies installed in the BTC, both for classroom materials and for on-line professional development of teachers; (4) incorporate MESSENGER-oriented material into on-line courses being developed by CERES; and (5) publicize training opportunities about MESSENGER for teachers. This activity is led by Dr. George F. Tuthill, PI and Project Director of CERES at MSU.

MESSENGER On-Line. 2. MESSENGERlink. Building on the development of Moonlink, a component of the Lunar Prospector Discovery Mission, Space Explorers, Inc., will refine the space science educational experience. Targeted to grades 9-12, MESSENGERlink will bring live interactive planetary exploration to the classroom via Internet. It provides students an opportunity to analyze actual data and interact with mission scientists. This effort is led by Ms. Tia S. Dutter of Space Explorers, Inc.

Other Routes. We plan to take full advantage of NASA's dissemination network by providing print materials to the ERCN, videotapes and CD-ROM products through NASA CORE, and Web-based products through NASA SpaceLink. In addition, we will take advantage of the AAAS dissemination network, which includes special alerts, bibliographies, and World Wide Web site information dissemination to public libraries and museums through use of the AAAS outlets, e.g., Science Education News, an AAAS newsletter (Web and print based) reaching thousands of leaders in science education. This effort is coordinated by Dr. S. Malcom.

Assessment and Quality Control-MESSENGER Feedback. A principal part of the education (and public awareness) effort is the assessment of the efficacy and delivered quality of the program. Dr. G. Nelson of AAAS is responsible for an independent evaluation of all materials produced against the assessment criteria used and tested by Project 2061. Ongoing feedback from CCSSE Fellows sponsored by

MESSENGER is overseen by Dr. J. Goldstein. Dr. S. Malcom is responsible for synthesizing these analyses and, with the input from the external advisory board, works directly with both Coordinators to keep the Education and the Public Awareness efforts (discussed next) on course.

E.1.2 Public Awareness

Our public awareness, or outreach, program is designed to engage many diverse audiences in the technical challenges of, and science results from, the MESSENGER mission. To ensure that the multiple audience needs are served, MESSENGER:

(1) Provides science journalists and other media with timely information in anticipation of the major MESSENGER "events", e.g., launch;
(2) Develops tools to be used in outreach and communication, including museum displays, plain language books, and radio spots;
(3) Develops specific strategies and materials for underserved, underutilized and minority communities;
(4) Runs a Mercury Watch program (modeled after the highly successful International Halley Watch and International Jupiter Watch programs) during the life of the mission; and,
(5) Develops an evolving documentary chronicling the MESSENGER mission.

Specific outreach products are timely, appropriate press releases; displays at the National Air and Space Museum (Washington, D.C.) and the American Museum of Natural History (New York City); the *MESSENGER Minute* radio program, two books on the Solar System and on Mercury, and the MESSENGER mission for non-scientific audiences; support of Solar System/Mercury-specific Family Science Nights as part of the Window on the Universe (WotU) programs to be carried out as part of the Challenger Center Regional Workshop effort; the Mercury Watch; and an evolving two-part television documentary with video clips that will be made available for outreach activities and for spots on commercial and public television.

Mercury Watch-The Eye of MESSENGER. A Mercury Watch program will coordinate observations by MESSENGER with those that can be made from Earth by lay observers and the professional planetary astronomy community. It is said that Copernicus never saw Mercury, yet Mercury is often an easily visible bright star after sunset or before sunrise. Through astronomy columns in newspapers and through organizations (e.g., planetaria, science museums, The Planetary Society) the MESSENGER Project will organize a public "Mercury Watch", keyed to events in the mission and to Mercury's visibility. Children and lay adults will have the fun of connecting MESSENGER's news from Mercury with their own participation in watching the planet dart back and forth around the Sun from month to month.

Science Journalism and Media Interactions - The Voice of MESSENGER. Newspapers, news magazines, television, and radio represent the backbone of the traditional outreach mechanisms. AAAS has unique relationships with this science journalism community, e.g., the Science Writers Association meets during the AAAS Annual Meeting, and AAAS is the base of EurekAlert, a Web-based resource used by science journalists to access stories of breaking science. In cooperation with the MESSENGER team and the Public Information Offices of APL and GenCorp Aerojet, Ms. J. Kass of AAAS coordinates the preparation and distribution of press releases, feature articles, photographs, and illustrations using their extensive network of affiliations and up-to-date technologies.

Building on AAAS's success with the radio shows *Science Update* and *Why Is It?* carried regularly on affiliated stations of the Mutual Broadcasting System, the MESSENGER team will develop the *MESSENGER Minute*, a regular radio segment in the same vein that will update the public on the development, progress, and ultimately, the results of the MESSENGER mission. This production will use the AAAS radio studio located in downtown Washington, D.C. This activity will be coordinated by Dr. S. Malcom with Science Team interface provided by Co-Is Drs. C. R. Chapman and R. L. McNutt, Jr.

Other Tools for Outreach and Communication-The MESSENGER Broadside. Beyond radio programs, to reach larger numbers we must develop tools that can be incorporated into other venues and forums where people go.

Museums and Displays. In particular, the National Air and Space Museum will incorporate a MESSENGER exhibit and real-time display in its Planetary Gallery. The American Museum of Natural History in New York City has also offered to incorporate MESSENGER data in their Hall of the Universe and Hall of Planet Earth.

General Audience Books. We shall develop two plain-language books on the exploration of the solar system, in general, and the exploration of Mercury and the MESSENGER mission, in particular. These books, targeted for the lay public, will be modeled after *Your Genes, Your Choices,* produced by the AAAS with funding from the Department of Energy and describing the Human Genome Project, now available in both hardcopy and on the Web (http://www.nextwave.org/ehr/books/html). Ms. J. Kass of AAAS is the lead for this effort.

Underserved, Underutilized, and Minority Communities-The MESSENGER Extended Family. AAAS has a history of over 25-years experience working to increase access to science by women, minorities, disadvantaged communities, and people with disabilities. AAAS networks and outreach in this area are unmatched by any other scientific organization. We will tap into these networks, working with them in the development of materials sensitive and responsive to local needs. Additionally, we will work with the Math, Science, and Engineering (MSE) group of Quality Education for Minorities Network (HBCUs, MIs, and other institutions that share the goals of minority career access to science and engineering) to provide materials to minority and women's science organizations that outline the availability of materials for local workshops with community-based groups. Speakers on the engineering development, design, and science of MESSENGER will be identified and their availability publicized. The primary point of contact with the Science Team will be Co-I Dr. Maria J. Zuber; the primary contact with the engineering team will be Mr. Andrew G. Santo; the E/PO lead is Ms. J. Kass.

Challenger Center is currently seeking support for a national *Window on the Universe* (WotU) program capable of delivering 10 WotU programs per year and building a network of 15 WotU communities within three years. WotU targets underserved communities, i.e., communities with limited opportunities, nationally. For example, recent programs in Broken Arrow, OK, and Presque Isle, ME, have presented space science topics to audiences that do not have easy access to large metropolitan science museums and planetaria. MEMs developed for MESSENGER will be incorporated into this national WotU effort. The E/PO lead is Mr. J. Goldstein.

Documentary Development- MESSENGER: The Movie. We have engaged a widely acclaimed television production team to involve the public, as never attempted before, by taking the audience from the drawing board through the entire mission to find answers to fundamental space science questions over the course of a decade.

To provide a highly-leveraged outreach effort, reaching tens of millions of people, the MESSENGER project has teamed with Ms. Nina Parmee, an independent producer, and Mr. Eitan Weinreich, an independent director, for the purposes of developing a carefully conceived film documentary proposal on the mission and for interesting outside funders and producer/programmers in the project. Parmee and Weinreich have a proven track record in collaboration on projects and in bringing them to fruition; their most recent documentary *Asteroids: Deadly Impact* featured the Shoemakers in an award-winning National Geographic special that aired to tens of millions. In the documentary television world, a significant financial or creative involvement by the subject is perceived to compromise the journalistic credibility of the film. Therefore, MESSENGER's financial involvement in the documentary effort is limited to the cost of proposal development (effective contributed costs by a broadcaster will be determined as part of the documentary proposal package preparation effort). Science Team interaction will be led by Co-Is Drs. M. S. Robinson and R. L. McNutt, Jr.

The documentary will tell the story of MESSENGER in an active, visually exhilarating style using a simple, classic narrative line: a bold idea, a big challenge, and how it is met. MESSENGER will be introduced against the background of current activity in space exploration and in the context of renewed interest in planetary studies including the relevance of exploring Mercury to such major current concerns as extra-solar planets. The story will capitalize on the fact that the MESSENGER project is a small, approachable group of people wrestling with such challenges as how to make a spacecraft go to a particular spot. It is through familiarity with these protagonists - through understanding their dreams and the obstacles they confront in achieving them - that the viewer relates to the project as a whole: vision, engineering, technology, science, and accomplishment.

Parmee and Weinreich propose anchoring the project in two major TV specials, one shortly after launch and one near the end of the mission. In the interim, a series of programs will follow the life of the project. Each program will build on the shows that precede it. Because of the project's time span, a stable viewer base cannot be taken for granted, so retelling significant portions of the story in every program is not only acceptable but necessary.

Such a long-term series of programs requires the interest of a channel or network. Our approach is to leverage the outreach effort during Phase A/B to produce a professional documentary proposal that can bring in a broadcaster partner prior to the start of phase C/D of mission development. The Discovery Channel and the National Geographic Society are potential partners we will approach.

E.2 Small Disadvantaged Business

MESSENGER Project Specifics. The MESSENGER project is committed to providing to small disadvantaged businesses (SDBs), women owned small businesses (WOSBs), historical black colleges and universities (HBCUs), and minority institutions (MIs) maximum practicable opportunities to participate in acquisitions in support of the MESSENGER mission. The MESSENGER team, which includes the Carnegie Institution of Washington (CIW), The Johns Hopkins University Applied Physics Laboratory (APL), GenCorp Aerojet, Composite Optics, Inc. (COI), the Laboratory for Atmospheric and Space Physics (LASP), the University of Michigan (UM), Science Team members, Education and Public Outreach Team members, and various NASA and NASA-associated organizations, intends to pursue proactively SDBs, WOSBs, HBCUs, and MIs for all open subcontract opportunities. The approach is to procure to the maximum extent, not only supplies, materials, off-the-shelf hardware, and computer equipment, but also significant project tasks that historically have been performed in-house by APL. An aggressive approach, specific to the MESSENGER project, has been undertaken in these early stages of the project, and specific procurements and potential vendors have been identified in support of the 8% participation goal as described in NASA procurement regulations (Subpart 1819.70).

This MESSENGER initiative has been implemented by the MESSENGER Project Manager (PM) and Project Scientist (PS) working with lead engineers and other personnel to identify key mission elements for minority institution participation. Initial plans (Table E-2) will be expanded to include such additional areas as spacecraft parts, ground support equipment, and flight-hardware test support.

These initial steps will be expanded through coordination with APL's Small Business Liaison Office (SBLO) and Procurement Office to pursue additional SDBs, WOSBs, HBCUs and MIs with capabilities matching those required for this mission. During Phase A/B, the MESSENGER PM and PS will concentrate on the identification

Table E-2 Targeted SDB Subcontract Areas

Subcontract Item	Possible Vendor	Potential Value (RY$)	Prime
Safety plan preparation and implementation	Futron Corporation, Bethesda, MD	$575,000	APL
Flight software independent validation and verification	Computer Engineering Systems, Silver Spring, MD	$420,000	APL
Science operations center support	Applied Coherent Technology Corporation, Herndon, VA	$3,082,138	APL
Documentary production	N. Parmee, Producer, Washington, DC	$209,783	CIW
Educator training (S. Stockman)	Proxemy Reseach	$155,298	CIW

and development of a specific list of qualified SDB, WOSB, HBCU and MI suppliers for all available procurements planned during Phase C/D. The SBLO, in support of APL's policy of providing equitable opportunity to minority institutions for APL requirements, will provide continual support throughout the entire procurement process. In addition to fostering and supporting early discussions of capabilities of SDBs, WOSGs, HBCUs, and MIs, the SBLO works within the procurement organization to monitor, support, and report on the entire procurement process. The SBLO is responsible for reporting to the government APL's subcontracting progress in accordance with Federal Acquisition Regulation (FAR) 52.219-9. Further support will be provided to the MESSENGER mission by APL's Procurement Office, which ensures that all applicable subcontracts that offer further subcontracting opportunities include the appropriate FAR and FAR Supplement clauses pertaining to 52.219-8.

APL Policy and Goals. APL's policy is that SBs, SDBs, WOSBs, HBCUs, and MIs be given an equitable opportunity to compete for APL's requirements for material, equipment, and services to the fullest extent possible, consistent with the efficient performance of the MESSENGER prime contract to APL. APL has an SB/SDB Subcontracting Plan in place for each of its prime contracts with the Navy, the Ballistic Missile Defense Organization, the Army, and NASA. In addition, APL's SBLO proactively seeks ways to reach new small and small disadvantaged organizations.

Previous Performance. Historically, procured items have included commercially available routine materials, supplies, and equipment; items of special instrumentation, including major custom-designed special-purpose systems; automatic data processing equipment; large and small supporting technical services, such as computer-aided designers, technicians, and software specialists; research and development efforts in specified technical disciplines; and special services and facilities furnished by government activities. The Laboratory has located and contracted with SDBs, WOSBs, HBCUs, and MIs in all categories except the last, where the services and facilities are available only from government sources. The Laboratory conducts an active program to identify new sources, particularly for special technical expertise, an area for which companies often spin off from larger businesses.

Recent Performance. Historical performance for SDB/HBCU/WOSB subcontracting at APL is given for all active contracts from Fiscal Years 1996-1998 in Table E-3. Breakouts for NASA programs are available only for FY98. Prior to that year, NASA monies came to APL via tasks in a Navy contract and subcontracting statistics are not readily available for individual agencies. For APL overall, in the past 3 years, typically ~1% of prime contract monies has gone to SDB/HBCU/WOSBs. The MESSENGER project has already taken steps to raise this percentage. In particular, by targeting SDB companies and using resources such as the Procurement Marketing and Access Network

Table E-3 Historical Performance on APL Programs under FAR 52.219-9

Business category	Dollar amount ($K)				Percentage of subcontracted total				Percentage of prime contract total			
Government Fiscal Year (Oct. 1 - Sept. 30)	1996	1997	1998	1998 NASA only	1996	1997	1998	1998 NASA only	1996	1997	1998	1998 NASA only
Total subcontract expenditures for all categories of small business	35,099	42,528	34,665	8,452	62.6	58.5	36.2	36.1	9.4	11.6	8.8	11.8
Total subcontract expenditures for large business	20,947	30,142	61,119	14,946	37.4	41.5	63.8	63.9	5.6	8.2	15.5	20.9
Subtotal	56,046	72,670	95,784	23,398	100.0	100.0	100.0	100.0	15.1	19.8	24.3	32.8
Small Disadvantaged Businesses (including Historically Black Colleges and Universities)	2,400	4,911	1,859	397	4.3	6.8	1.9	1.7	0.65	1.34	0.47	0.55
Women Owned Small Businesses	1,317	889	2,674	353	2.3	1.2	2.8	1.5	0.35	0.24	0.68	0.49
Total SDB,HBCU,WOSB	3,717	5,800	4,533	750	6.6	8.0	4.7	3.2	1.00	1.68	1.15	1.05
Total funding received (prime contracts)	371,700	366,700	393,900	71,316								

(Pro-Net), we believe that the NASA participation goal of at least 8% by SDBs/HBCUs/WOSBs can be met.

Subcontracting Plan Commitment. Upon the selection of MESSENGER for implementation APL will submit for negotiation with NASA a comprehensive and compliant Subcontracting Plan. The plan will be based on NASA's recommended participation goal of at least 8% of the total contract value for SDBs, WOSBs, HBCUs, and MIs (NASA Procurement Regulations 1819.201(a)(ii)). In all subcontracts that offer further subcontracting opportunities (except small business concerns), APL will include applicable FAR and FAR Supplement clauses including FAR 52.219-8 "Utilization of Small, Small Disadvantaged and Woman-Owned Small Business Concerns." APL will require all subcontractors (except small business concerns) who receive subcontracts greater than $500,000 to adopt a "Small, Small Disadvantaged and Women-Owned Small Business Subcontracting Plan" similar to the plan in place at APL.

For the MESSENGER Project prime contracts will be awarded to APL and to CIW. The rest of the total NASA cost goes directly to NASA entities (the Jet Propulsion Laboratory/Deep Space Network, Goddard Space Flight Center, and Orbital Launch Services). Within the APL prime contract, the structure and propulsion systems will be procured by APL via sole-source subcontracts with the MESSENGER industrial partners (GenCorp Aerojet and Composite Optics, Inc.) as will other items that are sole source by design, including two of the instruments/instrument subsystems, namely ASCS (from the Laboratory for Atmospheric and Space Physics) and the FIPS portion of EPPS (from the University of Michigan). Similarly, CIW has sole-source scheduled subcontracts for support of the Science and E/PO Teams, including to Parmee (WOSB) for support of the planned documentary support (Sec. E.1.2). At APL the remaining scheduled and unscheduled (<$2,500) subcontracted amounts will be openly available for bid, including by SDBs, HBCUs, MIs, and WOSBs. To aid in maximizing actual procurements to SDBs and WOSBs, APL will use data bases such as Pro-Net to locate potential appropriate subcontractors. A summary of the subcontracting opportunities with preliminary monetary amounts is given in Table E-4.

The targeted SDB subcontract areas listed in Table E-2 include areas of competition for which both SDBs and other SBs will be evaluated. For other areas, e.g., documentary productions and safety plan preparation and implementation, all vendors under current consideration fall within the SDB/WOSB/HBCU designation.

Specific goals are based primarily on an analysis of the unique requirements of the MESSENGER spacecraft and its instrumentation package, availability of proprietary components from the developers, and the sole-source expertise available only at the institutions that are developing some of the instrument payload.

During Phase A/B, the MESSENGER PM and PS will work proactively with the SBLO to identify and develop qualified suppliers for all procurements planned during Phase C/D. The goal for MESSENGER, to maximize the conversion of available procurements for SDBs, HBCUs, and WOSBs to actual procurements, reflects the commitment from APL to increase

Table E-4 SDB/HBCU/WOSB Subcontracting Opportunities

	APL	CIW	Total non-NASA
Prime contract value for MESSENGER (incl. reserves)	193,158,444 (219,048,593)	19,782,193 (19,782,193)	212,940,637 (238,830,786)
Total proposed subcontracts	40,474,083	16,073,143	56,547,226
Total proposed sole-source subcontracts	27,310,447	16,073,143	43,383,590
Total identified sole-source SDB/HBCU/WOSB subcontracts (from Table E-2)	4,077,138	365,081	4,442,219
Proposed scheduled competed materials and subcontracts	22,403,902	0	22,403,902
Proposed unscheduled competed subcontracts (Misc. Contracted Materials)	5,910,719	0	5,910,719
Total competed materials and subcontracts available for SDB/HBCU/WOSBs	28,314,621	365,081	28,679,702
% of prime contract value available for SDB/HBCU/WOSBs	16.8	1.85	15.5
% of prime contract value identified to date for SDB/HBCU/WOSBs	2.11	1.85	2.09

the level of participation of disadvantaged business groups.

E.3 New Technology

(1) Insertion of New Technology. MESSENGER employs a prudent combination of tried and cutting-edge technologies in both spacecraft and instrumentation design in order to accomplish its challenging mission. The leading new technologies employed on MESSENGER, and some of their potential commercial applications, are shown in Table E-5. All of these technologies can also play significant roles in future space missions, especially those with high launch energy and onboard propulsion requirements. Other new technologies and their fallbacks are discussed in Sec. G.4. These include technologies that are already in the commercial sector, notably thin-walled propellant tanks.

(2) Transfer of New Technology Between MESSENGER and Other Projects. The low-voltage, all-solid-state XRS instrument X-ray detectors have large active areas and integrated balanced filters, further miniaturizing the approach used on NEAR and exceeding the low-Z-element resolving capability of the alpha, proton, X-ray (APX) detector on the Sojourner rover of Mars Pathfinder. The use of photodiodes coupled to the central CsI detector in the GRS leads to high quantum efficiency without the need for a heavy, high-voltage photomultiplier tube.

Imager and Energetic Particle and Plasma Spectrometer designs incorporate new integrated circuit technologies developed at APL through competitive NASA grants under the Planetary Instrument Definition and Development Program (PIDDP). The MDIS camera head has been reduced to the CCD, two custom VLSI chips, and a field-programmable gate array (FPGA), while the EPPS time-of-flight measurements are accomplished in a single low-power, VLSI chip with ± 200-ps resolution. Both of these developments employ high-sensitivity, low-noise analog circuits on the same chip as high-speed digital circuits, a technology breakthrough.

A new engineering technique will be used for design and manufacture of the structure and its integrated propulsion system: the "Virtual Collocation Design Team." APL, Aerojet, and COI will be linked real-time with common computer-aided-design/computer-aided-manufacture (CAD/CAM) software using networked workstations at each facility. A master database provides configuration and manufacturing control. The network is currently in place and being exercised; it will be expanded to include access by the instrument teams during Phase A/B. As a new way of doing business, this approach has the potential for saving on engineering costs whenever subsystem development, test, and integration into a final product occur at multiple locations.

The evolution of spacecraft bus electronics from the industry standard box-and-harness concept to a card-cage integrated electronics module (IEM) saves an estimated 25 kg in harness, boxes, and structure, and has enabled us to design a realistic orbiter mission with a Delta-class launch vehicle. This design concept has the potential for lowering non-recurring engineering costs on otherwise unique spacecraft.

The X-band, phased-array medium-gain antenna is the culmination of an effort originated by APL for the Ballistic Missile Defense Organization (BMDO) for a new class of electronically steerable antennas. These antennas and their implementation on MESSENGER allow for effective omni-directional coverage within the severe mass and thermal requirements of the mission. Such antennas may have eventual application in the commercial air transportation industry.

Finally, the implementation of event-driven operations with autonomous data collection represents a new way of doing business in space that has possible applications for both the commercial space and robotics industries.

(3) Commercialization of New Technology. In order to (1) infuse appropriate other new technologies into the MESSENGER Project, (2) transfer the new technologies from MESSENGER to other projects or programs, and (3) commercialize this technology as appropriate, the MESSENGER Project has established an agreement with the Mid-Atlantic Technology Applications Center (MTAC) (refer to Endorsement letter in Appendix B).

MTAC was founded in 1992 specifically to aid NASA in broadening the scope and increasing

Table E-5 New Technologies, Status, and Transfer Potential

Technology	Implementation	Status	TRL	Backup	Transfer Potential
Si-PIN detectors with integrated thermal control	XRS with integrated balanced filters	Prototype now flying on NEAR; similar instrument on Sojourner rover (Mars Pathfinder)	6	XRS detectors have coverage redundancy; instrument is below baseline	Encourages AMPTEK to further their commercial X-ray detector product line; miniature, high-sensitivity X-ray detectors for medical applications and industrial laboratory instrumentation
Photodiodes coupled to CsI crystal for low-voltage γ-ray detector	GRS subsytem in GRNS	Efficiencies have been measured in laboratory environment	4	Use PMT for central detector; increases mass with no decrease in quantum detection efficiency	Eliminates high voltage PMTs in room temperature γ-ray detectors; applications in oil-well logging industry
Integrated camera: CCD plus VLSIs	Miniaturization of MDIS camera electronics	First-generation flight unit delivery in 1999; advanced version in third year of PIDDP grant; electronics successfully tested	5	Use conventional electronics and packaging techniques; increases mass at same capability	Potential for commercial, high-performance, ultra-miniature cameras; applications in robotics industry
Combined digital-analog VLSI	EPPS rad hard TOF chip	Now delivered as part of the High-energy Neutral Atoms (HENA) experiment on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE)	6	Separate analog and digital VLSI chips	TOF chip for time-interval measurements: numerous potential applications in new types of instruments including industrial laboratory instrumentation
"Virtual Co-location Design Team"	Common CAD/CAM software linked real time for joint APL/COI/Aerojet design of MESSENGER	Used in previous APL Discovery Mission Feasibility Study; similar to approach taken by Boeing on 777 design	NA	Conventional joint design procedure; moderate schedule and cost impact due to reduced efficiency	New way of doing business; increased design efficiency will lower non-recurring engineering costs
Integrated avionics package	Integrated Electronics Module (IEM) - subsystem integration at card rather than box level	IEM being implemented on TIMED and CONTOUR; advanced version for MESSENGER being developed as an APL project	6	Use TIMED/CONTOUR design; revised fault protection scheme required	Saves mass; "plug and play" design concept lowers non-recurring engineering costs on otherwise-unique research spacecraft
X-band phased array antenna	High-gain antennas on MESSENGER	Similar to use on Radarsat; measured and characterized MESSENGER version in laboratory	8	Conventional antenna with mass penalty	Eliminates mechanisms for steering antennas on spacecraft; possible applications to commercial aviation communications
Autonomy software	Event-driven operations and autonomous targeting and data collection	Partial implementation on TIMED, MSX, and Delta 183	6	Traditional mission and spacecraft operations	NASA and commercial satellites, advanced robotics

the effectiveness of NASA's technology commercialization program. As one of NASA's six Regional Technology Transfer Centers, MTAC's strategy in conducting its technology marketing program is to identify technologies whose commercialization will have the maximum impact on the economy, generate the greatest number of long-term developer/industry partnerships, and provide the developer with the largest return on investment.

For the MESSENGER Project, MTAC will identify those technologies whose infusion into MESSENGER could increase cost and schedule margins. Potential sources include federal, university, and private laboratories as well as commercial organizations. In Phase A/B MTAC participates in preliminary design review meetings to obtain detailed information about the technology requirements of the mission, and concentrates on possible infusion technologies ($29,290 is included for these tasks in the Phase A/B planned procurements, see Table I-7). In Phase C/D MTAC continues this same effort while also identifying potential commercialization opportunities for technology developed specifically for MESSENGER. Market analyses for these potential opportunities, including solicitation of interest from potential commercial partners, is undertaken and MTAC will facilitate joint development projects with commercial partners where mutual interests are identified. The Phase C/D cost estimate includes $53,715 for this effort, based on a cost proposal from MTAC.

F TECHNICAL APPROACH

A Mercury mission is challenging from thermal and mass perspectives. MESSENGER overcomes these challenges while avoiding esoteric technologies by using an innovative approach with commonly available materials, minimal moving parts, and maximum heritage. This approach produces a spacecraft with good margins in all categories and low technical risk. The key concepts are a ceramic cloth thermal shade, an integrated lightweight structure and high-performance propulsion system, and a solar array incorporating optical solar reflectors (OSRs). The thermal shade maintains the spacecraft at room temperature. The integrated structure and propulsion system provides ample mass margin. The solar array with OSRs, which has already undergone significant testing, provides thermal margin even if the panels are inadvertently pointed directly at the Sun at 0.3 AU.

The MESSENGER mission blends innovation, prudent margins, and multiple backup launch scenarios to implement a low-risk, high-scientific-payoff, orbital mission to Mercury. The overall passive thermal design allows for a comprehensive science mission while minimizing any chance of catastrophic failure from the thermal environment.

F.1 Mission Design

MESSENGER's trajectory begins with launch on March 23, 2004, and continues with unpowered gravity assists from Earth, Venus (twice), and Mercury (twice), arriving at Mercury on September 30, 2009. The cruise phase offers opportunity for early science at Mercury and Venus flybys. The Mercury orbit phase lasts one Earth-year (4.2 Mercury years). The total mission ΔV budget is 2700 m/s. Table F-1-1 summarizes the mission design.

Table F-1-1 Mission Design Summary

Two launch opportunities	March 23 - April 6, 2004 (15 days) August 2 - 16, 2004 (15 days)
Mission duration	6.5 years (1 year orbit phase)
Orbit type	Mercury orbit (inclined elliptical)
Orbital parameters (Mercury orbit phase)	Semimajor axis 10,136 km Eccentricity 0.7396 Inclination 80° Longitude of ascending node 326° Argument of periapsis 118°
Launch vehicle	Delta II 7925H-9.5
Launch energy	C_3 = 16.0 km^2/s^2
Launch mass (99% PCS)	M_0 = 1066 kg
Heliocentric S/C distances	Max 1.11 AU, min 0.30 AU
ΔV budget	2700 m/s (100 m/s margin)

F.1.1 Mission Design Overview

Trajectory optimization for a Delta II 7925H-9.5 launch vehicle yields two 15-day launch periods in 2004. A further opportunity in August 2005 also exists (Yen, 1985, 1989; McAdams et al., 1998). The launch energy (C_3) requirement is constant throughout the launch windows at 16.0 km^2/s^2 and the deterministic ΔV varies between 2470 and 2486 m/s. After launch from the Eastern Test Range, MESSENGER is delivered into a 185-km-altitude, 28.5°-inclination parking orbit before injection into the heliocentric transfer orbit using a short-coast solution. For the first day of the window, launch occurs at 1044 UTC. The first Deep Space Network (DSN) contact is scheduled 50 minutes after launch.

Fig. F-1-1 displays the ecliptic plane projection of the heliocentric trajectories and a key-event timeline. The heliocentric trajectory begins with an Earth-to-Earth transfer and an Earth flyby on August 2, 2005. A December 21, 2005, near-perihelion ΔV places MESSENGER in a transfer orbit to Venus. Venus flybys take place on October 25, 2006, and June 6, 2007. The initial Venus flyby reduces aphelion to 0.90 AU and aligns the spacecraft orbit plane with Mercury's orbit plane. The second Venus flyby lowers orbit perihelion to 0.33 AU. There is a 15-minute solar occultation followed by a 14-minute Earth occultation during this flyby. A maneuver on October 27, 2007, sends the spacecraft to Mercury. Mercury flybys include 200-km altitude, dark-side close approaches on January 15, 2008, and October 6, 2008. A deep-space maneuver (DSM) follows each Mercury flyby; both target the spacecraft for the next Mercury encounter. Flyby minimum altitudes, velocities, and phase angles are shown in Table F-1-2. The

Table F-1-2 Flyby Characteristics

Flyby event	Min. altitude (km)	Velocity (km/s)	Phase angle (°)
Earth	5,536	4.0	167
Venus #1	3,544	8.9	13
Venus #2	300	8.9	22
Mercury #1	200	5.8	112
Mercury #2	200	5.2	122

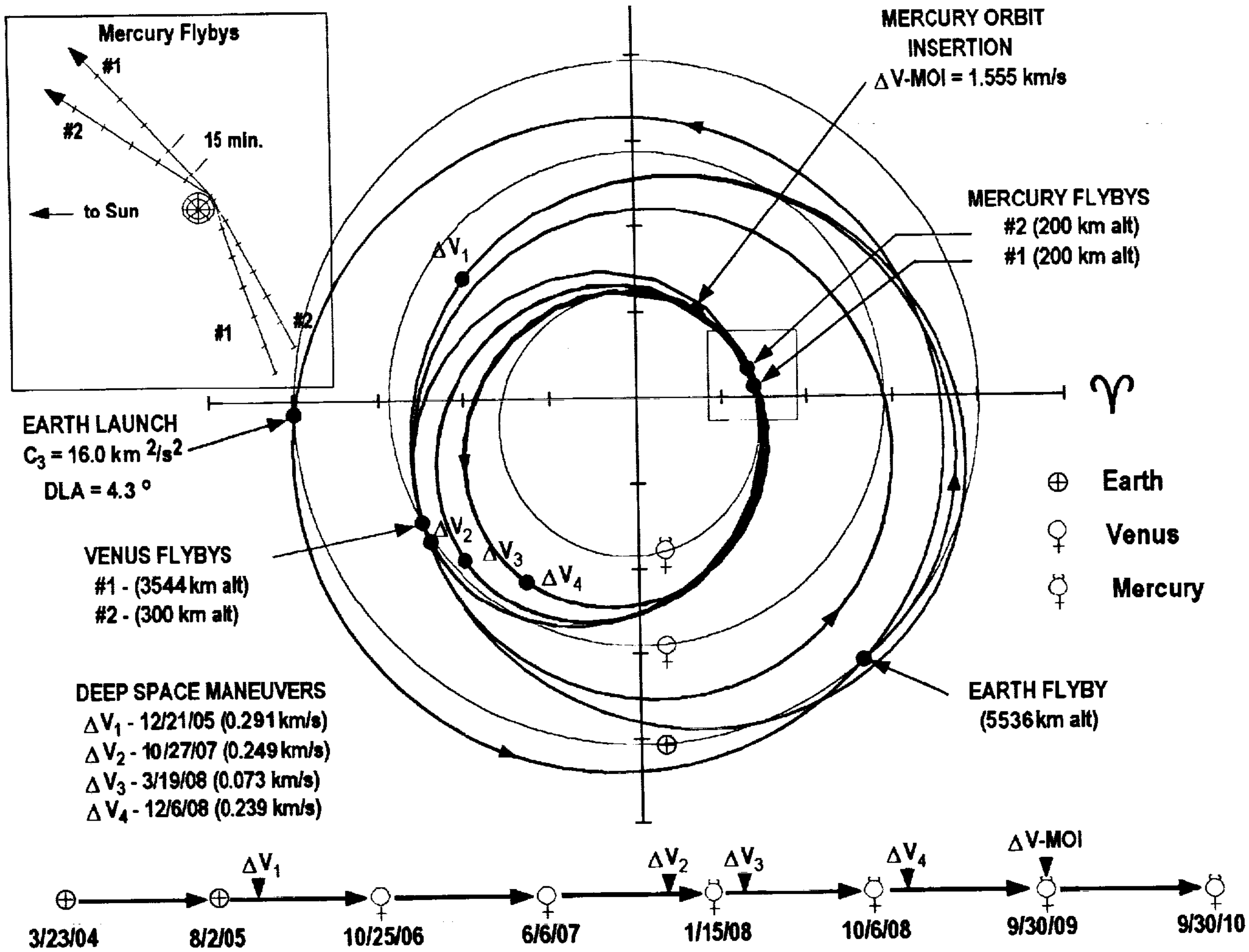


Fig. F-1-1 MESSENGER heliocentric trajectory.

heliocentric-phase mission design solution was verified by programs from Adasoft, Science Applications International Corp., and NASA/ Jet Propulsion Laboratory (JPL).

During the heliocentric phase there are two periods of solar conjunction, where communications are limited for more than 2.5 days while the spacecraft, Earth, and Sun are aligned within 2°. The first solar conjunction spans from three days before to 15 days after the first Venus flyby. This conjunction impacts the planning of the Venus flyby, but because the navigational uncertainties are small and are not critical for this high-altitude flyby, there is low risk in the mission design. The second solar conjunction is from 7 to 42 days after the second DSM. After the burn executes, and prior to the start of the conjunction period, the spacecraft is put into a safe state in preparation for the extended conjunction. During the 35-day conjunction, no time-triggered commands are executed. The spacecraft controls momentum through off-pointing to avoid momentum dumping and awaits commands from the ground.

At Mercury arrival the spacecraft performs an orbit-insertion maneuver to establish a 12-hour, 200-km by 15,193-km-altitude orbit inclined 80° to Mercury's equator (Fig. F-1-2). Mercury obstructs Earth-spacecraft line of sight (Earth occultation) for the final 6 minutes of Mercury orbit insertion (MOI) and for 21 minutes after MOI completion. The 91.5° approach phase angle and near-polar orbit set the initial orbit orientation nearly over the dawn-dusk terminator. The maximum eclipse period during orbital operations is 67 minutes. Given six ΔVs during the 12-month orbit phase, a trajectory integration shows that the descending node rotates from 24.7° anti-sunward to 29.1° anti-sunward, measured from the Mercury perihelion dawn-dusk terminator. The periapsis latitude drifts from 60.0° N to 68.4° N, and orbit inclination varies from 80.0° to 81.4°. There is

Table F-1-3 Mission Design Traceability Matrix

	Mission Design Objectives	Mission Design Requirements	Mission Design Features
CONSTRAINTS	Launch period prior to 9/30/04	30-day minimum launch period concluded by 9/30/04	3/23/04-4/6/04 and 8/2/04-8/16/04 launch periods
	Delta class or smaller launch vehicle	Minimize C_3, declination of launch asymptote (DLA), and post-launch ΔV to deliver science payload with 99.0% probability of command shutdown (PCS)	Use Delta II 7925H-9.5 with C_3=16.0 km²/s², DLA ≤4.3°, 2700 m/s post-launch ΔV, 1,066 kg maximum spacecraft mass with PCS >99.0%
	Observe planetary protection, minimize chance of impact with Venus and Mercury	Limit Venus and Mercury closest approach altitudes to 200 km and 150 km, respectively (3σ)	Venus minimum altitude ≥ 300 km (200 km + 3.3σ), Mercury minimum altitude ≥ 200 km (150 km + 3.2σ)
ENG REQTS	Keep thermal shade toward sun at all times	Inside 0.7 AU, angle between ΔV and plane normal to Sun-line < 11.7°	All ΔVs inside 0.7 AU are < 8.5° from plane normal to Sun-line
	Limit Mercury thermal input to spacecraft	Ensure dawn-dusk orbit and periapsis over shadow area when near Mercury perihelion	Dawn-dusk orbit at true anomaly = 337°; 80° inclination and descending node ~ 25° anti-sunward
	Provide sufficient power for peak spacecraft operational requirement	< 90 minute eclipse at Earth and Mercury	35 minute eclipse at launch, ≤ 67 minute eclipse at Mercury
	Provide early DSN contact after launch for contingency situations	First DSN contact < 120 minutes after launch	First DSN contact 50 minutes after launch
	Minimize effect of ΔV execution errors	Include navigation errors and 1% spherical execution error allowance (1σ)	100 m/s margin after allowance for execution errors
SCIENCE OBJECTIVES	Globally image surface at 250-m resolution	Provide two Mercury solar days at two geometries for stereo image of entire surface, near-polar orbit for full coverage (MDIS)	Orbital phase duration chosen at one Earth year with periapsis altitude controlled to 200-500 km, 80°-inclination orbit
	Determine the structure of Mercury's magnetic field	Minimize periapsis altitude; maximize altitude-range coverage (MAG)	Mercury orbit periapsis altitude from 200-500 km, apoapsis altitude near 15,200 km for 12-hour orbital period
	Simplify orbital mission operations to minimize cost and complexity	Choose orbit with period of 8, 12, or 24 hours	
	Map the elemental and mineralogical composition of Mercury's surface	Maximize time at low altitudes (GRNS, XRS)	
	Measure the libration amplitude and gravitational field structure	Minimize orbital phase thrusting events (RS, MLA)	Orbital inclination 80°; periapsis latitude drifts from 60°N to 68°N; primarily passive momentum management; two orbit-correction ΔVs (six hours apart) every 88 days
		Orbital inclination 80°, latitude of periapsis near 60°N (MLA, RS)	
	Determine the composition of radar-reflective materials at Mercury's poles	Orbital inclination 80°; latitude of periapsis maintained near 60°N (GRNS, MLA, ASCS, EPPS)	
	Characterize exosphere neutrals and accelerated magnetosphere ions	Wide altitude range coverage, visibility of atmosphere at all lighting conditions	Extensive coverage of magnetosphere. Orbit cuts bow shock, magnetopause, and upstream solar wind

one solar conjunction period, lasting six days in November 2009, during the orbit phase. Prior to this conjunction period, as in the heliocentric phase cases, the spacecraft is put into a safe state and awaits commands from the ground.

The Mission Design Traceability Matrix (Table F-1-3) depicts mission design compliance with the mission constraints, engineering requirements, and science objectives. The parameters of the near-polar orbit provide maximum science return when considering thermal, power, communication, and propulsion constraints. The 12.0-hour orbit period enables regular mission operations scheduling and maximizes time available to downlink science data around apoapsis. The first periapsis altitude after MOI is 124 km. This configuration is well within thermal design constraints because the initial orbit is in the dawn-dusk terminator, the sub-periapsis point moves into the night hemisphere, and solar perturbations raise periapsis altitude to 200 km within three weeks. Periapsis altitude continues to rise over the rest of the mission. Every 88 days, one Mercury year, a two-burn sequence is executed

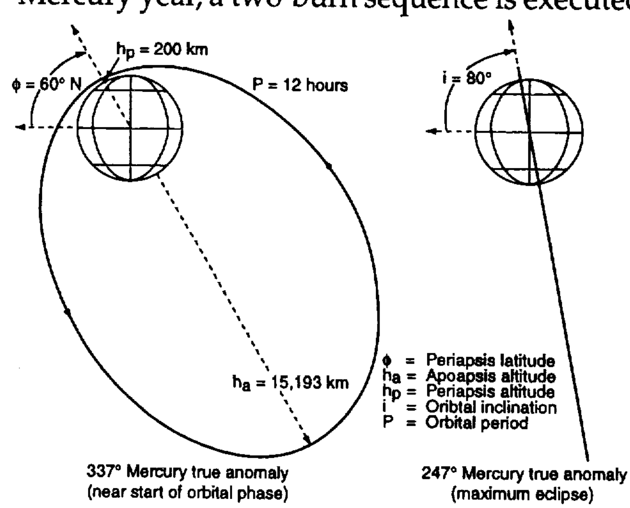


Fig. F-1-2 Orbit at Mercury.

to reduce the periapsis back to 200 km and adjust the orbit period to 12 hours. The periapsis altitudes at the end of the first three Mercury years, prior to the orbit-adjust maneuvers, are 411, 475, and 460 km, respectively. The ΔVs for lowering periapsis altitude and adjusting the orbit period for these maneuvers are 23, 29, and 27 m/s, respectively. After the last maneuver, at the end of the third Mercury year, the orbit is not adjusted further. At the end of the mission, 4.2 Mercury years after MOI, the periapsis altitude is 502 km. To meet navigation and science measurement objectives, ranging is performed for 30 minutes near periapsis and apoapsis every 5-10 orbits.

The ΔV allocation is shown in Table F-1-4. The cleanup of execution errors is calculated at a 99% probability level (ΔV_{99}), under the assumption of 1% spherical maneuver execution errors (1σ). The MOI maneuver includes a 68 m/s finite burn penalty and a periapsis rotation from 63.4° to 60.0° N. Small ΔVs (<<1 m/s) are executed approximately every fourth day during orbital phase to manage spacecraft momentum. The mission is designed so that all ΔVs inside 0.7 AU are within the thermal shade's umbra.

Implementing the MESSENGER mission using solar electric propulsion (SEP) was studied, but rejected. While shorter transit times to Mercury could, in theory, be realized using SEP with Venus gravity assists (Sauer, 1997; Kluever and Abu-Saymeh,1998), SEP presents an extreme set of technical problems. Their impact on the spacecraft design, operations, and reliability results in a far riskier and less robust mission. A recent JPL study (Gershman, 1998) concludes that significant new technology developments beyond those of Deep Space-1 (Williams and Coverstone-Carroll, 1997) are required in SEP thrusters, power processing electronics, propulsion tanks, solar panels, thermal control devices and materials, and high-temperature electronics and batteries. At the current stage of SEP development, conventional propulsion is the only low-risk approach for implementing a Discovery orbiter mission to Mercury.

Table F-1-4 ΔV Allocation

Category		ΔV (m/s)
Deterministic		**2486**
Heliocentric	2407	
Mercury orbit	79	
Statistical		**214**
Navigation (ΔV_{99}) and attitude control	114	
Margin	100	
Total		**2700**

F.1.2 Communications Resources

MESSENGER uses the DSN 34-m and 70-m antennas as the sole communications to the spacecraft. The mission timeline within Fig. F-1-1 shows the major mission events where enhanced DSN coverage is required. Overall usage of DSN is described in Sec. F.2.11. Detailed DSN tracking requirements are listed in Table F-6-1. Fig. G-2-2 relates high-demand events such as planetary flybys, data acquisition, and data downlink to mission phase and communication blackout periods (solar conjunction).

F.1.3 Navigation

A preliminary navigation accuracy analysis has shown that the planned DSN tracking coverage for MESSENGER mission design provides sufficient navigation performance and margin throughout all mission phases. Navigation studies used DSN Doppler and range tracking weighted at 0.5 mm/s and 30 m, respectively, according to the planned DSN schedule. Optical navigation is not needed for the flybys or orbit insertion because inner planet ephemerides are very well known. The navigation strategy for MESSENGER includes rather sparse DSN tracking for quiet cruise periods and additional tracking near critical events such as launch, gravity assist flybys of Earth, Venus, and Mercury, and propulsive maneuvers. This strategy relies on fitting longer arcs (up to 3.5 months) of tracking and characterizing the spacecraft non-gravitational accelerations to achieve acceptable navigation accuracies; this technique was proven in flight on Discovery-class missions such as NEAR and Stardust. Table F-1-5 shows navigation delivery accuracies for various mission events, with a data cut-off eight days before the event and a 1% spherical ΔV execution error (1σ).

The navigation strategy for the orbit about Mercury will include the estimation of a preliminary gravity field for Mercury. Data from the first 59 days of mapping (one rotation of Mercury) will be used to develop a twentieth degree and order model to enable adequate spacecraft predictions. The development of

Table F-1-5 Navigation Accuracies (1σ)

Target Event Uncertainties	B-plane* (km)		Downtrack (km)
Venus gravity-assist flybys	29.4		1.5
Mercury gravity-assist flybys	15.4		2.5
Mercury orbit insertion	10.3		6.0
In-Orbit Uncertainties	**Crosstrack**	**Downtrack**	**Out of plane**
Post Mercury orbit insertion (first ΔV one orbit after MOI)	2	8	1
Mercury orbit (face-on geometry)	4	19	2
Mercury orbit (edge-on geometry)	14	31	6

* The B-plane passes through the center of the target body and is perpendicular to the relative velocity vector.

more comprehensive gravity models and precision orbits for MESSENGER will be the responsibility of the Altimetry and Gravity Investigation of the MESSENGER Science Team.

Mission support services provided through end of mission by JPL will include radiometric data conditioning and validation, orbit determination, ancillary navigation data processing, and precision verification of APL-computed maneuvers. A similar APL-JPL partnership is working well for NEAR.

F.1.4 Risk Mitigation

Three important features of MESSENGER's mission design offer significant risk reduction.

Robust Launch-Window Strategy. MESSENGER has two 15-day launch periods in 2004. The first window opens on March 23 and closes on April 6. A second 15-day window opens four months later on August 2. It is clear that two 15-day windows four months apart are superior to a single 30-day window. A third launch opportunity in August 2005 also exists. MESSENGER's baseline trajectory is nearly the same for the three launch opportunities.

Recovery from Delayed Propulsive Events. It is highly desirable to relax time-criticality of major propulsive events. A variety of causes (e.g., spacecraft safe mode, DSN station unavailability) could force a delay in a scheduled propulsive maneuver. Therefore, it is prudent to assess ΔV costs associated with these delays, as well as to prepare a realizable recovery plan. Preliminary analyses for MESSENGER's first three DSMs showed that delays up to 10 days could be accommodated for a ΔV penalty under 22 m/s. For DSM 4 and the MOI maneuver, execution delays up to 100 days are possible for a ΔV penalty of as much as 70 m/s, which is well within the allocated 100 m/s ΔV margin. However, a delayed MOI maneuver would delay the final arrival date at Mercury by approximately 1.5 years.

Utilization of a Third Mercury Gravity-Assist Maneuver. Adding a third Mercury flyby and another DSM to the baseline trajectory reduces the total ΔV requirement by about 500 m/s, but extends the flight time by 1.47 years. Incorporating this option during the development phase would increase the spacecraft's mass margin to 43%. On the other hand, if the nominal flight plan is retained (i.e., MOI in September 2009), the option for a third Mercury flyby would effectively increase the postlaunch ΔV margin by 500 m/s.

F.2 Spacecraft

F.2.1 System Overview

A ballistic Mercury mission on a Delta vehicle is challenging from a mass, thermal, and fault-protection perspective. These challenges are met with a combination of carefully selected advanced technologies and a design philosophy that values simple, proven techniques. Mass is reduced through an integrated design for the composite structure and a high-performance propulsion system. The very challenging thermal environment at Mercury is addressed through innovative use of materials and by a carefully optimized mission geometry. Reliability is heightened by using maximum heritage from other missions and simplifying the hardware and software wherever possible. This approach produces a design with ample margin in all categories and low technical and cost risk.

Foldout Fig. F-2-1 shows the spacecraft in flight configuration. System level reserves and margins for mass and power are given in the master equipment list in Table F-2-1. Key requirements and margins are listed in Table F-2-2. For the spacecraft electronics, component volume is not a limited system resource and is therefore not listed in the tables. The products, procedures, and the expected end-items of Phases A through D are discussed in Sec. G.3.

MESSENGER is a 3-axis, zero-biased momentum-controlled spacecraft. It has only a single pointing mode during cruise; the thermal

Table F-2-1 Master Equipment List

Equipment List	Qty	Redundancy	Mass (kg) Estimated	Mass (kg) Reserve *	Cruise Power (W) Estimated	Cruise Power (W) Reserve *	Orbit Power (W) Estimated	Orbit Power (W) Reserve *
Imagers (MDIS)	1	Functional	5.5	0.8	0.0	0.0	10.0	1.5
Gamma-Ray Neutron Spectrometer (GRNS)	1	Functional	6.0	0.9	0.0	0.0	4.5	0.7
Magnetometer with boom (MAG)	1	None	3.0	0.5	0.0	0.0	1.0	0.2
Mercury Laser Altimeter (MLA)	1	None	5.0	0.8	0.0	0.0	20.0	3.0
ASCS	1	Functional	2.5	0.4	0.0	0.0	3.0	0.5
Energetic Particle and Plasma Spectrometer (EPPS)	1	None	1.3	0.2	0.0	0.0	1.0	0.2
X-Ray Spectrometer (XRS)	1	Functional	4.0	0.6	0.0	0.0	8.0	1.2
Data Processing Unit (DPU)	2	Full	5.0	0.8	0.0	0.0	18.0	2.7
Instrument Subtotal			**32.3**	**4.8**	**0.0**	**0.0**	**65.5**	**9.8**
Oxidizer tank	1	None	6.0	1.2				
Main fuel tanks	2	None	12.0	2.4				
Helium tank	1	None	7.6	0.4				
Auxiliary fuel tank	1	None	1.6	0.1				
645-N bipropellant thruster	1	None	4.0	0.2				
22-N bipropellant thrusters	4	None	1.6	0.3				
4.4-N monopropellant thrusters	10	Full	2.6	0.1				
Regulators, valves, filters, lines, and misc.	—	Selective	20.8	3.0	4.0	0.2	4.0	0.2
Propulsion Subtotal			**56.2**	**7.7**	**4.0**	**0.2**	**4.0**	**0.2**
Solar panels	2	Functional	17.3	3.3				
Solar array drives	2	Full	3.9	0.2				
Power system electronics	2	Full	16.5	2.5	12.0	1.8	12.0	1.8
Battery	1	Functional	17.6	0.8	13.4	0.7	13.4	0.7
Power Subtotal			**55.3**	**6.8**	**25.4**	**2.5**	**25.4**	**2.5**
Phased-array antenna assemblies	2	Functional	3.4	0.7				
Low-gain and medium-gain antenna assemblies	2	Functional	1.5	0.3				
Transponders	2	Full	6.2	0.3	6.0	0.3	12.0	0.6
RF power amplifiers (15-W distributed, 11-W lumped)	2	Functional	5.2	1.0	45.0	9.0	67.0	13.4
Diplexer, switches, waveguide, and coaxial cable	—	Full	3.0	0.4				
Telecommunication Subtotal			**19.3**	**2.7**	**51.0**	**9.3**	**79.0**	**14.0**
Reaction wheels	4	4 for 3	13.4	0.7	10.0	0.5	10.0	0.5
Star cameras	2	Block	5.3	0.3	8.0	0.4	8.0	0.4
Inertial measurement unit with accelerometers	1	Full	5.6	0.3	23.0	1.2	23.0	1.2
Digital sun sensors and electronics	2	Full	3.1	0.5	2.0	0.1	2.0	0.1
Guidance and Control Subtotal			**27.4**	**1.8**	**43.0**	**2.2**	**43.0**	**2.2**
Integrated electronics module (IEM)	2	Full	10.6	2.1	25.0	5.0	28.8	5.8
Remote interface units	8	Full	0.9	0.2	0.6	0.1	0.6	0.1
Terminal board for G&C-component fault isolation	1	Full	0.9	0.2				
IEM Subtotal			**12.4**	**2.5**	**25.6**	**5.1**	**29.4**	**5.9**
Thermal Subtotal (Shade, Blankets, Heaters)	—	Full	**24.1**	**4.8**	**64.0**	**12.8**	**55.6**	**11.1**
Structure Subtotal	—	None	**63.5**	**12.7**				
Harness	—	Selective	20.0	4.0				
Dry Mass and Power Totals			**310.5**	**47.8**	**216.2**	**32.1**	**301.9**	**43.5**
System mass and power capabilities			430.0		337.0		419.0	
Required propellant (2600 m/s @ 310.5 kg dry mass)			575.0					
Allocated propellant (2700 m/s @ 430 kg dry mass)			636.0					
Dry Mass and Power Reserves				**15.4%**		**14.8%**		**14.4%**
Dry Mass and Power Margins			**20.0%**		**35.7%**		**21.3%**	
Propellant Reserves				**10.6%**				

* Reserves of 20% added for NEW designs, 15% for MODIFIED designs, 5% for EXISTING designs

shade is pointed at the Sun and the rotation axis of the solar panels is aligned in the ecliptic plane. The direction of the bipropellant thruster is oriented normal to the spacecraft-Sun line to accommodate maneuvers in this attitude. Communication is maintained at all times in this fixed attitude by medium-gain and high-gain antenna clusters on the forward and aft sides of the spacecraft. During on-orbit operations, rotation about the Sun line is required to accommodate instrument viewing, since the instrument-view direction is normal to the spacecraft-Sun line. Although thermal requirements are always met, high-rate downlink communications are not maintained during the rotation periods. During the data downlink periods, generally scheduled when the spacecraft is away from periapsis, the

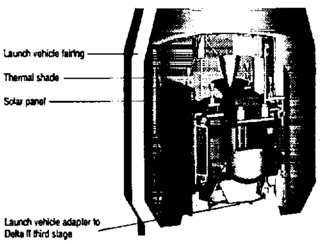
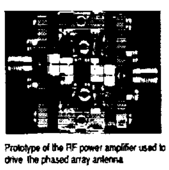


Fig. F-2-30 Launch configuration has ample clearances.



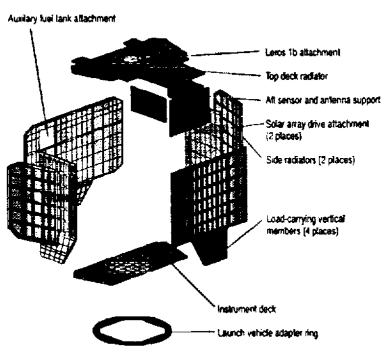


Fig. F-2-7 The simple design of the spacecraft primary structure is very light and low cost.

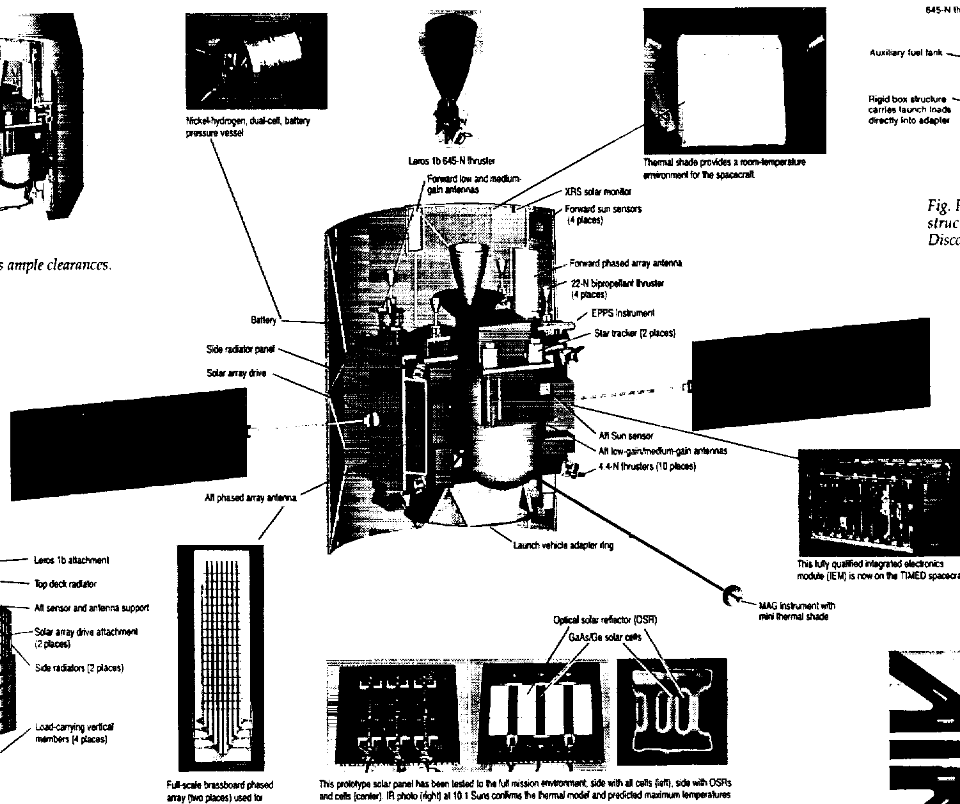


Fig. F-2-1 Spacecraft in flight configuration. Detail photos highlight the mission-critical components.

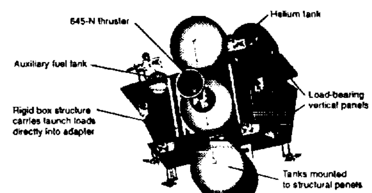


Fig. F-2-8 The light weight of the integrated structure and propulsion system enables a Discovery-class Mercury orbiter.

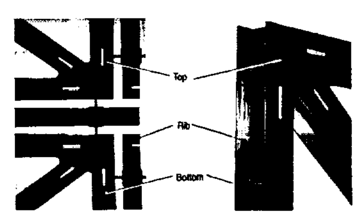


Fig. F-2-10 Snapsat™ construction cuts pieces with slots and tabs from simple flat sheets (left) and assembles them to form very rigid and light panels (right).

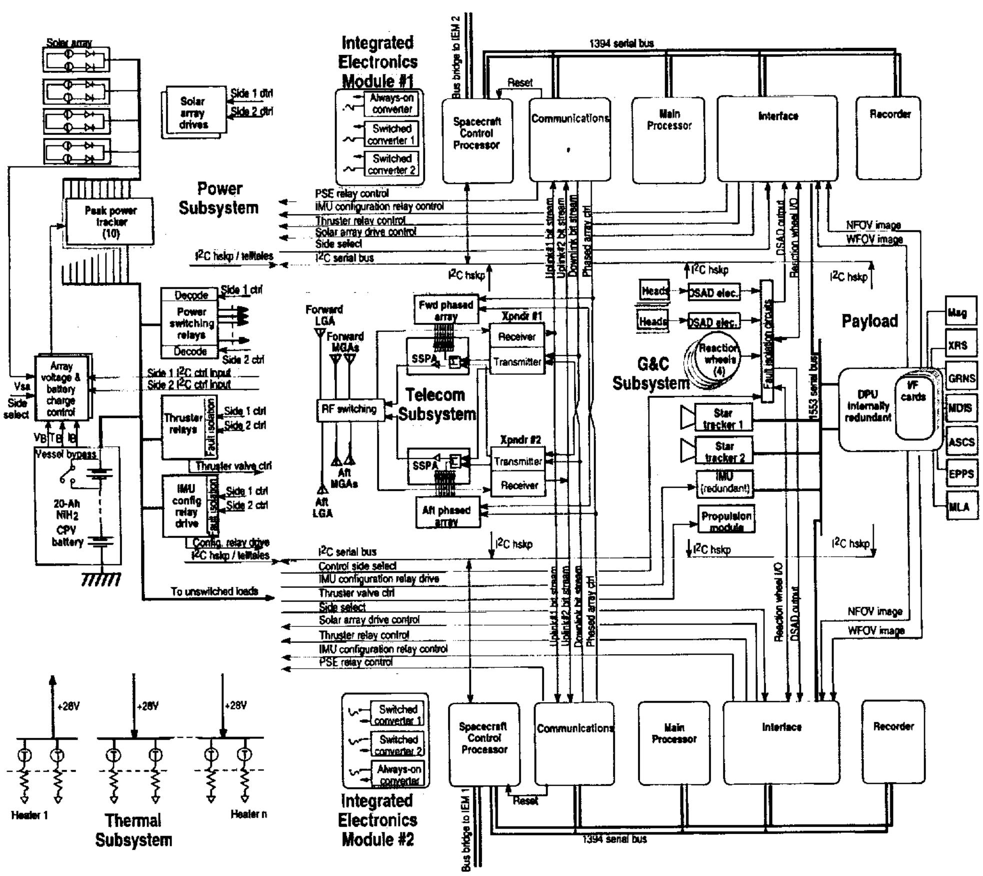


Fig. F-2-2 Block diagram of the highly-redundant MESSENGER system. The science payload is described in Sec. D.2 and Sec. F.3.

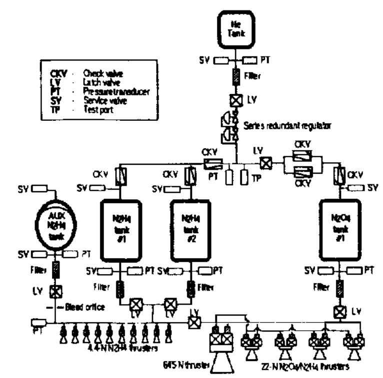


Fig. F-2-12 The dual-mode propulsion system minimizes mass while maintaining a high I_{sp}.

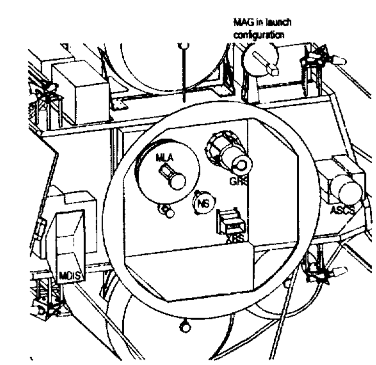


Fig. F-2-9 Most of the instruments are hard-mounted to the bottom deck with co-aligned fields of view. The launch-vehicle adapter provides thermal shadowing for MLA, GRNS/GRS, GRNS/NS, and XRS.

Table F-2-2 Requirements, Performance, and Margins

System		Requirement	Calculated Performance	Margin
Mass		430 kg maximum dry mass	310 kg	15.4% reserve, 20.0% margin
Propellant		575 kg (2600 m/s)	636 kg (2700 m/s)	10.6% reserve (100 m/s)
Power	- solar array, cruise - solar array, orbit - battery	216 W cruise phase 302 W orbit phase < 60% max discharge	337 W cruise phase 419 W orbit phase < 46% worst case	14.8% reserve, 35.7% margin 14.4% reserve, 21.3% margin 23%
Attitude system	- control - knowledge - maneuver - jitter	0.1° (1σ) pointing and control 350 μrad (1σ) 0.005 °/s² acceleration, 0.1°/s slew rate 25 μrad in 0.1 s (1σ)	500 μrad (1σ) 250 μrad (1σ) 0.006 °/s², 0.3 °/s 15 μrad in 0.1 s (1σ)	Factor of 2.5 40% 20% acceleration, factor of 3 slew 66%
Thermal (orbit avg.)	- electronics - instruments - solar arrays - battery	-29 to 60°C operational, < 5°C/min -20 to 25°C for in-cal, < 5°C/min 150°C operational, 180°C survival -10 to 25°C	-10 to 30°C, < 2°C/min -14 to 8°C, < 2°C/min 200°C operational, 250°C survival -5 to 19°C	19°C cold, 30°C hot, 3°C/min In calibration 99.5% of time at Mercury 50°C operational, 70°C survival 5°C cold, 6°C hot
Telemetry downlink		5.5 Mbytes/day, orbit phase	7.3 Mbytes/day, orbit phase	33% (with 3 dB link margin)
Recorders		4.22 Gbits	Two redundant 8-Gbit SSRs	Factor of 2.5
Flight software		2 Mongoose CPUs, 4 Mb memory	< 40% of CPU and memory	Factor of 2.5
1394 data bus		10 MHz with 25% retransmit overhead	50 MHz	Factor of 5
1553 data bus		194 kHz with 100% retransmit overhead	1.0 MHz	Factor of 5
Radiation tolerance		20 krad total dose behind 2 mm aluminum	Worst-case 13 krad total dose	53%

spacecraft roll axis is controlled so that one of the phased-array antennas can acquire Earth.

The system block diagram, detailing all the subsystem interfaces, is shown in foldout Fig. F-2-2. The subsystem interfaces are designed to limit the amount of time-sensitive, high-speed, or noise-sensitive data flowing across subsystem boundaries. In particular, the spacecraft interfaces only to the instrument Data Processing Unit (DPU) for access to the entire instrument suite. This method of clean-interface partitioning allows parallel subsystem development and minimizes the probability that a design change impacts more than a single subsystem. The majority of subsystem interfaces are over a MIL-STD 1553 serial data bus, compatible with many off-the-shelf standard industry components.

Since the Phase-One proposal there have been five design changes: (1) the power amplifiers used with the phased array antennas have been increased from 11 W to 15 W to add downlink data margin during the orbital phase, (2) the solar array area has been increased by 10% to accommodate the larger power amplifiers, (3) the locations of the forward and aft low-gain and medium-gain antenna assemblies have been changed to face the Sun and anti-Sun directions to improve the telecommunication margins at the maximum Earth distance, (4) the Ithaco reaction wheels have been replaced by longer-life Litton/Teldix wheels, and (5) a second Deep Space Network (DSN) contact has been added weekly during cruise phase, replacing the beacon-mode contacts, for gathering additional navigation and spacecraft health monitoring data.

Other highlights of the design are as follows:

Structure/Propulsion. A composite structure using the snap-together construction technique (Snapsat™) pioneered by Composite Optics, Inc. (COI), is integrated with a dual-mode propulsion system to achieve a lightweight spacecraft. The efficient, dual-mode propulsion system minimizes the number of tanks and associated plumbing, while maintaining a high average specific impulse (I_{sp}).

Thermal. A passive thermal design, based on innovative use of conventional materials, enables the use of standard space-grade electronic parts. Maintaining a fixed, opaque ceramic-cloth thermal shade between the spacecraft and the Sun creates a benign thermal environment for the spacecraft. The shade requires no deployment. It allows the spacecraft to be tilted normal to the Sun line by ± 15° in yaw and ± 12.7° in pitch without exposing the spacecraft body to direct solar illumination. The thermal design also protects the spacecraft when it is near the hot Mercury surface.

Dual-sided solar panels project beyond the thermal shade and are rotatable. On-board software controls the solar aspect to balance panel temperature and power generation. One side of the panels is fully packed with GaAs/Ge cells for power production during the outer-cruise phase. The opposite side is packed with 70% optical solar reflectors (OSRs) and 30% GaAs/Ge cells and is used for the inner-cruise and orbital phases. For the mixed cell/OSR side, heat from the cells is transferred through the panel's substrate to the OSRs where it is radiated. This design reduces the temperature by 150°C over a fully packed array under full sun at 0.3 AU (Fig. F-2-3). This innovation, used on Helios and on a classified spacecraft by our team, produces sufficient power at a solar incidence angle of 62° while limiting the maximum steady-state temperature of the array to 150°C at 0.3 AU. The panels are qualified to operate steady state at 200°C, providing 50°C margin, or alternately 16° of rotation angle margin (with a 48% increase in power production) at 0.3 AU.

Throughout the mission, the spacecraft power and solar panel thermal requirements are met within a range of solar incidence angles. The maximum and minimum allowable solar incidence angles vary with the Sun distance (Fig. F-2-4). At any given time, the solar incidence angle is chosen within the operational design range to provide comfortable power margin, temperature margin, and contingency margin. Nominally, the on-board software sets solar incidence angle as a function of the minimum required power and the maximum panel temperature. As the spacecraft executes maneuvers for instrument viewing, the on-board software autonomously rotates the panels as necessary to maintain the desired solar incidence angle at the particular Sun distance. The contingency margin allows the panels to remain fixed at a constant solar incidence angle for a minimum period (7 days) and still remain within the operational design range.

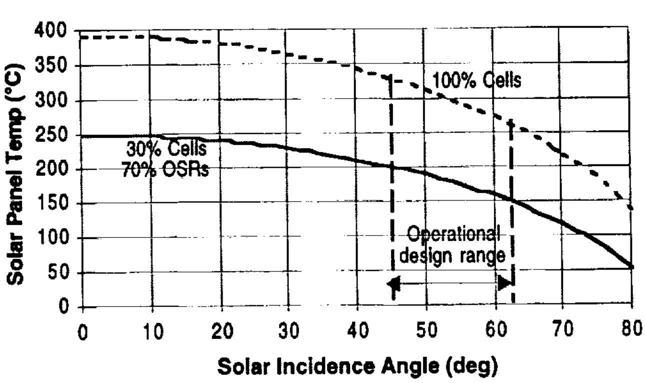


Fig. F-2-3 Solar panel temperature at 0.3 AU. OSRs reduce temperatures and increase operational range.

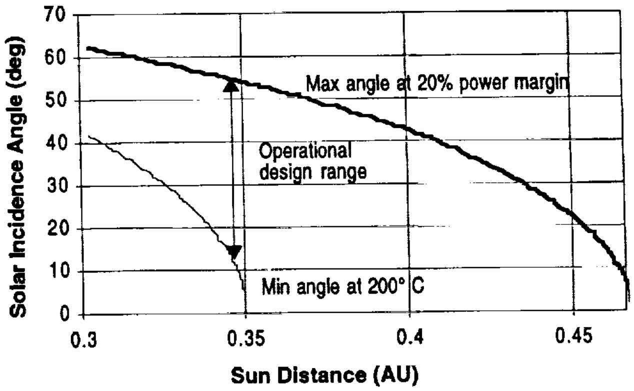


Fig. F-2-4 Solar panel operational-design range over the orbit phase. Large temperature and power margins are available.

Solar panel transient-temperature spikes, lasting under 25 minutes, occur during hot-planet crossings of the subsolar point at 0.4 AU (Fig. F-2-5). The slope of the temperature rise exiting eclipse is 33°C/min, which is typical in geosynchronous satellite design. The baseline design turns the panels edge-on to the Sun during the hot-planet crossings to limit the maximum temperature to 155°C. A trade study will be done in Phase A/B to investigate the feasibility of taking advantage of the robust panel design and simplify the flight-application software, fault-protection software, and test program by not rotating the panels over the hot-planet crossings at the expense of increasing the peak panel temperature to 250°C.

Prototype MESSENGER solar panels (foldout Fig. F-2-1) were recently thermal cycled at APL and illuminated at intensities appropriate for

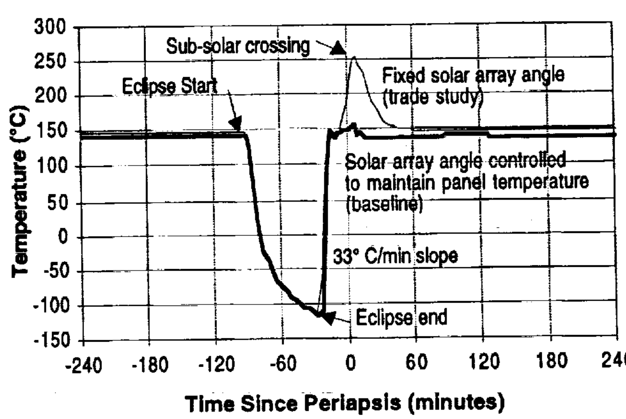


Fig. F-2-5 Solar array temperature over the worst-case, noon-midnight orbit. Baseline design maintains panel temperatures while over Mercury's hot surface.

Mercury using solar simulators under vacuum at NASA's John H. Glenn Research Center at Lewis Field. These tests validated many parts of the thermal model that depend on the optical properties of the panel, measured the thermal conduction properties of the panel, and demonstrated panel survivability at the worst-case, normal-incidence conditions. No failures were experienced (Sec. F.2.5).

Power. The power system uses a fault-tolerant peak-power tracking architecture, allowing a small solar array to handle the wide temperature range experienced between 0.3 AU and 1.1 AU. This system is employed on the APL Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) spacecraft. The battery uses available common-pressure-vessel technology, with two cells per vessel. It is designed to function with the failure of one vessel. The power system maintains in excess of 20% power margin over the entire mission with a maximum battery discharge of 46%.

Communications. An X-band coherent communications system incorporates redundant Motorola Small Deep-Space Transponders, two lightweight phased arrays for downlink, and medium-gain and low-gain antennas for uplink and downlink communications. The antennas are chosen to enable high-rate and safe-mode communications over the entire mission while maintaining the thermal shade pointing at the Sun. The electronically steerable phased arrays (foldout Fig. F-2-1) are used instead of a deployed, gimbaled high-gain antenna. They are simple, passive waveguide antennas fed by power amplifiers that are safely located inside the spacecraft body.

Electronics. Redundant integrated electronics modules (IEMs) incorporate all of the spacecraft avionics and software, including command and data handling and attitude processing. This approach, combining all of the digital spacecraft processing into a single unit, reduces box and harness mass. Each of the redundant IEMs contains two 32-bit Mongoose processors. The CPU and memory within both computers are budgeted at <40% of the machine resources. Communications within the IEM and between the redundant IEMs are carried over a high-speed, fault-tolerant, redundant IEEE-1394 serial bus. The instrument timing, commands, and low-rate telemetry collection are over a redundant, fault-tolerant MIL-STD 1553 serial data bus. The 1553 bus has the following attractive features: a reduction of interconnecting cables, built-in redundancy and cross-strapping, a highly fault-tolerant transformer-coupled interface, a common-data architecture for sharing information between subsystems, and a flexible software-defined interface. Both the IEEE-1394 and MIL-STD 1553 interfaces are budgeted at <20% of the available bandwidth.

Command and Data Handling. The command and data-handling system implements Consultative Committee for Space Data Systems (CCSDS) compliant uplink and downlink protocols. Command memory is sized to allow on-orbit storage of two weeks of orbital-phase operations. Data handling supports simultaneous telemetry collection from all of the instruments at their maximum data bandwidth, eliminating the need for data-collection resource planning.

Attitude Control. Attitude control is provided by a low-risk reaction-wheel attitude control system, which is very similar to the set of the hardware successfully used on the NEAR spacecraft. Pointing control of the solar panels and the phased array antennas are computed with an on-board guidance algorithm, similar to the one implemented on NEAR. Fault protection algorithms, implemented in redundant computers and based on redundant solar detectors and temperature sensors, override any attitude maneuver that compromises the thermal shade effectiveness or solar array thermal limits.

Trade Studies. The overall design was iterated several times, and many system and subsystem trade studies were evaluated. The key criteria in the design selection process are reliability and the reduction of technical and cost risk. Five examples of trade studies completed are: (1) a chemical propulsion system is selected over a solar-electric propulsion system that has shorter flight times, but a higher implementation risk, (2) a dual-sided solar array is chosen over a lighter, but hotter, single-sided array, (3) forward and aft phased-array antennas are selected over a gimbaled high-gain antenna with higher downlink potential, but lower reliability, (4) a linearly-polarized phased-array antenna is chosen over a circularly-polarized array with higher performance, but a lower technology readiness levels (TRL), and (5) an X-band communications system is chosen over a higher-performance Ka-band system that has higher cost and complexity. Trade studies, simulations, and tests to be completed during phase A/B are detailed within the subsystem sections. Design drivers, derived from the mission requirements, are shown in Table F-2-3.

Redundancy. Component-level redundancy is shown in Table F-2-1. The system-level redundancy philosophy is that all spacecraft-critical components that have a credible failure mode are block redundant or degrade gracefully. With the exception of the bipropellant thrusters, this philosophy is achieved. The other components listed as single-point failures — the structure, the propulsion tanks, and the propellant lines — do not have credible failure modes. The bipropellant thrusters are single-point failures, as the impact of adding redundancy to the system design (mass, complexity, cost) outweighs their probability of failure.

Heritage. Component and subsystem heritage and their TRLs are illustrated in Table F-2-4. The TRLs listed reflect the technology maturity, not necessarily the existence of previously-designed hardware. The design philosophy is to use off-the-shelf items without modification where possible. This approach reduces cost uncertainty, performance uncertainty, and overall implementation risk. Off-the-shelf components include most of the propulsion system components, battery, transponders, reaction wheels, star trackers, solar array drives, and inertial measurement unit (IMU). Other components are modified because of the unique MESSENGER environment. Examples of modified components are the Sun sensors and the power system electronics. Finally, some new design is necessary. New designs can either use existing technologies or require the development of new technologies. New technologies are incorporated only when necessary and when fallback plans exist.

Table F-2-3 Spacecraft Design Drivers

Item	Design Driver
Solar array	Orbit-phase power at 0.47 AU
Battery	Eclipse (67 min) during orbit phase
Recorder	Data volume during flybys
RF power amplifier	Orbit-phase data volume
Reaction wheel	Orbit-phase momentum storage, lifetime
IMU	Science pointing stability, lifetime
Data processing	Attitude control, data compression, and autonomy

Subsystem heritage is based on a number of flight-proven programs. In all cases, each subsystem architecture is evaluated for compatibility with MESSENGER's environmental and lifetime requirements. The propulsion system, telecommunication, and attitude control system architectures are based on NEAR; the power system architecture is based on TIMED; the integrated electronics module architecture is significantly upgraded from that on TIMED; the structure, while new, uses the same construction technique as Fast On-Orbit Recording of Transient Events (FORTÉ); and the thermal design, while new, utilizes materials flight proven on Helios, Mariner 10, and the Space Shuttle.

Margins. Instrument and spacecraft resources and the allocation of system-level margins are managed by the Mission System Engineer, Project Manager, and Principal Investigator (Sec. G.2.3). Managing the margins at the system level, with no pre-approved growth allocation, allows an optimum use of resources and enables a comprehensive risk-management program. System margins are tracked and presented at the weekly status meeting (Sec. G.2). The goals for mass and power resources are that total allowable growth (reserves plus margins) should be at least 35% at start of pre-Phase A, 25% at spacecraft Conceptual Design Review (CoDR), 20% at spacecraft Preliminary Design Review (PDR), and 10% at spacecraft Critical Design Review (CDR). Not meeting these goals may trigger descope options.

An innovative approach is used for commercial procurements to increase design margin. Rather than selecting the lowest-cost item that meets the minimum-performance requirement, commercial component procurements are evaluated to determine if extra performance margin can be purchased at a reasonable cost. The additional performance margin in one component can be used to offset a performance deficiency in another component, reducing the overall life-cycle cost, particularly when a deficiency is discovered late in the development cycle or while in-orbit. For the NEAR mission,

Table F-2-4 Component and Subsytem Heritage List

Equipment List	Manufacturer	TRL*		Heritage	Sparing
Oxidizer and main fuel tanks	PSI	5	N	New titanium tank design	Qulaified spare
Helium tank	PSI	9	E	Flown on A2100	Qualified spare
Auxiliary fuel tank	PSI	9	E	Flown on IUE	Qualified spare
645-N bipropellant thruster	Royal Ordnance	9	E	Flown on A2100	Long-lead items
22-N bipropellant thrusters	Royal Ordnance	6	N	New design, prototype built and tested for Lockheed Martin	Qualified spare
4.4-N monopropellant thrusters	Primex	9	E	Flown on NEAR, ACE	At manufacturer
Filters	Puroflow, Inc.	9	E	Flown on NEAR, Clementine	At manufacturer
Regulators, valves, transducers	Various	9	E	Standard hardware flown on NEAR and many other spacecraft	Qualified spares
Propulsion Subsystem	**Aerojet**	**7**		**NEAR dual-mode system with new tank, thruster design**	
Solar panels	TECSTAR	6	N	New design using standard OSRs and cells; demo tested by APL	Field repair
Solar array drives	Moog (Schaeffer Mag.)	9	E	Flown on UARS, Clementine	At manufacturer
Power system electronics	APL	7	M	TIMED design with minor changes for mass improvements	Qualified boards
Battery	Eagle Picher	9	E	Flown on MGS	Qualified spare
Power Subsystem	**APL**	**7**		**TIMED peak power tracker system with minor changes**	
Phased-array antenna assemblies	APL	8	N	Working brassboard developed; technology flown on Radarsat	Qualified spare
Low-gain and medium-gain antennas	APL	8	N	New design using established techniques; technology flown often	Qualified spare
Transponders	Motorola	9	E	Flown on Deep Space-1 (DS-1)	At manufacturer
RF power amplifiers	APL	8	N	New design; devices flown on Mars Climate Orbiter	Qualified boards
Diplexer, switches, and coaxial cable	Various	9	E	Standard hardware flown on NEAR and many other spacecraft	Qualified spares
Telecommunication Subsystem	**APL**	**8**		**System design similar to NEAR with new antenna design**	
Reaction wheels	Litton/Teldix	9	E	Flown on ROSAT, ISO, Beppo-SAX	At manufacturer
Star trackers	Ball Aerospace	9	E	Flown on NEAR, ACE, and many other spacecraft	At manufacturer
Inertial measurement unit (IMU)	Litton	9	E	Flown on NEAR, Cassini	At manufacturer
Digital sun sensors and electronics	Adcole	7	M	Modified sensors flown on NEAR, MSX, ACE	At manufacturer
Guidance and Control Subsystem	**APL**	**7**		**NEAR design with longer-life reaction wheels**	
Integrated electronics modules (IEM)	APL	6	N	New design based on TIMED w/ mass & reliabiity upgrades	Qualified boards
Remote interface units	APL	6	N	New design based on TIMED w/mass upgrade	Qualified spare
Terminal board for G&C-fault isolation	APL	7	M	Similar unit flown on NEAR	Field repair
IEM Subsystem	**APL**	**6**		**TIMED design w/ mass & reliablity upgrades**	
Thermal Subsystem	**APL**	**7**	**N**	**Standard materials used on Helios, Mariner 10, Shuttle**	**Field repair**
Structure Subsystem	**COI**	**7**	**N**	**New design based on Snapsat™ (FORTE)**	**Field repair**
Harness	**APL**	**8**	**N**	**New design based on NEAR, ACE**	**Field repair**

* N is for NEW designs, M is for MODIFIED designs, E is for EXISTING designs

extra margin in the telecommunication system enabled solar panels with suspect cell-to-cell interconnects to be accepted as manufactured and not compromise the launch date when discovered late in the integration phase. Margin in the telecommunication link allowed the cruise phase attitude profile to be modified to avoid extreme temperature cycles on the solar panels.

Risk Management. A system-level approach to risk management is a key element of the design process. Realistic fallback options are planned wherever risk is unavoidable. The spacecraft-level risk management plan and risk assessment chart are shown in Table G-4-1 and Fig. G-4-1. The principal risk is mass growth for most items. The total spacecraft mass margin is sufficient to cover the risk in these items.

Through the risk-reduction plan, technology risks are brought to a TRL of 6 or higher before spacecraft PDR. A decision to use a fallback option is made by the PI at the time that a milestone is not accomplished or at any time when the development is in jeopardy. Project-level risk-mitigation activities include: (1) breadboard and flight-like engineering models are developed for new designs, (2) all boxes pass environmental tests, at higher levels than experienced at system test, before delivery to spacecraft integration (Sec. F.5), (3) all inter-subsystem interfaces are tested with engineering models or breadboards prior to the start of flight fabrication, (4) engineering models of all purchased components are brought to APL for interface testing with the breadboard IEM prior to IEM flight-fabrication, (5) boxes are integrated and delivered to the spacecraft as subsystems, allowing performance testing to be done in parallel at subsystem level, and (6) all subcontracted items and inter-subsystem interfaces have interface control documents.

Spares. A well-planned and consistent sparing philosophy minimizes down time or ensures rapid repair in the event of failures during testing. A list of planned spares is shown in Table F-2-4. All off-the-shelf subcontracted units in production, which include the star trackers, IMU, reaction wheels, sun sensors, solar array drives, and transponders, have spare components at the manufacturer. A failure in any of these items would result in the unit being shipped back to the contractor for rapid repair and requalification. For these components, environmental requalification, both vibration and thermal cycling, is repeated at box levels (Sec. F.5). The solar panels, structure, and propulsion system are subcontracted items that can be repaired in the field by the manufacturer. Throughout integration, the propulsion tanks and thrusters have red-tag protective covers installed to reduce the chance of damage. For the battery, antennas, and propulsion tanks, fully-qualified spares are planned. All in-house electrical subsystems, which include the IEM, power system electronics, and power amplifiers, are spared and environmentally-qualified at the board and mechanical-assembly level. A failure in one of these items would result in the unit being returned to the APL fabrication facility for replacement of the failed board and a box-level requalification.

Testability. Ensuring reliable operation requires extensive testing. Designing for testability helps reduce MESSENGER costs. The thermal shade and side radiator panels are easily removed to allow access to all components, enhancing system testability. Separate packaging of most redundant spacecraft components allows system-level testing to proceed in the event of a component failure. Prudent interface partitioning, the use of standard interfaces, and early interface testing minimizes the risk of interface difficulties during integration.

Reliability. Historically, a leading cause of on-orbit failures is from the mechanical stress induced by thermal cycling. Fortunately, MESSENGER experiences only ~ 200 eclipse periods during orbital operations (less than a low-Earth orbiter experiences in three weeks). In addition, the thermal shade minimizes the thermal effects of the changing solar distance. These conditions yield a favorable spacecraft temperature profile, lowering the risk associated with a 6.5-year mission (Fig. F-2-6).

The system is designed for robustness by limiting deployables and moving parts. All devices with a limited lifetime, i.e., array drives and reaction wheels, are carefully selected to exceed the maximum 8-year lifetime

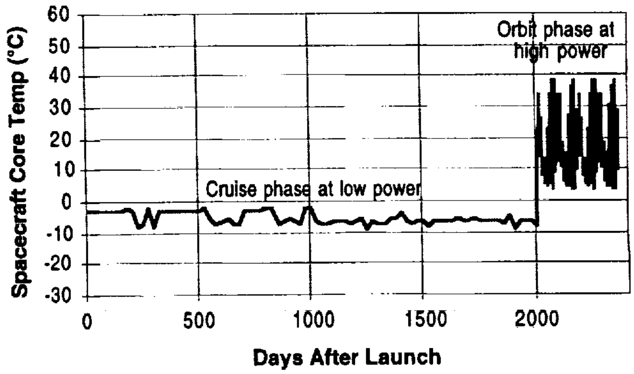


Fig. F-2-6 The limited number of thermal cycles enhances system reliability.

requirement. Each Moog (Schaeffer Magnetics) Type II array drive has redundant electronics and windings and an 8-year probability of success of 0.997. These drives have never suffered a mechanical failure in orbit. The Litton IMU contains no life-limiting items. It provides complete redundancy, including four hemispherical resonant gyroscopes (HRGs), four accelerometers, two sensor electronics modules, and two power supplies. The combination of a fault-tolerant design, the ultra-high reliability of the HRG (with no rotating parts or bearings), and the use of high-reliability electronics enables the unit to operate continuously over the mission with an calculated reliability of 0.998. During normal operations, one of the four gyroscopes is unpowered to enhance its reliability. Four Litton/Teldix RSI-4 reaction wheels are used in a configuration where any three can be used to provide 3-axis attitude control. Baseline planning is that all four wheels will be operational during the entire mission. This not only increases command response capability, it simplifies momentum management and extends wheel expected lifetime. These wheels have never suffered a bearing failure in flight, with over 500 wheels in orbit. The calculated reliability for at least three wheels working at the end of the mission is 0.996.

F.2.2 Structure/Propulsion System

The integrated structure/propulsion approach was developed jointly by team members GenCorp Aerojet, COI, and APL. Shown in foldout Figs. F-2-7 and F-2-8, the integrated structure utilizes two large vertical panels to support the two large fuel tanks, the helium tank, and the auxiliary fuel tank. A third internal vertical panel supports the heavier oxidizer tank and the plumbing hardware. A fourth vertical panel, symmetric with the third, completes a rigid, yet very light center column. The loads from this column flow directly into a circular aluminum adapter ring, compatible with the Delta II interface. This adapter is a 6061-T651 aluminum, machined flange that is bonded and bolted to the aft ends of the four vertical panels making up the center column.

A three-piece composite-sandwich bottom-deck panel adds stiffness and packaging area for the instruments (foldout Fig. F-2-9), while a single top deck panel mounts the large thruster, small thrusters, and battery. This deck also acts as a radiator. Two side radiator panels complete the box structure and add shear stiffness. The extremely short, direct load paths in this stiff-box arrangement result in a low primary structure mass. The compact structure (1.62 m wide x 1.65 m deep x 1.32 m tall) provides sufficient panel and deck area for all instruments and electrical components.

The thermal shade is supported by a welded 3Al-2.5V titanium-tube assembly. The assembly supports four sun sensors, a solar-flux monitor, the forward phased-array antenna, and the forward medium-gain and low-gain assembly.

Deployment mechanisms are limited to the solar array and the magnetometer. The solar array deployment mechanism is similar to the TIMED design. During launch, the solar arrays are supported using a ball-and-socket and two 'V'-flexure joints per wing. A pyrotechnic-release mechanism preloads each panel against the fittings. Two hinge mechanisms per wing, each with a torsion spring and a torsion damper, deploy the panels. The 3.6-m magnetometer boom is composed of a two-piece, two-hinge design. Both the root hinge and the mid-length hinge are lightweight versions of the Polar Beacon Experiment and Auroral Research (Polar BEAR) helix-antenna hinge. The pyrotechnic cable cutter release mechanism preloads the boom against the spacecraft prior to deployment.

The structure/propulsion unit will be collaboratively fabricated and integrated by team members Aerojet and COI, under subcontracts to APL. Its stiff, lightweight properties result from a deliberate effort to optimize launch load paths. All tanks are supported by brackets mounted to the vertical panels. Under thrust, tank loads and deck loads are reacted into the vertical panels and carried directly into the adapter ring. With the exception of the adapter ring, which is aluminum, the structure is made of graphite-cyanate-ester (GrCE) composite. APL has flown this material in the NEAR high-gain antenna, and COI has extensive experience with this material in many lightweight, low-cost spacecraft structural sandwich applications, including the Lockheed Martin A2100 satellites.

The structure readily lends itself to COI's Snapsat™ technique of using flat stock to create isogrid and orthogrid panels, composed of opposing face skins with discrete internal ribs (foldout Fig. F-2-10). The face skins are relieved in areas where structure is not required, leaving an 'T' flange as a cross section. Rib design and spacing are customized to react to specific loads. Egg-crating and mortis-tenon joining techniques are used to assemble flat stock to the panels and the panels into the box structure. This approach minimizes cost by eliminating molded details. It is self-tooling and uses computer-aided manufacturing software to verify the design and turn it into manufacturing databases. The composite design uses Fiberite M55/954-3 GrCE material in a pseudoisotropic lay-up. All details in the structure as well as the attachment to the adapter ring are bonded using the high-strength space-qualified adhesive Hysol EA9394.

A NASTRAN™ finite element analysis (Fig. F-2-11) of the spacecraft produced first-mode frequencies of 16 Hz lateral, 54 Hz thrust, meeting the Delta II minimum stiffness requirements (15 Hz lateral, 35 Hz thrust). This stiffness, combined with ample launch vehicle static-envelope clearance, provides sufficient launch vehicle dynamic-envelope margin. A NASTRAN™ static stress analysis calculated maximum stresses of 259 MPa, well below the 411 MPa ultimate tensile strength of the GrCE layup.

The propulsion system is mounted directly to the structure. The propulsion system schematic is shown in foldout Fig. F-2-12. The main thruster is a 645-N, 317-s I_{sp} Leros-1b bipropellant unit developed for the A2100 satellite family (foldout Fig. F-2-1). Four 22-N,

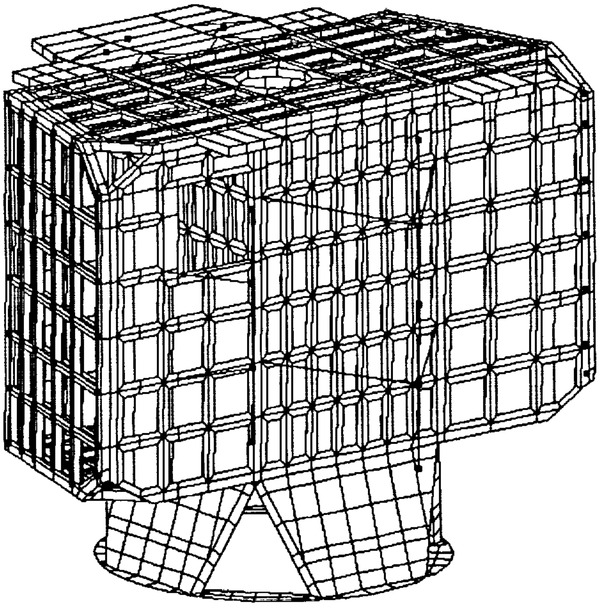


Fig. F-2-11 A finite element model, with thermal shade and solar panels removed for clarity, was used for the launch-loading analysis.

290-s I_{sp} bipropellant thrusters provide steering forces during main thruster burns and primary propulsion for most of the smaller ΔV maneuvers. Ten 4-N, 220-s I_{sp} monopropellant thrusters are arranged in two double-canted sets of four for attitude control, plus two for settling. They provide redundant three-axis attitude control, pure-couple momentum-dumping torques, propellant settling forces, and fine ΔV control in all three axes. A state-of-the-art, regulated dual-mode system, it has been designed to provide the mission required 2700 m/s using the highest performance, lightest weight components and technology presently available.

The performance is optimized by allocating over 95% of the propellants for bipropellant use, and by minimizing the tank mass. Tank mass and cost are minimized through an innovative application of a very small auxiliary fuel tank. Adding this small fuel tank enables the large fuel and oxidizer tanks to become much lighter and less expensive by allowing use of in-line trap propellant management devices and vortex baffles in place of diaphragms. Small, 2 m/s monopropellant settling burns use the auxiliary fuel tank, which has an elastomeric diaphragm, in blowdown mode prior to each bipropellant burn to settle the propellant at the tank outlets. The auxiliary fuel tank supports up to 25 m/s of maneuvers before refilling. It is refilled during the bipropellant firings through operation of the auxiliary tank latch valve. The propulsion system has sufficient capacity to hold the required 636 kg of mission propellant at its maximum temperature (40°C) over the specified range of main engine mixture ratio (0.75-0.80) with a 5% volume margin to allow extra propellant to be loaded if the dry spacecraft mass is below maximum at launch.

Propulsion system redundancy is similar to that used on NEAR. The high-pressure regulator is series redundant and leakage protected by the high-pressure latch valve. The Futurecraft check valves are internally parallel-redundant at the component level and series-redundant on the fuel side. The propellant latch valves have redundant coils. The monopropellant thrusters have series-redundant valves, redundant coils, and redundant cat bed heaters. The monopropellant thrusters provide redundant 3-axis attitude control. By design, there are no potential single-point failures throughout the wiring, connections, heaters, and thermostats. The list of single-string items includes all 5 tanks, all propellant latch valves, the high-pressure and oxidizer inlet latch valves, all latch valve position indicators, the propellant filters, and the bipropellant thrusters.

The system is pressurized from a 38.6 MPa, 5000 pounds per square inch absolute (PSIA), Maximum Expected Operating Pressure (MEOP) helium tank feeding a series-redundant regulator through a filter and a high-pressure latch valve. The Pressure Systems, Inc. (PSI), 80374 titanium-lined, graphite-composite overwrapped helium tank, qualified for A2100, satisfies all helium tank requirements. Regulated pressure at 1.85 MPa (240 PSIA) feeds the propellant tanks through redundant check valves and, on the oxidizer side, an additional isolating latch valve. The pressurization system is identical to the NEAR configuration built by team member Aerojet. The pressurization system design and heated pressurization manifold preclude any Mars-Observer-type vapor migration problems, and was successfully used on NEAR. During Phase A/B, an independent (one oxidizer, one fuel) pressurization system will be studied to trade further reducing vapor migration concerns against increased cost and mass.

Three identical main propellant tanks, two fuel and one oxidizer, feed the thruster complement through filters, activation-surge-limiting venturis, and flow-sequencing latch valves. The currently baselined titanium propellant tank will be designed per MIL-STD-1522A to a MEOP of 1.93 MPa (250 PSIA) gauge pressure and a Burst/MEOP factor of safety of 1.5. During all ground test and launch operations, tank pressure will be limited to 1.38 MPa (180 PSIA) to provide a >2.0 factor of safety. By using identical tanks, the tank qualification, tooling, and manufacturing costs are minimized. By selecting an all-titanium approach, the development risks and range safety issues associated with overwrapped propellant tanks are eliminated.

A small auxiliary diaphragm fuel tank uses PSI's 80222 titanium AF-E-332 diaphragm tank qualified for the International Ultraviolet Explorer (IUE) to provide the required 4.75-l capacity. All bipropellant burns are preceded by a settling burn sequence using the auxiliary fuel tank and two 4-N monopropellant thrusters.

APL, COI, and Aerojet use common software and data bases to reduce the total design cost. All three teams use Pro/Engineer™ software for the 3-D solid model design, NASTRAN™ and FEMAP™ software for structure analysis, and In-Person™ software for virtual meetings. The cost savings result from less travel, shorter design cycles, reduction of duplication of efforts, and reduction in communication errors.

The items of technical risk in the structure/propulsion area are the structure mass, the qualification of the main propellant tanks, and the qualification of the 22-N bipropellant thrusters. The structure mass estimate is created from the solid model database of the MESSENGER design. The data base includes the standard fitting and joint details that have measured mass properties. Also included are proven methods of accounting for joint adhesive bond-line and fillet mass based on number and length of structural bonds. The system-level mass properties and mass estimates are updated monthly, or after any major design change. The mass estimate is very firm at the time of the structure CDR, which is very close to the spacecraft PDR.

Development and qualification of the propellant tanks are planned during Phase A/B. By tank CDR (prior to spacecraft PDR), sufficient design and range-safety analysis is accomplished to determine if the mass, stiffness, safety, and strength goals can be met with the required margins. If not, a conventional tank design can be used as a fallback without impacting schedule, but with a 6-kg mass penalty.

The 22-N bipropellant thrusters are currently in development and qualification at Atlantic Research and Ishikawajima-Harima Heavy Industries (IHI) for communication satellite applications. Both programs are scheduled to have completed qualification before spacecraft PDR. If neither is ready, a standard 22-N Primex monopropellant thruster (used on NEAR) can be used with a 5 kg increase in propellant.

F.2.3 Thermal Design

The thermal design is completely passive, requires no louvers or other mechanisms, uses readily available materials, and needs little heater power. This elegant design is enabled by the mission geometry. During the orbital phase, the distance between the Sun and Mercury varies from 0.30 AU to 0.47 AU, corresponding to a solar flux variance from 10.6 to 4.6 times that received at Earth. This flux is unidirectional and is very successfully attenuated by the thermal shade. A second source of thermal input to the spacecraft is from the infrared (IR) energy emitted by the sunlit side of Mercury. The maximum surface temperature of Mercury reaches 433°C at perihelion and falls off to 298°C at aphelion. The temperature drops off as a cosine function from the maximum at the subsolar point to -173°C at the dawn terminator (Wertz, 1978). The IR heat flux is omnidirectional and can not be effectively attenuated. The spacecraft orbit is carefully chosen to minimize the IR radiation received from Mercury's surface. The orbit is highly elliptical and the periapsis latitude is at 60° N, well away from the subsolar point, but where the orbital velocity at the subsolar crossing point is still very fast. Further, the spacecraft crosses the subsolar point at true anomaly (TA) 247° or 0.4 AU, not at perihelion (Fig. F-2-13).

Throughout the mission the thermal shade is pointed at the Sun and the spacecraft is rotated about the Sun line to accommodate instrument viewing. The general approach for thermal management is to reduce the heat load on the

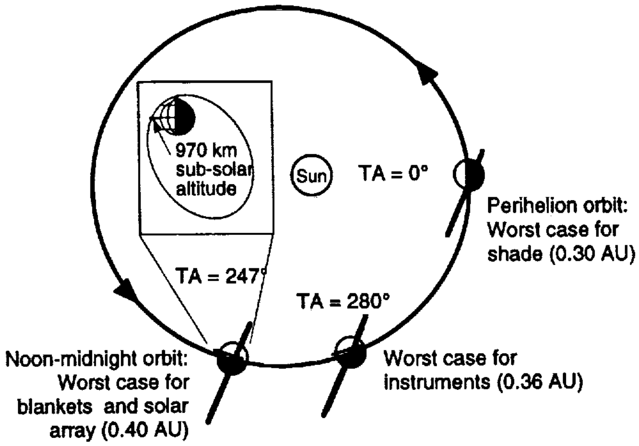


Fig. F-2-13 Orbit at Mercury showing worst-case thermal conditions for the thermal shade, blankets, solar array, and instruments.

Sun side of the spacecraft via the thermal shade to the point where radiating panels on three sides of the structure can remove any excess heat. As the spacecraft passes over the hot side of the planet, IR energy is absorbed into the spacecraft body through the side radiator panels, causing a brief temperature spike. When the spacecraft moves away from the planet this excess heat is radiated and the spacecraft returns to its steady-state temperature. The radiators have sufficient total area to handle the worst-case heat load. They are isolated from the spacecraft structure and spacecraft electronics, coupled only through radiation, dampening the effect of the IR heat flux received during the 25-minute planet crossings. During some of the near-noon, hot-spot transient orbits, one side radiator panel views the hot planetary surface while the other views a colder background, potentially creating a large temperature gradient across the bottom instrument deck. Heat pipes are attached to the top of this deck to minimize the effect of the gradient on the instruments and optimize the effectiveness of the side radiators. The solar arrays are placed on low-conductive struts, 0.76 m from the side radiator panels, to eliminate heat coupling to the spacecraft.

The spacecraft is designed to run near its cold-operating limit during cruise phase, when the spacecraft is in a low-power mode, so that when all instruments are powered during orbital operations the spacecraft remains below its upper-operating temperature limit. There are no thermal concerns during the Venus or Mercury flybys, as the closest approaches are all over shadowed portions of the planets. Thermal multilayer insulation covers the entire spacecraft, except for the radiator surfaces, which are covered with OSRs. The propulsion system, thermal shade, battery, solar array struts, and some instruments are thermally isolated from the spacecraft using multilayer insulation and low-conductivity mounting hardware. The large bipropellant thruster is surrounded by a gold-plated heat shield to protect the spacecraft during burns. All spacecraft heaters are redundant and are controlled by mechanical thermostats. The set-points of the primary and secondary heaters are offset so that the secondary heaters are never energized unless a primary heater fails.

A detailed time-stepped computer model was developed to compute the spacecraft orbit-average and transient temperatures over a Mercury year. The model was checked by comparing temperature predictions for the solar array, thermal shade, and spacecraft core against published results from Mariner 10 (NASA, 1978) when simulating similar environmental conditions. Planetary environments assumed are consistent with those of Wertz (1978) and past NASA Mercury-orbiter studies (JPL, 1990). The model's orbital geometry was verified by MESSENGER's mission designers.

The worst thermal case for the instruments occurs when the spacecraft periapsis is near the subsolar point (Fig. F-2-14, day 75) at a distance of 0.36 AU from the Sun. The maximum temperatures are due to the IR and visible radiation from the planet; temperatures were

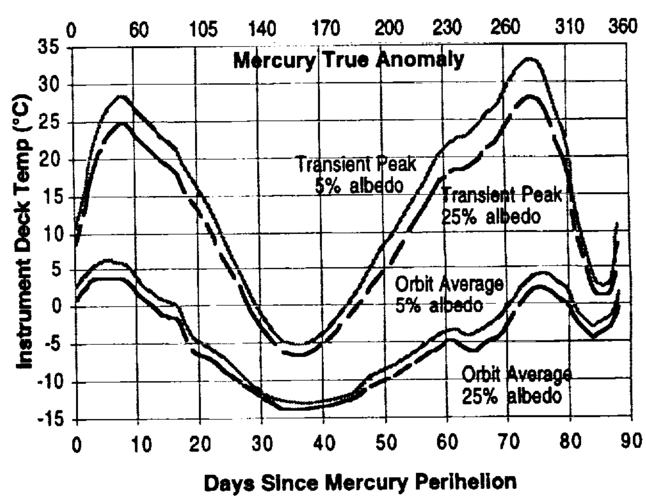


Fig. F-2-14 Instrument-deck temperature over a Mercury year. A survival margin of 20 °C exists.

computed for both 5% and 25% bond albedos for the planet, bracketing the uncertainty. The worst-case hot instrument-deck orbit-average temperature is 7°C, and the worst transient is 33°C. The temperature transient profile for this orbit lasts only 25 minutes, with a maximum temperature gradient of 1.5°C per minute (Fig. F-2-15). During the remainder of the 12-hour orbit, the temperature is near the orbit-average value of 25°C. The payload is thus kept within its calibration temperature range over ≥ 99.5% of the orbit phase and provides survival margins in excess of 20°C. (See Table F.4.1 for instrument temperature requirements.) Similar calculations verify that the spacecraft electronics are always within their -29°C to +60°C operating range with less than a 5°C per minute gradient. The battery always remains within its -10° to 25°C operating range. For the majority of the mission, the battery temperature is maintained by heaters to be between -5°C and 0°C. During the eclipse cycles, the battery temperature does peak to 19°C, but lifetime concerns are mitigated because only 200 discharge cycles are anticipated.

The thermal shade is constructed from 3M Nextel 312 ceramic cloth covering an opaque 3.2 mm Q-Felt core (foldout Fig. F-2-1). Both materials are rated in excess of 1000°C. This lightweight material is used for thermal protection on the Space Shuttle. The back side of the shade and the spacecraft body are covered with conventional all-Kapton multilayer insulation (MLI), rated in excess of 400°C. The predicted worst-case temperature for the thermal shade and the Sun-facing side of the MLI blanket on the back of the thermal shade is 350°C, assuming surface degradation for UV-radiation and particle contamination (Table F-2-5). This worst case occurs at perihelion. The worst-case

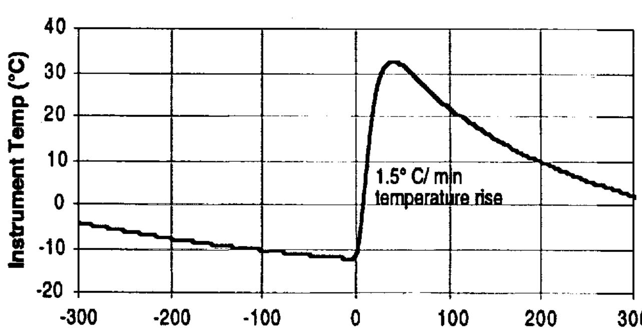


Fig. F-2-15 Instrument-deck worst-case temperature transient at orbit-day 75 due to heating from Mercury. The temperature-rate margin is 3.5°C/ min.

Table F-2-5 Surface Properties

Surface Material	End-of-Life Absorptivity (α)	End-of-Life Emissivity (ε)
Thermal shade	0.5	0.9
Thermal blankets	0.4	0.78
Radiator	0.2	0.78
Panel w/100% cells	0.85	0.85
Panel w/30% cells, 70% OSRs	0.39	0.81

temperature for the MLI blankets that cover the spacecraft is 270°C, which occurs in the noon-midnight orbit when the spacecraft is at 0.4 AU and passes over the subsolar point at 970-km altitude (assuming a worst-case planet albedo of 5%).

A sample thermal shade and thermal-shade blanket were fabricated and tested under solar simulation in vacuum at NASA's John H. Glenn Research Center at Lewis Field (GRC). The shade was not cleaned, and 30°C chamber walls were used, which biases the results on the hot side. At 10.7 times the solar flux received at Earth, the shade surface measured 350°C, the Sun-facing side of the MLI behind the shade measured 350°C, and the spacecraft-facing side of the MLI measured 35°C (Fig. F-2-16) (Mason, 1999). These tests demonstrated the utility of the thermal shade configuration to ameliorate high temperatures and validated the expected performance of the MLI. Results from the thermal model, with the shade thermal properties degraded at the worst-case end-of-life conditions, indicate that the orbit-average spacecraft temperature is between 5° to 25°C.

The solar monitor, four Sun sensors, a low-gain antenna, two medium-gain antennas, and the forward phased array look through the thermal shade (Fig. F-2-17). All are located at the ends

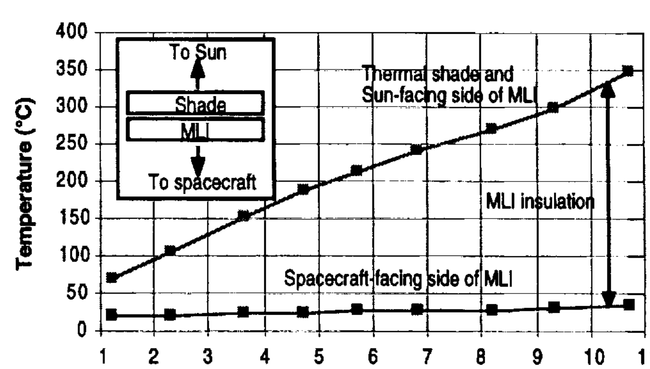


Fig. F-2-16 GRC shade and MLI test results demonstrate the insensitivity of the thermal design to varying solar distances.

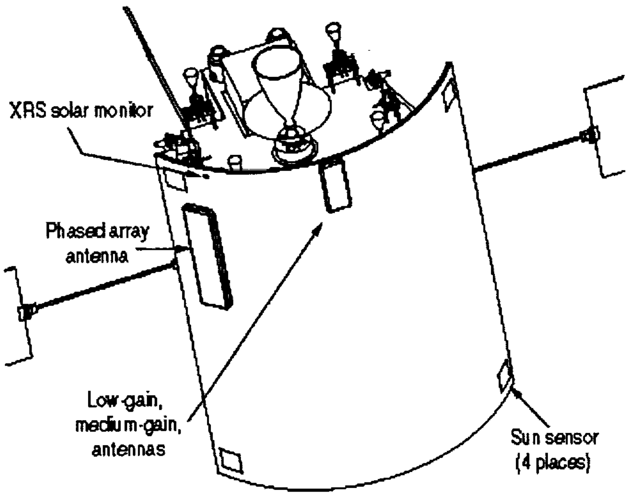


Fig. F-2-17 Shade-mounted components are located to allow clear backside heat radiation.

of the shade to give a clear view to space for backside heat radiation. The sunward-facing sides have opaque, white ceramic matrix composite (CMC) covers or attenuating filters as appropriate to reduce detector heating. For the antennas, the CMC cover acts as a radome at the same temperature as the Sun shade. The faces of the antennas that view the radomes are coated with a low-emissivity material (such as gold or vacuum-deposited aluminum) to reduce IR irradiance from the radome by at least an order of magnitude.

To estimate the effect of plume heating from the top deck thrusters on the shade-mounted components, a plume-heating model was created. The closest component to the thruster-generated heat flux, the phased-array antenna, increases in temperature by 40°C, but remains within its 200°C qualification range (Fig. F-2-18). Other shade-mounted components show a smaller plume-heating effect, all remaining within their qualification range. This conservative analysis assumes a Sun distance of 0.3 AU, and multiplies the worst-case predicted heat flux from all of the top-deck

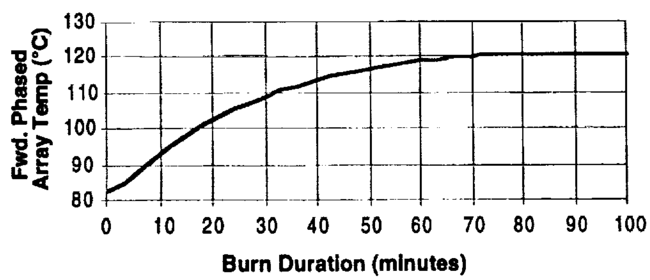


Fig. F-2-18 Assuming worst-case plume heating, a 75°C margin exists for the forward phased array.

thrusters firing continuously by a factor of 1000.

An area of potential risk is the mass of the thermal design. The thermal model, which includes both the spacecraft and mission geometry, is implemented using SINDA™. As the details of the spacecraft and instrument designs mature (box locations, constructions, and watt densities) the thermal model is refined. If during development, the model predicts that the thermal design margin is insufficient, options exist to add doublers, heat pipes, or louvers at the expense of increased mass.

F.2.4 Telecommunications System

The X-band telecommunications system is designed to provide the required science return, a reliable spacecraft command link, and precise radiometric tracking data. Detailed in Fig. F-2-2, it incorporates redundant X-band transponders to provide command, telemetry, and high-precision Doppler/ranging capability. Power amplification is provided by solid-state power amplifiers (SSPAs). The system is cross-strapped on both sides of the transponders, providing near-full redundancy on both the uplink and downlink. The only components not cross-strapped are the distributed power amplifiers; each is dedicated to one phased-array antenna. The distributed nature of the phased-array permits graceful degradation in the event of an amplifier-element failure. Even if a complete array were to fail, under worst-case conditions enough recorder capacity exists to store the orbit-phase science data and downlink those data later using the other array and a revised downlink schedule.

Antenna coverage is provided by two waveguide-based phased arrays (for the science downlink), four medium-gain antennas (for commanding and low bit-rate downlinking), and redundant low-gain antennas (for wide-angle emergency communications). Two identical 15 cm x 67 cm phased arrays, mounted on opposite sides of the spacecraft, eliminate the need for a gimbaled high-gain antenna (HGA). These arrays, constructed from established aluminum-waveguide technology, are rugged and low risk. The design is based on a similar X-band array built at APL for a military program. A similar phased array was flown on

Radarsat. The array design is kept simple by restricting the scanning capability to ± 45° in one dimension only. The design is further simplified by the use of transmit-only, linearly polarized elements. The array is passive, with the electronics located in a power-amplifier assembly mounted within the spacecraft body. The instantaneous antenna beamwidth is relatively large (12° x 3°), so effects due to thermal distortion are minimal. A full-scale brassboard model (foldout Fig. F-2-1) was built and tested with good performance (Fig. F-2-19). Each phased array covers one full hemisphere by controlling the beam direction in one axis and rotating the spacecraft up to 360° about the spacecraft-Sun line (Fig. F-2-20). The medium-gain antennas (MGAs) each have a fanbeam pattern with a wideplane beamwidth of 90° and are arranged to provide 360° coverage about the spacecraft equator. The low-gain antennas (LGAs), one mounted on each side of the spacecraft, provide hemispherical coverage. The MGAs and LGAs all support both transmit and receive. Prior to flight fabrication, brassboard antennas of each design are built and installed on a mock-up spacecraft and tested on APL's 76-m antenna range.

Motorola Small Deep Space Transponders (SDSTs) are the heart of the telecommunications system. The design is well-established, having been first used on the New Millennium Deep Space-1 mission. The X-band signals from the transponders are amplified using SSPAs, for which APL has a rich heritage. Examples of recent APL experience include 5-W SSPAs built for the NEAR and Midcourse Space Experiment (MSX) satellites and an 8-W X-band SSPA built for a military phased-array program. Two SSPA designs are required: a lumped SSPA providing 11 W to drive the MGAs and LGAs, and a distributed 15-W SSPA using eight 1.875-W amplifier modules (with phase shifters) to drive the phased array. During the majority of the cruise phase, the lumped amplifiers are used to provide low bit-rate communications through the MGAs.

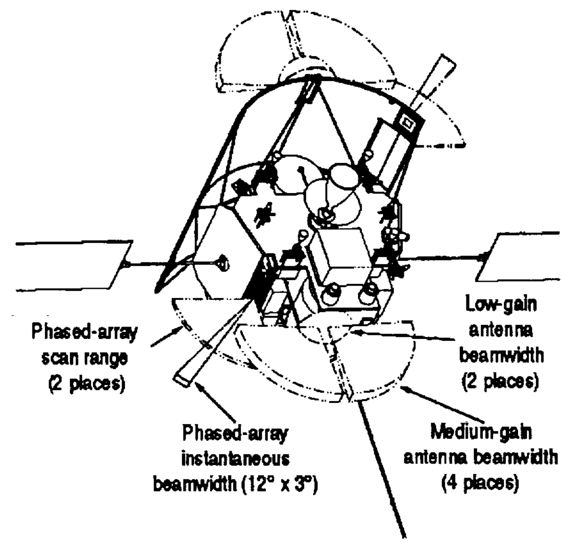


Fig. F-2-20 Antennas have clear fields-of-view.

To predict data return, a link analysis was performed (Table F-2-13). The cruise phase is discussed in Sec. F.2.11. For the orbital phase, a phased-array antenna for the downlink, an MGA for the uplink, and the DSN HEF (high-efficiency) and BWG (beam-waveguide) 34-m ground antennas are assumed (Fig. F-2-21). The analysis includes the varying effect of spacecraft-Earth distance, solar effects, array

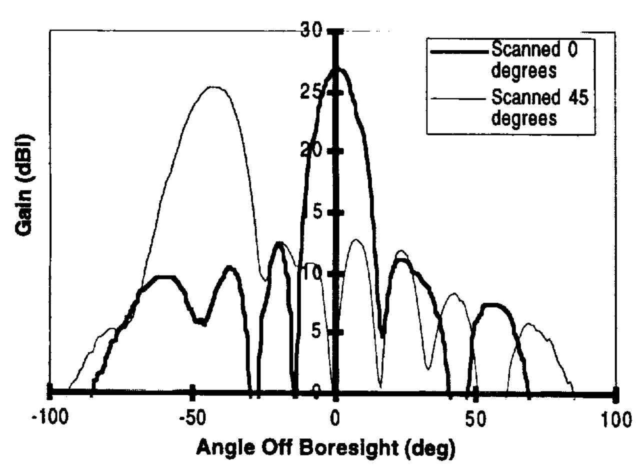


Fig. F-2-19 Brassboard phased-array results showing good scan-range performance.

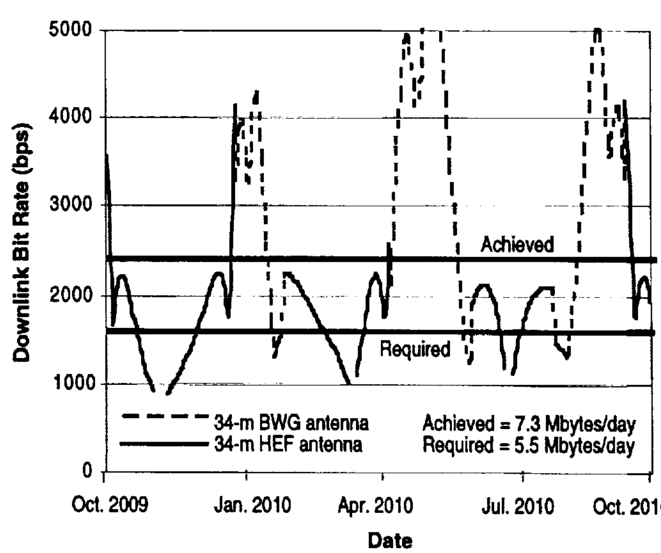


Fig. F-2-21 The orbital-phase downlink satisfies mission requirements (3 dB margin included).

scan-angle penalty, and linear-to-circular polarization loss. The DSN HEF antennas are used only when the larger 20-kW uplink ground transmitters are required to maintain a 3-dB uplink margin. The average downlink bit rate (including data loss due to solar conjunction periods) is 7.3 Mbytes/day with a 3 dB margin, which easily satisfies the science requirement of 5.5 Mbytes/day. The link analysis also shows that a Doppler precision of $\leq$0.1 mm/s and a ranging precision of $\leq$ 3 m are achievable during the Mercury orbit phase, satisfying the requirements of navigation and radio science. Compatibility with the DSN will be established at the subsystem level through testing at their DTF-21 facility and at the spacecraft level through their compatibility test trailer.

An area of modest technical risk is the distributed SSPA used with the phased array. The SSPA is planned to be implemented using off-the-shelf heterostructure field-effect transistor (HFET) power devices. This technology is mature and has flight heritage. For example, HFET power amplifiers are being flown on the Mars Climate Orbiter and Mars Polar Lander. The bulk of the new design effort for MESSENGER will be in packaging the technology for flight. APL has both the capability and the experience for chip-level packaging. For example, foldout Fig. F-2-1 shows an 8-W, 10-GHz power amplifier built at APL using HFET devices. To minimize risk, the SSPA design is initiated at the start of the Phase A/B effort. SSPA risk-assessment reviews will be held twice during Phase A/B, and a fallback decision can be triggered at either event. Should significant difficulties be encountered, there are two fallback options: (1) packaged devices can be incorporated in place of chip-level devices in the design, or (2) a 15-W purchased SSPA can be incorporated with the use of external phase shifters. Packaged devices were used successfully by APL for X-band SSPA designs on both the NEAR and MSX spacecraft. Both of the fallback options are less efficient than the baseline approach. The reduced efficiency would require increased DSN coverage to obtain the same science downlink bits.

F.2.5 Power System

The power system (foldout Fig. F-2-2) has a peak-power tracking (PPT) topology with strong heritage from the TIMED power system design. This architecture keeps any excess power at the array, eliminating the need for dissipative shunts within the spacecraft, while optimizing the solar array output over the highly varied operating conditions of the mission. The power system is composed of power-system electronics (PSE), a common-pressure vessel (CPV) 20-Ah NiH_2 battery, and a 2.5-m^2 dual-sided solar array. The power subsystem design has no single-point failures. Within the PSE the battery-charge electronics, power-switching and distribution electronics, and command and telemetry interfaces are fully redundant; the peak-power tracker (PPT) electronics are functionally redundant. The PPT electronics consist of 10 pulse-width-modulated buck converters, or PPT modules, operating in parallel and sized so that any nine can fully support the mission. The battery is fault tolerant in that each of the cell vessels is bypassed by a contactor that is automatically activated to short the cell in case of an open-circuit failure of that vessel. The solar array is fault tolerant in that the solar cells are grouped into individual strings that are isolated with decoupling diodes. The calculated array power output assumes the loss of one string.

The spacecraft bus is tied directly to the battery, maintaining it at an unregulated 22 to 34V. Within the PSE, the ten PPT modules are located in series between the solar array output and the spacecraft main power bus. The PPT modules control the power generated by the array by varying the operating voltage of the array. They set the array input voltage either at the maximum power point when the loads and battery recharge requirement can use the peak power of the array, or off the maximum point, toward the open-circuit voltage, when array power exceeds the loads. During peak-power operations, the array operating voltage is determined by an algorithm that is executed in an IEM processor. Hardware PPT backup controllers maintain a default array-voltage setting in the event of processor failure or restart. The PPT hardware and software algorithms are copied directly from TIMED. Power system circuit analysis uses PSPICE, particularly in the control-loops stability analysis. The analysis is verified by closed-loop gain/phase measurements on the flight hardware in the laboratory.

Normally, the battery-charge control is performed by an IEM processor using coulometry and pressure-monitoring telemetry. Hardware algorithms based on voltage, temperature, and pressure prevent battery overcharge. The battery-charge control hardware and software are copied from TIMED.

To execute power-switching control, the PSE receives commands from the IEM via a redundant, dedicated TIMED-heritage serial bus. Commands are decoded, error-checked and sent to a functionally redundant matrix arrangement of relays and power metal-oxide semiconductor field-effect transistor (MOSFET) drivers inside the PSE. The power switching design has heritage in the TIMED design, with improvements in mass-efficiency by using power MOSFETs in place of larger relays. Fusing of power lines to each load is done using replaceable, redundant fuse plugs attached to the PSE for easy fuse integrity verification throughout integration. This approach was used successfully on NEAR and is in place on TIMED.

The solar array consists of two dual-sided panels totaling 2.5 m^2 of area. One side is fully populated with GaAs/Ge cells and is used during the outer cruise phase. The other side is a 70%/30% mix of OSRs and GaAs/Ge cells and is used during the inner cruise and orbit phases. The arrays are connected to drive motors whose rotation axis is normal to the Sun line to allow the panels to be rotated off solar normal to maintain operational temperatures under 150°C. For the fully populated side, a minimum margin of 35.7% is reached shortly after launch, when the spacecraft is at 1.1 AU (Fig. F-2-22). In a 2-week interval, when the spacecraft is between 0.45 AU and 0.58 AU Sun distance, either side provides greater than 20% power margin and the panel can be flipped. The mixed OSR/cell side power margin is a minimum of 21.3% during the orbital phase at Mercury aphelion and during the orbits with eclipse periods. The array is constructed from materials that are each rated above 250°C for steady-state operation based on vendor-supplied information or have been qualified by APL to operate at greater than 250°C (Fig. F-2-23).

Cerium oxide doped borosilicate glass (CMX) is placed over the GaAs cells to mitigate radiation damage (Sec. F.2.12). The total charged particle radiation fluence, using 0.3-mm-thick CMX cover glass, is 4.0×10^{14} equivalent 1-Mev electrons/cm^2 over the mission life.

The array design is fabricated to be magnetically clean using nonmagnetic materials and loop-cancellation wiring. The OSR/GaAs side, which is illuminated during instrument activities, employs backside magnetic cancellation by routing the return wiring on the fully-populated side, directly under the circuits of the OSR/GaAs side. The cells on the fully-populated side are placed in the gaps of the OSR/GaAs wiring. This fabrication technique was demonstrated in the construction of the dual-sided panel test article (foldout Fig. F-2-1). Each side of each panel is instrumented with redundant temperature sensors that are used to maintain the solar-aspect angle. Array analyses account for all

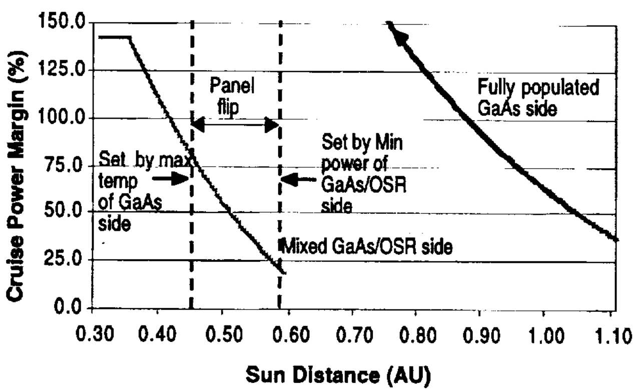


Fig. F-2-22 Ample margin on both panel sides allows the panel flip any time between 0.45 and 0.58 AU.

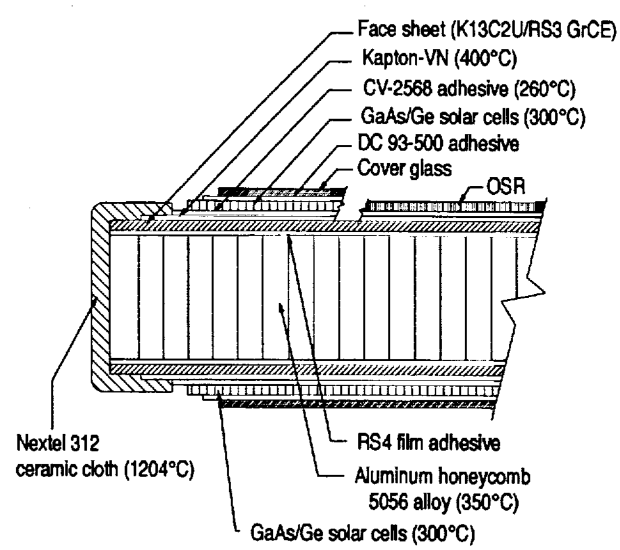


Fig. F-2-23 Solar panel cross-section showing maximum steady-state temperatures. Materials with temperatures not shown were tested to > 250°C.

extremes of mission environment, including incidence angle losses, UV and charged particle radiation, temperature effects, and iterative calculation of effective thermal absorptivity as a function of panel operating efficiency.

The battery is a 20-Ah NiH_2 CPV design, similar to the one now flying on Mars Global Surveyor (MGS) (foldout Fig. F-2-1). The CPV design offers significant mass and volume savings by combining two cells into each pressure vessel. The battery assembly consists of 11 vessels, each equipped with autonomous bypass circuitry in case of vessel failure. The bypass circuitry has heritage to Terra and TIMED. The NiH_2 technology is well suited for MESSENGER by virtue of its low mass and tolerance to overcharge. The ability to measure battery pressure also provides an additional level of confidence in maintaining battery health. The maximum depth of discharge during the launch phase is 21%. The total number of battery discharge cycles during the cruise and orbital phases is approximately 200, with each cycle having a maximum depth of discharge less than 46% (51% with one vessel failed). Sufficient battery cells are purchased for two flight-qualified batteries plus spares. The best cells are selected for the flight and spare batteries. The remaining cells are life tested. After launch, these cells will be maintained in conditions similar to the on-orbit battery. Periodically throughout the mission and prior to every major mission event, one of the spare battery cells will be discharged to provide additional confidence in the state-of-charge in the on-orbit battery.

To demonstrate the survivability and robustness of the solar panel design and to validate thermal analyses, APL has successfully completed a series of high temperature qualification tests including IR and solar simulator illumination heating of test articles. These tests were conducted on four test panels that were fabricated using standard manufacturing materials and processes. All panels were cycled in thermal vacuum from -120°C to 200°C and soaked at 250°C for one hour without damage. One panel has also demonstrated no degradation during a 20-day extended soak at 180°C in rough vacuum, and has shown no damage during a 30 minute vacuum soak of 310°C. Another panel has also been illuminated with simulated solar spectra in vacuum at the Tank 6 facility at NASA's John H. Glenn Research Center at Lewis Field. The illumination flux was varied over a range of intensities with a maximum flux of 10.1 suns, resulting in a maximum temperature of 257°C (Fig. F-2-24) (Mason, 1999). During the test, the chamber walls were 30°C, which conservatively biased the test results toward higher temperatures. The test procedure contained several inspection points consisting of visual, electrical, microscopic, and IR inspections to fully characterize panel survivability. The panels met all inspection criteria, demonstrating suitability for the MESSENGER mission. These results validated that the panel design can survive the worst-case failure mode of direct sun pointing at 0.3 AU. In addition, the excellent correlation between the predicted and measured temperatures verified many of the optical-surface and conduction properties of the materials used in the thermal model, giving confidence in the design and the thermal model's accuracy.

The thermal-stability characteristics of the panel's adhesives (Fig. F-2-23) were obtained by Thermal Gravimetric Analysis (TGA) and ASTM-E595 outgassing tests performed at APL. All materials tested showed good thermal stability and exceeded the total mass loss (TML) requirement of 1.0% only at temperatures over 300°C (Table F-2-6), proving their suitability for this challenging mission (Rooney and Jackson, 1999).

The APL tests complement industry experience in high-temperature testing. Mars Global Surveyor (MGS) successfully cycled solar panels to 194°C for aero-braking qualification. The Combined Release and Radiation Effects Satellite (CRRES) (Powe et al., 1991; Ray et al.,

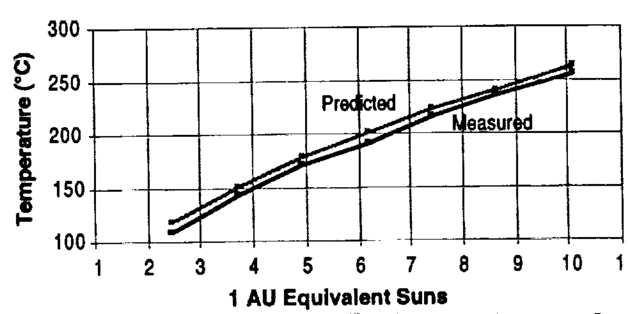


Fig. F-2-24 GRC solar panel test results correlate well with thermal model. The panel passed direct illumination at 10.1 Suns with no damage.

Table F-2-6 TGA Test Results

Adhesive	Temperature (°C) at 1% Total Mass Loss
CV-2568	309
DC 93-500	330

1993) successfully performed cycling to 180°C and 250°C in both ground tests and on-orbit as part of an experiment to anneal solar cells at elevated temperatures to recover from charged particle radiation damage. Cell manufacturer TECSTAR has conducted 300°C soaks of bare GaAs cells with no mechanical or electrical degradation.

A Phase A/B trade study will investigate substitution of the NiH_2 battery with a mass-saving lithium-ion battery (Sec. H.1). Lithium-ion technology is maturing rapidly and is well suited for the MESSENGER mission because of the limited number of discharge cycles. A second Phase A/B trade study will reevaluate the parameters of the dual-sided solar panel. The relationship between OSR/cell ratio, panel area, and incident solar angle will be explored to find the combination that may further optimize operating temperature, panel mass, and operational design range. Replacement of the GaAs cells on one or both panel sides with multi-junction cells will be studied to increase the power margin and lower the operating temperatures. Use of blue-red reflective coating on the cover glass will be studied to lower operating temperatures.

Evaluation of test solar panels to the full MESSENGER requirements is planned during Phase A/B. The solar cells, cover glass, interconnects, and adhesives will be qualified for the Mercury environment. The panel materials will be tested for suitability after prolonged exposure to high-temperature vacuum conditions. The panels will undergo mission simulation thermal cycling, long-term survivability testing, thermal characterization, and mechanical and electrical characterization. High-intensity solar simulation testing will be completed at GRC (small panel) and JPL (qualification-size panel). Panel design is scheduled to be completed before spacecraft PDR. Should a fallback option be necessary, the qualification temperature can be lowered by increasing the array size and operating at a greater solar incidence angle (Fig. F-2-3). Increasing the solar panel area by 35% (7 kg) could reduce the maximum operating temperature by 20°C.

F.2.6 Integrated Electronics Module

The spacecraft bus electronics are contained in redundant integrated electronics modules (IEMs), shown in detail in foldout Fig. F-2-2. Each function is implemented as a circuit card. Interfaces between cards and IEMs are over a high-speed, fault-tolerant, and redundant IEEE-1394 serial bus.

There are five cards in each IEM, all of which are designed and built at APL. The communications card receives the CCSDS-compatible uplink bit stream from the transponders. It decodes and executes a subset of critical commands in hardware, and passes the remaining commands to the Spacecraft Control Processor (SCP) card. The communications card also buffers and encodes CCSDS-compatible telemetry frames and sends the downlink bit stream to the transponders. The SCP distributes all noncritical commands to the addressed subsystem. It performs fault protection for the spacecraft as well as the IEM itself. The Main Processor (MP) card performs attitude determination and control, collects and processes instrument data, sequences downlink telemetry, and performs advanced autonomy algorithms for operations. A low-power, solid-state recorder (SSR) card, using Reed-Solomon error-correcting code, stores data between ground contacts. An interface card contains all spacecraft interfaces other than to the transponder, including those for the attitude sensors and actuators and the instrument DPU.

A redundant MIL-STD-1553 serial-data bus connects the IEMs with attitude sensors (the inertial measurement unit and star tracker) and the instrument DPU. Control of all instruments as well as low-speed science data collection is accomplished using the 1553 bus. A dedicated differential serial digital link (RS-422) is used to collect images at high bit rates. Large buffers on the interface cards lower the processor bandwidth for collecting image data. Each of the IEMs can energize power-switching relays located in the PSE. Finally, a small unpowered terminal board with passive circuits provides isolation between redundant IEM circuits and duplicated resources with non-redundant interfaces, i.e., Sun-sensor electronics and reaction wheel assemblies. Similar circuits were used on NEAR.

The IEM is designed to function in MESSENGER's radiation total dose and single-event-upset (SEU) environment. Key circuits are implemented with redundant triple-voting circuitry for SEU robustness. Rad-hard Actel field-programmable gate arrays (FPGAs) and Application Specific Integrated Circuits (ASICs) are used throughout the design. Both the MP and the SCP use rad-hard Synova Mongoose V 32-bit microprocessors, with an error-detecting and correcting main memory. SEUs in the solid-state recorder are detected and corrected by a Reed Solomon block code. Spot shielding is used on the few commercial ICs that are not sufficiently hard to satisfy MESSENGER's mission requirements, such as the RAM in the solid-state recorder. Watchdog timers and other fault-detection circuits can restart an IEM processor in the event of otherwise undetected and uncorrected errors.

Fault tolerance is achieved by box-level redundancy and careful interface design. The internal IEEE-1394 serial data bus is redundant. If one side of the bus fails, the redundant bus continues to operate transparently. The internal buses are bridged between the two IEM boxes. Data connections are thus effectively cross-strapped between all cards in both IEM chassis. If a fault on one side affects the buses in both chassis, the unaffected side can disconnect the bus bridge and continue to operate. Power distribution within the IEM is also an important factor in achieving fault tolerance. The SCP card and Communications card in both IEMs are always powered and cannot be switched off. Failure of one of these resources is not fatal since its backup will continue proper operation. The remaining boards are organized into two groups within each IEM. Each group has its own dedicated power converter, which receives switched power from the PSE. During normal operations, one IEM is fully powered and designated as prime. The prime IEM is the 1553 bus controller and is responsible for all spacecraft functions. If a failure in the prime IEM is detected, the other IEM is fully powered and designated as the new prime.

The MESSENGER IEM is qualified for space flight using the approach developed for TIMED. A breadboard is developed for each IEM card. An IEM tester that simulates the rest of the IEM and spacecraft is used to verify proper operation of each card. As tested designs are integrated into a fully-functional breadboard IEM, the actual cards replace the simulated functions within the tester. Multiple copies of IEM breadboards and IEM testers are distributed among the team to allow parallel subsystem development. After passing card-level verification, flight boards will be assembled into the flight chassis. When all boards are available for each flight IEM chassis, full functional, thermal, and mechanical testing is performed at the box level.

Of the five cards within each IEM, only the spacecraft interface card is a new design. The two processor cards, the communications card, and the solid-state recorder card are modifications of the TIMED design (foldout Fig. F-2-1). The main difference between MESSENGER's IEM and TIMED is the replacement of the backplane from a non-redundant Peripheral Component Interconnect (PCI) bus with a fault-tolerant IEEE-1394 bus interface.

Two potential risk areas exist in the avionics section. They are the 1394 bus-interface chip development and the packaging densities assumed in the electronics mass estimate. Under APL internal-research funds, an initial FPGA implementation of a 1394 design has been fabricated; while only a partial implementation of MESSENGER functionality, the parts were successfully tested. The second generation of this chip, incorporating all functions needed for MESSENGER, is currently in development under a NASA advanced technology grant. Prototype chips are planned by spacecraft PDR. Should technical progress not be sufficient, the 1394 design will be replaced by the TIMED PCI bus interface. This option results in the loss of card-level redundancy and requires a change in the fault-protection architecture.

The high-density avionics packaging scheme assumes that circuit cards consist of a single fiberglass substrate with components surface-mounted on both sides. To reduce manufacturing risk, a single detailed card layout is completed during Phase A/B to validate that the component packing density can be accommodated using a single substrate. If this study shows insufficient component density, then dual-substrate designs can be used with a mass penalty.

F.2.7 Command and Data Handling

The command and data handling (C&DH) subsystem is implemented by resources within the IEMs. The functions provided by the C&DH subsystem are command management, telemetry management, and time distribution.

The command function operates on cross-strapped inputs from the two command receivers at either of two rates: 62.5 bps (normal mode) or 7.8 bps (emergency rate). The format of the uplinked commands is CCSDS compliant, with a separate virtual channel for each side of the redundant C&DH subsystem. Commands can be executed in real time, or can be stored for later execution. Execution of stored commands can be triggered by reaching a specific mission elapsed time, or by the detection of a spacecraft event.

The telemetry function collects engineering status and science data for recording and downlink. Engineering data are collected by very small remote interface units (RIUs) that accumulate analog telemetry information and relay it to the IEM over a serial inter-integrated circuit (I^2C) data bus. Science data are collected over dedicated serial interfaces and the 1553 bus. Recorded data are read back and placed into the downlink on command. Recorder playback data can be interleaved with real-time data on the downlink, and data can be recorded on one of the redundant recorders while the other recorder is in playback.

The downlink data rate is selectable to match the downlink capability throughout the mission. While the C&DH subsystem controls the rate of collection of real-time data to match the real time downlink rate, the rate at which data are placed on the recorder is under the control of the subsystems. Each remote terminal on the 1553 bus can request the C&DH to pick up and record a variable amount of bits of data per second, up to a maximum rate. This feature allows the spacecraft operators complete flexibility with respect to the bandwidth used by each instrument and spacecraft subsystem.

Spacecraft time is maintained by a temperature-compensated oscillator inside the prime IEM that has stability good to one part in 10^{-7} and a drift of $3x10^{-9}$/day. Spacecraft time is synchronized within the IEM via the 1394 data bus, and delivered to the instruments over the 1553 data bus. Spacecraft time correlation to universal time is accomplished on the ground by comparing DSN time-tagged telemetry frames to spacecraft time within the frame. This technique has been successfully demonstrated on NEAR to meet the MESSENGER 70-ms timing accuracy requirement over one week.

An area of potential risk is the fabrication of the radiation-hard ASIC used inside the RIU. A version of this chip, limited to temperature collection, is under contract for a 2001 delivery to JPL for use in the X2000 Outer Planets Program. If MESSENGER RIU chips are not available by spacecraft PDR then the existing chip design will be used to implement MESSENGER's distributed-temperature monitoring architecture, and a traditional method of point-to-point data collection will be used for the remaining analog signals with a small mass penalty.

F.2.8 Guidance and Control

The guidance and control (G&C) subsystem is composed of a suite of sensors for attitude determination, actuators for attitude corrections, and algorithms that are executed in the main processor within the IEM to provide for continuous, closed-loop attitude control. The subsystem satisfies attitude control requirements listed in Table F-2-7. No science

Table F-2-7 Attitude Control Requirements

Control method	3-axis control through 4 reaction wheels
Control reference	Absolute inertial reference - star trackers; Differential reference - gyros
Attitude control	Absolute control: 0.1° (1σ) each axis, at all times Jitter/stability: 25μrad in 100 ms (1σ), each axis Slew rate > 0.1°/s, each axis
Attitude knowledge (instr. interface)	Absolute attitude: 350μrad, each axis (1σ), at all times Drift: < 0.005°/hr (see "Calibration" below)
Agility	Angular acceleration capability > 0.005°/s², each axis
Deployments	Solar arrays, magnetometer boom
Articulation	Solar arrays (one axis)
On-orbit calibration	Gyros continually calibrated and aligned to star tracker onboard
Attitude knowledge processing	Real-time, onboard from star tracker and gyro data (Ground confirmation)

instrument data are used for attitude determination or control. This subsystem is a duplicate of the NEAR attitude system, with the exception that the Ithaco reaction wheels used on NEAR are replaced by the longer-life Litton/Teldix wheels.

In operational mode, the attitude is controlled to a commanded pointing scenario. In safe modes, the G&C maintains the thermal shade at the Sun and places the Earth within the medium-gain antenna pattern to establish ground communications. The G&C subsystem also controls the thrusters for ΔV maneuvers and for momentum management. Finally, the G&C subsystem controls the solar array drives to maintain the correct solar incidence angle for power production and panel temperatures.

The G&C sensor suite is composed of five Sun sensors, an inertial measurement unit (IMU), and two star trackers (Table F-2-8, foldout Fig. F-2-1). The IMU, a key component of the G&C, contains four hemispherical resonator gyros (HRGs) and four accelerometers aligned such that any three are sufficient for three-axis rate or acceleration measurement. Thus a single failure of a gyro or accelerometer can be tolerated. In addition, the IMU contains block redundant power supplies and processing electronics. Normally, only three gyros are powered. Three of the accelerometers are powered approximately 24 hours before each ΔV maneuver to allow for thermal stabilization and are turned off shortly after the maneuver.

The baseline star trackers are the Ball Aerospace CT-631. They are block redundant. Normally, only one star tracker is powered. The baseline Sun sensors are a version of the Adcole digital solar aspect detector (DSAD) modified for thermal protection and isolation. Discussions with the vendor indicate that the necessary modifications are reasonable and feasible. Five sensors and redundant sensor-electronics units are used. Four of the DSAD heads, each with a field of view of 130°, are mounted looking through the Sun shade, with a field of view overlap of 20°. The dual electronics packages provide not only physical redundancy, but also the ability to read solar position from two heads simultaneously for consistency checks. A fifth DSAD head is mounted on the back of the spacecraft and provides partial coverage in the opposite hemisphere to aid in recovery from emergencies. Combining the fields-of-view of the five Sun sensors yields 99% of full omnidirectional coverage. During normal and safe-mode operations both DSAD electronics and all five of the sensors are powered and used for fault protection.

Table F-2-8 Attitude System Components

Item	Component Number and Type	Redundancy
IMU	Gyros (4): Litton HRG Accels (4): Sunstrand QA-3000	Sensors 4 for 3 Electronics - full
Star trackers	(2) Ball 631 CCD trackers	Full
Reaction wheels	(4) Litton/Teledix RSI-4	4 for 3
Sun sensors	Adcole digital solar aspect detector	Full
Array drives	(2) Moog (Schaeffer) type 2	Windings - dual Electronics - full
Thrusters	(1) 645-N, Leros 1b, bipropellant (4) 22-N, bipropellant (10) 4.4-N, monopropellant	Selective

The primary attitude sensors are the redundant star tracker and the redundant IMU. The star tracker operates at 5 Hz and is the primary absolute inertial reference. Differential measurements of attitude at 100 Hz are provided by the IMU's gyros. Measurements from these systems are combined in the attitude determination filter, a recursive estimator operating continually in the IEM main processor. It provides knowledge of fiducial frame attitude to approximately 250 μrad about the star tracker boresight, and approximately 35 μrad about the transverse axes. In addition to attitude and rate, the attitude determination filter estimates and compensates for gyro drift rates, thus greatly reducing the sensitivity of attitude accuracy to transient dropouts or blinding of the star tracker.

The attitude control actuators are the four reaction wheels and the propulsion system's small thrusters. During normal mission operations, all four wheels are powered and act as the primary attitude actuators. The wheels are arranged in a symmetric splayed configuration to provide redundancy in the event of any wheel failure, and provide for symmetric "null space torquing" in wheel speed and momentum management. The thrusters are used for attitude control during trajectory correction maneuvers, for momentum management (as required), and for emergency attitude corrections.

The outputs of the attitude sensor suite are processed at 1 Hz to provide a filtered estimate of the spacecraft state. These outputs are propagated in 40 ms steps until the next 1 Hz update. A desired state is computed from the commanded pointing scenario, which may be specified in an inertial or Mercury-centered coordinate system, using uploaded ephermerides of the Earth, Sun, Mercury, and the spacecraft. Control outputs are generated every 40 ms (25 Hz) to null the difference between the observed state and the commanded state. The fundamental control laws have been proven on NEAR and MSX, where control system accuracy has been demonstrated to be 0.01° or better under dynamic conditions similar to those for MESSENGER.

During ΔV maneuvers, control of thruster firings and the related attitude control is implemented within the 25 Hz loop. Linear velocity is determined by direct integration of IMU accelerometer outputs. To ensure that accelerometer outputs are sufficiently accurate to meet trajectory ΔV precision requirements, individual accelerometer output biases are estimated via long-term very-low-pass filtering of individual accelerometer data immediately prior to the burn. Incorporating a lesson learned from NEAR, accelerometer data are not used for fault-protection during the first second of a large bipropellant burn when large start-up transients are present.

Throughout the mission, solar radiation pressure produces an external force on the spacecraft. This force, if not acting through the spacecraft center-of-mass, results in a external torque. Over time, this torque builds system momentum. The magnitude and direction of the system momentum vector is a function of the solar intensity, spacecraft surface properties, and the offset between the force vector and the center-of-mass. Normally this momentum is captured by changing the rotation speed of the reaction wheels. If, however, this effect is not eventually countered, the wheel speed will increase to a point where a thruster firing is required to lower system momentum and preserve control authority. Frequent momentum dumps via thrusters are undesirable; they are events that introduce some risk and are expensive for mission operations to schedule, test, and execute. A non-propulsive momentum management technique using solar radiation pressure is planned to greatly reduce the number of momentum dumps. This technique has been successfully demonstrated on NEAR, where the spacecraft went over 30 months between thruster-based desaturation events. The G&C on-board software autonomously adjusts the spacecraft attitude, within predefined limits, using solar radiation pressure to produce opposing torques that reduce the system momentum. Preliminary studies indicate that this technique can effectively constrain the momentum buildup to a point where no momentum dumps are expected during the cruise phase, and momentum dumps are needed only once every four days during the orbit phase.

Commercial off-the-shelf design and analysis tools from The MathWorks, Inc., are used for G&C algorithm and flight-code development. These tools lower cost, speed software development, and reduce coding errors. The MathWorks Simulink™ environment allows extensive testing of the various G&C hardware models, as well as the control and attitude estimation algorithms. Following algorithm development, flight code is automatically generated with Real-Time Workshop™. Results from flight-code execution are compared with Simulink™ results for verification of the autocode function. This development process is being used on the TIMED mission.

F.2.9 Flight Software

Flight software (S/W) is contained in the star tracker, inertial measurement unit (IMU), instrument DPU, and IEM. The star tracker and IMU are off-the-shelf items requiring no software modifications. The DPU and IEM software are on-orbit reprogrammable. The DPU software is described in Sec. F.3.9. This software is vital for science, but it is not mission critical.

The IEM software operates in the spacecraft control processor (SCP) and the main processor (MP), described in detail in Sec. F.2.6. For the IEM software, the Accelerated Technologies, Inc., Nucleus Plus real-time operating system compiled with BSO/Tasking C compiler is baselined to provide the required tasking, synchronization, communication, and memory management functions. The TIMED program is using this operating system on their Mongoose processors, so an experience base with over 15 software engineers is in place at APL. Both

MESSENGER processors share a common overall architecture for task interfaces and resource use that prevents deadlock and decouples unrelated processes. Utilities for accessing the IEEE-1394 bus will be available within this architecture. Other areas of common code have been identified. Using common software on both processors will reduce the software development and test time. The flight software is baselined at 55,000 lines of code, or about 25% more than the comparable NEAR software. The software development process is discussed in Sec. F.5.

The functional allocation and CPU margin of the two processors is shown in Table F-2-9. The timing of baseline tasks for each processor has been estimated using adjustments to benchmarks and algorithms measured on similar hardware developed for the TIMED program. Good processing margins exist on both processors. Estimates of the program and large data structure memory requirements are given in Table F-2-10. None of the baseline tasks stretch the memory capacity of the processor design. The memory is sized to hold more than one copy of the applications program, to facilitate reprogramming.

All important communications within the IEM are carried on the IEEE-1394 bus. This is a 50-MHz serial bus with about 44 Mbps of usable bandwidth. The bus margin shown in Table F-2-2 includes estimates of all simultaneous transactions on the IEEE-1394 bus, normal transaction overhead, plus 25% overhead for retries of failed transfers. MESSENGER also uses a MIL-STD-1553 bus to communicate with the instrument DPUs and the G&C sensors. Table F-2-2 shows a 500% margin in 1553 bus traffic estimates, including all simultaneous traffic, normal bus overhead, and 100% overhead for failed transactions.

Table F-2-10 SCP and MP Memory Usage

Item	# kbytes
Nucleus plus	20
C library functions	200
Applications program	825
Stack (50 tasks @ 1000 words/stack)	200
Stack catalog	25
Autonomy rule storage (256 rules)	20
Stored commnads (10,000 8-byte commands)	80
Total	**1370**
% Memory Usage	**34%**

To implement autonomous functions for safing in the SCP and operations in the MP, execution of command sequences stored on board can be triggered at a specified time or when a specific event occurs. Both processors will use the same rule-based autonomy architecture for this function. The use of table-driven rules and stored command sequences eliminates the need for much special-purpose "autonomy software" and decouples the autonomy algorithms from the software development. Both the command processing and rule-based autonomy designs will be minor extensions of the designs used on NEAR and ACE, where the designs have proven powerful and flexible, yet predictable in operation.

The MP will provide considerable autonomous operational capability in carrying out its functions (Table F-2-11). Guidance algorithms use spacecraft, Mercury, and Earth orbit knowledge to maintain a continuous picture of how the spacecraft is oriented with respect to the Sun, Earth, and Mercury. The MESSENGER guidance function will be extended slightly over

Table F-2-9 S/W Heritage and CPU Usage

Function	Heritage	SCP CPU Usage (%)	MP CPU Usage (%)
Command processing	NEAR design	4	1.25
Autonomy rules	TIMED code	6	6.25
Telemetry processing	Normal development	2	8
1394 bus monitor	New	18	—
Guidance & control	NEAR algorithm	—	22
Peak power tracking	TIMED code	—	<<1
Antenna, solar array	New	—	<<1
SSR management	New	—	1.5
IEM Totals		**30**	**40**

Table F-2-11 MP Operability Heritage

Item	Heritage
Multi-body ephemerides guidance	NEAR
Autonomous MDIS scan mirror control	New
Autonomous antenna pointing	NEAR
Autonomous solar array pointing with temperature feedback	New
Event-driven commanding	NEAR
Autonomous momentum management	NEAR
Autonomous power management	New
File system for recorder management	New
File-based data compression	New

the NEAR implementation to include autonomous imager scan mirror positioning, phased-array antenna pointing at Earth, solar-array rotation control, and event-based triggering for data collection and other tasks. These extended capabilities will greatly simplify mission operations, by allowing the use of very high-level commanding, such as "take an image at Mercury latitude = X, longitude = Y". The passive solar pressure momentum management is carried out autonomously, exactly as it is on NEAR. In addition, the MP can implement autonomous power management, such that commanded data collection tasks will be shut down (and associated loads shed) in a priority order, if the spacecraft power is insufficient to carry out all tasks during Mercury hot spot transits. This capability allows the maximum possible data to be taken, given the solar array constraints, without taxing the mission operations planning capabilities.

The MP will implement a file system on the SSR, so that data from each instrument and data collection episode can be randomly accessed. This capability allows the MP to record data quickly during data collection episodes, retrieve selected data for compression during quiet periods, and rewrite the compressed data to the recorder for later downlink. A benchmark of lossless fast compression and 6-to-1 wavelet transform compression indicates background compression of a 12-Mbit image will take less than five minutes. This processing speed is more than sufficient to compress hundreds of images before downlink during the orbit phase.

F.2.10 Fault Protection

In common with other interplanetary spacecraft, MESSENGER will spend long periods of time out of ground contact. MESSENGER has one 35-day solar conjunction period where design for unattended operation is necessary. Even during ground contacts, the speed of light limits usefulness of real-time telemetry and commanding. Under these conditions, autonomous detection and correction of faults is a key area of spacecraft design. The goal of the fault protection design is to detect health-threatening faults, and to keep the spacecraft safe until the next ground contact. Fault diagnosis and correction (beyond that needed to keep the spacecraft safe until the next ground contact) is a ground-based mission operations team function.

Fig. F-2-25 is the operating mode state transition diagram. Recoverable faults are handled in Operational Mode. An example of a recoverable fault is an anomaly in a noncritical subsystem, such as an instrument. For a recoverable fault, the offending component is turned off and the spacecraft remains in Operational Mode. Any serious fault affecting a critical spacecraft subsystem results in remedial action (such as bringing a backup system on-line) and entry into Safe Hold Mode. Table F-2-12 lists candidate events that cause entry into Safe Hold Mode.

In Safe Hold Mode, the thermal shade is pointed at the Sun, the MGAs are placed in the ecliptic plane, and the top deck pointed to the North ecliptic pole. Safe Hold Mode requires inertial reference. The Inertial Reference Acquisition Mode is used if the fault causes the G&C subsystem to lose inertial reference, for example, when switching between redundant MPs. The spacecraft telecommunication and power configuration is set according to a reprogrammable table stored in nonvolatile memory that turns off instruments and other noncritical subsystems, while powering all of the necessary systems (such as the backup Star Tracker) that may be used for recovery. The table selects the MGA and LGA that are currently facing Earth. Uplink communications are received through both an MGA and an LGA. If an extended period with no ground communications occurs, the antenna configurations are switched in a round-robin fashion.

The most critical aspect of spacecraft safety is maintaining a safe thermal environment. Most

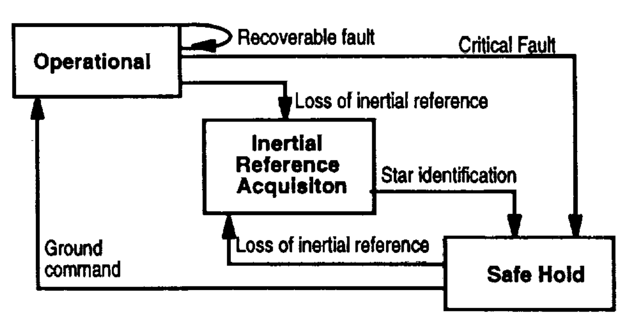


Fig. F-2-25 The state transition diagram for the fault-protection system is simple and robust.

Table F-2-12 Safe Hold Mode Events

Thermal shade pointing violation
Solar panel temperature exceeds maximum allowable limit
Top deck temperature exceeds maximum allowable limit
Low bus voltage
Main processor reset or processor-health check failure
Command-loss timer expires
ΔV abort (e.g, attitude, acceleration, or rate violation)
Autonomous thruster use
Star tracker failure or extended loss of star identification
Autonomous IMU reconfiguration (gyro failure)
Sun sensor failure or loss of sun vector when not in eclipse
Battery charger failure or battery over temperature
Invalid spacecraft configuration (minimum required loads not powered)
Fuel tank overpressure
Loss of mission time or invalid orbit
1553 or 1394 bus timeout failure or excessive number of failed transactions

importantly, the thermal shade must be between the spacecraft and the Sun. Second, the heat-sensitive top deck of the spacecraft must not be exposed to a large thermal input from the sunlit side of Mercury. (In normal operations, the top deck never views the hot planet at close distances.) Finally, the solar incidence angle on the arrays must be controlled to limit the maximum cell temperature.

All safing is performed in the IEM's SCPs. Both SCPs are continuously powered and perform identical health and safety checks. The SCPs monitor the Sun direction, to verify that it is within the keep-in zone allowed by the thermal shade at all times. A set of redundant DSADs provides not only physical redundancy for this important function, but also the ability to read solar position from two heads simultaneously for consistency checks. The SCPs monitor the redundant top deck and solar array temperature sensors to verify they are below a programmable, safe limit. If an SCP detects a violation of the thermal shade keep-in zone or that the top deck or arrays are outside acceptable temperature limits, it selects the backup MP, and initiates Safe Hold Mode.

During MP initialization, the spacecraft enters Inertial Reference Acquisition Mode. An initial dither of 5° around the thermal-shade normal fills in the missing 1% of full DSAD coverage, guaranteeing that a DSAD is illuminated if the spacecraft is not in eclipse. The dither is repeated until one or more DSADs give a Sun-line reference. The DSADs are used to point the thermal shade and control the solar array angle. The spacecraft goes to zero rate and the thermal shade points toward the Sun line, while waiting for the star trackers to provide an inertial reference. If, while waiting for the star trackers, the top deck temperature exceeds a high limit (higher than the safe limit used to initiate the MP switch), then the spacecraft is rolled about the Sun line, and again controlled to zero rate. When inertial reference is obtained, the spacecraft is sent to Safe Hold Mode. In this simple safing algorithm, knowledge of mission time or orbit is not required.

Recovery from Safe Hold mode is straightforward. Using data transmitted at the emergency rate, the on-board problem is diagnosed and corrected by mission operations. The spacecraft can then be commanded to Operational Mode; only ground command can promote to Operational Mode. The spacecraft has extensive facilities for diagnostics of on-board problems, including a command history buffer, an autonomy history buffer, an attitude history buffer, snapshots of spacecraft data when Safe Hold Mode was entered, and a data summary area that records time-tagged high and low values of each piece of spacecraft housekeeping data.

The safing function of the SCP is carried out completely through the use of rules that invoke command macros. These rules compare any of the spacecraft data — analog, relay telltale, digital from the IEEE-1394 bus — to limits or ranges that indicate improper operation. Each rule is associated with a timer, and the detected condition must persist for the rule-timeout before action is taken. Once a rule detects a condition that must be addressed, a series of commands is executed to correct the condition and safe the spacecraft. While the SCP carries a set of default rules and command macros that will be loaded in case of processor reset, any of the rules can be deleted or changed, new rules can be added, and the command series modified to meet changing conditions throughout the mission. The concepts incorporated in the rule-based system were developed and used on the NEAR and ACE spacecraft. On both NEAR and ACE, the safing has proved predictable and reliable.

In December 1998, NEAR aborted its rendezvous burn because the turn-on transient of the bipropellant engine exceeded expected levels. Following the burn abort, the main guidance and control system processor used the thrusters incorrectly, causing a loss of fuel and delaying the rendezvous for one year. The NEAR fault-protection rules were designed to detect and correct such a failure. Currently, the investigation into the anomaly has shown that the failure was properly detected and the desired corrective action was taken, but the action did not correct the problem immediately. As of this writing, the cause of the failure has not been definitively identified. Initial results suggest that a command sequence error was responsible for the problem, which continued until the fault protection switched to a completely different G&C software segment, using a different algorithm, that corrected the problem.

For MESSENGER, to prevent a software error replicated on redundant MPs from causing the loss of the mission, a small subset of critical functions are developed twice, by separate teams. Using this approach, a completely different implementation of each critical function is exercised if the redundant computer is used. Some candidate functions for this special treatment are the Inertial Reference Acquisition Mode, solar array temperature control loop, and autonomous thruster use for momentum management. A switch to the redundant MP and the separately-coded software is made swiftly when spacecraft-threatening conditions are detected.

The rule execution software is part of the SCP software development (Sec. F.2.9). Development of the fault-protection rules is a system-engineering function. The overall architecture, including spacecraft modes, is defined first. Subsystem error conditions and corrective actions are collected from the subsystem leads and integrated into a comprehensive rule set. The rule set is integrated with the SCP software and tested at the breadboard level. Wherever possible, subsystem and SCP breadboards are interfaced to verify rules prior to spacecraft integration. The entire rule set is retested at spacecraft level, with the flight hardware and software, particularly to identify any rule interactions. Postlaunch, rule modifications are tested using the engineering model simulator.

F.2.11 Communications Approach

The first scheduled DSN contact is 50 minutes after launch. The forward and aft hemispherical LGAs are connected to the redundant transponders to yield effective omnidirectional coverage. Twenty-four-hour DSN coverage is scheduled for the first five days. Uplink during all nominal contacts is at 62.5 bps; downlink during early operations is >1000 bps. DSN coverage is gradually reduced as initial instrument calibrations are completed and confidence is gained in spacecraft performance. The uplink and downlink designs are fully CCSDS-compatible.

Cruise phase is designed to minimize operations support except for short periods of intense activity around the flybys. Typical DSN coverage is two 4-hour passes per week. The DSN requirements for cruise phase and all critical mission events are shown in Table F-6-1. The 34-m coverage is split between the HEF and BWG antennas, depending on the required uplink transmitter power. During the 5.5-year cruise phase 26% of the coverage requires HEF antennas; 74% can use BWG antennas. The spacecraft antenna configuration is chosen so that all critical mission events are monitored with real-time telemetry. Normally, uplink is through the MGAs and downlink is through the phased-array antennas. See Table F-2-13 for the telecommunication parameters. Doppler tracking is used for navigation. During each DSN pass the APL Mission Operations Center (MOC) monitors spacecraft health, uplinks commands for the following two weeks, and downlinks recorded data.

During the orbital phase, one 8-hour 34-m DSN pass is scheduled daily, with one hour of each pass allocated for DSN setup. See Sec. F.2.4 for downlink analysis. For this phase 63% of the coverage requires HEF antennas, and 37% can use BWG antennas. Doppler tracking and occasional ranging are used to satisfy navigation and science requirements. During each pass, the MOC monitors spacecraft health and downlinks recorded data. The data flow through the MOC into the APL Science Operations Center (SOC).

Emergency communications are through the LGAs and MGAs. Uplink is 7.8 bps and downlink is 10 bps. The antenna configuration supports an LGA uplink and a MGA downlink over the entire mission using the 70-m DSN antenna while maintaining thermal shade attitude requirements (Fig. F-2-26).

Table F-2-13 Uplink, Downlink, and Telecommunication Parameters

Max spacecraft distance (AU)	1.87	S/C receiver bandwidth (Hz)	20
Mercury flyby distances (AU)	1.1, 0.65	Turnaround ranging	Limited use
Uplink transmitter power (kW)	4 - 20	S/C transmitting power (W)	11.0 and 15.0
Uplink frequency band (GHz)	7.2	Downlink modulation format	PCM/PM
Uplink transmitting antenna gain (dBi)	67.1	Downlink frequency band (GHz)	8.4
S/C receiving antenna minimum gain (dBi)	10.0 MGA, -2.0 LGA	S/C transmitting antenna gains (dBi)	27.0 HGA, 10.0 MGA (min.)
Telecommand data rates (b/s)	62.5, 7.8	Downlink receiving antenna gain (dBi)	68.2
Telecommand bit-error-rate	10^{-6} with 3 dB margin	Telemetry data rate (b/s)	Various, 10 to 40,000
Uplinks per week	1	Error detecting-correcting code	R=1/6, K=15 +RS
Bytes per uplink	84,000	Telemetry bit-error-rate	10^{-6} with 3 dB margin
On-board storage	2000 Mbytes	Average orbit phase data rate, volume	2.3 kbps, 7.3 Mbytes/day
Spacecraft data destination	APL MOC	Data dump frequency (cruise, orbit phase)	2/wk (4 hrs), 1/day (8 hrs)
Science data destination	APL SDC	Max data delivery lag to APL (hrs)	24

During both cruise and orbital operations, periods of solar conjunction preclude communications. Prior to these times, the spacecraft is placed into a safe-hold mode. No events requiring ground commands occur during solar conjunction periods.

The frequency licensing plan is shown in Table F-2-14. It is the same approach as used on NEAR.

F.2.12 Radiation Analysis

The standard JPL interplanetary radiation-dose model (Feynman et al., 1993), including solar cycle effects, was used to compute the annual fluence for the 2375-day MESSENGER mission. No appreciable contribution is expected from trapped radiation in any possible stable radiation belt at Mercury (Russell et al., 1988). On the basis of analyses described below of the best mission radiation data, there is nearly no radial dependence of radiation total dose with r, the spacecraft distance to the Sun. However, to provide additional margin, a r^{-1} radial dependence is assumed for generating the component-level radiation requirements.

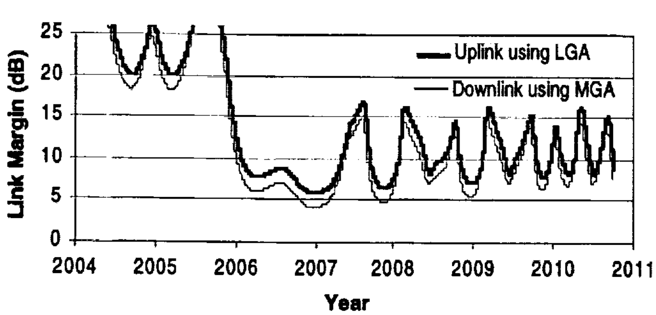


Fig. F-2-26 Emergency link margins, using the 70-m DSN, are > 3 dB.

Interplanetary proton fluence models contain little substantive information at distances <1 AU; early modelers postulated a conservative r^3 dependence inside Earth's orbit (Feynman et al., 1990), even though analysis of Helios data suggested r^2 as an upper limit (e.g., Roelof, 1979). More recent analyses of Ulysses and IMP-8 data show that, after an onset, there is no radial dependence during the majority of energetic proton events within the inner heliosphere (Roelof et al., 1992).

Only weak radial dependence of energetic particle fluence has also been confirmed by data collected simultaneously from Helios 1 at close Sun distances and IMP-8 at 1.0 AU over nearly a full solar cycle. Daily-averaged intensities from 1975-1983 of 45-56 MeV protons (enough to penetrate 11 mm or 3.0 g/cm^{-2} of Al) at each spacecraft are shown (Fig. F-2-27). Solar-rotation-averaged fluxes give a radial dependence of $r^{0.6}$, actually slightly lower than at Earth during this interval. Within the errors, the fluxes are the same, or slightly lower, at Mercury.

Using the Feynman et al. (1990) model for 1 AU fluxes at 95% confidence level and applying an r^{-1} intensity dependence yields 13,000 rads (Si) for 2-mm Al shielding and 4,000 rads (Si) with 13-mm Al shielding for boxes near the center of

Table F-2-14 Frequency License Plan

Frequency license approach	Request to National Telecommunication and Information Administration (NTIA) via NASA, with help of NASA Spectrum Manager
Frequency license schedule	Stage 2 request, International Telecommunication Union (ITU) advanced publication — April 2000 Stage 3 request — April 2001 Stage 4 request, ITU notification — April 2002 Final operational approval — March 2003

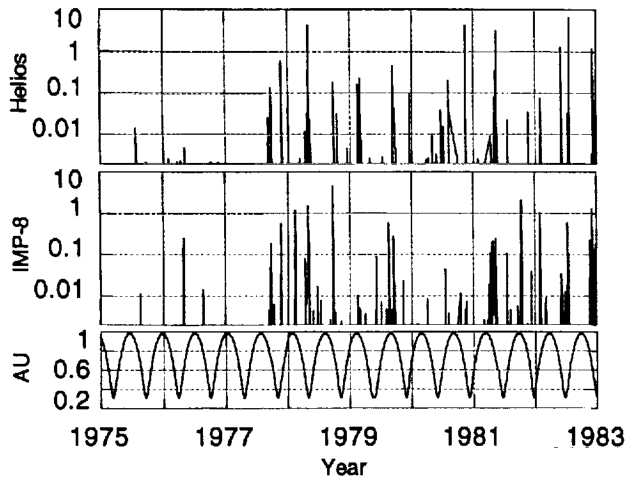


Fig. F-2-27 A regression analysis of daily average fluxes of 45-56 MeV protons from IMP-8 and Helios 1 yields a radial dependence of $r^{0.6}$. The bottom panel is the Helios-Sun distance.

the spacecraft (Fig. F-2-28). These doses are significantly lower than the 20,000 rads (Si) with 2-mm Al shielding component-level radiation requirement (Table F-2-2). The conservative r^{-1} intensity dependence of particle fluences was used in the solar panel degradation model that provided the requirements for the solar array size (Fig. F-2-29).

F.2.13 Launch Vehicle and Interface

Fig. F-2-30 on the foldout shows the spacecraft in the Delta II 7925H 9.5-ft fairing. Clearances exist in all areas. The standard 3712C payload-attach fitting provides the separation interface, separation actuators, electrical disconnects, and pads for the separation switches. The center of gravity of the spacecraft is 0.82 m above the separation plane, well within the allowable 1.65-m distance. Standard 12.8°C, class 10,000 air conditioning, a T-0 purge, and fairing cleaning to the VC 2 standard are required.

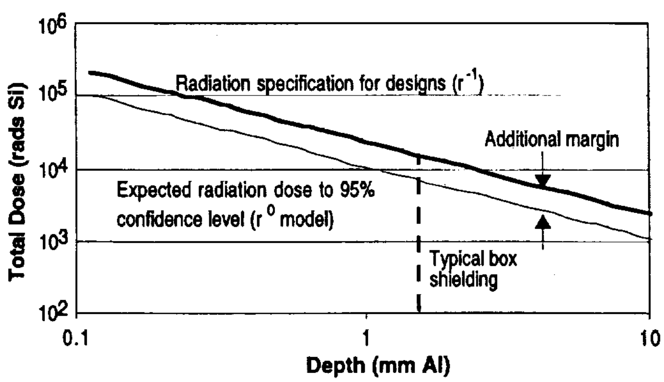


Fig. F-2-28 A conservative total dose estimate is used to provide additional design margin.

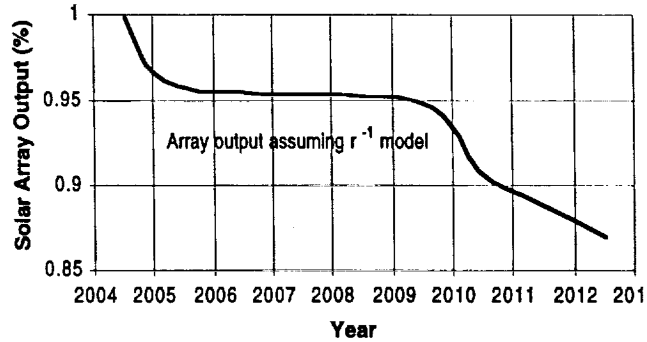


Fig. F-2-29 A conservative solar- array degradation model using r^{-1} dependence, assuming 0.3 mm cover glass.

F.3 Science Payload

The science payload described in the Phase-One proposal meets all of the mission requirements and remains unchanged. The Concept Study has examined the details of implementing the payload and its accommodation on the MESSENGER spacecraft. Key margins have been identified and allocated.

The science payload includes a highly integrated suite of seven instruments that are listed in Table D-1-10. The mass, power, data rate, daily data volume, heritage, and average Technical Readiness Level for the technologies used within each instrument are also contained in the table. The mass and power numbers are "not-to-exceed." However, since unavoidable design changes may be forced on one or more of the instruments during the development phase, a 5-kg reserve has been allocated to the science payload mass prior to applying the overall mass margin (Table F-2-1). This strategy helps ensure that the instruments can be built within cost and on schedule. The carefully developed integration of the payload forms an important element of the overall cost and schedule performance of the MESSENGER mission. In addition, multiple instruments contribute to each of the science objectives, and each of the instruments contributes to multiple science objectives. This extensive bidirectional overlap helps to reduce the criticality of any one instrument.

The science payload and the spacecraft implementation minimize both design and operations costs. This outcome is accomplished by keeping the designs as simple as possible and restricting most instruments to only a single operating mode, with integration time the only parameter changed during normal operation. All of the instruments, except MAG, are fixed body-mounted, and there are almost no moving parts. The MESSENGER spacecraft will automatically point the instruments at desired targets and autonomously snap images or change integration intervals based on spacecraft-computed events such as the distance from the planet or crossing the terminator (Sec. F.2.9).

All of the instruments communicate with the spacecraft through a common, fully redundant, data-processing unit (DPU). The entire instrument suite is integrated as a unit and thoroughly checked before integration with the rest of the spacecraft. This order helps to decouple instrument and spacecraft developments and reduces the possibility of problems late in the MESSENGER program.

A brief description of each instrument is presented in Sec. D.1.5. Fig. D-2-1 contains the instrument layouts and block diagrams as presented in the Phase-One proposal and updated with the Concept Study changes. During the Concept Study there have been only very minor changes made to the instruments from the Phase-One proposal. The specific changes are listed in Table F-3-1. These changes and the implementation features examined during the Concept Study are detailed within each instrument description below.

The risk management of the science payload development is handled as a consistent part of the overall spacecraft risk management plan (Sec. G.4.1). Each of the risk items in the payload has been accepted into the design because its benefits justify the risk. Each item has realistic fallback options if the development runs into difficulty. The science payload risk management plan has set specific milestone events for each risk item. Failure to meet these milestones triggers the switch to a fallback design. The principal payload development risks and their fallback options and impacts are listed in order of their importance in Table G-4-2. The subjective, normalized level of risk and the potential impact of that risk on the payload development are listed in Columns "R" and "I" of the table, and they are plotted in Fig. G-4-2. Specific plans to mitigate these risks are contained in each instrument discussion.

Table F-3-1 Instrument Changes

GRNS	Shield length extended to 100 mm; better defined field of view
MLA	Telescope diameter increased to 25 cm, baffle added
XRS	Discrete-reset feedback adopted; better thermal and radiation resistance
	Solar monitor mounted separately; simplifies testing and integration
DPU	Lossless and lossy compression available to all instrument data

F.3.1 Mercury Dual Imaging System (MDIS)

The basic features of the compact twin-imager MDIS are described in Sec. D.2.1. Principal characteristics are listed in Tables D-2-1 and D-2-2. The wide-angle (WA) and narrow-angle (NA) imagers are coaligned and view through the common scan mirror. WA has an aperture of 7 mm; NA's is 25 mm. The throughput of WA is 4.6 mm^2 sr; that of NA is 0.26 mm^2 sr. This difference reflects the focal ratios of the two systems. The WA system has a filter wheel, and the narrowing of the spectrum plus the insertion losses of filters bring the signal levels for the two detectors close to the same value. With the illumination at Mercury up to 10 times that at Earth, it is easy to fill the well of the CCD for both imagers and ensure high signal-to-noise ratios. The very high illumination at Mercury requires the ability to handle short exposure times, while stellar optical navigation images and peering into deep shadows require much longer exposures. MDIS has an exposure range of 0.1 ms to 10 s.

Wide Angle and Narrow Angle Imagers. The wide-angle imager (WA) uses a Ploessl reversed-eyepiece design. The small entrance aperture stop, close to the scan mirror, helps minimize the size of the mirror and reduces scattered light susceptibility. The lens is close to telecentric, i.e., the chief ray from each point in the object plane is parallel to the optic axis at the image plane. The telecentric design eliminates any off-axis spectral broadening in the filter wheel, and it provides more uniform illumination across the full field of view. A small field-flattening lens next to the CCD ensures a very small spot size over the full wavelength range. Ray-trace analysis shows good image quality (Fig. F-3-1). WA is achromatic; the spot size is smaller than a 14 μm pixel nearly to the edge of the field. The focal length is 35 mm and the lenses are 30 mm in diameter. In this very compact design the distance from the aperture stop to the image is only 79 mm.

The narrow-angle imager (NA) field of view was chosen for good resolution at large distances and excellent resolution when MESSENGER is near periapsis. A folded reflecting design is used for compactness. It is an off-axis section of a Ritchey-Chretien telescope. The optical layout is shown in Fig. D-2-1. The main resolution limitation is diffraction so the aperture is kept large, at 25 mm. The radius of the first diffraction dark ring is 11 μm, larger than the 7 μm radius of a pixel. Ray-trace results for NA are shown in Fig. F-3-2.

Filter wheel. An eight-position filter wheel in the WA selects seven wavelengths of interest and a "clear" filter as given in Sec. D.1.5. Filter thicknesses are optimized to minimize aberrations at each wavelength. The filters are square, and the wheel employs a compact "pie pan" design to eliminate unused space between filters, minimize the wheel diameter, and increase rigidity. The close filter spacing ensures that even a failed filter wheel will not block all light from the imager. The filter wheel stepper motor and drive electronics are the same high-reliability, compact units used on the Geotail's Energetic Particles and Ion-Particle Experiment (EPIC), NEAR's X-ray and Gamma-ray Spectrometer (XGRS), and NEAR's Multi-Spectral Imager (MSI) filter wheels.

Camera Heads. The focal plane assemblies for WA and NA imagers are identical (reducing development costs). They include a Thomson THX7887A 1024x1024 CCD detector, the camera electronics, a single-stage thermoelectric cooler, and a controller. The THX7887A is a frame-transfer device with 14 μm pixels, a full-well depth of 250,000 e^-, and anti-blooming and electronic shuttering. The THX7887A is divided into four zones of 1024x256 pixels, each of which is read out separately. This arrangement enables much more rapid readouts and permits exposures on 1-s intervals. APL-developed cameras operating on MSX and NEAR used a smaller but similar Thomson CCD.

The VLSI camera clocking and readout chips were developed for APL's 500-g miniature modular camera with a Planetary Instrument Definition and Development Program (PIDDP) grant. The frame-transfer time is 0.819 ms, limited by the peak clock-driver current. The pixels are read out at up to 1.25 million pixels per second and quantized to 12 bits for a total readout time of 0.919 s.

Non-rad-hard VLSI camera parts have been developed and successfully tested. The development of the rad-hard, flight parts is low risk; resources exist if an additional foundry run is necessary. Flight parts will be built by another program prior to MDIS PDR. If extended problems arise in their production, a discrete-component camera head can be built with a 0.5-kg mass impact.

The CCDs are cooled by small single-stage thermoelectric coolers (TECs) heat sunk to the spacecraft deck. They remove 0.88 W of thermal energy from the CCD (including up to 250 mW of Mercury thermal IR) for an input power of 4.7 W, including the controller. The CCD should be kept below 0°C for good SNR during short exposures, and the coolers provide nominal CCD operating temperatures of -52° to -30°C. In the worst case, viewing near the Mercury subsolar point, the CCD temperature is -17°C. The worst case dark current level at -10°C is 1012 e^- for a 1-s exposure.

MDIS has programmable electronic shuttering with exposure times from 0.1 ms to 10 s. The

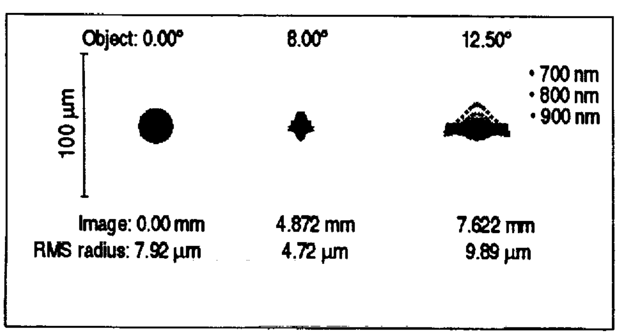


Fig. F-3-1 Ray-trace spot diagram for WA imager at three wavelengths and angles shows good spot size and very little chromatic aberration.

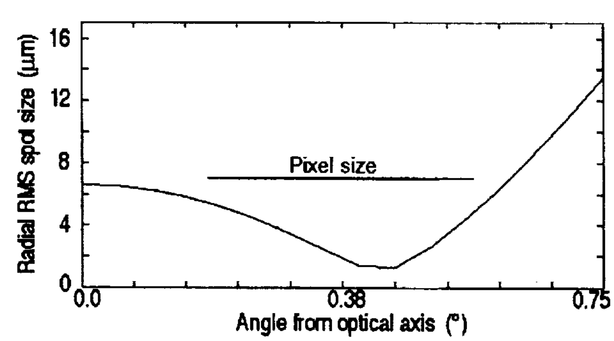


Fig. F-3-2 Ray trace of the NA imager shows spot radii are small compared with the pixels over most of the image field.

built-in automatic exposure algorithm can be selected for any image. It takes a test image ~5 s before the desired image and calculates the correct exposure with a two-parameter algorithm. The algorithm can be revised by ground command. The readout VLSI chip also has the ability to select 2 x 2 pixel on-chip binning for 512x512 images.

Scan Mirror and Heat Rejection Filter. The scan range extends from -20° (toward the spacecraft thermal shade) to +50° (away from the thermal shade) from the normal to the bottom deck as shown in Fig. D-2-1. This range provides enhanced resolution during the flybys and better coverage of lower to mid latitudes during the orbital phase. The design minimizes the size of the scan mirror and the entrance window. The WA aperture is located 26 mm in front of the lens, close to the mirror. The NA beam spread is small enough that its distance is not critical. Its aperture stop is close to the mirror to minimize stray light. The rotation axis of the mirror is offset from its center. Thus, as it rotates away from the lenses, it gives maximum clearance for the beam.

The scan mirror is actuated by a small 1.8° stepper motor with redundant windings. A 72:1 gearhead produces angular steps of 0.025° on the CCD, repeatable to 0.0025° (44 mrad). A fiducial system, with a small set of light-emitting diodes and phototransistors, is accurate to one step at nadir. Other fiducials are located at the ends of travel. The mirror can servo to nadir with the fiducials. Steps are accurate to within 10%. Continuous testing of the scan-mirror mechanism in hard vacuum at APL has now exceeded 3 years and 4.2 million scans.

Baffle (Sun Shade). MDIS is always in shadow, and no glint is expected. A baffle (sun shade) in front of the imager helps to reduce stray light from portions of the planet outside the FOV and also protects against any unexpected glint. The baffle also reduces heat loading on the camera from the subsolar regions of the planet. The baffle is constructed from thin, 0.125-mm (0.005-in), black-oxidized stainless steel that is thermally isolated from the MDIS body by insulating buttons. The exterior is thermally blanketed. The shadowing and poor thermal conductivity of the stainless steel further improve the already benign environment for MDIS and reduce the peak MDIS temperature. The baffle entrance reaches 200°C at low altitudes when viewing near the subsolar point, while the MDIS remains below 33°C (Fig. F-2-14).

Scattered light control is important for any imager design that has a first optical element that can be illuminated by areas outside the field of view. The baffle limits the ray paths that can reach the heat-rejection filter to those within the field of regard. Veiling glare calculations show that the expected full-field effect is less than 0.02%. Additional design features such as blackening of the MDIS interior body, internal baffles, the small WA entrance pupil, and careful contamination control during design and manufacture help keep scattered light under control. Scattered light will be characterized early in MDIS testing to help prevent any need for late design modifications.

F.3.2 Gamma-ray and Neutron Spectrometer (GRNS)

The GRNS measures a wide range of elemental abundances and looks for hydrogen (e.g., water ice) near the Mercury poles. Over the course of orbital operations, planetary composition is determined at a variety of scales. By detecting cosmic-ray-excited characteristic gamma-ray emissions from Mercury, GRS remotely senses the presence of many elements (O, Si, S, Fe, H) as well as natural radioactivity from K, Th, U. The absorption lengths for gamma-rays allows GRS to probe Mercury's surface to a depth of ~10 cm.

The generally weak gamma-ray emissions require the GRS to have a wide FOV (~45°) and long observation times. GRS observes continuously and produces telemetry at a low rate in a fixed-packet format. To optimize spatial resolution without increasing the overall data volume, GRS integration times are varied throughout the Mercury orbit to achieve a spatial resolution of approximately 1200-km x 160-km at periapsis. At higher altitudes the integration time is lengthened and the GRS footprint grows until it encompasses an entire hemisphere at altitudes above 6000 km. Spectra from repeated tracks will be summed during ground analysis to achieve the required sensitivity. Larger areas may also be combined as necessary to reduce the uncertainty in elemental composition at the expense of spatial resolution.

The GRS design is based on an active-shielded scintillator that provides high sensitivity and excellent background suppression and operates without cooling. The basic characteristics of GRS are listed in Table D-2-3. The central detector of GRS is a CsI(Tl) scintillator with a large-area photodiode coupled at each end. Photodiodes eliminate the heavy photomultiplier tube (PMT) and minimize the intervening mass between the planet and the central detector. CsI is a room-temperature detector that is nearly immune to radiation damage. For the shield, a single crystal Bismuth Germanate (BGO) cup couples to a PMT. The active shield eliminates the cosmic ray background and reduces the locally-generated backgrounds from the spacecraft. It suppresses the Compton and pair-production contribution to the background and defines the ~45° FOV. Coincident shield counts also recover the first and second photopeak escape events from the central detector. This design, demonstrated on NEAR (Fig. F-3-3), provides more than three orders of magnitude background suppression and allows the detector to be mounted directly to the spacecraft, eliminating the need for a long heavy boom.

Similar CsI(Tl) detectors coupled to photodiodes are being developed for the Gamma-ray Large Area Space Telescope (GLAST) mission, so they are not a large risk (see Table G-4-2). However, if there is a delay in the manufacture of the GRS detector, a NEAR-like design that uses a PMT for readout of the central crystal can be substituted with a small increase in mass (~0.5 kg) and reduced performance caused by the PMT mass in line with the detector.

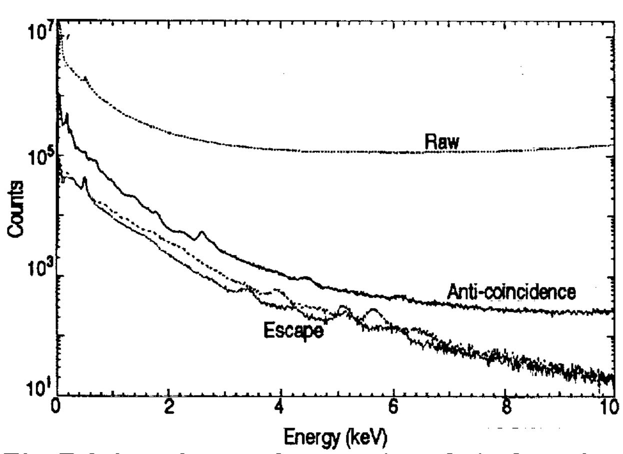


Fig. F-3-3 Background supression of 3 orders of magnitude on the NEAR γ-ray instrument.

The Neutron Spectrometer (NS) is a very sensitive indicator of materials with a significant hydrogen content, and it will help determine the composition of the radar-reflective regions at the Mercury north pole. The ^{6}Li-enriched glass scintillator material has a high neutron cross section, and the ^{6}Li(n,α) reaction releases 4.78 MeV, which makes it very resistant to cosmic-ray and gamma-ray backgrounds. The three segments of NS separate thermal neutrons and epithermal neutrons from the background cosmic rays and gamma rays. Segment one responds to thermal neutrons, epithermal neutrons, and background. Segment two responds to epithermal neutrons and background. Segment three, which uses a ^{7}Li scintillator, responds only to the background cosmic rays and gamma-rays. Difference pairs of these three segments are used to generate the pure thermal and epithermal neutron signals. The GS20, neutron-sensitive, glass scintillator material used for segments one and two contains 18% lithium oxide by weight, and the lithium is 95% ^{6}Li enriched. The GS30, neutron-insensitive glass scintillator material used for segment three is also 18% lithium oxide by weight, but the lithium is 99.99% ^{7}Li.

F.3.3 Magnetometer

The magnetometer (MAG) will characterize Mercury's magnetic field and achieve significant improvement over the present field models. Fig. F-3-4 shows MESSENGER coverage of the Mercury magnetosphere during the two noon-midnight orbits (at Mercury true anomaly of 67° and 247°) with hourly tic marks; approximate positions of the Mercury bow shock and magnetopause are also indicted. MESSENGER will provide excellent coverage of the interactions at the Mercury bow shock and magnetopause along with good substorm coverage in the close-in magnetotail.

Total magnetic field errors from all spacecraft sources are less than 1 nT at the MAG probe on the end of the 3.6-m boom. At this level, measurement error is the significant factor limiting either internal field or magnetospheric magnetic field models. The extensive latitude and longitude coverage at small radial distances decouples the low-degree terms in the spherical harmonic expansion of the field. Sampling of the vector magnetic field is nominally one vector every 10 s during the nine hours surrounding apoapsis and 10 samples per second during the three hours surrounding periapsis. In addition, 40-Hz data are taken periodically to characterize the boundary regions around the bow shock and magnetopause.

The design for the triaxial fluxgate sensor is the same as that used on many deep-space missions including Voyager, Giotto, Mars Global Surveyor, NEAR (Lohr et al., 1997), WIND, and Lunar Prospector. MAG uses 1.25-cm ring-core assemblies mounted on a boom deployed in the anti-Sunward direction with its own miniature thermal shade. This assembly can operate up to +180°C. The use of a thin-walled composite boom keeps the design within the mass allocation. Sensor electronics boards are packaged in a small chassis near the base of the boom and communicate via a serial interface to the DPU.

The sensor element is essentially used as a null detector in a feedback loop. The miniature electronics utilize a crystal oscillator to drive the sensor cores at 15 kHz. A 30-kHz signal clocks a synchronous detector. The synchronous detector output drives a field-canceling current to drive the circuit back to the zero field point. The three field-cancelling currents are digitized as the field measurement. This technique eliminates the need for high-gain, low-power, low-noise amplifiers, which can be extremely

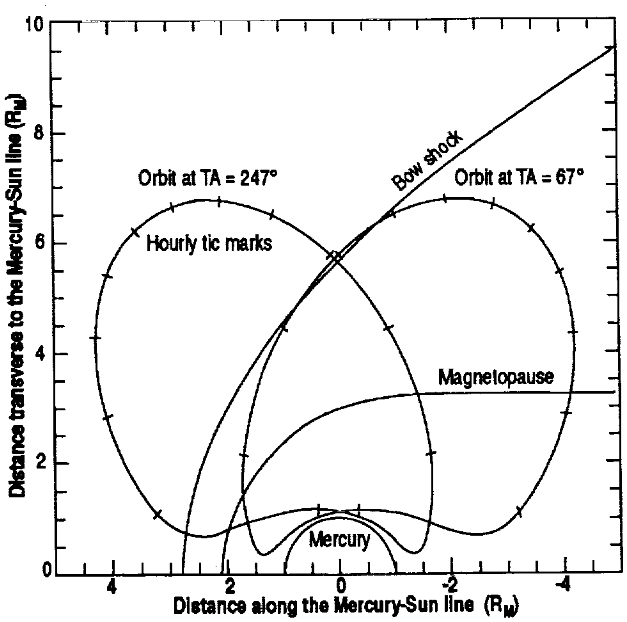


Fig. F-3-4 The MESSENGER orbit samples most of the Mercury magnetosphere.

sensitive to interference and radiation-induced degradation. DPU software processes suitable averages and low-pass filters the data. Filter cutoffs are selected between 0.5 and 20 Hz. Sampling below 0.5 Hz uses discrete samples of 0.5 Hz data. The digital electronics are the same advanced design as on NEAR. However, the packaging of the electronics has been miniaturized for MESSENGER.

The MAG ring-core geometry exhibits superior long-term stability with minimal drive power. The magnetic cores are an advanced molybdenum-permalloy developed in cooperation with the Naval Surface Weapons Center that has unmatched noise and offset performance. The MESSENGER cores have been selected from the remaining stock produced at NSWC. Sufficient numbers of flight and spare units exist at GSFC. With these cores, zero-offset stability is better than ±0.2 nT from -30° to +75°C for periods exceeding one year. Long-term drifts will be calibrated in-flight yearly with the solar wind and spacecraft roll, pitch, and yaw maneuvers.

The Science Team and spacecraft engineering team work closely together to control the spacecraft magnetic field during design and spacecraft integration (Sec. F.4). Major magnetic components, such as propulsion system valves and solar array drives, will be evaluated during the design phase. Plans will be developed to reduce their stray fields or to shield them before the flight systems are constructed. The Science Team will also assist in the plans for solar cell wiring and spacecraft harness routing to eliminate uncompensated current loops. This early cooperation greatly reduces the risk of finding magnetic problems during I&T (Table G-4-2).

F.3.4 Mercury Laser Altimeter (MLA)

The MLA determines the range to the Mercury surface by measuring the round-trip travel time of laser pulses transmitted from the spacecraft to the surface. Each detected laser pulse gives an independent, high-resolution measurement of the slant range and echo pulse width. From these, the height and slope or roughness of the Mercury surface can be determined, given corrections for the position and attitude of the spacecraft. The altimeter collects data continuously in a fixed packet format while it is pointed at the surface. MLA operates in a single autonomous mode.

For orbital altitudes between 200 and 1000 km, MLA provides topography with 10 to 45 m footprints at spacings of 100 to 300 m. The laser only fires for about 40 minutes per 12-hour orbit and is a candidate for event-driven commanding. Measurements are quantized to < 0.75 m. MLA design parameters are presented in Sec. D.1.5 and are summarized in Table D-2-4. Outline drawings and a block diagram are shown in Fig. D-2-1.

The arrival times of the photons in the echo pulse are recorded by the receiver's photon timing unit. The measured width of the echo pulse is used in post-processing analysis to adjust the timing estimate to the center of the echo pulse. The width and position of the range-gate mask is adjustable around the expected time of the echo pulse. If the echo pulses are lost, the gate is widened. When MLA is in "acquisition mode," the range gate width is > 900 km.

Knowledge of the tilt of the instrument's optical axis relative to the center of the planet is the most significant source of error in the range determination. Echo-pulse broadening is an important factor when MLA is pointed off nadir. However, at nadir, when the surface is flat to within 2°, the echo pulses undergo little broadening. When the tilt off normal is > 2° (or there are equivalent height variations), the echoes are broadened and the vertical precision is ~ 10% of the echo widths.

The MLA performance can be summarized by computing the measurement probability (Zuber et al., 1992) and the range jitter. Measurement probability quantifies how likely a successful measurement is for given orbital orientation, range, and instrument conditions. Worst-case conditions occur at the time of the noon-midnight orbit, where the limited allowable pitch about the spacecraft x-axis causes significantly longer slant ranges at lower latitudes (~1000 km at 32°N latitude) and large angles for the laser beam relative to the surface normal. Under these conditions, the pulse width is broadened to ~330 ns at 32°N latitude and to 1000 ns at 17°N latitude. The measurement probability for this case is > 90% at 32°N latitude, falling to > 10% at 22°N latitude. The dawn-dusk orbit is much more favorable, since the spacecraft can roll about the spacecraft-sun line. In this orbit MLA can range with > 90% probability to 11°N latitude and with > 10% probability to below the equator.

Members of the MESSENGER team have developed many space laser altimeters including Mars Observer Laser Altimeter (MOLA), NEAR Laser Rangefinder (NLR), Mars Orbiter Laser Altimeter (MOLA-2), and Shuttle Laser Altimeter (SLA). They are currently developing the Geoscience Laser Altimeter System (GLAS) for the ICESat mission. The heritage and technology from these instruments provide the basis of the MLA design.

Laser Design. The laser transmitter is a diode-pumped Cr:Nd:YAG laser in an oscillator-amplifier configuration (Fig. D-3-6d). The oscillator has a single, thin YAG slab, which is diode pumped and produces a 5 ns laser pulse with a nearly diffraction-limited spatial profile. For low mass and high reliability, and given the rapid temperature changes expected during the mapping cycle (>0.5°C/min), the laser is passively Q-switched with Cr^{4+}:YAG. This technique eliminates high-voltage switching electronics and improves reliability. Passive Q-switching keeps the pulse energy constant over temperature. The oscillator's output is amplified with a 2-pass Nd:YAG amplifier, and the amplifier's output is frequency doubled with a nonlinear crystal to 532-nm wavelength. The pump-diode configuration consists of stacks of 100-W laser diode bars operating in parallel. Since the laser operates for < 10^8 shots, the diodes can operate efficiently at full power without significant lifetime risk.

The laser is based closely on one being built for GLAS that is scheduled to fly in January 2001. The development of the GLAS laser will be closely monitored to ensure that the MLA laser will be ready in time for MESSENGER (Table G-4-2). If any problems delay the laser, a flight-proven design from NEAR can be substituted which meets the science requirements but has a lower maximum range.

Optical and Mechanical Design. The laser beam is transmitted through a beam expander to achieve the beam divergence of 50 μrad. A Risley pair in the laser assembly is used for alignment to the receiver telescope. The low-mass, 25-cm diameter, beryllium receiver telescope is based on space-qualified designs similar to those used on the MOLA and Composite Infrared Radiometer and Spectrometer (CIRS) instruments. The flatness of the telescope attachment interface plate is controlled to minimize distortions. A support tube holds the secondary mirror. The beryllium detector assembly is directly coupled to the receiver telescope. A beryllium interface plate supports all subsystems. Machined pockets enclose the laser capacitor bank and pulse-control board. The instrument interface plate also provides the thermal sink for the pump diodes. The beryllium instrument support provides primary structure for MLA. The number of mechanical components in MLA has been minimized to reduce fabrication costs, assembly time, and complexity. Beryllium is used extensively to meet the mass budget, to minimize thermal induced stress, and because it has a high heat capacity.

Thermal Design. The MLA thermal design minimizes the temperature excursion of the laser diode assembly during the operating portion of the orbits. It is thermally isolated from the spacecraft, to decouple MLA from the spacecraft thermal transients. MLA is decoupled by multilayer insulation and low-emittance surfaces. MLA is controlled at 20°C during the nonoperating portion of the orbit and then relies on the thermal inertia of the instrument during the operating portion of the orbit (> 40 minutes per 12-hour orbit), after which it slowly rejects the heat and recovers to 20°C. The beryllium structure is used to thermally couple all the available mass in the instrument, which absorbs both the operating power and the planetary IR and albedo flux on the receiver telescope and beam expander. The laser is designed to operate with a ≥ 15°C margin at the end of the hottest transient case.

Receiver Electronics and Internal Power Converter. In the MLA receiver timing electronics, photon arrival times are latched. The time-interval unit uses a several-hundred-MHz clock to collect data over a 6-km interval following the first return. The time resolution is ≤ 5 ns. MLA power electronics include the internal converter and the laser-drive electronics. The internal power converters are an integrated part of the instrument electronics. The laser diode pumps require a current pulse of ~100 A for 200 μs, and the laser pump duty cycle is 0.1%. A bank of capacitors are used to store the energy for the laser. The recharge converter, based on previously flown designs, is synchronized with the internal converter.

F.3.5 Radio Science (RS)

RS uses the MESSENGER telecommunications system to model the gravity field and analyze the radio occultations. No modifications to the system are required for RS. The X-band telecommunications system, in conjunction with the DSN, provides Doppler tracking data to 0.1 mm/s over a 10-s integration, and range to 3 m with an integration time of 10 minutes. One DSN pass each day is used for RS, with data collected in the orbit data file (ODF) format. No special facilities or new software are required.

Tracking data are used to determine precision orbits of MESSENGER throughout the mission for use by MLA and the other instruments. Orbital arcs of approximately 4 days in length are anticipated but depend on spacecraft activity that might affect the orbital trajectory, such as thrusting or momentum dumps. A gravity-field model is developed from the tracking data in conjunction with the planet's rotation rate, pole position, and librations.

Data acquired by the DSN of MESSENGER occultation ingress and egress provides an estimate of the radius of the planet at each occultation point. These observations are particularly important over the southern hemisphere (where no MLA data are acquired) to constrain the global shape of Mercury. During the few minutes before and after the occultation, DSN data are required in the auxiliary tracking data file (ATDF) format, which provides greater resolution of the time of signal loss.

F.3.6 Atmospheric and Surface Composition Spectrometer (ASCS)

The ASCS consists of a small Cassegrain telescope that simultaneously feeds UVVS and the VIRS spectrometers. The ASCS characteristics are shown in Table D-2-5, and outline drawings and a block diagram are shown in Fig. D-2-1.

The UVVS optical-mechanical design is identical to the Galileo Ultra-Violet Spectrometer (Hord et al., 1992) shown in Fig. D-2-1 except for three modifications: a new grating extends the long-wavelength limit from 420 nm to 600 nm; a two-position mask at the spectrometer entrance slit accommodates both atmospheric and surface measurements for the FUV and MUV channels; and the baffle is modified to act as a shield against planetary thermal emission.

The command and data-handling interface for the ASCS is provided through the DPU. An 80C32 microcontroller and an FPGA-based logic system within the ASCS provide the low-level control, grating stepping, clocking, and readout. ASCS communicates with the DPU through a serial interface. Use of the DPU for command and telemetry eliminates the need for a dedicated instrument processor, simplifies hardware, and minimizes software development.

A baffle (heat shield) surrounding the telescope aperture limits the telescope aperture field of view to < 20°, reducing the heat load into the 30-cm^2 entrance aperture. The shield is mounted to the telescope with thermal insulators. The shield is constructed of the same 0.125-mm-thick, black-oxidized, stainless steel as the MDIS baffle. The ASCS bulk temperature closely tracks that of the spacecraft aft deck.

The ASCS VIRS and UVVS spectrometers make Mercury surface reflectance measurements whenever the payload is pointed at the illuminated side of Mercury. In the noon-midnight orbit case the spacecraft can not view the equatorial zone. In the dawn-dusk orbit case, illuminated portions of the planet are always visible. UVVS atmospheric observations are made when the field of view crosses the limb. In the noon-midnight case this situation occurs in the equatorial zone. In the dawn-dusk case the limb can be viewed at any time by rolling the spacecraft about the spacecraft-sun line. All latitudes can be observed.

The sensitivity of ASCS is well matched to the Mercury surface reflectance. The spectra measured by the uncooled Si and InGaAs detectors of the VIRS have an expected signal-to-noise performance greater than 200:1 over the entire 300 to 1450 nm range (Fig. F-3-5). The scanning spectrometer of UVVS is well suited to observing weak atmospheric emission lines. Fig. F-3-6 shows the expected signal-to-noise ratios for atmospheric limb observations of selected species with a 1-s integration time.

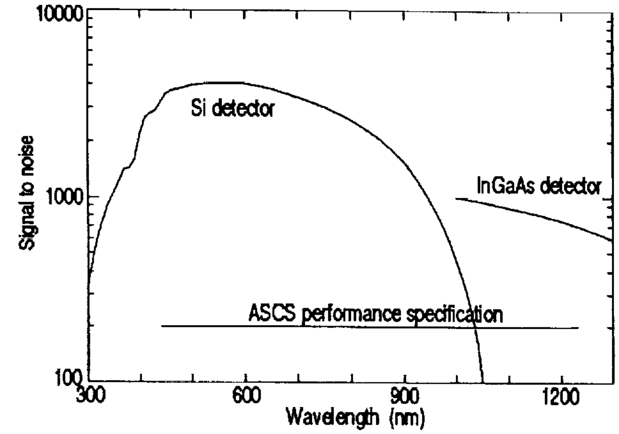


Fig. F-3-5 ASCS/VIRS surface reflectance observations have excellent signal-to-noise ratios.

F.3.7 Energetic Particle and Plasma Spectrometer (EPPS)

The EPPS measures the in situ mass, composition, energy spectra, and pitch-angle distributions of plasmas and energetic particles in the Mercury environment. The MESSENGER orbit (Fig. F-3-4) is excellent for sampling the interaction between the solar wind and the magnetosphere as well as sub-storm-accelerated particles. The characteristics of the Energetic Particle Spectrometer (EPS) head and the Fast Imaging Plasma Spectrometer (FIPS) head are listed in Table D-2-6. The EPPS layout and block diagram are shown in Fig. D-2-1.

The EPS head is a compact particle telescope with a time-of-flight (TOF) section and a solid-state detector (SSD) array. A mechanical collimator defines the acceptance angles for the incoming ions, while the time-of-flight section and its solid-state detectors measure the velocity

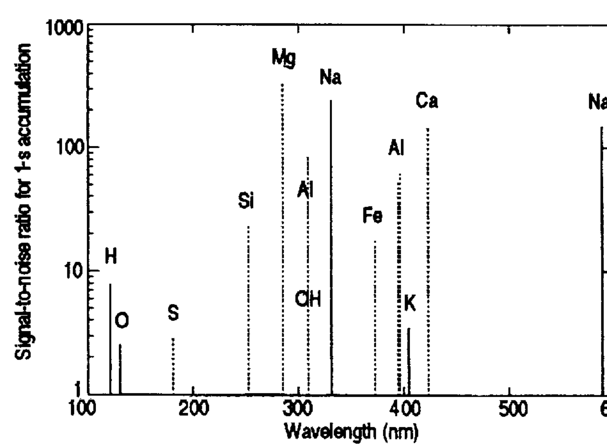


Fig. F-3-6 ASCS/UVVS achieves high signal-to-noise ratios for many lines with 1-s integration times.

and energy of the ions. The EPS electronics fit in the central section of EPPS between the EPS and FIPS heads. A spring-mounted cover bends across the collimator to protect the thin EPS front foil during launch.

A cutaway view of the TOF assembly is shown in Fig. D-2-1. The unit is axially symmetric; entrance and exit apertures are 6 mm wide with an azimuthal opening angle of 160°. The entry and exit apertures are covered by a thin (9 $\mu g/cm^2$) Polyimide/Aluminum foil mounted on high-transmittance stainless-steel grids. EPPS is mounted on the top deck with the EPS head in perpetual shadow to protect the foil from direct solar heating and planetary IR flux. As an ion passes through the head, it generates secondary electrons, which are then electrostatically steered to a microchannel plate (MCP), providing "start" and "stop" signals for the TOF measurements (from 100 ps to 200 ns). The electrostatic field within the central region is tailored to steer the electrons from the two apertures to well-defined separate regions on opposite sides of the MCP. Electron trajectory simulations with a 500-V accelerating potential between the outer and inner elements show that there is < 400 ps dispersion in the transit time of a secondary electron from the foil to the MCP. Sub-nanosecond dispersion is required so as not to misidentify ion species.

After the ion passes through the exit aperture, it then hits one of six solid-state detectors that measure total kinetic energy. The six detectors divide the FOV, providing an angular resolution of 25°. Internal event classification electronics determine the mass and produce an eight-point energy spectrum for each of four species (H, He, CNO, Fe) for six arrival directions. Electrons are recognized in the one solid-state detector equipped with a cover foil (ion absorber). The difference between this SSD and the neighboring SSD is the electron flux, under most conditions.

The FIPS head electrostatic analyzer is unique; with its hemispherical entrance aperture and cylindrical analyzer, it simultaneously measures particles over a nearly full hemisphere with different E/q at each elevation angle. This arrangement greatly enhances its effective geometry factor over traditional analyzers despite its small physical size. The full particle distribution function is determined over one minute as the analyzer voltage scans to ensure that all E/q values are covered for each analyzer elevation angle.

Normally shadowed behind the thermal shade, FIPS can always view Mercury's magnetospheric plasma. However, when the spacecraft yaws ~8°, the solar wind can reach FIPS; near the maximum-allowed 15° yaw FIPS is directly illuminated by the Sun. The FIPS dome is designed to handle the thermal and UV input, but its performance has not yet been tested with full solar illumination (Fig. D-2-1). High-temperature, high-illumination tests will be performed during Phase A/B to evaluate candidate internal coatings and to confirm the performance under direct solar illumination. If serious problems develop, the EPPS mounting position will be modified to keep FIPS in shadow. This relocation would allow the solar wind to be measured only near the maximum yaw range of the spacecraft and would therefore reduce the instrument's science return.

Key to EPPS is a custom VLSI TOF chip. Since the Phase-One proposal, flight-quality chips have been produced, and they have been incorporated in the qualified flight model of the High-Energy Neutral Atoms (HENA) instrument on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft. These chips have demonstrated TOF resolution of 50 ps while dissipating less than 30 mW at event rates as high as 1 MHz. Fast electronics, a key feature of the EPPS, are needed to avoid pulse pileup, due to potentially high incident particle rates into both the FIPS and EPS heads at Mercury.

The TOF chip is one piece of the electronics miniaturization required to meet the EPPS mass limit. Most other required electronics packaging elements have been demonstrated. The ability to produce fully miniaturized electronics will be demonstrated at the brassboard level prior to EPPS CDR (Table G-4-2).

F.3.8 X-ray Spectrometer (XRS)

The XRS measures the elemental composition of the surface of Mercury. By detecting characteristic X-ray fluorescence in the 1 to 10 keV region, the XRS can remotely sense the presence of many elements in the topmost layer of the planet surface excited by solar X-rays. Although the intensity of detected X-rays is strongly dependent on solar illumination and activity, the generally short observation times required allow spatial mapping. The instrument observes continuously and produces telemetry at a low rate in a fixed-packet format. Over the course of orbital operations, the XRS will provide compositional mapping of the elements Mg, Al, Si, S, Ca, Ti, and Fe.

The instrument is described in Sec. D.1.5, and its essential characteristics are listed in Table D-2-7. A mechanical honeycomb collimator provides a 6° FOV (Fig. D-2-1), which is less than a third the size of the planet at apoapsis and eliminates the X-ray sky background. At intermediate altitudes, spatial resolution improves until at periapsis it is about 400 km x 20 km. The XRS will vary its integration time in three steps throughout the Mercury orbit to optimize spatial resolution without increasing overall data volume. Each detector produces a 256-channel spectrum for each integration period. The only parameter that is normally changed during XRS operations is the integration period. Spectra from repeated tracks will be summed during ground processing to achieve the required sensitivity. Larger areas may also be combined for reduced atomic composition uncertainty at the expense of spatial resolution.

The five planet-viewing X-ray detectors are divided into three smaller detectors (5 x 5 mm) that provide higher energy resolution (350 eV) and a lower noise edge (~700 eV) plus two larger detectors that provide high sensitivity for higher energy X-rays. Thin matched filters mounted externally on two of the these detectors differentially separate the lower energy X-ray lines from Mg, Al, and Si as was done on NEAR. The thermoelectric coolers for the three high-resolution detectors will run in series to promote efficient power conversion. The two large-area detectors (10 x 10 mm) detect the higher energy lines from S, Ca, Ti, and Fe and will run independently.

The XRS collimator is fabricated from Be-Cu foil, because any X-ray lines excited in the collimator will not interfere with the line emissions from the planet surface. The collimator is compact, inexpensive, and rugged. Its small-cell honeycomb design eliminates the need for precise alignment with the detectors. Using 1.6-mm cells, the collimator is only 30 mm tall and achieves better than 98% transmission. The collimator is thermally isolated from the detector/electronics section and rejects most of the heat load from the planet.

A very small (0.12 mm^2) solar-flux monitor with a 30° FOV monitors the solar X-ray input to the planet from behind a Be window. During the Concept Study, its mounting has been separated from the antenna radome to simplify testing and calibration independently of the telecommunications system. The Be window thickness (including detector window) totals 75 µm and rejects the intense solar X-ray flux below 1 keV and keeps the maximum counting rate below 10 kHz. A slightly larger detector with an internal tungsten collimator to reduce the edge effects of the small detector will be studied during Phase A/B.

During the Concept Study, a discrete-reset feedback circuit has been adopted to provide even greater immunity to thermal and radiation-induced leakage currents in the detectors. This improvement will help ensure that the detector threshold can be held below 700 eV (Table G-4-2). If the threshold had to be raised above ~800 eV it would limit the ability to separate the Mg and Al signals.

F.3.9 Data Processing Unit (DPU), Software, and Data Compression

Data Processing Unit (DPU). All MESSENGER instruments are controlled by the common DPU, which provides power, command, downlink data, and time distribution interfaces to the Integrated Electronics Module (IEM). The DPU has been designed with sufficient redundancy and cross strapping so that no single-point failure can disable the entire instrument suite (Fig. F-3-7).

The DPU has fully-redundant and cross-strapped RTX2010RH processors. This core, dual-processor system, is operating on the Cassini Magnetospheric Imaging Instrument (MIMI). Each processor is capable of performing the full instrument-DPU function. The processors share common software for the boot memory, command and telemetry interfaces, and bus interfaces. Instrument-specific software for each instrument may run in either processor. Instrument command messages are decoded and processed in the DPU by one of the redundant processors. Processed command messages pass over an internal IEEE-1394 data bus and are then transferred to the selected instrument over dedicated, three-wire serial digital interfaces or analog control lines. Instrument power switching is controlled by the RTX2010RH processors, which activate dual coil relays in response to the IEM.

All MESSENGER instrument downlink data, except WA and NA images, are formatted into data packets by the DPU processors and transferred to the IEM. Instrument and DPU voltage, current, digital telltale, and temperature housekeeping data processed in the DPU are included in data packets, which may be used for health checking in the IEM fault-protection software.

Raw image data are recorded on the SSRs in the IEM, later read back into the IEM for compression, and again stored on the recorders prior to downlinking. Mercury flyby data are stored simultaneously on both recorders, providing redundant storage during the extended downlink period.

Dedicated power converters in the DPU provide power to the APL-built instruments MDIS, GRNS, EPPS and XRS. MAG, MLA, and ASCS receive raw 28-V power and have internal converters. This approach permits all instruments to be fully tested and flight qualified with their flight power supply. Independent converters power each of the RTX2010RH DPU processors. Active current limiting in each power converter protects the spacecraft from overcurrent fault conditions. Electromagnetic interference filters and surge limiting on each converter reduce instrument-conducted emissions and load-switching transients on the spacecraft power bus.

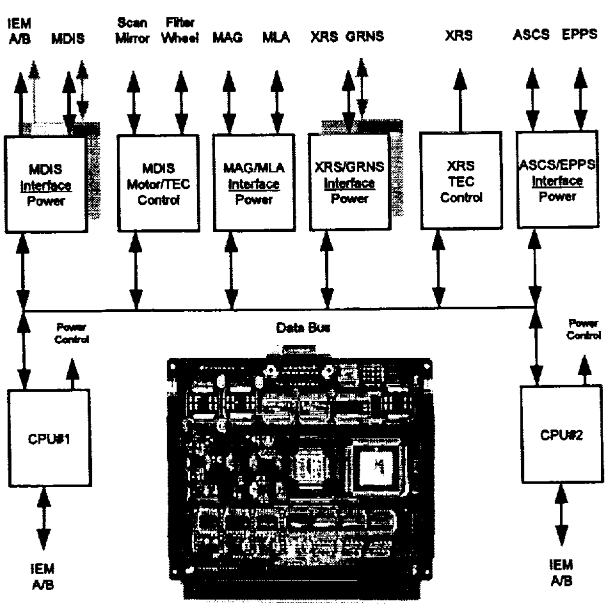


Fig. F-3-7 MESSENGER DPU has extensive heritage from the NEAR DPU design.

Instrument-Specific Software. Only one MDIS imager is operated at a time. The MDIS software enables or disables the selected imager, controls the scan mirror shared by the imagers, controls the filter wheel and cooler, and selects high-resolution (1024x1024) or low-resolution (512x512) operation. Image data are sent directly from the CCD to the recorder in the IEM; the DPU does not process the image. The MDIS software is very similar to the NEAR imager software.

The GRNS instrument accumulates seven types of gamma-ray spectra and neutron counts. The GRNS software reads, compresses, and telemeters these spectra. It sets internal operating points, and actively controls the GRS heater. DPU fault-protection software reduces the sensor high voltage (HV) if very high-flux solar particle events are encountered. The GRNS software is almost identical to the NEAR XGRS software.

The MAG software collects the data at different sample rates (higher sample rates are used close to the planet), anti-alias filters the data, then subsamples it. A digital bandpass filter is applied to a single axis to detect wave activity. This software is the same as the NEAR MAG software.

MLA generates range and reflectance data in a fixed format. The MLA software assembles and compresses these data into packets for downlink. It also processes the MLA commands and passes them to the MLA microcontroller. The MLA software is new.

ASCS produces visible, IR, and UV spectra. The ASCS software accumulates these spectra for a selectable time before compressing and telemetering the data. The software also controls the grating and ASCS parameters. The ASCS software is new.

EPPS software reads and compresses the plasma and energetic plasma data and telemeters the results. The software also sets thresholds, bias, and HV levels, and provides autonomous safe-mode control of HV. At start-up, the software also calculates lookup tables used to classify the particle energy and species. The EPPS software combines existing software and algorithms from similar instruments on Cassini and ACE.

XRS accumulates six different X-ray spectra. The XRS software reads, compresses, and telemeters these spectra at a selectable interval. The software also sets thresholds and actively controls the thermal-electric coolers (TECs). This software is the same as that used on the X-ray portion of the NEAR XGRS instrument.

As stated above, much of the software for the DPU already exists. The dual-processor operating system is very similar to that on the Cassini MIMI instrument. The small size and ample margins of the DPU software are shown in Table F-3-2, which lists the estimated lines of code, memory usage, and CPU loading using a single processor. Although software development is straightforward, the integration and testing of the DPU software will be closely watched. If testing becomes a problem, the software functionality can be limited to reduce risk (Table G-4-2).

Data Compression. Images are loaded onto the flight recorder when they are taken and read back later into the IEM flight computer for processing and compression before downlink (Sec. F.2.9). Image compression allows the maximum number of MDIS images to be acquired and provides for the return of data for the other instruments. The baseline mission assumes data compression only for the MDIS images.

For images, three compression options, or combinations of them, are available. Selections will be made to meet the varying science-driven image fidelity requirements (Table D-2-2). Compression options include: lossless methods (e.g., Fast and Rice); lossy 12-to-n bit point transformation implemented via an uploadable look-up table (e.g., linear-log mapping); and lossy adaptive multi-resolution compression (LAMRC) (e.g., adaptive wavelet-based algorithm). The 12:n bit mapping can be used as a preprocessing step; the resulting n-bit data may subsequently be compressed further via either the lossless or LAMRC methods. The LAMRC compression is done in the IEM main processor and has therefore been reserved for the images to limit the testing during spacecraft I&T.

When applied to monochrome image data, the LAMRC scheme first removes incompressible sensor- and radiation-induced noise and detects regions of high-spatial content in the image. It then compresses the data, allocating more image resolution (fidelity) to those regions with complex spatial structure and correspondingly lower resolution to others. The overall compression ratio is a settable parameter. Thus, data with the most scientific interest are encoded with little or no loss.

The LAMRC method can also be used with the color image data. One filter is chosen as the primary or key image and processed as a monochrome image. The adaptive-resolution map generated for this key image is applied to corresponding difference images for the remaining two to seven filters. Only the key image and the small difference images are downlinked. In reconstruction of the images on the ground, the key image is used as the a priori baseline for the other filter images. Since it is anticipated that certain filters may contain more useful information than others, the significance criteria used to encode these differences may be made to vary with the filter used. Any mis-registration of the images does not degrade the data; it only limits the image compressibility.

Lossless compression, which is used to preserve all of the scientific content of the data from an instrument, is limited by the inherent entropy of the data. It typically yields modest compression factors of 1.5:1 to 3:1. In addition, 12:n bit mapping (typically 12:8) is available to preprocess the data prior to any subsequent

Table F-3-2 DPU Software Margins

Software Segment	Lines of Code	Memory Usage (kB)	CPU Load Avg/Peak (%)
MDIS	3100	65	1/10
GRNS	6000	30	5/10
MAG	2800	30	10/10
MLA	2000	20	1/5
ASCS	2000	20	1/5
EPPS	6000	50	5/10
XRS	5000	30	5/10
Common software	2700	30	5/10
Totals	29800	275 (54%)	33/70

encoding. The LAMRC algorithm easily provides the minimum required compression ratio of 6:1 for a monochrome image, with target data reductions of greater than 12:1 as the scientists become familiar with the image content and image noise levels. This same algorithm applied to the color images provides compression ratios greater than 10:1, with target ratios of 20:1 or higher for an entire seven-color image set. During Phase A/B additional data compression algorithms will be studied to determine if sufficient image quality can be maintained with these or even greater compression ratios.

All other data, besides MDIS images, may be compressed by the lossless and 12-to-n bit lossy techniques. These compressions are carried out in the instrument DPU before forming instrument data packets. Compression of the other instrument data can add at least 12 Mbits/day (1.5 MB/day) of downlink margin that may be used to enhance science return.

F.4 Payload Integration

The resource requirements of all of the MESSENGER instruments are summarized in Table F-4-1. These resources are tracked by the Mission System Engineer (Sec. G.1.2 and Sec. G.2.3). Reserves for instrument resource requirements are allocated by the Mission System Engineer. The allocation of margins requires PI approval (Sec. G.2.3). The instrument interfaces with the spacecraft are managed through interface control documents (ICDs) maintained by APL. The ICDs are under configuration control after completion of the spacecraft Preliminary Design Review (Sec. G.6). The final versions of the ICDs are signed before the spacecraft Critical Design Review. By centralizing the instrument's electrical interfaces to an APL-built DPU, the risk of impacting the spacecraft integration schedule through late delivery of instruments is reduced. To reduce instrument-interface risk further, the DPU interfaces with the spacecraft are tested using breadboards prior to the start of flight fabrication. Throughout the instrument-test phase, a DPU emulator, supplied by the DPU designers, is used by each instrument.

MDIS, GRS, MLA, ASCS and XRS all mount directly to the spacecraft bottom deck and are coaligned so that they can simultaneously view the same region of Mercury. EPPS is mounted on the upper deck to allow it to view the Mercury magnetosphere and the solar wind while protecting the thin foil in the EPS head from the planetary heat load. The MAG sensor is on a 3.6-m boom. All instruments except MAG, GRS, and MLA are thermally tied to the deck. All instrument fields of view are unobstructed (Fig. F-4-1).

The thermal design, as described in Sec. F.2.3, provides a benign environment for all instruments. The thermal environment for the instrument deck throughout the mission is shown in Fig. F-2-14. The instruments are always in the shadow of the spacecraft thermal shade, except for the dome of the EPPS FIPS head. The orbit-average temperatures range from -10° to +15°C. During the ~1 week of noon-midnight orbital geometry each Mercury year, there is a thermal transient as MESSENGER passes in front of the subsolar region. The

Table F-4-1 Payload Resource Requirements

Instrument	Mass (kg)	Power (W)	Volume (cm^3)	FOV	Interface Temp: Survival/ In-Cal (°C)	Alignment/ Pointing Control/ Knowledge	Daily Data Volume Mb/day	Modes	Contamination Requirements
MDIS	5.50	10	25x12x10 + baffle	NA-1.5° WA-25°	-34 +65/ 30 +25	0.1°/0.1°/0.02°	15	1 + scan	N_2 purge
GRNS	6.0	1 + 3.5 htr	22.2x15x15	45°, 2π	-34 +65/ -30 +30	1°/2°/1°	6.9	1	—
MAG	3.0 with boom	1.0	3x2x2 10x10x4	4π sr	-90 +180/ -90 +180	1°/1°/1°	0.5	1	Field < 1.0 nT @ MAG
MLA	5.0	20	28x28x26	150 µrad	isolated	0.1°/0.1°/0.03°	2.7	1	N_2 purge
ASCS	2.5	3.0	34x19x12	1.0°x 0.05°	-34 +55/ -20 +40	0.1°/0.1°/0.05°	5.4	Scan, dither	N_2 purge
EPPS	1.3	2.0	21x12x9	160°x12°, 360°x75°	-34 +60/ -20 +35	1°/1°/1°	6.8	1	N_2 purge
XRS	4.0	8.0	8.6x8.6x10.6	6°	-34 +65/ -30 +35	1°/1°/0.1°	3.4	1	—

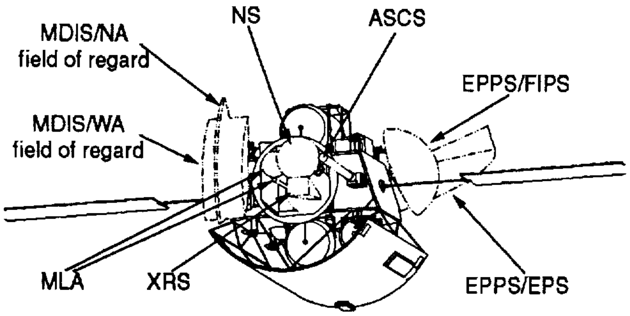


Fig. F-4-1 All instrument fields of view are clear.

transient lasts less than an hour with a peak temperature of 40°C. At that point in the orbit the instruments can not view the planet so the transient does not affect the science return. Thermal gradients while viewing Mercury are insignificant.

All instrument electrical interfaces with the spacecraft are through the redundant instrument DPU. A redundant MIL-STD 1553 bus is used for commands, time synchronization, and low-rate instrument data. Image data are transferred over two redundant RS-422 interfaces. Both the DPU and spacecraft sides of the MIL-STD 1553 and RS-422 interfaces are under software control, allowing flexibility for unforeseen on-orbit contingencies.

Calibration. Each of the instruments is environmentally tested and fully calibrated prior to delivery to the spacecraft. Specialized calibration facilities exist at MESSENGER team institutions for each of the instrument types. Along with the standard calibrations, each instrument is calibrated against natural samples that approximate expected surface materials or atmospheric constituents at Mercury. The payload also undergoes in-flight calibrations during cruise and at Mercury. Basic in-flight calibration plans for each instrument are defined.

Contamination. MDIS, MLA, ASCS, and EPPS are all sensitive to physical and molecular contamination. Each is kept under a pure N_2 purge and protected with red tag covers. All spacecraft materials are checked for outgassing at high temperature, and standard procedures for a class 10,000 environment are followed.

Measurement of the interplanetary magnetic field requires that the spacecraft residual field be kept less than 1.0 nT at the MAG sensor. A magnetics program controls the use of any magnetic materials and ensures the compensation of current loops in the solar panels, power system, and thermal circuits. The extensive expertise of the MAG team is used to achieve spacecraft magnetic cleanliness at a very low cost through up-front system engineering and close cooperation with spacecraft and subsystem designers. This procedure worked successfully on the recent ACE spacecraft, which has a residual field several times lower than the maximum allowable for MESSENGER.

Limited Life Items. The MLA laser has a limited life of $>10^7$ shots. A limited-life operations plan ensures that all laser testing is controlled and that it does not jeopardize the mission lifetime at Mercury.

F.5 Manufacturing, I&T

F.5.1 Manufacturing Strategy

By designing, building, and operating spacecraft in-house, APL assures quality while maximizing flexibility in schedule and simplifying system-level design trade-offs. A "protoflight" philosophy is used. The only deliverable end item is the flight model. The spares philosophy is described in Sec. F.2.1. Hardware manufacturing at APL is the responsibility of the APL Technical Services Department (TSD), which has a full capability for mechanical and electrical design and fabrication. A common data base is used for design, manufacturing, inspection, and testing. The web-addressable TSD data base also provides status reports on drawings, drawing tree lists, Engineering Change Requests (ECRs), and Drawing Change Notices (DCNs). Quality control is enforced throughout the manufacturing process (Sec. F.8.5).

Transition from Design to Manufacture. A trouble-free transition from design to manufacture starts with a comprehensive design process. Design engineers use software circuit simulators, such as the Mentor™ system and analog and digital mixed-mode simulators (e.g., PSPICE) in the design phase to assure that the designs meet specifications. To ensure that the design on the schematic is what is manufactured, the entire design and manufacturing system is built around intelligent databases, e.g., schematic netlist is input to the layout netlist, which is input to the automated circuit board tester. The manufacturing approach is based on a breadboard, brassboard, flight-unit progression. This three-step process ensures not only correct functionality, but also the correct "form and fit." In addition, hardware simulators are constructed and employed at all levels of design and testing. Each circuit board has its own simulator for board-level testing, and each flight electronics box has simulators for higher-level testing. For processor interfaces such as the instrument DPU, simulators are developed early and distributed to each user. Each instrument is assigned a DPU simulator to assist its development, and another is used for software development. This procedure allows early discovery of design and implementation problems, minimizing the risk of costly redesigns and reworks.

The formal transition between design and fabrication occurs at the Critical Design Review (CDR), during which the completed, signed-off design documents are presented for review. Fabrication begins after action items have been resolved. This formal flow is supplemented by the informal engineering design reviews (EDRs) and fabrication feasibility reviews (FFRs) (Sec. G.4), which provide the most detailed assurance of design quality and manufacturability.

Flight Hardware Fabrication Precesses and Procedures. A complete set of manufacturing processes and procedures is maintained by TSD. All are certified and NASA approved before they are used for the fabrication of flight hardware. TSD manufacturing processes are continually monitored to assure compliance with these documented and approved procedures. All TSD personnel are fully trained in these procedures. TSD fabrication personnel are NASA-certified. TSD has complete fabrication facilities, with comprehensive equipment for mechanical and electrical fabrication and extensive cleanroom facilities. All facilities have electrostatic discharge (ESD) control.

Production Personnel Resources. The detailed MESSENGER manufacturing and test schedule is summarized in Table F-5-1. The TSD workforce staffing plan for Phase C/D includes plans to supplement their workforce during peak manufacturing times with temporary resident subcontractors, who are hired with sufficient lead time for training in the APL standard practices and procedures. When production demands exceed the TSD capacity, design and manufacturing of less-demanding assemblies are subcontracted to some of the many regional NASA-qualified vendors with whom APL has successful working relationships.

Incorporation of New Technology/Materials. TSD has full state-of-the art facilities with automated systems for the production of electronic and mechanical subsystems. These advanced, computer-controlled machines use the same intelligent databases that are created in the design phase and later used for testing and verification. This facility is fully capable of producing MESSENGER without the need for any further new technologies or materials.

Software Development. All software is developed using a repeatable process that includes planning, requirements, design, implementation, test and validation, and maintenance. MESSENGER development uses an iterative incremental-build approach. A sequence of builds incrementally deliver functionality to the user. Each build adds fully-tested pieces that map to requirements. The final build is fully functional.

During Phase A/B, the Software System Engineer (SWSE) writes the MESSENGER Software Development Plan (SDP) (Sec. G.2.1). This plan assigns Quality Assurance Requirement Levels (QARLs), in accordance with *APL Quality Assurance Plan*, to all software program elements and describes how the software development process is tailored for the mission. The QARL levels are based on risk and mission criticality. The degree of documentation, formalism, and testing is selected on the basis of the QARL.

Table F-5-1 Manufacturing and Test Schedule

Submit design for drafting	December 2001 - April 2002
Mission Critical Design Review	March 18, 2002
Fabrication Feasibility Reviews	April 2002 - September 2002
Bare-board fabrication	June 2002 - October 2002
Populated boards to engineering	July 2002 - November 2002
Tested boards to TSD for surface coating	August 2002 - December 2002
Box-level assembly completed	November 2002 - January 2002
Box-level testing and qualification	December 2002 - March 2003
Subsystem-level testing and qualification	January 2003 - April 2003

The SDP test philosophy is hierarchical. The first layer is module tests. The next laywer, integration testing, is done on software components made up of several modules. The final layer is acceptance testing. Critical software applications are subjected to a stringent design, test, and verification program including independent validation and verification (IV&V) to confirm compliance with requirements.

The software development team holds informal peer reviews for software requirements, preliminary design, and detailed design. Walkthroughs are performed on the code. All software is included in the Conceptual, Preliminary, and Critical Design Reviews. All software, documents, and design materials are placed under configuration control, administered by the SWSE, at software delivery.

Post-launch, software configuration control is administered by the Change Control Board (CCB), led by the MSE. All flight-software changes and any ground software that could affect the operation and the safety of the spacecraft must be submitted for approval by the board. In addition, all flight parameters and command sequences are under configuration control. Prior to upload, new flight software and new command sequences are tested on the flight simulator.

F.5.2 Integration and Test

Integration starts at the breadboard level, where all designs undergo interface-compatibility testing prior to release for flight fabrication. This practice reduces the number of problems encountered during system-level integration. A hierarchical approach is taken to test. Piece part components and boards are environmentally tested at more stressful levels than boxes, which, in turn, are tested at higher levels than the system. By imposing more stressful tests at lower levels of integration, problems late in the project are minimized. This integration and test (I&T) approach is similar to other APL spacecraft programs, including NEAR. The APL Space Department maintains a rigorous, mandatory program for testing flight hardware and software, with written standards for qualification and acceptance testing. Part burn-in requirements are described in Sec. F.8.5 and Table F-8-1. All test equipment is calibrated with National Institute of Standards and Technology (NIST) traceability.

Boxes are each fully tested functionally and environmentally prior to delivery for system integration. As was done on the NEAR spacecraft, a protoflight approach (qualification levels, flight duration) will be adopted for the MESSENGER test program. Each unit is vibrated using sine-sweep (3-axis) and random vibration at protoflight levels, and undergoes operational and survival thermal cycling (Table F-5-2 for levels). Mechanical test margins are developed by APL based on the Delta II user's manual and the coupled-loads analyses specific to MESSENGER. The component-level vibration specifications are significantly greater than those at the launch vehicle interface to account for coupled-loads amplification. Thermal test margins are set beyond the worst-case predicted temperatures. Margins are 15°C at box level and 10°C at system level. Solar simulation tests are conducted on the solar arrays, the thermal shade, and the items that look through the shade to validate their properties under the extreme conditions at Mercury. Externally mounted boxes that may receive direct illumination for short durations in an attitude anomaly will undergo transient survival testing.

Spacecraft integration starts 16 months before launch with the delivery to APL of the fully qualified COI structure with its integrated Aerojet propulsion system. There are four weeks of schedule reserve allocated for this activity. The wiring harness is then installed, followed by the spacecraft subsystems. The instruments are integrated next, allowing maximum time for instrument testing and calibration. Last, the solar arrays are mated and

Table F-5-2 Environmental Test Levels

Level	Test	Test Specifications
Box	Vibration	Sine: 15.5 g thrust (8-100 Hz); 8.5 g lateral (15-20 Hz) Random: 0.08 g^2/Hz peak PSD; 8.5 g rms for 60 s
	Thermal	Operational: 6 cycles -29°C to +60°C (test at plateaus) Survival: 1 cycle -34°C to +65°C 0.3 AU survival tests: defined in Phase A/B
System	Spin	Vertical axis balance @ 60 rpm
	Vibration	Sine: 1.4 g thrust (8-100 Hz); 1.0 g lateral (6-100 Hz) Responses limited to coupled-loads analysis
	Acoustic	142.6 dB for 60 s
	Thermal	Cold balance: 1.1 AU, all instruments off Hot balance: 0.3 AU, all instruments on Hot transient: Sub-solar crossing simulation Cycling: 6 cycles -29°C to +55°C Minimum accumulated time of 100 hrs at each plateau

tested. Testing at the system level includes functional and performance verification, DSN compatibility, electromagnetic interference/radio frequency interference (EMI/RFI) compatibility, operational autonomy, and fault protection. There are six weeks of schedule reserve allocated for this activity. A dynamic attitude simulator is used to test the spacecraft in a flight-like environment.

The spacecraft test flow and schedule is illustrated in Fig. F-5-1. Static-mechanical testing and vibration are performed at APL with the propellant tanks filled with a simulant. Environmental testing continues at GSFC with spin balance and acoustics. Next, the separation test and the pyro tests are completed twice. The simulant is drained from the tanks and the solar panels are removed before the spacecraft is transported to the test chamber for thermal balance and vacuum testing. An IR thermal shroud is constructed inside the chamber to simulate heating from the Sun at 0.3 AU on the outside of the thermal shade. Thermal loading from Mercury is simulated using IR test plates. A cold case and hot case thermal balance are performed, followed by a hot transient subsolar crossing test and thermal cycling. System-level solar simulation vacuum testing is not planned, because the thermal shade eliminates direct solar irradiance on the spacecraft.

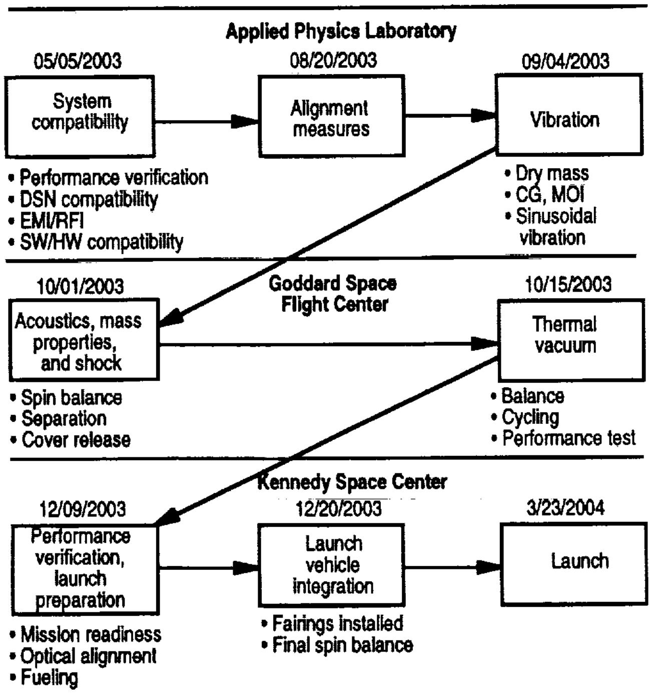


Fig. F-5-1 The environmental test program is thorough and has sufficient schedule margin to meet the launch date.

Upon completion of environmental testing the spacecraft is shipped to Florida via air ride van. Launch operations last 45 days. The launch processing is typical, with no special requirements placed on the launch system. Processing is divided between launch facilities, MIL-71, and the Delta pad. An overall 2-month schedule reserve has been allocated prior to launch.

F.6 Mission Operations, and Ground and Data Systems

The ground data system (GDS) consists of all the teams and ground facilities required to operate the mission, reduce the data, and publish and archive the results. The MESSENGER post-launch organization is shown in Fig. F-6-1, and the responsibilities of the key personnel are described in Sec. G.1 and G.2.

Key working groups within the post-launch organization are the Science Steering Committee (SSC), the Mission Planning Group (MPG), and the Data Working Group (DWG). The SSC is described in Sec. D.2.4. The MPG coordinates all the inputs to define the weekly operations plan. The DWG oversees instrument calibration and data product software development. It assures that the data products are produced in a timely manner, are validated, and represent the official output of the project; that the integrity of the data is guaranteed throughout the mission; and that the data are delivered to the Planetary Data System.

MESSENGER keeps operations quality high and costs low by using a common ground system and a single integrated team for both I&T and mission operations. Sharing common command and telemetry dictionaries, displays, and test scripts across I&T and mission operations reduces costs and provides an efficient transition from ground test, to early operations, to routine spacecraft support. This approach enables the command sequences to be fully tested before launch. The Mission Operations Team (MOT) helps optimize the spacecraft design for operability and is well prepared for post-launch operations. This infusion of experience into the MOT pre-launch allows missions operations to be conducted with a small team. The MOT and

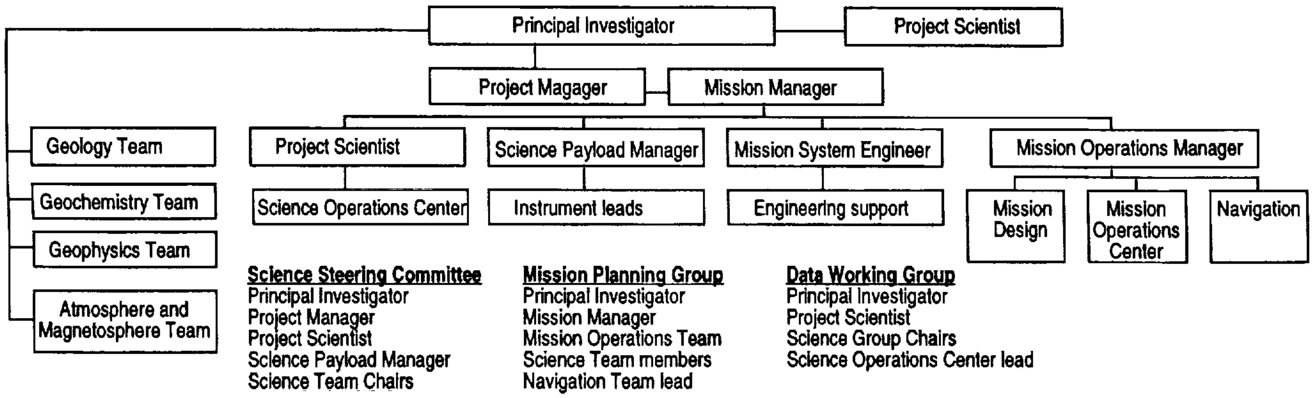


Fig. F-6-1 Post launch, the MESSENGER team is organized so that science drives mission operations.

science operations team staffing plan is shown in Fig. F-6-2.

F.6.1 Ground Data System (GDS)

The GDS includes all hardware, software, data links, and facilities used to conduct tests and operations, generate and uplink commands, and receive, process, and disseminate telemetry and test data. System information flow is shown in Fig. F-6-3. The GDS architecture and significant hardware and software will be inherited from NEAR, which developed a state-of-the-art Mission Operations Center (MOC) and Science Operations Center (SOC), at low cost, by capitalizing on commercial-off-the-shelf (COTS) components and designing for a small operations team. Software from NEAR and TIMED is reused on MESSENGER wherever possible. The same COTS control center software is reused, as well as the APL-developed telemetry router, server, and archive system. All communications between the MOC and the DSN are carried by the NASA Communications Network (NASCOM). With NEAR now operating via the DSN, the communications capability for MESSENGER is in place and operational. There are no mission-unique facilities. Modifications and upgrades of the NEAR MOS are planned to minimize implementation costs.

A single, highly modular and interchangeable system of components supports subsystem tests, spacecraft I&T, launch site support, and mission operations. This network of workstations, front-end processors, and network security systems operates from a common database. Redundancy within the system allows concurrent operations and development. The MOC and SOC both reside at APL. They communicate with each other over a secure local area network. All critical mission operations hardware is on uninterruptable power.

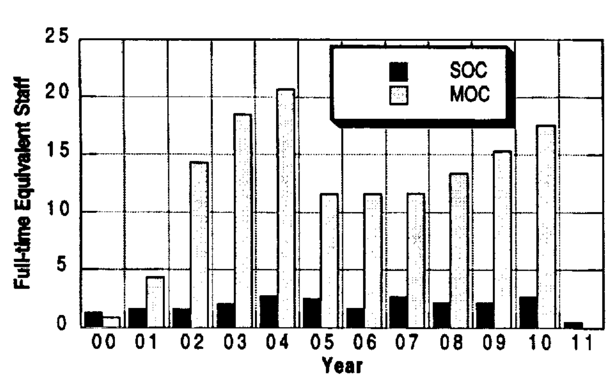


Fig. F-6-2 The MOC and SOC staffing are sufficient for efficient operation at low cost.

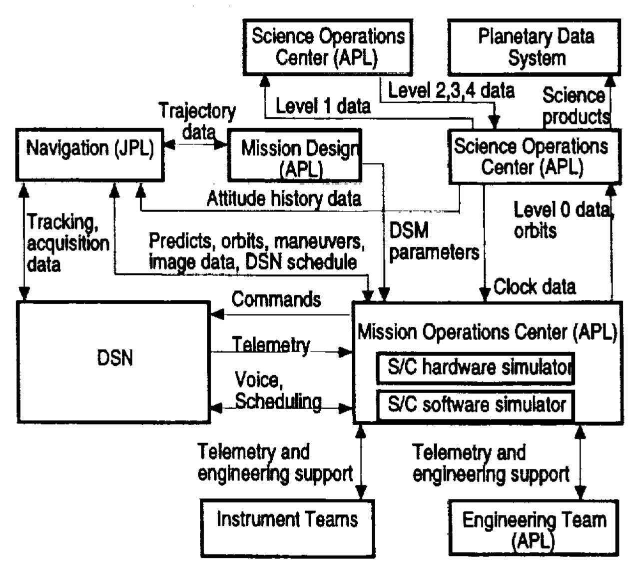


Fig. F-6-3 The ground system data flow is similar to NEAR.

The SOC converts spacecraft telemetry and navigation data to a form that can be processed by the science teams. Science data products produced by the science teams are archived by the SOC and distributed to science investigators, education and outreach programs, and the Planetary Data System. Clock-correlation processing is performed by the SOC and disseminated to the MOC, navigation, and science teams. Science data processing is described under Data Analysis and Archiving in Sec. D.2.3.

Spacecraft simulators are crucial to an efficient spacecraft operations system. MESSENGER has both a software simulator that runs faster than real time and a high-fidelity "hardware-in-the-loop" simulator used for operations rehearsal, command load validation, operator training, anomaly investigations, autonomy testing, and flight software load testing. The software simulator is used primarily for advanced operations planning to identify spacecraft resource conflicts. The hardware simulator is built from spacecraft component brassboards that are exact copies of the flight hardware and contain the flight software. All flight command sequences are tested on this simulator before upload to the spacecraft.

F.6.2 Ground Software

All software is developed using the process is described in Sec. F.5.1. The core command and telemetry processing functions are provided by a COTS software package (EPOCH 2000 from Integral Systems, Inc.). NEAR uses this software, as will TIMED. A time-tested COTS package reduces both risk and cost, compared to a custom design. The system fully conforms to the guidelines of the Consultative Committee for Space Data Systems (CCSDS). Planning and resource modeling uses the NASA-developed SEQGEN software as used on NEAR and many other interplanetary missions. Its modeling capability permits a thorough check against mission constraints.

The SOC software is based on commercial database products and standard languages. Science data processing consists of converting spacecraft telemetry and navigation data to a form that can be easily manipulated by the Science Team, production of science products by the Science Team, and archiving of those data to the Planetary Data System. Science data processing is described in Sec. D.2.3.

Computer Security. The security of the computers and networks is protected by system and network firewalls, by system monitoring, and by trained, experienced system administrators. There are multiple levels of security within the ground data system. The most protected area is the network of workstations that do the actual control of the spacecraft within the MOC. Systems within this area have limited access lists and are connected to the DSN and the rest of MOC using network routers, which disallow access for other machines and protocols. The rest of the MOC, which performs planning and performance evaluation, is isolated from the JHU/APL campus by network routers with limited access lists. Access is restricted to the planning, engineering support, and SOC teams. All MOC systems are administered using CERT (Computer Emergency Response Team) practices. The NEAR MOC network has passed audits by NASCOM security representatives.

F.6.3 DSN Usage

All tracking of MESSENGER is by the NASA Deep Space Network (DSN). The DSN coverage requirements in Table F-6-1 show total tracking hours for 34- and 70-m DSN stations for each type of event. During cruise there are an average of two 4-hour DSN contacts per week. During the orbital phase there are daily 8-hour DSN contacts during the time surrounding orbital apoapsis. Details of these contacts are in Sec. F.2.11. JPL analysis of the MESSENGER Project Service Level

Table F-6-1 DSN Usage

Major Events	34 m (HEF/BWG)	70 m
Launch phase	L+5 days, continuous (100% BWG)	0
Cruise phase (nominal)	Two 4-hr pass/wk (26% HEF, 74% BWG)	0
Flyby nav: Earth, Venus (2), Mercury (2); orbit insertion	E-2 to E+2 wks 8 hrs/day (100% BWG)	Two 8-hr passes per event
Mercury flyby science return	0	9 days, 8 hrs/day
Mercury orbit phase	8 hrs/ day (63% HEF, 37% BWG)	0
TOTAL HOURS	**3712 HEF, 3390 BWG**	**168**

Agreement revealed no oversubscribed DSN antennas required by MESSENGER during any high-activity event. There are no near-real-time requirements.

F.6.4 Mission Operation Team

The MOT is responsible for daily mission operations including real-time spacecraft operations, DSN scheduling, command-load generation and validation, and spacecraft health and safety. The mission operations staff includes a Mission Operations Manager, spacecraft analysts, schedulers, flight controllers and a ground system engineer. Sufficient mission operations personnel already reside at APL who have all the skills required for MESSENGER. During the development phase, a MESSENGER Operations Handbook is prepared. It is a "living document" that is updated though I&T and post-launch operations and details all aspects of spacecraft operations, both normal and contingency. The first version includes a detailed activity plan for all spacecraft and instrument configurations, data collection for the flybys, and the first 180 days of orbital phase operations.

All DSN contacts are staffed. During cruise, all of the flyby sequences are planned and simulated, and dress rehearsals are conducted to test the procedures, timelines, and sequences. During the orbital phase, the MOT supports a single shift seven days a week synchronized with the Mercury orbit period. However, as the DSN contact times vary depending on relative geometry over a Mercury year, the real-time control schedule will also move. During this phase, the development and implementation of the sequence of events proceeds on a routine fixed-shift basis.

F.6.5 Design for Low-cost Operations

Low-cost operations are enabled by: (1) early integration of the MOT with spacecraft development and operations, (2) on-board operational autonomy combined with event-driven data collection, (3) use of exactly 12-hour orbital periods of the spacecraft about Mercury during the orbital phase of the mission, and (4) lessons learned and implemented from experiences with the NEAR mission.

MESSENGER's operability is greatly eased by the implementation of much on-board automation. From routine housekeeping functions to critical safing functions and the inclusion of event-based commanding, the mission-operations-intensive planning effort is greatly reduced. Some of the routine house-keeping functions that are autonomous include solar panel pointing, attitude control, momentum management, and pointing of the phased-array antenna.

Next generation fault-protection software, enhanced from that used on NEAR, is baselined for Mercury. It has all of the NEAR capabilities along with autonomous solar panel temperature safing and a fast override of the spacecraft attitude to keep the thermal shade in position. Standard safing functions are also included, such as low-voltage detection and load shedding, watchdog timer functions in critical processors, detection of failures, and the autonomous switching to redundant components in case of failures. The fault-protection S/W is described in F.2.10.

The science requirements at Mercury (Sec. D) give rise to orbital periods of the order of half a day. By defining and maintaining the orbital period to be exactly 12 hours at the planet, work staffing and DSN scheduling is simplified. At the end of every Mercury year of 88 days a correction is made to maintain the orbital period at 12 hours (Sec. F.1).

Lessons learned from the successful NEAR encounter of the asteroid Mathilde highlighted the utility of enhanced flight software features such as on-board stored-command memory management, a file system on the SSR, event-driven commanding, a simplified command interface, on-board engineering data processing and summary, and parameterized command macros (Sec. F.2.9). The use of event-driven instrument configuration and pointing allow automated data taking and contribute to workload reduction in the planning operations and reduction of ground commanding requirements. The file system on the SSR will be especially important for reducing MOT workload. Replacing the normal data pointers with a true file system will make recorder management as easy as organizing a desktop PC.

F.6.6 Mission Operations Planning

All of the Earth, Venus, and Mercury flyby sequences are planned and simulated before the encounters. This process validates the procedures, timelines, and sequences to be used for the flybys and orbital operations. The processes and procedures used during the flybys are the same as those planned for orbital operations. Cruise operations and the flybys serve to refine these processes to ensure smooth operations following Mercury Orbit Insertion.

The command development process is shown in Fig. F-6-4, much of it reused from NEAR. The SSC defines the long-term science objectives on a four-month rolling schedule. The MPG takes multiple inputs and generates the activity plan. It receives inputs from the SSC, MOT, Navigation, and Mission Design. The activity plan is developed monthly during cruise phase and weekly during Mercury orbital operations, two-weeks in advance. The MOT receives the activity plan and builds the weekly-command loads using previously defined command activity fragments that have been developed, tested, and stored in a database. The activity plan is iterated to eliminate all conflicts. Following final engineering review it is ready for uplink, one week in advance.

F.6.7 Science Operations and Analysis

The SOC gathers instrument data, relevant spacecraft housekeeping information, and navigation and pointing data and combines them in a form that can be readily ingested into processes developed by the Science Team and archived with the Planetary Data System (PDS). The SOC provides a quicklook capability to view the science data and provides validated science data products to the Science Team. The Science Team perform the detailed scientific data analysis to produce level 2, 3, and 4 science products. These products are delivered to the SOC to archive with the PDS.

The SOC is developed and operated by ACT (Applied Coherent Technology), a small-disadvantaged-business (SDB). ACT has successfully provided mission operations and image processing support for a number of missions, including Clementine and NATO's Rapid Environmental Assessment (REA). ACT is experienced in the application of image processing software working with the PDS. The SOC will participate in the early development of data processing requirements. Science data products, their producers, and schedules for release are shown in Table F-6-2.

F.6.8 Mission Operations Timeline

The timeline for the entire postlaunch phase of MESSENGER is shown in Fig. F-6-5. The granularity of the segments gets finer from top to bottom through four levels, with significant events marked at each level. The top level depicts the overall operational phase of the mission and compares directly with Fig. G-2-2 that indicates periods of data acquisition, downlink, and analysis. All of the major events during the mission are listed. There are scientifically important planetary flybys spaced throughout the cruise phase. During the Mercury flybys, 85% of the planet is imaged in monochrome and color (Sec. D.1.4). The propulsive events, shown above the years, are described in Sec. F.1.

The second level expands most of the orbital operations phase, which covers 4.2 Mercury years and one Earth year (September 30, 2009, through September 30, 2010). The four Mercury years correspond to two Mercury solar days because of Mercury's orbit-rotation resonance. MESSENGER enters orbit at a Mercury true anomaly (TA) of 342° (0° TA labels Mercury's azimuthal position in orbit at the time of its perihelion). The first solar day is dedicated to global-survey science by all instruments. During the second solar day most instruments conduct targeted observations aimed at interesting features revealed during the first solar day. During the second solar day, the MDIS imagers use a different scan mirror position to build up

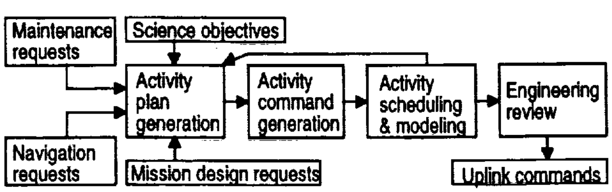


Fig. F-6-4 Planning and sequence generates command loads every week, one week in advance.

Table F-6-2 Data Product Delivery

Deliverable	Source	Web Display	Submission
Flight instrument data	SOC	Immediate	EOM + 6 mo.
Navigation and hskp data	SOC	Immediate	EOM + 6 mo.
Data products, Table D-1-1	Science Team	Monthly	EOM + 1 yr
Analysis products,Table D-1-1	Science Team	Recipt + 2 mo.	EOM + 1 yr

global stereo coverage. Throughout the entire period data accrue on the gravity field, elemental composition, and magnetosphere and exosphere of the planet.

The third level breaks out one Mercury year from perihelion to perihelion. Since the MESSENGER orbit is fixed in inertial space, it goes through a continuum of orientations relative to the Sun over the year. The dates of noon-midnight and dawn-dusk orbits about the planet are shown and are keyed to the sketch of Mercury's orbit about the Sun. The sketch indicates the projection of MESSENGER's orbit into the plane of the ecliptic, which is nearly edge on due to the 80° inclination of MESSENGER.

The fourth level depicts the geometry of the MESSENGER orbit relative to the Sun and the observing geometry for the noon-midnight and dawn-dusk extreme orbit cases. MESSENGER's highly elliptic orbit is viewed from the local perpendicular. For the dawn-dusk orbit (TA 157°) the view is from the direction of the Sun, and the thermal shade always points out of the page. In the dawn-dusk geometry, Mercury is continuously observable. MESSENGER rotates continuously about the spacecraft-sun line to keep the instruments pointed at the planet. The observing sequence is keyed to the distance from the planet, and the orbit is color coded to match the headings in Table D-1-5. This table describes the activities in each zone. Alternate orbits are used to downlink data; typically the eight hours of the orbit farthest from the planet are used. Limited observations can be made during the downlink and recorded for later playback, depending on the combined downlink and observing geometries.

The other viewing extreme occurs for a TA of 247°. The view is again from the local perpendicular to the orbit, and the Sun is on the left. In this geometry most instruments can not view the equatorial zone of Mercury because of the allowable spacecraft pitch angle of ±12.7° required to keep it in shadow. MDIS can still view all latitudes by moving its scan mirror. Alternate orbits are again used for downlink.

In the intermediate geometry orbits, combinations of pitch, yaw, and roll are used to maximize the observing coverage. Coverage calculations verify that global coverage during each solar day can be obtained at reasonable phase angles for all instruments. Ranging and Doppler measurements are made at various times during MESSENGER's orbits of Mercury to provide the radiometic data crucial to providing the detailed gravity model of the planet.

F.7 Facilities

No new facility or major construction is required for implementing the MESSENGER project. The Mission Operation Center (MOC) at APL for MESSENGER will be an upgrade to the existing NEAR MOC; this upgrade will occur during Phase C/D.

An optical attachment upgrade to the existing APL X-25 solar simulator is planned by the APL Space Department to occur by early 2000. This upgrade will be used by multiple projects and is being financed from APL capital-equipment funds. It will be used to investigate further the effects of high solar intensity and high temperature on the prototype solar array design during the Phase A/B risk mitigation studies (Sec. H). All other facilities for instruments and spacecraft already exist and require no modification.

F.8 Product Assurance and Safety

MESSENGER product assurance is based on: (1) a strong design integrity program, including rigorous design reviews; (2) careful control of parts, materials, and processes; and (3) a thorough program of inspections and tests. Consistent execution of this program has contributed to APL's outstanding record of reliability in space over the past 40 years. APL is currently working toward ISO-9000 certification.

Design Integrity Program. The design integrity program features consistent guidelines for technical risk assessment, redundancy allocation, reliability-requirements apportionment, parts selection, margins, derating, worst case analysis, failure mode effects analysis (FMEA), software development, testing, and other important functions. At program start, a Performance Assurance Implementation Plan is tailored to include NASA-agreed standards and practices for MESSENGER. These requirements extend to in-house fabrication and subcontracted items. Trade studies and design reviews are part of the overall design process. They are used to enhance reliability within the cost and schedule constraints. Trade studies are discussed in Sec. F.2.1 and Sec. H; design reviews are discussed in Sec. G.4. A top-level system reliability analysis will evaluate design configurations. New technology is incorporated only when it holds the promise of enhancing performance or reducing costs and its reliability is consistent with the overall mission.

The MESSENGER mission is relatively benign with regard to safety hazards. Safety hazards include pressure vessels, propellants, pyrotechnic release elements, high voltages in some instruments, and RF radiation. No ionizing radiation sources are used. APL has experience with all aspects of mission safety. A comprehensive safety plan will be developed by an SDB subcontractor working with the APL quality group (Table E-2).

Parts and Materials. APL has component engineers who provide part selection advice early in the design process. Parts are selected according to *GSFC Preferred Parts List PPL-21* where possible. All parts are screened and tested in accordance with *NASA/GSFC 311-INST-001*. MESSENGER uses a mix of NASA Grade 2 and 3 parts. APL has comprehensive facilities for parts screening, radiation testing, burn-in, failure analysis, destructive physical analysis, material analysis, and bonded storage. All components are burned in to reduce the effects of infant failures. Piece-part components, boards, electrical boxes, and the entire MESSENGER system are extensively tested to uncover latent defects. Burn-in requirements are listed in Table G-8-1.

Inspections and Tests. APL fabrication facilities perform their own quality inspections by both the operator and an independent inspector. The on-site Government Office can provide additional source inspections at critical points. Configuration verification is provided by periodic and final inspections in accordance with the drawing package and the APL workmanship standards document.

Table F-8-1 Burn-in Requirements

	System	Box	Board	Component	Total at Launch
Total hours	1000	250	250	168	1668
Failure-free hours	500	120	120	168	908

Configuration management is initiated at the start of flight hardware fabrication and maintained throughout the fabrication cycle (Sec. G.2.5).

All test and measurement equipment is maintained in calibration in accordance with APL calibration procedures. MESSENGER will have a tailored Contamination Control Plan. Contamination requirements and activities are described in Sec. F.4.

A formal system of Problem/Failure Reports (P/FRs) begins with box-level environmental testing. All test histories prior to environmental testing are recorded in engineering logbooks. P/FRs are closed in a formal process that emphasizes corrective and preventive actions. All P/FRs are closed-out before launch. After launch, a the P/FR process continues to record any errors, failures, and anomalies during mission operations.

Software is developed through a controlled and repeatable process (Sec. F.5.1). Software quality assurance is maintained through processes, procedures, and controls commensurate with the software criticality as defined in APL SD document SDO-9989, *Software Quality Assurance Guidelines* (Sec. G.2.5). Software acceptance tests are completed on each element and at the system level. Independent software validation and verification (IV&V) is performed on critical flight software. After delivery, all software is under configuration control. Any changes must be approved by the software Change Control Board (CCB), led by the MSE.

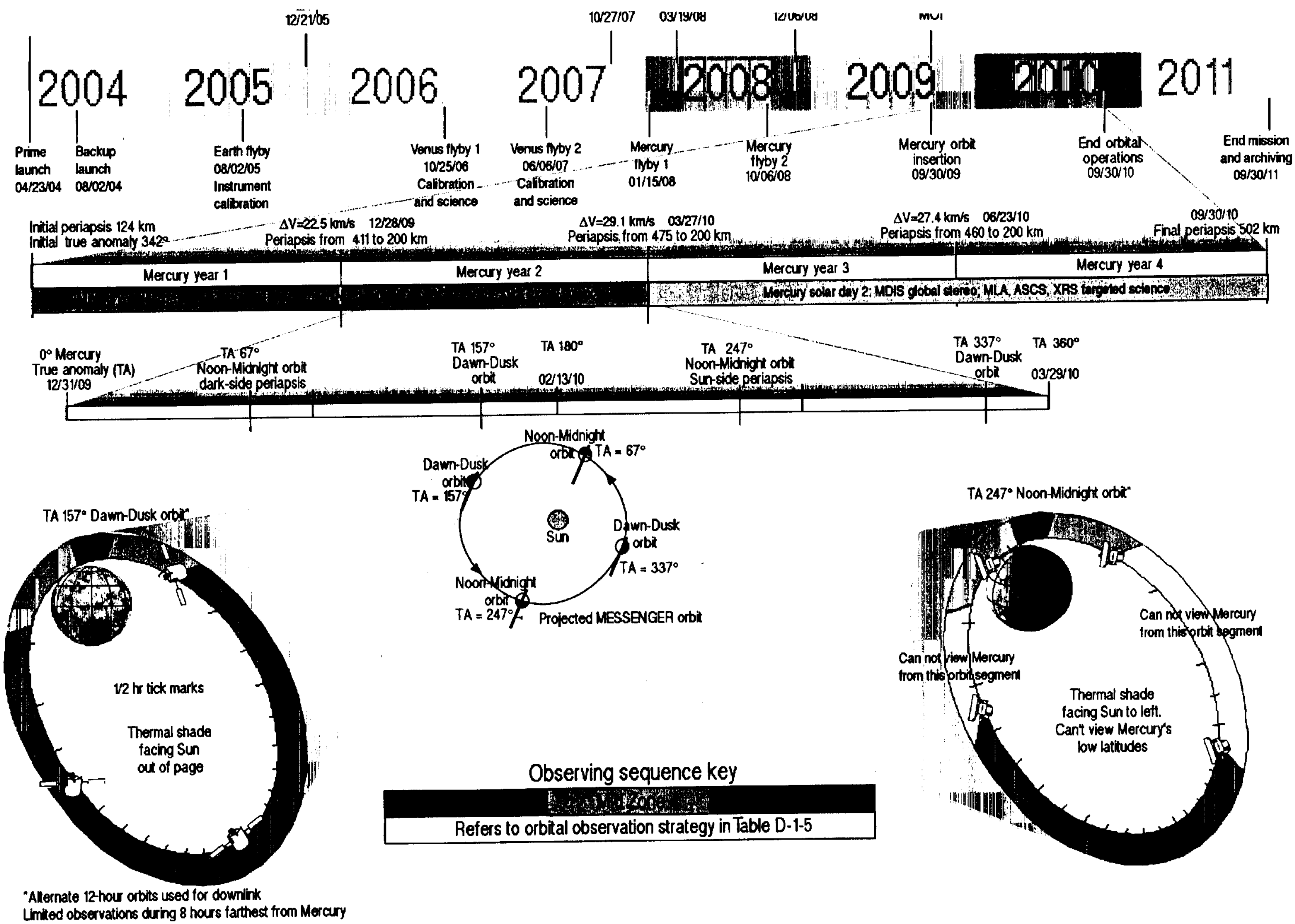


Fig. F-6-5 The mission timeline is expanded to show the 4.2 Mercury years (one full Earth year) of Mercury observations. One Mercury year is expanded to show the progression of the orbit in local time. The noon-midnight and dawn-dusk cases are shown with the three observing zones in red, yellow, and green. These color codes correspond to those in Table D-1-5, which describes the observation strategies for each instrument.

G MANAGEMENT PLAN

The management of MESSENGER includes monitoring, planning, and control of all facets of the mission. Overall project planning starts with the mission objectives, which flow down to the engineering team as level-one requirements. These are distributed to the subsystem lead engineers, who implement the designs. The subsystem leads are responsible for their design, cost, and schedule. Their status and planning are reported to the Project Manager, who maintains the overall project plan.

Responsibilities among all members of the team have been clearly delineated, and the lines of authority and delegation are understood. Communication among the team members is assured through an established meeting structure, reporting system, and common tracking software. Detailed plans for schedule and risk management are in place, and milestones for key management decisions have been established. The institutions supporting MESSENGER provide the support and resources required for the mission.

G.1 Team Member Responsibilities

The Principal Investigator (PI), Dr. Sean C. Solomon, leads the MESSENGER team and has responsibility for the ultimate success of the MESSENGER mission. He is responsible for establishing both the baseline mission and the minimum science performance floor. In conjunction with the Project Scientist (PS), the PI organizes and chairs Science Team meetings and leads the preparation of the Science Analysis Plan. He is also supported by an experienced organization, APL, which will manage the mission implementation. The PI reports progress and status to NASA and has sole authority to request the release of funds by NASA to all major participants in the project.

The top-level MESSENGER organization and team commitments are displayed in the foldout in Fig. G-1-1 and Table G-1-1, respectively. A strong Science Team (Sec. D.2.4 and Appendix A) is coupled with an experienced project implementation team (Appendix I) led by the Project Manager (PM). The Science Team is responsible for the scientific output of MESSENGER. The implementation team is responsible for the design, construction, and operation of all of the components of the system through Phases A to D. Many of these team members have worked together on previous missions (e.g., NEAR), interleaving science and implementation considerations for a balanced approach resulting in mission success. The scientific and technical leads have a considerable collective depth of experience, and they have already established a cohesive and efficient working relationship through the extensive series of meetings and mission planning efforts completed to date.

The Science Steering Committee (SSC), chaired by the PI, leads the Science Team (Sec. D.2.4). In addition to the PI, the SSC consists of the leaders of the four science groups, PS, PM, and Science Payload Manager (SPM). The SSC reviews status on science and mission implementation and strategic planning. Any problems encountered are discussed to ascertain the impact on the mission. Where appropriate, recommendations are given to the PI.

The PM leads the implementation team, which is organized in a manner similar to that used successfully by APL for the NEAR and ACE programs. He is responsible for the spacecraft, ground system, launch vehicle interface, mission design, and science payload. The PM, in turn, is supported by the Mission System Engineer (MSE) with full authority in all technical matters for the project.

The PS coordinates science requirements with the PI, Science Team, SPM, and MSE. He co-chairs Science Team meetings with the PI, and he provides day-to-day contact on science issues with the PM and technical staff.

Further details on roles, responsibilities, time commitment, unique capabilities, relevant experience, proposed funding, and contractual relationships for MESSENGER team organizations and personnel follow. The letters of endorsement are included in Appendix B.

G.1.1 Organizational Structure

The project is led by the Carnegie Institution of Washington (CIW) and The Johns Hopkins University Applied Physics Laboratory (APL). The pre-launch organization is shown in foldout Fig. G-1-1. The organization for Phase E is shown in Fig. F-6-1. This type of organizational structure has been chosen because of its proven ability to work in many previous missions. The participating major organizations and their funding methods are described below.

Carnegie Institution of Washington (CIW). The Carnegie Institution of Washington, a private, nonprofit organization engaged in basic research and advanced education in biology, astronomy, and the Earth sciences, was founded by Andrew Carnegie in 1902 and incorporated by Act of Congress in 1904. From its earliest years, the Carnegie Institution has been a pioneering research organization, devoted to fields of inquiry that are among the most significant in the development of science and scholarship. Recognizing that fundamental research is closely related to the development of outstanding young scholars, the Institution conducts a strong program of advanced education at the predoctoral and postdoctoral levels. Carnegie also conducts distinctive programs for elementary school teachers and children in Washington, D.C.

CIW provides the PI, Dr. Sean. C. Solomon, Director of the Department of Terrestrial Magnetism (DTM), and associated administrative support (Fig. G-1-2). DTM studies the multidisciplinary nature of the Earth, planetary, and astronomical sciences. In addition to DTM, CIW provides an important part of the classroom and educator training of the MESSENGER project (Sec. E.1.1). CIW is funded directly from the NASA Management Office (NMO) via a contract for the PI, his associated support, several Co-Investigator (Co-I) Science Team members, and members of the E/PO team (Sec. I). Funding for MESSENGER development does not pass through CIW, but the PI does control its release, with the agreement of the NMO. This procedure provides the PI with cost control over the entire project.

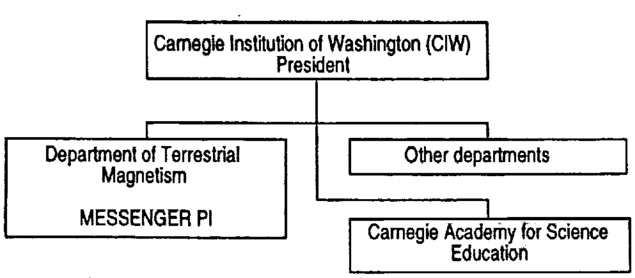


Fig. G-1-2 CIW supplies the PI and contributes an important component of the education and outreach program.

Johns Hopkins University Applied Physics Laboratory (APL). APL is a not-for-profit University Affiliated Research Center (UARC) with a long history of success in both NASA and DoD space missions. The APL Space Department (SD) has built and launched 57 spacecraft (11 to NASA) and over 100 instruments to date. In addition, the APL SD has an excellent record in providing spacecraft and instruments under budget and on time (Crawford et al., 1996). For several of these missions, an organization similar to MESSENGER was used. Most recently APL successfully developed and managed the NEAR mission, performing the function of a NASA center.

APL has capabilities in all aspects of a mission, from concept design to delivery of data and analysis, and is well qualified to perform the implementation of the MESSENGER mission and provide several Co-Is (Sec. D.2.4, foldout Table G-1-1, and Appendices A and I). The SD has approximately 380 Full-Time Equivalent (FTE) staff of the total 2,680 APL FTE staff. There are currently another 570 Resident Subcontract Employees (RSEs) at APL to assist in accomplishing shorter-term tasks. The SD offers the benefits of a small, efficient organization, but with the advantages of being part of the larger APL organization and the Johns Hopkins University that can provide a variety of disciplines and expertise for specialized support and services that may be needed only for short periods of time.

The APL SD is the line organizational unit responsible to the PI for the technical implementation of the MESSENGER project (Fig. G-1-3). The project will use APL in-house mechanical and electronic design and fabrication facilities of the Technical Services Department (TSD) as appropriate to implement several of the MESSENGER instruments and spacecraft bus subsystems. APL has in-house procedures and controls to ensure cost, schedule, quality, and technical performance consistent with NASA requirements (Sec. F.5.1). APL is funded by the NMO via NASA contract NAS5-97271, a cost-plus-fixed-fee (CPFF) task order under that contract.

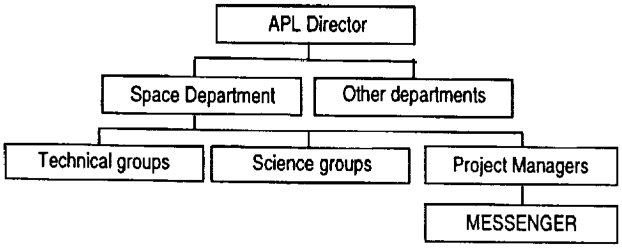


Fig. G-1-3 APL's matrix management supplies the technical and scientific support for MESSENGER.

NASA/GSFC. Goddard Space Flight Center (GSFC) provides the MLA instrument and analog electronics for MAG. GSFC has experienced staff and extensive fabrication facilities. The GSFC MLA and MAG teams, headed by Drs. D. E. Smith and M. H. Acuña, respectively, have provided similar instruments on previous missions, including NEAR. In addition, GSFC will provide access to its environmental test facility to perform flight qualification of the MESSENGER spacecraft. Funding for the GSFC Co-Is, instruments, and environmental test facility is via an internal NASA transfer performed by the NMO.

NASA/JPL. The Jet Propulsion Laboratory (JPL) Telecommunications and Mission Operations Directorate (TMOD) provides targeting and tracking for MESSENGER. The directorate has performed these functions for the NEAR mission. In addition, APL will use the environmental test facility at JPL to perform qualification testing of the MESSENGER solar arrays. Funding for JPL responsibilities is via an internal NASA transfer performed by the NMO.

NASA/OLS. Orbital Launch Services (OLS) provides the launch vehicle and associated services (e.g., propellant, launch site processing facilities). APL has worked with OLS on many missions to coordinate technical and programmatic activities between the spacecraft and launch vehicle. Funding for OLS and the launch service is provided directly from the NMO.

NASA/NMO. The NMO has oversight responsibility and performs independent reviews and assessments. NMO performs the internal NASA funding transfers required for MESSENGER (foldout Table G-1-1).

Science Team Organizations. The Science Team is composed of individuals from a variety of universities, research institutions, and government laboratories who are experts in their field (Sec. D.2.4 and Appendix A). Funding for the Science Team is provided via subcontracts from CIW to their organizations, with the exception of the Science Team members from APL and GSFC. APL Co-Is are funded through the primary APL contract. GSFC Co-Is are funded by the NMO through an internal transfer to GSFC.

Education/Public Outreach (E/PO) Team. The American Association for the Advancement of Science (AAAS) guides a team of skilled educational leaders from a wide variety of professional organizations experienced in education and outreach endeavors. Implementation of the E/PO plans are led by Dr. S. M. Malcom, AAAS Director of Education and Human Resources, and Dr. G. D. Nelson, AAAS Director of Project 2061 (Sec. E.1 and Appendix A). Funding for this team is provided via subcontracts from CIW to the organizations listed in Sec. E.1.

Laboratory for Atmospheric and Space Physics (LASP). The University of Colorado LASP provides the ASCS instrument. LASP built the Galileo Ultraviolet Spectrometer, which is very similar to ASCS. LASP is funded by APL via a subcontract for the ASCS and by CIW via a subcontract for Co-I activities.

University of Michigan (UM). UM provides the FIPS portion of the EPPS instrument. They have experienced personnel (some formerly at University of Maryland) and the required facilities for the instrument. This team has worked closely with APL on Cassini/MIMI. UM is funded by APL via a subcontract for the FIPS and by CIW via a subcontract for Co-I activities.

Industrial Partners. Secondary teaming arrangements for mission implementation are planned with Composite Optics, Inc. (COI), and GenCorp Aerojet for the design and fabrication of the spacecraft structure and its integrated propulsion system. APL has a long and successful history of teaming with each of these organizations for spacecraft propulsion systems and structural components. The development process and the close-team interaction is described in Sec. F.2.2. These implementation team members will work under direct subcontract to APL.

Aerojet is a major supplier of spacecraft propulsion systems and supplied APL a similar integrated structure and propulsion system on NEAR. Aerojet is funded by APL via a cost-plus-incentive-fee (CPIF) subcontract, with incentive tied to performance (Appendix H).

COI is a small business that supplied a similar type of structure for FORTÉ, and the graphite-epoxy truss structure to APL for the Midcourse Space Experiment (MSX). COI is funded by APL via a CPIF subcontract, with incentive tied to performance (Appendix H).

Changes in Personnel. Personnel changes during the life cycle of a mission are inevitable. The orderly transition of personnel is of critical importance for planned personnel changes. For these cases, each team member organization consults with the PI prior to effecting any change in key personnel. The PI monitors changes in project personnel to assure that all changes result in as smooth a transition as possible. For APL, planned changes are not expected very often since the average yearly turnover rate has historically been only about 4%, well below the industry average.

There may also be situations where an abrupt change in personnel (e.g., accident, illness, or death) must be addressed. The team member organizations have a great deal of resilience with technical depth and breadth. In such a situation, the management of these organizations will support the MESSENGER project with all of the resources required to ensure that there are sufficient personnel familiar with the project so that a competent replacement can be assigned.

G.1.2 Experience and Commitment of Key Personnel

Details of many of the responsibilities, experience, and qualifications of MESSENGER key personnel as well as points of contact are given in Sec. D.2.4, foldout Table G-1-1, Table G-1-2, and Appendix A. Responsibilities are described in Sec. G.1.1.

Principal Investigator. Dr. S. C. Solomon has been the Director of the DTM at CIW since 1992 and has considerable experience on science teams for NASA planetary missions, including Magellan and Mars Global Surveyor. He recently completed a two-year term as President of the American Geophysical Union. Currently a member of the Solar System Exploration Subcommittee of the NASA Space Sciences Advisory Committee as well as a member of the agency's Earth System Science and Applications Advisory Committee, Dr. Solomon is a past member of the Space Studies Board, its Committee on Planetary and Lunar Exploration, and many other NASA advisory committees. His time commitment averages 30% over the duration of the project.

Table G-1-2 Key Personnel Points of Contact

Name	Address	Phone/Fax/Email
Dr. S.C. Solomon	Carnegie Institution of Washington Department of Terrestrial Mag. 5421 Broad Branch Rd, NW Washington, DC 20015	(202) 686-4370, ext. 4444 (202) 364-8726 scs@dtm.ciw.edu
Mr. M.R. Peterson	The Johns Hopkins University Applied Physics Laboratory 11100 Johns Hopkins Rd. Laurel, MD 20723	(240) 228-5832 (240) 228-1093 max.peterson@ jhuapl.edu

Project Manager. Mr. M. R. Peterson joined APL in 1961 as a member of the engineering staff. From 1989 to 1998, Mr. Peterson was PM of the MSX program. Prior to 1989, he held a number of other program-management positions, including Assistant Project Manager and Project System Engineer for NASA's Active Magnetospheric Particle Tracer Explorer/Charge Composition Explorer (AMPTE/CCE) program and Program System Engineer for the DoD Polar Beacon Experiment and Auroral Research (Polar BEAR) program. Time commitment for the PM is 100% for Phases A-D, and approximately 20% for Phase E (averaged over cruise, each flyby, and Mercury orbital operations).

Project Scientist. Dr. R. L. McNutt, Jr., is a Co-I. He is the Assistant Group Supervisor of the Space Instrumentation Group. Dr. McNutt has been an APL staff member since 1992. In addition to his space physics research activities, he has served on several NASA committees, including currently the Sun-Earth Connections Advisory Subcommittee of the NASA Space Sciences Advisory Committee. The PS responsibilities are described in Sec. G.1. Time commitment for all of Dr. McNutt's activities is 60% during Phases A-D, 50% during Phase E cruise, 90% from the first flyby through Mercury orbital operations, and 50% for one year following Mercury operations.

Mission System Engineer. Mr. A. G. Santo joined APL in 1985 as the Lead Engineer for the

Ground Support System on the Delta 180, 181, and 183 spacecraft. Since then he has served as the Spacecraft System Engineer on the Altair program (a space-based acquisition, tracking, and pointing system) and most recently as the System Engineer on the NEAR program. The MSE responsibilities are described in Sec. G.2.1 and G.2.3. His time commitment is 100% for Phases A-D and 30% for Phase E.

Mission Manager (MM). Dr. R. W. Farquhar has a long and distinguished career in mission design for NASA programs. He is well known for his innovation and creativity in designing missions. Dr. Farquhar joined APL in 1990 and is currently the NEAR and Comet Nucleus Tour (CONTOUR) Mission Manager. The MM responsibilities are described in Sec. G.2.1 and G.2.3. His time commitment averages 20% during Phases A-E, with the highest levels occurring during launch and immediate post launch, during deep-space maneuvers, during each planetary flyby, and during Mercury orbital operations.

Science Payload Manager (SPM). Dr. R. E. Gold is a MESSENGER Co-I and the Assistant Branch Supervisor of the Space Engineering and Technology Branch. Dr. Gold has been involved in space physics research and instrumentation design since joining APL in 1975. Most recently, he was responsible for the development of the NEAR instrument payload, including the Multi-Spectral Imager (MSI), X-ray spectrometer, gamma-ray spectrometer, laser altimeter, and magnetometer. The SPM responsibilities are described in Sec. G.2.1 and G.2.3. His commitment averages 20% during Phases A-E, with the highest level occurring during instrument design and development.

G.2 Management Processes and Plans

Standard APL project planning tools and processes were used during the MESSENGER Concept Study and will continue to be used throughout the project. A work breakdown structure (WBS) covers all project elements and all organizations (Appendix G, Table Ap. G-APL-2). The WBS is used as a resource management tool for planning and tracking cost. A master schedule has been developed during the Concept Study. During Phase A/B, the Phase C/D schedule will be further defined and baselined. Critical Phase C/D milestones will be developed and negotiated among the PM, PI, and NMO.

Performance will be measured by comparing status with project plans, schedules, commitments, and expenditures. The project will carefully follow the design and development process as part of the cost and schedule management (i.e., "design to cost") technique that has proven successful on APL space programs for many years. This approach entails the use of negotiated subsystem costs versus time, weekly status meetings with the lead engineers, detailed tracking of progress and adherence to schedules, and semimonthly cost-accounting reports. These reports track and control the in-house subsystem development and fabrication efforts, as well as external procurements. This process is described in more detail in the following paragraphs.

G.2.1 Integrated Engineering Plan

APL emphasizes system engineering during all phases of a project. A critical part of the system engineering function is to document and flow down requirements. The result of this process is captured in a mission system-level specification that is developed and maintained by the MSE. The flow down of the hardware and software requirements is thoroughly and formally reviewed prior to the start of design at the System Requirements Review/Conceptual Design Review (SRR/CoDR), which will be held early in Phase A/B.

The MSE is responsible for leading the technical evaluation of all system issues while maintaining cognizance of the total mission objectives. He is responsible for the overall spacecraft and ground-system architecture, launch vehicle interface, operations development, integration, and performance verification. The MSE is responsible for the requirements-definition and interface-control documents, with assistance from the Spacecraft System Engineer (SCSE), SPM, Software System Engineer (SWSE), and Ground System Engineer (GSE). The MSE works with the Mission Operations Team after launch to bring important spacecraft understanding to bear during the early mission phases. Mr. Santo is currently serving in a similar capacity for NEAR and will be able to apply directly the experience of that mission to MESSENGER.

During the Concept Study, the MSE developed the top-level mission requirements and formulated the MESSENGER design by working with the experienced spacecraft subsystem and instrument engineers. This design satisfies the science requirements in Sec. D, as well as the constraints of technical feasibility and programmatic considerations. This process has resulted in an integrated system design covering spacecraft, instruments, ground systems, mission operations, and science data processing.

During program development, the MSE tracks, maintains, and trades the requirements to the spacecraft, instrument interfaces, and ground systems. These requirements are documented and signed by the appropriate lead engineers, the MSE, and the PM. The MSE follows the technical progress of all mission elements to ensure that design, development, and testing proceeds in an integrated manner to achieve the mission requirements. The MSE makes any adjustment of lower-level requirements between components, as long as the overall system requirements (and cost and schedule) are not affected. The MSE participates in all system-level trade studies and is responsible for ensuring that existing designs from recent and ongoing programs, such as NEAR, ACE, TIMED, and CONTOUR, are fully evaluated for possible use in the MESSENGER technical implementation (Sec. F). This assessment has been done to the board level during the Concept Study, but detailing remains to be done. The MSE allocates design reserves for all spacecraft resources (power, mass, etc.) to the subsystems and instruments.

The Performance Assurance Engineer (PAE) reports to the PM, but has direct access to the SD Head. This individual is assigned early in Phase A/B and continues through launch and mission operations. This early establishment of the PAE role, typical of APL projects, provides designed-in performance assurance to the product, rather than attempting to correct performance assurance problems that arise during manufacture or after the product has been manufactured. The PAE is responsible for all aspects of quality assurance for MESSENGER, including APL and subcontractors, and develops a preliminary version of the Performance Assurance Implementation Plan (PAIP) that is submitted to the NMO for approval. The PAIP describes all of the quality assurance requirements for the mission. The PAIP includes mission standards for materials, parts testing and derating guidelines, verification, design assurance and reliability, and safety. The final version of the PAIP is signed off before spacecraft PDR.

The SCSE, working under the MSE, provides the technical leadership for development of the spacecraft bus and the integration and test of the instrument payload with the bus. The SCSE makes risk assessments, contributes to make/buy decisions, oversees all spacecraft-level testing, and monitors spacecraft mass and power budgets.

The SWSE is cognizant of the development of all software for MESSENGER flight and ground systems, including definition and management of software interfaces, management of software design methodologies, planning and execution of software testing at the system and subsystem level. The SWSE has responsibility for all fault-protection software development and testing and works closely with the PAE to generate the software portion of the PAIP. The SWSE, in conjunction with the PAE, implements the requirements of the PAIP and directs the processes established by the SD to assure that delivered software, whether prepared in-house or purchased, performs as expected and is well controlled. This effort ensures that all aspects of the APL *Software Quality Assurance Guidelines* are implemented (Sec. G.2.5).

The GSE has responsibility for all ground-based functions in support of the mission. A single ground system is designed for both the integration and testing pre-launch and the mission operations phase. The hardware, software, and data bases developed to test the individual subsystems become the ground support system for spacecraft integration and test and, finally, become the core of the Mission Operations System. Consequently, the GSE must coordinate the development of all elements of this system from conception through mission operations (Sec. F.6).

The MM directs the mission design and navigation and interfaces with the Telecommunications and Mission Operations Directorate (TMOD) Deep Space Network (DSN) and Radio Metric Navigation Service Group.

Many of the subsystem leads not listed in foldout Fig. G-1-1 have been assigned. These leads are formally designated and carry the responsibility for the delivery of that subsystem. Lead engineers are selected from a cadre of individuals who have extensive experience in space development. They are assigned by the line supervisors and approved by the PM and the SD Chief Engineer. The leads are given authority to marshal the necessary resources in consultation with the PM. They develop bottom-up, detailed, Critical Path Method (CPM) schedules (Pisacane, 1994) for their subsystems. They remain with their subsystem from design through fabrication, test, integration, and launch. In most cases, because of APL's unusually low turnover rate, the same individual is available throughout the mission duration for consultation on any anomalous behavior. This is a significant benefit to a long-duration mission such as MESSENGER.

This lead-engineer approach establishes a strong sense of ownership in the subsystem and minimizes the need to transfer detailed knowledge from individual to individual. At the same time, these lead individuals work under a formal process with fabrication drawings and documentation requirements that are sufficiently rigorous so that the required information can be transferred between team members or to a replacement individual if necessary.

G.2.2 Hardware and Software Acquisition

Early in Phase A/B, an overall hardware and software acquisition plan is developed. As a part of this plan, make/buy criteria are established. The criteria are evaluated at the system level to balance cost, performance, availability, and margin. Those items selected for in-house development are fabricated by the APL Technical Services Department (TSD). Use of TSD allows the MESSENGER lead engineers to work directly with the designers, assemblers, technicians, and machinists to monitor development closely and to resolve problems quickly. This production capability has been used for all of APL's 57 spacecraft. The experience gained in the design and fabrication efforts for these previous programs and the ability to have this direct interface greatly reduces schedule risk. This was a significant factor in enabling NEAR's completion within 27 months.

When the decision is made to purchase major components, the PM assigns a contract technical representative (CoTR) for each major subcontract. Working with the Business and Information Services Department (BISD), the CoTR develops a statement of work, a procurement specification, and proposal evaluation criteria so that a request for proposal (RFP) can be issued. After technical evaluation, a supplier is selected and a subcontract is issued. Early subcontracts must be established with our industrial partners, Aerojet and COI, for detailed design so that flight-hardware development is immediate at the start of Phase C/D. All flight-hardware procurements are awarded after the start of Phase C/D. Following contract award, the CoTR works with the BISD Subcontract Administrator (SCA) to monitor technical and financial progress. To the extent possible under the specific contract type, APL forms a "teaming" arrangement with each vendor to establish close engineering and product assurance level contact. Interface coordination is enhanced, and if problems arise they are quickly addressed. Financial progress is tracked against the vendor expenditure plan. This expenditure plan is reviewed on a monthly basis to evaluate cost performance against technical progress. This process has been used on previous APL programs, including MSX and NEAR, and has contributed significantly to the success of our programs.

Software acquisition includes the embedded software in the inertial measurement unit and star tracker and the mission operations control software. These are all existing products that require no new development. The acquisition is handled similarly to other subcontracts.

G.2.3 Lines of Authority

The lines of authority for decision-making follow the organizational chart in foldout Fig. G-1-1, and the general hierarchy for decision making is shown in Table G-2-1. The PI is the individual responsible for accomplishing the total mission success. He holds the final decision-making authority in all areas and has the sole authority to authorize the release of funds by the NMO. He will obtain NASA approval before implementing any changes affecting mission scope or NASA contractual requirements and agreements.

The PM has authority for all implementation decisions that do not impact science requirements, cost, schedule, or other resources except where this authority is specifically delegated by the PI. The PM is supported closely by the MSE, the PS, the MM, and the SPM. The MSE has authority for technical implementation decisions that do not impact implementation requirements, cost, or schedule. System engineers are designated for the spacecraft, software, and ground systems. Following APL practice, lead engineers are assigned for all major subsystems and disciplines for the implementation phase. These leads have authority for decisions within their areas of responsibility that do not impact others, but these decisions are monitored by the PM, MSE, and appropriate spacecraft, software, or ground system engineers. The SPM has the authority for technical implementation of the instruments within requirements, cost, and schedule. Lead engineers are assigned for each individual instrument at the appropriate organizations to track technical progress, cost, and schedule. Specific Science Team members also participate in instrument development as described in Sec. D.2.4 and Appendix A.

These lines of authority are rigorously enforced, and team members are held accountable for decisions and are required to bring matters beyond their delegated authority to the next level. This accountability requires close communication among the PI, PM, PS, MM, SPM, and MSE. Major activities and decisions are discussed among these individuals to ensure that all possible consequences have been considered. Close communications among the PM, MSE, and the lead engineers for implementation are also required for ensuring that all aspects of technical implementation are being properly pursued. This communication is facilitated by the relatively small number of primary organizations involved in the MESSENGER mission, and by the geographic proximity of CIW and APL, where most of the implementation effort is planned.

Table G-2-1 Decision Responsibility

PI	Cost, mass, power, and science margin allocation; descopes
PM	Cost trades among subsystems; approval of reserve allocations
MSE	Trades across subsystems; allocation of mass, power reserves
MM	Mission design trades; mission operations trades post-launch
SPM	Payload trades across instruments that do not affect resources
Eng. leads	Local trades within subsystem

Reserves for spacecraft resources (power, mass, bit rate) are allocated by the MSE. Margins and cost reserves are released by the PI, on the recommendation of the PM and the concurrence of the SSC. The plan for reserve allocation requires a continuous trade space in which the evaluation of the request is balanced against all other potential risks and impacts in other systems as a function of cost-to-completion while maintaining the science-gathering integrity of the mission. This continuous trade space is managed by the MSE through the weekly status meeting and monthly progress reporting. The process for margin allocation is similar, except that approval of the PI is required. The goal for mass and power resources are that total allowable growth (reserves plus margins) should be at least 35% at the start of Phase A/B, 25% at mission SRR/CoDR, 20% at PDR, and 10% at CDR. Not meeting these goals may trigger descope options.

G.2.4 Coordination and Communication

Effective decision-making requires good communication among all team elements and the use of standard planning and tracking tools. Good communication is ensured through regularly scheduled meetings (Table G-2-2) and maximum use of electronic media and teleconferencing. The PI will hold full Science Team meetings twice yearly prior to launch, annually from launch to first Mercury flyby, and twice yearly from the first Mercury flyby to Mercury orbit insertion. Science Team meetings will be held every two months during Mercury orbital operations and every four months in the year following Mercury orbital operations. Teleconferencing will be used between meetings to maintain frequent communications without the expense of travel. The E/PO team has monthly meetings, usually by teleconference, and is represented at Science Team meetings.

The PI and PM will hold monthly implementation team meetings at APL. These meetings cover mission design, instrument progress, spacecraft progress, and ground system progress. Lead engineers from each technical implementation element are required to attend. For team members not in the immediate area, a teleconference is established. While these meetings have an established agenda, they are working meetings in which discussion is encouraged to identify areas where coordination is needed. Action items from these meetings are assigned and tracked by the MSE. The minutes of these meetings are the basis for the monthly status reports to the NMO. The NMO is also encouraged to attend.

Weekly meetings of the PI, PM, PS, MSE, MM, and SPM are held to assure that status is understood and problem areas identified are communicated to the other principal leaders. These weekly meetings, started during the Concept Study, have no formal agenda, but are working meetings lasting no more than two hours. Technical leads are invited to attend these weekly meetings, as appropriate. Such coordination meetings have high value, since they keep minor problems from becoming major problems. Several mission-level reviews are held to communicate across the project, and to ensure that all elements are progressing in accordance with the cost and schedule (Sec. G.6).

A MESSENGER Internet web site has been established and will be maintained by CIW and APL. This site is used to communicate materials among implementation team and Science Team personnel, to disseminate data from the mission (Sec. D.2.3), and to tie implementation activities to E/PO activities (Table E-1). Project documents, requirements, schedules, and other team material will be made available on-line for quick access by the team members to enhance communication within the project.

G.2.5 Configuration Management

The Chief Engineer of the APL SD is responsible to the Department Head for overall configuration management, which includes establishing processes and standards for engineering design, fabrication, and test and for the overall design integrity of the hardware and software products developed by the SD. Configuration management is initiated at the start of flight-hardware fabrication and maintained throughout the fabrication cycle. The PAE is responsible for ensuring that established configuration management practices and procedures are properly followed.

Guidelines issued by the Reliability and Quality Assurance (RQA) group in accordance with the PAIP provide the basis for parts selection and derating for any new designs that may be required. Based on these guidelines, subsystem and instrument lead engineers perform the basic engineering design, including breadboard or model testing as necessary.

Flight article engineering drawings and drawing-change control for the spacecraft bus is Level 2 as defined in the *APL Design Documentation Manual* (TFO-STD-200.1). Level 2 provides full configuration control during fabrication and supports a post-delivery configuration verification audit. Level 2 is selected to provide the optimum documentation for flight-hardware configuration control. The instruments and spacecraft wiring harness are built to Level 2a. Level 2a provides rapid response by allowing fabrication to red-line changes that are later incorporated into the drawing package. The entire design, drawing, and manufacturing system is coordinated through the use of intelligent data bases, which insure that the flight articles conform to the design (Sec. F.5.1). Materials, processes, and design parameters are identified in engineering drawings, test specifications, and procurement specifications. The APL drawing system establishes rigorous identification of all individual items of hardware, as well as all required assemblies and installations.

All flight-qualified electrical and electronic parts to be used in fabrication are held in a controlled stockroom operated by the SD RQA group and are issued only to authorized persons. Control of APL-fabricated articles is led by RQA group personnel who perform a module-kit inspection as the flight-qualified parts are released for fabrication and assembly. The serial numbers and lot codes for the parts are recorded to establish traceability. Fabrication is performed in the APL TSD, utilizing a system of fabrication control cards to document the fabrication and inspection sequence. Each operator initials the control card as each fabrication or assembly step is completed, and inspection is provided at specified points during fabrication. The completed card provides evidence that the article has met the applicable fabrication and quality requirements.

Fabrication is initiated and controlled by a drawing-release work request that accompanies the drawings needed to build a particular assembly. Such a work request provides the fabrication shop with final electrical and mechanical parts lists and detailed fabrication instructions. It authorizes manufacturing to draw parts from the bonded flight stockroom, prepare any required special tooling or jigs, and build detailed subassemblies. Configuration identification is maintained by a unique part number. Details of the identification system and the controls for traceability are contained in the APL TSD *Hardware Configuration Management Manual* (TSD-STD-400.1).

Configuration verification is provided by the planned inspections, which inspect the workmanship and the as-built configuration in accordance with the drawing package. Hardware and drawing changes are controlled by the use of Engineering Change Request (ECR) forms and Material Review Disposition Forms (MRDFs). Formal procedures for drawing changes and Material Review Board activity are defined in existing APL standards. ECR processing is controlled by the Design Drafting Section, and MRDF processing is controlled by the RQA group.

Software development controls and procedures are defined in APL SD document SDO-9989, *Software Quality Assurance Guideline*. Issues covered include personnel responsibilities, areas of applicability, task planning, systems evaluation, and control of products and processes. Software life-cycle considerations, validation and verification (V&V), configuration management, documentation, quality assurance, and commercial software and services are also covered. For critical flight software, a full-independent V&V is conducted.

G.2.6 Schedule Management

Significant experience resides at APL for the detailed scheduling of major space activities (Pardoe, 1996). Project-level schedules are constructed by the PM. He first establishes the milestones for the major phases of the project. The establishment of the launch window and the allowable time for each major activity leading up to launch are set from project cost and mission-design constraints and recent program experiences. Within those constraints, lead individuals are tasked to develop their own schedule for their required activities.

The schedule shown in foldout Fig. G-2-1 is built from the bottom up. It is constructed from integrating subsystem schedules developed during the Concept Study by the lead engineers into a system schedule. As an example, spacecraft software development is shown as a second-level task under Phase C/D Spacecraft Development. Although not shown on this summary schedule, at the third level of detail are CPM schedules defining the activities needed to accomplish each of these important software development tasks. All other rolled-up activities in foldout Fig. G-2-1 are supported by a similar underlying level of detail.

During Phase A/B, the individual tasks for accomplishing these efforts are further planned to the appropriate level of detail (Table H-1). Since all the elements of the schedule are themselves CPM charts, the integrated whole is also a CPM chart. Consequently, the effect of delay in completion of any task can be quickly assessed and appropriate adjustments made.

The monthly implementation team meetings and weekly status meetings are augmented with specific subsystem schedule-status reviews, in which progress on individual subsystems is reviewed against the CPM schedule developed by the cognizant lead engineer. At these schedule reviews, chaired by the PM and attended by the MSE and the SCSE, programmatic decisions and prioritization can be made. In addition, the line supervisor for the lead engineer's group is present so adjustment of personnel resources can also be made. These schedule-status reviews are held on a cycle to cover all subsystems at approximately one-month intervals.

Microsoft Project™ (MSProject), a cross-platform scheduling software package, has been selected for use by the entire MESSENGER project. All leads use this scheduling tool and prepare a CPM schedule for all activities down to a granularity of approximately one staff-month of effort.

G.2.7 Progress Reporting

The MESSENGER Project Manager at APL, under the cognizance of the PI, prepares and submits monthly progress reports to NASA covering all project activities. These reports discuss current and planned progress and the status of any unresolved problems. The reports are coordinated and signed by the PM and the PI. The basis for these monthly progress reports are the minutes of the monthly implementation team meetings led by the PI and PM. Within those meetings, information on technical and schedule progress are required from each lead individual. Specific areas covered are master schedule and critical-milestone status of major subcontracts and electronic piece-part procurements, detailed instrument and subsystem status, and problem areas with resources or delivery dates. The fiscal status of each organization is reported at the meeting. The summation of this information provides an overall project assessment and is the starting point for any required corrective action. Variances in actual spending or progress versus the plan are investigated by the PM and explained; if needed, action is taken to maintain baseline costs.

The PAE appends a report to the PM's monthly progress report giving an independent status of the product assurance activities. The contents of this report are defined in detail in the PAIP.

The resource manager prepares and submits monthly financial reports to NASA covering all project activities. The monthly financial reports use the format of NASA Forms 533M and 533Q. Costs for these reports are summarized at the first and the second levels of the WBS. APL has considerable experience with this method of reporting costs to NASA and is using it currently on the NEAR and TIMED programs.

G.2.8 Resource Management

During the Concept Study, firm budgets (Sec. I) were allocated to the MESSENGER team member organizations (foldout Fig. G-1-1, foldout Table G-1-1) for their work using in-place management tools for establishing and tracking cost and schedule information. MSProject is used across all elements for scheduling.

Management of the technical-implementation effort is based on a central database of planning and fiscal data for all SD programs. For this purpose, the APL SD has a Microsoft Excel™-based Resource Manage-ment Information System (RMIS) to plan and track all costs, including staffing, procurements, and subcontracts. This system interfaces with the official APL financial system but allows off-line flexibility to assess project-planning activities and progress. The RMIS is available to resource managers, project managers, and technical group supervisors and contains details of all planned resources, by WBS, responsible technical group, and time. It integrates all resource and cost-accounting data at APL. It generates project planning documents, cost estimates, and funding projections; prepares material for inclusion in funding letters; and preserves project cost baselines. Cost elements include APL and resident subcontract employee (RSE) direct labor, consultant labor, subcontracts, material and equipment procurements, and travel. Costs are tracked on a monthly basis for each WBS element. A resource manager assists the PM in initial planning of project resources, tracking spending and procurement status,and controlling work via work authorization documents. The RMIS has been used to prepare all cost estimates for MESSENGER.

Control of resource commitments is handled by the resource manager and the PM. The resource manager assists the PM in preparing procurement and obligation authorizations that initiate and terminate commitment authority by the technical groups. No charges are accepted by the accounting system without this authorization. All TSD electronic and mechanical fabrication time is budgeted and controlled using work authorization documents initiated by the lead design engineers and approved by the PM. Purchases and subcontracts must be approved by the PM and recorded in the baseline plan by the resource manager. When necessary, personnel resource conflicts between projects are resolved by meetings between the SD Programs Manager and the affected project managers to assure success of all projects.

G.3 Schedules

The top-level schedule, including schedule reserves, for achieving the primary launch date is provided in foldout Fig. G-2-1. The basis for the Phase A-D top level schedule is an underlying MSProject CPM-schedule network currently containing more than 500 individual-linked tasks, which are "rolled-up" to produce the summary schedule presented. The project-implementation schedule is unchanged from the Phase-One proposal. MESSENGER implementation has an 18-month Phase A/B and a 34-month Phase C/D (launch plus 30 days). The Phase E schedule has a number of critical events (foldout Fig. G-2-2). Reviews and milestones are in place to ensure that the project is prepared to support these events. Schedule risk-management is discussed in Sec. G.4.1. Each of the tasks in the CPM schedule has ample time for completion. In addition, 20 weeks of funded schedule reserve are allocated at the top level, specifically 4 weeks for instrument delivery, 4 weeks for integrated structure and propulsion system delivery, 6 weeks for integration and test activities, and an additional 6 weeks prior to launch site shipment. Sixteen of these weeks are on the critical path. The schedule is ample compared to the NEAR 27-month implementation from start of funding to launch +30 days. Appropriate activities are overlapped to allow flexibility in individual instrument and spacecraft component deliveries.

The primary workflow for the mission phases is summarized in the following sections, including specific discussion of major activities, interdependencies, delivery of end items, critical paths, schedule margins, and long-lead procurements. The Phase A/B Study Plan, not to be confused with the Phase A/B Work Plan, is described in detail in Sec. H. The Study Plan addresses those activities identified as risks, and provides the plan to be used to reduce those risks to acceptable levels.

G.3.1 Phase A/B Work Plan

Phases A and B have been combined in an 18-month period. The first major activity is the development and documentation of the flow down of the mission and science requirements to the subsystems, instruments, ground system, and mission operations. This plan is presented by the MSE at the SRR/CoDR and serves as the baseline for the remaining preliminary design effort during Phase A/B. E/PO activities begin at a modest level, raising awareness of the MESSENGER mission.

Preliminary design takes place in parallel for all subsystems and instruments and requires close coordination by the MSE. A lead integration and test (I&T) engineer and a Mission Operations Center (MOC) lead engineer are assigned to work closely with the MSE. Trade studies are performed (Table H-2), and procurement activities for the major subcontracts are conducted, as the requirements for these components are determined. All procurement preparation activities are completed by the end of Phase A/B for all subcontracts listed in Table G-3-1. The contract award for the integrated structure and propulsion system design will be made as soon as possible after the start of Phase A/B. The only identified long-lead flight procurements, which must be initiated mid-way through Phase A/B, are components required by the MLA instrument. The PDR is scheduled for early June 2001.

Preliminary agreements are developed with OLS for the launch vehicle (LV) and launch services, JPL for use of their environmental test facilities and services of the Navigation Team, GSFC for use of environmental test facilities, and DSN for the use of the ground antenna compatibility testing and tracking services. A Space Act Agreement is already in place with the John H. Glenn Research Center at Lewis Field for use of their solar-simulation facilities.

G.3.2 Phase C/D Work Plan

During Phase C/D the baseline developed in Phase A/B is implemented and tracked, and design detailing continues. Part procurement is initiated, subcontracts awarded, and delivery dates confirmed. The integrated structure and propulsion system is on the critical path, and these contract awards are given priority. Drafting for mechanical and electronics designs is initiated. Software development continues.

The transition from design to manufacturing and the manufacturing process are detailed in Sec. F.5 and G.2.5. The design review process ensures that flight hardware conforms to the requirements and matches the design (G.6). Flight fabrication begins after Mission CDR.

The I&T lead ensures, along with the MSE, that any existing test equipment from the TIMED and CONTOUR projects are used effectively. The I&T engineer oversees the definition of the spacecraft harnesses, prepares the I&T plan, supervises the spacecraft buildup, performs interface verification, verifies ambient and environmental performance, arranges the transportation of the spacecraft to the environmental test and launch sites, and supervises environmental test and launch operations. Coordination of delivery schedules of in-house fabrication, subcontracted items, and instruments for integration will be performed by the PM.

The MOC lead ensures, along with the MSE, that the existing hardware and software designs from TIMED and CONTOUR are used effectively for MESSENGER. He is responsible for making any modifications to these designs. He monitors development of subsystem simulators and incorporates these simulators into the MOC spacecraft simulator. The MOC lead is also responsible for developing the training tools for the Mission Operations Team.

Table G-3-1 Major Hardware and Software Acquisition Plan

Item	Source Type	Contract Type	Candidates
Propulsion unit	Sole source	CPIF	Gencorp Aerojet
Structure	Sole source	CPIF	Composite Optics
Solar arrays	Compete	FFP	Tecstar, Spectrolab
Solar array drive	Compete	FFP	Moog (Schaeffer)
Battery	Compete	FFP	Eagle Picher
Transponder	Sole source	FFP	Motorola
Reaction wheels	Compete	FFP	Litton/Teldix
IMU	Compete	FFP	Litton
Star tracker	Compete	FFP	Ball Aerospace
Sun sensors	Compete	FFP	Adcole
MOPS software	Compete	FFP	ISI
MOPS hardware	Compete	FFP	Various
MDIS	In-house		APL
GRNS	In-house		APL
MAG sensor and analog electonics	Sole source	N/A	NASA/GSFC
MLA	Sole source	N/A	NASA/GSFC
ASCS	Sole source	CR	U. Colo./LASP
EPPS-FIPS	Sole source	CR	U. Michigan
EPPS (other)	In-house		APL
XRS	In-house		APL
Other electronics	In-house		APL

CPIF- Cost plus incentive fee; FFP- Firm fixed price;
CR- Cost reimbersible

Launch operations will take place at Kennedy Space Center (KSC), leading up to the launch on March 23, 2004. Phase C/D extends for 30 days after launch for checkout of the spacecraft. E/PO activities raise awareness of the mission and help the public appreciate the exciting start of this scientific and technical endeavour.

Final agreements are developed with OLS for LV and launch services, JPL for use of their environmental test facilities and services of the Navigation Team, GSFC for use of environmental test facilities, and DSN for the use of tracking services.

G.3.3 Phase E Work Plan

Phase E begins 30 days after launch. There are a number of major events, including planetary flybys, maneuvers, and orbital operations at Mercury (foldout Fig. G-2-2). Planning for these events involves coordination among the Science Team, Mission Operations Team, Navigation Team, Mission Design Team, and the E/PO Team. The process for planning these activities is described in Sec. F.6. There are reviews associated with each major operations event. The Mission Operations Team monitors and maintains the state-of-health of the MESSENGER spacecraft. They also perform activities associated with calibration of the instruments.

The central products of Phase E are the publication of science results, their dissemination to the public, and the archiving of all data products with the PDS. Science Team activities are coordinated by the PI (Sec. D). E/PO activity continues throughout Phase E, but is most intense around the times of planetary flybys and during orbital operations (Sec. E).

G.4 Risk Management

Risk management is a continuous process that has five components: identify, analyze, plan, track, and control. Identification describes the risk in terms of conditions and consequences. It captures the context of science, development, schedule, and cost risk within the program. Analysis evaluates the probability and the impact of individual risks, along with the timeframe when action needs to be taken. It classifies similar or related risks by priority.

Plans assign responsibilities for risk, and they determine the approach to risk, which may involve research, acceptance, or mitigation of risks. Plans have the goal of eliminating the risk from the program. Tracking compiles, organizes, and updates the risk data. It includes a method for risk measurement and communication of risk status throughout the organization. Control is the process of making risk decisions. It may replan mitigation activities, close out risk areas, invoke contingency plans, or continue to track risks. Control feeds back into risk identification, and the process begins again. During the development program, items are added or deleted from this list as decided jointly by the PI, PM, and MSE.

MESSENGER risk management assigns responsibility for each of the five steps to appropriate members of the project team. A four-tier system is employed. At the lowest level, subsystem lead engineers have the responsibly to manage all five elements of risk within their subsystem and within their resource allocations. These resources include mass, power, bit rate, cost, and schedule. The second level of risk management is the responsibility of the Mission System Engineer (MSE). The MSE has the authority to delegate reserves and make technical trades that do not affect level-one requirements, cost, or schedule. The MSE gathers the risk management data from the subsystem leads and adds system-level information when risk areas cross subsystem boundaries or involve trades with system-level consequences. The third level of risk management is the responsibility of the Project Manager (PM). The PM accumulates the risk item information for all facets of the development and operation of the mission including the spacecraft, instrumentation, launch vehicle, ground system, and mission operations. He is responsible for risk mitigation plans that affect all areas outside of science, cost, and schedule. For impacts to science, cost, or schedule he recommends solutions or mitigation plans to the PI, who has ultimate responsibility. The PI and PM also advise the implementing organizations of resource needs that are outside the control of the project.

The specific risk items for the MESSENGER spacecraft and science payload development are listed in Tables G-4-1 and G-4-2, respectively. Mission design risks and mitigation plans are discussed in Sec. F.1.4. Each of the spacecraft and science payload risk items has been incorporated in the design because its benefits justifies the risk. Each item has a realistic fallback option if the development runs in to trouble. The spacecraft and science payload risk items are listed in the tables in order of overall importance, which involves both the probability and the impact of the risk item. The entries in the event column represent the milestones that each risk item must pass to remain an element in the baseline design. The trigger-date column contains the epoch at which the milestone must be passed. If the milestone is not reached on time, the fallback option is enacted. Each fallback has a system-level impact, which is listed in the last column. The subjective, normalized level of risk and the potential impact of that risk on the development are listed in columns "R" and "I", respectively, and are plotted in Figs. G-4-1 and G-4-2. The items of greatest importance are those closest to the upper right-hand corner of each figure. For the spacecraft, the top three items are the propulsion tanks, the G&C software, and the structure mass. For the instruments, the top three items are the MLA laser, the EPPS electronics packaging, and MDIS stray light. Specific plans to mitigate these risks are contained in each of the subsystem descriptions in Sec. F.2 and F.3.

Some of the risk items are themselves the development of new technologies. These items include the propellant tank development, solar panels, and IEEE-1394 ASIC. The development of new technologies is a high priority for those organizations responsible. The organizational management is committed to supplying the resources required to complete the development of the these technologies on schedule. In addition, once MESSENGER is selected, the priorities for these technology rise within the organizations through the use of internal research funds. Additionally, outside resources from NASA Planetary Instrument Definition and Development Program (PIDDP), other NASA advanced technology grants, Department of Defense (DoD) grants and contracts, and commercial sources of support are applied to these high-priority technologies.

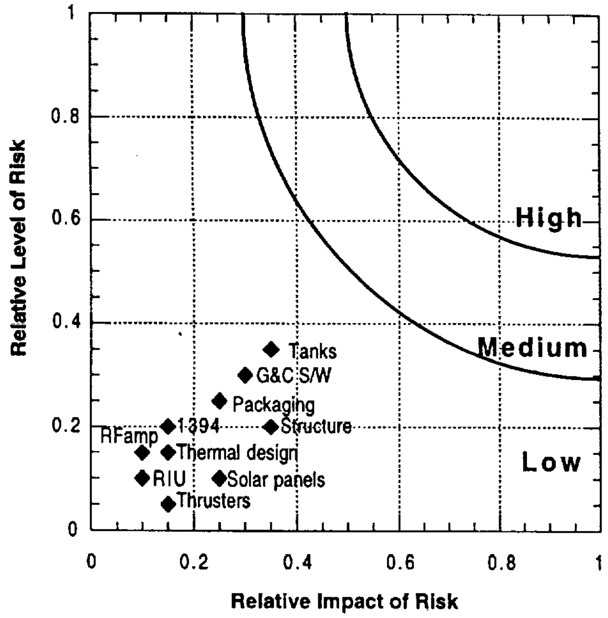


Fig. G-4-1 The subjective spacecraft impacts and risks are all low.

Some MESSENGER technologies have a potentially high commercial value, and industrial partners are sought to supplement their development (Sec. E.3). The high priority of these technology developments within the responsible organizations assures that the necessary facilities and staff with the proper skills are available. During Phase A/B the development of the required technologies are completed (Sec. H.3).

G.4.1 Overall Risk Mitigation

The MESSENGER instruments and the spacecraft subsystem designs are carefully selected and balanced with the science objectives to provide robustness for both the implementation and operational phases. Spacecraft subsystems are either fully redundant or have graceful degradation. Mass and power margins of over 20% are maintained (Table F-2-1). Reserves are the first option for dealing with any resource growth. Additional resource growth may be accommodated by releasing margins, which requires PI approval. Descope options are available for extreme cases. The process for releasing reserves and margins is detailed in Sec. G.2.3. The descope savings in mass, power, and dollars along with their benefits and impacts are enumerated in foldout Table G-4-3. Dollar savings are separately totaled for descope decisions at spacecraft PDR and CDR. Descope options will be further investigated during Phase A/B. A summary of cost reserves that mitigate cost risk is shown in Table I-4 by product element and phase and in Table I-1 by year.

Schedule Risk. APL has experience with development schedules far shorter than MESSENGER. A firm schedule helps identify problems and allows appropriate actions to be taken early. The implementation schedule is

Table G-4-1 Spacecraft Risk Assessment Matrix

Risk	Risk Type	R	Risk Impact	I	Event	Fallback	Trigger Date	Fallback Impact
Fuel tank development	Technology (light, thin walls)	0.35	Delayed I&T start	0.35	Tank qualification complete	Use existing technology	Propulsion tank CDR	6 kg mass increase
G&C software	Design/test of complex system	0.3	Delay I&T start and launch preps	0.3	Start of software acceptance test	Reduce functionality at launch (no orbit S/W)	Start of spacecraft I&T	Finish test of orbit S/W during cruise
Structure	Design and implementation	0.2	Mass growth	0.35	Final coupled loads analysis completed	Use as is, consider mass descope	Spacecraft PDR	Increased mass, consider descope
Electronics packaging	Manufacturing (high density)	0.25	Mass growth	0.25	Brassboard design using flight densities	Use existing technology	Spacecraft PDR	Increased mass, consider descope
IEM - 1394 backplane	Technology (new design)	0.2	Delayed IEM delivery	0.15	Fully-working 1394 ASIC parts	PCI bus	Spacecraft PDR	Lower system-level reliability
Solar panels	Technology (high temp.)	0.1	Delayed, extended qual program	0.25	Testing complete on small panel	1) Larger panels 2) Multi-junction cells	Spacecraft PDR	1) 7 kg mass increase 2) Increased cost
Thermal design	Design (maintain temp. limits)	0.15	Increased mass and complexity	0.15	Thermal System PDR	Add heatpipes, doublers, louvers	Spacecraft PDR	Increased mass, consider descope
RF power amplifier	Manufacturing (packaging)	0.15	Delayed telecom testing	0.1	Working engineering model	1) Packaged devices 2) Purchased SSPA	Spacecraft PDR	Reduced downlink or extra DSN coverage
22-N biprop. thrusters	Qualification, (new design)	0.05	Propulsion system delayed	0.15	Quaualified flight modules	1) 22-N IHI thrusters 2) 22-N monoprop	Propulsion PDR	1) Procurement delayed 2) 5 kg mass increase
Remote Interface Unit	Manufacturing of rad-hard ASIC	0.1	Extra foundry run, delayed delivery	0.1	Successful test of flight parts	1) Use X2000 chip 2) Use existing chip	1) Spacecraft CoDR 2) Spacecraft PDR	1) Reduced capability 2) Reduced capability

R = Relative level of risk, I = Relative impact of risk

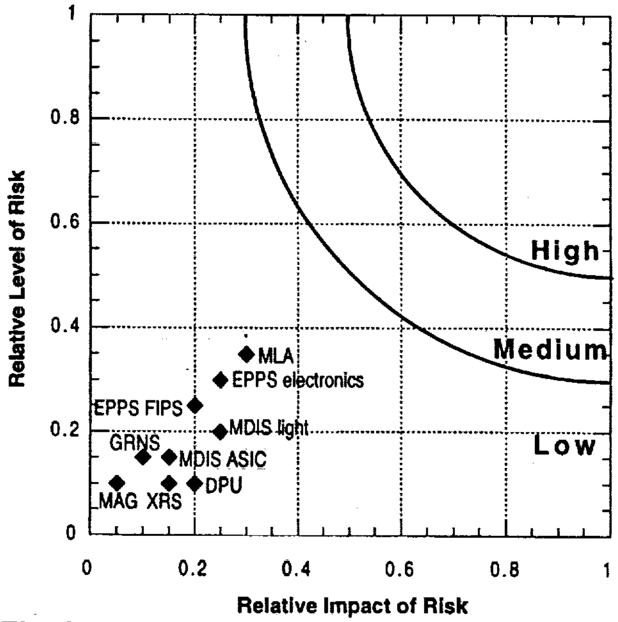


Fig. G-4-2 The subjective science payload impacts and risks are all low.

conservative, with 16 weeks of reserve in the critical path. The structure-propulsion system delivery has four weeks of reserve to avoid any delay at the start of integration. Six weeks of reserve are allocated just prior to spacecraft environmental qualification. An additional six weeks are allocated prior to the Pre-Ship Review. While the instruments are not on the critical path, four weeks of reserve are included at the end of instrument delivery. In addition, the instruments and the DPU are mechanically and electrically pre-integrated with the spacecraft during their development (Sec. F.4).

The Phase A/B development and the early contract arrangements for the propulsion system help reduce risk (Sec. G.2.2). The use of off-the-shelf or standard designs for major subcontract spacecraft components helps mitigate schedule risk. Delivery times have been verified in writing with candidate vendors during the Concept Study to ensure accurate schedule development.

MESSENGER also reduces risk by using the NEAR ground support equipment and Mission Operations Center. MESSENGER will follow the development of TIMED and CONTOUR closely to minimize problems with out-of-date equipment or parts. The staffing schedules also merge well so that experienced staff can transfer easily to MESSENGER.

The mission design provides flexibility in the launch date and window. There are two 15-day launch opportunities, separated by four months (Sec. F.1). While all schedules are based on the first launch opportunity, the second opportunity provides flexibility in the event of launch vehicle problems or higher level NASA coordination schedules that might impact the launch date. This option is included in the funded reserves.

There are two additional options, not explicitly funded, in the mission design. The first option increases the mass margin to 43% by extending the cruise phase by 1.47 years (Sec. F.1.4). The second option, delay of launch until 2005, trades additional development time against a reduction in cruise-phase duration by one year.

Table G-4-2 Payload Risk Assessment Matrix

Risk	Risk Type	R	Risk Impact	I	Event	Fallback	Trigger Date	Fallback Impact
MLA- laser	Design and Implementation	0.35	Delay of MLA delivery	0.3	Successful test of flight-like laser	Use copy of NEAR laser	MLA PDR	Reduced performance, increased mass
EPPS- elect. miniaturization	Manufacturing (packaging)	0.3	Mass growth	0.25	Brassboard fab	Use existing technology	EPPS CDR	1 kg mass increase
MDIS- scattered light	Design and schedule	0.2	Design mods delay delivery	0.25	First-light testing	Add baffles, reduce scan mirror range	First-light testing	Reduced capability, schedule delay
EPPS- FIPS head	Development (high temp, UV)	0.25	Delay of delivery, lower performance	0.2	Brassboard test (high temp., UV)	Mount so it can not see the sun	EPPS CDR	Reduced performance, no solar wind data
MDIS- CCD ASIC	Manufacturing (rad-hard ASIC)	0.15	Extra foundry run, delay in delivery	0.15	Successful test of flight parts	Use discrete electronics	MDIS PDR	0.5 kg mass increase
DPU- software	Testing complex system	0.1	Reduced capability	0.2	Start of instrument-suite I&T	Limited instrument S/W functions	Start of instrument-suite I&T	Reduced science
GRNS- detector	Development schedule	0.15	Delay in delivery	0.1	Successful test of flight-like detector	Use PMT detector readout	GRNS PDR	Reduced capability, increased mass
XRS- detector noise	Design	0.1	Reduced sensitivity to Mg, Al, Si	0.15	Brassboard test of detectors	Raise detector thresholds	XRS CDR	Reduced performance
MAG- spacecraft field	Schedule and performance	0.1	Delay in I&T for additional tests	0.05	Spacecraft functional test	Add compensation magnets	Spacecraft functional test	Possible lower sensitivity

R = Relative level of risk, I = Relative impact of risk

Cost Risk. The strategy for maintaining reserves as a function of cost-to-completion consists of (1) initial planning for reserves as a function of time, (2) reviewing actual costs against the plan (Table I.1) each month, and (3) continually estimating the cost-to-completion with the RMIS tool. Decisions to release reserves are based on these cost-to-completion estimates (foldout Fig. G-4-3).

G.4.2 Principal MESSENGER Risks

The top three risks items are: (1) overall mass margin, (2) propellant tank development, and (3) system-level requirements of the Mercury environment. Although only one of these items is listed in Tables G-4-1 and G-4-2, the mass margin and system-level environmental concerns represent the accumulation of smaller risks across the program with a similar theme that together rise to a principal risk.

Mass Margin. MESSENGER has a low allowable dry mass, and mass growth is a fallback option common to many of the individual risk items. Therefore, while there are adequate margins for the individual risk items, maintenance of the overall mass margin remains the highest risk for MESSENGER. The mass list is maintained by the MSE. This list is under continual review on a weekly basis. The MSE works with the subsystem leads to ensure that the designs have uniform efficiency in their mass usage. Prior to releasing mass reserves, alternative solutions (possibly at a system level) are explored. An overall MESSENGER packaging engineer will be assigned to ensure that all electrical and mechanical assemblies use the latest packaging techniques and the most modern manufacturing methods. This packaging approach is one element of the overall mass optimization process.

Propellant Tanks. The propellant tanks are a risk because they are needed early in the development, they use a state-of-the-art design in tank fabrication, and all pressure vessels require a lengthy qualification period. These conditions place the tanks on the critical path for spacecraft development. The risk mitigation plan for this risk incorporates the use of conventional tank design as described in Sec. F.2.2 and Sec. H.3.

Mercury Environment. MESSENGER must function in the severe near-Sun environment at Mercury. This has implications for thermal, power, mission operations, and fault protection. The thermal model is refined as subsystem design matures. The thermal design for MESSENGER has been modeled extensively, but more analysis is planned as the design progresses. Prototypes of the solar arrays and thermal shade have already passed solar simulation testing at 10.1 Suns. However, throughout the design process continued risk reductions are carried out, including systems studies to optimize instrument and spacecraft survival margins versus safing recovery times, specialized solar simulation testing and thermal testing for validation of the final solar array design, and special solar simulation testing for the components that look through the thermal shade. Mission operations risks are reduced by having a highly-automated spacecraft that requires very little ground commanding for normal operations. For example, no ground-based mission operations thermal modeling, power modeling, solar array control modeling, or data-allocation modeling are needed because they are automatically managed on-board. Other operations-mitigation plans include the heavy use of the hardware-in-the-loop spacecraft simulator to validate the sequences early and to test all of the operational scripts prior to execution on the spacecraft. On-board fault protection is designed to handle the two primary causes of operational risk: improper commanding and on-board failure. The fault protection system has the ability to ensure that the thermal shade is always between the spacecraft and the Sun.

G.5 Government-Furnished Property, Services, Facilities

The Government-furnished services and facilities required for the MESSENGER project are summarized in Table G-5-1. All other required facilities already exist within either APL or their subcontractors. Specific details and schedules for these services have been discussed earlier. Costs for these elements are included in Total Mission Costs of Sec I.

G.6 Reviews

There is a comprehensive review system that includes both informal and formal sets of reviews. The informal design review process includes Engineering Design Reviews (EDRs), Fabrication Feasibility Reviews (FFRs), and Integration Readiness Reviews (IRRs). Informal EDRs are held for each subsystem at the circuit, box, and card level. These reviews are initiated by the lead engineer with a small group of reviewers (2 to 5) selected from his peers. These are the most important reviews for catching design errors and ensuring design reliability. Following the EDRs, preliminary package design and layout commences. Prior to manufacturing, an FFR is held for each released design. This review covers the materials, processes and tolerances to ensure that the design can be manufactured at cost and on schedule. Prior to subsystem delivery to the spacecraft, an IRR is held to assure that the unit is ready for spacecraft integration. This review process helps catch errors that would otherwise cause costly rework and schedule delays. It also provides milestones that allow schedule and cost performance to be measured.

The formal design review process is overseen by the SD chief engineer and documented in APL document SDO-8336, *Space Department Design Review Guidelines*. APL's design review process and guidelines have been used on many other NASA projects and were recently adopted by NASA/GSFC for their internal use. These reviews, which routinely engage experts outside of APL as reviewers, ensure that appropriate scrutiny is brought to bear on all elements of the design. These reviews establish agreement between NASA and the PI on the principal requirements and characteristics of the MESSENGER design. The APL design review process requires that a complete design review package be made available at a reasonable time before each review; that minutes of the review, including action items, be published in a timely fashion; and that all action items be closed out by written memorandum.

The following formal reviews are held on the MESSENGER project (foldout Fig. G-2-1). The NMO is invited to participate actively as part of a combined review board or to conduct an independent review in parallel with these reviews. In addition to these reviews, reporting will continue on a monthly basis throughout the mission (Sec. G.2.7).

Table G-5-1 Government Furnished Services

Services, Equipment, and Facilities	NASA Supplier
Environmental test facilities	GSFC
MLA instrument	GSFC
MAG sensor and analog electronics	GSFC
Navigation services	JPL
Environmental test facilities	JPL
DSN tracking and test	DSN
Environmental test facilites	GRC
Launch vehicle and services	OLS

System Requirements Review/Conceptual Design Review (SRR/CoDR) – to establish the baseline of top-level requirements and set the starting point for preliminary design effort.

Mission Preliminary Design Review (PDR) - to review and assess the preliminary designs of all MESSENGER mission elements for feasibility and compliance to requirements, and to establish the baseline for detail design effort to proceed.

Mission Critical Design Review (CDR) - to review and assess the detailed designs for feasibility and compliance with requirements before commitment to major fabrication efforts, and to establish the baseline for configuration control.

Pre-Environmental Review (PER) - to establish that the instrument and spacecraft hardware and software are ready for environmental test, based on subsystem test results and an evaluation of the configuration status.

Pre-Ship Review (PSR) - to determine that the integrated spacecraft is ready for delivery to the launch site for integration with the launch vehicle, that all configuration items conform to the latest configuration identification, and that the acceptance data package is complete and satisfactory.

Mission Readiness Review (MRR) - to verify that all elements of the mission are ready for operations, in particular the ground systems and mission operations, and to ensure that the mission operations team is ready and procedures for early operations have been tested and verified.

Launch Readiness Review (LRR) - to verify that all technical problems and deficiencies have been resolved, that the spacecraft and its supporting systems are ready for launch, and that the ground system and operations facilities and staff are in place and ready to conduct mission operations.

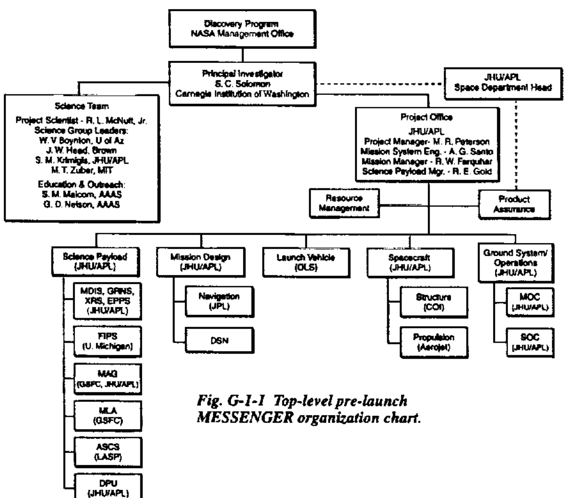


Fig. G-1-1 Top-level pre-launch MESSENGER organization chart.

Table G-1-1 MESSENGER Institutional Team Members Responsibilities/Commitments

MESSENGER	Responsibilities/Commitments
Carnegie Institution of Washington (CIW)	Provide PI, Dr. S. C. Solomon, and associated support, including contracting interface with NASA, subcontracting to non-APL, non-GSFC Science Team members, subcontracting to E/PO Team members
The Johns Hopkins University Applied Physics Laboratory (JHU/APL)	Provide personnel, facilities, and associated support including contracting interface with NASA; Project Manager, Mission System Engineer, Mission Manager, Project Scientist, Science Payload Manager, APL Co-Is; mission design, including interface with JPL TMOD; MDIS, GRNS, XRS, EPPS, common DPU, MAG digital portion; launch vehicle interface with OLS; spacecraft (integration, test, launch); ground system; Mission Operations Center and Science Operations Center
University of Colorado LASP	Provide ASCS instrument and Co-Is
University of Michigan	Provide FIPS sensor and Co-I
Various universities and research institutions	Provide Co-Is and associated support (Section D.2.4)
American Association for the Advancement of Science (AAAS) and other organizations	Provide Education/Public Outreach; led by AAAS, in coordination with Science Team (Section E.1)
GenCorp Aerojet	Provide integrated propulsion system
Composite Optics, Inc.	Provide integrated structural components
NASA Organizations	
GSFC/Code 920	Provide MLA and Co-I
GSFC/Code 695, 696	Provide MAG sensor and analog circuits and Co-Is
GSFC/Code 691	Provide Co-I
GSFC/Code 549	Provide environmental test facilities
NASA/JPL	Provide TMOD support to APL mission design, targeting, and tracking, and test facility (solar simulator)
NASA/OLS	Provide launch vehicle and associated services
NASA Management Office (NMO)	Provide contracting/funding: to CIW and APL; for standard NASA services, e.g., launch vehicle and support services, DSN, and GSFC and JPL test facilities; for MESSENGER-specific support including GSFC MLA and MAG, JPL TMOD, and GSFC; and for Science Team members

Table G-4-3 MESSENGER Descope Options

Descope Options (in priority order)	Savings				Benefit	Mission Impact
	Mass (kg)	Power (W)	At PDR ($K)	At CDR ($K)		
Reduce battery size	8.0	-	50	-	Lower mass	Reduced science during eclipses (~ 5% of orbits)
Delete event-driven software (Sec. F.2.9)	-	-	800	300	Reduced software cost	Increased MOC activity or reduced science
Reduce transmitter output power	3.0	22.5	200	-	Reduced solar array size, mass	Increased DSN time or reduced science return
Remove XRS	4.0	8.0	1,900	1,400	Lower mass, lower power, lower cost	Reduced science; refer to Sec. D.1.6
Remove EPPS	1.3	2.0	6,000	4,500		
Remove VIRS portion of ASCS	1	1.5	1,200	800		
Remove rest of ASCS	1.5	1.5	4,100	2,700		
Commensurate reductions in DPU	2.0	6.0	1,000	500		
Total descope savings	20.3	41.5	15,050	10,200		

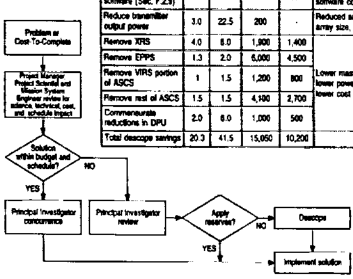


Fig. G-4-3 Maintenance of reserves as a function of cost-to-completion.

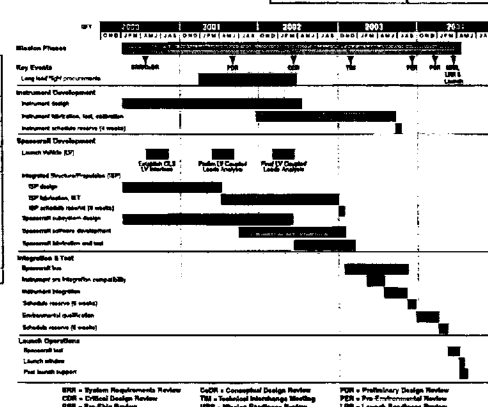


Fig. G-2-1 MESSENGER development timeline.

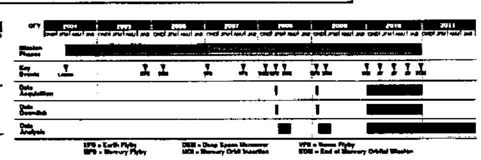


Fig. G-2-2 MESSENGER mission operations and data analysis timeline.

Table G-2-2 Meetings Summary

Meeting	Purpose	Phase	Frequency
SSC	Review status of science and implementation	All	Monthly/telecon
ScienceTeam	Mission status and science results	All	Varies (Sec. G)
E/PO	E/PO status	All	Monthly/telecon
Implementation Team	Subsystem progress	A-D	Monthly
Status	Identify status and problem areas	All	Weekly
Schedule-status	Review progress against CPM schedule	A-D	One-month interval
Mision-level reviews	Formal progress and status	A-D	Refer to Section G.6
Mission Planning Group	Define weekly operations plan	E	Weekly (Sec. F.6)

H PHASE A/B STUDY PLAN

Following selection of MESSENGER by NASA for implementation in mid-1999 and receipt of funding from the NMO by CIW and APL, Phase A starts January 1, 2000. The management is in place (Sec. G.1) as are the preparations with the industrial partners, GenCorp Aerojet (AJ) and COI. Detailed trade studies and requirements will flow down to specific subsystems. Phase A/B concludes with the Preliminary Design Review (PDR).

Phase A/B has three principal activities: system-level studies to examine possible design alternatives, a wide variety of standard engineering tasks required to complete the conceptual and preliminary designs to be accomplished in Phase A/B, and technology developments to ensure that the required new technologies are ready by PDR. A preliminary top-level schedule is shown in Table H-1.

Table H-1 Preliminary Top-level Schedule

Task	Start	End	Duration (days)
Phase A/B	01/04/00	07/06/01	385
Requirements validation	01/04/00	04/24/00	80
Establish OLS interface with LV	01/04/00	08/02/00	150
Establish contracts with COI, AJ	01/04/00	03/27/00	60
Structure PDR	03/28/00	10/26/00	150
Mission SRR/CoDR	04/24/00	04/24/00	0
Spacecraft component layout	04/25/00	07/05/00	50
Tank vendor selection	05/23/00	08/23/00	65
Solar cell and material testing	06/01/00	09/29/00	85
Delta prelim coupled loads	08/03/00	10/26/00	60
Tank PDR	09/28/00	09/28/00	0
Tank range safety consent	09/29/00	11/24/00	39
Solar array testing	04/02/01	07/02/01	65
Tank CDR	04/04/01	04/04/01	0
Structure/propulsion system PDR	04/04/01	04/04/01	0
Delta final coupled loads analysis	04/05/01	06/28/01	60

Phase A Activities, Products, and Schedule. Phase A lasts through the joint System Requirements Review (SRR)/Conceptual Design Review (CoDR). During this time all subsystems are brought to the conceptual-design level. The design addresses mission objectives and technical requirements in a quantitative form, including organizational and technical interfaces, functions, specification, performance parameters, and constraints imposed by the environment. System drivers are examined and sensitivity analyses are completed to identify risk areas and enable optimum margin allocation. Sensitivity analyses point to those areas where small changes in requirements can produce large enhancements in margin with limited or no performance impact. Make/buy decisions are completed for major subsystems and formulated for minor components. Conceptual design is completed for all subsystems, including block diagrams, mission timelines, schematic and layout drawings, theoretical calculations, computer modeling, flowcharts, and experimental results. Updates are made for all risk areas, including plans to mitigate those risks and contingency plans for any problems that develop. The reliability and redundancy philosophy is enforced system-wide to ensure a uniform approach to cost and mission risk. The output of the conceptual design is a baseline that is accepted at the CoDR. The goal for the system-level power and mass margins plus reserves at this time are 25% (Sec. F.2.1). This baseline is the foundation for the detailed design that occurs in Phase B.

Phase B Activities, Products, and Schedule. During Phase B, the detailed design is developed to the point that commitment can be made to drafting and preparations for manufacturing. This design defines each subsystem and all interfaces through block diagrams, signal-flow diagrams, power-flow diagrams, operational timelines, error budgets, schematic diagrams, logic and timing diagrams, first-interface circuit details, packaging plans, layout drawings, data-flow diagrams, modeling, analyses, and breadboard testing results. Supporting data are developed for mechanical, thermal, and circuit designs. Stress, reliability, and radiation analyses are completed and design margins examined. Software requirements are completed and the preliminary software design developed. Software design includes data and software structure diagrams, timing constraints for real-time systems, interrupt structure, flowcharts, memory maps, CPU loading, languages and development systems, and the method of change control.

The preliminary design addresses reliability concerns including parts selection; parts derating; unusual or unproven materials, parts or processes; critical sole-source items; and any life-limiting parts. Preliminary reliability calculations and failure-mode effects analyses are completed. Specific concerns of these analyses are any single-point failure modes and how the design minimizes such modes and limits or prevents the propagation of failures.

Phase B concludes with the PDR, where all designs are presented along with any special requirements, processes, or inspections. Plans for testing the system and preliminary ground system and mission operations plans are also completed. The output of the PDR is a detailed baseline design that is used for the completion of the drafting and manufacturing package and the purchase of remaining flight parts.

H.1 Key Mission Tradeoffs and Options

System-level trade studies are used to reduce risk, improve performance, or lower cost. The study goals are not required in order to enable the mission. The system-level trade studies for Phase A/B are listed in Table H-2. The system-level advantages of each of these alternatives to the baseline design are described in the appropriate subsections of Sec. F.2. During Phase A/B the maturity of these alternatives will be examined and balanced against their costs and risks. The outcome will be folded into the conceptual and preliminary designs.

H.2 Conceptual/Preliminary Design

Development of the conceptual and preliminary designs is the result of a great many "standard engineering" tasks for each of the subsystems. Each subsystem will be developed to meet the required level of detail in the definitions of "conceptual" and "preliminary" design. For MESSENGER the particularly important efforts are in the areas of power, thermal, mechanical, and propulsion subsystems. The power and thermal systems are unique designs to adapt to the Mercury environment. The mechanical and propulsion systems are needed early, and they are on the critical path. All of the remaining subsystems will have a more standard Phase A/B program. The Phase A/B accomplishments for all subsystems are described in Sec. F.2. Two examples of such efforts are the solar-array qualification program and the solid-state power amplifier (SSPA) assembly in the communications subsystem.

Table H-2 MESSENGER Phase A/B Studies

System	Study Item	Type	Study goal
Power	Lithium-ion battery	P	Reduce S/C mass by ~10 kg
Power	Multi-junction cells	P	Reduce mass, temperatures, or increase power margin
Propulsion	Separate fuel, oxidizer pressure systems	R	Further reduce vapor-migration concerns
Telecom	Circularly-polarized phased-array	P	Increase downlink, reduce RF power-amplifier mass, or both
Software	Fault protection algorithms	R	Further simplify and improve reliability
Thermal	Thermal design tolerances	R	Investigate attitude anomaly survival constraints
Mission design	Shift DSM dates	R	Maximize DSM contingency-burn window
Mission design	Thrust vector pointing constraints	R	Determine thermal shade pointing limits to extend burn windows
Attitude	Momentum control strategy	P	Reduce thruster firings required to unload wheels
MDIS	Shift heat-rejection filter location	P	Improve scattered-light at cost of higher MDIS temperature
MDIS	Data compression algorithms	P	Investigate various compression methods to improve performance
GRNS-GRS	Alternative, multiple small detectors	P	Improve sensitivity at cost of electronic complexity
MLA	Design alternative	P	Use TOF chip to reduce mass
EPPS-EPS	Latest PIDDP design	P	Improve performance
EPPS-FIPS	Solar-UV sensitivity	P	Solar wind sensitivity with low UV background response

P = performance, R = risk reduction

Solar Arrays. A comprehensive set of tests will be conducted to ensure that the final array design will work throughout the mission. Small prototype solar arrays have already been successfully tested beyond the extremes of the worst-case mission environment. A candidate set of components and materials has been selected to meet the MESSENGER environment. Phase A/B engineering will evaluate different combinations of standard materials and processes and select the design that yields the greatest operational margins. All of the solar array components will be tested in detail and final material choices made. These component tests will examine the cells, all of the materials in the panels, the cell attachments, and the interconnections. A variety of cells (approximately 80 types) with minor design, processing, and materials differences will be evaluated at thermal and illumination extremes. A selection of these cells will be irradiated with UV and energetic particles to simulate the end-of-mission case; then they will be reevaluated. These tests will determine the optimum cell technology for the mission.

Simultaneously, the solar panel substrate materials and construction details will be examined. This evaluation may lead to lighter, stronger, more thermally uniform, or lower cost alternatives. Following the selection of the cell technology, small test panels will be fabricated with all of the flight materials and processes. These panels will undergo a full set of thermal and illumination qualification tests at APL, GRC, and JPL. This extensive set of tests will qualify the baseline solar panel design. All that will remain to finalize the design in Phase C/D is the final cell layout and the panel interface details.

Solid-State Power Amplifiers. The SSPA assembly uses off-the-shelf HFET power devices. During Phase A/B the packaging of this mature technology for flight will be examined in detail. APL has full chip-level packaging capabilities. Initiating the SSPA design at the start of the Phase A/B effort will reduce the risk (Table G-4-1). Should difficulties be encountered, the fallback option is to use packaged devices with lower power efficiency.

H.3 Technology Development

Technology will be developed for those items that are not at the required TRL for phase C/D. For the spacecraft, these items include: (1) development of lightweight titanium propellant tanks, (2) development of standard practices and procedures for high-density electronics circuit board design and packaging, (3) completion of the development of the rad-hard 1394 backplane ASIC for the IEM, (4) high-temperature solar panel design and qualification, (5) miniature RF-power amplifier design and packaging, (6) completion of the development of the RIU ASIC and package, and (7) completion of the qualification of the bipropellant 22-N thrusters. For the instruments, these items include: (1) development of the laser for MLA, (2) development high-density electronics packaging for EPPS, (3) completion of radiation-hardened readout ASIC for MDIS, and (4) development of large-area detectors for XRS with very low noise characteristics.

Each of these technologies has been adopted into the baseline design because its benefit to the mission is relatively large compared to the inherent risk in the new technology development. The roles of these technologies are described with each subsystem in Sec. F.2 and Sec. F.3. Each technology also has a fallback position in case of problems, as described in the risk-mitigation plan in Sec. G.4. All of the technology and instrument development items are listed in Tables G-4-1 and G-4-2 with their subjective levels of risk, the impact of the risk, and the fallback options. Also contained are the decision events, the trigger dates by which the events must be completed, and the impacts of the fallbacks.

For example, the propellent tank development and qualification are planned during Phase A/B. By tank CDR (Table H-1) sufficient design and range safety analyses are accomplished to determine if the mass, stiffness, safety, and strength goals can be met. If not, a conventional tank design will be used without impacting the schedule, but with a 6-kg mass penalty.

H.4 Long-Lead Procurements

No long-lead procurements are required for MESSENGER, except for MLA. Some MLA optical and laser components, while standard production items, have very long lead times. Spacecraft components on the critical path, such as the propellent tanks and solar panels, will be sufficiently developed during Phase A/B so that a contract for the flight articles can be let immediately at the start of Phase C.

H.5 Other Phase A/B Items

Although no planetary protection concerns are anticipated for the MESSENGER mission, during Phase A/B a preliminary Planetary Protection Plan is developed. This task is budgeted and will be led by the Project Scientist.

Areas of rapid-technology development will be examined for significant performance improvements of benefit to MESSENGER. Examples include radiation-hardened microprocessors, newer space-qualified high-density memory and other electronic parts, and more modern, off-the-shelf software development tools.

Use of the NASA Consolidated Space Operations Center will be investigated to reduce MESSENGER's Phase E cost.

I COST PLAN

The cost plan resulting from the Concept Study meets all funding requirements and constraints of the AO and applies to Phases A-E. This plan provides detailed information on anticipated costs for all phases of the mission. A detailed cost proposal for Phase A/B and detailed estimates for Phases C/D and E are provided in this section. Completed SF1411-equivalents are provided for Phase A/B activities for both CIW and APL in Appendix E, in accordance with the Statements of Work and the Work Breakdown Structure (WBS) for CIW and APL in Appendix G.

As the implementing organization, APL led the cost-estimating performed for the MESSENGER project. APL's cost-estimating philosophy is to employ a "bottoms-up" process for the entire estimate, as opposed to the use of cost models for any project phases. This procedure maximizes the cost-plan robustness and minimizes cost risk for implementers and NASA. Accordingly, cost and staffing estimates were requested from all team members, vendors, and NASA centers on the basis of full-cost accounting. This process is described in greater detail below, with cost information presented in tables in the format prescribed by the AO.

The MESSENGER Total Mission Cost (TMC) has increased by less than 1.6% of TMC to $339.1M in real-year FY dollars from our Phase-One TMC of $333.8M in real-year FY dollars. The detailed discussion of this change is described in Sec. I.4 below.

Summary information regarding MESSENGER mission costs is presented in

- Table I-1 MESSENGER Total Mission Cost Funding Profile (ref AO Fig. 1),
- Table I-2 MESSENGER FY Costs in Fixed FY99 Dollars (ref AO Fig. 3),
- Table I-3 MESSENGER Development Costs in Fixed FY99 Dollars (ref AO Fig. 4), and
- Table I-4 MESSENGER Cost Reserve Summary.

Forward-pricing rates and rate-history information are presented in

- Table I-5 APL Forward Pricing Rates for MESSENGER and
- Table I-6 APL Indirect Overhead Rate History.

Additional detailed information required by the AO is presented in

- Table I-7 MESSENGER Phase A/B Planned Procurements,
- Tables I-8, I-10, and I-12 MESSENGER Staffing by WBS and Major Cost Category for Phase A/B, Phase C/D, and Phase E, respectively, and
- Tables I-9, I-11, and I-13 MESSENGER Cost Breakdown by WBS and Major Cost Category (ref. AO Fig. 2) for Phase A/B, Phase C/D, and Phase E, respectively.

Long-lead procurement costs, representing flight hardware procurements that must be initiated prior to the start of Phase C/D are not included in the costs for Phase A/B, but are included in costs for Phase C/D. These are minimal, as discussed below.

Cost Reserves. To insure the MESSENGER mission is successfully completed within the proposed cost, a reserve plan has been prepared and applied to the MESSENGER costs consistent with the AO requirement. The cost reserve plan, allocated by cost element and phase, is developed to mitigate cost risk, which is greatly reduced by funded reserves.

Reserves are assumed to contain any and all applicable costs. There has been no apportionment of reserves between labor and procurements; rather the reserves are held as a dollar amount and will be used as necessary in the manner required by the situation. All reserves are held by the MESSENGER project in the APL contract. As stated throughout this Concept Study report, no reserves will be used without direction of the PI. Further, since the Discovery Program carries no reserves and since the AO and applicable documents make no statements to the contrary, it is assumed that reserves remaining at the conclusion of Phase C/D will be available for potential use in Phase E, in addition to those stated specifically for Phase E.

The cost reserves are summarized in Table I-4, and cost reserves are included in each table, where required by the AO. These reserves are in addition to the descope options in Sec. G, Table G-4-3. Although estimated by cost element, reserves are retained as a lump sum by the PM and distributed as directed by the PI.

All reserves will be tracked in conjunction with the risk item list (Sec. G.4; Table G-4-1 for the spacecraft and Table G-4-2 for the science payload) maintained by the PM and MSE. An allocation or "lien" is put on reserves for each item on the risk list by the PM and assessed monthly among the PI, PM, and MSE.

No reserve is allocated for Phase A/B, since activity during this phase is controllable level of effort.

In Phase C/D the spacecraft bus and all instruments are designed, fabricated, tested, and delivered for integration. This phase represents the highest cost risk, so holding of reserve is prudent. A percentage of the baseline costs in each cost element is used to calculate reserve. Reserves vary from 5% to 25%, depending on the assessment of the amount of engineering development needed for a specific work effort and any specific risks identified. Consistent with the rationale that tasks requiring a level of effort (management, mission analysis, system engineering, science support, education and public outreach) can be controlled to eliminate the possibility of cost overrun, no cost reserve is held for these WBS elements. For WBS elements that contain some uncertainty (pre-launch GDS/MOS preparations), a reserve of 5% is included. For WBS elements that contain more uncertainty (spacecraft, integration & test, and launch checkout and orbit operations), a reserve of 10% is included. For WBS elements with the most uncertainty (instruments, reflecting their relatively higher development requirements), a reserve of 15% is included, except the MLA instrument carries a reserve of 25%. A 10% reserve is estimated for the DSN to account for uncertainties in application of the AO-specified cost algorithms and use of the compatibility test trailer at APL and the launch site.

A $5M real-year dollar reserve is specifically allocated for the second launch opportunity in August 2004, to cover the cost of maintaining the mission team, should there be difficulties with the launch vehicle or higher-level NASA coordination schedules that might impact the launch date. (Note that this includes $1M in real-year dollars as recommended in the NASA/OLS letter (Sec. I.1.4) to support the launch vehicle team.) Also recommended in the NASA/OLS letter is an expendable launch vehicle (ELV) development reserve between $2M and $3M real-year dollars, pending final pricing of the Delta II 7925H launch vehicle. We have chosen the conservative recommendation, and $3M is included for ELV development reserve.

As a percentage of the total Phase C/D costs (not including launch vehicle cost), these items represent an overall reserve of 13.6%. Given the maturity of our discrete cost estimate for this phase, we believe this amount is adequate.

Using a similar rationale for Phase E, a reserve of 5% has been applied to the costs for Mission Operations & Data Analysis (a partial level-of-effort task) and 10% for DSN costs (due to uncertainty in the effects of NASA full-cost accounting), without including any reserve for level-of-effort tasks. These reserves represent 4.7% of the total Phase E costs.

Costs of Hardware by Recurring and Non-recurring Components. As required by the AO, Table I-3 presents MESSENGER development costs separated into Non-Recurring Engineering (NRE) and Recurring Engineering (RE) costs. FAR 17.103 is used as the basis for NRE and RE costs. In particular, FAR 17.103 states in part:

"... Nonrecurring costs means those costs which are generally incurred on a one-time basis and include such costs as plant or equipment relocation, plant rearrangement, special tooling and special test equipment, pre-production engineering, initial spoilage and rework, and specialized workforce training.

Recurring costs means costs that vary with the quantity being produced, such as labor and materials. . . ."

Using these definitions, we estimated the RE cost of instruments and subsystems associated with hardware fabrication and test and the software costs associated with detailed coding and test from the Critical Design Review, when fabrication begins, through Phase C/D, which ends at launch plus 30 days. All other costs are assigned to NRE.

I.1 Phase A/B Cost Proposal

The detailed cost proposal for performing Phase A/B work and the Phase A/B Studies (Sec. H) is provided below. There are no long-lead flight component procurements included in the Phase A/B cost. The only long-lead flight hardware procurement parts are for the MLA, and these procurements are included in the Phase C/D cost estimate.

For brevity and clarity the applicable AO Concept Study report guidelines paragraph is shown after the heading in brackets, e.g., "Contract Pricing Proposal Cover Sheet [I.1.a]", to indicate compliance with the requirements.

For budgeting purposes, guidelines given to the Science Team members include a breakout into up to four tasks: (1) Support Science Team activities associated with Science Working Group (SWG) meetings as scheduled by the PI, (2) prepare for data analysis activities (Phases A through D), (3) conduct data analysis (Phase E), and (4) provide flight-hardware (Phases A through D and applicable only to flight hardware providers) as detailed in Sec. G.1.1: D. E. Smith for MLA (GSFC), M. A. Acuña for MAG (GSFC), W. E. McClintock for ASCS (LASP), and G. Gloeckler for the FIPS portion of EPPS (UM). These tasks are split across mission Phases A/B, C/D, and E where:

- Phase A/B is from January 1, 2000, through June 30, 2001,
- Phase C/D is from July 1, 2001, through April 30, 2004.
- Phase E (cruise from launch to first Mercury flyby) is from May 1, 2004, through December 31, 2007,
- Phase E (cruise from first Mercury flyby to Mercury orbit insertion) is from January 1, 2008, through September 30, 2009,
- Phase E (Mercury orbit) is from October 1, 2009, through September 30, 2010, and
- Phase E (Mercury final data analysis and archiving) is from October 1, 2010, through September 30, 2011.

The subdivision of Phase E reflects varying levels of science activity during spacecraft operations.

The travel guidelines below were provided to team members to use as the basis for estimating travel cost, either discretely or by the use of a Cost Estimating Relationship (CER), based on similarity to past programs.

The MESSENGER-specific travel plan for Science Team meetings and activities are based on four-day trips with travel (airfare, car rental, per diem, hotel, etc.) assumed as follows:

1. For Phase A/B (January 1, 2000, through June 30, 2001), one trip every six months (e.g., SSR/CoDR, PDR, etc.) for a total of three trips. Travel expenses are based on round-trips between the Co–I's home institution and the Baltimore-Washington area.

2. For Phase C/D (July 1, 2001, through April 30, 2004), one trip every six months (e.g., CDR, TIM, PER, etc.) for a total of six trips. Travel expenses are based on round-trips between the Co–I's home institution and the Baltimore-Washington area.

During Phase E, travel expenses are based on two different scenarios: (1) a round-trip between the Co–I's home institution and the Baltimore-Washington area, and (2) a round-trip between the Co–I's home institution and the farthest of Boston, Chicago, Denver, Saint Louis or Tucson (locations of Co-I institutions).

3. For Phase E cruise from launch to first Mercury flyby (May 1, 2004, through December 31, 2007), approximately one trip per year until Mercury flybys. A total of four trips are estimated: Two trips based on Scenario 1 and two trips based on Scenario 2.

4. For Phase E cruise from first Mercury flyby to Mercury orbit insertion (January 1, 2008, through September 30, 2009), approximately two trips per year until Mercury orbit insertion. A total of four trips are estimated: Two trips based on Scenario 1 and two trips based on Scenario 2.

5. For Phase E during Mercury orbital operations (October 1, 2009, through September 30, 2010), one trip every two months. A total of six trips are estimated: Four trips based on Scenario 1 and two trips based on Scenario 2.

6. For Phase E during the year of data analysis and archiving after Mercury orbital operations conclude (October 1, 2010, through September 30, 2011), three trips are estimated: Two trips based on Scenario 1 and one trip based on Scenario 2.

This travel plan contains a total of twenty-six trips for each non-APL Co-I. In addition, travel costs have been included in the overall E/PO budget to allow some of those team members to attend the science-activity meetings (an allotment is made of $5000 per meeting in FY99$ for E/PO interaction with the Science Team).

CIW. The MESSENGER science costs have been budgeted by the PI and Science Team members. The Science Team members participated in these negotiations and formally endorsed the final agreements as indicated in Appendix B. The members of the Science Team not at GSFC or APL are subcontracted by CIW for Science Team support tasks (1), (2), and (3). All E/PO efforts except that at APL are also subcontracted by CIW. This methodology keeps all science and E/PO activities under the direct control of the PI and minimizes the overhead on these level-of-effort tasks. Dollar budgets have been developed for each team member not at APL rather than simply specifying staffing levels.

APL. Detailed costing performed during this Concept Study has confirmed our confidence in the MESSENGER Phase-One cost figures. APL costs are generated using a discrete-estimate method. Part of this confidence comes from the fact that the experienced individual subsystem leaders who will be performing the work are those who perform the detailed bottom-up estimates, based on the WBS and project schedule, and draw on historical data that is at their desk-top "fingertips" through the APL Resource Management Information System (RMIS). The RMIS is consistent with the APL Estimating System, as documented in the APL Cost Estimating Manual dated April 18, 1996, and most recently revised February 1999.

I.1.1 Contract Pricing Proposal Cover Sheets [I.1.a]

The required contract pricing proposal cover sheets [form BSB-98-F-001 (SF1411-equivalent)] for CIW and APL, for Phase A/B are provided in Appendix E of this report.

I.1.2 Work Breakdown Structure [I.1.b]

The Work Breakdown Structure used to plan all phases of the MESSENGER project is provided in Appendix G, Table Ap. G-APL-2, defined per AO requirements.

I.1.3 Workforce Staffing Plan [I.1.c]

As required by the AO, the workforce-staffing plan for Phase A/B is presented by month in Table I-8. Time commitments of the PI, PM, and key personnel have been discussed in the Management Plan, Section G.1.2, and are shown in the table.

I.1.4 Proposal Pricing Technique [I.1.d]

The proposal pricing technique for Phase A/B is also used in estimating Phase C through E costs. As the implementing organization, APL led the cost estimating performed for the MESSENGER project. The pricing technique used to arrive at the costs of each organization is described below, with detailed cost information presented in tables in the format prescribed by the AO.

Anticipated costs from all MESSENGER team organizations to be funded directly by the NMO are presented. These organizations include components from NASA Orbital Launch Services (OLS), NASA/GSFC, JPL, CIW, and APL. Costs for CIW and APL include costs for all other team member organizations except government team member organizations. The NMO is requested to transfer funds to the relevant MESSENGER government team member agency only on direction by the Principal Investigator (PI).

NASA/OLS-Specific Proposal Pricing Technique. The Delta II 7925H launch vehicle cost is based on a letter from K. Poniatowski, Director, Expendable Launch Vehicle Requirements, per AO directions. The cost for the MESSENGER launch vehicle, based on MESSENGER requirements provided to OLS, is $64M in real-year dollars. We have included the NASA-recommended reserve stated in the letter as a reserve for ELV development and as a reserve for a second launch attempt, if required, as described in detail above.

NASA/GSFC-Specific Proposal Pricing Technique. NASA/GSFC costs are divided into four elements:

- (1) GSFC/Code 549, environmental test facilities,
- (2) GSFC/Code 691, Co-I support for J. Trombka

- (3) GSFC/Code 695, 696, Co-I support for M. Acuña and J. Slavin and portions of the MAG instrument, and
- (4) GSFC/Code 920, Co-I support for D. Smith and the MLA instrument.

Costs for the GSFC environmental test facilities (Phase C-D) have been obtained via letter from S. Wojnar/Code 549. This estimate is based on a written description of the tests to be performed by APL.

Cost estimates have been provided by each of the three GSFC organizations for instruments [Science Team activity task (4)], and Co-I Science-Team mission operations and data-analysis activities [tasks (1)-(3)], as appropriate. Cost elements include civil service and other labor costs, benefits, other direct costs, travel, and General and Administrative (G&A) Overhead. All estimates are based on previous experience, and full-cost accounting, as defined by GSFC, is used for all estimates. All civil service labor is charged directly to the project.

NASA/JPL-Specific Proposal Pricing Technique. The largest cost to the MESSENGER Project for the JPL/TMOD facilities is the DSN tracking aperture fees. These costs are based on the mission design (Sec. F.1) and the AO-provided costing algorithm, in the revised *NASA's Mission Operations and Communications Services* document dated November 1998, received at the Discovery-Program kickoff meeting, November 17, 1998. APL will use the TMOD Compatibility Test Trailer (CTT) before launch to verify MESSENGER compatibility with DSN. Cost for testing the telecommunication links using the CTT is included in the February 1999 DSN-quoted base rate fee of $553 per month. The DSN costs are provided in FY99$ based on a review of our projected DSN use, and have been inflated per AO directions.

The JPL Radio Metric and Navigation Service group of TMOD was funded by APL (for $20K) to perform their portion of the Concept Study. As part of that effort, cost estimates are provided for the group's participation in all phases of the MESSENGER project. Cost elements provided include staff years per year and real-year costs, in accordance with full cost accounting.

A letter confirming TMOD support of the MESSENGER mission is included in Appendix B.

A menu-based cost for qualification testing of the MESSENGER solar array panels using the JPL Environmental Test Laboratory and Space Simulation Facilities (Phase A-D) has been obtained via letter from T. C. Fisher, Supervisor. This estimate is based on a written description of the operations to be performed by APL and provides costs for tasks necessary to perform solar array testing. Based on our estimated test profile, we have applied NASA JPL fees and inflated to real-year dollars per AO directions.

CIW-Specific Proposal Pricing Technique. The Carnegie Institution has a long history of proposal submission and has done well in projecting the associated costs of its programs. Project objectives under grants and contracts from such Federal agencies as NASA, the National Science Foundation, and the United States Geological Survey have been met successfully, and within cost.

APL-Specific Proposal Pricing Technique. Over the past two decades, cost estimation of space science missions at APL has been highly successful in arriving at program costs that are within a few percent of the actual costs at program completion. The range of cost growth for spacecraft produced by APL in the past twenty years is between -5% and +8% (Crawford et al., 1996). This reference does not include the most recent example, the Advanced Composition Explorer (ACE) spacecraft launched in 1997, that had Phase C/D costs estimated at approximately $52M in real-year dollars and was delivered at $6M (11.5%) *under* budget. ACE benefited by closely following NEAR and using many of the same subsystems, which significantly reduced costs. The same synergy will likely exist with MESSENGER closely following TIMED and CONTOUR, although no "discount" (or sharing) is used to estimate the MESSENGER costs.

APL's demonstrated cost performance has been achieved without the direct use of formal cost models, such as those in growing use by government and industry, e.g., the Small Satellite Cost Model of the Aerospace Corporation. We, as well as others, have found that gross parameterization of costs such as the traditional spacecraft weight, power, and length of the program commonly included in typical models does not reliably predict actual costs (Bearden et al., 1996). To the contrary, such treatments typically grossly overestimate the actual cost of APL projects. However, we do invoke cost models in a comparative manner after arriving at a discrete estimate to help locate inconsistencies or omissions.

The cost-estimating methodology successfully used by the APL Space Department over the past 20 years, and followed for MESSENGER, utilizes a discrete-estimate, bottom-up approach. A team of experienced spacecraft engineers, led by the Mission System Engineer (MSE), performed the Concept Study. The MESSENGER Phase-One proposal design was used as the starting point and carried forward to a concept level. As part of the study, lead engineers, working with their functional supervisors, the proposal manager, and the MSE, estimated labor based on the specific MESSENGER designs and experience from recent comparable programs, such as NEAR and TIMED, using the MESSENGER WBS (Appendix G). These estimates include APL Technical Services Department labor hours for package design and fabrication of APL-developed hardware. Labor-hour estimates are phased over time (monthly in Phase A/B and quarterly in Phases C-E) and entered in the RMIS for costing. Non-labor costs include Special Test Equipment (STE), materials, and subcontracts. Major items are identified and costed specifically for MESSENGER. Smaller and/or routine items are costed on the basis of past program history using Cost Estimating Relationships (CERs). CERs are used to estimate travel, Miscellaneous Contract Materials (MCM), and Miscellaneous Other Direct Costs (MODC), based on historical actual cost experience with similar past programs. Before being used, the CERs are reviewed for cost realism. The major MESSENGER subcontract acquisition plan is shown in Table G-3-1. Requests for Information (RFI) or Requests for Proposal (RFP) were sent to candidate vendors. A brief description of the MESSENGER Project and its requirements (including schedule, cost growth restrictions, and standard APL terms and conditions) was provided in the letter, with a Statement of Work (SOW) and component specification attached. Appropriate responses from the candidate vendors are used as the basis of estimate for subcontract costs, and vendor-supplied delivery dates are used in the MESSENGER CPM schedule. The MESSENGER costing effort included comparisons to the APL cost history for the NEAR spacecraft and mission and to the Aerospace Small Spacecraft Cost Model (SSCM) for planetary missions (Version 3.0).

The SSCM for planetary missions has been used to evaluate cost reasonableness to the extent possible. The SSCM-derived cost estimate for the spacecraft bus is comparable to that obtained by the bottoms-up approach in Table I-2. The SSCM cost estimate for integration, assembly, and test is significantly less than the bottoms-up estimate. This cost difference is understandable, however, because of the increased thermal testing required for a Mercury mission, the funded implementation schedule reserve, and the inclusion of engineering support throughout the environmental-test period.

Comparison with NEAR and the SSCM, taking the above factors into account, shows good agreement in overall cost magnitude.

I.1.5 Phase A/B Time-Phased Cost Summary [I.1.e]

The Phase A/B Time-Phased Cost Summary representing all costs from all team members is shown in Table I-9 (reference AO Fig. 2), providing a time-phased cost breakdown for each month by WBS and major cost category, consistent with the AO Guidelines for Concept Study Report Preparation (Revised January 8, 1999) cost templates. Table I-2 (reference AO Fig. 3) and Table I-3 (reference AO Fig. 4) There is no development work planned for Phase A/B.

I.1.6 Cost Elements Breakdown [I.1.f]

Cost-element breakdowns for CIW and APL are provided immediately below. There is no civil servant labor included in CIW or APL costs. Civil servant labor is included in the government costs above.

I.1.6.1 CIW Cost Elements Breakdown [I.1.f]

The cost structure for proposal submission is composed of direct and indirect costs and is in conformity with the rules and regulations stipulated by CIW's cognizant Federal agency, the National Science Foundation. Components of direct cost consist of personnel salary support, employee fringe benefits, equipment, travel, materials and supplies, and other assorted items.

CIW Direct Labor [I.1.f.i]

CIW Basis of Labor-Hour Estimates and Number of Productive Work Hours Per Month [I.1.f.i(1) and I.1.f.i(2)]

CIW staff are salaried, so labor hours are not normally tracked. Estimated personnel effort is based on person-months or fractions thereof, plus applicable employee fringe benefit costs based on an Institution-wide average rate of 28.5% of total salaries. Full-time staff work 40 hours per week. CIW provides 17 paid holidays per year. Annual-leave and sick-leave days accrue at the rate of 2 and 1.25 days per month to maximum accruals of 24 and 130 days, respectively.

CIW Schedule of Direct Labor Rates and Forward Pricing Rate Agreements [I.1.f.i(3) and I.1.f.i(4)]

Budgeted labor costs are based on current salaries of the individuals supporting this project. Forward pricing of staff salaries is based on an average annual increase of 4% per year, effective 1 July of each year.

CIW Direct Material and Subcontract Costs [I.1.f.ii and I.1.f.iii]

CIW subcontracts for Co-I and E/PO team members are shown in Table I-7.

Procurement procedures at CIW follow Office of Management and Budget (OMB) Circular A-110, Subpart B, Sections 41 - 48, designed to attain consistency and uniformity among Federal agencies in the administration of grants to and agreements with institutions of higher education and non-profit organizations.

The following procedures and guidelines apply to the procurement of supplies, equipment, and other services.

1. Anticipated ordering is planned and in advance to avoid purchasing unnecessary items.
2. Where appropriate, an analysis is made of lease and purchase alternatives to determine which would be the most economical and practical procurement.
3. Solicitations of goods and services provide for all of the following:

- A clear and accurate description of the technical requirements for the material, product, or services to be procured. In competitive procurements, such a description shall not contain features that unduly restrict competition.
- Requirements which the bidder/offeror must fulfill and all other factors to be used in evaluating bids or proposals.
- A description, whenever practicable, of technical requirements in terms of functions to be performed or performance required, including the range of acceptable characteristics or minimum acceptable standards.
- The specific features of "brand name or equal" descriptions that bidders are required to meet when such items are included in the solicitation.
- The acceptance, to the extent practicable and economically feasible, of products and services dimensioned in the metric system of measurement.
- Preference, to the extent practicable and economically feasible, for products and services that conserve natural resources and protect the environment and are energy efficient.

4. Effort is made to utilize small and small disadvantaged businesses (SDBs) and women-owned small businesses (WOSBs), whenever possible.

5. The type of procuring instruments used, e.g. purchase orders, fixed price contracts, cost reimbursable contracts, is determined by CIW as appropriate for the particular procurement and for promoting the best interest of the program or project involved.

6. Contracts are made only with responsible contractors who possess the potential ability to perform successfully under the terms and conditions of the proposed procurement. Consideration is given to such matters as contractor integrity, record of past performance, financial and technical resources, or accessibility to other necessary resources.

7. CIW shall, on request, make available for the Federal awarding agency pre-award review and procurement documents, such as request for proposals or invitations for bids, independent cost estimates, etc., when the following conditions apply:

- The procurement is expected to exceed the small purchase threshold currently fixed at $25,000 and is to be awarded without competition or only one bid or offer is received in response to a solicitation.
- The procurement, which is expected to exceed the small purchase threshold, specifies a "brand name" product.
- The proposed award over the small purchase threshold is to be awarded to other than the apparent low bidder under sealed bid procurement.
- A proposed contract modification changes the scope of a contract or increases the contract amount by more than the amount of the small purchase threshold.

8. Cost and price analysis is carried out and documented in the procurement files in connection with every procurement action. Price analysis may be accomplished in various ways, including the comparison of price quotations submitted with market prices and similar indicia, together with discounts. Cost analysis includes the review and evaluation of each element of cost to determine reasonableness, allocability, and allowability.

9. Procurement records and files for purchases in excess of the small purchase threshold ($25,000) include the following at a minimum: (a) basis for contractor selection, (b) justification for lack of competition when competitive bids or offers are not obtained, and (c) basis for award cost or price.

10. A system for contract administration is maintained to ensure contractor conformance with the terms, conditions, and specifications of the contract and to ensure adequate and timely follow-up of all purchases. CIW evaluates contractor performance and documents, as appropriate, whether contractors have met the terms, conditions, and specifications of the contract.

11. CIW includes, in addition to provisions to define a sound and complete agreement, the following in all contracts and subcontracts:

- Contracts and subcontracts in excess of the small purchase threshold ($25,000) contain contractual provisions or conditions that allow for administrative, contractual, or legal remedies in instances in which a contractor violates or breaches the contract terms, and provide for such remedial actions as may be appropriate.
- Contracts and subcontracts in excess of the small purchase threshold contain suitable provisions for termination by CIW, including the manner by which termination shall be effected and the basis for settlement.
- Except as otherwise required by statute, an award that requires the contracting (or subcontracting) for construction or facility improvements provides for the recipient to follow its own requirements relating to bid guarantees, performance bonds, and payment bonds unless the construction contract or subcontract exceeds $100,000. For those contracts or subcontracts exceeding $100,000, CIW expects that the Federal awarding agency will make a determination that the Federal Government's interest is adequately protected.

12. All negotiated contracts (except those for less than the small purchase threshold) include a provision to the effect that CIW, the Federal awarding agency, the Comptroller General of the United States, or any of their duly authorized representatives, shall have access to any books, documents, papers, and records of the contractor which are directly pertinent to a specific program for the purpose of making audits, examinations, excerpts, and transcriptions.

13. All contracts and subcontracts, including small purchases, awarded by CIW and their contractors contain the procurement provisions of Appendix A of OMB Circular A-110, including those pertaining to Equal Employment Opportunity, Debarment and Suspension, and other Federal acts.

CIW Other Direct Costs [I.1.f.iv]

Other direct costs are based on current expense outlays. Forward pricing of such costs is based on an average annual increase of 3% per year.

CIW Indirect Costs [I.1.f.v]

CIW uses the Total Modified Direct Cost (TMDC) allocation base in calculating indirect cost. The TMDC is the total direct cost, less any equipment items costing more than $5,000 and the total of all consultant and/or subcontract costs over the life of the grant or contract in excess of $25,000. The indirect cost is determined from the TMDC at a rate consistent with that approved by NSF, CIW's cognizant Federal agency. The indirect cost rate used by the Department of Terrestrial Magnetism (DTM) in all grants and contracts is presently 57%.

CIW Indirect Rate History [I.1.f.v(3)]

The indirect cost rate at DTM has been constant since 1990-91 and has consistently been less than the rate authorized by NSF. The indirect cost rate to be used by CIW is projected to remain at this level through the duration of the MESSENGER project.

I.1.6.2 APL Cost Elements Breakdown [I.1.f]

There are five cost categories in the APL cost estimates used for all phases of this proposal: direct labor, direct procurement, other direct costs, indirect costs, and fee. Following is a description of each of these elements.

APL Direct Labor [I.1.f.i]

APL Basis of Labor-Hour Estimates [I.1.f.i(1)]

APL Direct labor. APL labor is defined in the forward-pricing rate submission in Labor-Hours by Labor Classification. However, for presentation consistency across MESSENGER organizations, workforce staffing levels are presented in staff months. Each labor classification is priced on the basis of its forward-pricing labor rate by fiscal year. The Labor Classifications within APL labor consist of:

- Principal Professional Staff
- Senior Professional Staff (Upper)
- Senior Professional Staff (Lower)
- Associate Professional Staff
- Technical Supporting Staff
- Clerical Supporting Staff
- Craft and Service Support Staff

Cost history from previous programs is used as the basis to compute the direct labor cost. For MESSENGER Phase A/B, the TIMED project Phase A/B (now completed) cost history is used. For MESSENGER Phase C/D and Phase E, the NEAR project Phase C/D (completed) and Phase E (ongoing) cost histories are used, respectively.

APL Resident Subcontract Employee (RSE) Direct labor. RSE labor is defined in Labor Hours in accordance with disclosed practices. However, for presentation consistency across MESSENGER organizations, workforce staffing levels are presented in staff months. RSE cost is based on the historical average RSE cost per Labor Hours for similar programs (as for the Direct Labor calculations). For MESSENGER the same time-phasing and labor mixes are used as described above for the Direct labor mix, i.e., Phase A/B from the TIMED project and Phases C through E from the NEAR project. The total cost is separated into labor and non-labor-related cost by application of a historically derived percentage. The RSE labor portion is burdened the same as APL direct labor; the non-labor-related portion of the cost is burdened the same as Other Direct Costs (ODC).

APL Number of Productive Work Hours Per Month. [I.1.f.i(2)]

Labor Hours are defined as actual time worked on a designated task, for both APL and RSE direct labor. Labor Hours exclude time absent from work. Absent time, e.g., vacation, sick leave, administrative leave (for bad weather), and holidays, is included in Employee Benefits. Workforce staffing levels are presented in staff months, with one staff month equivalent to 148 Labor Hours per month. Therefore, staff month rates are computed by multiplying the forward-pricing standard labor rates by 148 Labor Hours per month.

APL Schedule of Direct Labor Rates and Forward Pricing Rate Agreements [I.1.f.i(3) and I.1.f.i(4)]

Direct labor and forward-pricing rates used for this proposal are summarized by fiscal year in Table I-5. APL has submitted a forward-pricing rate proposal to the Defense Contract Management Command (DCMC) Administrative Contracting Officer (ACO) via APL letter BSB-99-L-048R, dated 3 March 1999. These rates are used for all APL proposals until final rates are negotiated with DCMC. APL direct labor rates shown in Table I-5 are escalated by 4.6% for exempt staff and 4.0% for nonexempt staff, from GFY 1999 to GFY 2000, and thereafter by 3.8% for exempt staff and 4.1% for nonexempt staff. The escalation rates are documented in APL's forward-pricing rate submission. Derivation of the direct labor rates is contained in the submitted forward-pricing rate letter. Labor rates do not include overtime, shift differential, incentives, or allowances. Rate verification may be obtained from the DCAA representative residing at APL.

These forward-pricing rates differ from those in effect at the time of the Phase-One Proposal submission and employed in that proposal. This difference is one element in the cost-estimate change between that proposal and this Concept Study.

APL Direct Material and Subcontract Costs [I.1.f.ii and I.1.f.iii]

Planned procurements for Phase A/B, including those required to perform the Phase A/B Studies (Sec. H), are provided in Table I-7.

APL Material. Material costs include procured items, e.g., miscellaneous parts, supplies, and deliverable hardware. These costs are based on purchase history, vendor quotations, or engineering estimates.

APL Subcontracts. The category "Subcontract Costs" includes the estimated cost of all subcontracted items. These costs are based on subcontract history, vendor proposals in response to Requests for Information (RFIs), and engineering estimates.

APL sent out RFIs to vendors with a specific statement of work with the understanding that once APL is awarded this program by NASA, APL will issue detailed RFPs. APL's standard RFPs require vendors to provide SF 1411 forms, or their equivalent, and certified cost or pricing data for all cost proposals of $500,000 or more for which there is not adequate price competition. Before awarding any subcontract, APL requires that Subcontract Administrators (SCAs) conduct a thorough analysis of the prospective subcontractor's cost elements such as labor, indirect rates, ODC, and profit or fee. The cost analysis includes (1) comparison of the proposed labor rates with those recommended in labor surveys, (2) information from the lead engineer on the reasonableness of the types and quantity of labor and ODC, and (3) comparison of indirect rates with the DCAA recommended rates for Overhead and G&A costs, and/or rate verifications and audits through DCAA. APL uses weighted guidelines to establish applicable fee/profit margins for large subcontracts for which there is not adequate price competition. APL negotiates cost elements and fees and documents the cost analysis and negotiation in a memorandum that conforms to FAR 15.406-3.

APL Miscellaneous Contract Material (MCM). Proposed MCM cost includes the cost of minor material items such as adhesives, containers, cables, wire, gaskets, o-rings, screws, standoffs, nuts, pipe, switches, etc., that will be required for contract performance. This cost element is proposed as a Cost Estimating Relationship (CER) based on NEAR or TIMED program history depending upon the project phase (as with the Labor Rates).

APL Other Direct Costs [I.1.f.iv]

APL Travel. Travel cost is computed as a CER based on NEAR or TIMED program history, depending upon the project phase. This method of estimating travel cost is used due to the similarity of these programs to MESSENGER instead of a discrete estimate.

APL Consultants. Consultant costs are estimated on the basis of program history, vendor proposals, or engineering estimates. No consultant services are anticipated for the MESSENGER project during Phase A/B.

APL RSE Non-Labor. In accordance with disclosed APL practice, RSE cost is calculated on the basis of the historical average RSE cost. The total cost is separated into labor cost of RSE and non-labor-related cost by application of a historically-derived percentage. Other non-labor costs such as RSE travel and ODC are discretely estimated and added to RSE non-labor. The RSE labor portion receives Department Overhead, G&A, and fee burdening; the non-labor-related portion of the cost is designated as ODC and receives G&A and fee burdening only.

APL Special Test Equipment (STE). STE includes either single or multipurpose integrated test units engineered, designed, fabricated, or modified to accomplish special purpose testing in performing a contract. STE is estimated on the basis of program history, vendor proposals, or engineering estimates. No STE cost is planned in MESSENGER Phase A/B.

APL Miscellaneous Other Direct Cost (MODC). MODC includes such other direct costs as telephone, postage and shipping, equipment rentals, reproduction expenses, computer supplies, computer software, software maintenance, etc., which will be required for performance of the contract. MODC is proposed as a CER based on NEAR or TIMED program history depending upon phase.

APL Indirect Costs [I.1.f.v]

All indirect costs itemized below are disclosed as previously described. No off-site APL rates are used in this cost proposal. The APL indirect cost for this proposal are based on Table I-5.

APL Employee Benefits. Employee benefits are calculated by application of forward-pricing rates to direct APL Labor Hours by fiscal year.

APL Department Overhead on Direct Labor. Department overhead on direct labor is computed from APL departmental-burden rates that are applied as required. Departmental overhead is applied to the sum of APL direct labor and RSE direct labor.

APL Procurement Burden. Procurement burden, proposed as part of the APL forward-pricing submittal, is applied to the sum of material, subcontract, and MCM costs.

APL General and Administrative Overhead (G&A). G&A is applied to the sum of APL and RSE direct labor costs, procurement burden, and Other Direct Costs.

APL Cost of Money. The cost of money is calculated by the application of pool cost-of-money rates to their respective bases. These latter rates are shown in Table I-5.

APL Indirect Rate History [I.1.f.v(3)]

In accordance with AO instructions, Table I-6 provides the APL Indirect Overhead Rate History for the past five fiscal years.

APL recognizes the need for reduced, and more predictable, overhead and forward pricing rates. The Laboratory experienced anomalous growth in both categories in GFY 1998 (cf. Table I-6 for indirect overhead rate history; a new rate package was submitted for approval during the month following the Phase-One proposal submission). This growth experience is an anomaly in that the Laboratory has experienced a long history of stable, predictable rates. To address this issue APL has taken an aggressive approach to rate management with the goal of reducing and stabilizing overall rates in each of the next three years (GFY 1999-GFY 2001). The approach to achieve this goal is multi-faceted and includes:

(1) Implementation of a comprehensive plan to reduce overhead spending (now in place), and (2) implementation of a recently completed Laboratory-wide Strategic Plan that targets growth in business outside of traditional activity areas. Implementation of this plan (now in progress) will increase the direct-charge Laboratory base, resulting in lower and more stable rates.

I.1.7 Fee Arrangements [I.1.f.v(4)]

CIW Fee. CIW is a non-profit educational institution. No fee is proposed.

APL Fee. Fee amounts established are intended to compensate the Laboratory for its performance and risks it will incur. Further, fee establishment is intended to offset costs of working capital and the costs associated with financing investments in capital equipment and facilities. The Laboratory, in establishing the fee, uses the Weighted Guideline method as a verification of the reasonableness of the amount proposed. Fee is calculated and applied to costs excluding Cost of Money (COM). The fee used for the MESSENGER Concept Study proposal is 5.5%; the same fee was proposed in the Phase-One cost proposal.

COI and Aerojet Fee. Fee arrangements are discussed in Appendix H.

Others. All other participating organizations are either government entities or educational institutions. No fees for these organizations are appropriate or proposed.

I.2 Design/Development (Phase C/D) Cost Estimate

The detailed cost estimate for performing Phase C/D design and development is provided below. This estimate is based upon, and correlates with, the plans set forth in the Science (Sec. D), Technical Approach (Sec. F), and Management (Sec. G) sections of the proposal.

I.2.1 Phase C/D Work Breakdown Structure

The Work Breakdown Structure is provided in Appendix G, Table Ap. G-APL-2, per AO requirements.

I.2.2 Phase C/D Cost Estimating Technique

The cost estimating technique for Phase C/D is described in Section I.1, above. The same approach, techniques, and cost-elements breakdown is the same as that used in preparing the Phase A/B cost proposal. No models are employed in estimating the Phase C/D costs. Forward-pricing rates now in effect are used to generate the estimate. Given that these rates are based on projections farther into the future than the ones appropriate for Phase A/B (Table I-5), these rates and NASA-predicted future inflation rates represent the greatest amount of uncertainty in this estimate. No "discounts" based on changes in ways of doing business are assumed.

I.2.3 Phase C/D Workforce Staffing Plan

As required by the AO, the workforce staffing plan for Phase C/D is presented by GFY in Table I-10. Time commitments of the PI, PM, and key personnel have been discussed in the Management Plan, Section G.1.2, and are shown in the table.

I.2.4 Phase C/D Time-Phased Cost Summary

A Phase C/D Time-Phased Cost Summary of all costs from all team members is shown in Table I-11, providing a time-phased cost breakdown for each fiscal year by WBS and major cost category. Included in this cost summary are the only identified long-lead flight component procurements that must be ordered during Phase A/B. These parts are required by the GSFC Code 920-provided MLA to meet the required schedule. All information is provided in a format consistent with the AO Guidelines for Concept Study Report Preparation (revised January 8, 1999) cost templates. This summary provides all costs to NASA; there are no contributions, and hence, there are no contributed costs.

I.3 Mission Operations (Phase E) Cost Estimate

The detailed cost estimate for performing Phase E mission operations and data analysis is provided below.

I.3.1 Phase E Work Breakdown Structure

The Work Breakdown Structure is provided in Appendix G, Table Ap. G-APL-2, per AO requirements.

I.3.2 Phase E Cost Estimating Technique

The cost estimating technique for Phase E is described in Section I.1 above and is the same as used for Phase C/D cost estimating.

I.3.3 Phase E Workforce Staffing Plan

As required by the AO, the workforce-staffing plan for Phase E is presented by GFY in Table I-12. Time commitments of the PI, PM, and key personnel have been discussed in the Management Plan, Section G.1.2, and are shown in the table.

I.3.4 Phase E Time-Phased Cost Summary

A Phase E Time-Phased Cost Summary of all costs from all contributors is shown in Table I-13, providing a time-phased cost breakdown for each fiscal year by WBS and major cost category. All information is provided in a format consistent with the AO Guidelines for Concept Study Report Preparation (revised January 8, 1999) cost templates. This summary provides all costs to NASA; there are no contributions, and hence, there are no contributed costs.

I.4 Total Mission Cost (TMC) Estimate

The total mission cost estimate by fiscal year and phase and summed across fiscal years and Phases is shown in Table I-2, consistent with the AO Guidelines for Concept Study Report Preparation (revised January 8, 1999) Figure 1 template. The table entries are consistent with the Work Breakdown Structure and summarize the cost proposal for Phase A/B (Sec. I.1 and Table I-9), the cost estimate for Phase C/D (Sec.

I.2 and Table I-11), and the Phase E cost estimate (Sec. I.3 and Table I-13).

Detailed plans for all aspects of the mission are discussed elsewhere in the Concept Study Report: the launch vehicle, upper stages, and launch services include the use of a Delta II 7925H with standard launch services in Sec. F.1 and I.1.d; Deep Space Network and other ground system in Sec. F.2.11; and activities associated with social, educational, and commercial benefits in Sec. E.

All cost proposals and estimates are on a commitment, as opposed to an expenditure, basis. Hence, obligation authority *is never* in excess of identified costs.

I.4.1 Total Mission Cost

A summary of the Total Mission Cost time-phased by fiscal year is provided in Table I-1, consistent with the AO Guidelines for Concept Study Report Preparation (revised January 8, 1999) Figure 1 template. This table gives total costs by phase and by organization during each phase by fiscal year and totaled, all in real-year dollars. Total costs are summarized in real-year dollars in the last column of the table. This summary represents the optimum funding profile for the mission. There are *no* assets provided as contributions by international or other partners to the MESSENGER project.

I.4.2 Major Cost Changes from Phase One.

Recognizing the importance of maintaining our cost within the MESSENGER Total Mission Cost (TMC) constraint, CIW and APL have carefully analyzed the major differences between the MESSENGER Phase-One cost estimate and the cost estimate presented in this Concept Study. We have a mature cost estimate, for which the principal uncertainty comes from out-year rate changes, including NASA center implementation of full-cost accounting. APL cost is the largest portion of MESSENGER TMC, and is based on the current forward-pricing rates, which contain a more conservative estimate of labor escalation and indirect cost parameters than the rates in effect when the Phase-One proposal was submitted. Although this rate schedule has resulted in an increase in cost, we have partially offset this increase by implementing a policy that also provides the PI with additional control of the team members. Because CIW has stable indirect rates and a limit on the indirect cost applied to subcontracts, the MESSENGER project will fund Science Team Co-Is by subcontracts from CIW for PI support, data analysis preparations, and data analysis and archiving, rather than by subcontract from APL. E/PO Team members will also be supported by subcontracts from CIW. Although these changes increase the CIW cost, they reduce the TMC to NASA. Co-I institutions that provide instruments (i.e., Univ. of Colorado and Univ. of Michigan) will still be funded by subcontracts from APL, providing the control needed to assure the delivery of reliable, flight-qualified instruments. NASA team members will continue to be funded via internal transfers effected by NMO.

The Concept Study TMC is $339.1M real-year dollars ($286.2M fixed FY99 dollars), compared to the Phase-One TMC of $333.8M real-year dollars ($279.3M fixed FY99 dollars), an increase of $5.3M in TMC, or less than 1.6%. The fixed FY99 dollar increase of less than 2.5% in TMC is due to differences in time phasing of resources between the Phase-One proposal and the Concept Study. This difference in time phasing results from increases in our Phase A through D cost and decreases in our Phase E cost, the result of additional planning performed during the Concept Study.

The major cost differences between our Phase-One proposal and this Concept Study are described below. The italicized headings correspond to the level one WBS elements. All changes include the effects of more recent vendor quotations, conservative forward-pricing rates, and NASA center implementation of full-cost accounting. All cost differences are provided in real-year dollars.

Project Management, System Engineering, Mission Design and Analysis (Phases A-E). The cost for this element increased by $0.8M, due to more conservative forward pricing rates. JPL/TMOD support of mission design and analysis remained unchanged from our Phase-One proposal.

Instruments (Phases A-D). The total instrument cost has increased by $2.7M. There have been no major changes in instrument design during the Concept Study. The changes are due to more recent vendor quotes and the effect of conservative forward pricing rates.

Spacecraft Bus Subsystems (Phases A-D). Attitude Determination and Control Subsystem (ADCS). The ADCS cost increased approximately $2.2M due to more recent quotations received for major components (gyros, etc.), reflective of the mission duration and commensurate requirement for high reliability components.

Power Subsystem. As described in sections F and H, we have enhanced the testing and qualification program of the solar array, resulting in a cost increase of approximately $3M. This increase includes labor, procurement of test solar cells, substrates, assembly, materials testing, and testing of qualification samples and flight acceptance testing in the solar simulation chambers at John H. Glenn Research Center at Lewis Field and JPL.

Other Subsystems. There is a net increase of $2.2M in all other spacecraft subsystem costs, which are attributable to more recent vendor quotes and the effect of conservative forward pricing rates.

Integration, Assembly and Test (IA&T, Phase C/D). IA&T costs have decreased by $1.9M, the result of additional Concept Study planning, removal of duplicated efforts with Pre-launch GDS/MOS Development, and properly identifying costs which should have been assigned to Pre-launch GDS/MOS Development, compared with our Phase-One proposal.

Science Team Support (Phases A-D). The estimate for Science Team support increased by $1.1M for this mission phase. The cost of this labor-intensive element increased because of the more conservative forward-pricing rates. Our decision to fund the majority of MESSENGER Co-Is through CIW keeps the cost from increasing further.

Pre-launch GDS/MOS Development (Phases A-D). Cost for this element has increased by $2.2M. Contributing factors are transfer of costs from IA&T and the use of more conservative forward-pricing rates.

Launch Vehicle. As noted above (Sec. I.6), the estimate for the Delta II 7925H has decreased from our Phase-One estimate of $68.5M to $64M. We have no unusual requirements that cannot be easily accommodated by OLS. As recommended, we have transferred $3M of the decrease to reserves for ELV development and $1M to reserves for the second launch window, if needed.

Mission Operations Center (MOC, Phase E). The estimate in the Phase-One proposal was extremely conservative, and has decreased by $1.9M. This decrease is the result of additional planning performed during the Concept Study, allowing a level of comfort that we have estimated the costs correctly.

Science Operations Center (SOC, Phase E). The costs for science operations decreased by $3.8M. This decrease results from a decision to request a quotation from a qualified SDB specialist in spacecraft science data handling, Applied Coherent Technology (ACT) Corporation, to operate the SOC. This action removed considerable direct labor from our Phase-One proposal to produce the corresponding decrease in cost.

Science Team Support (Phase E). Data analysis and archiving costs have decreased by $1.9M. This change is the result of more recent Co-Investigator quotations based on a refined plan for activities during the cruise portion of the mission and a reduction in indirect cost resulting from the decision to fund the majority of MESSENGER Co-Is through CIW.

Reserves. Reserves increased by $4.4M, primarily due to the reduced costs of the ELV and transferring this reduced cost to reserve as indicated in the discussion of launch vehicle changes.

Other (Phases A-E). The net aggregate of all other changes is an increase of $0.7M. The E/PO cost increased due to the explicit inclusion of developing and maintaining a MESSENGER E/PO-specific internet web site and addition of travel monies for E/PO representation at Science Team meetings. A slight change in our DSN estimate (which has been verified by JPL/TMOD) also contributed to the increase in this element.

Table I-1 MESSENGER Total Mission Cost Funding Profile

(FY costs in Real Year Dollars, Totals in Real Year Dollars)

Cost Element	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	FY2007	FY2008	FY2009	FY2010	FY2011	Total
Phase A/B	10,805,500	20,641,064											31,446,564
- Applied Physics Laboratory (APL)	9,360,215	18,273,561											27,633,776
- Carnegie Institution of Washington (CIW)	575,456	578,311											1,153,767
- NASA/GSFC Code 549 (Test Facilities)													
- NASA/GSFC Code 691 (Science)	114,500	89,224											203,724
- NASA/GSFC Code 695, 696 (MAG and Science)	135,330	364,228											499,558
- NASA/GSFC Code 920 (MLA and Science)	352,000	668,750											1,020,750
- NASA/JPL TMOD/AMMOS (Navigation)	268,000	194,250											462,250
- NASA/JPL (Test Facilities)		472,739											472,739
- NASA/JPL TMOD/DSN													
- Reserves													
Phase C/D		25,843,296	71,729,729	42,471,101	23,095,644								163,139,771
- Applied Physics Laboratory (APL)		20,143,681	57,588,907	33,847,724	12,928,716								124,509,029
- Carnegie Institution of Washington (CIW)		453,319	1,126,311	1,450,251	775,432								3,805,313
- NASA/GSFC Code 549 (Test Facilities)					917,457								917,457
- NASA/GSFC Code 691 (Science)		29,742	133,719	141,678	97,163								402,301
- NASA/GSFC Code 695, 696 (MAG and Science)		316,097	509,073	448,362	403,977								1,677,510
- NASA/GSFC Code 920 (MLA and Science)		2,192,250	3,677,000	1,143,196	21,937								7,034,384
- NASA/JPL TMOD/AMMOS (Navigation)		64,750	270,000	300,000	351,751								986,500
- NASA/JPL (Test Facilities)			597,465	546,433									1,143,898
- NASA/JPL TMOD/DSN					528,230								528,230
- Reserves		2,643,458	7,827,254	4,593,458	7,070,980								22,135,149
Phase E					4,395,343	7,553,848	7,416,072	9,250,802	11,157,360	13,764,798	19,990,997	7,003,844	80,533,064
- Applied Physics Laboratory (APL)					2,804,332	4,377,624	4,352,221	5,160,475	6,099,472	6,965,033	8,159,695	3,096,788	41,015,639
- Carnegie Institution of Washington (CIW)					795,487	1,380,091	1,328,158	1,808,971	2,253,600	2,570,106	2,945,572	1,741,128	14,823,113
- NASA/GSFC Code 549 (Test Facilities)													
- NASA/GSFC Code 691 (Science)					69,402	180,851	155,465	132,218	134,335	139,574	237,306	246,561	1,295,712
- NASA/GSFC Code 695, 696 (MAG and Science)					21,230	50,418	65,481	68,035	156,927	246,774	288,448	299,698	1,197,011
- NASA/GSFC Code 920 (MLA and Science)					15,670	114,702	200,371	221,793	373,232	1,111,953	1,452,925	1,301,862	4,792,508
- NASA/JPL TMOD/AMMOS (Navigation)					251,250	595,001	573,000	572,001	594,000	610,000	714,999		3,910,250
- NASA/JPL (Test Facilities)													
- NASA/JPL TMOD/DSN					258,688	548,425	439,397	882,668	1,042,057	1,479,424	5,093,173		9,743,832
- Reserves					179,285	306,737	301,979	404,642	503,736	641,934	1,098,878	317,808	3,755,000
ELV and Launch Services													
- NASA/Orbital Launch Services (OLS)		20,000,000	24,000,000	13,000,000	7,000,000								64,000,000
DSN and Tracking Services	Included in Phase C/D above as NASA/JPL TMOD/DSN					Included in Phase E above as NASA/JPL TMOD/DSN							
Total Cost to NASA	10,805,500	66,484,360	95,729,728	55,471,102	34,490,988	7,553,848	7,416,072	9,250,802	11,157,360	13,764,798	19,990,997	7,003,844	339,119,399
Additional Contributions (Foreign or Domestic)													
Contributed Costs (Total)													
											Mission Totals		339,119,399

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Table I-2 MESSENGER FY Costs in Fixed Year FY99 Dollars

(Rounded to nearest Thousand)

Cost Element	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	FY2007	FY2008	FY2009	FY2010	FY2011	TOTALS FY99 $K	TOTALS RY $K
Phase A/B	10,380	19,084											29,464	31,447
Phase A/B Total Reserves														
Total Phase A/B	10,380	19,084											29,464	31,447
Phase C/D (Development)														
Project Management/Mission Analysis/System Engineering		636	2,454	2,472	1,524								7,086	8,181
Mercury Dual Imaging System (MDIS)		488	2,393	1,366									4,246	4,811
Gamma-ray and Neutron Spectrometer (GRNS)		464	1,977	1,013									3,454	3,906
Magnetometer (MAG)		425	1,072	737									2,234	2,525
Mercury Laser Altimeter (MLA)		2,027	3,272	474									5,773	6,423
Atmospheric and Surface Composition Spectrometer (ASCS)		501	1,918	1,548									3,967	4,504
X-ray Spectrometer (XRS)		195	875	530									1,600	1,813
Energetic Particle and Plasma Spectrometer (EPPS)		772	2,955	1,790									5,517	6,246
Data Processing Unit (DPU)		415	1,970	879									3,264	3,689
Instrument Integration, Assembly, Test				1,328									1,328	1,551
Subtotal Instruments		5,287	16,432	9,663									31,383	35,468
Spacecraft Bus		13,967	28,891	7,310	99								50,267	56,229
Spacecraft Integration, Assembly, Test		182	1,001	6,083	3,592								10,857	12,781
Launch Operations (Launch + 30 days)					3,319								3,319	4,026
Subtotal Spacecraft		14,148	29,891	13,393	7,009								64,442	73,036
Science Team		522	1,792	2,110	1,163								5,587	6,453
Pre-Launch GDS/MOS Development		670	5,881	4,353	2,767								13,671	15,773
Education and Public Outreach		187	412	448	311								1,359	1,566
DSN and Tracking Services					435								435	528
Subtotal Phase C/D before Reserves		21,450	56,864	32,440	13,209								123,963	141,005
Phase C/D Total Reserves		2,444	6,965	3,934	5,829								19,172	22,135
Instrument Reserves		996	2,792	1,521									5,308	5,990
Spacecraft Bus Reserves		1,397	2,889	731	10								5,027	5,623
Spacecraft Integration, Assembly, Test Reserves		18	100	608	359								1,086	1,278
Launch Operations (Launch + 30 days) Reserves					332								332	403
Pre-Launch GDS/MOS Development Reserves		33	294	218	138								684	789
Second Launch Opportunity Reserves					4,122								4,122	5,000
ELV Development Reserves			890	856	824								2,571	3,000
DSN Reserves					44								44	53
Total Phase C/D		23,894	63,829	36,374	19,038								143,135	163,140
Phase E (Operations)														
Mission Operations and Data Analysis					2,529	3,997	3,941	4,650	5,652	6,726	7,726	4,008	39,229	55,612
DSN and Tracking Services					213	435	336	649	737	1,007	3,337		6,714	9,744
Project Management/Mission Analysis/System Engineering					606	995	930	912	894	889	941	208	6,375	8,784
Education and Public Outreach					127	323	226	290	253	312	374		1,905	2,638
Subtotal Phase E before Reserves					3,475	5,750	5,432	6,501	7,536	8,934	12,379	4,216	54,223	76,778
Phase E Total Reserves					148	243	231	297	356	437	720	200	2,633	3,755
Mission Operations and Data Analysis Reserves					126	200	197	233	283	336	386	200	1,961	2,781
DSN Reserves					21	44	34	65	74	101	334		671	974
Total Phase E					3,623	5,993	5,663	6,799	7,892	9,371	13,099	4,417	56,856	80,533
ELV and Launch Services		18,491	21,356	11,134	5,770								56,752	64,000
Total NASA Cost	10,380	61,469	85,185	47,508	28,431	5,993	5,663	6,799	7,892	9,371	13,099	4,417	286,206	339,119
Total Contributions														
Total Mission Cost													286,206	339,119

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Table I-3 MESSENGER Development Costs in Fixed Year FY99 Dollars

(Rounded to nearest Thousand)

Cost Element	Non-Recurring	Recurring	Total (FY1999 $)	Total (RY $)
Mercury Dual Imaging System (MIDS)	1,690	2,708	4,398	4,989
Gamma-ray and Neutron Spectrometer (GRNS)	1,525	2,035	3,561	4,031
Magnetometer (MAG)	935	1,349	2,284	2,583
Mercury Laser Altimeter (MLA)	3,663	2,347	6,010	6,700
Atmospheric and Surface Composition Spectrometer (ASCS)	1,460	2,711	4,171	4,743
X-ray Spectrometer (XRS)	632	1,017	1,650	1,871
Energetic Particle and Plasma Spectrometer (EPPS)	2,478	3,228	5,706	6,467
Data Processing Unit (DPU)	1,354	2,249	3,603	4,085
Subtotal Instruments	13,738	17,645	31,383	35,468
Attitude	3,882	2,574	6,455	7,119
Power	4,105	4,325	8,429	9,488
Electrical (Harness)	507	508	1,015	1,138
Mechanical	1,670	1,987	3,657	4,124
Thermal	633	253	886	995
RF/Communication	5,720	2,166	7,886	8,714
Integrated Electronics Module (IEM)	3,933	3,096	7,029	7,865
Flight Software	1,885	3,212	5,098	5,801
Propulsion	3,669	2,357	6,026	6,716
Spacecraft Bus Performance Assurance	1,955	1,830	3,785	4,270
Subtotal Spacecraft Bus	27,959	22,308	50,267	56,229
Spacecraft Integration, Assembly, Test (IA&T)	596	10,261	10,857	12,781
Launch Checkout and Orbital Operations		3,319	3,319	4,026
Pre-launch GDS/MOS Development	4,375	9,297	13,671	15,773
Total Development - Phase C/D	46,667	62,829	109,496	124,277

Table I-4 MESSENGER Cost Reserve Summary

Cost Element	Total RY $K (*) Phase C/D	Total RY $K (*) Phase E	Rationale
Proj. mgmt./miss. analysis/sys. eng.	0	0	Level of effort, controllable
Instruments	5,990	0	25% MLA, 15% others, varies with individual heritage level
Spacecraft bus	5,623	0	10% overall, varies with individual heritage level and known risk allocations
Spacecraft integration, assembly, and test	1,278	0	10% overall, varies with individual heritage level and known risk allocations
Launch checkout and orbit operations	403	0	10% overall, varies with individual heritage level and known risk allocations
Science team support	0	0	Level of effort, controllable
Pre-launch GDS/MOS development	789	0	5%, experience from NEAR
Mission operations and data analysis	0	2,781	5%, partial level of effort
Education/public outreach	0	0	Level of effort, controllable
ELV development	3,000	0	Recommended by OLS
DSN	53	974	10%, DSN full cost accounting
Second launch window (Aug 2004)	5,000	0	Support mission and ELV team between launch opportunities, if needed
Reserve totals	22,135	3,755	

* Includes all applicable costs. No reserves for Phase A/B – level of effort

Table I-7 MESSENGER Phase A/B Planned Procurements (Sheet 1 of 2)

MESSENGER PHASE A/B PLANNED PROCUREMENTS: APL MATERIALS (REAL YEAR DOLLARS)							
WBS	COST ELEMENT	DESCRIPTION	PROPOSED AMOUNT	VENDOR	LOCATION	CONTRACT TYPE	BASIS OF ESTIMATE
3.1	Material	MatLab/SIMULINK/Real-time workshop ACS development software tools	$20,000	The MathWorks Inc.	Natick, MA	FFP	Vendor quote
3.4	Material	(6) Test panels (15" x 15")	$81,107	Applied Aerospace Structures Corp	Stockton, CA	FFP	Vendor quote
3.6	Material	Solid state power amp DC/DC converter breadboard parts	$15,000	Various	-	FFP	Engineering judgement, cost history
3.6	Material	Solid state power amplifier and antenna breadboard parts	$31,500	Various	-	FFP	Engineering judgement, cost history
3.6	Material	Phased array RF control assembly	$18,509	Waveline Inc.	New Jersey	FFP	Vendor quote
3.6	Material	Phased array computer	$10,500	Gateway Computer	-	FFP	Catalog
3.6	Material	Solid state power amplifier transistors	$18,707	TriQuint Semiconductor	Richardson, TX	FFP	Vendor quote
3.6	Material	Solid State power amplifier phase shifters	$11,035	Northrop Grumman	Baltimore, MD	FFP	Vendor quote
3.8	Material	IEM and flight software development 1394 test set parts	$27,000	Various	Various	-	Engineering judgement, cost history
3.8	Material	IEM and flight software development 1395 test set I/O boards	$2,547	National Instruments	Austin, TX	FFP	Vendor quote
3.8	Material	IEM and flight software development Nucleus Plus ops systems	$24,038	Accelerated Technology Inc.	Mobile, AL	FFP	Vendor quote
3.8	Material	IEM and flight software development stations	$20,982	DELL	-	FFP	Catalog
3.8	Material	IEM and flight software development compilers/debuggers	$42,547	TASKING	Dedham, MA	FFP	Vendor quote
3.8	Material	IEM and flight software development Turbo Rocket boards	$22,500	SYNOVA	Melbourne, FL	FFP	Vendor quote
ALL	Material	Miscellaneous material purchases for engineering model, prototypes, testing, etc.	$380,364	Various	-	FFP	Cost estimating relationship
		Total (Unburdened)	$726,336				

MESSENGER PHASE A/B PLANNED PROCUREMENTS: APL SUBCONTRACTS (REAL YEAR DOLLARS)							
WBS	COST ELEMENT	DESCRIPTION	PROPOSED AMOUNT	VENDOR	LOCATION	CONTRACT TYPE	BASIS OF ESTIMATE
1.0	Subcontract	Technology transfer planning	$29,290	Mid-Atlantic Technology Applications Center (MTAC)	Pittsburgh, PA	Cost	Proposal
1.0	Subcontract	High thrust heliocentric trajectory optimization tool	$306,559	Aerospace Corp.	Houston, TX	CPFF	Vendor quote
2.5	Subcontract	ASCS instrument preliminary design	$1,000,999	University of Colorado	Boulder, CO	Cost Reimbursable	Proposal
2.7	Subcontract	FIPS instrument preliminary design	$132,180	University of Michigan	Ann Arbor, MI	Cost Reimbursable	Proposal
3.2	Subcontract	Solar array testing-solar simulator	$196,250	NASA Lewis Research Center	Cleveland, OH	FFP	APL contract #805950 with NASA Lewis Research dated 1/2/99
3.2	Subcontract	Solar array coupon procurements	$347,270	Tecstar	City of Industry, CA	ROM	Vendor quote
3.2	Subcontract	Solar array coupon irradiation (MeV)	$30,000	Brookhaven Labs	Upton, NY	FFP	Vendor quote
3.2	Subcontract	Solar array coupon substrate procurement and test	$96,730	To Be Competed	TBD	FFP	Engineering judgement
3.4	Subcontract	Structure preliminary design	$594,538	Composite Optics	San Diego, CA	CPIF	Proposal
3.9	Subcontract	Propulsion system preliminary design	$4,505,893	GenCorp Aerospace	Sacramento, CA	CPFF	Proposal
3.A	Subcontract	Safety assurance analysis	$21,738	Futron, Inc.	Bethesda, MD	CPFF	Proposal
7.2	Subcontract	Science Operation Center preliminary design	$341,444	Applied Coherent Technology(ACT)	Herndon, VA	CPFF	Proposal
		Total (Unburdened)	$7,602,891				

Table I-7 MESSENGER Phase A/B Planned Procurements (Sheet 2 of 2)

MESSENGER PHASE A/B PLANNED PROCUREMENTS: CIW SUBCONTRACTS (REAL YEAR DOLLARS)							
WBS	COST ELEMENT	DESCRIPTION	PROPOSED AMOUNT	VENDOR	LOCATION	CONTRACT TYPE	BASIS OF ESTIMATE
6.0	Subcontract	Science Team Support Co-Investigators Baker and McClintock	$135,409	University of Colorado	Boulder, CO	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Boynton	$103,582	University of Arizona	Tucson, AZ	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Chapman	$98,449	Southwest Research Institute	San Antonio, TX	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Gloeckler	$28,931	University of Michigan	Ann Arbor, MI	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Head	$50,922	Brown University	Providence, RI	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Peale	$6,024	University of California/Santa Barbara	Santa Barbara, CA	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Phillips	$39,581	Washington University	St. Louis, MO	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Robinson	$33,634	Northwesten University	Evanston, IL	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Strom	$5,510	University of Arizona	Tucson, AZ	Cost Reimbursable	Proposal
6.0	Subcontract	Science Team Support Co-Investigator Zuber	$9,085	Massachusetts Institute of Technology	Cambridge, MA	Cost Reimbursable	Proposal
9.0	Subcontract	Education/Public Outreach Malcom and Nelson	$63,272	American Association for the Advancement of Science	Washington, DC	Cost Reimbursable	Proposal
9.0	Subcontract	Education/Public Outreach Goldstein	$26,098	Challenger Center for Space Education	Alexandria, VA	Cost Reimbursable	Proposal
9.0	Subcontract	Education/Public Outreach Stockman	$15,790	Proxemy Research	Greenbelt, MD	Cost Reimbursable	Proposal
9.0	Subcontract	Education/Public Outreach MESSENGER Movie	$65,168	Independent Film Producer/Director Weinreich and Parmee	New York, NY	FFP	Proposal
9.0	Subcontract	Education/Public Outreach MESSENGER Web Site development	$54,080	To Be Competed	TBD	TBD	Engineering judgement
		Total (Unburdened)	$735,535				

Table I-8 MESSENGER Phase A/B Staffing by WBS and Major Cost Category

(Staffing in Staff Month per Month (SM/M))

Work Breakdown Structure (WBS)/Cost Category Description	Jan2000	Feb2000	Mar2000	Apr2000	May2000	Jun2000	Jul2000	Aug2000	Sep2000	Oct2000	Nov2000	Dec2000	Jan2001	Feb2001	Mar2001	Apr2001	May2001	Jun2001	Phase Average
Total Staffing	43.7	42.7	42.6	50.5	52.8	50.5	60.2	61.2	60.3	72.1	71.1	71.7	78.0	76.0	75.5	90.4	92.4	93.4	65.8
1.0 Project Management/Mission Analysis/System Engineering	9.2	9.2	9.2	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.4	9.4	9.4	9.7	9.7	9.7	9.2
Project Manager	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mission System Engineer	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mission Manager	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
Performance Assurance Engineer	.7	.7	.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Other	6.3	6.3	6.3	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	6.2	6.2	6.2	6.5	6.5	6.5	6.1
2.0 Instruments	10.6	10.6	10.6	12.3	12.3	12.3	13.8	13.8	13.8	23.4	23.4	23.4	24.8	24.8	24.8	30.3	30.3	30.3	18.2
2.1 Mercury Dual Imaging System (MDIS)	1.0	1.0	1.0	.9	.9	.9	1.0	1.0	1.0	2.5	2.5	2.5	3.1	3.1	3.1	4.8	4.8	4.8	2.2
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	1.4	1.4	1.4	1.2	1.2	1.2	2.0	2.0	2.0	2.2	2.2	2.2	2.2	2.2	2.2	4.0	4.0	4.0	2.1
2.3 Magnetometer (MAG)	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.2	1.2	3.0	3.0	3.0	3.4	3.4	3.4	3.7	3.7	3.7	2.3
2.4 Mercury Laser Altimeter (MLA)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	.5	.5	.5	.5	.5	.5	.5	.5	.5	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	2.9
2.6 X-ray Spectrometer (XRS)	1.1	1.1	1.1	1.3	1.3	1.3	1.3	1.3	1.3	1.5	1.5	1.5	1.7	1.7	1.7	1.7	1.7	1.7	1.4
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	2.2	2.2	2.2	3.9	3.9	3.9	4.1	4.1	4.1	5.0	5.0	5.0	5.0	5.0	5.0	5.7	5.7	5.7	4.3
2.8 Data Processing Unit (DPU)	1.2	1.2	1.2	1.2	1.2	1.2	1.7	1.7	1.7	1.8	1.8	1.8	2.0	2.0	2.0	3.0	3.0	3.0	1.8
3.0 Spacecraft Bus	17.8	18.8	18.8	22.3	24.8	22.3	30.4	31.4	30.4	30.9	29.8	30.5	34.1	32.1	31.6	37.7	39.7	40.7	28.9
3.1 Attitude	1.3	1.3	1.3	1.3	1.3	1.3	1.7	1.7	1.7	1.7	1.7	1.7	3.0	3.0	3.0	2.7	2.7	2.7	1.9
3.2 Power	4.1	3.1	3.1	4.0	6.3	4.0	6.9	7.9	6.9	7.9	6.9	7.5	7.2	5.2	4.7	4.1	6.1	7.1	5.7
3.3 Electrical (Harness)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	1.0	1.0	.2
3.4 Mechanical	2.3	2.3	2.3	3.2	3.2	3.2	4.7	4.7	4.7	4.7	4.7	4.7	3.8	3.8	3.8	5.0	5.0	5.0	3.9
3.5 Thermal	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.2	1.2	1.2	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.1
3.6 RF/Communication	6.6	6.6	6.6	10.0	10.0	10.0	11.0	11.0	11.0	8.7	8.7	8.7	8.7	8.7	8.7	10.3	10.3	10.3	9.2
3.7 Integrated Electronics Module (IEM)	.2	.2	.2	.2	.2	.2	.9	.9	.9	1.7	1.7	1.7	2.8	2.8	2.8	5.7	5.7	5.7	1.9
3.8 Flight Software	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.2
3.9 Propulsion	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3.A Spacecraft Bus Performance Assurance	.3	.3	.3	.7	.7	.7	1.2	1.2	1.2	1.2	1.2	1.2	3.7	3.7	3.7	3.9	3.9	3.9	1.8
4.0 Spacecraft Integration, Assembly, Test (IA&T)	.3	.3	.3	.3	.3	.3	.8	.8	.8	.8	.8	.8	1.0	1.0	1.0	2.6	2.6	2.6	.8
5.0 Launch Checkout and Orbital Operations	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
6.0 Science Team	4.8	4.8	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.3	5.3	5.3	5.5	5.6	5.6	5.5	5.6	5.5	5.2
Principal Investigator	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
Project Scientist	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
Science Payload Manager	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
Other	3.7	3.7	3.7	3.9	3.9	3.9	3.9	3.9	3.9	4.2	4.2	4.2	4.4	4.4	4.4	4.4	4.4	4.4	4.1
7.0 Pre-launch GDS/MOS Development	.7	.7	.7	1.3	1.3	1.3	1.1	1.1	1.1	2.4	2.4	2.4	2.9	2.9	2.9	4.3	4.3	4.3	2.1
8.0 Mission Operations and Data Analysis (MO&DA)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Principal Investigator	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Project Scientist	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Science Payload Manager	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Other	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
9.0 Education and Public Outreach	.3	.3	.3	.3	.3	.3	.3	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
TOTAL STAFFING FOR PHASE A/B	43.7	42.7	42.6	50.5	52.8	50.5	60.2	61.2	60.3	72.1	71.1	71.7	78.0	76.0	75.5	90.4	92.4	93.4	65.8

NOTES:

1. Staffing levels include Principal Investigator, Co-Investigators, and Science Team members
2. Staffing levels include civil service labor
3. Staffing levels include JPL TMOD/Navigation Team, government-furnished instruments (part of MAG and all of MLA), and procured instruments (all of ASCS and part of EPPS)
4. Staffing levels for other procurements (e.g., hardware, software, etc.) or government-furnished services (e.g., ELV, DSN, etc.) are not included
5. Phase average figures reflect weighting by the actual number of months in each FY for a given mission phase

Table I-9 MESSENGER Phase A/B Cost Breakdown by WBS and Major Cost Category (Sheet 1 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	Jan2000	Feb2000	Mar2000	Apr2000	May2000	Jun2000	Jul2000	Aug2000	Sep2000	Oct2000	Nov2000	Dec2000	Jan2001	Feb2001	Mar2001	Apr2001	May2001	Jun2001	Total (FY1999 $)	Total (RY $)
Total APL Direct Labor Cost	289,918	291,808	291,525	353,925	373,008	354,008	432,382	440,872	432,382	468,391	458,058	463,040	517,783	501,176	487,024	616,622	633,328	641,532	6,064,243	6,589,547
1.0 Project Management/Mission Analysis/System Engineering	63,988	63,988	63,988	62,575	62,575	62,575	61,810	61,810	61,810	63,273	63,273	63,273	66,014	66,014	66,014	68,754	68,754	68,754	1,158,545	1,231,207
2.0 Instruments	60,664	60,664	60,664	74,625	74,625	74,625	86,758	86,758	86,758	103,330	103,330	103,330	114,734	114,734	114,734	160,188	160,188	160,188	1,800,836	1,920,737
2.1 Mercury Dual Imaging System (MDIS)	8,310	8,310	8,310	7,084	7,084	7,084	8,476	8,476	8,476	20,709	20,709	20,709	25,554	25,554	25,554	38,455	38,455	38,455	338,702	352,619
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	11,634	11,634	11,634	9,889	9,889	9,889	18,537	18,537	18,537	17,853	17,853	17,853	17,853	17,853	17,853	33,287	33,287	33,287	321,180	342,783
2.3 Magnetometer (MAG)	6,648	6,648	6,648	7,728	7,728	7,728	6,399	6,399	6,399	8,394	8,394	8,394	10,296	10,296	10,296	12,538	12,538	12,538	150,012	158,723
2.4 Mercury Laser Altimeter (MLA)																				
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)																				
2.6 X-ray Spectrometer (XRS)	9,141	9,141	9,141	11,052	11,052	11,052	11,052	11,052	11,052	12,706	12,706	12,706	14,033	14,033	14,033	14,033	14,033	14,033	218,050	229,874
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	14,958	14,958	14,958	29,086	29,086	29,086	30,498	30,498	30,498	30,474	30,474	30,474	30,474	30,474	30,474	38,038	38,038	38,038	514,584	547,495
2.8 Data Processing Unit (DPU)	9,972	9,972	9,972	9,808	9,808	9,808	13,795	13,795	13,795	15,198	15,198	15,198	16,524	16,524	16,524	24,808	24,808	24,808	279,397	289,294
3.0 Spacecraft Bus	147,086	138,785	138,785	181,998	201,102	181,998	246,714	255,074	246,714	250,517	242,214	247,198	280,238	263,831	258,478	308,198	322,798	331,070	4,241,484	4,516,894
3.1 Attitude	10,803	10,803	10,803	11,052	11,052	11,052	13,786	13,786	13,786	13,784	13,784	13,784	24,828	24,828	24,828	22,088	22,088	22,088	288,050	308,294
3.2 Power	34,072	25,781	25,781	32,083	51,198	32,083	56,018	64,320	56,018	64,882	56,570	61,560	58,371	42,794	38,812	34,211	50,910	59,122	845,234	898,885
3.3 Electrical (Harness)																8,304	8,304	8,304	24,911	26,844
3.4 Mechanical	19,113	19,113	19,113	26,343	26,343	26,343	36,988	36,988	36,988	36,935	36,935	36,935	31,803	31,803	31,803	38,798	38,798	38,798	568,783	600,238
3.5 Thermal	8,310	8,310	8,310	8,310	8,310	8,310	8,888	8,888	8,888	9,987	9,987	9,987	8,304	8,304	8,304	8,304	8,304	8,304	158,848	168,888
3.6 RF/Communication	54,021	54,021	54,021	80,350	80,350	80,350	87,888	87,888	87,888	88,252	88,252	88,252	88,252	88,252	88,252	80,277	80,277	80,277	1,316,480	1,388,839
3.7 Integrated Electronics Module (IEM)	1,862	1,862	1,862	1,862	1,862	1,862	7,728	7,729	7,728	13,867	13,867	13,867	23,001	23,001	23,001	47,331	47,331	47,331	285,753	307,724
3.8 Flight Software	8,310	8,310	8,310	8,310	8,310	8,310	16,620	16,620	16,620	24,911	24,911	24,911	24,911	24,911	24,911	24,911	24,911	24,911	323,819	346,302
3.9 Propulsion	8,310	8,310	8,310	8,310	8,310	8,310	8,310	8,310	8,310	8,304	8,304	8,304	8,304	8,304	8,304	8,304	8,304	8,304	148,824	158,888
3.A Spacecraft Bus Performance Assurance	2,493	2,493	2,493	5,588	5,588	5,588	9,723	9,723	9,723	9,715	9,715	9,715	31,488	31,488	31,488	33,883	33,883	33,883	277,883	298,382
4.0 Spacecraft Integration, Assembly, Test (IA&T)	2,078	2,078	2,078	2,078	2,078	2,078	6,233	6,233	6,233	8,228	8,228	8,228	8,304	8,304	8,304	21,423	21,423	21,423	138,027	148,108
5.0 Launch Checkout and Orbital Operations																				
6.0 Science Team	19,944	19,944	19,944	21,191	21,191	21,191	21,191	21,191	21,191	22,503	22,503	22,503	23,831	23,831	23,831	23,831	23,831	23,831	387,474	422,317
7.0 Pre-launch GDS/MOS Development	5,734	5,734	5,851	11,052	11,052	11,138	9,141	9,141	9,141	19,680	19,680	19,680	23,831	23,831	23,831	36,498	36,498	36,498	314,885	337,295
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach	416	416	416	416	416	416	416	416	416	830	830	830	830	830	830	830	830	830	11,215	11,876
Total APL Direct Material and Equipment Cost	81,314	13,031	13,027	84,251	16,668	15,819	47,116	19,821	19,250	124,888	20,399	20,821	22,795	22,064	21,888	73,043	27,708	28,079	1,228,055	726,338
1.0 Project Management/Mission Analysis/System Engineering	2,858	2,858	2,858	2,786	2,786	2,786	2,786	2,786	2,786	2,827	2,827	2,827	2,950	2,950	2,950	3,072	3,072	3,072	51,814	56,017
2.0 Instruments	2,711	2,711	2,711	3,335	3,335	3,336	3,877	3,877	3,877	4,817	4,817	4,817	5,127	5,127	5,127	7,167	7,167	7,167	924,872	98,838
2.1 Mercury Dual Imaging System (MDIS)	371	371	371	316	316	316	379	379	379	925	925	925	1,142	1,142	1,142	1,783	1,783	1,783	14,888	15,757
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	520	520	520	442	442	442	739	739	739	798	798	798	798	798	798	1,488	1,488	1,488	14,352	15,318
2.3 Magnetometer (MAG)	297	297	297	345	345	345	288	288	288	288	288	288	480	480	480	580	580	580	6,703	7,137
2.4 Mercury Laser Altimeter (MLA)																				
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)																				
2.6 X-ray Spectrometer (XRS)	408	408	408	494	494	494	494	494	494	566	566	566	627	627	627	627	627	627	9,664	10,272
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	888	888	888	1,300	1,300	1,300	1,363	1,363	1,363	1,362	1,362	1,362	1,362	1,362	1,362	1,610	1,610	1,610	22,994	24,488
2.8 Data Processing Unit (DPU)	446	446	446	438	438	438	616	616	616	679	679	679	738	738	738	1,108	1,108	1,108	12,078	12,881
3.0 Spacecraft Bus	64,498	6,202	6,202	78,908	8,888	8,132	38,820	11,325	10,894	115,243	10,753	10,978	12,181	11,439	11,254	61,170	19,836	14,208	812,730	844,384
3.1 Attitude	483	483	483	10,100	494	494	616	616	616	616	616	616	1,108	1,108	1,108	10,233	987	987	31,798	33,778
3.2 Power	1,522	1,151	1,151	1,434	2,288	1,434	2,500	2,874	2,500	2,888	2,520	2,751	2,883	1,911	1,725	1,520	2,271	2,842	443,188	40,187
3.3 Electrical (Harness)																371	371	371	1,113	1,204
3.4 Mechanical	78,787	854	854	1,177	1,177	1,177	1,862	1,852	1,852	1,860	1,850	1,850	1,421	1,421	1,421	1,732	1,732	1,732	103,373	108,187
3.5 Thermal	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	6,881	7,081
3.6 RF/Communication	2,414	2,414	2,414	82,420	3,890	3,890	31,784	3,917	3,917	3,060	3,060	3,080	3,050	3,050	3,050	17,450	3,387	3,387	158,381	167,888
3.7 Integrated Electronics Module (IEM)	74	74	74	74	74	74	345	345	348	620	620	620	1,028	1,028	1,028	2,118	2,118	2,118	12,788	13,731
3.8 Flight Software	371	371	371	371	371	371	740	743	743	108,231	1,113	1,113	1,113	1,113	1,113	28,076	1,113	1,113	143,888	155,088
3.9 Propulsion	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	371	6,881	7,081
3.A Spacecraft Bus Performance Assurance	111	111	111	249	249	249	434	434	434	434	434	434	1,085	1,086	1,086	918	918	918	8,831	10,320
4.0 Spacecraft Integration, Assembly, Test (IA&T)	93	93	93	93	93	93	279	279	279	279	279	279	371	371	371	987	987	987	6,212	6,883
5.0 Launch Checkout and Orbital Operations																				
6.0 Science Team	891	891	891	947	947	947	947	947	947	1,008	1,008	1,008	1,085	1,085	1,085	1,085	1,085	1,085	17,781	18,871
7.0 Pre-launch GDS/MOS Development	298	298	283	494	494	498	408	408	408	879	879	879	1,085	1,085	1,085	1,584	1,584	1,584	14,082	15,088
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach	19	19	19	19	19	19	19	19	19	37	37	37	37	37	37	37	37	37	601	635

Table I-9 MESSENGER Phase A/B Cost Breakdown by WBS and Major Cost Category (Sheet 2 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	Jan2000	Feb2000	Mar2000	Apr2000	May2000	Jun2000	Jul2000	Aug2000	Sep2000	Oct2000	Nov2000	Dec2000	Jan2001	Feb2001	Mar2001	Apr2001	May2001	Jun2001	Total (FY1999 $)	Total (RY $)
Total APL Other Direct Costs	20,915	20,338	20,330	24,691	26,014	24,987	30,041	30,821	30,041	32,413	31,834	32,181	35,579	34,419	34,129	42,093	43,242	43,621	557,357	595,999
1.0 Project Management/Mission Analysis/System Engineering	4,482	4,482	4,482	4,384	4,384	4,384	4,317	4,317	4,317	4,412	4,412	4,412	4,804	4,804	4,804	4,795	4,795	4,795	80,882	85,859
2.0 Instruments	4,230	4,230	4,230	5,204	5,204	5,204	8,050	8,050	8,050	7,208	7,208	7,208	8,001	8,001	8,001	11,169	11,169	11,169	125,583	133,944
2.1 Mercury Dual Imaging System (MDIS)	580	580	580	495	495	495	591	591	591	1,444	1,444	1,444	1,782	1,782	1,782	2,751	2,751	2,751	22,922	24,990
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	811	811	811	690	690	690	1,153	1,153	1,153	1,245	1,245	1,245	1,245	1,245	1,245	2,322	2,322	2,322	22,399	23,900
2.3 Magnetometer (MAG)	494	494	494	539	539	539	446	446	446	446	446	446	718	718	718	874	874	874	10,401	11,139
2.4 Mercury Laser Altimeter (MLA)																				
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)																				
2.6 X-ray Spectrometer (XRS)	837	837	837	771	771	771	771	771	771	888	888	888	979	979	979	979	979	979	15,098	16,030
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	1,043	1,043	1,043	2,028	2,028	2,028	2,127	2,127	2,127	2,129	2,129	2,129	2,129	2,129	2,129	2,813	2,813	2,813	35,885	38,180
2.8 Data Processing Unit (DPU)	895	895	895	984	984	984	982	982	982	1,080	1,080	1,080	1,152	1,152	1,152	1,730	1,730	1,730	18,848	20,102
3.0 Spacecraft Bus	10,258	9,879	9,879	12,691	14,024	12,691	17,095	17,874	17,098	17,301	18,782	17,129	19,019	17,852	17,583	20,439	21,891	22,170	290,779	309,599
3.1 Attitude	753	753	753	771	771	771	982	982	982	981	981	981	1,731	1,731	1,731	1,540	1,540	1,540	20,187	21,499
3.2 Power	2,376	1,798	1,798	2,237	3,570	2,237	3,908	4,486	3,809	4,535	3,846	4,293	4,140	2,982	2,893	2,386	3,844	4,123	58,843	62,688
3.3 Electrical (Harness)																579	579	579	1,737	1,878
3.4 Mechanical	1,333	1,333	1,333	1,837	1,837	1,837	2,578	2,578	2,578	2,578	2,578	2,578	2,218	2,218	2,218	2,704	2,704	2,704	38,734	42,277
3.5 Thermal	580	580	580	580	580	580	580	580	580	579	579	579	579	579	579	579	579	579	10,427	11,088
3.6 RF/Communication	3,787	3,787	3,787	5,003	5,003	5,003	8,114	8,114	8,114	4,780	4,780	4,780	4,780	4,780	4,780	5,588	5,588	5,588	81,806	87,410
3.7 Integrated Electronics Module (IEM)	116	116	116	116	116	116	539	539	539	987	987	987	1,804	1,804	1,804	3,301	3,301	3,301	19,927	21,499
3.8 Flight Software	580	580	580	580	580	580	1,159	1,159	1,159	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	1,737	22,988	24,150
3.9 Propulsion	580	580	580	580	580	580	580	580	580	579	579	579	579	579	579	579	579	579	10,427	11,088
3.A Spacecraft Bus Performance Assurance	174	174	174	398	398	398	678	678	678	678	678	678	1,062	1,062	1,062	1,430	1,430	1,430	15,030	16,105
4.0 Spacecraft Integration, Assembly, Test (IA&T)	145	145	145	145	145	145	435	435	435	434	434	434	579	579	579	1,494	1,494	1,494	9,895	10,399
5.0 Launch Checkout and Orbital Operations																				
6.0 Science Team	1,391	1,391	1,391	1,479	1,479	1,479	1,479	1,479	1,479	1,589	1,589	1,589	1,062	1,062	1,062	1,062	1,062	1,062	27,718	29,451
7.0 Pre-launch GDS/MOS Development	400	400	394	771	771	777	837	837	837	1,372	1,372	1,372	1,062	1,062	1,062	2,473	2,473	2,473	21,845	23,515
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach	29	29	29	29	29	29	29	29	29	58	58	58	58	58	58	58	58	58	782	836
Total APL Subcontracts	156,019	208,870		1,064,530				57,637		5,148,238	169,420		108,887	82,498		20,098		72,679	7,084,712	7,602,881
1.0 Project Management/Mission Analysis/System Engineering	17,713			144,082						154,780									316,585	335,849
2.0 Instruments	137,306									815,537									1,052,843	1,133,179
2.1 Mercury Dual Imaging System (MDIS)																				
2.2 Gamma-ray and Neutron Spectrometer (GRNS)																				
2.3 Magnetometer (MAG)																				
2.4 Mercury Laser Altimeter (MLA)																				
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	92,988									635,883									828,871	1,000,999
2.6 X-ray Spectrometer (XRS)																				
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	44,317									78,584									123,871	132,180
2.8 Data Processing Unit (DPU)																				
3.0 Spacecraft Bus		208,870		674,333				57,637		3,989,479	169,420		108,887	82,498		20,098		72,679	5,280,737	5,782,419
3.1 Attitude																				
3.2 Power		89,298		38,425				57,637			169,420		108,887	82,498				72,679	620,080	670,250
3.3 Electrical (Harness)																				
3.4 Mechanical		118,573								435,563									554,136	594,538
3.5 Thermal																				
3.6 RF/Communication																				
3.7 Integrated Electronics Module (IEM)																				
3.8 Flight Software																				
3.9 Propulsion				635,909						3,553,916									4,189,825	4,505,893
3.A Spacecraft Bus Performance Assurance																20,098			20,098	21,738
4.0 Spacecraft Integration, Assembly, Test (IA&T)																				
5.0 Launch Checkout and Orbital Operations																				
6.0 Science Team																				
7.0 Pre-launch GDS/MOS Development				238,105						86,442									324,847	341,444
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach																				

Table I-9 MESSENGER Phase A/B Cost Breakdown by WBS and Major Cost Category (Sheet 3 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	Jan2000	Feb2000	Mar2000	Apr2000	May2000	Jun2000	Jul2000	Aug2000	Sep2000	Oct2000	Nov2000	Dec2000	Jan2001	Feb2001	Mar2001	Apr2001	May2001	Jun2001	Total (FY1999 $)	Total (RY $)
Total APL Indirect Costs	293,466	264,460	274,281	387,509	350,978	333,085	407,898	417,261	408,645	700,815	440,172	436,586	493,040	476,581	468,049	583,733	596,007	607,446	7,868,087	8,479,342
1.0 Project Management/Mission Analysis/System Engineering	61,058	60,199	60,199	65,869	58,875	58,873	58,250	58,250	58,250	87,375	58,681	58,681	62,264	62,264	62,264	84,852	84,652	84,652	1,107,811	1,178,399
2.0 Instruments	63,736	57,071	57,071	70,210	70,212	70,210	81,628	81,628	81,628	142,979	97,464	97,464	108,218	108,218	108,218	151,078	151,078	151,078	1,748,188	1,868,293
2.1 Mercury Dual Imaging System (MDIS)	7,818	7,818	7,818	8,848	8,848	8,848	7,875	7,875	7,875	19,533	19,533	19,533	24,102	24,102	24,102	37,218	37,218	37,218	308,870	332,423
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	10,845	10,845	10,845	9,304	9,304	9,304	15,559	15,559	15,559	18,839	18,839	18,839	18,839	18,839	18,839	31,409	31,409	31,409	302,984	323,021
2.3 Magnetometer (MAG)	6,254	6,254	6,254	7,271	7,271	7,271	6,020	6,020	6,020	6,031	6,031	6,031	9,712	9,712	9,712	11,827	11,827	11,827	141,347	150,800
2.4 Mercury Laser Altimeter (MLA)																				
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	4,515									41,555									46,070	49,848
2.6 X-ray Spectrometer (XRS)	8,600	8,600	8,600	10,399	10,399	10,399	10,399	10,399	10,399	11,983	11,983	11,983	13,238	13,238	13,238	13,237	13,237	13,237	203,981	218,880
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	16,224	14,072	14,072	27,365	27,365	27,365	28,695	28,695	28,695	32,899	28,744	28,744	28,743	28,743	28,743	33,993	33,993	33,992	490,944	522,378
2.8 Data Processing Unit (DPU)	9,382	9,382	9,382	9,226	9,226	9,226	12,979	12,979	12,979	14,333	14,333	14,333	15,586	15,586	15,586	23,388	23,388	23,388	254,711	271,848
3.0 Spacecraft Bus	142,167	140,707	130,999	207,285	189,208	171,222	233,328	242,990	231,973	438,626	238,982	233,008	288,887	252,509	243,996	280,888	303,163	314,603	4,272,408	4,552,457
3.1 Attitude	10,183	10,183	10,183	10,889	10,399	10,399	12,979	12,979	12,979	13,001	13,001	13,001	23,418	23,418	23,418	21,294	20,834	20,834	273,310	291,807
3.2 Power	32,054	28,820	24,236	32,051	49,185	30,185	62,704	63,321	62,704	61,188	61,639	58,085	61,410	44,931	36,419	32,299	47,934	59,374	827,284	880,010
3.3 Electrical (Harness)																7,832	7,832	7,832	23,497	25,414
3.4 Mechanical	21,764	23,734	17,881	24,785	24,785	24,785	34,779	34,779	34,779	55,489	34,839	34,839	29,997	29,997	29,997	36,596	36,596	36,596	568,037	604,866
3.5 Thermal	7,818	7,818	7,818	7,819	7,819	7,818	9,150	9,149	9,150	9,154	9,154	9,154	7,832	7,832	7,832	7,832	7,832	7,832	148,814	157,808
3.6 RF/Communication	50,822	50,822	50,822	73,452	75,500	75,500	83,639	82,466	82,466	64,377	64,377	64,377	64,378	64,378	64,378	76,411	76,721	76,721	1,246,952	1,321,011
3.7 Integrated Electronics Module (IEM)	1,564	1,564	1,564	1,564	1,564	1,564	7,271	7,271	7,271	13,080	13,080	13,080	21,895	21,895	21,895	44,845	44,845	44,844	269,453	280,174
3.8 Flight Software	7,818	7,818	7,818	7,819	7,819	7,819	15,638	15,638	15,638	28,672	23,497	23,497	23,496	23,496	23,496	24,736	23,497	23,497	311,708	333,334
3.9 Propulsion	7,818	7,818	7,818	38,993	7,819	7,819	7,819	7,819	7,819	184,480	7,832	7,832	7,832	7,832	7,832	7,832	7,832	7,832	348,389	372,708
3.A Spacecraft Bus Performance Assurance	2,345	2,345	2,345	5,230	5,230	5,230	9,148	9,148	9,148	9,184	9,184	9,184	28,832	28,832	28,832	31,488	30,467	30,467	258,882	275,808
4.0 Spacecraft Integration, Assembly, Test (IA&T)	1,955	1,956	1,955	1,965	1,968	1,965	5,894	5,894	5,894	5,874	5,874	5,874	7,832	7,832	7,832	20,208	20,208	20,208	131,061	140,885
5.0 Launch Checkout and Orbital Operations																				
6.0 Science Team	18,793	18,793	18,793	19,937	19,938	19,937	19,938	19,938	19,938	21,225	21,225	21,225	22,479	22,479	22,479	22,479	22,479	22,479	374,482	397,878
7.0 Pre-launch GDS/MOS Development	5,384	5,384	5,318	21,862	10,399	10,477	8,601	8,601	8,601	22,959	18,882	18,882	22,478	22,478	22,478	33,444	33,444	33,444	312,494	334,887
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach	391	391	391	391	391	391	391	391	391	783	783	783	783	783	783	783	783	783	10,887	11,287
APL Fee	47,336	48,008	32,953	104,768	42,168	40,017	30,463	53,120	48,838	288,999	61,429	52,264	84,793	61,987	96,199	73,967	71,510	79,040	1,330,126	1,428,544
APL Cost of Money	7,254	7,043	6,919	8,990	8,764	8,340	10,153	10,368	12,138	14,974	11,387	11,411	12,671	12,445	13,200	15,128	15,488	15,791	199,436	212,522
Total APL Cost	918,222	870,375	836,015	2,018,667	817,832	775,856	978,134	1,029,300	947,291	8,843,399	1,189,888	1,016,236	1,258,725	1,201,078	1,089,514	1,426,271	1,387,198	1,495,847	25,889,511	27,830,776
Total C/W Direct Labor Cost	13,571	13,571	13,571	13,571	13,571	13,571	13,571	13,571	13,571	10,712	10,712	10,712	10,712	10,712	10,712	10,712	10,712	10,712	218,949	231,422
6.0 Science Team	13,571	13,571	13,571	13,571	13,571	13,571	13,571	13,571	13,571	10,186	10,186	10,186	10,186	10,186	10,186	10,186	10,186	10,186	213,817	226,306
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach										526	526	526	526	526	526	526	526	526	4,732	5,116
Total C/W Direct Material and Equipment Cost																				
6.0 Science Team																				
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach																				
Total C/W Other Direct Costs	1,121	1,121	1,121	1,121	1,121	1,121	1,121	1,121	1,121	1,947	1,947	1,947	1,947	1,947	1,947	1,947	1,947	1,947	27,807	29,480
6.0 Science Team	1,121	1,121	1,121	1,121	1,121	1,121	1,121	1,121	1,121	833	833	833	833	833	833	833	833	833	17,585	18,630
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach										1,114	1,114	1,114	1,114	1,114	1,114	1,114	1,114	1,114	10,022	10,840
Total C/W Subcontracts	331,902									360,581									692,484	736,531
6.0 Science Team	231,915									249,384									481,299	511,125
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach	99,987									111,627									211,214	224,406
Total C/W Indirect Costs	22,063	8,375	8,375	8,375	8,375	8,375	8,375	8,375	8,375	6,642	6,642	6,642	6,642	6,642	6,642	6,642	6,642	6,642	148,834	157,363
6.0 Science Team	22,063	8,375	8,375	8,375	8,375	8,375	8,375	8,375	8,375	6,281	6,281	6,281	6,281	6,281	6,281	6,281	6,281	6,281	145,586	153,852
8.0 Mission Operations and Data Analysis (MO&DA)																				
9.0 Education and Public Outreach										361	361	361	361	361	361	361	361	361	3,249	3,511
C/W Fee																				
Total C/W Cost	388,258	23,067	23,067	23,067	23,067	23,067	23,067	23,067	23,067	380,281	19,300	19,300	19,300	19,300	19,300	19,300	19,300	19,300	1,087,473	1,153,787

Table I-9 MESSENGER Phase A/B Cost Breakdown by WBS and Major Cost Category (Sheet 4 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	Jan2000	Feb2000	Mar2000	Apr2000	May2000	Jun2000	Jul2000	Aug2000	Sep2000	Oct2000	Nov2000	Dec2000	Jan2001	Feb2001	Mar2001	Apr2001	May2001	Jun2001	Total (FY1999 $)	Total (RY $)
Phase A/B Total Reserves																				
Instrument Reserves																				
Spacecraft Bus Reserves																				
Spacecraft Integration, Assembly, Test Reserves																				
Launch Operations (Launch + 30 days) Reserves																				
Pre-Launch GDS/MOS Development Reserves																				
Second Launch Opportunity Reserves																				
ELV Development Reserves																				
Mission Operations and Data Analysis (MO&DA) Reserves																				
DSN Reserves																				
Total APL and Carnegie Cost	1,283,479	893,442	682,082	2,041,723	840,898	799,003	1,001,200	1,062,388	970,358	7,223,670	1,208,898	1,036,536	1,275,025	1,220,378	1,108,614	1,445,571	1,408,495	1,505,147	26,873,984	28,787,543
Total Other Costs to NASA	835,571									1,217,138					229,992			207,082	2,489,791	2,850,021
ELV and Launch Services																				
DSN and Tracking Support																				
Total Other Cost to NASA - NASA/GSFC	578,126									1,037,941									1,615,887	1,724,032
4.0 NASA/GSFC Code 549 (Spacecraft Environmental Test Facilities)																				
6.0 NASA/GSFC Code 691 (Science Team Support)	109,990									82,493									192,483	203,724
8.0 NASA/GSFC Code 691 (MO&DA)																				
2.3 NASA/GSFC Code 695, 696 Magnetometer (MAG) Instrument	94,000									309,750									403,750	432,879
4.0 NASA/GSFC Code 695, 696 Spacecraft Integration, Assembly, Test																				
5.0 NASA/GSFC Code 695, 696 Launch Checkout/Orbital Operations																				
6.0 NASA/GSFC Code 695, 696 Science Team Support	36,000									27,000									63,000	66,879
8.0 NASA/GSFC Code 695, 696 (MO&DA)																				
2.4 NASA/GSFC Code 920 Mercury Laser Altimeter (MLA) Instrument	338,136									618,798									956,434	1,020,750
4.0 NASA/GSFC Code 920 Spacecraft Integration, Assembly, Test																				
5.0 NASA/GSFC Code 920 Launch Checkout/Orbital Operations																				
6.0 NASA/GSFC Code 920 Science Team Support																				
8.0 NASA/GSFC Code 920 (MO&DA)																				
Total Other Cost to NASA - NASA/JPL	257,445									178,985					229,992			207,082	874,114	934,888
1.0 NASA/JPL TMOD/AMMOS (Navigation)	257,445									178,985									437,040	462,250
3.2 NASA/JPL Environmental Test (Solar Array Qualification)															229,992			207,082	437,074	472,739
TOTAL COST FOR PHASE A/B	2,119,050	893,442	682,082	2,041,723	840,898	799,003	1,001,200	1,062,388	970,358	8,440,808	1,208,898	1,036,536	1,275,025	1,220,378	1,338,606	1,445,571	1,408,495	1,712,229	29,463,795	31,446,564

Table I-10 MESSENGER Phase C/D Staffing by WBS and Major Cost Category

(Staffing in Staff Year per Year (SY/Y))

Work Breakdown Structure (WBS)/Cost Category Description	FY 2001	FY 2002	FY 2003	FY 2004	Phase Average
Total Staffing	148.4	193.7	143.6	82.1	149.1
1.0 Project Management/Mission Analysis/System Engineering	11.7	11.7	11.8	12.8	12.0
Project Manager	1.0	1.0	1.0	1.0	1.0
Mission System Engineer	1.0	1.0	1.0	1.0	1.0
Mission Manager	.2	.2	.2	.2	.2
Performance Assurance Engineer	1.0	1.0	1.0	.8	.9
Other	8.5	8.5	8.6	9.9	8.8
2.0 Instruments	54.0	70.6	46.8	.0	46.2
2.1 Mercury Dual Imaging System (MDIS)	7.9	9.0	7.0	.0	6.3
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	5.2	6.9	5.4	.0	4.8
2.3 Magnetometer (MAG)	4.9	4.9	3.5	.0	3.4
2.4 Mercury Laser Altimeter (MLA)	10.0	14.5	4.0	.0	7.4
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	2.5	11.3	9.0	.0	7.4
2.6 X-ray Spectrometer (XRS)	2.9	3.5	2.8	.0	2.5
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	14.7	13.5	9.5	.0	9.4
2.8 Data Processing Unit (DPU)	5.9	7.2	5.6	.0	5.0
3.0 Spacecraft Bus	63.5	82.6	27.6	.0	44.5
3.1 Attitude	3.3	2.4	.9	.0	1.5
3.2 Power	10.6	14.9	4.2	.0	7.7
3.3 Electrical (Harness)	1.4	3.6	.0	.0	1.4
3.4 Mechanical	5.6	9.3	3.3	.0	4.9
3.5 Thermal	1.5	1.8	.4	.0	.9
3.6 RF/Communication	10.1	11.1	5.4	.0	6.7
3.7 Integrated Electronics Module (IEM)	14.5	17.0	1.7	.0	7.9
3.8 Flight Software	6.9	10.8	9.3	.0	7.7
3.9 Propulsion	.9	.9	.2	.0	.5
3.A Spacecraft Bus Performance Assurance	8.7	10.9	2.2	.0	5.4
4.0 Spacecraft Integration, Assembly, Test (IA&T)	3.4	4.4	26.5	17.2	14.7
5.0 Launch Checkout and Orbital Operations	.0	.0	.0	21.4	4.4
6.0 Science Team	7.3	8.6	11.1	8.9	9.4
Principal Investigator	.3	.3	.3	.3	.3
Project Scientist	.6	.6	.6	.6	.6
Science Payload Manager	.2	.2	.2	.2	.2
Other	6.2	7.5	10.0	7.8	8.3
7.0 Pre-launch GDS/MOS Development	8.2	14.1	18.3	20.3	16.3
8.0 Mission Operations and Data Analysis (MO&DA)	.0	.0	.0	.0	.0
Principal Investigator	.0	.0	.0	.0	.0
Project Scientist	.0	.0	.0	.0	.0
Science Payload Manager	.0	.0	.0	.0	.0
Other	.0	.0	.0	.0	.0
9.0 Education and Public Outreach	.3	1.6	1.6	1.4	1.5
TOTAL STAFFING FOR PHASE C/D	148.4	193.7	143.6	82.1	149.1

NOTES:

1. Staffing levels include Principal Investigator, Co-Investigators, and Science Team members
2. Staffing levels include civil service labor
3. Staffing levels include JPL TMOD/Navigation Team, government-furnished instruments (part of MAG and all of MLA) and procured instruments (all of ASCS and part of EPPS)
4. Staffing levels for other procurements (e.g., hardware, software, etc.) or government-furnished services (e.g., ELV, DSN, etc.) are not included
5. Phase average figures reflect weighting by the actual number of months in each FY for a given mission phase

Table I-11 MESSENGER Phase C/D Cost Breakdown by WBS and Major Cost Category (Sheet 1 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	FY 2001	FY 2002	FY 2003	FY 2004	Total (FY1999 $)	Total (RY $)
Total APL Direct Labor Cost	2,741,049	13,676,899	10,417,210	3,789,232	30,624,390	35,094,676
1.0 Project Management/Mission Analysis/System Engineering	235,674	941,973	941,251	528,105	2,647,003	3,053,158
2.0 Instruments	757,010	3,587,726	2,842,883		7,187,619	8,169,977
2.1 Mercury Dual Imaging System (MIDS)	181,766	825,518	645,850		1,653,134	1,878,400
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	116,641	609,875	479,148		1,205,664	1,370,982
2.3 Magnetometer (MAG)	60,548	267,738	221,360		549,647	624,831
2.4 Mercury Laser Altimeter (MLA)						
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)						
2.6 X-ray Spectrometer (XRS)	66,329	308,353	247,995		622,677	707,824
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	196,248	911,434	727,482		1,835,164	2,085,929
2.8 Data Processing Unit (DPU)	135,478	664,807	521,048		1,321,333	1,502,011
3.0 Spacecraft Bus	1,375,844	7,005,773	2,412,436		10,794,053	12,177,850
3.1 Attitude	75,507	219,489	81,484		376,480	423,467
3.2 Power	228,979	1,246,020	346,731		1,821,730	2,052,764
3.3 Electrical (Harness)	30,889	303,955			334,845	374,989
3.4 Mechanical	115,694	741,174	271,392		1,128,261	1,274,932
3.5 Thermal	34,685	165,618	31,752		232,056	260,708
3.6 RF/Communication	217,348	940,491	453,861		1,611,700	1,821,921
3.7 Integrated Electronics Module (IEM)	296,418	1,334,179	153,616		1,784,213	1,999,294
3.8 Flight Software	157,879	987,425	853,675		1,998,979	2,277,170
3.9 Propulsion	20,593	82,308	20,561		123,463	138,777
3.A Spacecraft Bus Performance Assurance	197,852	985,112	199,364		1,382,328	1,553,827
4.0 Spacecraft Integration, Assembly, Test (IA&T)	77,700	402,663	2,069,889	872,245	3,422,497	4,011,526
5.0 Launch Checkout and Orbital Operations				1,000,740	1,000,740	1,214,044
6.0 Science Team	106,015	438,978	473,672	293,730	1,312,395	1,517,381
7.0 Pre-launch GDS/MOS Development	186,518	1,290,641	1,667,941	1,083,758	4,228,857	4,914,394
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	2,288	9,145	9,138	10,653	31,225	36,346
Total APL Direct Material and Equipment Cost	1,870,519	6,830,765	1,851,450	772,984	11,325,717	12,798,948
1.0 Project Management/Mission Analysis/System Engineering	37,657	150,512	150,396	84,382	422,947	487,844
2.0 Instruments	215,262	1,161,452	469,661		1,846,376	2,086,426
2.1 Mercury Dual Imaging System (MIDS)	56,780	302,756	110,904		470,440	531,137
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	43,600	204,230	76,560		324,390	366,060
2.3 Magnetometer (MAG)	9,675	69,476	43,078		122,228	138,838
2.4 Mercury Laser Altimeter (MLA)						
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)						
2.6 X-ray Spectrometer (XRS)	18,919	86,644	39,625		145,188	164,098
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	31,357	229,278	116,239		376,875	427,297
2.8 Data Processing Unit (DPU)	54,931	269,068	83,255		407,254	458,996
3.0 Spacecraft Bus	1,502,603	4,562,639	505,987		6,571,229	7,343,417
3.1 Attitude	12,065	199,693	21,584		233,342	262,663
3.2 Power	36,587	199,093	55,402		291,082	327,997
3.3 Electrical (Harness)	4,936	258,572			263,508	295,917
3.4 Mechanical	33,990	272,274	43,364		349,628	393,372
3.5 Thermal	4,936	343,587	3,285		351,808	395,291
3.6 RF/Communication	780,928	165,224	72,519		1,018,671	1,115,001
3.7 Integrated Electronics Module (IEM)	501,228	2,341,423	24,545		2,867,196	3,202,034
3.8 Flight Software	25,226	543,080	136,403		704,710	796,854
3.9 Propulsion	3,290	13,152	3,285		19,727	22,174
3.A Spacecraft Bus Performance Assurance	99,418	226,540	145,598		471,557	532,114
4.0 Spacecraft Integration, Assembly, Test (IA&T)	12,415	64,339	302,958	132,988	512,700	600,801
5.0 Launch Checkout and Orbital Operations				237,368	237,368	287,962
6.0 Science Team	16,939	70,141	75,685	46,933	209,699	242,452
7.0 Pre-launch GDS/MOS Development	85,276	820,221	345,303	269,610	1,520,410	1,744,238
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	366	1,461	1,460	1,702	4,989	5,808

Table I-11 MESSENGER Phase C/D Cost Breakdown by WBS and Major Cost Category (Sheet 2 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	FY 2001	FY 2002	FY 2003	FY 2004	Total (FY1999 $)	Total (RY $)
Total APL Other Direct Costs	214,557	1,063,982	821,744	321,049	2,421,333	2,776,703
1.0 Project Management/Mission Analysis/System Engineering	19,147	76,531	76,473	42,906	215,058	248,056
2.0 Instruments	61,504	291,488	230,972		583,964	663,776
2.1 Mercury Dual Imaging System (MIDS)	14,768	67,070	52,473		134,310	152,612
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	9,477	49,550	38,929		97,955	111,386
2.3 Magnetometer (MAG)	4,919	21,753	17,985		44,656	50,765
2.4 Mercury Laser Altimeter (MLA)						
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)						
2.6 X-ray Spectrometer (XRS)	5,389	25,052	20,149		50,590	57,508
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	15,944	74,050	59,105		149,099	169,473
2.8 Data Processing Unit (DPU)	11,007	54,013	42,333		107,353	122,032
3.0 Spacecraft Bus	103,640	521,982	185,514		811,135	915,297
3.1 Attitude	6,135	17,833	6,620		30,587	34,405
3.2 Power	18,604	101,234	28,170		148,008	166,778
3.3 Electrical (Harness)	2,510	24,695			27,205	30,466
3.4 Mechanical	9,400	60,217	22,049		91,666	103,583
3.5 Thermal	2,510	12,539	1,671		16,719	18,755
3.6 RF/Communication	17,659	76,411	36,874		130,944	148,023
3.7 Integrated Electronics Module (IEM)	24,083	108,396	12,481		144,960	162,434
3.8 Flight Software	12,827	80,224	69,357		162,409	185,010
3.9 Propulsion	1,673	6,687	1,671		10,031	11,275
3.A Spacecraft Bus Performance Assurance	8,241	33,746	6,620		48,607	54,566
4.0 Spacecraft Integration, Assembly, Test (IA&T)	6,313	32,715	154,046	70,094	263,168	308,492
5.0 Launch Checkout and Orbital Operations				95,268	95,268	115,574
6.0 Science Team	8,613	35,665	38,484	23,864	106,627	123,281
7.0 Pre-launch GDS/MOS Development	15,154	104,859	135,513	88,051	343,577	399,274
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	186	743	742	866	2,537	2,953
Total APL Subcontracts	9,612,744	12,872,291	4,062,004	1,451,695	27,998,734	31,366,724
1.0 Project Management/Mission Analysis/System Engineering	22,394	11,931	13,777		48,102	53,715
2.0 Instruments	994,829	3,349,304	1,834,741		6,178,874	6,982,151
2.1 Mercury Dual Imaging System (MIDS)	28,661	248,269			276,930	310,000
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	147,929	391,535			539,464	600,000
2.3 Magnetometer (MAG)						
2.4 Mercury Laser Altimeter (MLA)						
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	452,575	1,731,770	1,582,287		3,766,632	4,283,128
2.6 X-ray Spectrometer (XRS)	27,737	102,333			130,070	145,000
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	282,453	661,832	252,454		1,196,739	1,344,023
2.8 Data Processing Unit (DPU)	55,473	213,565			269,038	300,000
3.0 Spacecraft Bus	8,440,345	7,483,328	990,178	89,489	17,003,340	18,803,397
3.1 Attitude	2,930,298	1,930,965			4,861,262	5,339,389
3.2 Power	1,286,059	714,114	864,770		2,864,943	3,203,221
3.3 Electrical (Harness)						
3.4 Mechanical	26,859	725,305			752,164	844,135
3.5 Thermal						
3.6 RF/Communication	2,958,583				2,958,583	3,200,000
3.7 Integrated Electronics Module (IEM)						
3.8 Flight Software						
3.9 Propulsion	1,184,639	3,996,018			5,180,656	5,771,954
3.A Spacecraft Bus Performance Assurance	53,906	116,928	125,408	89,489	385,732	444,698
4.0 Spacecraft Integration, Assembly, Test (IA&T)		54,018	890,433	590,608	1,535,059	1,816,875
5.0 Launch Checkout and Orbital Operations				656,263	656,263	796,143
6.0 Science Team						
7.0 Pre-launch GDS/MOS Development	155,176	1,973,710	332,875	115,335	2,577,096	2,914,443
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach						

Table I-11 MESSENGER Phase C/D Cost Breakdown by WBS and Major Cost Category (Sheet 3 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	FY 2001	FY 2002	FY 2003	FY 2004	Total (FY1999 $)	Total (RY $)
Total APL Indirect Costs	3,145,703	13,821,695	10,087,496	3,676,013	30,730,908	35,172,742
1.0 Project Management/Mission Analysis/System Engineering	225,212	896,460	895,702	501,652	2,519,026	2,905,420
2.0 Instruments	773,968	3,607,861	2,795,411		7,177,240	8,155,516
2.1 Mercury Dual Imaging System (MIDS)	175,642	805,947	614,554		1,596,143	1,813,241
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	119,506	604,798	455,646		1,179,951	1,340,936
2.3 Magnetometer (MAG)	57,575	255,961	210,886		524,422	596,149
2.4 Mercury Laser Altimeter (MLA)						
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	22,497	86,083	78,652		187,232	212,906
2.6 X-ray Spectrometer (XRS)	64,863	300,207	235,832		600,902	682,883
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	200,650	903,883	704,349		1,808,882	2,055,194
2.8 Data Processing Unit (DPU)	133,236	650,981	495,492		1,279,709	1,454,209
3.0 Spacecraft Bus	1,781,829	7,149,438	2,336,772	4,448	11,272,487	12,695,462
3.1 Attitude	217,458	312,910	77,908		608,276	677,811
3.2 Power	281,660	1,220,537	372,730		1,874,927	2,111,463
3.3 Electrical (Harness)	29,372	299,524			328,896	368,369
3.4 Mechanical	112,118	748,603	258,088		1,118,809	1,263,879
3.5 Thermal	32,582	172,176	29,018		233,776	262,610
3.6 RF/Communication	390,830	895,201	431,614		1,717,645	1,932,688
3.7 Integrated Electronics Module (IEM)	304,420	1,374,664	146,086		1,825,169	2,044,652
3.8 Flight Software	150,124	958,251	811,773		1,920,148	2,187,071
3.9 Propulsion	78,467	276,914	19,554		374,935	418,892
3.A Spacecraft Bus Performance Assurance	184,798	890,659	190,001	4,448	1,269,906	1,428,026
4.0 Spacecraft Integration, Assembly, Test (IA&T)	73,884	385,643	1,994,043	854,534	3,308,103	3,878,227
5.0 Launch Checkout and Orbital Operations				986,277	986,277	1,196,498
6.0 Science Team	100,808	417,492	450,404	279,009	1,247,714	1,442,578
7.0 Pre-launch GDS/MOS Development	187,828	1,356,103	1,606,476	1,039,972	4,190,379	4,864,490
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	2,176	8,698	8,689	10,120	29,683	34,550
APL Fee	967,151	2,654,610	1,498,195	550,603	5,670,559	6,446,539
APL Cost of Money	72,259	325,409	250,825	95,608	744,101	852,696
Total APL Cost	18,623,982	51,245,651	28,988,924	10,657,185	109,515,742	124,509,029
Total CIW Direct Labor Cost	32,623	131,150	132,437	83,807	380,017	438,974
6.0 Science Team	30,552	122,316	122,406	71,463	346,738	400,119
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	2,071	8,834	10,030	12,344	33,280	38,855
Total CIW Direct Material and Equipment Cost						
6.0 Science Team						
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach						
Total CIW Other Direct Costs	5,353	21,570	24,383	26,114	77,420	90,180
6.0 Science Team	2,506	9,913	9,823	5,671	27,913	32,200
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	2,848	11,657	14,560	20,443	49,507	57,980
Total CIW Subcontracts	361,218	769,651	1,004,468	478,090	2,613,428	3,008,432
6.0 Science Team	185,412	404,005	607,441	231,944	1,428,802	1,645,190
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	175,806	365,647	397,027	246,146	1,184,626	1,363,242
Total CIW Indirect Costs	19,925	79,879	80,781	51,180	231,765	267,727
6.0 Science Team	18,643	75,371	75,371	43,967	213,551	246,422
8.0 Mission Operations and Data Analysis (MO&DA)						
9.0 Education and Public Outreach	1,082	4,509	5,410	7,213	18,214	21,304
CIW Fee						
Total CIW Cost	419,119	1,002,251	1,242,069	639,191	3,302,630	3,805,313

Table I-11 MESSENGER Phase C/D Cost Breakdown by WBS and Major Cost Category (Sheet 4 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Work Breakdown Structure (WBS)/Cost Category Description	FY 2001	FY 2002	FY 2003	FY 2004	Total (FY1999 $)	Total (RY $)
Phase C/D Total Reserves	2,444,028	6,965,104	3,934,073	5,828,633	19,171,837	22,135,149
Instrument Reserves	995,715	2,792,057	1,520,614		5,308,386	5,990,108
Spacecraft Bus Reserves	1,396,662	2,889,064	731,024	9,910	5,026,660	5,622,877
Spacecraft Integration, Assembly, Test Reserves	18,174	100,062	608,316	359,151	1,085,703	1,278,083
Launch Operations (Launch + 30 days) Reserves				331,862	331,862	402,597
Pre-Launch GDS/MOS Development Reserves	33,477	294,068	217,668	138,346	683,559	788,662
Second Launch Opportunity Reserves				4,121,517	4,121,517	5,000,000
ELV Development Reserves		889,853	856,451	824,303	2,570,607	3,000,000
Mission Operations and Data Analysis (MO&DA) Reserves						
DSN Reserves				43,542	43,542	52,823
Total APL and Carnegie Cost	21,487,129	59,213,006	34,165,066	17,125,008	131,990,209	150,449,490
Total Other Costs to NASA	20,897,614	25,972,362	13,343,226	7,682,933	67,896,135	76,690,280
ELV and Launch Services	18,491,141	21,356,467	11,133,866	5,770,124	56,751,598	64,000,000
DSN and Tracking Support				435,422	435,422	528,230
Total Other Cost to NASA - NASA/GSFC	2,346,608	3,843,979	1,484,432	1,187,438	8,862,457	10,031,652
4.0 NASA/GSFC Code 549 (Spacecraft Environmental Test Facilities)				756,263	756,263	917,457
6.0 NASA/GSFC Code 691 (Science Team Support)	27,498	118,990	121,340	80,092	347,920	402,301
8.0 NASA/GSFC Code 691 (MO&DA)						
2.3 NASA/GSFC Code 695, 696 Magnetometer (MAG) Instrument	283,250	417,000	261,000		961,250	1,079,726
4.0 NASA/GSFC Code 695, 696 Spacecraft Integation, Assembly, Test			87,000	154,000	241,000	288,406
5.0 NASA/GSFC Code 695, 696 Launch Checkout/Orbital Operations				154,000	154,000	186,824
6.0 NASA/GSFC Code 695, 696 Science Team Support	9,000	36,000	36,000	25,000	106,000	122,553
8.0 NASA/GSFC Code 695, 696 (MO&DA)						
2.4 NASA/GSFC Code 920 Mercury Laser Altimeter (MLA) Instrument	2,026,860	3,271,989	711,069		6,009,918	6,699,500
4.0 NASA/GSFC Code 920 Spacecraft Integation, Assembly, Test			237,023		237,023	276,750
5.0 NASA/GSFC Code 920 Launch Checkout/Orbital Operations						
6.0 NASA/GSFC Code 920 Science Team Support			31,000	18,083	49,083	58,133
8.0 NASA/GSFC Code 920 (MO&DA)						
Total Other Cost to NASA - NASA/JPL	59,865	771,916	724,928	289,949	1,846,658	2,130,398
1.0 NASA/JPL TMOD/AMMOS (Navigation)	59,865	240,260	256,935	289,949	847,009	986,500
3.2 NASA/JPL Environmental Test (Solar Array Qualification)		531,656	467,993		999,649	1,143,898
TOTAL COST FOR PHASE C/D	42,384,743	85,185,368	47,508,292	24,807,942	199,886,344	227,139,770

Table I-12 MESSENGER Phase E Staffing by WBS and Major Cost Category

(Staffing in Staff Year per Year (SY/Y))

Work Breakdown Structure (WBS)/Cost Category Description	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Phase Average
Total Staffing	28.8	25.3	25.3	27.3	34.2	42.0	45.0	22.5	31.5
1.0 Project Management/Mission Analysis/System Engineering	7.4	5.2	4.9	4.8	4.7	4.7	5.2	1.0	4.5
Project Manager	.2	.2	.2	.2	.2	.2	.2	.2	.2
Mission System Engineer	.3	.3	.3	.3	.3	.3	.3	.3	.3
Mission Manager	.2	.2	.2	.2	.2	.2	.2	.2	.2
Performance Assurance Engineer	.0	.0	.0	.0	.0	.0	.0	.0	.0
Other	6.7	4.5	4.2	4.1	4.0	4.0	4.5	.3	3.8
2.0 Instruments	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.1 Mercury Dual Imaging System (MDIS)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.2 Gamma-ray and Neutron Spectrometer (GRNS)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.3 Magnetometer (MAG)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.4 Mercury Laser Altimeter (MLA)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.6 X-ray Spectrometer (XRS)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.7 Energetic Particle and Plasma Spectrometer (EPPS)	.0	.0	.0	.0	.0	.0	.0	.0	.0
2.8 Data Processing Unit (DPU)	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.0 Spacecraft Bus	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.1 Attitude	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.2 Power	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.3 Electrical (Harness)	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.4 Mechanical	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.5 Thermal	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.6 RF/Communication	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.7 Integrated Electronics Module (IEM)	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.8 Flight Software	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.9 Propulsion	.0	.0	.0	.0	.0	.0	.0	.0	.0
3.A Spacecraft Bus Performance Assurance	.0	.0	.0	.0	.0	.0	.0	.0	.0
4.0 Spacecraft Integration, Assembly, Test (IA&T)	.0	.0	.0	.0	.0	.0	.0	.0	.0
5.0 Launch Checkout and Orbital Operations	.0	.0	.0	.0	.0	.0	.0	.0	.0
6.0 Science Team	.0	.0	.0	.0	.0	.0	.0	.0	.0
Principal Investigator	.0	.0	.0	.0	.0	.0	.0	.0	.0
Project Scientist	.0	.0	.0	.0	.0	.0	.0	.0	.0
Science Payload Manager	.0	.0	.0	.0	.0	.0	.0	.0	.0
Other	.0	.0	.0	.0	.0	.0	.0	.0	.0
7.0 Pre-launch GDS/MOS Development	.0	.0	.0	.0	.0	.0	.0	.0	.0
8.0 Mission Operations and Data Analysis (MO&DA)	20.1	18.8	19.2	21.2	28.2	36.0	38.6	21.6	25.9
Principal Investigator	.3	.3	.3	.3	.3	.3	.3	.3	.3
Project Scientist	.5	.5	.5	.5	.9	.9	.9	.5	.7
Science Payload Manager	.2	.2	.2	.2	.2	.2	.2	.2	.2
Other	19.1	17.8	18.2	20.2	26.8	34.6	37.2	20.6	24.7
9.0 Education and Public Outreach	1.3	1.3	1.2	1.3	1.3	1.3	1.2	.0	1.1
TOTAL STAFFING FOR PHASE E	28.8	25.3	25.3	27.3	34.2	42.0	45.0	22.5	31.5

NOTES:

1. Staffing levels include Principal Investigator, Co-Investigators, and Science Team members
2. Staffing levels include civil service labor
3. Staffing levels include JPL TMOD/Navigation Team, government-furnished instruments (part of MAG and all of MLA), and procured instruments (all of ASCS and part of EPPS)
4. Staffing levels for other procurements (e.g., hardware, software, etc.) or government-furnished services (e.g., ELV, DSN, etc.) are not included
5. Phase average figures reflect weighting by the actual number of months in each FY for a given mission phase

Table I-13 MESSENGER Phase E Cost Breakdown by WBS and Major Cost Category (Sheet 1 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

reakdown Structure (WBS)/Cost Category Description	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Total (FY1999 $)	Total (RY $)
PL Direct Labor Cost	748,812	1,441,072	1,434,096	1,463,573	1,749,614	2,050,422	2,294,432	861,050	12,043,071	16,946,890
Project Management/Mission Analysis/System Engineering	182,210	238,695	224,734	224,544	216,281	216,089	215,909	94,986	1,613,447	2,225,079
nstruments										
2.1 Mercury Dual Imaging System (MIDS)										
2.2 Gamma-ray and Neutron Spectrometer (GRNS)										
2.3 Magnetometer (MAG)										
2.4 Mercury Laser Altimeter (MLA)										
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)										
2.6 X-ray Spectrometer (XRS)										
2.7 Energetic Particle and Plasma Spectrometer (EPPS)										
2.8 Data Processing Unit (DPU)										
Spacecraft Bus										
3.1 Attitude										
3.2 Power										
3.3 Electrical (Harness)										
3.4 Mechanical										
3.5 Thermal										
3.6 RF/Communication										
3.7 Integrated Electronics Module (IEM)										
3.8 Flight Software										
3.9 Propulsion										
3.A Spacecraft Bus Performance Assurance										
Spacecraft Integration, Assembly, Test (IA&T)										
Launch Checkout and Orbital Operations										
Science Team										
Pre-launch GDS/MOS Development										
Mission Operations and Data Analysis (MO&DA)	558,504	1,192,667	1,199,661	1,229,337	1,523,649	1,824,858	2,068,858	766,064	10,363,395	14,631,197
Education and Public Outreach	8,098	9,710	9,701	9,693	9,684	9,676	9,668		66,229	90,614
APL Direct Material and Equipment Cost	385,898	143,042	142,573	253,168	353,488	146,635	147,891	5,830	1,578,524	2,129,739
Project Management/Mission Analysis/System Engineering	1,234	1,616	1,522	1,520	1,464	1,463	1,462	643	10,924	15,065
) Instruments										
2.1 Mercury Dual Imaging System (MIDS)										
2.2 Gamma-ray and Neutron Spectrometer (GRNS)										
2.3 Magnetometer (MAG)										
2.4 Mercury Laser Altimeter (MLA)										
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)										
2.6 X-ray Spectrometer (XRS)										
2.7 Energetic Particle and Plasma Spectrometer (EPPS)										
2.8 Data Processing Unit (DPU)										
0 Spacecraft Bus										
3.1 Attitude										
3.2 Power										
3.3 Electrical (Harness)										
3.4 Mechanical										
3.5 Thermal										
3.6 RF/Communication										
3.7 Integrated Electronics Module (IEM)										
3.8 Flight Software										
3.9 Propulsion										
3.A Spacecraft Bus Performance Assurance										
.0 Spacecraft Integration, Assembly, Test (IA&T)										
.0 Launch Checkout and Orbital Operations										
.0 Science Team										
.0 Pre-launch GDS/MOS Development										
.0 Mission Operations and Data Analysis (MO&DA)	384,609	141,360	140,986	251,582	351,958	145,107	146,364	5,187	1,567,152	2,114,060
.0 Education and Public Outreach	55	66	66	66	66	66	65		448	613

Table I-13 MESSENGER Phase E Cost Breakdown by WBS and Major Cost Category (Sheet 2 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

reakdown Structure (WBS)/Cost Category Description	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Total (FY1999 $)	Total (RY $)
PL Other Direct Costs	74,526	143,424	142,730	145,664	174,132	204,070	228,356	85,697	1,198,600	1,686,657
Project Management/Mission Analysis/System Engineering	18,135	23,756	22,367	22,348	21,526	21,506	21,489	9,454	160,580	221,453
Instruments										
2.1 Mercury Dual Imaging System (MIDS)										
2.2 Gamma-ray and Neutron Spectrometer (GRNS)										
2.3 Magnetometer (MAG)										
2.4 Mercury Laser Altimeter (MLA)										
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)										
2.6 X-ray Spectrometer (XRS)										
2.7 Energetic Particle and Plasma Spectrometer (EPPS)										
2.8 Data Processing Unit (DPU)										
Spacecraft Bus										
3.1 Attitude										
3.2 Power										
3.3 Electrical (Harness)										
3.4 Mechanical										
3.5 Thermal										
3.6 RF/Communication										
3.7 Integrated Electronics Module (IEM)										
3.8 Flight Software										
3.9 Propulsion										
3.A Spacecraft Bus Performance Assurance										
Spacecraft Integration, Assembly, Test (IA&T)										
Launch Checkout and Orbital Operations										
Science Team										
Pre-launch GDS/MOS Development										
Mission Operations and Data Analysis (MO&DA)	55,586	118,701	119,398	122,351	151,643	181,601	205,905	76,243	1,031,428	1,456,186
Education and Public Outreach	806	966	965	965	964	963	962		6,591	9,018
APL Subcontracts	225,305	152,719	31,770	286,613	93,795	93,763	157,677	60,585	1,102,228	1,504,468
Project Management/Mission Analysis/System Engineering										
Instruments										
2.1 Mercury Dual Imaging System (MIDS)										
2.2 Gamma-ray and Neutron Spectrometer (GRNS)										
2.3 Magnetometer (MAG)										
2.4 Mercury Laser Altimeter (MLA)										
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)										
2.6 X-ray Spectrometer (XRS)										
2.7 Energetic Particle and Plasma Spectrometer (EPPS)										
2.8 Data Processing Unit (DPU)										
) Spacecraft Bus										
3.1 Attitude										
3.2 Power										
3.3 Electrical (Harness)										
3.4 Mechanical										
3.5 Thermal										
3.6 RF/Communication										
3.7 Integrated Electronics Module (IEM)										
3.8 Flight Software										
3.9 Propulsion										
3.A Spacecraft Bus Performance Assurance										
0 Spacecraft Integration, Assembly, Test (IA&T)										
0 Launch Checkout and Orbital Operations										
0 Science Team										
0 Pre-launch GDS/MOS Development										
0 Mission Operations and Data Analysis (MO&DA)	225,305	152,719	31,770	286,613	93,795	93,763	157,677	60,585	1,102,228	1,504,468
0 Education and Public Outreach										

Table I-13 MESSENGER Phase E Cost Breakdown by WBS and Major Cost Category (Sheet 3 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Breakdown Structure (WBS)/Cost Category Description	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Total (FY1999 $)	Total (RY $)
APL Indirect Costs	738,446	1,377,357	1,364,725	1,410,763	1,676,641	1,950,797	2,184,768	817,497	11,520,994	16,205,362
) Project Management/Mission Analysis/System Engineering	172,356	225,787	212,581	212,401	204,584	204,403	204,233	89,850	1,526,193	2,104,748
) Instruments										
2.1 Mercury Dual Imaging System (MIDS)										
2.2 Gamma-ray and Neutron Spectrometer (GRNS)										
2.3 Magnetometer (MAG)										
2.4 Mercury Laser Altimeter (MLA)										
2.5 Atmospheric and Surface Composition Spectrometer (ASCS)										
2.6 X-ray Spectrometer (XRS)										
2.7 Energetic Particle and Plasma Spectrometer (EPPS)										
2.8 Data Processing Unit (DPU)										
) Spacecraft Bus										
3.1 Attitude										
3.2 Power										
3.3 Electrical (Harness)										
3.4 Mechanical										
3.5 Thermal										
3.6 RF/Communication										
3.7 Integrated Electronics Module (IEM)										
3.8 Flight Software										
3.9 Propulsion										
3.A Spacecraft Bus Performance Assurance										
) Spacecraft Integration, Assembly, Test (IA&T)										
) Launch Checkout and Orbital Operations										
) Science Team										
) Pre-launch GDS/MOS Development										
) Mission Operations and Data Analysis (MO&DA)	558,430	1,142,385	1,142,968	1,189,194	1,462,896	1,737,242	1,971,391	727,647	9,932,153	14,014,900
) Education and Public Outreach	7,660	9,185	9,176	9,168	9,160	9,152	9,145		62,647	85,713
PL Fee	119,514	179,169	171,374	195,788	222,622	244,513	275,722	100,686	1,509,388	2,116,021
PL Cost of Money	19,118	36,259	36,011	36,971	44,076	51,482	57,631	21,598	303,147	426,502
APL Cost	2,311,620	3,473,041	3,323,280	3,792,539	4,314,368	4,741,683	5,346,477	1,952,943	29,255,952	41,015,639
CIW Direct Labor Cost	58,073	133,693	128,659	134,740	139,287	139,827	157,060	123,078	1,014,420	1,427,979
) Science Team										
) Mission Operations and Data Analysis (MO&DA)	51,032	122,590	122,677	122,756	122,836	122,917	122,997	123,078	910,883	1,281,214
) Education and Public Outreach	7,042	11,103	5,982	11,984	16,452	16,911	34,064		103,537	146,765
CIW Direct Material and Equipment Cost										
) Science Team										
) Mission Operations and Data Analysis (MO&DA)										
) Education and Public Outreach										
CIW Other Direct Costs	5,218	23,127	11,767	13,883	21,630	21,091	48,939	9,151	154,804	220,540
) Science Team										
) Mission Operations and Data Analysis (MO&DA)	4,064	9,639	9,552	9,473	9,393	9,313	9,232	9,151	69,818	98,040
) Education and Public Outreach	1,154	13,487	2,214	4,410	12,237	11,778	39,707		84,986	122,500
CIW Subcontracts	559,224	857,311	796,559	1,101,850	1,351,450	1,507,086	1,632,428	890,417	8,696,324	12,329,180
) Science Team										
) Mission Operations and Data Analysis (MO&DA)	460,394	585,816	601,555	852,966	1,154,966	1,251,202	1,369,456	890,417	7,166,772	10,218,052
) Education and Public Outreach	98,830	271,495	195,004	248,884	196,484	255,884	262,972		1,529,553	2,111,128
CIW Indirect Costs	33,206	80,781	77,174	78,977	81,682	81,682	91,600	75,371	600,475	845,413
) Science Team										
) Mission Operations and Data Analysis (MO&DA)	31,404	75,371	75,371	75,371	75,371	75,371	75,370	75,371	558,999	786,175
) Education and Public Outreach	1,804	5,410	1,803	3,607	6,311	6,311	16,230		41,475	59,238
W Fee										
CIW Cost	655,723	1,094,912	1,014,158	1,329,450	1,594,049	1,749,687	1,930,027	1,098,017	10,486,023	14,823,113

Table I-13 MESSENGER Phase E Cost Breakdown by WBS and Major Cost Category (Sheet 4 of 4)

(Phased costs in Fixed FY1999 Year Dollars, Totals in Fixed FY1999 and Real Year Dollars)

Breakdown Structure (WBS)/Cost Category Description	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Total (FY1999 $)	Total (RY $)
e E Total Reserves	147,786	243,353	230,586	297,380	356,310	437,019	720,018	200,421	2,632,872	3,755,000
strument Reserves										
pacecraft Bus Reserves										
pacecraft Integration, Assembly, Test Reserves										
unch Operations (Launch + 30 days) Reserves										
e-Launch GDS/MOS Development Reserves										
econd Launch Opportunity Reserves										
LV Development Reserves										
ission Operations and Data Analysis (MO&DA) Reserves	126,462	199,843	197,034	232,511	282,601	336,302	386,298	200,421	1,961,472	2,780,616
SN Reserves	21,324	43,510	33,552	64,869	73,708	100,717	333,720		671,400	974,383
APL and Carnegie Cost	3,115,128	4,811,307	4,568,024	5,419,369	6,264,727	6,928,388	7,996,523	3,251,381	42,354,847	59,593,751
l Other Costs to NASA	507,968	1,181,631	1,094,759	1,379,236	1,627,260	2,442,466	5,102,179	1,165,490	14,500,989	20,939,313
LV and Launch Services										
SN and Tracking Support	213,237	435,100	335,516	648,691	737,083	1,007,168	3,337,200		6,713,995	9,743,832
otal Other Cost to NASA - NASA/GSFC	87,625	274,480	321,710	310,170	470,020	1,020,020	1,296,490	1,165,490	4,946,005	7,285,231
4.0 NASA/GSFC Code 549 (Spacecraft Environmental Test Facilities)										
6.0 NASA/GSFC Code 691 (Science Team Support)										
8.0 NASA/GSFC Code 691 (MO&DA)	57,208	143,480	118,710	97,170	95,020	95,020	155,490	155,490	917,588	1,295,712
2.3 NASA/GSFC Code 695, 696 Magnetometer (MAG) Instrument										
4.0 NASA/GSFC Code 695, 696 Spacecraft Integation, Assembly, Test										
5.0 NASA/GSFC Code 695, 696 Launch Checkout/Orbital Operations										
6.0 NASA/GSFC Code 695, 696 Science Team Support										
8.0 NASA/GSFC Code 695, 696 (MO&DA)	17,500	40,000	50,000	50,000	111,000	168,000	189,000	189,000	814,500	1,197,011
2.4 NASA/GSFC Code 920 Mercury Laser Altimeter (MLA) Instrument										
4.0 NASA/GSFC Code 920 Spacecraft Integation, Assembly, Test										
5.0 NASA/GSFC Code 920 Launch Checkout/Orbital Operations										
6.0 NASA/GSFC Code 920 Science Team Support										
8.0 NASA/GSFC Code 920 (MO&DA)	12,917	91,000	153,000	163,000	264,000	757,000	952,000	821,000	3,213,917	4,792,508
otal Other Cost to NASA - NASA/JPL	207,106	472,051	437,533	420,375	420,157	415,278	468,489		2,840,989	3,910,250
1.0 NASA/JPL TMOD/AMMOS (Navigation)	207,106	472,051	437,533	420,375	420,157	415,278	468,489		2,840,989	3,910,250
3.2 NASA/JPL Environmental Test (Solar Array Qualification)										
AL COST FOR PHASE E	3,623,096	5,992,938	5,662,783	6,798,605	7,891,987	9,370,854	13,098,702	4,416,871	56,855,836	80,533,064

APPENDIX A

RESUMES

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SEAN CARL SOLOMON

Current Position Director, Department of Terrestrial Magnetism, Carnegie Institution of Washington

Education B.S. (Geophysics with honor), California Institute of Technology, 1966
Ph.D. (Geophysics), Massachusetts Institute of Technology, 1971

Positions Held Assistant Professor of Geophysics, MIT, 1972-1977
Associate Professor of Geophysics, MIT, 1977-1983
Professor of Geophysics, MIT, 1983-1992
Director, DTM, Carnegie Institution of Washington, 1992-present

Honors and Awards

Tau Beta Pi, 1965; National Science Foundation Graduate Fellow, 1966-1968; Fannie and John Hertz Foundation Fellow, 1968-1971; National Science Foundation Postdoctoral Fellow, 1971-1972; Alfred P. Sloan Research Fellow, 1977-1981; Fellow, American Geophysical Union, 1980; John Simon Guggenheim Memorial Fellow, 1982-1983; Fellow, American Academy of Arts and Sciences, 1995; Fellow, American Association for the Advancement of Science, 1995; Fellow, Geological Society of America, 1997; Arthur L. Day Prize and Lectureship, National Academy of Sciences, 1999.

Relevant Experience

Magellan (previously Venus Orbiting Imaging Radar and Venus Radar Mapper): Project Science Group and Radar Investigation Group, 1982-94; Mars Global Surveyor (previously Mars Observer): Mars Orbital Laser Altimeter Team, 1986-present.

Professional Service (last 12 months)

President, American Geophysical Union, 1996-98; Solar System Exploration Subcommittee, Space Science Advisory Committee, NASA, 1996-99; Earth Systems Science and Applications Advisory Committee, NASA, 1998–99; Task Force on MO&DA and R&A, Space Science Advisory Committee, NASA 1997-98; Visiting Committee, National Astronomy and Ionosphere Center, Cornell University 1995-98; Visiting Committee, Earth and Planetary Sciences, Harvard University 1993-99; Chair, Academic Review Committee, Department of Geosciences, Princeton University 1998; Chair, External Review Committee, MIT/WHOI Joint Program in Oceanography and Applied Ocean Science and Engineering 1998; Chair, Earth and Environmental Sciences Directorate Review Committee, Lawrence Livermore National Laboratory, 1998–99.

Selected Publications (from more than 150 in refereed journals)

Solomon, S. C., Some aspects of core formation in Mercury, *Icarus, 28,* 509-521, 1976.

Solomon, S. C., The relationship between crustal tectonics and internal evolution in the Moon and Mercury, *Phys. Earth Planet. Inter., 15,* 135-145, 1977.

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Solomon, S. C. et al., Venus tectonics: An overview of Magellan observations, *J. Geophys. Res., 97,* 13199-13255, 1992.

SEAN CARL SOLOMON

Roles and Responsibilities

As Principal Investigator has overall responsibility for design, execution, and success of the mission, with responsibility to report on project progress and status to NASA. Leads preparation of a Science Plan. Serves as Co-Chair of all Science Team meetings with Project Scientist, as well as ex-officio member of each Science Team group. Leads overall scientific analysis effort and participates in interpretation of imaging and geochemical measurements to determine volcanic and tectonic history, and in analysis of gravity and topography data and physical libration measurements to determine planetary internal structure, state of the core, and planetary thermal history.

9 March 1999

Date

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MARIO H. ACUÑA

Current Position Research Staff, Goddard Space Flight Center

Education Ph.D. (Space Science), Catholic University, 1974
MSEE, University of Tucumann, Argentina, 1967

Relevant Experience

US Project Scientist for the ISTP Program (an international research effort by Japan, Europe, and the US involving more than 300 investigators and multiple spacecraft); Principal Investigator or Lead Scientist for the magnetometer investigations on the Near Earth Asteroid Rendezvous Mission and the Mars Global Surveyor. Associate Investigator, MAG Team; Project Scientist, NASA ISTP Project; Principal/Co-Investigator/Instrument Scientist for more than 12 spacecraft including Voyager, and more than 150 rockets.

Professional Societies

Member of AGU, IEEE, Sigma Xi, The Scientific Research Society

Honors and Awards

NASA Group Achievement Awards, NASA Exceptional Service Medal, GSFC Senior Fellow, GSFC Moe I. Schneebaum Memorial Award, the Medal for Exceptional Scientific Achievement, and the Exceptional Service Medal in recognition for his contributions to magnetometry and space research.

Selected Publications

Acuña, M. H., First results from the Giotto magnetometer experiment during the P/Grigg-Skjellerup encounter, *Astrono. and Astrophys., 268,* 5-8, 1992.

Acuña, M. H., Mars Observer magnetic fields investigation, *J. Geophys. Res., 97,* 7799-7814, 1992.

Acuña, M. H., et al., The Global Geospace Science Program and its investigators, *Space Sci. Rev., 72,* 5-21, 1995.

Acuña, M. H., L. J. Zanetti, and C. T. Russell, Near Earth Asteroid Rendezvous magnetometer, *Lunar Planet. Sci.*, 3-4, 1995.

McNutt, Jr., R. L., R. E. Gold, E. P. Keath, D. M. Rust, S. M. Krimigis, L. J. Zanetti, C. E. Willey, B. D. Williams, W. S. Kurth, D. A. Gurnett, M. H. Acuña, L. F. Burlaga, G. Gloeckler, F. M. Ipavich, A. J. Lazarus, J. T. Steinberg, G. Brückner, D. Socker, T. E. Holzer, P. A. Bochsler, R. Kallenbach, and A. Roux, An ADvanced SOlar Probe Experiment Module (AD SOLEM), *Proc. SPIE International Symposium, Optical Science, Engineering, and Instrumentation - Mission to the Sun, 2804,* 1-13, 1996.

Acuña, M. H., C. T. Russell, L. J. Zanetti, and B. J. Anderson, The NEAR magnetic field investigation: Science objectives at asteroid Eros 433 and experimental approach, *J. Geophys. Res., 102,* 23751-23759, 1997.

Lohr, D. A., L. J. Zanetti, B. J. Anderson, T. A. Potemra, J. R. Hayes, R. E. Gold, R. M. Henshaw, F. F. Mobley, D. B. Holland, M. H. Acuña, and J. L. Scheifele, NEAR magnetic field investigation, instrumentation, spacecraft magnetics and data access, *Space Sci. Rev., 82,* 255-281, 1997.

Lohr, D. A., L. J. Zanetti, B. J. Anderson, T. A. Potemra, and M. H. Acuña, The NEAR magnetic field instrument, *JHU/APL Tech. Dig., 19, 2,136-141,* April-June 1998.

MARIO H. ACUÑA

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and shares in the oversight of the design, fabrication, and testing of the magnetometer, the sensor and analog electronics for which will be supplied by GSFC. Participates in the analysis of magnetometer data for magnetic field structure and magnetospheric processes.

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DANIEL N. BAKER

Current Position Professor of Astrophysical and Planetary Sciences
Director, Laboratory for Atmospheric and Space Physics, University of Colorado

Education B.A. (with Honors) University of Iowa, 1969
M.S. University of Iowa, 1973
Ph.D. University of Iowa, 1974

Positions Held

1967-1969: Research Aide, Dept. of Physics and Astronomy (U of Iowa); 1970-1974: Graduate Research Assistant, Dept. of Physics and Astronomy (U of Iowa); 1974-1975: Research Associate, Dept. of Physics and Astronomy (U of Iowa); 1975-1977: Research Fellow, Div. of Physics, Mathematics, and Astronomy (California Institute of Technology); 1977-1981: Staff Member, Los Alamos Scientific Laboratory; 1981-1987: Group Leader, Space Plasma Physics, Earth and Space Science Division, Los Alamos National Laboratory; 1987-1994: Laboratory Chief, Laboratory for Extraterrestrial Physics, Space Sciences Directorate, NASA/Goddard Space Flight Center; 1994-present: Director, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder.

Honors and Awards

Space Studies Board Service Commendation 1986; Selected to U.S. Senior Executive Service 1987; NASA Group Achievement Award 1989, 1993; Senior Executive Excellence Award 1992; GSFC Outstanding Performance Award 1993; NASA Scientific Group Achievement Award 1994; Elected to International Academy of Astronautics 1993; Elected as Fellow of American Geophysical Union 1994; Am. Assoc. Pub. Award, 1998.

Relevant Experience

Spacecraft instrumental design and calibration, space physics data analysis, and magnetospheric modeling. Studied plasma physical and energetic particle phenomena in the magnetospheres of Jupiter and Mercury, and has studied extensively the plasma sheet and magnetopause boundary regions of the Earth's magnetosphere. Experience in the analysis of large data sets from spacecraft at geostationary orbit and involved in missions to the Earth's deep magnetotail and comets, in the study of solar wind-magnetospheric energy coupling, and in theoretical modeling of the role of heavy ions in the development of magnetotail instabilities. Presently working on magnetosphere-atmosphere coupling and applying space plasma physics to the study of astrophysical systems. Devoted recent research effort to understanding magnetospheric substorms. Has shown how these disturbances contribute to anomalies in operation of near-Earth spacecraft and has developed nonlinear (chaos) models of substorm processes. Presently on the National Academy of Sciences Space Science Board. Served on Committee on Solar and Space Physics, Board on Atmospheric Sciences and Climate Panel on Long-Term Observations, NASA Management and Operations Working Group, and Committee on Data Management and Computation.

Selected Publications (from over 300 scientific papers)

Baker, D. N., R. D. Zwickl, J. F. Carbary, S. M. Krimigis, and M. H. Acuña, Energetic particle transport in the upstream region of Jupiter, *J. Geophys. Res., 89,* 3775, 1984.

Baker, D. N., Jovian electron populations in the magnetosphere of Mercury, *Geophys. Res. Lett., 13,* 789, 1986.

Baker, D. N., J. E. Borovsky, J. O. Burns, G. R. Gisler, and M. Zeilik, Possible calorimetric effects at Mercury due to solar wind-magnetosphere interactions, *J. Geophys. Res., 92,* 4707, 1987.

Baker, D. N. and J. A. Slavin, The Mercury Dual Orbiter Mission, in *Particle Astrophysics, Proc. AIP Conference, 203* (Amer. Inst. Phys.), 111, New York, 1990.

Baker, D. N., Energy coupling in the magnetospheres of Earth and Mercury, *Adv. Space Res., 10,* (S)23, 1990.

Baker, D. N., Clementine particle measurements in lunar orbit, *Adv. Space Rev., 19,* 1587, 1997.

DANIEL N. BAKER

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and participates in the analysis of MAG, EPPS and UVVS data. Leads effort to characterize magnetospheric processes from an integration of these observations.

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WILLIAM V. BOYNTON

Current Position Professor, University of Arizona

Education B.A. (Chemistry), Wesleyan University, 1966
Ph.D (Physical Chemistry), Carnegie-Mellon University, 1971

Positions Held Professor, Dept. of Planetary Sciences, University of Arizona, 1987-present
Associate Professor, Department of Planetary Sciences, 1981-1987
Assistant Professor, Department of Planetary Sciences, 1977-1981
Assistant Research Geochemist, University of California/LA, 1974-1977
Research Associate, Oregon State University, 1971-1974

Relevant Experience

Mars Global Surveyor: Team Leader, Gamma-Ray Spectrometer; Comet Rendezvous/Astroid Flyby Mission: Principal Investigator, Comet Penetrator-Lander; Near Earth Asteroid Rendezvous (NEAR) X-Ray/Gamma-Ray Spectrometer Science Team; Member, Curation and Analysis Planning Team for Extraterrestrial Materials, 1993-present; Member, Lunar and Planetary Sample Team, NASA Advisory Committee, 1993-present; Member, Small Bodies Science Working Group, NASA Advisory Committee, 1992-present; Member, Mars Environmental Survey (MESUR) Science Definition Team, 1991-present; Principal Investigator, Comet Penetrator-Lander, Comet Rendezvous/Asteroid Flyby Mission, 1986-1990; Team Leader, Mars Observer Gamma Ray Spectrometer, 1986-1994; National Research Council, Senior Research Fellowship, 1984; Member, Joint NASA/ESA Science Advisory Group-Primitive Body Mission Study, 1984-1986; Member, Space Science Board Study on Major Directions for Space Science: 1995-2015, 1984-1986; Member, Comet Rendezvous Science Working Group - NASA Advisory Committee, 1983-1985; Group Chief, Lunar and Planetary Geosciences Review Panel, 1984-1985; Member, Committee on Planetary and Lunar Exploration of the Space Science Board - NAS/NRC Advisory Committee, 1980-1983; Member, Lunar and Planetary Sample Team, NASA Advisory Committee, 1979-1982; Member, Meteorite Working Group-NSF Advisory Committee, 1978-1983.

Honors and Awards

NASA Group Achievement Award for Payload Development, Mars Observer Gamma Ray Spectrometer, 1993, NASA Group Achievement Award, 1982.

Professional Societies

Elected Fellow of the Meteoritical Society, 1980

Selected Publications

Hildebrand, A. R., G. T. Penfield, D. A. Kring, M. Pilkington, A. Camargo, Z. S. Jacobsen, and W. V. Boynton, The Chicxulub Crater: A possible Cretaceous-Tertiary boundary impact crater on the Yucatan Peninsula, Mexico, *Geology 19,* 867-871, 1991.

Palme, H. and W. V. Boynton, Meteoritic constraints on conditions in the solar nebula, in *Protostars and Planets III,* E. H. Levy, J. I. Lunine, and M. S. Matthews (eds.), University of Arizona Press, 979-1004, 1992.

Feldman, W. C., W. V. Boynton, and D. Drake, Planetary neutron spectroscopy from orbit, in *Remote Geochemical Analyses, C.* Pieters and P. Englert (eds.), Cambridge University Press, 213-234, 1993.

Feldman, W. C., R. C. Byrd, B. L. Barraclough, J. E. Nordholt, H. O. Funsten, W. V. Boynton, S. H. Bailey, and J. Moersch, Calibration of a space thermal/epithermal neutron detector: The Mars Observer gamma-ray spectrometer anticoincidence shield, *Nuclear Instruments and Methods in Physical Research,* Section A 362, 561-573, 1995.

WILLIAM V. BOYNTON

Roles and Responsibilities

Chair of the Geochemistry (GC) Group and participates in the selection of detector heads for γ-ray/neutron and X-ray spectrometers, and in the integration, characterization, and calibration of the detectors. Leads the analysis of γ-ray/neutron and X-ray measurements for surface chemistry and exploring the implications for planetary formational processes.

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CLARK R. CHAPMAN

Current Position Institute Scientist, Southwest Research Institute

Education
A.B. (Astronomy), Harvard College, 1967
M.S. (Meteorology), Massachusetts Institute of Technology, 1968
Ph.D. (Planetary Science), Massachusetts Institute of Technology, 1972

Positions Held
Southwest Research Institute, 1996-present
Planetary Science Institute, SAIC, 1971-1996

Relevant Experience

Galileo Imaging Science Team (1977-present); Near Earth Asteroid Rendezvous (NEAR) Mission (MSI/NIS Imaging/Spectroscopy Team; 1994-present); Principal Investigator of numerous NASA and NSF research grants in Planetary Astronomy, Planetary Geology and Geophysics, etc.; Served on COMPLEX; many NASA advisory committees, MOWG's, and SWG's.

Professional Societies

American Astronomical Society Division for Planetary Sciences, Chairman (1982-1983); American Geophysical Union, Editor, *Journal of Geophysical Research-Planets* (1991-1994); American Association for the Advancement of Science; Meteoritical Society, Chairman of Leonard Medal Committee (1983-1984); Council Member (1992-1996); International Astronomical Union (elected 1976) President, Commission 15 (1982-1985).

Selected Publications (technical and popular, from hundreds)

Chapman, C. R., *The Inner Planets: New Light on the Rocky Worlds of Mercury, Venus, Earth, the Moon, Mars, and the Asteroids,* Scribner's, 1977.

Chapman, C. R., Contributor, chapter on Mercury: The Sun's Closest Companion, *The Planets,* Bantam Books, #11 on B. Dalton's Bestseller List, 1985.

Chapman, C. R., Solar System Exploration: Discovering our Origins and Destiny, *NASA Brochure,* 1988.

Chapman, C. R., S-type asteroids, ordinary chondrites, and space weathering: The evidence from Galileo's Fly-bys of Gaspra and Ida, *Meteoritics and Planet. Sci., 31,6,* 699-725, 1996.

Chapman, C. R. et al., Preliminary results of Galileo direct imaging of S-L 9 impacts, *Geophys. Res. Lett., 22,* 1561-1564, 1995.

Chapman, C. R. et al., Discovery and physical properties of Dactyl, a satellite of asteroid 243 Ida, *Nature, 374,* 783-785, 1995.

Belton, M. J. S., C. R. Chapman, *et al.,* First images of asteroid 243 Ida, *Science, 265,* 1543-1547, 1994.

Chapman, C. R., A clean, well-lighted place - Mercury, *The Planetary Report 11 (September-October),* 8-11, 1991.

Chapman, C. R., Mercury's heart of iron, *Astronomy, 16 (11),* 20-35, 1988.

Leake, M. A., C. R. Chapman, S. J. Weidenschilling, D. R. Davis, R. Greenberg, The chronology of Mercury's geological and geophysical evolution: The vulcanoid hypothesis, *Icarus 71,* 350-375, 1987.

Dollfus, A., C. R. Chapman, M. E. Davies, O. Gingerich, R. Goldstein, J. Guest, D. Morrison, B. A. Smith, IAU nomenclature for albedo features on the planet Mercury, *Icarus, 34,* 210-214, 1978.

Chapman, C. R., Chronology of terrestrial planet evolution: Evidence from Mercury, *Icarus, 29,* 523-536, 1976.

Chapman, C. R., Optical evidence on the rotation of Mercury, *Earth Plan. Sci. Lett., 3,* 381-385,1967.

Vilas, F., C. R. Chapman, and M. S. Matthews (eds), *Mercury*, Univ. of Arizona Press, 1988.

CLARK R. CHAPMAN

Roles and Responsibilities

Member of the Geology (GG) Group and participates in the analysis of imaging and IR spectral measurements of the surface. Leads the interpretation of the impact cratering record. Science Team Liaison to the Education and Public Outreach team.

Clark R. Chapman (signature) 2/25/99

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ANDREW F. CHENG

Current Position	Physicist, Principal Professional Staff The Johns Hopkins University Applied Physics Laboratory
Education	B.S. (Physics), Princeton University, 1971 M.S. (Physics), Columbia University, 1974 Ph.D. (Physics), Columbia University, 1977
Positions Held	Supervisor, Theoretical Space Physics Section, 1984-Present Principal Professional Staff, 1986; Senior Physicist, 1983-1984 Assistant Professor, Dept. of Physics and Astronomy, Rutgers Univ., 1978-1983 Postdoctoral Fellow, Bell Laboratories, 1976-1978

Relevant Experience

Project Scientist for the Near Earth Asteroid Rendezvous mission; Interdisciplinary Scientist for Galileo mission; Co-Investigator for MIMI investigation on CASSINI mission.

Honors and Awards

Maryland Academy of Sciences Outstanding Young Scientist Award for 1985; NASA Group Achievement Award for Voyager Science Investigations, 1986 and 1990; and Galileo, 1996.

Professional Societies

Fellow, American Physical Society 1992; Member, NAS/NRC Committee on Planetary and Lunar Exploration 1987-1990; Member, NASA Solar System Exploration Subcommittee 1992-1995; Editor for *Solar-Planetary Relations, Eos-Trans. of the American Geophys.* Union 1989-1991; Associate Editor, *J. Geophys. Res.* 1987-1989; Associate Editor, *Geophys. Res. Lett.* 1989-1994.

Selected Publications

Cheng, A. F., Adiabatic theory in rapidly rotating magnetospheres, *J. Geophys. Res., 89,* 5453-5459, 1984.

Cheng, A. F., R. E. Johnson, S. M. Krimigis, and L. J. Lanzerotti, Magnetosphere, exosphere and surface of Mercury, *Icarus, 71,* 430-440, 1987.

Cheng, A. F., Two classes of models for temporal variability of the Io torus, *J. Geophys. Res., 93,* 12751-12760, 1988.

Cheng, A. F., Magnetosphere of Neptune: Auroral zone field-aligned potential drops, *Geophys. Res. Lett., 16,* 953-956, 1989.

Cheng, A. F. and S. M. Krimigis, A model of global convection in Jupiter's magnetosphere, *J. Geophys. Res., 94,* 12003-12008, 1989.

Cheng, A. F., S. M. Krimigis, and L. J. Lanzerotti, Energetic particles at Uranus, in *Uranus,* J. Bergstrahl, E. Miner, and M. Matthews (eds.), University of Arizona Press, 831-893, 1990.

Hawkins, III, S. E., A. F. Cheng, L. J. Lanzerotti, and C. G. Maclennan, Rotational anisotropy of the Jovian magnetosphere at high latitudes, *J. Geophys. Res., 100,* 14807-14820, 1995.

Paranicas, C. P., A. F. Cheng, and B. H. Mauk, Charged particle phase space densities in the magnetospheres of Uranus and Neptune, *J. Geophys. Res., 101,* 10681-10693, 1996.

Cheng, A. F., J. Veverka, C. Pilcher, and R. W. Farquhar, Missions to near Earth objects, in *Hazards due to Asteroids and Comets,* T. Gehrels and M. Matthews (eds.), University of Arizona Press, 651-670, 1995.

Landshof, J. A. and A. F. Cheng, NEAR mission and science operations, *J. Astronautical Sci., 43,* 477, 1995.

Zuber, M, D. Smith, A. F. Cheng, and T. D. Cole, The NEAR Laser Ranging Experiment, *J. Geophys. Res., 102,* 23761-23773, 1997.

Cheng, A. F., A. Santo, K. Heeres, R. Farquhar, R. Gold, and S. Lee, Near Earth Asteroid Rendezvous: Mission Overview, *J. Geophys. Res., 102,* 23695-23708, 1997.

ANDREW F. CHENG

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and leads the analysis of magnetometer, EPPS, and UVVS data in terms of the interaction of the magnetosphere and the planetary surface.

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GEORGE GLOECKLER

Current Position: Distinguished University Professor, Dept. of Physics and Institute for Physical Sciences and Technology, University of Maryland and Adjunct Professor, University of Michigan

Education B.S. (Physics), University of Chicago, 1960
M.S. (Physics), University of Chicago, 1961
Ph.D. (Physics), University of Chicago, 1965

Positions Held Research Associate, University of Chicago, 1965-67; Asst. Professor of Physics, University of Maryland, 1967-73; Assoc. Professor of Physics, University of Maryland, 1973-78; Professor of Physics, University of Maryland, 1973-present

Honors and Awards

NASA: Exceptional Scientific Achievement Medal (Voyager), 1981; Group Achievement Award (Voyager), 1981; Special Achievement Award (AMPTE Mission), 1986; Group Achievement Award (Uranus Encounter, Voyager), 1986; Group Achievement Award (AMPTE Mission Operations), 1990 Group Achievement Award (Voyager Science Investigation), 1990; Public Service Group Achievement Award (Ulysses Mission), 1992; Group Achievement Award (Ulysses Jupiter fly-by) 1993; Fellow, American Physical Society, 1982; Fellow, AGU, 1990; ESA Certificate of Valuable Contribution to Ulysses, 1991; Member, National Academy of Sciences, 1997-present; Univ. of Chicago Professional Achievement Citation, 1997.

Relevant Experience

PI: IMP 7 and 8 Explorers-Ions and Electrons,1968-1982, Ulysses—SWICS, 1978-present; ISTP/Wind-SMS Investigation, 1989-present; Lead Co-I: Voyager 1/2-LECP, 1971-present; ISEE 1 and 3-Nuclear and Charge Composition, 1974-1993; AMPTE/CCE-CHEM Spectrometer 1978-91; ISTP/Geotail-EPIC Experiment, 1987-present; ACE-SWICS/SWIMS, 1991-present; Co-I: ISTP/SOHO-CELIAS Investigation, 1988-present; ISTP/SOHO-UVCS Investigation, 1988-present; Cassini MIMI/CHEMS, 1991-present.

Professional Services (selected list)

Chair, Solar Probe Science Definition Team, 1997-present; IACG Working Group 1, 1993-present; Space Science Working Group, 1982-present; Fast Pluto Flyby Particles and Fields Study Group, 1993; Comm. on Solar and Space Physics, NAS,1985-88; Mgmt/Oper. Working Group, Solar/Heliosphere Physics, 1982-85; Star Probe Study Group, Particles and Fields Panel, 1980-82; Secretary, Cosmic Ray/AGU, 1980-82.

Selected Publications (from more than 220 in refereed journals)

Gloeckler, G. and J. R. Jokipii, Solar modulation and the energy density of galactic cosmic rays, *Astrophys. J., 148,* L41-44, 1967.

Gloeckler, G., Characteristics of solar and heliospheric ion populations observed near Earth, *Adv. Space Res., 4,* 127-137, 1984.

Gloeckler, G., et al., First composition measurement of the bulk of the storm time ring current (1 to 300 keV/e) with AMPTE-CCE, *Geophys. Res. Lett., 12,* 325-328, 1985.

Gloeckler, G., Ion composition measurement techniques for space plasmas, *Rev. Sci. Instrum., 61,* 3613-3620, 1990.

Gloeckler, G., L. A. Fisk, and J. Geiss, Anomalously small magnetic field in the local interstellar cloud, *Nature, 386,* 374-377, 1997.

Gloeckler, G. and J. Geiss, Interstellar and inner source pickup ions observed with SWICS on Ulysses, *Space Sci. Revs., 86,* 127-159, 1998.

GEORGE GLOECKLER

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and oversees the design, fabrication, and calibration of the thermal plasma detector subsystem of EPPS to be supplied by the University of Michigan. Participates in the interpretation of thermal plasma data.

George Gloeckler

March 3, 1999

Date

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ROBERT E. GOLD

Current Position	Physicist, Principal Professional Staff The Johns Hopkins University Applied Physics Laboratory
Education	B.S. (Physics), The City College of New York, 1965 Ph.D. (Physics), University of Denver, 1972
Positions Held	Assistant Supervisor, Space Engineering & Technology Branch, JHU/APL, 1998-present Supervisor, Space Sciences Instrumentation Group JHU/APL, 1992-1998 Principal Staff, JHU/APL, 1988-present Senior Staff Physicist, JHU/APL, 1977-1988 Physicist, JHU/APL, 1975-1977 Physicist, University of New Hampshire, 1972-1975 Graduate Research Assistant, University of Denver, 1967-1972 Delay Line Engineer, ESC Electronics, Inc., 1966-1967 Physicist, Quartz Crystal Filters, Burnell and Co., 1965-1966

Relevant Experience

Payload Manager, Near Earth Asteroid Rendezvous (NEAR), 1993-present; Co-Investigator, Ulysses HI-SCALE Instrument, 1978-present; Co-Investigator, Geotail EPIC Instrument, 1988-present; Project Scientist, Delta Star, 1988-1991; Lead Investigator, Advanced Composition Explorer ULEIS Instrument, 1986-present; Lead Investigator, Advanced Composition Explorer EPAM Instrument, 1986-present.

Honors and Awards

American Geophysical Union, 1969-present

Professional Societies and Awards

NASA Group Achievement Award for AMPTE Project, 1985; STIP Award, 1987; ESA Certificate for Ulysses Project, 1990; NASA Group Achievement Award for Ulysses Instrument Design, 1992.

Selected Publications (from over 50 since 1969)

Gold, R. E., L. J. Lanzerotti, and C. G. Maclennan, Enhanced low energy (1 MeV) ion fluxes in the outer heliosphere, *Planet. Space Sci., 35,* 11, 1359-1366, 1987.

Gold, R. E., R. B. Decker, S. M. Krimigis, L. J. Lanzerotti, and C. G. Maclennan, The latitude and radial dependence of shock acceleration in the heliosphere, *J. Geophys. Rev., 93,* 991-996, 1988.

Lanzerotti, L. J., R. E. Gold, K. A. Anderson, T. P. Armstrong, R. P. Lin, S. M. Krimigis, M. Pick, E. C. Roelof, E. T. Sarris, G. M. Simnett, and W. E. Frain, Heliosphere instrument for spectra, composition, and anisotropy at low energies, *Astron. Astrophys. Suppl. Ser., 92,* 349-363, 1992.

Lanzerotti, L. J., T. P. Armstrong, R. E. Gold, K. A. Anderson, S. M. Krimigis, R. P. Lin, M. Pick, E. C. Roelof, E. T. Sarris, G. M. Simnett, C. G. Maclennan, H. T. Choo, and S. J. Tappin, The hot plasma environment at Jupiter: Ulysses results, *Science, 257,* 1518-1524, 1992.

Lanzerotti, L. J., T. P. Armstrong, C. G. Maclennan, G. M. Simnett, A. F. Cheng, R. E. Gold, D. J. Thomson, S. M. Krimigis, K. A. Anderson, S. E. Hawkins, III, M. Pick, E. C. Roelof, E. T. Sarris, and S. J. Tappin, Measurements of hot plasmas in the magnetosphere of Jupiter, *Planet. Space Sci., 41,* 893-917, 1993.

Lanzerotti, L. J., T. P. Armstrong, R. E. Gold, C. G. Maclennan, E. C. Roelof, G. M. Simnett, D. J. Thomson, K. A. Anderson, S. E. Hawkins, III, S. M. Krimigis, R. P. Lin, M. Pick, E. T. Sarris, and S. J. Tappin, Over the southern solar pole: Low-energy interplanetary charged particles, *Science, 268,* 1010-1013, 1995.

ROBERT E. GOLD

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and serves as overall coordinator for science instruments, with responsibility for hardware implementation and spacecraft integration for all experiments. Oversees the design, fabrication, and testing of the EPPS, to be supplied by JHU/APL. Participates in the analysis of energetic particle data.

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JAMES W. HEAD, III

Current Position Louis and Elizabeth Scherck Distinguished Professor, Department of Geological Sciences, Brown University, Providence, RI.

Education B.S., Washington and Lee University, 1964
Ph.D., Brown University, 1969.

Positions Held

Department of Geological Sciences, Brown University, Providence (1973-present; James Manning Professor, 1990-1995, Louis & Elizabeth Scherck Distinguished Professor, 1995-Present). Interim Director of Lunar Science Institute, Houston, Texas, 1973-1974. Systems Analyst, Bellcomm, Inc., NASA Headquarters, Washington, DC, 1968-1972.

Honors and Awards

Geological Society of America, Fellow, 1995; AGU Fellow, 1997; AAAS Fellow, 1993; Meteoritical Society, Fellow, 1994; NASA Medal for Exceptional Scientific Achievement; NASA Public Service Medal; Geological Society of America Special Commendation; Council for Advancement & Support of Education Professor of the Year for Rhode Island, 1990; Alpha Circle of Omicron Delta Kappa Leadership Society, 1990; Honorary Doctor of Science, Washington and Lee University, 1995.

Relevant Experience

Apollo Lunar Exploration Missions: Site selection, astronaut training, traverse and timeline planning, mission operations, data analysis; Viking Lander Mission: Guest Scientist; Shuttle Imaging Radar Mission B Investigator; Soviet Venera 15-16 Missions: Guest Investigator; Soviet Phobos Mission: Interdisciplinary Scientist; Magellan Mission: Project Science Group and Radar Investigation Group; Galileo Mission: Imaging Team and primary planner for first lunar encounter and for Ganymede encounters during the prime mission; Galileo Europa Mission: Imaging Team and primary planner for even numbered Europa orbits; Mars Global Surveyor: Laser Altimeter Team; Mars 2001: Steering Comm. Landing Site Selection.

Recent Professional Service

Editorial Board: *Planetary and Space Science*; Member: NASA New Millennium Science Working Group; NASA Office of Space Science Strategic Planning to 2015 Committee; U.S. Delegation to the US/Russian Joint Working Group on Solar System Exploration; IAVCEI Task Group on Large-Volume Basaltic Provinces; James B. Macelwane Medal Comm., AGU; Smithsonian Council; NASA Solar System Exploration Subcommittee; Chair: NASA Comm. on the Strategy for Earth-Like Planets; President-Elect: AGU Planetology Section; Co-Convener: Brown University-Vernadsky Institute Microsymposia.

Selected Publications (from several hundred in refereed journals)

Basilevsky, A.T. and J.W. Head, The geologic history of Venus: A stratigraphic view, *J. Geophys. Res., 103,* 8531-8544, 1998.

Head, J. W. and A. T. Basilevsky, Sequence of tectonic deformation in the history of Venus: Evidence from global stratigraphic relations, *Geology, 26,*35-38, 1998.

Head, J. W., Volcano instability development: A planetary perspective, volcano instability on the Earth and other planets, in *Spec. Pub. 10,* W. J. McGuire, A. P. Jones, and J. Neuberg (eds.), Geological Society of London, London, 25-43, 1996.

Head, J.W., L. Crumpler, J. Aubele, J. Guest and R.S Saunders, Venus volcanism: Classification of volcanic features and structures, associations, and global distribution from Magellan data, *J. Geophys. Res., 97,* 13153-13197, 1992.

JAMES W. HEAD, III

Roles and Responsibilities

Chair of the Geology (GG) Group and leads the analysis of imaging data for the identification of volcanic features and the stratigraphic analysis of geologic units.

James W. Head, III ______________________ 2/28/99 ______________

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Date

STAMATIOS M. KRIMIGIS

Current Position Head, Space Department
The Johns Hopkins University Applied Physics Laboratory

Education B. S. (Physics), University of Minnesota, 1961
M. S. (Physics), University of Iowa, 1963
Ph.D. (Physics), University of Iowa, 1965

Positions Held Head, Space Dept., 1991-present; Chief Scientist, Space Dept., 1980-1990; Supervisor, Space Physics and Instrumentation Group, 1974-1981; Supervisor, Space Physics Section, 1968-1974, all at JHU/APL. Assistant Professor of Physics, 1966-1968; Research Associate 1965-1966, both at Dept. of Physics and Astronomy, Univ. of Iowa.

Relevant Experience

Principal or Co-Investigator on several NASA spacecraft, including the Low Energy Charged Particle (LECP) Experiment on Voyagers 1 and 2, the Active Magnetospheric Particle Tracer Explorers (AMPTE), and the Advanced Composition Explorer (ACE). He is currently PI for Cassini and Co-I on Galileo and Ulysses. He is a specialist in solar, interplanetary, and magnetospheric physics. He has designed, built and flown instruments on many Earth-orbiting (Injuns 4,5, IMP-7, 8, CCE, ACE) and planetary (Mariners 4, 5, Voyagers 1, 2, Galileo, Ulysses, Cassini) spacecraft.

Professional Societies and Awards

Member or Chair of more than 40 national and international committees, panels and boards on issues of space science, technology, programmatics, management, publications, and conference activities; NASA Medal of Exceptional Scientific Achievement, 1981, 1986; American Geophysical Union Fellow, 1980; American Physical Society Fellow, 1984; American Institute of Aeronautics and Astronautics Associate Fellow, 1994; Basic Sciences Award, International Academy of Astronautics, 1994; Chair, Subcommittee on Small Planetary Missions for the International Academy of Astronautics; Member, American Association for the Advancement of Science; Member, Solar System Exploration Subcommittee of NASA.

Selected Publications (from over 310 scientific papers)

Krimigis, S. M., Interplanetary diffusion model for time behavior of intensity in a solar cosmic ray event, *J. Geophys. Res., 70*, 2943-2960, 1965.

Krimigis, S. M. and J. A. Van Allen, Geomagnetically trapped alpha particles, *J. Geophys. Res., 72*, 5779-5797, 1967.

Armstrong, T. P., S. M. Krimigis, and L. J. Lanzerotti, A reinterpretation of the reported energetic particle fluxes in the vicinity of Mercury, *J. Geophys. Res., 80*, 4015-4017, 1975.

Krimigis, S. M., J. F. Carbary, E. P. Keath, C. O. Bostrom, W. I. Axford, G. Gloeckler, L. J. Lanzerotti, and T. P. Armstrong, Characteristics of hot plasma in the Jovian magnetosphere: Results from the Voyager spacecraft, *J. Geophys. Res., 86*, 8227-8257, 1981.

Krimigis, S. M., T. P. Armstrong, W. I. Axford, C. O. Bostrom, A. F. Cheng, G. Gloeckler, D. C. Hamilton, E. P. Keath, L. J. Lanzerotti, B. H. Mauk, and J. A. Van Allen, Hot plasma and energetic particles in Neptune's magnetosphere, *Science, 246*, 1483-1494, 1989.

Krimigis, S. M., Voyager energetic particle observations at interplanetary shocks and upstream of planetary bow shocks: 1977-1990; *Space Sci. Rev., 59*, 167-201, 1992.

Mauk, B. H., S. M. Krimigis, and M. H. Acuña, Neptune's inner magnetosphere and aurora: Energetic particle constraints, *J. Geophys. Res., 99*, 14781-14788, 1994.

Krimigis, S. M., The new solar system: Solar activity and the solar wind interaction with the planets, *Proc. Israel Institute of Advanced Studies at Tel Aviv University, Raymond and Beverly Sackler Distinguished Lectures in Geophysics and Planetary Sciences*, 22 pp., May 27-June 7, 1996.

STAMATIOS M. KRIMIGIS

Roles and Responsibilities

Chair of the Atmosphere and Magnetosphere (AM) Group and leads analysis of EPPS data to characterize ionized and accelerated species in Mercury's magnetosphere and the local interplanetary medium.

S. M. Krimigis 3/10/99

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WILLIAM McCLINTOCK

Current Position Research Associate and Lecturer, University of Colorado

Education
B.A. (Physics), The Johns Hopkins University, 1968
M.A. (Physics), The Johns Hopkins University, 1971
Ph.D. (Physics and Astrophysics), The Johns Hopkins University, 1977

Positions Held
Research Associate, Joint Institute for Laboratory Astrophysics and Laboratory for Atmospheric and Space Physics, University of Colorado, 1977-1978
Research Associate, Laboratory for Atmospheric and Space Physics, University of Colorado, 1978-present
Lecturer, Department of Aerospace Engineering Sciences, University of Colorado, 1986-present

Relevant Experience

Principal Investigator, Ultraviolet Spectrometer Imager for JPL Pathfinder mission; Co-Investigator, LASP High Resolution Astronomy Rocket Program and LASP Planetary Rocket Program; Co-Investigator and instrument scientist, Cassini UltraViolet Imaging Spectrometer; Principal Investigator, Planetary Instrument Definition and Development Program, An ultraviolet imaging spectrometer for the Pluto/Charon mission; Principal Investigator, Neutral density and temperature spectrograph.

Research Interests

Development of state-of-the-art instrumentation for high resolution spectroscopy for the 500-3000 Å wavelength range. Ultraviolet observations of planetary atmospheres. Structure and composition of the Earth's lower thermosphere.

Selected Publications

McClintock, W. E., C. A. Barth, R. E. Steele, G. M. Lawrence, and J. G. Timothy, Rocketborne instrument with a high-resolution microchannel plate detector for planetary UV spectroscopy, *Applied Optics, 21,* 3071, 1982.

McClintock, W. E. and W. C. Cash, Jr., Grazing incidence optics: New techniques for high sensitivity spectroscopy in the space ultraviolet, *Instrumentation in Astronomy IV, SPIE*, 331, 321, 1982.

McClintock, W. E., G. M. Lawrence, R. A. Kohnert, and L. W. Esposito, Optical design of the Ultraviolet Imaging Spectrograph for the Cassini Mission to Saturn, *Instrumentation for Planetary and Terrestrial Atmospheric Remote Sensing, Optical Engineering, 32,* 3038-3046, 1993.

McClintock, W. E., C. A. Barth, and R. A. Kohnert, Sulfur dioxide in the atmosphere of Venus: I. Sounding rocket observations, *Icarus, 112,* 382-388, 1994.

WILLIAM McCLINTOCK

Roles and Responsibilities

Member of the Geochemistry (GC) and Atmosphere and Magnetosphere (AM) Groups and oversees the design, fabrication, and calibration of the ASCS, to be supplied by the University of Colorado. Leads the interpretation of UV spectra for characterizing composition of Mercury's atmosphere. Participates in the interpretation of IR spectra for surface chemical and mineralogical composition.

William McClintock — 3-1-99

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Date

RALPH L. McNUTT, JR.

Current Position Physicist, Principal Professional Staff
The Johns Hopkins University Applied Physics Laboratory

Education B.S. (Physics), Summa Cum Laude, Texas A&M University, 1975
Ph.D. (Physics), Massachusetts Institute of Technology, 1980

Positions Held

1996-present Principal Professional Staff, The Johns Hopkins University Applied Physics Laboratory (JHU/APL); 1992-1996 Senior Staff, JHU/APL; 1991-1992 Research Associate Professor, Boston University; 1990-1992 Senior Project Scientist, Visidyne, Inc.; 1990 Sponsored Research Staff, MIT; 1986-1990 Associate Professor of Physics, MIT; 1986-1988 Consultant, Visidyne, Inc.; 1982-1986 Assistant Professor of Physics, MIT; 1981-1987 Consultant, Sandia National Laboratories; 1981-1982 Sponsored Research Staff, MIT; 1980-1981 Technical Staff, Sandia National Laboratories.

Relevant Experience

Co-I, Voyager PLS, LECP; Member, Ion Neutral Mass Spectrometer Team, Cassini Orbiter spacecraft; JHU/APL Instrument Scientist, NEAR XGRS Facility Instrument; Study Lead JHU/APL Pre-Phase A study of a solar probe spacecraft; PI, NASA Space Physics Division SR&T grants; PI, Solar System Exploration Division PIDDP grant for development of a compact energetic particle detector; Worked on physics of the magnetospheres of the outer planets, physics of the outer heliosphere including solar wind dynamics and properties of the VLF radiation, Pluto's atmosphere, pulsars, physics of high current electrons beams, the physics of active experiments in the mesosphere/thermosphere (artificial aurora), and the solar neutrino problem; Associate Editor of *Geophysical Research Letters* 1994-1996; Member, NASA Science Definition Team for Pluto Express; Deputy Chairman of Science Definition Team for Solar Probe; Member, NASA Sun-Earth Connections Advisory Subcommittee, 1997-present.

Professional Societies and Awards

Member, American Astronomical Society and the Division of Planetary Sciences, American Geophysical Union, Sigma Xi, The Planetary Society, and The British Interplanetary Society; National Finalist in the competition for the 1987-1988 class of White House Fellows; NASA Group Achievement Award, Voyager Science, 1990; NASA Group Achievement Award, Voyager Uranus Interstellar Mission, 1986; NASA Group Achievement Award, Voyager Project, 1981.

Selected Publications (from over 55)

McNutt, Jr., R. L., Models of Pluto's upper atmosphere, *Geophys. Res. Lett.*, *16*, 1225-1228, 1989.

McNutt, Jr., R. L., The magnetospheres of the outer planets, *Rev. Geophys. Suppl.*, 985-997, April 1991.

McNutt, Jr., R. L., Possible in situ detection of K^{2+} in the Jovian magnetosphere, *J. Geophys. Res.*, *98*, 21221-21229, 1993.

McNutt, Jr., R. L., Correlated variations in the solar neutrino flux and the solar wind and the solar neutrino problem, *Science*, *270*, 1635-1638, 1995.

McNutt, Jr., R. L., R. E. Gold, E. C. Roelof, L. J. Zanetti, E. L. Reynolds, R. W. Farquhar, D. A. Gurnett, and W. S. Kurth, A sole/ad astra: From the Sun to the stars, *J. Brit. Interplanet. Soc.*, *50*, 463-474, 1997.

Trombka, J. I., S. R. Floyd, W. V. Boynton, S. Bailey, J. Brückner, S. W. Squyres, L. G. Evans, P. E. Clark, R. D. Starr, E. M. Fiore, R. E. Gold, J. J. Goldsten, and R. L. McNutt, Jr., Compositional mapping with the NEAR X-ray/gamma-ray spectrometer, *J. Geophys. Res.*, *102*, 23729-23750, 1997.

Trombka, J. I., S. R. Floyd, W. V. Boynton, S. Bailey, J. Bruckner, S.W. Squyres, L. G. Evans, P. E. Clark, R. D.Starr, E. M. Fiore, R. E. Gold, J. J. Goldsten, and R. L. McNutt, Jr., The x-ray/gamma-ray spectrometer on the NEAR Earth Asteroid Rendezvous Mission, *Space Sci. Rev.*, *82*, 169-216, 1997.

McNutt, Jr., R. L., J. Lyon, and C. C. Goodrich, Simulation of the heliosphere: Model, *J. Geophys. Res.*, *103*, 1905-1912, 1998.

RALPH L. McNUTT, JR.

Roles and Responsibilities

Member of the Geochemistry (GC) and the Atmosphere and Magnetosphere (AM) Groups. Serves as Project Scientist and assists Principal Investigator. Oversees the design, fabrication, and calibration of the γ-ray/neutron and X-ray spectrometers, to be supplied by JHU/APL. Participates in the analysis of γ-ray/neutron and X-ray spectrometer data to determine Mercury's surface composition, and in comparisons of those results with compositional information obtained from energetic particle and thermal plasma data.

Ralph L. McNutt, Jr. — 3/9/99

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SCOTT L. MURCHIE

Current Position Geologist, Principal Professional Staff
The Johns Hopkins University Applied Physics Laboratory

Education Ph.D. (Geological Sciences), Brown University, 1988
M.S. (Geology and Geophysics), University of Minnesota, 1984
B.A. (Geology/Environmental Studies, Biology), Colby College, 1981

Positions Held The Johns Hopkins University Applied Physics Laboratory, 1994-present
Visiting Research Scientist, Lunar and Planetary Institute, 1992-1994
Research Associate, Brown University, 1988-1992
Research Assistant, Brown University, 1983-1988
Teaching Assistant, University of Minnesota, 1982-1983
Research Assistant, Minnesota Geological Survey, 1981-1982

Relevant Experience

Co-I and Instrument Scientist for NEAR Multispectral Imager and Near-Infrared Spectrograph. Participating Scientist in Mars Pathfinder onground and inflight instrument calibration, data analysis, and planning of observation sequences. Small-body composition and geology. Evaluating composition, surface heterogeneity, and geology of Phobos and Eros from space- and ground-based UV-visible-NIR imagery and spectroscopy. Martian surface composition and weathering. Reduction and analysis of space and ground-based visible-NIR imaging spectroscopic data and in situ measurements for Mars, with emphasis on characterization of altered soils and their relationship to crustal rock.

Current Professional Services

Member, AGU, GSA, DPS, Meteoritical Society; Associate Editor, *Journal of Geophysical Research-Planets.*

Selected Publications

Belton, M. and 19 co-authors, Galileo encounter with 951 Gaspra: First pictures of an asteroid, *Science*, *257*, 1647-1652, 1992.

Pieters, C., J. Head, J. Sunshine, E. Fischer, S. Murchie, M. Belton, A. McEwen, L. Gaddis, R. Greeley, G. Neukum, R. Jaumann, and H. Hoffman, Crustal and mantle diversity of the Moon: Compositional analyses of Galileo SSI data, *J. Geophys. Res.*, *98*, 17127-17148, 1993.

Murchie, S., J. Mustard, J. Bishop, J. Head, C. Pieters, and S. Erard, Spatial variations in the spectral properties of bright regions on Mars, *Icarus*, *105*, 454-468, 1993.

Treiman, A., K. Fuks, and S. Murchie, Layering in the upper walls of Valles Marineris, Mars: A diagenetic origin, *J. Geophys. Res.*, *100*, 26339-26344, 1995.

Murchie, S. and C. Pieters, Spectral properties and rotational spectral heterogeneity of 433 Eros, *J. Geophys. Res.*, *101*, 2201-2214, 1996.

Veverka, J., J. Bell, P. Thomas, A. Harch, S. Murchie, E. Hawkins, J. Warren, C. Chapman, L. McFadden, M. Malin, and M. Robinson, An overview of the NEAR Multispectral Imager (MSI)–Near-Infrared Spectrometer (NIS) investigation, *J. Geophys. Res*, *102*, 23709-23727, 1997.

Smith, P., and 25 co-authors, Results from the Mars Pathfinder camera, *Science*, *278*, 1758-1765, 1997.

Veverka, J., and 16 co-authors, NEAR's Flyby of 253 Mathilde: Images of a C Asteroid, *Science*, *278*, 2109-2114, 1997.

McSween, H., S. L. Murchie, J. Crisp, N. Bridges, and 16 co-authors, Chemical, multispectral and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site, *J. Geophys. Res.*, in press, 1999.

SCOTT L. MURCHIE

Roles and Responsibilities

Member of the Geology (GG) and Geochemistry (GC) Groups and oversees the design, fabrication, and calibration of the imaging system. Leads the development of the observing sequence for flybys and the interpretation of imaging and spectral data for surface chemical and mineralogical composition.

Scott L. Murchie — 3/11/1999

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STANTON J. PEALE

Current Position Research Professor and Professor Emeritus, Univ. of California, Santa Barbara

Education

Ph.D., Cornell University, Ithaca, New York, 1965
M.S., Cornell University, Ithaca, New York, 1962
B.S., Purdue University, West Lafayette, Indiana, 1959

Positions Held

Research Professor, Professor Emeritus 1994-present, Professor, 1976-1994, Associate Professor, 1970-1976, Assistant Professor, 1968-1970, University of California, Santa Barbara, Dept. of Physics; Assistant Professor, 1965-1968, University of California, Los Angeles, Dept. of Astronomy, Institute of Geophysics and Planetary Physics; Research Associate, 1964-1965, Cornell University, Center for Radio Physics and Space Research; Research Engineer, 1959-Summer, G. E. Corporation, Cincinnati, Ohio.

Honors

Dirk Brouwer Award; American Astronomical Society Division of Dynamical Astronomy (1993); Asteroid Named Peale 3612 (1988); Fellow: American Geophysical Union (1988); James Craig Watson Award: National Academy of Sciences (1982); Fellow of the Association: American Association for the Advancement of Science (1981); Exceptional Scientific Achievement Medal: NASA (1980); Newcomb Cleveland Prize: American Association for the Advancement of Science (1979); Visiting Fellowship: University of Colorado J.I.L.A. (1979-1980) (1972-1973).

Relevant Experience

Member, NRC Commitee on Astronomy and Astrophysics, 1997-present; Member, NASA Keck Time Allocation Committee, 1995-1997; Member, NASA Roadmap Committee for the Exploration of Neighboring Planetary Systems, 1995-1996; Member, NASA Planetary Geology and Geophysics MOWG, 1995-1996; Member, NASA Europa Campaign Strategy Working Group, 1996; Member, NRC Committee on Lunar and Planetary Exploration, 1980-1983; Member, Lunar and Planetary Science Council, 1984-1989; Member, NASA Planetary Systems Science Working Group, 1988-1993; Subcommittee Chairman, NAS Summer Study for the determination of strategy of the exploration of comets and asteroids, Snowmass, CO, July 1978; Member, NASA Science advisory group for the study of the outer solar system, JPL, 1972-1973.

Memberships

American Geophysical Union (Fellow); American Astronomical Society, Division of Dynamical Astronomy and Division of Planetary Sciences; American Association for the Advancement of Science (Fellow, 1981); International Astronomical Union Commission 7 (Celestial Mechanics).

Selected Publications

Peale, S. J., Determination of parameters related to the interior of Mercury, *Icarus, 17,* 168, 1972.

Peale, S. J., Does Mercury have a molten core?, *Nature, 262,* 765-766, 1976.

Peale, S. J., Inferences from the dynamical history of Mercury's rotation, *Icarus, 28,* 459, 1976.

Peale, S. J. and A. P. Boss, Mercury's core: The effect of obliquity on the spin-orbit constraints, *J. Geophys. Res., 82,* 3423, 1977.

Peale, S. J., Measurement accuracies required for the determination of a Mercurian liquid core, *Icarus, 48,* 143-145, 1981.

Peale, S. J., Rotational dynamics of Mercury and the state of its core, in *Mercury,* F. Vilas, C. Chapman, and M. S. Matthews (eds.), Univ. of Arizona Press, 461-493, 1988.

STANTON J. PEALE

Roles and Responsibilities

Member of the Geophysics (GP) Group and provides guidance to the mission strategy for detecting the fluid core of the planet. Leads in the interpretation of measurements of planetary orientation and physical libration.

Stanton J. Peale ____________________ 2/26/99 ____________

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Co-Investigator

ROGER J. PHILLIPS

Current Position Professor, Geophysics, Washington University, St. Louis, Missouri

Education B.S. (Geol. Eng.), Colorado School of Mines, Golden, Colorado, 1963
M.S. (Applied Geophysics), University of California, Berkeley, 1965
Ph.D. (Applied Geophysics), University of California, Berkeley, 1968

Positions Held Jet Propulsion Laboratory, Pasadena, CA; 1968-1980
Lunar and Planetary Institute, Houston, Texas, Director; 1979-1983
Southern Methodist University, Dallas, Texas, 1982-1992
Visiting Fellow, The Australian National University, 1987
Fellow, McDonnell Center Washington University, St. Louis, MO, 1991-

Relevant Experience

PI Planetary Interior Modeling and Tectonic Implications 1983-present; Co-I Mars Global Surveyor Mission 1985-; Geophysics Subnode Manager, Planetary Data System 1992-present; PI Lunar and Asteroid Data Analysis Program 1996-1997; Co-I Apollo and Magellan Missions; PI Pioneer Venus Mission; Project Director, Basaltic Volcanism Study Project, 1979-1981; Co-Chair, Lunar and Planetary Science Conference, 1980-1983; Co-Editor, Origin of the Moon, Lunar and Planetary Institute, Houston, 1986; Editor, *Geophys. Res. Lett.* 1988-1990; Co-Convenor, Venus II (U. of Arizona series) Conference and Book (Co-Editor); Chair, Lunar Exploration SWG, 1988-1992; National Academy of Sciences/National Research Council, Space Science Board, 1986-1990; Numerous NASA review panels and committees.

Professional Societies and Awards

Tau Beta Pi; American Geophysical Union President-Elect, Planetology Section, 1992-1994; President, Planetology Section, 1994-1996; Geological Society of America NASA Group Achievement Award, Apollo Lunar Sounder Investigator Team, 1973; NASA Group Achievement Award Pioneer Venus Orbiter Science Team, 1980; NASA Public Service Medal, 1983; Fellow American Geophysical Union, 1989.

Selected Publications (selected from over 100)

Phillips, R. J., Techniques in Doppler gravity inversion, *J. Geophys. Res., 79,* 2027-2036, 1974.

Phillips, R. J., W. L. Sjogren, E. A. Abbott, and S. H. Zisk, Simulation gravity modeling to spacecraft-tracking data: Analysis and application, *J. Geophys. Res., 83,* 5455-5464, 1978.

Phillips, R. J. and K. Lambeck, Gravity fields of the terrestrial planets: Long-wavelength anomalies and tectonics, *Rev. Geophys. and Space Phys. 18,* 27-76, 1980.

Phillips, R. J., Convection-driven tectonics on Venus, *J. Geophys. Res., 95,* 1301-1316, 1990.

Phillips, R. J., C. L. Johnson, S. J. Mackwell, P. Morgan, D. T. Sandwell, and M. T. Zuber, Lithospheric mechanics and dynamics of Venus, in *Venus II,* S. W. Bougher, D. M. Hunten, and R. J. Phillips (eds.), 1163-1204, 1997.

Wieczorek, M. A. and R. J. Philips, The structure and compensation of the lunar highland crust, *J. Geophys. Res., 102,* 10933-10943, 1997.

Phillips, R. J. and S. C. Solomon, Compressional strain history of Mercury, *Lunar and Planet. Sci. XXVIII,* 1107-1108, 1997.

Wieczorek, M. A. and R. J. Phillips, Potential anomalies on a sphere: Applications to the thickness of the lunar crust, *J. Geophys. Res., 103,* 1715-1724, 1998.

Phillips, R. J. and V. L. Hansen, Geological evolution of Venus: Rises, plains, plumes, and plateaus, *Science, 279,* 1492-1497, 1998.

Hauck II, S. A., R. J. Phillips, and M. Price, Venus: Crater distribution and plains resurfacing models, *J. Geophys. Res., 103,* 13635-13642, 1998.

ROGER J. PHILLIPS

Roles and Responsibilities

Member of the Geophysics (GP) Group and leads the analysis of topography and gravity data for regional tectonics and interior dynamics.

[signature] 2/26/99

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MARK S. ROBINSON

Current Position Geologist, Department of Geological Sciences, Northwestern University

Education Ph.D. (Geology and Geophysics), University of Hawaii, 1993
M.S. (Geology and Geophysics), University of Hawaii, Honolulu, 1991
Graduate Fellowship, Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington DC, 1990
B.S. (Geology), University of Alaska, Fairbanks, AK, 1988
B.A. (Political Science and Fine Arts), Univ. of the South, Sewanee TN, 1982

Positions Held USGS Branch of Astrogeology, 1994-1996
Graduate Fellow National Air and Space Museum, 1993

Relevant Experience

Currently involved in three major research projects: Clementine lunar mapping, investigation of the color and albedo of Mercury from Mariner 10 digital image data, and the Near Earth Asteroid Rendezvous (NEAR) Imaging and Spectrometry Science team. During the lunar mapping phase of the Clementine mission I inspected and validated UVVIS image data as it was received at the mission operations center. This work involved extensive real time interaction with spacecraft engineers as well as with the Clementine Science Team to maximize the scientific content of the returned data. Since completion of the flight mission I have been working extensively with the Clementine Science Team as well as with USGS computer personnel reducing the large data return for systematic product generation and scientific analyses. My proposal to calibrate and analyze the Mariner 10 digital image data of Mercury was funded through the Planetary Geology and Geophysics program for FY 97-98. This project is underway and initial results are published in *Science*. My proposal as team member for the NEAR mission was selected by NASA for funding through FY 2000. This mission is underway and I am currently involved in calibration of the NEAR Multi-Spectral Imaging (MIS) system and science planning.

Selected Publications

Watters, T. W., M. S. Robinson, and A. C. Cook, Topography of lobate scarps on Mercury: New constraints on the planet's contraction, *Geology, 26, 11,* 991-994, November 1998.

Discovery Rupes and lobate scarps on Mercury: New constraints on the decrease in the planet's radius, *Geology*, submitted 1998.

Veverka, J., J. Bell, P. Thomas, A. Harch, S. Murchie, E. Hawkins, J. Warren, C. Chapman, L. McFadden, M. Malin, and M. Robinson, An overview of the NEAR Multispectral Imager (MSI)–Near-Infrared Spectrometer (NIS) investigation, *J. Geophys. Res., 102,* 23709-23727, 1997.

Robinson, M. S. and P. G. Lucey, Recalibrated Mariner 10 color mosaics: Implications for Mercurian volcanism, *Science, 275,* 197-200, 1997.

Nozette, S., C. L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. S. Robinson, and E. M. Shoemaker, Clementine bistatic radar experiment: Backscatter enhancement suggests possible cold-trapped volatiles at the lunar south pole, *Science, 274,* 1495-1498, 1996.

Shoemaker, E. M., M. S. Robinson, and E. M. Eliason, The South Pole region of the Moon as seen by Clementine, *Science, 266,* 1851-1854, 1994.

McEwen, A. S., M. S. Robinson, E. M. Eliason, P. G. Lucey, T. C. Duxbury, and P. D. Spudis, Clementine observations of the Aristarchus Region of the Moon, *Science, 266,* 1858-1861, 1994.

Robinson, M. S., B. R. Hawke, P. G. Lucey, and G. A. Smith, Mariner 10 multispectral images of the eastern limb and farside of the Moon, *J. Geophys. Res., 97,* 18265-18274, 1992.

MARK S. ROBINSON

Roles and Responsibilities

Member of the Geology (GG) and Geochemistry (GC) Groups and leads the development of mosaicking and geometrical correction procedures for the imaging system. Leads the analysis of imaging and spectral data to map major rock units.

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Date

JAMES A. SLAVIN

Current Position Head, Electrodynamics Branch, NASA/GSFC

Education Ph.D., Space Physics, University of California, Los Angeles, 1981

Relevant Experience

Dr. Slavin worked as a scientist in the Magnetometer Group at the Caltech/Jet Propulsion Laboratory from 1982 to 1986. While at JPL he conducted heliospheric and magnetospheric research in support of the Pioneer 10/11 and ISEE-3 Missions. During this period Dr. Slavin was particularly active in the Geotail and P/Giacobini-Zinner phases of the ISEE-3/ICE Mission and was later appointed a Co-Investigator to the Magnetic Fields Investigation (PI-E.J.Smith). Dr. Slavin also worked as Study Scientist for the Mars Aeronomy Observer mission (1985-1986). He transferred to NASA Headquarters in 1987 where he served as Discipline Scientist for Magnetospheric Physics in the newly formed Space Physics Division (Director-S.D.Shawhan). Dr. Slavin later moved to NASA/GSFC to become the lead US Co-I for the Dynamics Explorer-1/2 Magnetic Fields Investigation (PI-M.Sugiura/Kyoto University) with responsibility for the infight operations, calibration, data processing, and archiving. He also worked as Deputy Project Scientist for POLAR (1988-1991) and Study Scientist for the Mercury Orbiter Mission (1989-1990). In 1989 he was appointed Head of the Electrodynamics Branch. He is presently very active in the ISTP Program as a Co-I on the WIND and IMP-8 Magnetic Fields Investigations (PI-R.P.Lepping), the Cluster Magnetometer Investigation (PI-A.Balogh), and the Oersted Mission (Project Scientist-E.Friis-Christenson). Dr. Slavin is also involved in the study of the solar wind interaction with weakly magnetized bodies as a NASA Co-I on the Mars-96 MAREMF Investigation (PI-W.Reidler) and as a Participating Scientist assigned to the Mars Global Surveyor MAG-ER Investigation (PI-M.H.Acuña).

Selected Publications (from over 170 scientific articles)

Slavin, J. A. and R. E. Holzer, The effect of erosion on the solar wind standoff distance at Mercury, *J. Geophys. Res., 84,* 1076, 1979.

Slavin, J. A. and R. E. Holzer, Solar wind flow about the terrestrial planets, 1. Modeling bow shock position and shape, *J. Geophys. Res., 86,* 11401, 1981.

Slavin, J. A., E. J. Smith, and B. T. Thomas, Large scale temporal and radial gradients in the IMF: Helios 1, 2, ISEE 3, and Pioneer 10, 11, *Geophys. Res. Lett., 11,* 279, 1984.

Slavin, J. A., E. J. Smith, D. G. Sibeck, D. N. Baker, R. D. Zwickl, and S.-I. Akasofu, An ISEE-3 study of average and substorm conditions in the distant magnetotail, *J. Geophys. Res., 90,* 10875, 1985.

Slavin, J. A., E. J. Smith, B. T. Tsurutani, G. L. Siscoe, D. E. Jones, and D. A. Mendis, Giacobini-Zinner magnetotail: ICE magnetic field observations, *Geophys. Res. Lett., 13,* 283, 1986.

Slavin, J. A., D. S. Intriligator, and E. J. Smith, Pioneer Venus Orbiter magnetic field and plasma observations within the Venus magnetotail, *J. Geophys. Res., 94,* 2383, 1989.

Slavin, J. A., M. F. Smith, E. L. Mazur, D. N. Baker, T. Iyemori, and E. W. Greenstadt, ISEE-3 observations of traveling compression regions in the Earth's magnetotail, *J. Geophys. Res., 98,* 15425, 1993.

Slavin, J. A., C. J. Owen, M. M. Kuznetsova, and M. Hesse, ISEE 3 observations of plasmoids with flux rope magnetic topologies, *Geophys. Res. Lett., 22,* 2061, 1995.

Slavin, J. A., C. J. Owen, J. E. P. Connerney, and S. P. Christon, Mariner 10 observations of field-aligned currents at Mercury, *Planet. Space Sci., 45, 1,* 133-141, 1997.

JAMES A. SLAVIN

Roles and Responsibilities

Member of the Atmosphere and Magnetosphere (AM) Group and participates in the development, calibration, and in-flight operation of the magnetometer. Leads the analysis of magnetometer data for magnetic field structure and magnetospheric processes.

James A. Slavin   2-25-99

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Date

DAVID E. SMITH

Current Position Chief, Laboratory for Terrestrial Physics, NASA/GSFC

Education Ph.D. (Satellite Geodesy), University of London, England, 1966
M.Sc. (Plasma Physics, distinction), University of London, England, 1962
B.Sc. (Mathematics, honors), University of Durham, England, 1958

Research Interests

Planetary altimetry, gravity field modeling, planetary rotation, crustal motions, tectonic plate kinematics, tides, celestial mechanics, atmospheric density structure, magneto-hydrodynamics, laser ranging.

Positions Held

Chief, Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, 1990-present; Associate Chief, Laboratory for Terrestrial Physics, NASA/GSFC, 1987-1990; Head, Geodynamics Branch, Laboratory for Terrestrial Physics, NASA/GSFC, 1971-1987; Staff Scientist, Trajectory Analysis Division, NASA/GSFC 1969-1971; Senior Scientist, Wolf Research and Development Corporation, Riverdale, MD, 1968-1969; Research Scientist, Radio and Space Research Station, Slough, England, 1958-1968.

Honors and Awards

Fellow, American Geophysical Union, 1985; GSFC Lindsay Memorial Award, 1978; NASA Exceptional Scientific Achievement Medal, 1974; Meritorious Senior Executive, 1997.

Relevant Experience

PI Jason-Topex Mission, 1996-present; Member, GSFC NEAR Geophysics Team, 1994-present; PI Mars Global Surveyor Laser Altimeter, 1994-present; Member, Mars Global Surveyor Radio Science Team, 1994-present; PI Clementine Lunar Gravity and Topography, 1993-1995; PI Mars Observer Laser Altimeter, 1986-1993; Member, Mars Observer Radio Science Team, 1986-1993; PI LAGEOS 2, 1988-1995; Project Scientist, Crustal Dynamics Project, 1980-1991; Project Scientist, LAGEOS 1 Spacecraft, 1976-1980; PI Crustal Dynamics Project, 1980-1991; PI LAGEOS 1, 1976-1980; PI GEOS 3, 1975-1978.

Professional Societies

American Geophysical Union, 1973-present; President of Geodesy, 1990-1992; President-Elect of Geodesy, 1988-1990; Royal Astronomical Society, 1953-1994; American Astronomical Society, Division of Planetary Sciences, 1996-present.

Selected Publications

Smith, D. E., M. T. Zuber, H. V. Frey, J. B. garvin, J. W. Head, G. H. Pettingill. R. J. Phillips, S. C. Solomon, H. J. Zwally, W. B. Banerdt, and T. C. Duxbury, Topography of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter, *Science, 279,* 1597-1818, 1998.

Zuber, M. T., D. E. Smith, A. F. Cheng, and T. D. Cole, The NEAR laser ranging investigation, *J. Geophys. Res., 102*, 23761-23773, 1997.

Lemoine, F. G., D. E. Smith, M. T. Zuber, G. A. Neumann, and D. D. Rowlands, A 70th degree and order lunar gravity model from Clementine and historical data, *J. Geophys. Res.*, in press, 1997.

Smith, D. E., M. T. Zuber, G. A. Neumann, and F. G. Lemoine, Topography of the Moon from the Clementine LIDAR, *J. Geophys. Res., 102,* 1591-1611, 1997.

Neumann, G. A., M. T. Zuber, D. E. Smith, and F. G. Lemoine, The lunar crust: Global signature and structure of major basins, *J. Geophys. Res., 101,* 16841-16863, 1996.

Smith, D. E. and M. T. Zuber, The shape of Mars and the topographic signature of the hemispheric dichotomy, *Science, 271,* 184-188, 1996.

DAVID E. SMITH

Roles and Responsibilities

Member of the Geophysics (GP) Group and oversees the design, fabrication, and testing of the MLA, to be supplied by GSFC. Leads the investigation of radio science, including the determination of precision orbits, analysis of spacecraft occultation data, and measurement of the planetary gravity field. Participates in the analysis of MLA data for the determination of planetary topography, including the measurement of planetary orientation and physical libration.

David E. Smith

3/2/99

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Co-Investigator

ROBERT GREGSON STROM

Current Position Director and Professor, Lunar and Planetary Laboratory, University of Arizona

Education B.S. (Geology), University of Redlands, 1955
M.S. (Geology), Stanford University, 1957

Positions Held

Petroleum Geologist, Standard Vacuum Oil Co., White Plains, NY, 1957-60; Research Geologist, Space Sciences Laboratory, Univ. of CA, Berkeley, CA., 1961-63; Assistant Professor, Lunar and Planetary Laboratory, Univ. of Arizona, 1963-72; Visiting Senior Fellow, Univ. of London Observatory, England (Summer), 1970; Associate Professor, Dept. of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, 1972-81; Director, Space Imagery Center, Lunar and Planetary Laboratory, Univ. of Arizona, 1977-present; Professor, Dept. of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, 1981- present; Visiting Professor, Institute for Space Astrophysics, University of Rome, Rome, Italy (Spring Sabbatical Leave), 1985; Secretary/Treasurer, Board of Trustees, Center for Image Processing in Education, 1995-present; Visiting Professor, Dept. of Earth and Planetary Sciences, Univ. d' Anunzia, Pescara, Italy (Spring Sabbatical Leave), 1997.

Professional Societies

American Geophysical Union (Planetology Section); American Astronomical Society (Division of Planetary Sciences); International Astronomical Union (Commission 17).

Honors and Awards

NASA Public Service Group Achievement Award for Mariner 10 Venus/Mercury Television Science Team, 1974; NASA Special Recognition for serving as a Principal Investigator in the Lunar Program, 1979; NASA Group Achievement Award, Voyager Jupiter/Saturn Imaging Science Investigation, 1981; NASA Group Achievement Award, Voyager Uranus Imaging Science Investigation, 1986; NASA Group Achievement Award, Voyager Neptune Imaging Science Investigation, 1990.

Relevant Experience

Mariner 10 Mission: Member of the Venus/Mercury Television Science Team; Voyager Mission: Member of the Jupiter/Saturn/Uranus/Neptune Imaging Science Team.

Selected Publications

Strom, R. G., *Mercury: The Elusive Planet,* Solar System Series, Smithsonian Institution Press, 1987.

Strom, R. G. and G. Neukum, The cratering record on Mercury and the origin of impacting objects, in *Mercury,* Space Science Series, University of Arizona Press, 1988.

Strom, R. G., Mercury, *Yearbook of Science and Technology,* McGraw-Hill Book Co., 1990.

Strom, R. G., Mercury: The Forgotten Planet, *Sky and Telescope, 80, 3,* 256-260, September 1990.

Strom, R. G., M. C. Malin, and M. A. Leake, Geologic map of the Bach region of Mercury, *US Geological Survey Map I-2015,* 1990.

Baker, V. R., R. G. Strom, V. C. Gulick, J. S. Kargel, G. Komatsu, and V. S. Kale, Ancient oceans, ice sheets, and the hydrological cycle on Mars, *Nature, 352,* 589-594, 1991.

Schaber, G. G., R. G. Strom, et al., Geology and distribution of impact craters on Venus: What are they telling us?, *J. Geophys. Res., 97,* 13257-13301, 1992.

Strom, R. G., G. G. Schaber, and D. D. Dawson, The global resurfacing of Venus, *J. Geophys. Res., 99,* E5, 10899-10926, 1994.

Strom, R. G., Mercury, *McGraw-Hill Encyclopedia of Science and Technology, 8th Edition,* McGraw-Hill Book Co., 1994.

Strom, R. G., Mercury: An Overview, *Adv. Space Res., 19,* 1471-1485, 1997.

ROBERT GREGSON STROM

Roles and Responsibilities

Member of Geology (GG) Group and participates in the analysis of imaging and IR spectral measurements of the surface. Leads the interpretation of the volcanic and tectonic history of the planet.

Robert G. Strom

Feb. 24, 1999
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JACOB I. TROMBKA

Current Position Astrophysicist, Senior Goddard Fellow, Goddard Space Flight Center

Education B.S. (Physics), Wayne University, 1952
M.S. (Physics), Wayne University, 1954
Ph.D. (Nuclear Science), University of Michigan, 1961

Positions Held Adjunct Professor Geology, University of Maryland
Adjunct Professor of Law, Georgetown Law School
Program Manager, Manned Space Flight, NASA Headquarters
Senior Scientist, Jet Propulsion Laboratory

Relevant Experience

Team Leader-NEAR Mission; PI US/Russian Antarctic Gamma Ray Balloon Flight Program; Project Scientist-Mars Observer; Co-I Russian Mars '94 Mission; Member Flight Investigation Team Mars Observer Remote Sensing Gamma-Ray Spectrometer, Member, NASA Instrument Design Science Team for X-Ray/Gamma-Ray Remote Sensing (PIDDP); Member NASA Comet Rendezvous Asteroid Flyby SWG; Member Mercury Orbiter Project WG; Member NAS Primitive Body WG (European and USA) on Cooperative Planetary Exploration; Co-I Gamma-Ray Spectrometer, WIND Mission; Guest Investigator, Gamma-Ray Spectrometer, Solar Maximum Mission; Guest Investigator, X-Ray Fluorescence Experiment, Viking Mission; Member Terrestrial Bodies SWG; PI US/Russian Program for the Development of Remote Sensing X-Ray and Gamma-Ray Sensing Techniques; Member Editorial Advisory Board, *Nuclear Technology;* Co-I NATO Project on Non-Destructive Testing of Historic Monuments (Venice); PI Apollo-Soyuz Crystal Activation Experiment; Co-I Apollo Gamma-Ray Spectrometer; Co-I Apollo X-Ray Spectrometer.

Professional Societies, Honors, Awards, and Patents

American Physics; American Nuclear Society; Sigma Xi; New York Academy of Science; John Lindsay Award, Most Significant Scientific Achievement, Goddard Space Flight Center, 1972; Exceptional Scientific Achievement Medal, NASA, 1971; Group Achievement Award, Lunar Orbit Experiments Team, NASA, 1971; Group Achievement Award, Lunar Science Working Panel, NASA, 1973; Group Achievement Award, Apollo-Soyuz Experimenters Group, NASA, 1976; Member of Sigma Xi; Outstanding Graduate, Nuclear Department, University of Michigan, 1979; Exceptional Scientific Achievement Award, Goddard Space Flight Center, 1993; Senior Goddard Fellows Program Award, 1994. Patent Number 4,483,817, Neutron/ Gamma-Ray Methods for Mapping Distribution of Contamination in Building Materials, November 20, 1984.

Selected Publications (selected from over 150)

Fichtel C. E. and J. I. Trombka, *Gamma Ray Astrophysics, New Insight into the Universe*, 2nd Edition NASA Reference Publication 1386, October 1997.

Clark, P. E. and J. I. Trombka, Remote X-ray fluorescence experiments for future missions to Mercury, *Planet. Space Sci., 45,* 57-65, 1997.

Rester A. C. and J. I. Trombka, *High Energy Radiation Background in Space,* A. Rester, Jr. and J. I. Trombka (eds.), American Institute of Physics, New York, 1989.

Evans, L. G., J. I. Trombka, and W. V. Boynton, Elemental analysis of a comet nucleus by passive gamma-ray spectrometry from a penetrator, *J. Geophys. Res., 91,* 525-532, 1986.

Trombka J. I. and C. E. Fichtel, Gamma-ray astrophysics, *Physics Reports, 97,* 172-218, 1983.

JACOB I. TROMBKA

Roles and Responsibilities

Member of the Geochemistry (GC) Group and will oversee selection of detector heads for the γ-ray/neutron and X-ray spectrometers and the integration, characterization, and calibration of detectors. Participates in the analysis of γ-ray/neutron and X-ray measurements for planetary surface chemistry.

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MARIA T. ZUBER

Current Position Earle A. Griswold Professor of Geophysics and Planetary Sciences, Massachusetts Institute of Technology

Education B.A. (Astrophysics (honors) and Geology), University of Pennsylvania, 1980
Sc.M. (Geophysics), Brown University, 1983
Ph.D. (Geophysics), Brown University, 1986

Positions Held

National Research Council Research Associate, Geodynamics Branch, NASA/GSFC, 1985-1986; Geophysicist, Geodynamics Branch, NASA/GSFC, 1986-1992; Associate Research Professor of Geophysics, JHU, 1991-1992; Second Decade Society Associate Professor of Geophysics, JHU, 1993-1995; Senior Research Scientist Laboratory for Terrestrial Physics, NASA/GSFC, 1994-Present; Professor of Geophysics, The Johns Hopkins University, 1995; Professor of Geophysics and Planetary Science, Massachusetts Institute of Technology, 1995-1998.

Honors and Awards

NASA Peer Award 1988; NASA Outstanding Performance Award 1988-1992; NASA Group Achievement Award Mars Observer Laser Altimeter Project 1991; Harold S. Masursky Lecturer, 24th Lunar and Planetary Science Conf. 1993; NASA Group Achievement Award Mars Observer Payload Development Team 1993; JHU *Oraculum* Award for Excellence in Undergraduate Teaching 1994; NASA Group Achievement Award Deep Space Program Science Experiment Lunar Orbit Mission Operations Support Team 1994; JHU David S. Olton Award for outstanding contributions to undergraduate student research 1995; NASA Exceptional Scientific Achievement Medal 1995; Planetary Society Thomas O. Paine Memorial Award for the Advancement of the Human Exploration of Mars, 1998 (awarded to MGS and Pathfinder Teams).

Professional Societies

American Geophysical Union; American Association for the Advancement of Science; American Astronomical Society, Division of Planetary Sciences.

Relevant Experience

Co-I, Mars Observer Laser Altimeter, 1990-93; BMDO/NASA Clementine Mission Gravity and Altimetry Team, 1993-95; NAS Comm. on Planetary and Lunar Exploration, 1994-97; Deputy PI, Mars Orbiter Laser Altimeter, Mars Global Surveyor Mission, 1994-present; Team Leader, Laser Ranging Investigation, NASA NEAR Mission, 1994-present; Chair, NASA/Mars Surveyor 1998 Lander Science Payload Selection Panel, 1995; NASA Mars Exploration Working Group, 1996-97; NAS Comm. on Earth Gravity from Space, 1996-97; President-Elect, Planetology Section, AGU, 1996-Present; NASA Europa Science Definition Team, 1997-present.

Selected Publications

Zuber, M. T., D. E. Smith, F. G. Lemoine, and G. A. Neumann, The shape and internal structure of the Moon from the Clementine mission, *Science, 266,* 1839-1843, 1994.

Neumann, G. A., M. T. Zuber, D. E. Smith, and F. G. Lemoine, The lunar crust: Global signature and structure of major basins, *J. Geophys. Res., 101,* 16841-16863, 1996.

Zuber, M. T., D. E. Smith, A. F. Cheng, and T. D. Cole, The NEAR laser ranging investigation, *J. Geophys. Res., 102,* 23761-23773, 1997.

Smith, D. E., M. T. Zuber, H. V. Frey, J. B. Garvin, J. W. Head, G. H. Pettengill, R. J. Phillips, S. C. Solomon, H. J. Zwally, W. B. Banerdt, and T. C. Duxbury, Topography of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter, *Science, 279,* 1686-1692, 1998.

MARIA T. ZUBER

Roles and Responsibilities

Chair of the Geophysics (GP) Group and leads the analysis of MLA data for the determination of planetary topography, including the measurement of planetary orientation and physical libration. Participates in orbit determination, analysis of occultation data, measurement of the planetary gravity field, and analysis of topography and gravity data for regional tectonics and interior dynamics.

[signature] 2/26/99

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ROBERT W. FARQUHAR

Current Position Principal Professional Staff

Education Ph.D. Astronautical Sciences, Stanford University (1969)
M.S. Engineering, UCLA (1961)
B.S. Aeronautical Engineering, University of Illinois (1959)

Honors and Awards

International Academy of Astronautics full member 1996; Asteroid #5256 named Farquhar 1992; NASA Medal for Exceptional Engineering Achievement 1988; Visiting Professor, Institute of Space and Astronautical Science (JAPAN) 1987; American Astronautical Society Fellow 1986; Space Achievement Award, American Institute of Aeronautics and Astronautics 1985; Dirk Brouwer Space Flight Mechanics Award, American Astronautical Society 1984; Moe I. Schneebaum Memorial Award, Goddard Space Flight Center 1984; Letter of Commendation from President Reagan, 1984; American Institute of Aeronautics and Astronautics Associate Fellow 1983; Aviation Week Laurels, 1982; Mechanics and Control of Flight Award, American Institute of Aeronautics and Astronautics 1981; Distinguished Alumnus Award, University of Illinois 1980; NASA Exceptional Service Medal 1979

Relevant Experience

Mission Manager for Comet Nucleus Tour (CONTOUR) Mission; Mission Director for Near Earth Asteroid Rendezvous (NEAR) Mission, 1990-present; NASA/GSFC and NASA Headquarters Primary Assignments, 1970-1990 (Program Manager: Discovery Program, Solar System Exploration Division, 1989-1990; Senior Scientist & Chief, Advanced Programs, Space Physics Division, 1987-1990; Study Manager: Halley's Comet Mission, 1981; Study Manager: OPEN Program, 1978-1979); Mission Definition Manager: International Solar-Terrestrial Physics Program, 1978-1990; Flight Director: ISEE-3/ICE Mission, 1983-1987; Flight Dynamics Manager: ISEE-3 Project, 1972-1982; Mission Definition Manager: Lunar Polar Orbiter, 1973-1975; Study Manager: Cometary Explorer, 1972-1975; Studies of Lunar Shuttle Transportation System, 1970-1972; Studies of Post-Apollo Lunar Exploration Concepts, 1970-1972

Professional Society Memberships

American Institute of Aeronnautics and Astronautics (1959-present); The Planetary Society (1980-present); American Astronautical Society (1984-present); International Academy of Astronautics (1993-present)

Selected Publications (from more than 70 in refereed journals)

Farquhar, R. W., The control and use of libration-point satellites, *NASA TR R-346,* 1970.

Farquhar, R. W., The utilization of Halo orbits in advanced lunar operations, NASA TN D-6365, July 1971.

Farquhar, R. W., Two early missions to the comets, Astronautics and Aeronautics, 10(10), 1972.

Farquhar, R. W., Quasi-periodic orbits about the translunar libration point, *Celestial Mechanics, 7,* 4, June 1973.

Farquhar, R. W., Mission design for a Halo Orbiter of the Earth, *Journal of Spacecraft and Rockets, 14 (3),* March 1977.

Farquhar, R. W., A new trajectory concept for exploring the Earth's geomagnetic tail, *Journal of Guidance and Control, 4(2),* 1981.

Farquhar, R. W., Alternative cometary targets for the Giotto extended missions, *Proc. Symposium on the Diversity and Similarity of Comets,* ESA SP-278, 727-731, 1987.

Farquhar, R. W., Teaching old spacecraft new tricks, Sky and Telescope, 87(2), 1988.

Farquhar, R. W., D. W. Dunham, and J. V. McAdams, Near Earth Asteroid Rendezvous (NEAR) mission overview and trajectory design, AAS/AIAA Astrodynamics Specialist Conf., Paper AAS 95-378, 1995.

Farquhar, R. W., D. W. Dunham, and S.-C. Jen, CONTOUR mission overview and trajectory design, *AAS/AIAA Space Flight Mechanics Meeting,* Paper AAS 97-175, February 1997.

ROBERT W. FARQUHAR

Roles and Responsibilities

As Mission Manager oversees the development of the detailed launch scenario and trajectory maneuver timetable; interfaces with the JPL Navigation group and Deep Space Network for communications with the spacecraft.

Robert W. Farquhar — 3/11/99

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Date

SHIRLEY M. MALCOM

Current Position Director, Education and Human Resources Programs
American Association for the Advancement of Science

Education B.S. (Zoology, with Distinction), University of Washington, 1967
M.A. (Zoology), University of California, Los Angeles, 1968
Ph.D. (Ecology), The Pennsylvania State University, 1974

Positions Held
Director, AAAS Directorate for Education and Human Resourses Programs, 1989-present
Director, AAAS Office of Opportunities in Science, 1979-1989
Program Officer, Science Education Directorate, National Science Foundation, 1977-1979
Staff, AAAS Office of Opportunities in Science, 1975-1977
Assistant Professor of Biology, University of North Carolina, 1974-1975

Honors and Awards
Regents Fellow, UCLA, 1971
Phi Kappa Phi Honor Society, 1973
Sigma Xi, 1995
Fellow, American Academy of Arts and Sciences, 1995
Fellow, American Association for the Advancement of Science, 1995
Distinguished Alumna Awards: Pennsylvania State University, 1995
University of Washington, 1995

Relevant Experience
Presidential Appointments, National Science Board (Senate confirmation), 1994-1998
Member, Executive Committee of the NSB and Chair of the NSB Standing Committee on Education and Human Resources, 1994-1998
President's Committee of Advisors on Science and Technology, 1994-present
Member of various panels on technology and education, stresses on research universities and education research and technology boards
Board Memberships: Morgan State University Board of Regents, 1997-2003; Adelphi University, 1997-present; Carnegie Corporation of New York, 1992-present; American Museum of Natural History, 1992-present
Member, ICSU Committee on Capacity Building in Science, 1994-present; Gender Working Group, UN Commission on Science and Technology for Development

Selected Publications
Malcom, S. M., Who will do science, *Scientific American,* February 1990.
Malcom, S. M. and G. Kulm, *Science Assessment in the Service of Reform,* 1991.
Malcom, S. M., Science and diversity: A compelling national interest, *Science, 27,* 1817-1819, 1996.
Malcom, S. M., Making mathematics the great equalizer, in *Why Numbers Count,* Lynn Arthur Steen (ed.), The College Board, 1997.

SHIRLEY M. MALCOM

Roles and Responsibilities

A member of the National Science Board and Director of Education and Human Resources Programs, American Association for the Advancement of Science. Co-leads MESSENGER's Education and Public Outreach effort with Dr. George "Pinky" Nelson. Plans and implements strategies to provide science journalists with information in anticipation of MESSENGER's major "events," develops tools for use in outreach and communication, and infuses MESSENGER science and education into existing AAAS programs, including those that target HBCU's, MI's, and underseved, underutilized, and minority communities. Periodically reviews the planning and output of all education and outreach efforts.

Shirley M. Malcom — March 12, 1999

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Date

JAMES V. McADAMS

Current Position Mission Design Analyst, Senior Professional Staff
The Johns Hopkins University Applied Physics Laboratory

Education B.S. (Aeronautical and Astronautical Engineering), Purdue University, 1984
M.S. (Aeronautical and Astronautical Engineering), Purdue University, 1985

Positions Held Mission Design Analyst, Mission Concept and Analysis Group, JHU/APL, 1994-present
Mission Analyst, Science Applications International Corporation, 1986-1994
Teaching Assistant, Purdue University, 1985
Technical Aide, Galileo Mission Design, Jet Propulsion Laboratory, 1980-1983

Honors and Awards

The Journal of the Astronautical Sciences 1996 Outstanding Publications Award, Farquhar, R. W., D. W. Dunham, and J. V. McAdams, NEAR mission overview and trajectory design, Special Issue on the Near Earth Asteroid Rendezvous Mission, *J. Astronautical Sciences, 43,* 4, 353-371, 1995; Society for Technical Communication Art Acheivement Award, NEAR Mathilde Website, Quick Reference Handout, 1998; Society for Technical Communication Communication Acheivement Award, NEAR Mathilde Encounter, 1998; The Johns Hopkins University Applied Physics Laboratory Improvement Award, DataBase Driven Interactive NEAR Website Team, 1998.

Relevant Experience

Mr. McAdams has 15 years experience in conducting mission design and analysis for planetary exploration missions. This includes: (1) nearly two years of pre-launch Galileo support for the Jupiter orbital phase, (2) eight years of pre-phase A mission planning with prime focus areas of Mars missions (heliocentric and orbital phases), asteroid and comet missions (member of the original NEAR-Discovery Concept Study Team), and multiple gravity assist missions, and (3) five years on the NEAR Mission Design Flight Team, spanning Phase C/D to E, with three years part-time as Mercury Orbiter Mission Designer.

Professional Societies

Senior Member, American Institute of Aeronautics and Astronautics, 1979
American Astronautical Society, 1986

Selected Professional Involvement

AIAA Astrodynamics Technical Committee, 1990-1993

Selected Publications

McAdams, J., J. Horsewood, and C. Yen, Discovery-Class Mercury Orbiter trajectory design for the 2005 launch opportunity, AIAA/AAS Astrodynamics Specialist Conference, AIAA 98-4283, August 1998.

Yeomans, D. K., J.-P. Barriot, D. W. Dunham, R. W. Farquhar, J. D. Giorgini, C. E. Helfrich, A. S. Konopliv, J. V. McAdams, J. K. Miller, W. M. Owen, Jr., D. J. Scheeres, S. P. Synnott, and B. G. Williams, Estimating the mass of asteroid 253 Mathilde from tracking data during the NEAR flyby, *Science, 278,* 2106-2109, December 1997.

McAdams, J. V., Post-launch contingency trajectories for the Near Earth Asteroid Rendezvous Mission, *Journal of Guidance, Control and Dynamics, 20, 4,* 819-823, July-August 1997.

Farquhar, R., D. Dunham, and J. McAdams, NEAR Mission overview and trajectory design, *The Journal of the Astronautical Sciences, 43, 4,* 353-371, 1996.

McAdams, J., Mission options for rendezvous with the most accessible near-Earth asteroid - 1989 ML, *Journal of the Astronautical Sciences,* 40, 3, 351-368, July-September 1992.

JAMES V. McADAMS

Roles and Responsibilities

As Mission Designer, works with the Mission Manager to refine and implement the detailed launch scenario and trajectory maneuvers.

James V. McAdams

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Date

GEORGE D. NELSON

Current Position Director, American Association for the Advancement of Science (AAAS) Science, Project 2061

Positions Held Associate Vice Provost for Research, Associate Professor of Astronomy and Education, University of Washington (currently on leave)
Astronaut, Mission Specialist, NASA 1978-1989
Manager, Mission Development Branch of the Astronaut Office, NASA

Honors and Awards

Fellow, American Council on Education
American Institute of Aeronautics and Astronautics Halley Space Flight Award
NASA Exceptional Engineering Achievement Medal
NASA Exceptional Service Medal
NASA Spaceflight Medals (3)
U.M. Komarov Diploma, Federation Aeronautique Internationale
American Astronautical Society Flight Achievement Award
Golden Key National Honor Society

Relevant Experience

Administrative responsibility: research policy, government-university-industry interactions, university-K-12 education interactions, and federal relations

Research interests: fields of radiative transfer and hydrodynamics applied to interesting problems in stellar and solar astrophysics. Established the Office of Research Corporate Outreach Program, which provides industry a visible gateway into the university research effort, encouraging collaborative research and technology transfer interactions

Initiated and administers the Royalty Research Fund, which distributes university royalty income to the faculty for innovative research projects through a peer reviewed grant process.

Fellow, American Council on Education, 1992-93

Selected Publications

Nelson, G. D., Benchmarks and standards as tools for science education reform, paper commissioned by the *National Education Goals Panel,* 1997.

Nelson, G. D., Human space exploration: NASA's missing piece, *Newsday,* 1996.

Nelson, G. D., Thoughts on teacher certification, endorsement and assignment, *Washington Science Teachers Association Journal, 34,* 4, 1994.

Nelson, G. D., Scientific opportunities in the human exploration of space, *National Research Council, Space Studies Board,* Committee on the Human Exploration of Space, National Academy Press, 1994.

Nelson, G. D., Scientific Prerequisites for the Human Exploration of space, *National Research Council, Space Studies Board,* Committee on the Human Exploration of Space, National Academy Press, 1993.

Nelson, G. D., L. J. DeLucas, et. al., Protein crystal growth results for shuttle flights STS-26 and STS-29, *Journal of Crystal Growth,* 110, 1991.

Nelson, G. D., An Astronaut in Raikonur, *Final Frontier,* 3, 1990.

Nelson, G. D., L. J. DeLucas, et. al., Protein crystal growth in microgravity, *Science,* 246, 1989.

Nelson, G. D., Granulation in a main-sequence F-type start, *The Astrophysical Journal,* 238, 1980.

GEORGE D. NELSON

Roles and Responsibilities

Astrophysicist, astronaut, educator, and the Director of Project 2061, American Association for the Advancement of Science. Co-leads MESSENGER's Education and Public Outreach effort with Dr. Shirley Malcom. Oversees the alignment of MESSENGER-related science with the National Science Education Standards and Benchmarks for Science Literacy; trains developers and monitors development of good examples (lessons, modules, and training models) consistent with standards. Periodically reviews the planning and output of all education and outreach efforts.

George D. Nelson — 3/17/99

Date

Dr. George D. Nelson
American Association for the Advancement of Science
Project 2061
1333 H Street, N.W.
P.O. Box 3446
Washington, DC 20005
gnelson@aaas.org

MAX RODERIC PETERSON

Current Position Engineer, Principal Professional Staff

Education M.S. Engineering, The Johns Hopkins University (JHU), 1969
B.S. Electrical Engineering, Kansas State University, 1961

Honors and Awards

NASA Group Achievement Award-AMPTE Mission Operations, 1990; NASA Group Achievement Award-AMPTE Project Team, 1985; Sigma Tau Engineering Honorary Society, 1960-present; Eta Kappa Nu Electrical Engineering Honorary Society, 1960-present; Blue Key National Men's Honorary Society, 1960-present; Boeing Company Scholarship, 1959-1960; Salina Supply Company Scholarship, 1958

Relevant Experience

Program Manager, Ballistic Missile Defense Organization (BMDO) Midcourse Space Experiment (MSX), 1989-1998; Proposal Manager, Plasma Energization with Radio Frequency Emission, Coupling and Transport (PERFECT) spacecraft proposal; Program System Engineer, Polar Beacon Experiment and Auroral Research (Polar BEAR) spacecraft; Assistant Program Manager and Program System Engineer, NASA Active Magnetospheric Particle Tracer Explorer/Charge Composition Experiment (AMPTE/CCE) spacecraft; Lead Engineer, ground support system design and development for AMPTE/CCE spacecraft; Lead Engineer (design, development, and testing) of data handling systems, Magnetic Survey Satellite (MAGSAT) spacecraft, Geodetic Earth Orbiting Satellite (GEOS-C), and Small Astronomy Satellite (SAS-A,B,C) spacecraft series.

Skills and Capabilities

Experience with Macintosh PC includes the use of software for word processing, spreadsheet, presentation, graphics, scheduling, management information system, and network communication applications. Instructional experience includes serving as instructor for Space Systems, JHU G.W.C. Whiting School of Engineering (1989-1995); Space Systems Engineering, US Naval Academy (1985-1989); Space Communications, The JHU Evening College Center at APL (1974-1978); and Associate Staff Training Program at APL (1970, 1972, and 1977)

Selected Publications

Peterson, M. R. and D. L. Zitterkopf, The small astronomy satellite-A telemetry system, *JHU/APL Tech. Dig., 10 (4&5),* 11-18, March-June1971.

Peterson, M. R., The small astronomy satellite-3 programmable telemetry system *JHU/APL Tech. Dig., 14 (4),* 7-13, October-December 1976.

Dassoulas, J., D. L. Margolies, and M. R. Peterson, The AMPTE/CCE spacecraft, *IEEE Transactions on Geoscience and Remote Sensing, GE-23 (3),* 182-191, May 1985.

Peterson, M. R. and D. G. Grant, The Polar BEAR Spacecraft, *JHU/APL Tech. Dig., 8 (3),* 295-302, July-September 1987.

Peterson, M. R., Spacecraft integration and test, *Space Systems,* Chapter 13, V. L. Pisacane, (ed.), Johns Hopkins University G. W. C. Whiting School of Engineering Continuing Professional Programs, 1991.

Peterson, M. R., Spacecraft integration and test, Chapter 1, *Fundamentals of Space Systems,* V. L. Pisacane and R. C. Moore, (eds.), Oxford University Press, Inc., New York, 721-749, 1994.

Peterson, M. R., Midcourse Space Experiment Technology: Guest Editor's Introduction, *JHU/APL Tech. Dig., 17 (2),* 134-136, April-June 1996.

Peterson, M. R., Midcourse Space Experiment Overview: Guest Editor's Introduction, *JHU/APL Tech. Dig., 17 (1),* 2-3, January-March 1996.

MAX RODERIC PETERSON

Roles and Responsibilities

As Project Manager, supports the Principal Investigator to meet science goals within cost and schedule. Manages all JHU/APL responsibilities and directs detailed planning and scheduling, cost tracking and reporting, and allocation of resources. Oversees product assurance, project coordination, and review activities.

[signature]

March 11, 1999
Date

Mr. Max R. Peterson
The Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-6099
Phone: 240-228-5832
Fax: 240-228-5295
m.peterson@jhuapl.edu

ANDREW G. SANTO

Current Position System Engineer, Principal Professional Staff

Education B.S. (Engineering Science, Magna Cum Laude), The Pennsylvania State University, 1983
M.S. (Electrical Engineering and Computer Science, Magna Cum Laude), The Johns Hopkins University, 1985
M.S. (Technical Management) The Johns Hopkins University, 1994

Positions Held The Johns Hopkins University Applied Physics Laboratory, Space Department, 1985-present; Lawrence Livermore Laboratory, 1984; IBM, 1983

Honors and Awards

Principal Professional Staff, 1997
JHU/APL Outstanding Publication Award, 1996

Revelant Experience

Technical Lead for NEAR Mission Operations including Mathilde Flyby; Spacecraft System Engineer for NEAR spacecraft; Spacecraft System Engineer for ALTAIR spacecraft; Ground System Lead for UVISI instrument on MSX spacecraft; Launch Vehicle Interface Lead for Delta 183 spacecraft; Ground System Lead for Delta 180, 181 spacecraft

Professional Societies

AIAA, 1987-present

Selected Publications

Cheng, A. F., A. G. Santo, K. J. Heeres, J. A. Landshof, R. W. Farquhar, R. E. Gold, and S. C. Lee, Near Earth Asteroid Rendezvous: Mission overview, *Special Issue J. Geophys. Res., 102,* 23695-23708, 1997.

Cheng, A. F., R. W. Farquhar, and A. G. Santo, Near Earth Asteroid Rendezvous, *JHU/APL Tech. Dig.,* 19, 2, 95-106. 1998.

Santo, A. G., S. M. Krimigis, and T. B. Coughlin, The NEAR mission to the Asteroid Eros, Paper IAA 96-IAA.11.2.06, *Proc. 47th International Astronautical Congress,* Beijing, China, 1996.

Santo, A. G. S. M. Krimigis, R. E. Jenkins, E. L. Reynolds, and T. B. Coughlin, Lessons for the future: The NEAR mission in NASA's Discovery Program, Paper IAA-IAF.11.2.04, *Proc. 47th International Astronautical Congress,* Beijing, China, 1996.

Santo, A. G., S. C. Lee, and A. F. Cheng, Near Earth Asteroid Rendezvous (NEAR) spacecraft overview, Proc. IEEE Aerospace Applications Conference, 131-144, Aspen, CO, 1996.

Bearden, D. A., N. Y. Lao, T. B. Coughlin, A. G. Santo, J. T. Hemmings, and W. L. Ebert, Incorporation of NEAR costs in a small-spacecraft cost model, *Proc. 10th Annual AIAA/USU Conference on Small Satellites, Utah State University, Technical Session IV, Better, Cheaper, Faster,* 1996.

Lee, S. C. and A. G. Santo, Near Earth Asteroid Rendezvous (NEAR) spacecraft safing design, *Proc. 2nd IAA International Conference on Low-Cost Planetary Missions,* Paper IAA-L-0517, 1996.

Lee, S. C. and A. G. Santo, Tradeoffs in functional allocation between spacecraft autonomy and ground operations: The NEAR (Near Earth Asteroid Rendezvous) experience, *Proc. 10th Annual AIAA/USU Conference on Small Satellites, Technical Session VI, Mission Operations,* 1996.

Maurer, R. H. and A. G. Santo, The NEAR Discovery Mission: Lessons learned, *Proc. 10th Annual AIAA/USU Conference on Small Satellites, Technical Session I, Hardware in Space,* 1996.

Santo, A. G., S. C. Lee, and R. E. Gold, NEAR spacecraft and instrumentation, *J. Astronomical Sciences, 43(4),* 373-397, 1995.

ANDREW G. SANTO

Roles and Responsibilities

As Mission System Engineer, provides the technical lead for mission implementation, working closely with the Project Manager, Project Scientist, Science Payload Manager, and Principal Investigator. Develops mission-level requirements derived from science requirements and flow-down requirements to spacecraft, instrument interfaces, ground system, and mission operations. Leads trade-off studies, makes risk assessments, maintains liaison with science payload for interface control, monitors mass and power, oversees spacecraft integration and test, and oversees mission operations for spacecraft.

2/11/99

Date

Mr. Andrew G. Santo
The Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel, MD 20723-6099
Phone: 240-228-6120
Fax: 240-228-6556
andrew.santo@jhuapl.edu

APPENDIX B

LETTERS OF ENDORSEMENT

Co-Investigators:

Brown University	James W. Head, III
Massachusetts Institute of Technology	Maria T. Zuber
NASA/Goddard Space Flight Center	Mario H. Acuña
	James A. Slavin
	David E. Smith
	Jacob I. Trombka
Northwestern University	Mark S. Robinson
Southwest Research Institute	Clark R. Chapman
The Johns Hopkins University	Andrew F. Cheng
Applied Physics Laboratory	Robert E. Gold
	Stamatios M. Krimigis
	Ralph L. McNutt, Jr.
	Scott L. Murchie
University of Arizona	William V. Boynton
	Robert G. Strom
University of California, Santa Barbara	Stanton J. Peale
University of Colorado	Daniel N. Baker
	William McClintock
University of Michigan	George Gloeckler
Washington University	Roger J. Phillips

Partners:

Composite Optics Incorporated	Theodore G. Stern
GenCorp Aerojet	Robert D. Harris
Jet Propulsion Laboratory	A. L. Berman
	G. K. Noreen
	G. F. Squibb
Mid-Atlantic Technology Applications Center	Lani S. Hummel

Education and Public Outreach:

American Association for the Advancement of Science	Shirley M. Malcom
	George D. Nelson
	Judy Kass
American Museum of Natural History	Nancy Hechinger
Carnegie Academy for Science Education	Charles C. James
Challenger Center for Space Science Education	Jeffrey J. Goldstein
Independents	Nina Parmee
	Eitan Weinreich
Montana State University, Center for Educational Resources	George F. Tuthill
Minority University-Space Interdisciplinary Network	James L. Harrington
National Air and Space Museum, Smithsonian Institute	Thomas R. Watters
Proxemy Research, Inc.	Stephanie A. Stockman
Space Explorers, Inc.	Tia S. Dutter

BROWN UNIVERSITY *Providence, Rhode Island • 02912*

DEPARTMENT OF GEOLOGICAL SCIENCES
401 863-2526, 2417, 3338

March 2, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon,

Brown University extends its full and enthusiastic support for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. Brown is please to endorse the participation of Dr. James W. Head, III as MESSENGER Co-Investigator. Brown shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Alice Tangredi-Hannon
Director, Office of Research Administration

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139-4307

DEPARTMENT OF EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

February 10, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Sean
Dear Dr. Solomon:

The Department of Earth, Atmospheric and Planetary Sciences of the Massaachusetts Institute of Technology extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. The Department is pleased to endorse the participation of Professor Maria T. Zuber as a MESSENGER Co-Investigator. The Department shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Ron Prinn

Ronald G. Prinn
TEPCO Professor and Department Head

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 696

Dr. Sean C. Solomon, Director
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, D.C. 20015

Dear Dr. Solomon:

It gives me great pleasure to endorse the participation of Drs. Mario Acuña and James A. Slavin, as Co-investigators on the MESSENGER Mission being proposed by you and your team in response to Discovery Announcement of Opportunity. It is my understanding that the Laboratory for Extraterrestrial Physics will be providing a Magnetometer flight instrument as part of the MESSENGER science instrument payload as well as participating in all phases of the mission and subsequent science data analysis. Enclosed you will find a separate budget summary listing the staffing and funding levels necessary to carry out each of these tasks.

We, at the Goddard Space Flight Center wish you and your team the best of luck in this endeavor.

Sincerely,

Stephen S. Holt
Director of Space Sciences

Enclosure

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 920

MAR 1999

Mr. Max Peterson
The Johns Hopkins University
Applied Physics Laboratory (APL)
11100 Johns Hopkins Road
Laurel, MD 20723-6099

Dear Mr. Peterson:

The Goddard Space Flight Center extends its full and enthusiastic support for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. GSFC is pleased to endorse the participation of Dr. David E. Smith as a MESSENGER Co-Investigator. GSFC shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

A. V. Diaz
Director

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 691

Dr. Sean C. Solomon, Director
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, D.C. 20015

Dear Dr. Solomon:

It gives me great pleasure to endorse the participation of Dr. Jacob I. Trombka as Co-investigator on the MErcury: Surface, Space ENvironment, GEochemistry, Ranging, (MESSENGER) Mission being proposed by you and your team in response to Discovery Announcement of Opportunity AO-98-0SS-04. It is my understanding that the Laboratory for Extraterrestrial Physics will be providing science and engineering guidance throughout the development and calibration of the x-ray/gamma-ray instrument as well as participating in all phases of the mission and subsequent science data analysis. We wish you and your team the best of luck in this endeavor.

Sincerely,

Stephen S. Holt
Director of Space Sciences

NORTHWESTERN
UNIVERSITY

OFFICE OF RESEARCH AND SPONSORED PROGRAMS

February 25, 1999

Letter of Endorsement

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washingon, DC 20015

Dear Dr. Solomon:

Northwestern University (JHU/APL) extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the NASA Discovery Announcement of Opportunity AO-98-OSS-04. Northwestern University is pleased to endorse the participation of Mark S. Robinson as a Messenger Co-Investigator and will support his participation in all mission phases.

Sincerely,

Barbara E. Siegel

Barbara E. Siegel, Director

633 CLARK STREET EVANSTON, ILLINOIS 60208-1110 847-491-3003 FAX: 847-491-4800
Office of the Vice President for Research and Graduate Studies

SOUTHWEST RESEARCH INSTITUTE

DIVISION 15 — BOULDER EXTENSION OFFICE • 1050 WALNUT, SUITE 429 • BOULDER CO 80302 • (303) 546-9670 • FAX (303) 546-9687

GEOPHYSICAL, ASTROPHYSICAL, AND PLANETARY SCIENCES SECTION

March 1, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

Southwest Research Institute extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. Southwest Research Institute is pleased to endorse the participation of Dr. Clark R. Chapman as a MESSENGER Co-Investigator. Southwest Research Institute shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Alan Stern

Dr. S. Alan Stern
Director,
Department of Space Studies

cc: Dr. Clark R. Chapman
Dr. William J. Merline

SAN ANTONIO, TEXAS
BOULDER, COLORADO • HOUSTON, TEXAS • DETROIT, MICHIGAN • WASHINGTON, D.C.

JOHNS HOPKINS
UNIVERSITY

Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel MD 20723-6099
240-228-5000 / Washington
443-778-5000 / Baltimore

March 8, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) extends its full and enthusiastic support for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. JHU/APL is pleased to endorse the participation of Drs. Andrew F. Cheng, Robert E. Gold, Stamatios M. Krimigis, Ralph L. McNutt, Jr., and Scott L. Murchie as MESSENGER Co-Investigators. The Laboratory shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

G. L. Smith
Director

Department of Planetary Sciences
Lunar and Planetary Laboratory

THE UNIVERSITY OF
ARIZONA
TUCSON ARIZONA

Tucson, Arizona 85721
Tel: (602) 621-6963
Fax: (602) 621-4933
Telex: 187167 AZUTUC UT

February 25, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Sean:

The Lunar and Planetary Laboratory extends its full and enthusiastic support of the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (Messenger) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. The Laboratory is pleased to endorse the participation of Professors William V. Boynton and Robert G. Strom as Messenger Co-Investigators. The Laboratory will provide its full support to the MESSENGER Mission in executing all mission phases consistent with its obligations under the terms of the grants or contracts.

Sincerely,

Michael J. Drake
Head/Director

UNIVERSITY OF CALIFORNIA, SANTA BARBARA

UCSB

BERKELEY · DAVIS · IRVINE · LOS ANGELES · RIVERSIDE · SAN DIEGO · SAN FRANCISCO

SANTA BARBARA · SANTA CRUZ

Office of the Vice Chancellor
Research
Santa Barbara, CA 93106-2050
Tel: (805) 893-4188
Fax: (805) 893-2611
Web: research.ucsb.edu

February 26, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington DC 20015

Dear Dr. Solomon:

The University of California at Santa Barbara (UCSB) estends its full and enthusiastic support for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. UCSB is pleased to endorse the participation of Dr. Stanton J. Peale as a MESSENGER Co-Investigator.

Sincerely,

France A. Córdova
Vice Chancellor for Research
& Professor of Physics

University of Colorado at Boulder
Office of the Associate Vice Chancellor for Research
and Dean of The Graduate School

February 8, 1999

Dr. Sean C. Solomon, Director
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Brand Road, N.W.
Washington, DC 20015

Dear Dr. Solomon,

The University of Colorado enthusiastically endorses the participation of Dr. William E. McClintock and Dr. Daniel N. Baker in Mercury: Surface, Space, Environment, Geochemistry, Ranging (MESSENGER) Discovery mission. We look forward to taking part in this exciting project. This letter certifies, that, if the project is selected and funded by NASA, the University of Colorado is committed to carry out the work assigned to the University as described in this proposal according to the stated budget and schedule.

Sincerely,

Carol B. Lynch

Carol B. Lynch
Associate Vice Chancellor for Research
and Dean of the Graduate School

CBL:bp

CC: Max Peterson
The Applied Physics Laboratory
The Johns Hopkins University

UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
ATMOSPHERIC, OCEANIC AND SPACE SCIENCES

SPACE RESEARCH BUILDING
2455 HAYWARD
ANN ARBOR, MICHIGAN 48109-2143
TELEPHONE: 734 764-3335 FAX: 734 764-4585

(734) 647-3660

February 22, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Sean,

The University of Michigan's Department of Atmospheric, Oceanic and Space Sciences (AOSS) extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. On behalf of this department, I am pleased to endorse the participation of Dr. George Gloeckler as a MESSENGER Co-Investigator. AOSS shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Lennard A. Fisk
Professor and Chair

George M. Gloeckler
Adjunct Professor

LAF/jl

Washington
WASHINGTON · UNIVERSITY · IN · ST · LOUIS

Department of
Earth and Planetary Sciences

February 26, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road
Washington, DC 20015

Dear Dr. Solomon:

The Department of Earth and Planetary Sciences at Washington University is pleased to support the MErcury: Surface, Space, ENvironment, GEochemistry Ranging (MESSENGER) Mission proposal with Professor Roger J. Phillips as a member of the Messenger Science Team.

Yours sincerely,

Raymond E. Arvidson
Chairman

REA/gk

Washington University
Campus Box 1169
One Brookings Drive
St. Louis, Missouri 63130-4899
(314) 935-5610

FAX: (314) 935-7361

COI-0399-26707
March 17, 1999

Carnegie Institution of Washington
Department of Terrestrial Magnetism
5241 Broad Branch Road, N.W.
Washington, DC 20015

Attention: Dr. Sean C. Solomon

Subject: Program Endorsement

Reference: COI Proposal #PL-5168 Revision 4 for the MESSENGER Mercury Orbiter Spacecraft Structure

Dear Dr. Solomon:

Composite Optics, Incorporated (COI), is pleased to support The Johns Hopkins University Applied Physics Laboratory in the proposed Mercury: Surface Space /Environment, Geochemistry, Ranging (MESSENGER) mission. COI operates towards the objectives of our company's core goals - Customer Satisfaction, Business Success, Technology Growth and Work Gratification. The MESSENGER program provides an ideal vehicle for achieving these goals through the advanced technology that will be incorporated into the spacecraft structure, the gratification felt by all team members working on such an exciting project for planetary exploration, and the customer satisfaction and business success that will result from COI's commitment to on-time delivery and high performance hardware.

It is a central focus of COI to provide the composite technology and hardware needed to enable advanced planetary missions. We are proud to have been part of the teams for the Stardust, Mars '98 and Deep Space 1 missions, just to mention a few of the more recent flight successes. We look forward to our contribution to this program, which we are sure will prove to be both exciting and challenging.

Should you have any questions, please do not hesitate to contact me.

Sincerely,

Theodore G. Stern
General Manager
Structures & Systems

cc: E. Derby
G. Tremblay
New Business File

Composite Optics, Inc. • 9617 Distribution Ave. • San Diego, CA 92121
Tel: 619.621.5700 • Fax: 619.621.5770 • EMail: coi@coi-world.com • Web: www.coi-world.com

GENCORP
AEROJET

Robert D. Harris
Vice President,
Strategic & Space Propulsion

PO Box 13222
Sacramento CA 95813-6000

Tel: 916-355-2721
Fax: 916-355-3743
E-Mail: Robert.Harris@Aerojet.com

12 March 1999
RDH:ltr:99-002.doc

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

Aerojet is pleased to extend its enthusiastic endorsement for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. Aerojet would like to commend you on this effort and offer you its support.

As part of Johns Hopkins University Applied Physics Laboratory suppliers, Aerojet brings over 57 years of rocket propulsion expertise to the MESSENGER mission and offers support from key personnel including members of our Near Earth Asteroid Rendezvous team: Samuel R. Wiley, David B. Gallet, Douglas H. Anderson and Christopher P. Lucas. Aerojet confirms its full support to the MESSENGER Mission and is pleased at the opportunity to be part of this exciting endeavor.

Sincerely,

[signature]

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-4321

JPL

March 10, 1999

Refer to: 920-99.002:GKN

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

Enclosed please find our estimate for support of the proposed MESSENGER mission using Telecommunications and Mission Operations Directorate (TMOD) services. Estimated are costs for adaptation of multimission services and operational support of these services throughout the life of the mission.

It is our understanding that, at this time, your interest in TMOD services is limited to Deep Space Network (DSN) tracking and support from the Radio Metric and Navigation Service Group. DSN aperture fees of $7,150 K (w/o reserve) are based on the algorithm in the February 1999 Handbook for Mission Costing, with a $553/month base rate (FY 99 dollars).

DSN facilities are shared with other missions, and specific tracking commitments are made through a resource allocation process in which all missions participate. We thus cannot make commitments to specific tracking support for specific missions at this time.

The support provided by the Radio Metric and Navigation Services includes radio metric orbit determination, trajectory and maneuver analysis, and Mercury ephemeris updates during the pre-launch, launch, and operational phases of the MESSENGER mission. The services include software modifications and documentation peculiar to this mission. Software maintenance services will also be provided during the operational phase of the mission. The estimated cost for this service is $5,359 K (w/o reserve). This estimate is in real-year dollars. Also provided is a list of proposed tasks to be completed as part of the Phase A/B activity.

This letter affirms JPL's commitment of support to the proposed MESSENGER mission with DSN and navigation services, if selected. TMOD management will review the cost estimates as the MESSENGER proposal matures during phase A/B studies. If necessary these estimates will be renegotiated to account for changes in requirements.

DSN tracking costs provided in this estimate are based on "prices" rather than true costs and are set by NASA policy. That policy is still evolving as NASA moves into full-cost accounting. The pricing algorithm was frozen for this Discovery round.

A. L. Berman	G. K. Noreen	G. F. Squibb, Director for
TMS Manager	Future Missions Office	Telecommunications and Mission Operations

Mid-Atlantic Technology Applications Center

March 19, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

MTAC works one-on-one with U.S. firms to improve their competitiveness by assisting them in the location, assessment, acquisition, utilization and commercialization of technologies and expertise within the federal laboratory system.

Dear Dr. Solomon:

The Mid-Atlantic Technology Applications Center (MTAC) extends its full and enthusiastic support for the MErcury Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. MTAC is pleased to endorse the participation of John Bacon, Robert Grimes, Robert Saba, Charles Taylor, Dr. Kevin Smith, Joseph Gielas, and Rebecca Watkins, and myself. MTAC will fully support all technology commercialization and technology infusion aspects of the mission.

As one of NASA's six Regional Technology Transfer Centers, MTAC helps US firms improve their competitiveness by assisting them in the location, assessment, acquisition and utilization of technologies and scientific and engineering expertise within the federal government. In pursuit of this mandate, MTAC developed an in-depth knowledge of industry needs and capabilities.

As a result, MTAC now offers a technology marketing service for federal, university and corporate laboratories. We have been highly successful in generating licensing opportunities as well as dual-use, industry-sponsored research projects. MTAC also provides technology infusion expertise to its clients in search of existing commercial technologies/expertise to incorporate into their R&D programs. This service provides significant value by reducing research costs and by exposing R&D project scientists to new technologies, approaches and processes.

MTAC's technology commercialization/technology infusion program is very effective with a demonstrated record of success. We look forward to bringing that same level of success to the MESSENGER project.

Sincerely,

Lani S. Hummel

Lani S. Hummel
Executive Director

University of Pittsburgh • 3400 Forbes Avenue, Fifth Floor • Pittsburgh, Pennsylvania 15260
phone: 412-383-2500 / *fax:* 412-383-2595 • http://oracle.mtac.pitt.edu/WWW/MTAC.html

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Richard S. Nicholson
Executive Officer

1200 New York Avenue, NW
Washington, DC 20005
Tel: 202 326 6639
Fax: 202 371 9526
Internet: rnichols@aaas.org

March 15, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, NW
Washington, DC 20015

Dear Dr. Solomon:

The American Association for the Advancement of Science (AAAS) is pleased to join the Carnegie Institution of Washington in its proposed MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission submitted in response to the Discovery Announcement of Opportunity AO-98-OSS-04. AAAS strongly endorses the participation of our education and outreach team, especially Drs. Shirley Malcom and George Nelson, Co-Directors of MESSENGER Education and Public Outreach, and Ms. Judy Kass, the team leader for AAAS Public Outreach.

We are delighted to support their efforts and to have such recognition of our outstanding leadership in science, mathematics and technology education..

Sincerely,

Richard S. Nicholson

American Museum of Natural History

National Center for Science Literacy, Education and Technology

March 16, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institute of Washington
5241 Broad Branch Road, NW
Washington, DC 20015

Dear Dr. Solomon:

I am pleased to provide this letter in support of your funding proposal for the Mercury: Surface, Space ENvironment, GEochemistry, Ranging Mission (MESSENGER). The American Museum of Natural History, through its newly established National Center for Science Literacy, Education, and Technology, is very interested in working with you to maximize the educational impact of this tremendously important project.

With its tradition of excellence in research, the array of scientific resources on which it can draw, the size of its audience, and its dedication to public education, the American Museum of Natural History is positioned to assume a significant new role in advancing standards of scientific literacy nationwide.

The National Center creates a wide variety of educational programs and materials by working closely with partners who share our vision. We see the MESSENGER Mission as a prime example of this sort of partnership, one that will enable us to share the latest scientific thinking with a broad and, as evidenced by the tremendous response to the Mars Pathfinder mission, interested public. A collaboration with the MESSENGER Mission is of particular interest given that the Museum is in the midst of a major initiative to completely update its Hayden Planetarium as part of the construction of the Frederick Phineas and Sandra Priest Rose Center for Earth and Space, which also includes two new permanent exhibition halls—the Hall of the Universe and the Hall of Planet Earth.

The following staff will participate and lead this project: Nancy Hechinger, Director, Caroline Nobel, Assistant Director, and Dr. Steve Soter, Scientist. The remaining National Center staff will provide its committed support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Nancy Hechinger
Director
National Center for Science Literacy,
Education and Technology

Central Park West at 79th Street, New York, N.Y. 10024-5192 USA 212-769-5000

CARNEGIE INSTITUTION

Extending the Frontiers of Science

CARNEGIE INSTITUTION OF WASHINGTON

Department of Plant Biology

Department of Embryology

Department of Terrestrial Magnetism

Geophysical Laboratory

The Observatories

Carnegie Academy for Science Education and First Light

March 11, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5341 Broad Branch Road, N.W.
Washington, D.C. 20015

Dear Dr. Solomon:

The Carnegie Academy for Science Education (CASE) extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (Messenger) Mission being proposed by your and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. CASE is pleased to endorse the participation of Charles C. James and Dr. Julie Edmonds. CASE shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Maxine F. Singer
President

Challenger CENTER®

Challenger Center for Space Science Education

March 10, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

The Challenger Center for Space Science extends its full and enthusiastic support for the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. Challenger Center is pleased to endorse the participation of Dr. Jeff Goldstein and Mr. Daniel LaBry. Challenger Center shall provide its full support to the MESSENGER Mission in executing all mission phases.

Sincerely,

Vance R. Ablott
President and CEO

1029 North Royal Street Suite 300 Alexandria, Virginia 22314 703-683-9740 FAX 703-683-7546

Nina Parmee

357 WEST 12TH STREET, #2R NEW YORK, NY 10014 212 414 9122

March 19, 1999

Dr. Sean C. Solomon
Dept. of Terrestrial Magnetism
Carnegie Institution of Washington
5241Broad Branch Road, N.W.
Washington, D.C. 20015

Dear Dr. Solomon,

I am writing to confirm my enthusiastic interest in developing and producing a series of television shows on the MESSENGER project.

As producer of the National Geographic Special "Asteroids: Deadly Impact" I'm certainly familiar with the rich dramatic and educational potential of television programming on space.

The popularity of the Mars Pathfinder mission clearly demonstrates the wide appeal of space exploration; a series of programs following a mission like MESSENGER from its very inception onward promises to be especially attractive to the viewing public.

MESSENGER offers an opportunity to create groundbreaking science programming; I look forward to participating in this exciting venture.

Yours truly,

Nina Parmee

EITAN WEINREICH

March 19, 1999

Dr. Sean C. Solomon
Dept. of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road
Washington, DC 20015

Dear Dr. Solomon:

Having recently written and directed the National Geographic Television Special "Asteroids – Deadly Impact," which was broadcast in prime time on NBC, I am keenly aware that the viewing public as well as the broadcast industry are highly receptive to and interested in compelling space programming.

The MESSENGER project presents an extraordinary opportunity to respond to that interest with television programming which would offer the public an unprecedented sense of involvement in space exploration. I would be delighted to participate in the development and production of this programming, and am confident it will prove attractive and rewarding to major broadcast and cable concerns.

Sincerely,

Eitan Weinreich

357 WEST 12TH STREET # 2-R, NEW YORK, NY 10014
voice/fax: 212 366 9625 e-mail: eweinreich@aol.com

MONTANA STATE UNIVERSITY
BOZEMAN

George F. Tuthill
Dept. of Physics, EPS 264
Montana State University
Bozeman, Montana 59717-3840

Telephone 406-994-6177
FAX 406-994-4452
E-mail: tuthill@physics.montana.edu

March 17, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

The MSU Center for Educational Resources (CERES) Project is very pleased to support the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission proposal that your group has prepared. We are prepared to commit the resources and efforts of Drs. George Tuthill, Tim Slater and Dave Thomas, as well as Kim Obbink (Director of MSU's Burns Telecommunications Center) in furthering the educational and public outreach programs of the MESSENGER Mission.

Yours,

George Tuthill
Professor of Physics and Director, CERES Project

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 933

March 16, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

The Minority University-SPace Interdisciplinary Network Project of NASA Goddard Space Flight Center is proud to be a collaborator for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. The MU-SPIN project is pleased to endorse the participation of its Network Resources and Training Sites (NRTS) which serve as NASA broker facilitators for the Historically Black Colleges (HBCUs) and Hispanic Serving Institutions (HSIs) and Tribal Colleges. As part of the Outreach team, we are excited about the ability to access the mission data and research outcomes to further strengthen science opportunities for participation for the minority institutions and increase the national benefits for funding such a mission.

Sincerely,

James L. Harrington, Jr.
MU-SPIN Project Manager

Smithsonian
National Air and Space Museum

Office of the Director

March 12, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Board Branch Road
Washington, DC 20015

Dear Dr. Solomon:

The National Air and Space Museum of the Smithsonian Institution extends its full and enthusiastic support for the Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. The National Air and Space Museum is pleased to endorse the participation of Dr. Thomas R. Watters as a member of the MESSENGER Education and Public Outreach team. We are delighted to have the opportunity to work with you to bring the results of the MESSENGER Mission to the public.

Sincerely,

Donald D. Engen
Director

SMITHSONIAN INSTITUTION
Office of the Director
Independence Avenue at Sixth Street SW
Washington DC 20560-0310
202.357.1745 Telephone
202.357.2426 Fax

Proxemy Research

20528 Farcroft Lane • Laytonsville, MD 20882 • (301) 869-0838• Email: Proxemy@aol.com

March 12, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

Proxemy Research is pleased to endorse the participation of Ms. Stephanie Stockman as Education Coordinator on the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04. Proxemy Research shall provide its full support to the MESSENGER Mission in executing Education and Outreach objectives in all mission phases.

Sincerely,

Dr. Lori S. Glaze
Vice President

cc S. Stockman

SPACE EXPLORERS INC.

March 12, 1999

Dr. Sean C. Solomon
Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Dear Dr. Solomon:

Space Explorers, Inc. (SEI) is pleased to extend its support and endorsement of the MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER) Mission being proposed by you and your team in response to the Discovery Announcement of Opportunity AO-98-OSS-04.

SEI, a private organization who's mission is "*to create learning opportunities by bring live space exploration missions to the classroom*," is fully committed to developing and supporting the Education and Outreach activities being created by the MESSENGER Mission. We are pleased to commit the involvement of Ms. Tia Dutter, Vice President of Education Programs in support of the mission.

We welcome the opportunity to be part of this exciting mission and are fully committed to supporting you and your team.

Sincerely,
SPACE EXPLORERS, INC.

Tia S. Dutter
Vice President

1825 Nimitz Drive
De Pere, WI 54115
920-339-4600
1-800-965-3763
Fax 920-339-4612
E-Mail moonlink@space-explorers.com
www.space-explorers.com

APPENDIX C

NASA PI HARDWARE SELECTION PROCESS

Not applicable.

APPENDIX D

Mission Definition and Requirements Agreement (Draft)

1.0 MESSENGER Mission Overview

MESSENGER is a scientific mission to Mercury. Understanding this extraordinary planet and the forces that have shaped it is fundamental to understanding the processes that governed the formation, evolution, and dynamics of the terrestrial planets.

MESSENGER is a *ME*rcury *S*urface, *S*pace *EN*vironment, *GE*ochemistry and *R*anging mission to orbit Mercury for one Earth year after completing two flybys of the planet. The necessary flybys will return significant new data prior to orbit insertion. The orbital phase, guided by the flyby data, will perform a focused scientific investigation of this least-studied terrestrial planet. Answers to key questions about Mercury's high density, crustal composition and structure, volcanic history, core structure, magnetic field generation, polar caps, exosphere, overall volatile inventory, and unique magnetosphere will be provided by an optimized set of miniaturized space instruments.

The first of MESSENGER'S two 15-day launch windows opens on March 23, 2004, the most favorable opportunity for the next decade. After launch by a Delta II 7925H, two flybys of Venus and two flybys of Mercury are needed before orbit insertion at the third Mercury encounter on September 30, 2009. Orbital science observations are then carried out for one Earth year. An additional year of analysis provides a full suite of results conveyed to the science community, thepublic, and thePlanetary Data System.

MESSENGER's orbit about the planet has an initial periapsis altitude of ~145 km and initial latitude of periapsis of 60°N; the orbit is inclined 80° to the equatorial plane of the planet and has a 12-hour period. The periapsis altitude and orbit phasing have been optimized to maximize the science return while staying within the thermal constraints. The inclination and latitude of periapsis result from balancing the complex trade-space driven by imaging coverage with the scan mirror, altimetry coverage that is limited by altitude and allowable spacecraft tilts, thermal input from the planet, and spacecraft mass. Solar perturbations impose changes in the periapsis altitude and latitude that are corrected periodically in accord with science measurement requirements.

MESSENGER's mission design is well matched to a comprehensive science investigation. Significant scientific return can be expected from each flyby, and the orbital phase of the mission will achieve all principal scientific objectives.

During the flybys, regions unexplored by Mariner 10 will be seen for the first time. New data will be gathered on Mercury's atmosphere and magnetosphere as well as the first information on the surface composition. Approach and departure movies as well as high-resolution imagery will bring the mission alive both to the scientific community and the public at large.

During the orbital phase of the mission, MESSENGER's science strategy shifts to detailed global mapping, characterization of the atmosphere, magnetosphere, and polar caps, geophysical studies, and focused study of high-priority targets identified during the flyby phase. Details of the observations follow from the key science questions.

To implement the mission, the Principal Investigator, Dr. Sean C. Solomon, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (CIW), and The Johns Hopkins University Applied Physics Laboratory (hereinafter referred to as APL), are heading a consortium to provide the spacecraft and instrumentation consisting of Composite Optics, Inc., a leader in light-weight spacecraft structures, GenCorp Aerojet, a leader in spacecraft propulsion systems, Goddard Space Flight Center, the University of Michigan, and the Laboratory for Atmospheric and Space Physics at the University of Colorado. Co-engineered with planetary-science specialists from 12 institutions, MESSENGER has been designed to overcome the severe thermal inputs and provide a benign thermal environment, supply the required large ΔV of 2700 m/s, while enabling all science observations. The integrated structure, propulsion, and thermal design; fully-redundant integrated electronics module (IEM) for avionics functions; dual phased-array antennas; radiation-hardened, high-temperature solar panels; and high level of spacecraft autonomy all assist in providing a mission with robust margins.

2.0 Science Requirements

Mercury holds many keys to terrestrial planet evolution. The science requirements, defined and prioritized in the Phase-One proposal and validated during the Concept Study, are designed to answer the following questions:

What planetary formational processes led to the high metal/silicate ratio in Mercury?

What is the geological history of Mercury?

What is the nature and origin of Mercury's magnetic field?

What is the structure and state of Mercury's core?

What are the radar-reflective materials at Mercury's poles?

What are the important volatile species and their sources and sinks on and near Mercury?

These science questions map into science objectives, the required elements of the instrument suite, and the measurement strategy. The mapping from the science objectives to the required MESSENGER data products and instrument performance is shown in Table C-1. The instrument suite consists of a dual imaging system (MDIS) for wide and narrow fields-of-view, monochrome and color imaging, and stereo; γ-ray and neutron spectrometer (GRNS) and X-ray spectrometer (XRS) for surface chemical mapping; a magnetometer (MAG); a laser altimeter (MLA) and radio science (RS); a combined UV-visible (ASCS/UVVS) and visible-near-infrared (ASCS/VIRS) spectrometer to survey both exospheric species and surface mineralogy; and an energetic particle and plasma spectrometer (EPPS) to sample charged species in the magnetosphere.

Primary Requirements. The instruments required to accomplish the primary and secondary requirements are indicated in Table C-1. The primary requirements constitute the science performance floor and represent the minimum science necessary to ensure that the mission is a success. Decisions to descope the science requirements require mutual agreement between the MESSENGER Project partners and NASA.

The payload instrumentation has been selected to provide functional redundancy across scientific objectives and to ensure complementarity of observations in case of problems. Such redundancy also provides for important cross checks in the consistency of results obtained with more than one instrument.

3.0 Mission and Project Requirements

3.1 There are no proprietary science rights for the MESSENGER mission. Public dissemination of images and data will occur immediately following calibration with the best currently available calibration algorithms. All relevant mission data will be validated by the project and archived to the Planetary Data System (PDS). Selected additional data products of scientific interest will be disseminated in electronic and printed formats. In parallel with final archiving at the PDS, scientific results will be shared with the science community via scientific meetings and peer-reviewed publications as determined by the PI.

3.2 The MESSENGER mission shall be accomplished within the budgetary requirements contained in Table C-2. Adjustments within the overall funding level may be made between development, operations and launch vehicle funding accounts, or between years, only if approved by NASA. The ELV cost is based on the AO cost level with additional information provided by the KSC ELV Program Office. Reduction in funding for education and public outreach activities must be approved by NASA. Other adjustments may be made within the project as required.

3.3 The level-1 schedule milestones are given in Table C-3.

3.4 The MESSENGER mission will establish an effective and efficient management approach that will assure the science requirements can be

Table Ap.D-1 MESSENGER Science Performance Requirements

Science Objective	Primary/ Secondary	Required Product	Minimum Required Performance	Instruments
Map Mercury surface composition	P	Low-resolution global map, by element	O, Si, S, Fe, H, K, Th, U to 10% relative uncertainty	GRNS
	P	Global color-unit map	2.5/5.0 km pixels in northern/southern hemispheres	MDIS
	S	High-resolution global map, by element	Mg, Al, Si, S, Ca, Ti, Fe to 10% relative uncertainty	XRS
	S	Spectral unit map	Spectra of >50,000 globally distributed sites	ASCS/VIRS
Image Mercury at high resolution	P	Global monchrome map	250-m average resolution, > 90% coverage	MDIS
	P	Global multispectral map	2.5/5.0-km pixels in northern/southern hemispheres	MDIS
	P	Stereo map	80% coverage of planet	MDIS
	P	Northern hemisphere topographic profiles	Half of northern hemisphere at 1.5 m average height resolution	MLA
Determine structure of Mercury magnetic field	P	Multipole magnetic field model	Resolve at least through quadrupole	MAG
	P	Time-dependent magnetospheric model	Triaxial magnetic field sampling rates from 0.1 to 20 Hz; global particle intensities of H, He, CNO, Fe, ≥ spacecraft potential to 3 MeV	EPPS, MAG
Measure libration amplitude and gravity field structure	P	Libration amplitude and pole position	50-m root-mean-square libration amplitude, 5-μrad pole position	MLA, RS
	P	Spherical harmonic gravity field	16x16 degree and order	RS
Determine composition of radar-reflective polar deposits	P	Map of polar region, by element	O, S, H to 10% relative uncertainty	GRNS
	P	Topographic profiles across polar craters	1.5-m average height resolution	MLA
Characterize exosphere neutrals, magnetosphere ions	S	Volatile species and sources	Profiles of H, O, Na at 25-km altitude resolution; plasma composition and distribution functions; energetic H, He, CNO, Fe, ≥2 keV/nuc. to 3 MeV	ASCS/UVVS, EPPS/FIPS, EPPS/EPS

accomplished with the schedule and cost limitations. The following management requirements shall be met:

3.4.1 A fully integrated scheduling system shall be established and implemented during Phase A/B to manage all project elements. This system will include the development of network schedules and critical paths with appropriate budgeting and tracking of staffing.

3.4.2 A performance measurement system shall be established and implemented during Phase A/B that is compatible with the scheduling and cost-control systems.

3.4.3 A level-1 baseline schedule will be developed during Phase A/B and approved by NASA.

3.4.4 The key personnel, including the Principal Investigator, the Project Manager, and the Project Scientist, must be approved by NASA.

Table Ap.D-2 MESSENGER Project Cost Commitment

Entries by fiscal year in real year dollars rounded to nearest thousand		FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	Total (Real Yr.)
Development	Phase A/B	10,806	20,641											31,447
	Phase C/D		25,843	71,730	42,471	23,096								163,140
	Subtotal	**10,806**	**46,484**	**71,730**	**42,471**	**23,096**								**194,586**
Operations	Phase E					4,395	7,554	7,416	9,251	11,157	13,765	19,991	7,004	80,533
Dev + Ops	**Total**	**10,806**	**46,484**	**71,730**	**42,471**	**27,491**	**7,554**	**7,416**	**9,251**	**11,157**	**13,765**	**19,991**	**7,004**	**275,119**
Launch Vehicle	**Subtotal**		**20,000**	**24,000**	**13,000**	**7,000**								**64,000**
	FY Totals	**10,806**	**66,484**	**95,730**	**55,471**	**34,491**	**7,554**	**7,416**	**9,251**	**11,157**	**13,765**	**19,991**	**7,004**	**339,119**

3.4.5 The major subcontracts to GenCorp Aerojet and Composite Optics, Inc., will be established with incentives as part of contract negotiations during Phase A/B. Major contracts, where appropriate, should reflect the science nature of the investigation and incentive plans for the corresponding science deliveries. For example, construction and performance of the integrated primary structure and propulsion system as designed will enable the inclusion of the entire science payload. Hence for these contracts, the incentive plan will reflect technical performance as well as cost and schedule commitments.

3.5 The Project shall abide by all necessary Federal (including NASA), state, and local laws and regulations.

3.6 There are no new project-specific major (capital) facilities required for this mission.

4.0 MESSENGER Mission Responsibilities

4.1 Principal Investigator and Science Team

The Principal Investigator (PI), Dr. Sean C. Solomon of the Carnegie Institution of Washington (CIW), has overall responsibility for design, execution, and success of the mission, with responsibility to report on project progress and status to NASA. He is responsible for assuring that the baseline science requirements are met and will establish programmatic constraints and criteria for evaluating trade-offs as required. He will lead the preparation of a Science Plan and serve as co-chair of all Science Team meetings with the Project Scientist, as well as be an ex-officio member of each Science Team group. He will work with the Project Manager

Table Ap.D-3 MESSENGER Milestones (Preliminary Draft Schedule)

Milestone	Date
MESSENGER Project Start	January 1, 2000
System Requirements Review/Conceptual Design Review	April 24, 2000
Technical Interchange Meeting (Instruments)	August 16, 2000
Preliminary Design Review	June 7, 2001
Confirmation Review	June 7, 2001
Critical Design Review	March 18, 2002
Start Assembly, Test, and Launch Operations (ATLO) (Start of integration and test)	November 6, 2002
Pre-Environmental Review	September 3, 2003
Pre-Ship Review	December 6, 2003
Mission Readiness Review and Launch Readiness Review	March 21, 2004
Launch	March 23, 2004
Earth flyby	August 2, 2005
DSM 1	December 21, 2005
Venus flyby 1	October 25, 2006
Venus flyby 2	June 6, 2007
DSM 2	October 27, 2007
Mercury flyby 1	January 15, 2008
DSM 3	March 19, 2008
Mercury flyby 2	October 6, 2008
DSM 4	December 6, 2008
Orbit insertion at Mercury	September 30, 2009
End mission operations	September 30, 2010
End project (end of analysis and final archiving)	September 30, 2011

to achieve the baseline science mission within the cost constraints and will endeavor to achieve as much margin as possible beyond the "Performance Floor" mission. He must approve any descoping, for whatever reason it is required.

The MESSENGER Science Team consists of 21 highly qualified individuals who collectively bring an extraordinary range of technical and scientific expertise. To facilitate the design, development, and testing of instrumentation, and to carry out the analysis of mission data in an effective manner, the science team is divided into four broad groups with different but complementary interests: a Geology Group (GG), a Geochemistry Group (GC), a Geophysics Group (GP), and an Atmosphere and Magnetosphere Group (AM). The chairs of each group are responsible to the PI for the analysis of mission data within their purview. The PI will arrange for and execute all subcontracts with all Science Team Co-Investigator Team members not supplying hardware to the MESSENGER Project.

An Education and Public Outreach plan has been developed in accordance with the National Science Education Standards and NASA's vision of the implementation of these standards. The PI will be responsible for assuring that the Education and Public Awareness plan is carried out to its full extent as the mission develops. The PI will arrange for and execute all subcontracts with members of the Education and Public Outreach Team.

The PI is responsible for assuring that progress is reported to the appropriate NASA offices and officials.

4.2 The Johns Hopkins University Applied Physics Laboratory (JHU/APL)

JHU/APL will provide the project management and implementation of the mission as delegated by the PI through the Project Manager (PM). This role includes providing a design-to-cost spacecraft that will achieve the primary science goals, as well as providing for the integration, test, and launch of the MESSENGER spacecraft, including instruments being supplied externally by the Goddard Space Flight Center, the University of Michigan, and the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder.

This management role also includes responsibilities for integrating all the elements in the technical and financial areas, reporting progress consistent with a Performance Management System, and ensuring effective communication among all elements of the investigation team.

4.3 GenCorp Aerojet

The Aerojet division of GenCorp is responsible for providing the propulsion system for the MESSENGER spacecraft and will participate in the virtual collocation design of the integrated propulsion system/primary structure.

4.4 Composite Optics, Inc. (COI)

COI will be responsible for the development, design and manufacture of the integrated structure. As part of the virtual collocation design team, COI will be responsible to the PM for integrating the propulsion system into the primary structure and delivering the integrated unit to JHU/APL for further integration with other spacecraft subsystems.

4.5 The Jet Propulsion Laboratory (JPL)

JPL will have the technical responsibility for interplanetary navigation and for finalizing the interplanetary transfer orbit design from launch through orbit insertion at Mercury. JPL will also make available its thermal vacuum system for the qualification and environmental testing of the solar arrays for the MESSENGER spacecraft.

4.6 Laboratory for Atmospheric and Space Physics (LASP)

LASP will be responsible for designing, developing, calibrating, and testing the ASCS and delivering it to JHU/APL for integration with the MESSENGER spacecraft. LASP will also be responsible for operation of the ASCS and analysis of data obtained with it during the Venus and Mercury flybys and Mercury orbit.

4.7 University of Michigan (UM)

UM will be responsible for designing, developing, calibrating, and testing the FIPS subsystem and delivering it to JHU/APL for integration with the EPPS prior to spacecraft integration. UM will also be responsible for operation of the FIPS and analysis of data obtained with it during the Venus and Mercury flybys and Mercury orbit.

4.8 Goddard Space Flight Center (GSFC)

GSFC will be responsible for designing, developing, calibrating, and testing the MLA and delivering it to JHU/APL for integration with the MESSENGER spacecraft. GSFC will be responsible as well for operation of the MLA and analysis of data obtained with it during the Mercury flybys and Mercury orbit. GSFC will also be responsible for developing portions of the Magnetometer and consulting on the Gamma-ray and X-ray Spectrometers and for supporting science data analysis from these instruments. GSFC will provide its thermal vacuum facilities for final thermal vacuum testing of the assembled MESSENGER spacecraft.

4.9 Deep Space Network (DSN)

The DSN will be responsible for all communications with the MESSENGER spacecraft following launch, including the transmission of all command data to the spacecraft and reception of all telemetry data from the spacecraft. Telemetry data will be retransmitted by suitable means to JHU/APL for further processing.

5.0 NASA Responsibilities

The Delta II-7925H will be provided by the NASA Launch Vehicle Office. NASA's launch services contract provides for vehicle production, standard launch site assembly, checkout, launch countdown, and range support, as well as spacecraft/vehicle integration, analysis, and post-flight mission data evaluation. Orbital Launch Services (OLS) at GSFC will provide technical oversight of the launch vehicle and will coordinate mission integration through an OLS-Mission Integration Manager.

The Discovery Program Manager will provide coordination support for DSN communication services with the Office of Space Communications.

6.0 Reporting and Independent Reviews

Reporting requirements and independent reviews will be kept to a minimum, consistent with ensuring that NASA maintains an effective oversight of the progress of the development and execution of the mission. To this end, reports and supporting materials will be based on internal Project products and processes to the maximum extent practical. The details will be developed during Phase A/B among the PI, the PM, and the Discovery Program Manager.

APPENDIX E

SF-1411

CONTRACT PRICING PROPOSAL COVER SHEET
(Cost or Pricing Data Required)

1. SOLICITATION/CONTRACT/MODIFICATION NUMBER
AO 98-OSS-04

2a. NAME OF OFFEROR
The Carnegie Institution of Washington

2b. FIRST LINE ADDRESS

2c. STREET ADDRESS
1530 P Street, NW

2d. CITY	2e. STATE	2f. ZIP CODE
Washington	DC	20005-1910

3a. NAME OF OFFEROR'S POINT OF CONTACT
John J. Lively

3b. TITLE OF OFFEROR'S POINT OF CONTACT
Director of Administration and Finance

3c. TELEPHONE

AREA CODE	NUMBER
202	939-1118

4. TYPE OF CONTRACT ACTION *(Check)*

X	a. NEW CONTRACT		d. LETTER CONTRACT
	b. CHANGE ORDER		e. UNPRICED ORDER
	c. PRICE REVISION/ REDETERMINATION		f. OTHER *(Specify)*

5. TYPE OF CONTRACT *(Check)*

- [ ] FFP
- [x] CPFF
- [ ] CPIF
- [ ] CPAF
- [ ] FPI
- [ ] OTHER *(Specify)*

6. PROPOSED COST *(A+B=C)*

A. COST	B. PROFIT/FEE	C. TOTAL
$1,153,767	$0	$1,153,767

7. PERFORMANCE

PLACE		PERIOD	
a.	The Carnegie Institution of Washington	a.	01 Jan 2000 - 30 Jun 2001
b.		b.	

8. List and reference the identification, quantity and total price proposed for each contract line item. A line item cost breakdown supporting this recap is required unless otherwise specified by the Contracting Officer. *(Continue on reverse, and then on plain paper, if necessary. Use same headings.)*

a. LINE ITEM NO.	b. IDENTIFICATION	c. QUANTITY	d. TOTAL PRICE	e. PROP. REF. PAGE
001	Mercury: Surface, Space Environment, Geochemistry, Ranging (MESSENGER) - Phase A/B	Total Effort	$1,153,767	See Concept Study

9. PROVIDE THE FOLLOWING *(If available)*

NAME OF CONTRACT ADMINISTRATION OFFICE
Carnegie Institution of Washington

STREET ADDRESS
1530 P Street, NW

CITY	STATE	ZIP CODE
Washington	DC	20005-1910

TELEPHONE	AREA CODE	NUMBER
	202	387-6400

NAME OF AUDIT OFFICE
NSF - Division of Contracts, Policy, and Oversight

STREET ADDRESS
4201 Wilson Boulevard

CITY	STATE	ZIP CODE
Arlington	VA	22230

TELEPHONE	AREA CODE	NUMBER
	703	306-1244

10. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS WORK? *(If "yes" identify)*
[ ] YES [X] NO

11 a. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT? *(If Yes," complete Item 11B)*
[ ] YES [X] NO

11 b. TYPE OF FINANCING *(Check one)*
[ ] ADVANCE PAYMENT [ ] PROGRESS PAYMENTS [ ] GUARANTEED LOANS

12. HAVE YOU BEEN AWARDED ANY CONTRACTS OR SUBCONTRACTS FOR THE SAME OR SIMILAR ITEMS WITHIN THE PAST 3 YEARS? *(If "Yes," identify item(s), customer(s) and contract number(s) on reverse of form.)*
[ ] YES [X] NO

13. IS THIS PROPOSAL CONSISTENT WITH YOUR ESTABLISHED ESTIMATING AND ACCOUNTING PRACTICES AND PROCEDURES AND FAR PART 31, COST PRINCIPLES? *(If "no," explain on reverse of form)*
[X] YES [ ] NO

14. COST ACCOUNTING STANDARDS BOARD (CASB) DATA *(Public Law 91-379 as amended and FAR PART 30)*

a. WILL THIS CONTRACT ACTION BE SUBJECT TO CASB REGULATIONS? *(If "No," explain in proposal)*
[X] YES [ ] NO

b. HAVE YOU SUBMITTED A CASB DISCLOSURE STATEMENT (CASB DS-1 or 2)? *(If "Yes," specify in proposal the office to which submitted and if determined to be adequate)*
[ ] YES [X] NO

c. HAVE YOU BEEN NOTIFIED THAT YOU ARE OR MAY BE IN NONCOMPLIANCE WITH YOUR DISCLOSURE STATEMENT OR COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*
[ ] YES [X] NO

d. IS ANY ASPECT OF THIS PROPOSAL INCONSISTENT WITH YOUR DISCLOSED PRACTICES OR APPLICABLE COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*
[ ] YES [X] NO

This proposal reflects our estimates and/or actual costs as of this date and conforms with the instructions in FAR 15.403-5(b)(1) and Table 15-2. By submitting this proposal, we grant the Contracting Officer and authorized representative(s) the right to examine, at any time before award, those records, which include books, documents, accounting procedures and practices, and other data, regardless of type and form or whether such supporting information is specifically referenced or included in the proposal as the basis for pricing, that will permit an adequate evaluation of the proposed price.

15. NAME OF OFFEROR *(Type)*	15. TITLE OF OFFEROR *(Type)*	16. NAME OF FIRM
John J. Lively	Director of Administration and Finance	The Carnegie Institution of Washington

17. SIGNATURE: John J. Lively

18. DATE OF SUBMISSION: 3-19-99

Use or disclosure of data contained on this sheet is subject to the restriction on the title page of this proposal or quotation.

CONTRACT PRICING PROPOSAL COVER SHEET
(Cost or Pricing Data Required)

1. SOLICITATION/CONTRACT/MODIFICATION NUMBER: **NASA AO 98-OSS-04**

2a. NAME OF OFFEROR: **THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY**

3a. NAME OF OFFEROR'S POINT OF CONTACT: **R. E. Nimmo**

3b. TITLE OF OFFEROR'S POINT OF CONTACT: **Assistant Director for Business Operations**

3c. TELEPHONE: AREA CODE **240** NUMBER **228-5974**

2b. FIRST LINE ADDRESS:

2c. STREET ADDRESS: **11100 JOHNS HOPKINS ROAD**

2d. CITY: **LAUREL** 2e. STATE: **MD** 2f. ZIP CODE: **20723-6099**

4. TYPE OF CONTRACT ACTION *(Check)*

X	a. NEW CONTRACT		d. LETTER CONTRACT
	b. CHANGE ORDER		e. UNPRICED ORDER
	c. PRICE REVISION/ REDETERMINATION		f. OTHER *(Specify)*

5. TYPE OF CONTRACT *(Check)*

[ ] FFP [X] CPFF [ ] CPIF [ ] CPAF
[ ] FPI [ ] OTHER *(Specify)*

6. PROPOSED COST *(A+B=C)*

A. COST	B. PROFIT/FEE	C. TOTAL
$26,204,234	$1,429,542	$27,633,776

7. PERFORMANCE

PLACE		PERIOD	
a.	THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY	a.	01 Jan 2000 - 30 Jun 2001
b.		b.	

8. List and reference the identification, quantity and total price proposed for each contract line item. A line item cost breakdown supporting this recap is required unless otherwise specified by the Contracting Officer. *(Continue on reverse, and then on plain paper, if necessary. Use same headings.)*

a. LINE ITEM NO.	b. IDENTIFICATION	c. QUANTITY	d. TOTAL PRICE	e. PROP. REF. PAGE
0001	MESSENGER MErcury: Surface, Space ENvironment, GEochemistry, Ranging A Mission to Orbit and Explore the Planet Mercury Concept Study - Phase B	Total Effort	$27,633,776	See Proposal Table of Contents

9. PROVIDE THE FOLLOWING *(If available)*

	NAME OF CONTRACT ADMINISTRATION OFFICE	NAME OF AUDIT OFFICE
Name	DCMC	DCAA JHU/APL
STREET ADDRESS	11100 JOHNS HOPKINS ROAD	11100 JOHNS HOPKINS ROAD
CITY	LAUREL	LAUREL
STATE	MD	MD
ZIP CODE	20723-6098	20723-6099
TELEPHONE AREA CODE	240	240
NUMBER	228-5245	228-5741

10. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS WORK? *(If "yes" identify)*
[X] YES [ ] NO **See attachment**

11 a. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT? *(If Yes," complete Item 11B)*
[ ] YES [X] NO

11 b. TYPE OF FINANCING *(Check one)*
[ ] ADVANCE PAYMENT [ ] PROGRESS PAYMENTS [ ] GUARANTEED LOANS

12. HAVE YOU BEEN AWARDED ANY CONTRACTS OR SUBCONTRACTS FOR THE SAME OR SIMILAR ITEMS WITHIN THE PAST 3 YEARS? *(If "Yes," identify item(s), customer(s) and contract number(s) on reverse of form.)*
[X] YES [ ] NO **N00039-95-C-0002; N00024-97-C-8119**

13. IS THIS PROPOSAL CONSISTENT WITH YOUR ESTABLISHED ESTIMATING AND ACCOUNTING PRACTICES AND PROCEDURES AND FAR PART 31, COST PRINCIPLES? *(If "no," explain on reverse of form)*
[X] YES [ ] NO

14. COST ACCOUNTING STANDARDS BOARD (CASB) DATA *(Public Law 91-379 as amended and FAR PART 30)*

a. WILL THIS CONTRACT ACTION BE SUBJECT TO CASB REGULATIONS? *(If "No," explain in proposal)*
[X] YES [ ] NO

b. HAVE YOU SUBMITTED A CASB DISCLOSURE STATEMENT (CASB DS-1 or 2)? *(If "Yes," specify in proposal the office to which submitted and if determined to be adequate)*
[X] YES [ ] NO **See attachment**

c. HAVE YOU BEEN NOTIFIED THAT YOU ARE OR MAY BE IN NONCOMPLIANCE WITH YOUR DISCLOSURE STATEMENT OR COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*
[X] YES [ ] NO **See attachment**

d. IS ANY ASPECT OF THIS PROPOSAL INCONSISTENT WITH YOUR DISCLOSED PRACTICES OR APPLICABLE COST ACCOUNTING STANDARDS? *(If "Yes," explain in proposal)*
[ ] YES [X] NO

This proposal reflects our estimates and/or actual costs as of this date and conforms with the instructions in FAR 15.403-5(b)(1) and Table 15-2. By submitting this proposal, we grant the Contracting Officer and authorized representative(s) the right to examine, at any time before award, those records, which include books, documents, accounting procedures and practices, and other data, regardless of type and form or whether such supporting information is specifically referenced or included in the proposal as the basis for pricing, that will permit an adequate evaluation of the proposed price.

15. NAME OF OFFEROR *(Type)*	15. TITLE OF OFFEROR *(Type)*	16. NAME OF FIRM
R.E. Nimmo	ASSISTANT DIRECTOR FOR BUSINESS OPERATIONS	THE JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY

17. SIGNATURE: Ruth E. Nimmo

18. DATE OF SUBMISSION: 3/23/99

BSB-98-F-001 (REV. 01-98)

Use or disclosure of data contained on this sheet is subject to the restriction on the title page of this proposal or quotation.

Attachment to Proposal Pricing Form

The Johns Hopkins University Applied Physics Laboratory and the Defense Contract Management Command have entered into a Forward Pricing Rate Agreement for Direct Labor Rates effective April 10, 1998. The Direct Labor rates used in this proposal are consistent with this agreement.

The following statements are in response to the correspondingly labeled questions of the Proposal Pricing Form.

10. Government Property is covered under a Laboratory Facilities Contract with the Government (N00039-95-E-0116). This Facilities Contract allows the Laboratory to use government property for any U.S. Government Contract or grant and modifications or subcontracts thereunder, provided such use is on a non-interference basis relative to the contract under which the facilities are acquired.

14b. Revision 21 of the Laboratory's Disclosure Statement, effective starting GFY 1998, was deemed adequate December 3, 1997 .

14c. The ACO has made a final determination that the Laboratory does not recognize carryover funding from prior years when proposing follow on contract costs and that this practice is in noncompliance with CAS 401 and 406 (letter Ref. DCMDE - GTWE dated May 13, 1997). The Laboratory disagrees with this determination. This issue is applicable to the manner in which Navy Omnibus follow-on tasks are priced. Under the current Navy Omnibus contract N00024-97-C-8119 (the first Navy Omnibus contract which required task level cost or pricing data), the Laboratory instituted specific procedures which ensure that follow-on task period of performance and cost estimates consider funding carryover from prior tasks. Tasks are priced based on the period of performance for that task. The Laboratory provides continuing training and guidance to APL staff which re-enforces this requirement. The Laboratory has responded to the ACO to this effect in Laboratory letter AC-23716 dated July 21, 1997. We will continue to discuss this matter with the ACO.

The ACO has determined that the Laboratory is in technical noncompliance with Cost Accounting Standards in certain areas which means that the cost impacts of such noncompliance are not considered material at this time. These areas include the Laboratory use of a cost accounting year different from its financial year and the manner in which Service department direct labor is loaded with overhead.

APPENDIX F

CERTIFICATION FORMS

CERTIFICATION REGARDING DEBARMENT, SUSPENSION, AND OTHER RESPONSIBILITY MATTERS PRIMARY COVERED TRANSACTIONS

This certification is required by the regulations implementing Executive Order 12549, Debarment and Suspension, 34 CFR Part 85, Section 85.510, Participants' responsibilities. The regulations were published as Part VII of the May 28, 1988 Federal Register (pages 19160-19211). Copies of the regulations may be obtained by contacting the U.S. Department of Education, Grants and Contracts Service, 400 Maryland Avenue, S.W. (Room 3633 GSA Regional Office Building No. 3), Washington, D.C. 20202-4725, telephone (202) 732-2505.

A. The applicant certifies that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this application been convicted or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State, or Local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a government entity (Federal, State, or Local) with commission of any of the offenses enumerated in paragraph A.(b) of this certification;

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State, or Local) terminated for cause or default; and

B. Where the applicant is unable to certify to any of the statements in this certification, he or she shall attach an explanation to this application.

C. Certification Regarding Debarment, Suspension, Ineligibility and Voluntary Exclusion - Lowered Tier Covered Transactions (Subgrants or Subcontracts)

(a) The prospective lower tier participant certifies, by submission of this proposal, that neither it nor its principles is presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from participation in this transaction by any federal department of agency.

(b) Where the prospective lower tier participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

Carnegie Institution of Washington — AO-98-AO-04

Organization Name — NRA or AO Number and Title

Mr. John J. Lively — Director, Administration and Finance

Printed Name and Title of Authorized Representative

John J. Lively — 2-15-99

Signature — Date

Dr. Sean C. Solomon — MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER)

Printed Principal Investigator Name — Proposal Title

CERTIFICATION REGARDING LOBBYING

As required by S 1352 Title 31 of the U.S. Code for persons entering into a grant or cooperative agreement over $100,000, the applicant certifies that:

(a) No Federal appropriated funds have been paid or will be paid by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, in connection with making of any Federal grant, the entering into of any cooperative, and the extension, continuation, renewal, amendment, or modification of any Federal grant or cooperative agreement;

(b) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting an officer or employee of any agency, Member of Congress, or an employee of a Member of Congress in connection with this Federal grant or cooperative agreement, the undersigned shall complete Standard Form - LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(c) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subgrants, contracts under grants and cooperative agreements, and subcontracts), and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by S1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Carnegie Institution of Washington	AO-98-AO-04
Organization Name	NRA or AO Number and Title
Mr. John J. Lively	Director, Administration and Finance
Printed Name and Title of Authorized Representative	
[signature]	2-19-99
Signature	Date
Dr. Sean C. Solomon	MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER)
Printed Principal Investigator Name	Proposal Title

CERTIFICATION REGARDING DRUG-FREE WORKPLACE REQUIREMENTS

This certification is required by the regulations implementing the Drug-Free Workplace Act of 1988, 34 CFR Part 85. Subpart F. The regulations, published in the January 31, 1989 Federal Register, require certification by grantees, prior to award, that they will maintain a drug-free workplace. The certification set out below is a material representation of fact upon which reliance will be placed when the agency determines to award the grant. False certification or violation of the certification shall be grounds for suspension of payments, suspension or termination of grants, or government-wide suspension or debarment (see 34 CFR Part 85, Sections 85.615 and 85.620).

I. GRANTEES OTHER THAN INDIVIDUALS

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about (I) The dangers of drug abuse in the workplace; (2) The grantees policy of maintaining a drug-free workplace; (3) Any available drug counseling, rehabilitation, and employee assistance programs; and (4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will (I) Abide by the terms of the statement; and (2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d) (2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d) (2), with respect to any employee who is so convicted –

(1) Taking appropriate personnel action against such an employee, up to and including termination; or

(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or Local health, Law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e), and (f) B. The grantee shall insert in the space provided below the site(s) for the performance or work done in connection with the specific grant:

Place of Performance (Street address, city, county, state, zip code)

____

____

____

____

Check ____ if there are workplaces on file that are not identified here.

II. GRANTEES WHO ARE INDIVIDUALS

The grantee certifies that, as a condition of the grant, he or she will not engage in the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance in conducting any activity with the grant.

Carnegie Institution of Washington	AO-98-AO-04
Organization Name	NRA or AO Number and Title
Mr. John J. Lively	Director, Administration and Finance
Printed Name and Title of Authorized Representative	
John J Lively	2-19-99
Signature	Date
Dr. Sean C. Solomon	MErcury: Surface, Space ENvironment, GEochemistry, Ranging (MESSENGER)
Printed Principal Investigator Name	Proposal Title

Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs

Carnegie Institution of Washington

The *(Institution, corporation, firm, or other organization on whose behalf this assurance is signed, hereinafter called "Applicant ")* hereby agrees that it will comply with Title VI of the Civil Rights Act of 1964 (P.L. 88-352), Title IX of the Education Amendments of 1962 (20 U.S.C. 1680 et seq.), Section 504 of the Rehabilitation Act of 1973, as amended (29 U.S.C. 794), and the Age Discrimination Act of 1975 (42 U.S.C. 16101 et seq.), and all requirements imposed by or pursuant to the Regulation of the National Aeronautics and Space Administration (14 CFR Part 1250) (hereinafter called "NASA") issued pursuant to these laws, to the end that in accordance with these laws and regulations, no person in the United States shall, on the basis of race, color, national origin, sex, handicapped condition, or age be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any program or activity for which the Applicant receives federal financial assistance from NASA; and hereby give assurance that it will immediately take any measure necessary to effectuate this agreement.

If any real property or structure thereon is provided or improved with the aid of federal financial assistance extended to the Applicant by NASA, this assurance shall obligate the Applicant, or in the case of any transfer of such property, any transferee, for the period during which the real property or structure is used for a purpose for which the federal financial assistance is extended or for another purpose involving the provision of similar services or benefits. If any personal property is so provided, this assurance shall obligate the Applicant for the period during which the federal financial assistance is extended to it by NASA.

This assurance is given in consideration of and for the purpose of obtaining any and all federal grants, loans, contracts, property, discounts, or other federal financial assistance extended after the date hereof to the Applicant by NASA, including installment payments after such date on account of applications for federal financial assistance which were approved before such date. The Applicant recognized and agrees that such federal financial assistance will be extended in reliance on the representations and agreements made in this assurance, and that the United States shall have the right to seek judicial enforcement of this assurance. This assurance is binding on the Applicant, its successors, transferees, and assignees, and the person or persons whose signatures appear below are authorized to sign on behalf of the Applicant.

CERTIFICATION REGARDING DEBARMENT, SUSPENSION, AND OTHER RESPONSIBILITY MATTERS PRIMARY COVERED TRANSACTIONS

This certification is required by the regulations implementing Executive Order 12549, Debarment and Suspension, 34 CFR Part 85, Section 85.510, Participants' responsibilities. The regulations were published as Part VII of the May 28, 1988 Federal Register (pages 19160-19211). Copies of the regulations may be obtained by contacting the U.S. Department of Education, Grants and Contracts Service, 400 Maryland Avenue, S.W. (Room 3633 GSA Regional Office Building No. 3), Washington, D.C. 20202-4725, telephone (202) 732-2505.

A. The applicant certifies that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this application been convicted or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State, or Local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a government entity (Federal, State, or Local) with commission of any of the offenses enumerated in paragraph A.(b) of this certification;

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State, or Local) terminated for cause or default; and

B. Where the applicant is unable to certify to any of the statements in this certification, he or she shall attach an explanation to this application.

C. Certification Regarding Debarment, Suspension, Ineligibility and Voluntary Exclusion - Lowered Tier Covered Transactions (Subgrants or Subcontracts)

(a) The prospective lower tier participant certifies, by submission of this proposal, that neither it nor its principles is presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from participation in this transaction by any federal department of agency.

(b) Where the prospective lower tier participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

The Johns Hopkins University Applied Physics Laboratory — AO-98-AO-04

Organization Name — NRA or AO Number and Title

Ms. Ruth E. Nimmo — Assistant Director for Business Operations

Printed Name and Title of Authorized Representative

Ruth E. Nimmo — 2/22/99

Signature — Date

Dr. Sean C. Solomon — MErcury: Surface, Space ENvironment, GEochemistry, Ranging

Printed Principal Investigator Name — Proposal Title

CERTIFICATION REGARDING LOBBYING

As required by S 1352 Title 31 of the U.S. Code for persons entering into a grant or cooperative agreement over $100,000, the applicant certifies that:

(a) No Federal appropriated funds have been paid or will be paid by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, in connection with making of any Federal grant, the entering into of any cooperative, and the extension, continuation, renewal, amendment, or modification of any Federal grant or cooperative agreement;

(b) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting an officer or employee of any agency, Member of Congress, or an employee of a Member of Congress in connection with this Federal grant or cooperative agreement, the undersigned shall complete Standard Form - LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(c) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subgrants, contracts under grants and cooperative agreements, and subcontracts), and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by S1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

The Johns Hopkins University Applied Physics Laboratory — AO-98-AO-04
Organization Name — NRA or AO Number and Title

Ms. Ruth E. Nimmo — Assistant Director for Business Operations
Printed Name and Title of Authorized Representative

Ruth E. Nimmo — 2/22/99
Signature — Date

Dr. Sean C. Solomon — MErcury: Surface, Space ENvironment, GEochemistry, Ranging
Printed Principal Investigator Name — Proposal Title

CERTIFICATION REGARDING DRUG-FREE WORKPLACE REQUIREMENTS

This certification is required by the regulations implementing the Drug-Free Workplace Act of 1988, 34 CFR Part 85. Subpart F. The regulations, published in the January 31, 1989 Federal Register, require certification by grantees, prior to award, that they will maintain a drug-free workplace. The certification set out below is a material representation of fact upon which reliance will be placed when the agency determines to award the grant. False certification or violation of the certification shall be grounds for suspension of payments, suspension or termination of grants, or government-wide suspension or debarment (see 34 CFR Part 85, Sections 85.615 and 85.620).

I. GRANTEES OTHER THAN INDIVIDUALS

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about (I) The dangers of drug abuse in the workplace; (2) The grantees policy of maintaining a drug-free workplace; (3) Any available drug counseling, rehabilitation, and employee assistance programs; and (4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will (I) Abide by the terms of the statement; and (2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d) (2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d) (2), with respect to any employee who is so convicted –

(1) Taking appropriate personnel action against such an employee, up to and including termination; or

(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or Local health, Law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e), and (f) B. The grantee shall insert in the space provided below the site(s) for the performance or work done in connection with the specific grant:

Place of Performance (Street address, city, county, state, zip code)

____

____

____

____

Check ____ if there are workplaces on file that are not identified here.

II. GRANTEES WHO ARE INDIVIDUALS

The grantee certifies that, as a condition of the grant, he or she will not engage in the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance in conducting any activity with the grant.

The Johns Hopkins University Applied Physics Laboratory	AO-98-AO-04
Organization Name	NRA or AO Number and Title
Ms. Ruth E. Nimmo	Assistant Director for Business Operations
Printed Name and Title of Authorized Representative	
Ruth E. Nimmo	2/22/99
Signature	Date
Dr. Sean C. Solomon	MErcury: Surface, Space ENvironment, GEochemistry, Ranging
Printed Principal Investigator Name	Proposal Title

Certification of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs

The Johns Hopkins University Applied Physics Laboratory

The *(Institution, corporation, firm, or other organization on whose behalf this assurance is signed, hereinafter called "Applicant ")* hereby agrees that it will comply with Title VI of the Civil Rights Act of 1964 (P.L. 88-352), Title IX of the Education Amendments of 1962 (20 U.S.C. 1680 et seq.), Section 504 of the Rehabilitation Act of 1973, as amended (29 U.S.C. 794), and the Age Discrimination Act of 1975 (42 U.S.C. 16101 et seq.), and all requirements imposed by or pursuant to the Regulation of the National Aeronautics and Space Administration (14 CFR Part 1250) (hereinafter called "NASA") issued pursuant to these laws, to the end that in accordance with these laws and regulations, no person in the United States shall, on the basis of race, color, national origin, sex, handicapped condition, or age be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any program or activity for which the Applicant receives federal financial assistance from NASA; and hereby give assurance that it will immediately take any measure necessary to effectuate this agreement.

If any real property or structure thereon is provided or improved with the aid of federal financial assistance extended to the Applicant by NASA, this assurance shall obligate the Applicant, or in the case of any transfer of such property, any transferee, for the period during which the real property or structure is used for a purpose for which the federal financial assistance is extended or for another purpose involving the provision of similar services or benefits. If any personal property is so provided, this assurance shall obligate the Applicant for the period during which the federal financial assistance is extended to it by NASA.

This assurance is given in consideration of and for the purpose of obtaining any and all federal grants, loans, contracts, property, discounts, or other federal financial assistance extended after the date hereof to the Applicant by NASA, including installment payments after such date on account of applications for federal financial assistance which were approved before such date. The Applicant recognized and agrees that such federal financial assistance will be extended in reliance on the representations and agreements made in this assurance, and that the United States shall have the right to seek judicial enforcement of this assurance. This assurance is binding on the Applicant, its successors, transferees, and assignees, and the person or persons whose signatures appear below are authorized to sign on behalf of the Applicant.

APPENDIX G

DRAFT STATEMENTS OF WORK

The Johns Hopkins University Applied Physics Laboratory
(Page G-1)

Carnegie Institution of Washington
(Page G-6)

Funding Allocations

JHU/APL (Phase A-E, Real Year $K)	219,049 (Including reserves)
CIW (Phase A-E, Real Year $K)	19,782

Note: Funding to Government Organizations is not included in above

Draft Statement of Work
The Johns Hopkins University
Applied Physics Laboratory (JHU/APL)

1.0 Purpose

The purpose of this document is to provide a Statement of Work for The Johns Hopkins University Applied Physics Laboratory (referred to herein as APL), the prime contractual interface for NASA with the MESSENGER Mission investigation team, that covers all aspects and phases of the mission and includes the scope of work, deliverable products, and Government responsibilities.

2.0 Applicable Documents

2.1 Controlling Documents

Task order TBD for the MESSENGER Mission under NASA Contract No. NAS5-97271.

2.2 Documents Incorporated by Reference

(a) NASA AO 98-OSS-04 dated March 31, 1998, with changes
(b) Guidelines for Concept Study Report, NASA Discovery Program Library

2.3 Order of Precedence

In case of any conflict or contradiction, any controlling document takes precedence over this Statement of Work, and this Statement of Work takes precedence over any documents incorporated by reference.

3.0 Concept Study Scope of Work

Under the direction of the Principal Investigator (PI), APL has performed a Concept Study that has:

(a) Provided project and business management, administrative, performance assurance, science, and engineering support to the PI, the Science Team, and the project technical team in the conduct of the study.
(b) Prepared a Concept Study Report in accordance with Reference 2.2 (b) above.
(c) Formed the basis of the Phase A/B, C/D, and E Statement of Work contained in this document.

4.0 Phase A/B Scope of Work

Under the direction of the PI, APL will perform the following tasks during the preliminary design phase (Phase A/B), providing directly, or through subcontracts and agreements, all required labor, materials, facilities, and equipment, except as noted in Section 8.0 below.

(a) Provide project and business management, administrative, performance assurance, science, and engineering support to the PI, the Science Team, and the project technical team in the conduct of the project.
(b) Formalize commitments with institutional team members by executing subcontracts or memoranda of agreements, as appropriate.
(c) Conduct risk-reduction and tradeoff studies and complete the baseline mission design, spacecraft design, and instrument design.
(d) Conduct a combined System Requirements Review and Conceptual Design Review (SRR/CoDR) to confirm that the science requirements and their flow-down to the spacecraft, instruments, and mission operations are sufficient to meet project objectives.
(e) Conduct a Preliminary Design Review (PDR) and support the Confirmation Review (CR) to assure that the project baseline meets system requirements, that subsystem allocations are optimum, and that the approach entails acceptable risk.
(f) Provide management, performance assurance, and technical direction and oversight to GenCorp Aerojet and Composite Optics, Inc., for the design of the primary structure and integrated propulsion system and for the definition of associated ground support equipment.
(g) Perform the definition and preliminary design of the MDIS (Mercury Dual Imaging System), EPPS (Energetic Particle and Plasma Spectrometer), GRNS (Gamma-Ray and Neutron

Spectrometer), and XRS (X-Ray Spectrometer) instruments and their associated ground support equipment, as well as the digital portion of the MAG (Magnetometer) instrument electronics.

(h) Provide management, technical direction, and oversight to the Laboratory for Atmospheric and Space Physics of the University of Colorado for the definition and preliminary design of the ASCS (Atmospheric and Surface Composition Spectrometer) instrument, and to the University of Michigan for the definition and preliminary design of the FIPS (Fast Imaging Plasma Spectrometer) sensor for the EPPS instrument.

(i) Provide management, technical direction, and oversight to the Goddard Space Flight Center (GSFC) for the definition and preliminary design of the MLA (Mercury Laser Altimeter) and the GSFC portion of the MAG instrument.

(j) Prepare a Project Plan for the conduct of Phases C/D and E of the mission.

(k) Work in cooperation with the American Association for the Advancement of Science (AAAS) to define and initiate Education/Public Outreach (E/PO) programs.

(l) Initiate Phase C/D long-lead procurements, if required.

5.0 Phase C/D Scope of Work

Under the direction of the PI, APL will perform the following design and development (Phase C/D) activities as proposed, providing directly, or through subcontracts and agreements, all required labor, materials, facilities, and equipment except as noted in Section 8.0 below.

(a) Provide continuing project and business management, administrative, performance assurance, science, and mission system engineering support to the PI, the Science Team, and the project technical team in the conduct of the project.

(b) Provide management, performance assurance, and technical direction and oversight to GenCorp Aerojet and Composite Optics, Inc., for the design, development, fabrication, assembly, integration, test, and delivery to the spacecraft of the primary structure and integrated propulsion system and associated ground support equipment.

(c) Perform the design, development, fabrication, assembly, integration, test, calibration, delivery to the spacecraft, and post-delivery support of the MDIS, EPPS, GRNS, and XRS instruments and their associated ground support equipment, as well as the digital portion of the MAG instrument electronics.

(d) Provide management, performance assurance, and technical direction and oversight to the University of Colorado for the ASCS instrument, to the University of Michigan for the FIPS sensor on the EPPS instrument, and to the Goddard Space Flight Center for the MLA instrument and their portion of the MAG instrument.

(e) Conduct a Critical Design Review (CDR) to confirm that the project baseline meets system requirements, that subsystem allocations are optimum and that the approach entails acceptable risk to proceed to Instrument and Subsystem fabrication.

(f) Perform the design, development, fabrication, assembly, integration, test, and delivery to the spacecraft of all spacecraft subsystems and components.

(g) Perform the assembly and integration of the instruments and spacecraft subsystems, and conduct environmental qualification testing of the integrated MESSENGER spacecraft and testing of its compatibility with the ground station.

(h) Conduct a Pre-Environmental Review (PER) to confirm that the project baseline meets system requirements, that spacecraft and instrument integration has been satisfactorily completed, and that the approach entails acceptable risk to proceed to spacecraft environmental test.

(i) Provide management and engineering support to define and document the interface of the MESSENGER spacecraft with the launch vehicle as required by the launch vehicle provider.

(j) Conduct a Pre-Ship Review (PSR) to confirm that the project baseline meets system requirements and that the approach entails acceptable risk to ship the spacecraft to the launch site.

(k) Pack for shipment and ship the integrated MESSENGER spacecraft to the launch site, and support its checkout in the field and its integration with the launch vehicle.

(l) Conduct a Launch Readiness Review (LRR) to confirm that the project baseline meets system requirements and that the approach entails acceptable risk to launch.

(m) Perform all planning, software development, and procurement activities required to prepare the Mission Operations Center (MOC) and Science Operations Center (SOC) to support mission operations, science data retrieval and validation, and delivery of validated data to public archives.

(n) Conduct E/PO programs in cooperation with the AAAS.

(o) Within the first 30 days after launch, perform initial engineering and science checkout and verification of spacecraft in-flight operation.

6.0 Phase E Scope of Work

Under the direction of the PI, APL will conduct the following mission operations and data collection, processing, and analysis (Phase E) activities as proposed, providing all required labor, materials, facilities, and equipment except as noted in Section 8.0 below.

(a) Provide continuing project and business management, administrative, performance assurance, science, and system engineering support to the PI, the Science Team, and the project technical team in the conduct of the mission operations.

(b) Perform the day-to-day ground station operations of the MOC for data collection and spacecraft health and status monitoring.

(c) Perform the day-to-day operations for producing validated science data and delivering it in a timely manner to the MESSENGER SOC, Planetary Data System, and public archives.

(d) Conduct E/PO programs in cooperation with AAAS.

(e) Analyze the science data and disseminate the results at scientific meetings, in refereed journals, and to the public.

7.0 Contract Deliverables and Schedule

The deliverables to be provided by APL to NASA and their schedule for delivery are shown in Table Ap. G-APL-1, APL Contract Deliverables and Schedule. APL shall provide the deliverables in APL format. Financial data shall be provided on NASA Form 533, in a mutually agreeable format.

8.0 NASA Responsibilities

The Delta II-7925H launch vehicle and associated launch services will be provided by the NASA Launch Vehicle Office. NASA's launch services contract provides for vehicle production, standard launch site assembly, spacecraft propellant, checkout, launch countdown and range support, as well as spacecraft/vehicle integration, analysis, and post-flight mission data evaluation. The Orbital Launch Services (OLS) Project at Goddard Space Flight Center (GSFC) will provide technical oversight of the launch vehicle and will coordinate mission integration through an OLS Mission Integration manager. The NASA Management Office (NMO) will provide mission contract administration and oversight.

NASA will directly provide required funding to the Jet Propulsion Laboratory (JPL) for its participation in the Navigation Group activities, and DSN and Compatibility Test Trailer support.

NASA will directly provide required funding to the JPL for its participation in qualification testing of the MESSENGER Solar Array in Phase A/B, and flight acceptance testing of the Solar Array in Phase C/D.

NASA will directly provide required funding to the GSFC/Code 549 covering the cost of using the Goddard test facilities for qualification testing of the MESSENGER spacecraft in Phase C/D.

NASA will directly provide required funding to GSFC/Code 691 for Co-I support.

NASA will directly provide required funding to GSFC/Code 695 and 696 for development of the MAG sensor and analog circuits and Co-I support.

NASA will directly provide required funding to GSFC/Code 920 for development of the MLA instrument and Co-I support.

9.0 Work Breakdown Structure (WBS)

APL will perform the work described above in accordance with the WBS shown in Table Ap. G-APL-2.

Table Ap. G-APL-1 APL Contract Deliverables and Schedule

Deliverable	Schedule for Delivery
Monthly Project Status and Financial Report	10 days following the month being reported
Concept Study Report	March 1999
SRR/CoDR* documentation package	15 days prior to SRR/CoDR
SRR/CoDR	~4 months after project start
PDR documentation package	15 days prior to PDR
Preliminary Design Review (PDR)	~17 months after project start
Publish PDR action items	15 days after PDR
Confirmation Review (CR) documentation package	15 days prior to CR
Phase C/D Project Plan	15 days prior to CR
Confirmation Review (CR)	~17 months after project start
Publish CR action items	15 days after CR
Critical Design Review (CDR) documentation package	15 days prior to CDR
CDR	~26 months after project start
Publish CDR action items	15 days after CDR
Pre-Environmental Review (PER) documentation package	15 days prior to PER
PER	~44 months after project start
Publish PER action items	15 days after PER
Pre-Ship Review (PSR) documentation package	15 days prior to PSR
PSR	~47 months after project start
Publish PSR action items	15 days after PSR
MESSENGER spacecraft to launch site	~48 months after project start
Launch Readiness Review (LRR) documentation package	15 days prior to LRR
LRR	~51 months after project start
Publish LRR action items	1 day after LRR
Launch of MESSENGER spacecraft	~51 months after project start
Verified operational MESSENGER spacecraft	~52 months after project start (launch + 30 days)
Validated science data products	As generated
Final data archive products (End of Mission)	~90 months after project start

* System Requirements Review/Conceptual Design Review

Table Ap. G-APL-2 MESSENGER Work Breakdown Structure (WBS)

WBS	Subtask	Description (Active Phase)
100		Management (Phase A-E)
	110	Project Management and Administrative Support (Phase A-E)
	120	System Engineering (Phase A-E)
	130	Mission Design and Analysis (Phase A-E)
	140	Performance Assurance Engineering (Phase A-D)
200		Instruments (Phase A-D) Provide Instruments and Disciplines: Includes management, system engineering, performance assurance, design, analysis, flight procurements, fabrication, test, and calibration. (Support for spacecraft integration, assembly and test is included in WBS 420 and support for launch operations is included in WBS 520.)
	210	Mercury Dual Imaging System (MDIS) Instrument (Phase A-D)
	220	Gamma-ray and Neutron Spectrometer (GRNS) Instrument (Phase A-D)
	230	Magnetometer (MAG) Instrument (Phase A-D)
	240	Mercury Laser Altimeter (MLA) Instrument (Phase A-D)
	250	Atmospheric and Surface Composition Spectrometer (ASCS) Instrument (Phase A-D)
	260	X-ray Spectrometer (XRS) Instrument (Phase A-D)
	270	Energetic Particle and Plasma Spectrometer (EPPS) Instrument (Phase A-D)
	280	Data Processing Unit (DPU) (Phase A-D)
300		Spacecraft Bus (Phase A-D) Provide Subsystems and Disciplines: Includes design, analysis, flight procurements, performance assurance, fabrication, subsystem ground support equipment, and test. (Spacecraft Management and System Engineering is included in WBS 100; Support for spacecraft integration, assembly and test is included in WBS 430 and support for launch operations is included in WBS 530.)
	310	Attitude Determination and Control Subsystem (Phase A-D)
	320	Power Generation and Control Subsystem (Phase A-D)
	330	Harness Subsystem (Phase A-D)
	340	Structures and Mechanisms (Phase A-D)
	350	Thermal (Phase A-D)
	360	RF/Communications Subsystem (Phase A-D)
	370	Integrated Electronics Module (IEM) Subsystem (Phase A-D)
	380	Flight Software (Phase A-D)
	390	Propulsion Subsystem (Phase A-D)
	3A0	Spacecraft Bus Performance Assurance (Phase A-D)
400		Spacecraft Integration, Assembly, and Test (Phase A-D) Develop Integration and Test procedures, ground support equipment, ground software, GSFC test facilities (acoustic, TV), logistics/transportation. Integrate and test spacecraft bus and instruments.
	410	Spacecraft Integration Team Integration, Assembly and Test (Phase A-D)
	420	Instrument Team Integration, Assembly and Test (Phase D)
	430	Spacecraft Subsystem Team Integration, Assembly and Test (Phase D)
500		Launch Checkout and Orbital Operations (Phase D) Support launch operations from end of spacecraft environmental test through launch plus 30 days.
	510	Spacecraft Integration Team Launch Checkout and Orbital Operations (Phase D)
	520	Instrument Team Launch Checkout and Orbital Operations (Phase D)
	530	Spacecraft Subsystem Team Launch Checkout and Orbital Operations (Phase D)
600		Science Team Support (Phase A-D)
	610	Solomon, PI (Phase A-D)
	620	Co-Investigator Support (Phase A-D)
700		Pre-Launch GDS/MOS Development (Phase A-D) Modify NEAR and CONTOUR Mission Operations Center (MOC) for MESSENGER, develop simulator, develop procedures/software, train Flight Operations Team (FOT). Develop TMOD/DSN Interface. Modify NEAR Science Operations Center (SOC) for MESSENGER instruments, develop procedures/software, train operators.
	710	Flight Operations Preparations (Phase A-D)
	720	Science Operations Preparations (Phase A-D)
800		Mission Operations and Data Analysis (Phase E) Provide Flight Operations Team (FOT): TMOD/AMMOS support, prepare raw science for Science Operations Center (SOC), Spacecraft engineering telemetry assessment, operations planning for science data collection. Provide Science Operations Team (SOT): Produce data for analysis and archiving. Provide Science Team: analysis and delivery of data to NASA
	810	Mission Operations Team (Phase E)
	820	Science Operations Team (Phase E)
	830	Science Team Support/Analysis (Phase E)
900		Education/Public Outreach (Phase A-E)

Draft Statement of Work
Carnegie Institution of Washington (CIW)

1.0 Purpose

The purpose of this document is to provide a Statement of Work for the Carnegie Institution of Washington (referred to herein as CIW), the home institution of the Principal Investigator for the MESSENGER Mission, that covers all aspects and phases of the mission and includes the scope of work, deliverable products, and Government responsibilities.

2.0 Applicable Documents

2.1 Controlling Documents

NASA Contract No. ____________ to CIW for the MESSENGER Mission.

2.2 Documents Incorporated by Reference

(a) NASA AO 98-OSS-04 dated March 31, 1998, with changes
(b) Guidelines for Concept Study Report, NASA Discovery Program Library

2.3 Order of Precedence

In case of any conflict or contradiction, any controlling document takes precedence over this Statement of Work, and this Statement of Work takes precedence over any documents incorporated by reference.

3.0 Concept Study Scope of Work

The Principal Investigator (PI), Dr. Sean C. Solomon, CIW, has directed all aspects of the Concept Study, and Concept Study Report preparation in accordance with Reference 2.2 (b), above. The Concept Study Report is the basis for the Phase A/B, C/D, and E Statement of Work contained in this document.

4.0 Phase A/B Scope of Work

The CIW will provide administrative support to the Principal Investigator (PI), Dr. Sean C. Solomon, in his performance of the following tasks during the preliminary design phase (Phase A/B) of the project.

(a) Provide overall leadership and oversight of the MESSENGER project.
(b) Chair the MESSENGER Science Team and the MESSENGER Science Steering Committee.
(c) Chair the MESSENGER Implementation Team.
(d) Co-Chair, together with the mission Project Scientist, regular meetings of the MESSENGER Science Team as defined by the project master schedule.
(e) Lead the development of MESSENGER science requirements, and their flow-down to the spacecraft, instruments, and mission operations as part of the combined System Requirements Review and Conceptual Design Review (SRR/CoDR).
(f) Lead the preparation of the Science Analysis Plan.
(g) Lead the preparation of the Education/Public Outreach (E/PO) Plan, oversee MESSENGER E/PO activities, and participate in regular meetings of the MESSENGER E/PO partners.
(h) Oversee the Preliminary Design Review (PDR) and support the Confirmation Review (CR) to confirm that the project baseline meets system requirements, that subsystem allocations are optimum, and that the approach entails acceptable risk.
(i) Oversee the preparation of a Project Plan for the conduct of Phases C/D and E of the mission.
(j) Provide management and oversight of subcontracts to Co-Investigator and Education/Public Outreach team member institutions for their participation in the MESSENGER project.

5.0 Phase C/D Scope of Work

The CIW will continue to provide administrative support to the MESSENGER PI, in his performance of the following tasks during the design and development phase (Phase C/D) of the project.

(a) Provide continuing overall leadership and oversight of the MESSENGER project.

(b) Continue to Chair the MESSENGER Science Team, the MESSENGER Science Steering Committee, and the MESSENGER Implementation Team.
(c) Update, as necessary, the Science Analysis Plan, and oversee all planning, software development, and procurement activities required to prepare the Mission Operations Center (MOC) and Science Operations Center (SOC) to support mission operations, science data retrieval and validation, and delivery of validated data to public archives.
(d) Oversee MESSENGER E/PO activities and participate in regular meetings of the MESSENGER E/PO partners.
(e) Lead the preparation of a plan for the timely dissemination of MESSENGER data and scientific findings.
(f) Lead the preparation of a plan for the timely publication of MESSENGER scientific results in refereed journals.
(g) Within the first 30 days after launch, oversee initial engineering and science checkout and verification of spacecraft in-flight operation.
(h) Provide management and oversight of subcontracts to Co-Investigator and Education/Public Outreach team member institutions for their participation in the MESSENGER project.

6.0 Phase E Scope of Work

The CIW will continue to provide administrative support to the MESSENGER PI, in his performance of the following tasks during the mission operations and data collection, processing, and analysis phase (Phase E) of the project.

(a) Provide continuing overall leadership and oversight of the MESSENGER project.
(b) Continue to Chair the MESSENGER Science Team, the MESSENGER Science Steering Committee, and the MESSENGER Implementation Team.
(c) Oversee the day-to-day ground station operations of the MOC for data collection and spacecraft health and status monitoring.
(d) Oversee the day-to-day operations for producing validated science data and delivering it in a timely manner to the MESSENGER SOC, Planetary Data System, and public archives.
(e) Oversee MESSENGER E/PO activities, and participate in regular meetings of the MESSENGER E/PO partners.
(f) Lead the analysis of MESSENGER science data, the dissemination of results at scientific meetings and to the public, and the timely publication of scientific results in refereed journals.
(g) Provide management and oversight of subcontracts to Co-Investigator and Education/Public Outreach team member institutions for their participation in the MESSENGER project.

7.0 Contract Deliverables and Schedule

The deliverables to be provided by CIW to NASA and their schedule for delivery are shown in Table Ap. G-CIW-1, CIW Contract Deliverables and Schedule. CIW shall provide the deliverables in CIW format. Financial data shall be provided on NASA form 533, in a mutually agreeable format.

8.0 NASA Responsibilities

The Delta II-7925H launch vehicle and associated launch services will be provided by the NASA Launch Vehicle Office. NASA's launch services contract provides for vehicle production, standard launch site assembly, spacecraft propellant, checkout, launch countdown and range support, as well as spacecraft/vehicle integration, analysis, and post-flight mission data evaluation. The Orbital Launch Services (OLS) Project at Goddard Space Flight Center (GSFC) will provide technical oversight of the launch vehicle and will coordinate mission integration through an OLS Mission Integration manager. The NASA Management Office (NMO) will provide mission contract administration and oversight.

NASA will directly provide required funding to the Jet Propulsion Laboratory (JPL) for its participation in the Navigation Group activities, and DSN and Compatibility Test Trailer support.

NASA will directly provide required funding to the JPL for its participation in qualification testing of the MESSENGER Solar Array in Phase A/B, and flight acceptance testing of the Solar Array in Phase C/D.

NASA will directly provide required funding to the GSFC/Code 549 covering the cost of using the Goddard test facilities for qualification testing of the MESSENGER spacecraft in Phase C/D.

NASA will directly provide required funding to GSFC/Code 691 for Co-I support.

NASA will directly provide required funding to GSFC/Code 695 and 696 for development of the MAG sensor and analog circuits and Co-I support.

NASA will directly provide required funding to GSFC/Code 920 for development of the MLA instrument and Co-I support.

Table Ap. G-CIW-1 CIW Contract Deliverables and Schedule

Deliverable	Schedule for Delivery
Monthly Project Status and Financial Report	10 days following the month being reported
Education and Outreach Plan	~12 months after project start
Science Analysis Plan	15 days prior to PDR
Education and Outreach products	As generated
Validated science data products	As generated
Final data archive products (End of Mission)	~90 months after project start

APPENDIX H

INCENTIVE PLAN

Specific incentive plans with the MESSENGER industrial partners COI and Aerojet have not yet been finalized but will be once MESSENGER is selected for award. Both companies have agreed with JHU/APL on cost incentives (see following letters in this Appendix), but agreement has not yet been reached on specific performance-based incentives. Areas currently under discussion include delivery schedule for the spacecraft structure with COI and performance events for the propulsion system with Aerojet.

Due to the nature of their contracts with NASA through which the MESSENGER effort will be implemented with CIW and JHU/APL, an incentive-based contract structure is not possible. Negotiating such a contract would introduce additional costs to NASA as well as cost and schedule delays for the MESSENGER project. As a result, such a change has not been considered for implementing the contracts with CIW and APL.

Subcontracts to Co-I and E/PO partners are with institutions that do not accept incentive-based contracts.

JOHNS HOPKINS
UNIVERSITY

Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel MD 20723-6099
240-228-5000 / Washington
443-778-5000 / Baltimore

APL's MESSENGER MISSION INCENTIVE PLAN

For the AEROJET General Corporation subcontract to be issued by JHU/APL, a cost plus incentive fee contract will be issued. The incentive plan for this subcontract will meet the following requirements:

The proposed subcontract must ensure the contractor's adherence to cost commitments, performance and schedule. The specifications for the subcontract will be specific with respect to performance requirements for each of the subsystems. Specific performance incentives are deemed unnecessary as improvements in the products' performance above the specification are not applicable. Specific interim and final hardware delivery dates and interim progress and cost reviews will be included in the terms and conditions for each subcontract. Provisions for withholding interim payment of fee will be incorporated to protect against failure to make progress on the part of the subcontract. Additional incentives on performance and schedule will not be incorporated into the incentive plans for this subcontract.

The total incentive therefore will be applied to cost incentives. A simple CPIF contract with straight share lines covering cost will be used. The contractor will earn the maximum fee only when notable cost reductions are obtained. A balance incentive structure will be developed based on probable cost and target cost. Provisions for provision payment of fee during the performance of the contract will be incorporated but final incentive fee earned will be determine after the hardware is integrated and fully tested as an integral part of the satellite.

A cost range, target cost, target fee, minimum and maximum fee and cost sharing ratio will be established for this subcontract. The JHU/APL and Subcontractor share line will be derived based on not exceeding the target cost.

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY

By Polly Hessler 3/15/99
Signature Date

Typed Name: Polly E. Hessler

Title: Senior Contract Representative

AEROJET General Corporation

By George V. Perrin 3/15/99
Signature Date

Typed Name: George V. Perrin

Title: Contract Manager

JOHNS HOPKINS
U N I V E R S I T Y

Applied Physics Laboratory
11100 Johns Hopkins Road
Laurel MD 20723-6099
240-228-5000 / Washington
443-778-5000 / Baltimore

APL's MESSENGER MISSION INCENTIVE PLAN

For the Composite Optics, Incorporated subcontract to be issued by JHU/APL, a cost plus incentive fee contract will be issued. The incentive plan for this subcontract will meet the following requirements:

The proposed subcontract must ensure the contractor's adherence to cost commitments, performance and schedule. The specifications for the subcontract will be specific with respect to performance requirements for each of the subsystems. Specific performance incentives are deemed unnecessary as improvements in the products' performance above the specification are not applicable. Specific interim and final hardware delivery dates and interim progress and cost reviews will be included in the terms and conditions for each subcontract. Provisions for withholding interim payment of fee will be incorporated to protect against failure to make progress on the part of the subcontract. Additional incentives on performance and schedule will not be incorporated into the incentive plans for this subcontract.

The total incentive therefore will be applied to cost incentives. A simple CPIF contract with straight share lines covering cost will be used. The contractor will earn the maximum fee only when notable cost reductions are obtained. A balance incentive structure will be developed based on probable cost and target cost. Provisions for provision payment of fee during the performance of the contract will be incorporated but final incentive fee earned will be determine after the hardware is integrated and fully tested as an integral part of the satellite.

A cost range, target cost, target fee, minimum and maximum fee and cost sharing ratio will be established for this subcontract. The JHU/APL and Subcontractor share line will be derived based on not exceeding the target cost.

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY

By [signature] 3/12/99
Signature Date

Typed Name: Polly E. Hessler

Title: Senior Contract Representative

COMPOSITE OPTICS, INCORPORATED

By [signature] 3/19/99
Signature Date

Typed Name: Ted. G. Stern

Title: Gen. Mgr. Structures & Sys.

APPENDIX I

RELEVANT EXPERIENCE AND PAST PERFORMANCE

1.0 Introduction

The MESSENGER team is exceptionally well qualified to design and execute this technically challenging and scientifically rewarding mission. This Appendix contains a description and quantification of the relevant experience and past performance over the past 10 years in the following critical areas:

- Development and implementation of scientific concepts
- Mission design and implementation
- System engineering and performance assurance necessary for carrying out highly reliable, long-duration missions
- Management of large, diverse programs that include participants from many organizations
- Spacecraft bus design, development, fabrication, integration, assembly, and test
- Scientific instrument design, development, fabrication, integration, assembly, test, and calibration of the type of instruments included on MESSENGER
- Launch vehicle interface development and launch operations
- Operation of long duration missions requiring complex trajectory maneuvers
- Data recovery, processing, analysis, publication of results, and archiving

2.0 Carnegie Institution of Washington

The Carnegie Institution of Washington has provided scientific leadership in the fields of astronomy, biology, and Earth science since its founding 97 years ago. Two of the five scientific departments of the institution – the Geophysical Laboratory and the Department of Terrestrial Magnetism have occupied a common campus in northwestern Washington, D.C., since 1990. Led by the two department directors, Dr. Wesley T. Huntress, Jr., and Dr. Sean C. Solomon, the Geophysical Laboratory and the Department of Terrestrial Magnetism have combined forces to tackle the increasingly interdisciplinary field of planetary system science, spanning the research areas of star and planet formation, extra-solar planets, presolar materials, meteoritics, astrobiology, high-pressure physics and chemistry, and planetary evolution.

The Principal Investigator for the MESSENGER mission, Dr. Sean C. Solomon, brings a broad range of experience in spacecraft mission implementation and scientific management. As a member of experiment teams for the Magellan and Mars Global Surveyor missions, he played key roles in experiment and mission planning efforts and in the analysis, interpretation, and dissemination of mission data over a 17-year period. His management experience ranges from providing scientific leadership for multiple oceanographic expeditions to serving as Principal Investigator for one of the research consortia selected for founding membership in the NASA Astrobiology Institute, and from directing for seven years a department at a front-rank research institution to serving for two years as the President of a scientific society with more than 35,000 members. His scientific management advise has been widely sought by government agencies and laboratories and by academic institutions. In the past year alone, he has chaired the Academic Review Committee for Geosciences at Princeton University, the External Review Committee for the Joint Program in Oceanography and Applied Ocean Physics and Engineering of the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution, and the Advisory Committee of the Earth and Environmental Sciences Directorate of Lawrence Livermore National Laboratory.

3.0 APL Relevant Experience and Past Performance

3.1 Introduction

The APL Space Department traces its origins to the Laboratory's development of the satellite tracking technique based on observations of the Doppler shift of signals from Sputnik and the subsequent invention, design, development, and operational deployment of the Transit Navy Navigation Satellite System. A strong engineering capability based on experience in developing Navy guided missiles has grown into a broadly based department with strengths in a number of relevant scientific disciplines. A unique management and technical approach has been developed over the years, and the department has compiled an outstanding record of accomplishment. Included in these accomplishments are scientific contributions, invention and innovation of new technologies and systems, and an excellent record in the design, development, and launch of spacecraft and satellites.

The Space Department's staff has an unusual depth of experience across all necessary space-related engineering and scientific disciplines, which has led to numerous achievements. APL has built (in-house) and launched 54 spacecraft; APL has also built three satellites jointly with another organization for a total of 57 satellites. Forty-nine of the spacecraft were successfully inserted into orbit. (In eight cases, the launch vehicle failed to deliver the spacecraft to orbit.) Of the 49, 45 achieved their mission objectives. (Two Navy Navigation Satellite System (NNSS) spacecraft launched in the early 1960s and two NNSS Transit Improvement Program (TIP) spacecraft launched in the mid 1970s achieved only part of their mission objectives.) Our NNSS spacecraft have demonstrated greater that 14 years mean-time-to-failure (MTTF) in orbit. Oscar-13 set a record for the longest continuously operational satellite (21.7 years). APL's 5E-1 environmental research satellite operated for 13 years (greater than one full solar cycle). In addition, we have built more than 100 instruments for non-APL spacecraft.

The extraordinary capability of the Space Department is demonstrated by the performance, reliability, and innovative nature of our space instruments and our spacecraft as well as by the cost and schedule discipline that has characterized our programs.

3.2 Specific Project Experience and Performance, 1989-1999

The APL experience during the past 10 years relevant to MESSENGER is presented below, organized into sections on APL's experience gained while performing NASA-funded projects and on APL's relevant experience gained while performing projects for DoD. For many of the projects, APL provided full service support to the government in the context of the full range of capabilities listed above. The APL Space Department's 40-year NASA experience ranges from providing space subsystem components, to providing full spacecraft bus and payload design, fabrication, integration and testing, to inventing space mission concepts including deep space missions, to providing launch and mission operations, to publication of results, and to functioning as NASA's Project Office (e.g., managing and staffing of the NEAR and TIMED Project Offices for NASA are the responsibilities of APL). Tables Ap.I-1, 2, and 3 summarize APL's relevant experience and past performance in the areas of Program/Mission support and satellite bus development, space instrumentation development, and space subsystems development, respectively. As shown in these Tables, APL has an excellent record of delivering quality products within short development schedules (typically, 12 to 36 months) and within cost for the class of missions similar to MESSENGER. In many cases APL has returned money to the government as a result of delivering products under the contracted cost estimate.

APL evaluates its past performance in the following general areas:

Quality of product or service. The quality of products and services are evaluated in terms of APL's compliance with contract requirements and APL's conformance to standards of good workmanship.

Timeliness of performance. Timeliness of APL's performance is measured by how well APL adhered to contract schedules and APL's responsiveness to technical direction. The project duration of the C/D development phase to launch plus 30 days is also quantified and presented in Tables Ap.I-1, 2, and 3.

Cost control and growth. Cost control is evaluated in terms of whether APL operated at or below budget, whether APL submitted reasonably priced change proposals, and whether APL provided current, accurate, and complete billings. The percent cost growth during the C/D development phase is also

Table Ap. I-1
JHU/APL Relevant Experience and Past Performance
Program/Mission Support and Satellite Bus Development
(non-APL spacecraft)

	Relevant Experience 1989-1999	Launch Date	Point of Contact	Quality of Product/Service	Performance: Cost: Control	Performance: Cost: % Growth	Performance: Schedule: Timeliness	Performance: Schedule: Duration (months)	Customer Satisfaction	Review Dates	Comments
Delta 181	Mission design and support; bus development	2/88	Mr. Andrew Green Program Manager BMDO 301-897-6000	4	+	-1	+	17	+	1986-1988	Note 1
Delta 183	Mission design and support; bus development	3/89	Dr. Michael D. Griffin Director of Technology BMDO 703-406-5755	+	4	8	+	13	+	no dates provided	Note 1
MSX	Mission design and support; bus development	4/96	Mr. Bruce Guilmain Program Manager BMDO 202-822-8246	4	4	13	+	40	+	11/88-7/96	Notes 1 and 2
	Mission operations		Major Pete Kurucz Program Manager BMDO 703-604-3246	4	4	N/A	+	(ongoing)	+	8/96-9/98	Note 3
NEAR	Deep space mission design and support; bus and instrument development	2/96	Mr. Louis J. Demas Program Manager NASA Headquarters 202-358-0882	+	+	-6.6	+	26	+	12/93-7/97	Note 1
			Dr. Anthony Carro Program Manager NASA Headquarters 202-358-0349	+	+	—	+	—	+	8/97-9/98	
ACE	Bus development	8/97	Mr. John Thurber Contract Officer NASA/GSFC 301-286-8360	4 4	4 4+	-10 —	4 4+	47 —	4 4+	4/90-7/97 8/97-1/98	Note 1
FUSE	Manage bus development (OSC commercial built)	5/99	Mr. Dennis McCarthy JHU Program Manager 410-516-5545	+ 4	+ 4	— 31	+ +	49 59	+ 4	9/94-11/98 8/97-9/98	Note 1
TIMED	Mission design and support; bus development	5/00	Mr. John Wolff NASA/GSFC Program Manager 301-286-0986	4 3	4 2	+5	4 3	33 planned 37 extended	+ 3	10/96-7/97 8/97-12/98	Note 1 Note 4

NOTES:
(1) From initial cost estimate at start of Phase C/D to project completion (Launch +30 days).
(2) Cost adjusted for 3.5 year program schedule slip due to funding shortfalls, GFE instrument delays, and programmatic delays.
(3) Cost % growth not applicable. This is a continuing, funding-constrained task.
(4) Change of scope and launch delay.

Table Ap. I-2
JHU/APL Relevant Experience and Past Performance
Space Instrumentation Development

	Relevant Experience 1989-1999	Launch Date	Point of Contact	Quality of Product/Service	Performance: Cost: Control	Cost: % Growth	Schedule: Timeliness	Schedule: Duration (months)	Customer Satisfaction	Review Dates	Comments
Galileo	Energetic Particle (EPD)	10/89	Dr. Guenter R. Rieger NASA Headquarters 202-358-1588	+	3	33	4	88	+	no dates provided	Initial launch date December 1981; actual launch following Challenger loss. Change of PI institution from NOAA to APL. Instrument performance and science analysis and reporting deemed exceptional. Note 2.
	Mission operations		Mr. James K. Erickson Jet Propulsion Laboratory 818-393-1529	4	4	—	3	111 (ongoing)	4	10/97-10/98	Note 1
Ulysses	Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies	10/90	Mr. Edward B. Massey Jet Propulsion Laboratory 818-354-1886	4	3	-2	4	108	4		Initial launch date September 1982, actual launch October 1990. Further mission operations and data analyses extensions are in negotiation. Note 2.
	Mission operations			+	3	—	4	100 (ongoing)	4	7/97-6/98	Note 1
UARS	Magnetic Field Experiment	9/91	Dr. Charles H. Jackman Project Scientist NASA/GSFC 301-286-8399	4	4	-14	4	47	4	no dates provided	Note 2
TOPEX	Radar Altimeter	8/92	Mr. Ron Ziger Jet Propulsion Lab 818-354-6729	4	3	31	4	64	4	no dates provided	Major redesign in instrument required to reflect a major change in spacecraft design. Note 2
Freja	Magnetic Field Experiment	10/92	Dr. George Withbroe NASA Headquarters 202-358-2150	4	3	23	4	27	4	no dates provided	Logic family change for added radiation harness. Part and screening cost deltas. Rework for circuit timing changes. Note 2.
ISTP/ EPIC	Energetic Particle and Ion Composition	7/92	Dr. Mario Acuña NASA/GSFC 301-286-7258	4	3	10	3	67	4	no dates provided	Four month slip. Launch vehicle change – high launch loads. Note 2
	Mission operations		Dr. D. H. Fairfield NASA/GSFC 301-286-7472	4	4	—	4	79 (ongoing)	4		Note 1
ACE/ ULEIS	Ultra Low Energy Isotope Spectrometer	8/97	Mr. J. F. Laudadio NASA/GSFC 301-286-1698	4	4	-12	3	84	4	no dates provided	The APL portion of the instrument met all performance space; the UMD portion did not despite APL's attempts to resolve UMD problems. Notes 2 and 3.
	Mission operations		John Thurber NASA/GSFC 301-286-8360	4 4	4 4+	— —	4 4+	19 (ongoing)	4 4+	4/90-7/97 8/97-1/98	Note 1 Note 1
ACE/ EPAM	Electron Proton Alpha-Particle Monitor	8/97	Mr. J. F. Laudadio NASA/GSFC 301-286-1698	4	4	-13	3	50	4	no dates provided	Notes 2 and 3.
	Mission operations		John Thurber NASA/GSFC 301-286-8360	4 4	4 4+	— —	4 4+	19 (ongoing)	4 4+	4/90-7/97 8/97-1/98	Note 1 Note 1
Cassini MIMI	Magnetospheric Imaging Instrument	10/97	Mr. M. R. Dahl NASA Headquarters 202-358-0306	3	3	4	3	50	4	no dates provided	The APL portion of the instrument met all performance Specs; the French portion did not and APL was given resources to provide a Data Processing Unit. A capacitor mounted backwards In a non-mission critical circuit Reduces an otherwise perfect Product. Note 2.
	Mission operations		L. J. Miller Jet Propulsion Lab 818-354-3239	4	+	—	3-4+	16 (ongoing)	4	10/97-9/98	Note 1
DMSP	Developed mission level ultraviolet spectrographic imager (SSUSI)	Note 4	Capt. Joseph Cagle USAF 310-336-4940	3	3	20	3	90	3	no dates provided	Loss of vendors required changes in design and additional resources. Initial flight dates of the five units delayed from late '90s to late 00's due to stretch-out of DMSP flight schedules. Notes 2 and 4.

NOTES:
(1) Sponsor evaluations provided in Section 5.0
(2) APL evaluations.
(3) The ACE ULEIS and EPAM Instruments are contracted separately from the ACE spacecraft.
(4) Five instruments to be launched on DMSP Block 5D3 between 2000 and 2007.

Table Ap. I-3
JHU/APL Relevant Experience and Past Performance
Space Subsystem Development
(flown on non-APL spacecraft)

	Relevant Experience 1989-1999	Launch Date	Point of Contact	Quality of Product/ Service	Performance: Cost: Control	Performance: Cost: % Growth	Performance: Schedule: Timeliness	Performance: Schedule: Duration (months)	Customer Satisfaction	Review Dates	Comments
COBE	Momentum management assembly	11/89	Mr. David Zillig NASA/GSFC 301-286-8003	4	3	10	3	24	4	no dates provided	
	Ultrastable Oscillator			4	4	1	4	12	4	no dates provided	Inexpensive oscillator for radio science experiment. COBE USO came in under cost. Note 2.
STE-35 and STE-67	Hopkins Ultraviolet Telescope	12/90 3/95	Dr. Robert Jayroe Marshall SFC 205-544-1968	4	4	Note 3	4	108	+	no dates provided	Note 1
EUVE	Ultrastable oscillator	6/92	Mr. David Zillig NASA/GSFC 301-286-8003	4	4	3	4	12	4	no dates provided	Similar to COBE oscillator. Successfully launched on the EUVE spacecraft. Note 2.
TOPEX	Laser Retroflector Array	8/92	Mr. Ron Zieger Jet Propulsion Lab 818-354-6729	4	3	10	4	36	4	no dates provided	Laser retroflector array launched on TOPEX. Employed for precision orbit altitude calibrations. Note 2.
TOPEX	Frequency reference unit	8/92	Mr. Ron Zieger Jet Propulsion Lab 818-354-6729	4	3	15	3	40	4	no dates provided	Frequency reference unit including oscillators and synthesizers for TOPEX radio frequency system. Cost over run due to change in scope and additional technical NASA requirements including Class S program requirements. Note 2.
DPCS	Dual precision clock system	ongoing	Mr. C. Lichtenberg Naval Research Lab 202-767-1893	4 3	3 4	10 —	3 3	9 12	4 3	no dates provided 6/96-9/98	APL's longest continuing oscillator program. Program deliverables include over 45 clock systems. Application on DoD communication satellites. Notes 1 and 2.
Mars Observer/ Mars Global Surveyor	Ultrastable oscillator	9/92	Dr. Carol Hamilton Jet Propulsion Lab 818-354-2081	4	4	2	3	24	4	no dates provided	Oscillator for the Mars Observer and Mars Global Surveyor programs. Note 1.
Nozomi	Ultrastable oscillator	10/97	Dr. Carol Hamilton Jet Propulsion Lab 818-354-2081	4	3	2	4	24	4	no dates provided	Oscillator from Cassini program. Launch date October 1997. Note 1.
Pluto Express	Prototype ultrastable oscillator	N/A	Dr. Len Tyler Stanford University 415-723-3535	4	3	-5	4	18	+	no dates provided	Prototype innovative oscillator for the proposed mission to Pluto. Smallest and lightest weight oscillator ever developed. Note 1.
FUSE	System engineering instrument data system	5/99	Mr. D. K. McCarthy JHU 410-516-5545	+	+	—	+	49	+	9/94-11/98	Note 1.
	Instrument power switching and distribution unit Electrical ground support equipment			4	4	31	+	59	4	8/97-9/98	Notes 1 and 4.

NOTES:
(1) Sponsor evaluations provided in Section 5.0
(2) APL evaluations.
(3) The ACE ULEIS and EPAM Instruments are contracted separately from the ACE spacecraft in Ap. I-2.
(4) Change of scope and launch delay.

computed and summarized in Tables Ap.I-1, 2, and 3.

Customer (end user) satisfaction. Customer satisfaction is evaluated by contacting each customer (end user) and ascertaining the degree of their satisfaction with the APL supplied product or service.

Business practices. Business practices is an evaluation category that measures APL's performance in how well APL worked with the contracting officer and technical representative.

These indices of past performance are consistent with the Federal guidelines developed by the Office of Federal Procurement Policy and documented in their report entitled "A Guide to Best Practices for Past performance," dated May 1995 (http://www.arnet.gov/BestP/BestPract.html). A past performance evaluation form was sent to each of the end users of APL's products and services, and they were asked to rate APL's performance on their projects. The completed forms and rating guidelines are provided for reference at the end of this appendix. The numerical quantification of APL's performance by these end users is summarized in Tables Ap.I-1, 2, and 3. The reader is also referred to the individual evaluation forms for additional insight into APL's performance as documented in the many end user written comments.

3.2.1 NASA Project Experience and Performance, 1989-1999

Near Earth Asteroid Rendezvous (NEAR)

NEAR is the first mission in NASA's Discovery Program of low-cost planetary missions. APL had full mission responsibility and was the Project Office reporting directly to NASA Headquarters. The NEAR spacecraft was launched in February 1996 and is on its way to rendezvous with asteroid 433 Eros in February 2000. The spacecraft will orbit Eros for approximately one year, performing scientific measurements with a payload consisting of six facility-class instruments. APL played a major role in the development of each of the six instruments:

- Laser altimeter
- Multi-spectral imager
- Infrared spectrograph
- Gamma-ray spectrometer
- X-ray spectrometer
- Magnetometer

The highly redundant spacecraft was developed by APL and was launched in less than 27 months. The unique mission design, which included an Earth swingby in January 1998, allowed for a less expensive (Delta II) launch vehicle to be utilized.

In June 1997 the NEAR spacecraft performed a flyby of a main-belt asteroid 253 Mathilde very successfully.

On December 20, 1998, just 21 days from its scheduled rendezvous with asteroid Eros, NEAR failed to complete a crucial engine burn, leaving scientists and engineers frustrated and scurrying to save the mission. A major bipropellant burn that would put the spacecraft on track for an orbit insertion was aborted after sensors detected values that exceeded limits programmed into its onboard computers. The spacecraft defaulted to a safe mode, waiting for further instructions, and communications between NEAR and the Mission Operations Center stopped.

The team anxiously waited for an opportunity to send a command to the spacecraft, telling it to remain pointed to Earth to receive further communications. Three hours later they got their chance when NEAR made a preprogrammed 360° sweep, looking for a signal from Earth. Only a 10-minute window of opportunity existed for the DSN to locate a signal, but they found it and Mission Operations Center staff immediately started uploading crucial commands.

They were then faced with a new challenge: get as much as you can from a "flyby" of the asteroid. New programs were written that would allow the spacecraft to take images of Eros and collect valuable data as it flew past on December 23, 1998.

The aborted burn of December 20, 1998, was accomplished successfully on January 3, 1999, and NEAR is now on a trajectory to rendezvous with Eros in February 2000. APL has convened a NEAR Anomaly Review Board (NARB) to determine the cause of the aborted burn. The NARB includes members with relevant experience from government, industry, and APL.

The design/development phase (Phase C/D) for NEAR was performed under the original cost estimate of $122M real-year dollars. The Mission Operations phase is presently being performed within budget.

The NEAR mission is highly relevant to MESSENGER as it demonstrates the capability at APL for complete "end-to-end" responsibility. It should also be noted that approximately 50% of the spacecraft was subcontracted to industry. The subcontracts ranged from complete subsystems to electronic black boxes.

Advanced Composition Explorer (ACE)

APL built the spacecraft bus (i.e., the operating platform) of the ACE spacecraft for NASA. General program management was through NASA's GSFC. The instrument management portion of the mission was the responsibility of the California Institute of Technology.

ACE is studying the energetic particles that constantly bombard Earth from the Sun and interstellar and galactic sources. The ACE spacecraft uses six high-resolution sensors and three monitoring instruments to sample low-energy particles of solar origin and high-energy galactic particles. From a vantage point approximately 10^6 miles from Earth, ACE takes measurements over a wide range of energy and nuclear mass, under all solar-wind flow conditions, and during large and small particle events, including solar flares. ACE can provide about an hour of advance warning of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts.

The ACE mission was expanded on August 2, 1996. NASA Headquarters (Shuttle Office) requested that ACE data from the Solar Isotope Spectrometer instrument be captured by the spacecraft command and data handling subsystem and incorporated in the Real-Time Solar Wind instrument near-real-time telemetry stream. These data provide information on high-energy radiation levels, a possible safety concern for astronauts working outside the Space Shuttle.

The ACE spacecraft was launched from Kennedy Space Center on August 25, 1997. The ACE spacecraft bus was delivered on schedule and 10% below the original cost estimate.

ACE has been on-orbit around the L1 point since December 1997. Science data from ACE are posted on Web pages and their interpretation has been presented at numerous scientific conferences.

ULEIS Instrument. The Ultra Low Energy Isotope Spectrometer (ULEIS) and Electron, Proton, and Alpha Monitor (EPAM) instruments are part of the science instrumentation on the Advanced Composition Explorer (ACE) spacecraft. A prime objective of the ACE mission is to determine and compare the elemental and isotopic composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and galactic matter. This goal will be accomplished by performing comprehensive and coordinated determinations of the elemental and isotopic composition of energetic nuclei accelerated on the Sun, in interplanetary space, and galactic cosmic ray energies, and will cover the element range from ^{1}H to ^{40}Zr.

The Ultra Low Energy Isotope Spectrometer (ULEIS) measures ion fluxes over the mass range from He through Ni from about 20 keV/nucleon to 10 MeV/nucleon. Exploratory measurements of ultra-heavy species (mass range above Ni) are also performed in a more limited energy range near 0.5 MeV/nucleon. ULEIS was jointly developed by the Applied Physics Laboratory of The Johns Hopkins University and the University of Maryland.

ULEIS is composed of three items: the time-of-flight (TOF) telescope, the analog electronics box, and the digital system box. The telescope is mounted on the sunward side of the spacecraft and points at a 60° angle to the spacecraft spin axis. The analog and digital electronics boxes are located nearby to minimize detector lead lengths. The ULEIS sensor telescope is a time-of-flight mass spectrometer that identifies ions by measuring the time-of-flight and residual kinetic energy of particles that enter the telescope cone and stop in one element of the silicon solid-state detector array. The time of flight is determined by START and STOP pulses from microchannel plate (MCP) assemblies, which detect secondary electrons that are emitted from the entrance foil and other foils within the telescope when the ion passes through them.

EPAM Instrument. The EPAM instrument on ACE measures solar and interplanetary particle fluxes with a wide dynamic range while covering nearly all directions of the full unit sphere. The EPAM instrument is the flight spare of the LAN instrument from the Ulysses spacecraft. EPAM uses low-energy solar particle fluxes as probes of the morphological changes of coronal and large-scale interplanetary magnetic field structures. EPAM is also used to investigate solar flare processes by means of non-relativistic and relativistic electrons.

Far Ultraviolet Spectroscopic Explorer (FUSE)

FUSE is a NASA-supported astronomy mission to explore the Universe using the technique of high-resolution spectroscopy in the far-ultraviolet spectral region. The Johns Hopkins University has the lead role in developing and operating the mission, in collaboration with APL and other universities, contractors, and international partners. The FUSE satellite is composed of the spacecraft and the science instrument.

The spacecraft contains all of the elements necessary for powering and pointing the satellite, including the Command and Data Handling System, the Attitude Control System, the Power System, and communications electronics and antennas. The spacecraft was purchased from Orbital Sciences Corporation on a fixed-price contract using a performance specification and a hybrid-type contract which included both fixed-price and cost-plus type controls. APL was responsible for the RFP, contract negotiations, contract administration, and technical oversight of the spacecraft development through delivery to satellite integration.

The science instrument collects the light of astronomical objects and contains the equipment necessary to disperse and record the light: the telescope mirrors, the spectrograph (and its electronic detectors), power-switching electronics, the Instrument Data System (IDS), and an electronic guide camera called the Fine Error Sensor (FES). The IDS and FES are used for pointing and guiding the satellite during science observations. The spacecraft and the IDS 'talk' to each other to coordinate the satellite's activities.

The IDS stores and forwards commands to the other instrument subsystems: the Instrument Power Switching and Distribution Unit (IPSDU), Focal Plane Assembly (FPA), Mirror Positioning Assembly (MPA), FES, and Detector. The IDS harvests telemetry from other subsystems and reports those data to the spacecraft solid-state recorder. The IDS is responsible for implementing instrument autonomy, operational modes, thermal control, and health and safety. The IDS provides science data preprocessing and storage. The IDS provides fine pointing information for the spacecraft attitude control system, and implements the 'peak-up' algorithm by which the four optical channels of the spectrograph are co-aligned. The IDS flight software is capable of identifying a star field and tracking a selected target within the visible star field. Development of bench test equipment and simulator development were part of the task.

FUSE is designed for a very specialized and unique task that is complementary to other NASA missions. FUSE looks far into the ultraviolet portion of the spectrum of light, extending to shorter ultraviolet wavelengths (905 to 1195 Å) than can be observed by the Hubble Space Telescope. FUSE observes these wavelengths with much greater sensitivity and/or with much higher resolving power than previous instruments that have been used in this wavelength range.

The Satellite Control Center located in the Bloomberg Center for Physics and Astronomy, at The Johns Hopkins University, will provide command and control through a remote ground station located at the University of Puerto Rico. Funded by NASA's Explorer Program, this Origins Mission has three years of on-orbit operations planned.

APL supported the University in several areas:

- Program management and technical consultation
- Mission system engineering and software system engineering
- Contracting Officer Technical Representative and Technical Direction Agent (TDA) for the FUSE spacecraft developed by industry
- TDA for the Instrument Data System hardware procurement from industry
- Instrument Data System software development and associated Bench Test Equipment
- IPSDU and associated Bench Test Equipment
- Instrument Electrical Ground Support Equipment and software
- Instrument database
- Spacecraft/instrument integration and test facilities and engineering support
- Electronic parts engineering support
- Instrument baffle fabrication

In August 1998, FUSE completed integration and test at APL and was shipped to the GSFC for environmental tests. Thermal vacuum testing was completed in January 1999, and the satellite will remain at GSFC for additional pre-launch testing with the Satellite Control Center prior to shipment to the Cape at the end of March 1999. A Delta II vehicle provided by NASA will launch FUSE into a 775-km, 23.5° inclination orbit, from Cape Canaveral, scheduled for Spring 1999.

Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED)

The TIMED program is the first mission of the NASA Solar Terrestrial Probes satellite series and is designed to measure key energetic and dynamic processes at the edge of the atmosphere, a region especially sensitive to global change. The TIMED program is being managed by APL for NASA GSFC. APL has been selected as the TIMED Project Office. The Laboratory is responsible for mission system engineering, spacecraft development, scientific payload management, satellite integration and test, mission operations, and science data center operations.

The TIMED satellite has incorporated significant advances in technology to reduce power and weight, and it is highly autonomous. All of these enhancements help to reduce overall mission cost.

The TIMED Preliminary Design Review took place in February 1997. Fully funded design and development activities commenced in April 1997. TIMED has a May 2000 launch date with an anticipated two-year mission lifetime.

Galileo - Energetic Particles Detector (EPD)

The EPD system was developed by APL in collaboration with the Max Planck Institute for Aeronomie (MPAe), Germany, as part of NASA's Galileo Program. The EPD was successfully launched on the Galileo spacecraft in October 1989 from the Space Shuttle and soon thereafter achieved its initial Delta VEEGA trajectory towards Jupiter. During the flight to Jupiter, Galileo has flown by Venus on February 9, 1990, and by Earth on December 8, 1990. It returned to Earth for a final flyby on December 8, 1992, and was placed on a trajectory to Jupiter. It arrived at that giant planet on December 7, 1995.

The mission objectives are to (1) measure the energy and angular distribution, composition, and stability of trapped radiation at Jupiter; (2) study the interaction of these energetic particles with the Galilean satellites and the solar wind; (3) derive thermal plasma flow velocities and temperatures; and (4) examine adiabatic and non-thermal processes in the trapped radiation.

The EPD system has operated according to design throughout the flight, and the data obtained from Venus, Earth, and Jupiter are superb. The EPD measures the detailed energy and angular distribution of ions from 0.020 to 55 MeV, electrons from 0.015 MeV to more than 11 MeV, ion composition from 0.010 MeV/nucleon to over 10 MeV/nucleon, and nuclei from hydrogen to nuclei heavier than iron. These data will allow the determination of the properties of the Jovian magnetosphere.

Thus far EPD has been operating successfully in the Jovian environment and has returned a very rich set of particle data that are enabling scientists to understand better that planet's magnetospheric dynamics, with potential application to the understanding of similar processes at Earth. APL has continued monitoring of the instrument in flight, making adjustments to operating parameters. Further, APL has analyzed additional data from the Galileo Mission and the EPD in particular, including close flybys of the Jovian moon Europa.

Information on JHU/APL's role in the EPD instrument aboard the Galileo spacecraft is available on the World Wide Web at http://sd-www.jhuapl.edu/sdhome/projects.html.

Ulysses - HI-SCALE Instrument

APL, in collaboration with an international team, designed, built, and calibrated the HI-SCALE instrument that was launched aboard the Ulysses spacecraft on October 6, 1990. The Ulysses Program is a joint international project by NASA and the European Space Administration (ESA) to study the interplanetary environment at high heliospheric latitudes. The HI-SCALE instrument was designed to make measurements of energetic ions and electrons throughout the mission. Since its launch, the Ulysses spacecraft has carried out an encounter with Jupiter in February 1992 and measurements over the solar poles in 1994-1995. The second polar passes will occur in 2001. Throughout this period HI-SCALE has provided continuous measurement of the energetic particles environment. Detailed reduction and analysis of the Ulysses data are being carried out at APL and at other HI-SCALE team sites. As a result of this analysis, over 62 refereed papers have been published in scientific journals, and over 77 abstracts have been accepted for presentation at the American Geophysical Union meetings. A detailed description of the Ulysses mission can be found on the web at http://sd-www.jhuapl.edu/sdhome/projects.html

UARS Vector Magnetometer Instrument

The Vector Magnetometer (VMAG) instrument included in the Particle Environment Monitor (PEM) experiment on the Upper Atmosphere Research Satellite (UARS) was designed, developed, and fabricated by APL. UARS was launched on September 12, 1991, and is still providing useful data (at a much reduced rate). The VMAG team at APL provided processing, analysis, validation, and archiving of magnetic field data acquired by this instrument. The VMAG consists of a fluxgate sensor mounted on the end of a 6-m boom and has provided the most accurate measurements of the geomagnetic field since MAGSAT (also developed by APL).

International Solar-Terrestrial Physics (ISTP) Mission Geotail/EPIC Instrument

The Energetic Particle and Ion Composition (EPIC) instrument was developed by APL in collaboration with the University of Maryland and the Technical University of Braunschweig (TUB), Germany, as part of the NASA International Solar-Terrestrial Program (ISTP). The EPIC instrument was designed for operation on the Geotail spacecraft built by NEC Corporation for the Institute of Space and Astronautical Science (ISAS) in Japan. The spacecraft, which was launched aboard a Delta II expendable launch vehicle in July 1992, is spending its mission exploring the Earth's magnetotail region between apogees of approximately 8 and 250 Earth radii.

The EPIC instrument is composed of two separate sensor and processing subsystems. The Supra-Thermal Ion Composition Spectrometer (STICS) subsystem measures charge state, mass, and energy properties of energetic ions with energies of 10-200 keV/charge, 2 MeV max. It uses an electrostatic analyzer with a geometry factor of 0.05 cm^2sr, time-of-flight, and energy analysis. In addition to the sensor assembly, the STICS subsystem includes an analog electronics and interface controller assembly in a separate enclosure. The analog electronics and controller unit perform power filtering and switching, alarm monitoring, command decoding, telemetry formatting, and instrument control.

The Ion Composition Subsystem (ICS) measures mass and energy properties of energetic ions with energies of less than 50 keV to 5 MeV. It uses a pair of collimators with sweeping magnets to reject electrons, followed by time-of-flight and energy analysis, with a geometry factor of 0.2 cm^2 sr. A thin-foil solid-state detector electron telescope measures electrons with energies >30 keV. The ICS is comprised of two assemblies, a sensor assembly and an analog electronics and interface controller unit.

In addition to the sensors, the EPIC instrument has a Data Processing Unit (DPU) that handles all the necessary interfaces to the spacecraft, and to the STICS and ICS subsystems.

APL has provided EPIC instrument operations and science data collection for both the deep-tail and near-tail phase of the mission. On the basis of the successes of Geotail and EPIC, plans have been made for further extension of the Geotail Mission and EPIC operations, data processing, and analyses.

Papers/presentations continue to be prepared by the APL EPIC team for scientific conferences (e.g., American Geophysical Union meetings).

TOPEX (developed for JPL)

Launched on August 10, 1992, the TOPEX/Poseidon spacecraft carries three components supplied by APL, a Laser Retro-reflector Array, a Frequency Reference Unit (FRU), and a Radar Altimeter.

The Laser Retro-reflector is employed for precision orbit determination. Sub-centimeter ranging data between the array and ground-based laser tracking stations are obtained by illuminating the retro-reflector array and measuring the difference between the transmit and receive times of the laser light. The spacecraft orbit is calculated from these measurements.

The TOPEX/Poseidon frequency reference unit (FRU) developed for NASA/JPL represents one of APL's most accurate frequency reference systems ever developed. With stabilities better than 2×10^{-13} at 100 s and aging rates $<10^{-11}$ per day, these systems have had a great impact on the TOPEX science mission. The TOPEX FRU encompasses oscillators, frequency multipliers, frequency distribution systems, command and control systems, and power converters. This totally redundant system represents one of the most complex frequency reference standards ever developed. TOPEX was the first mission on which a new class of quartz crystals flew in space. The mission also represented significant challenges for the design of the FRU with respect to the magnitude of the radiation environment at the TOPEX orbit. The TOPEX FRU is presently in its sixth year of operation on-board the spacecraft.

The main instrument for the TOPEX/Poseidon spacecraft, a Radar Altimeter, was designed and built by APL. This instrument is the first dual-frequency (C and Ku bands) radar altimeter operating in space, and its electronics are fully redundant. It provides 1-cm-precision measurements of ocean topography and utilizes the second frequency to provide corrections for ionospheric delay of the radar signals. The altimetry data are being used to gain knowledge of ocean circulation, a major factor in controlling Earth's climate.

Freja - Magnetic Field Experiment

Freja was a joint Swedish and German scientific satellite launched on October 6, 1992, to acquire high-resolution measurements of plasmas, fields, and ultraviolet emissions associated with auroral phenomena. The Freja Magnetic Field Experiment was designed, developed, and fabricated by APL. The experiment incorporated a ring-core fluxgate sensor mounted on a 2-m boom and an APL-designed Forth reduced-instruction-set computer microprocessor. This design provided the most sophisticated magnetic field instrument to date, yielding samples of the magnetic field to 256 Hz, an onboard capability for fast Fourier transforms (FFTs), and an ability to provide real-time monitoring of auroral boundaries and auroral activity.

Cassini Mission to Saturn/Titan

General Scientific Objectives of the Cassini Mission. Saturn and its atmosphere, rings, moons, and plasma envelope (magnetosphere) are all closely coupled and, consequently, interact through the exchange of matter and energy. A comprehensive study and understanding of Saturn's plasma environment is a central objective for the Cassini mission. Voyager and Pioneer encounters with Jupiter and Saturn, as well as the Voyager 2 encounters with Uranus and Neptune, have provided important new insights into magnetospheric processes. Titan presents a dense atmosphere within Saturn's magnetosphere where the escape of atmospheric constituents contributes to a neutral gas cloud that is an important (perhaps dominant) source of plasma for the magnetosphere.

MIMI Instrumentation. APL provided a Magnetospheric Imaging Instrument (MIMI) for this NASA mission that will measure and characterize energetic particles — ions, electrons and neutral atoms — and provide the first imaging of that planet's magnetosphere through neutral atom emissions. MIMI will significantly advance the understanding of Saturnian magnetospheric processes and their coupling to the satellites, rings, and the planetary ionosphere. Furthermore, MIMI will image Jupiter's magnetosphere and study unexplored regions of its magnetotail, shock acceleration processes in the interplanetary medium, and interstellar pick-up ions.

The MIMI instrument consists of one set of main electronics servicing three detector heads that perform a broad variety of measurements. The Main Electronics Unit (MEU) contains the Data Processing Unit (DPU) as well as the analog and digital processing electronics for the three detector heads:

- The Low Energy Magnetospheric Measurements System (LEMMS), provided by the Max Planck Institute for Aeronomie (MPAe), is a double-ended sensor with oppositely directed conical fields of view. Mounted on a rotating platform with its electronics package, LEMMS measures high-energy ions and electrons.
- The Charge-Energy-Mass-Spectrometer (CHEMS) sensor, provided by the University of Maryland, is mounted to the spacecraft fields and particles pallet and measures both the charge state and the composition of ions comprising the most energetically important portion of the Saturnian magnetospheric plasma.

The Ion and Neutral Camera (INCA) sensor, provided by APL, obtains remote images of the global distribution of the energetic neutral emission from hot plasmas in the Saturnian magnetosphere, measuring the rough composition and energy spectrum of those energetic neutrals for each image pixel. INCA also provides the three-dimensional distribution function, energy spectrum, and rough composition of magnetospheric ions between approximately 7 keV/nucleon and 8 MeV/nucleon.

The different MIMI sensors share common electronics and provide complementary measurements of the energetic plasma distribution, composition, and energy spectrum, as well as the interaction of that plasma with the extended atmosphere and moons of Saturn. The MEU developed by APL contains the DPU provided by Centre d'Etude Spatiale des Rayonnements (CESR).

The flight instrument, consisting of three sensors and an electronics support/processing subsystem, was delivered to JPL in September 1996 and participated in the spacecraft qualification testing. MIMI returned to APL on March 6, 1997, for final refurbishment, qualifications, and calibrations and was delivered to KSC for final integration to the Cassini spacecraft in May. Launch occurred in October 1997, with arrival at Saturn scheduled for July 2004 following flybys of Venus in April 1998 and June 1999, Earth in August 1999, and Jupiter in December 2000. In January 1999 a comprehensive spacecraft and instruments turn-on and checkout occurred, indicating excellent state of health and operational viability for the entire mission.

Ultra-Stable Oscillator (USO). The unmatched frequency stability of APL space-qualified ultra-stable quartz oscillators has been proven in 39 years of space applications. APL oscillators have demonstrated frequency stability of 3.7×10^{-14} (10 s) and a temperature coefficient of $4 \times 10^{-13}/°C$. Over 380 APL ultra-stable oscillators have been placed in orbit on a wide variety of spacecraft beginning in 1958. One oscillator provided continuous service for over 21 years.

The inherent stability of our ultra-stable oscillator can be translated to other frequencies that are coherent to the oscillator frequency by using very-low-noise frequency multipliers and frequency synthesis. High isolation low-noise buffer amplifiers provide multiple outputs with minimum cross-coupling between ports.

APL used these techniques to develop precision oscillator systems for the Cassini mission. Based on the Mars Observer design, these oscillators combine an ultra-stable oscillator with a novel frequency multiplier. Similar multiplier designs will be used for the NASA Discovery programs, where reliability and performance are the number one goal. Reliability, proven design, and performance are inherent in all of APL's RF systems.

Hopkins Ultraviolet Telescope (HUT)

APL developed a 0.9-m aperture spectrophotometer designated the Hopkins Ultraviolet Telescope for use as a Shuttle Spacelab payload. The instrument was developed in the early 1980s, but launch was delayed (due, in part, to the Challenger accident) until December 1990 when it flew as part of the ASTRO-1 payload. Based on the success of the ASTRO-1 mission, the instrument was refurbished by upgrading the primary mirror coating and the spectrograph grating and re-flown on the ASTRO-2 mission in March of 1995. Although the instrument is not of the class flown on a Discovery mission, the focal plane of the instrument was one of the early array detectors to support photon counting. The program grew from an upgraded sounding-rocket-class instrument to a very sophisticated instrument for use on the Shuttle Spacelab and the schedule changed from a program of approximately 3 years to 17 years due to changes in program direction and Shuttle manifest changes. The cost changed due to these various program changes.

Cosmic Background Explorer (COBE) and Extreme Ultraviolet Explorer (EUVE)

APL developed several precision oscillators for NASA's COBE and EUVE missions. These precision oscillators incorporate an advanced design capable of frequency stabilities better than 5 x 10^{-13} at 100 s. Through careful design the effects of environmentally induced changes of the oscillator output frequency were reduced to levels approaching the noise on the output frequency, resulting in superior performance and reliability as proven by the space mission accomplishments.

Mars Observer and Mars Global Surveyor

The ultra-stable oscillator developed for the NASA Mars Observer program is based on a design that originated from the COBE oscillator. The Mars Observer USO achieved stabilities of the order of 10^{-13} at 100 s. Typically APL's oscillators find application as precision reference sources in radio science experiments. Currently, this type of oscillator is on the Mars Global Surveyor spacecraft.

Pluto Oscillator Program

APL, in close collaboration with Stanford University, designed a miniature oscillator and radio science RF section for the proposed mission to Pluto. A very small oscillator was developed that had aging rates smaller than 10^{-10} per day as well as a frequency stability of 2 x 10^{-13} at 100 s. Using advanced light-weight materials in combination with a new generation quartz crystal resonator, the oscillator used half the electrical power as well as half the weight of the more conventional APL oscillator.

This type of design will find application on Discovery missions, since lighter-weight oscillators with greater frequency stability will result in better navigation of the spacecraft.

Dual Precision Clock System (DPCS)

Over the last 22 years, APL has been involved in the design of oscillators for the Department of the Navy. These oscillator systems should actually be considered frequency reference systems, since they not only include oscillators, but also frequency multipliers, frequency distribution systems, and advanced power conditioners. Because the quartz oscillator is often critical to the spacecraft mission, long-term, reliable operation of the oscillator is as important as its frequency stability. Oscillators used in this Navy Navigation Satellite System accumulated over one million hours of operation in orbit without a failure. The long heritage of these oscillators forms the foundation of all of APL's precision frequency source designs. Several of the RF systems proposed for the discovery programs will find their heritage closely tied to the DPCS reference frequency system design. Furthermore, the power conditioners designed for the DPCS represent a standard high-efficiency design, presently used in many APL spacecraft. Over 15 of these systems have been launched and operated for the mission life of the spacecraft without any failures.

3.2.2 DoD Project Experience and Performance, 1989-1999

Delta 181

Delta 181 was a comprehensive phenomenology mission. Using instruments integrated in the Sensor Module, the Delta 181 Mission conducted a number of experiments that were crucial to development of the Strategic Defense Initiative. The experiments were designed to fulfill the principal objectives of the mission: observation and characterization of various test objects, rocket exhausts, and vehicle outgases.

The Delta 181 mission itself represented one of the most complex and ambitious unmanned experiments ever conducted. The McDonnell Douglas Delta rocket boosted the various instruments, computers, test objects, and observation rockets into a low-Earth orbit. The test objects were ejected from the satellite for observation and tracking against the natural backgrounds expected to be seen by an attacking ballistic missile in midcourse flight.

To attain these objectives, the mission used an array of state-of-the-art observation instruments covering wavelengths from the far ultraviolet through the visible and out to the long-long wavelength infrared range. The passive and active instruments, along with support functions (power, telemetry, recorder, flight processor), were mounted on the exterior of a 3.66-m (2-ft.) extension of the D2 that was a component of the spacecraft in orbit. The spacecraft's flight processor, working with sensor measurements, maneuvered the 2725-kg (6000-lb.) spacecraft as it made observations. Closed-loop tracking, acquisition, and reacquisition of multiple objects were required during the mission, and the data are being used for future system development.

The seven-instrument complement for the SDIO space platform experiment consisted of two infrared imagers, an infrared spectrometer, an ultraviolet and visible instrument, two laser instruments, and a microwave radar.

Remarks by President Ronald Reagan to the Institute for Foreign Policy Analysis Conference marking the fifth anniversary of his speech outlining the Strategic Defense Initiative (SDI), as reported in the *Washington Times,* Tuesday, 15 March 1988, stated that "Space tests of Delta 180 and 181 have demonstrated their ability to track fast moving targets in space and distinguish dummy warheads from the real thing. American Scientists and engineers are not constructing a bargaining chip but building a future free from nuclear terror."

Delta 183 (Delta Star)

The Delta 183 program was initiated in early February 1988 with a highly accelerated schedule aiming for a launch date initially in late May 1988, but subsequently changed by the sponsor to January 1989. McDonnell Douglas Corporation, Huntington Beach, California, was to design part of the spacecraft. APL was to design and integrate a suite of sensors (the Sensor Module) and to provide technical advice to the SDIO sponsor.

Among the instruments were seven video imagers, a lidar, an infrared imager, and a materials experiment. The experiments were mounted around the exterior of the module.

The ultraviolet and visible instruments included four imagers and four photometers. Two were high-sensitivity intensified video cameras responsive to ultraviolet light. Two other cameras imaged in visible light with different fields of view. These instruments were built by APL. One of the ultraviolet video cameras was built by the Air Force Academy; the other, for imaging selected targets in four ultraviolet bands, was built by the Jet Propulsion Laboratory.

A third optics-based experiment was the midwave infrared video camera, developed by General Electric's Astro-Space Division. Designed for the space shuttle and modified for the Delta Star mission, it acquired infrared information on plumes and the space environment and acquired and tracked targets. This tracking ability was used to keep the target within the fields of view. The long-wave infrared camera was developed by Hughes Aircraft. Together, these instruments provided greater understanding of plume emissions and the environmental backgrounds against which they may be observed.

The Sensor Module consists of ten modular platforms, five containing sensors and five containing support systems. The sensors were scheduled for delivery to APL in mid-July 1988. The support systems developed by APL were ready for integration in late June 1988.

The Sensor Module integration was completed during August 1988 and shipped to Goddard Space Flight Center in late August 1988 for launch environment acoustics and thermal vacuum testing. After these two major tests were accomplished, the Sensor Module was shipped to McDonnell Douglas, Huntington Beach, California, for integrated testing with the remainder of the spacecraft. The integrated tests involved mechanical fit check, software, and transient power turn-ons. Because of the close coordination of efforts by teams on opposite sides of the country over a period of seven months, these tests were completed without any significant incident. The Sensor Module was shipped to Cape Canaveral Air Force Station in early December 1988, ten months after program initiation. The mission had been redesigned several times. Each time the schedule was extended, we found time to enhance the instrument suite.

During December 1988, the Sensor Module was mated with the remainder of the spacecraft and all testing was completed in order to support the launch date. Our program, however, got involved in a launch queue with several other programs.

On March 24, 1989, the Delta Star spacecraft was ready for launch. A near-perfect countdown followed by a completely nominal launch put the Delta 183 spacecraft into orbit. All sensors worked well. The mission, which was originally estimated to last three months, ended with hydrazine fuel depletion after nine months, in December 1989.

During the nine months in orbit, 126 experiments were completed. These experiments included observing Earth and space backgrounds, observing missile plumes, observing space resident objects, and many other studies that cannot be discussed in the open literature.

Midcourse Space Experiment (MSX)

The MSX program, conducted by APL for the Ballistic Missile Defense Organization (BMDO) is a data collection experiment, concentrating on the phenomenology of target detection and tracking. MSX also gathered both celestial and Earth limb background data and data on the understanding and control of spacecraft contamination.

The MSX spacecraft collected complete data sets needed for ground data processing demonstrations by future space and ground-based surveillance and tracking systems. APL developed and procured the spacecraft subsystems, integrated and tested the spacecraft and instruments, and provided launch support. APL also developed and implemented the concept of mission operations and continues to operate the spacecraft on-orbit.

On board instrumentation includes an Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instrument and a Contamination Experiment (CE) instrument complement provided by APL, a cryogenically-cooled Spatial Infrared Imaging Telescope (SPIRIT III), a Space Based Visible (SBV) instrument, and several Reference Objects. An Onboard Signal and Data Processor (OSDP) experiment, demonstrated real-time onboard processing and provided information on orbital radiation effects.

The MSX spacecraft was launched from Vandenberg AFB, California into a 99.37°-inclination, 904-km-altitude near Sun-synchronous polar orbit on April 24, 1996, using a Delta II launch vehicle.

MSX cryogen phase operations were extremely successful. MSX met all of the primary data collection objectives, as well as many secondary objectives. High quality multi-spectral data from dedicated and cooperative target launches were collected. The successful tracking and observation of a dedicated target was the first time cold-body midcourse targets have been tracked from space, and data from the UVISI hyperspectral sensor indicated an altitude dependence of UV plume radiance for both solid and liquid rocket motors. MSX was an integral part of sensor fusion demonstrations performed using the spacecraft closed-loop tracking capability. Additionally, the UVISI image processor and spacecraft attitude control and tracking system demonstrated aided acquisition, track, and intra-sensor hand-over on several resident space objects.

MSX collected a statistically significant set of celestial and Earth limb background data and completed an infrared celestial survey. Space-based surveillance demonstrations using the SBV instrument were performed. Data on the understanding and control of spacecraft contamination were collected and will provide valuable information on the design of future spacecraft and instruments. MSX data and lessons learned were (and will continue to be) provided to the Space-Based Infrared Surveillance (SBIRS) system. Many MSX operations concepts have been incorporated into the SBIRS Low plans.

Since depletion of the SPIRIT III cryogen supply, MSX continues to collect data with the ultraviolet and visible sensor systems (UVISI and SBV) and the contamination sensors.

Defense Meteorological Satellite Program (DMSP)

The Special Sensor Ultraviolet Spectrographic Imager (SSUSI) is part of the Block 5D3 spacecraft series of the Defense Meteorological Satellite Program. The APL has delivered five spectrographic imagers and the associated ground data analysis software that will produce near-real-time electron and neutral density profiles of the upper Earth atmosphere. The instrument was used as a baseline for instruments on both the NEAR and TIMED missions. As such it represents one element of heritage used in APL programs. The program experienced several significant changes due to vendor availability and some vendor performance. These were particularly significant as the number of vendors supplying specialty imaging tubes decreased dramatically during the early 1990s. The schedule has also changed significantly due to operational success of the current DMSP satellites. The present plans are for the SSUSI instruments to fly starting in 2000 with the last launch being planned for 2007. These changes in expected operation have extended the instrument integration dates from the early 1990s to a period ending in 1999.

4.0 GenCorp Aerojet Relevant Experience and Past Performance

4.1 Introduction

Aerojet's overall relevant experience and past performance are demonstrated by their long history in the development and production of liquid rocket engines and systems. Beginning with the Titan I in 1957, they have delivered more than 1600 first and second-stage Titan engines, more than 250 Delta second-stage engines, and 14 orbital maneuvering subsystem (OMS) engines for the Space Shuttle. Their innovative propulsion design and production capabilities have been further demonstrated on a wide range of other liquid rocket propulsion systems such as Near Earth Asteroid Rendezvous (NEAR), Alliant Evolved Expendable Launch Vehicle (EELV), X-33, Advanced Liquid Axial Stage (ALAS), and DC-XA.

4.2 Relevant Experience and Past Performance

Aerojet's recent history of flight demonstrated experience most applicable to MESSENGER is described in Table Ap.I-4. The first five programs, all performed within the past five years, highlight their successful relevant past performance and outstanding credentials that support the MESSENGER program.

Aerojet's successful past performance on numerous stage and engine programs – such as NEAR, Delta, Orbit Maneuvering System (OMS), ALAS, Brilliant Pebbles, and Alliant Evolved Expendable Launch Vehicle (EELV) – provides the confidence that they will deliver the MESSENGER Propulsion System on budget and on time. Aerojet has the necessary disciplines and processes in place to accomplish successfully the proposed tasks.

Table Ap. I-4
Recent Relevant History of Aerojet Flight-Demonstrated Experience Most Applicable to MESSENGER

Program	Description	Relevance to MESSENGER
NEAR 1994-1996	Spacecraft propulsion module stage with dual-mode pressure-fed bipropellant/monopropellant propulsion subsystem, fast-track program	Designed, qualified, and delivered in less than 16 months a dual-mode bipropellant/monopropellant axial and attitude-control propulsion system with a composite structure, propellant tanks, and thermal management systems. Integration tasks included assembly, development of Ground Support Equipment (GSE), Electrical Ground Support Equipment (EGSE), electronic propulsion module simulator, and propellant loading.
Delta, Japanese N-II, Able, Able Star and Vanguard 1960-2003	Pressure-fed storable upper stage for Delta, Able, Able Star Vanguard, and Japanese N-II launch vehicle	Forty-year history of flight-qualified storable propellant, pressure-fed upper stage propulsion systems from the same basic design. Seventeen year history with 100% flight success as the third stage for the U.S. Air Force Titan and as the second stage for the U. S. Delta and Japan's N-II launch vehicles. System includes the main engine, stage structure, propellant tankage, and pressurization subsystem (Aerojet only supplies the engine on the current Delta Stage II).
X-33 1996-1999	Reusable launch vehicle reaction control system using cryogenic and nontoxic propellants, fast-track program	Designing and developing the reaction control system and turboalternator power supply required for the X-33 program. System included reaction control thrusters, pressurization subsystem, and composite propellant and pressurant tanks along with a gas generator-fed turboalternator Auxiliary Power Unit (APU). Also developing electronic propulsion system sequencer for vehicle interface to Reaction Control System (RCS) and an electronic simulator for vehicle checkout and mission simulation.
DC-X 1992-1993	Reusable launch vehicle, reaction control system using cryogenic propellants, fast-track program	Designed, qualified, and delivered a reaction-control propulsion system for the Reusable Single Stage Rocket Technology program. System included reaction control thrusters, pressurization subsystem, and composite propellant and pressurant tanks. Also developed electronic propulsion system sequencer for vehicle interface to RCS systems.
Kistler K-1 1996-2000	Commercial reusable launch vehicle propulsion system for Stage I, Stage II, and Deorbit Orbit Maneuvering System (OMS) using cryogenic and nontoxic propellants, fast-track program	Designing and developing for flight qualification the entire vehicle propulsion systems for the Kistler K-1 Commercial Launcher. System includes qualification of Russian NK-33 engines for boost and main-stage propulsion, development of a nontoxic Orbit Maneuvering System (OMS) engine for deorbit, and development of the tankage, structure, and pressurization subsystem for all stages, along with the electronic controller and propulsion system avionics. Design and development of Kistler launch facilities, launch support systems, GSE, propellant loading, and vehicle assembly facilities.
ALAS 1988-1993	Space-based axial upper stage using high-energy storable propellants (ClF_5 and N_2H_4) for an SDIO ballistic mission interceptor, fast-track program	Developed, fabricated, and tested pressure-fed space-based stage design including GSE development for ClF_5 propellant loading. System included reaction control thrusters, a pressurization subsystem, composite structure, propellant and pressurant tanks, and pyrotechnic propellant isolation. Pathfinder Program used life cycle cost and design-to-cost methodology to drive design.
Brilliant Pebbles 1991-1994	Space-based SDIO kinetic kill vehicle propulsion system	Designed, developed, and tested a bipropellant pressure-fed kinetic kill vehicle propulsion system for a space-based missile interceptor. Developed divert and Attitude Control System (ACS) thrusters, pressurization subsystem, pryotechnic propellant isolation systems, composite structure, propellant, and pressurant tanks. Integrated components into a system, and perform system hot-fire testing.
Mark VI ACS 1991-1997	Space-based SDIO kinetic kill vehicle propulsion system	Designed, developed, and tested a bipropellant pressure-fed kinetic kill vehicle propulsion system for a space-based missile interceptor. Developed divert and ACS thrusters, pressurization subsystem, pyrotechnic propellant isolation systems, and composite structure, propellant and pressurant tanks. Integration of components into a system, and perform system hot-fire testing.
EKV 1995-1997	Ground based kinetic kill vehicle propulsion system	Designing and developing a bipropellant pressure-fed kinetic kill vehicle propulsion system for a ground-based missile interceptor. Developing divert and ACS thrusters, pressurization subsystem, pyrotechnic propellant isolation systems, and composite structure, propellant, and pressurant tanks. Integration of components into a system and perform system hot-fire testing.
Alliant EELV (LOCUS) 1995-1996	Low cost storable-upper stage, fast-track program	Designed a full launch vehicle pressure-fed upper stage for the Alliant Evolved Expendable Launch Vehicle (EELV) Concept. Full stage included a low-cost axial engine, pressurization subsystem, and composite structure, propellant, and pressurant tanks. Program used life-cycle cost and design-to-cost methodology to drive design.
Titan Launch Vehicle Family 1959-2003	Storable propellant rocket engines	Forty-year successful history. Designed, qualified, produced, and supported launch for storable propellant rocket engines for the Air Force Titan Launch Vehicle for stages I and II. Extensive experience with storable propellant engine design, turbopumps, combustion components, pyrotechnic start systems, integration, propellant properties, ground handling procedures, and safety.

5.0 Composite Optics Inc. Relevant Experience and Past Performance

5.1 Introduction

Composite Optics Incorporated (COI) is an employee-owned small business dedicated to the application of advanced composite materials and processes in the design and manufacture of lightweight, high-performance hardware. COI is a full-service organization having complete design and analysis capability, manufacturing capability and test facilities. COI's capabilities are traceable to its origins in the development of highly stable lightweight structures to support optical components and assemblies. COI's early work in mirror substrate and optical bench structures developed over the last twenty years into a full composite structure capability suitable to a wide variety of applications. In addition, COI has developed related capability in antennas and radomes, plated composite hardware for RF applications, thermal management components for spacecraft and airborne equipment including composite electronic packaging, and more recently, optical mirror components fabricated directly out of composites. COI composite components have flown or are awaiting launch on over one hundred spacecraft, including many well-known missions such as the Hubble Space Telescope, Solar and Heliospheric Observatory (SOHO), Activated Carbon Treatment System (ACTS), Superbird, Anik, MSX, Starlab, UARS, Telstar, as well as numerous commercial satellite missions. COI's reputation for high-quality, reliable components for spaceflight applications is recognized throughout the industry.

COI's population of over 450 associates includes about 50% in manufacturing, 30% in engineering, and 20% in management and administrative support. Included in our professional staff is a group dedicated to Product Development representing about 20% of engineering and technical support personnel. COI's core goals of Customer Satisfaction, Business Success, Technology Growth and Work Gratification form the basis for implementing the company's vision to become the "World Leader in Advanced, High Technology Composite Products" and, as an ESOP (Employee Stock Ownership Plan) company, COI's associates have a personal stake in the success of every project in the company. COI has experiences in all phases of programs to produce spacecraft bus structures, including:

- Conceptual design tradeoffs
- Preliminary and detailed design
- Preliminary and detailed analysis, including structural, thermal and thermo-mechanical
- Material characterization and allowables generation
- Lay-up and cure of flat and contoured laminates
- Bonding of sandwich panels and discrete rib structures
- Work-in-process testing
- Component testing in various environments, including thermal cycling, thermal vac, static load, vibration, acoustic, centrifuge, pyroshock
- Packaging, delivery and post-delivery support

COI Associates have many years of combined experience in the design and fabrication of state-of-the-art aerospace structures, as well as a consistent record of successful performance in the on-schedule completion of technically demanding programs. COI has qualified personnel at all levels who have considerable hands-on experience with composite materials and complex structural assemblies. These Associates are comfortable operating to standard NASA and U.S. Department of Defense contract provisions with respect to review, reporting and scheduling formats, quality assurance, and configuration control requirements. Workmanship standards are maintained at high levels through a comprehensive training program that emphasizes process control and improvement as well as skill enhancement and professional development.

5.2 Structures and Systems Business Area

COI's Structures and Systems Business Area provides spacecraft structures for all applications not requiring optical accuracy and stability or RF performance. Spacecraft Products has four main product lines - spacecraft bus structures, solar array substrates, structural components (yokes, booms and trusses), and thermal products/electronic packaging. Each of these product lines takes advantage of COI's capabilities in high stiffness/weight composite materials, bonded joints, thermal management materials, and advanced producibility techniques for low cost.

5.3 Specific Project Experience and Performance, 1989-1999

COI's experience base in spacecraft bus structures has grown significantly in the last ten years through key programs, including several performed for the U.S. Government through USAF and NASA. Specific Project Experience related to composite structures is summarized in Table Ap.I-5 and detailed on the following pages.

FORTÉ (Fast On-Orbit Recording of Transient Events). The FORTÉ spacecraft bus structure, fabricated for Los Alamos National Laboratory, was the first structure to be designed and fabricated using COI's patented SNAPSAT design technique. Copper foils were co-cured to graphite composite laminates, and waterjet cut to form the interlocking side panels of this structure. Using this approach, no forming tools were required, and assembly tools were limited to final assembly jigs for controlling a small number of key features. As a result, COI was able to deliver a structure 12 weeks after CDR, at a cost comparable to the previously baselined aluminum structure and with a >30% weight reduction. The FORTÉ structure, launched in October 1998, was the first all-composite spacecraft structure ever flown, and has performed on orbit as expected.

Mightysat. The Mightysat spacecraft was built under contract to Air Force Phillips lab using the SNAPSAT approach, adapted to the requirements of a large number of inserts through the use of lower and middle decks comprising aluminum honeycomb sandwich construction. COI performed all design and analysis of the structure. A qualification unit and a flight unit were fabricated and tested, and test results were correlated well to the analysis results. This spacecraft was launched on a Shuttle Get-Away-Special (GAS) canister and is meeting all mission objectives. The follow-on Mightysat II.1 spacecraft uses a thermally integrated multi-functional composite bus structure and has been delivered to the Air Force Research Laboratory for integration and launch in 2001.

Indostar. The Indostar spacecraft structure includes a composite central cylinder, which also serves as a launch vehicle adapter, and a spacecraft bus structure comprising a set of bolted graphite-faceskin/aluminum-honeycomb-core sandwich panels. Special edge connection channels were developed that provide the means of assembling the spacecraft. COI fabricated and assembled the spacecraft bus structure, performed static load and pyroshock testing, and integrated and tested the spacecraft bus structure with the antenna system, including feed-tower, horn, and waveguide. This testing included RF verification in COI's Assembly, Integration, and Test facility. Indostar was launched in October 1998 and is meeting all mission objectives.

R2100. This research and development spacecraft bus was fabricated for Lockheed Martin under LM's Independent Research and Development (IR&D) program. With a major dimension of over 4.57 m (15-ft.) in length, this structure was fabricated from bolted graphite-faceskin/aluminum-honeycomb-core sandwich panels. Heat-pipe panels using high conductivity composite faceskins were developed as part of the program, as was a square-to-round launch vehicle adapter made using lay-up of unitape on a unique mandrel.

Other Recent NASA Programs. COI has been involved in numerous NASA programs requiring high-performance composite space hardware. These include the Microwave Limb Sounder (MLS) reflector, optical bench, and sensor assemblies; the Shuttle Radar Topographic Mapper (SRTM) Outboard Support Structure; the Thermal Emission Spectrometer (TES) instrument structure, optics mirror housing, and optical bench assemblies; the Far Infra-Red Space Telescope primary reflector and the Deorbit Propulsion Stage Structure for NASA's X-38 vehicle precursor to the Crew Return Vehicle; and the Small

Table Ap. I-5
COI Composite Spacecraft Bus Structure Experience

Mission	Features	Status
FORTE/LANL	SNAPSAT flatstock construction, co-cured copper foils, flexure mount to launch vehicle adapter, 1.22 m diameter, 1.98 m high octagonal structure, 12-week turnaround	Successfully launched in October 1998. First all-composite spacecraft bus structure ever flown. Performing well on orbit.
SMEX-WIRE/NASA GSFC	SNAPSAT flatstock construction, K1100/954-3 composite thermal control doublers, 91.4 cm diameter, 91.4 cm high octagonal structure	Flight article passed all environmental tests, March 1999 launch.
Mightysat/AFPL	SNAPSAT flatstock construction, isogrid equipment panel	Successfully launched in December 1998.
Mightsat II.1/AFRL	Multi-functional composite bus structure with integrated electronics, thermal and structure	Fabrication complete, unit passed qualification tests, composite thermal control performance verified, planned launch in 2001.
Indostar/CTA	Composite faceskin/aluminum honeycomb core construction, composite central cylinder, COI in-house static load test, antenna/feed tower/feedhom fabrication, integration, and verification	Successfully launched in October 1998. Performing well on orbit.
R2100/L-M	Composite faceskin/aluminum honeycomb core construction, composite square to round launch vehicle adapter	Fabrication complete; ready for protoqual tests.

Explorer/Wide Infrared Explorer (SMEX/WIRE). In addition, COI was selected to perform a multi-year Contract Word Order that provides the NASA/Jet Propulsion Laboratory with all required composite hardware for research and flight needs.

6.0 APL Past Performance Reports

Contractor performance reports by sponsors of APL performance are provided here for the following completed APL programs.

Advanced Composition Explorer (ACE)
Cassini-MIMI MO&DA
Delta 181
Delta 183
Dual Precision Clock System (DPCS)
Far Ultraviolet Spectroscopic Explorer (FUSE)
GEOSAT-Follow-On
Galileo-Energetic Particle Detector (EPD)
High Energy Neutral Atom (HENA)
ISTP/EPIC MO&DA
Midcourse Space Experiment (MSX)
Near Earth Asteroid Rendezvous (NEAR)
Oscillator for proposed Pluto mission
Oscillator for Mars Observer and Cassini
Polymer Battery Development Program
Special Sensor Ultraviolet Spectrographic Imager (SSUSI)
Telescope for Shuttle Spacelab
Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED)
Ulysses HI-SCALE

The numeric breakdown of these programs is shown in Table Ap.I-6. Evaluation criteria describing numbers and categories is explained in Section 3.2 and on the Rating Guidelines in Table Ap. I-7.

7.0 Contractor Performance Report and Rating Guidelines

Copies of the Contractor Performance Reports assessing APL are available on request.

Table Ap. I-6
Original Program Performance Evaluation Reports on File

Program Title	Review Date	Quality	Cost Control	Timeliness of Performance	Business Relations	Satisfaction	Overall
Advanced Composition Explorer (ACE)	4/1/90-7/31/97	4	4	4	3	4	3.8
Advanced Composition Explorer (ACE)	8/1/97-1/31/98	4	4+	4+	4	4+	4.6
Cassini-MIMI MO&DA	10/1/97-9/30/98	4	+	3-4+	4	4	N/A
Delta 181	1986-1988	4	+	+	+	+	N/A
Delta 183	no dates provided	+	4	+	+	+	5
Dual Precision Clock System (DPCS)	6/1/96-9/30/98	3	4	3	3	3	3.2
Far Ultraviolet Spectroscopic Explorer (FUSE)	9/94-11/98	+	+	+	+	+	N/A
Far Ultraviolet Spectroscopic Explorer (FUSE)	8/1/97-9/30/98	4	4	+	4	4	N/A
GEOSAT-Follow-On	10/1/91-9/30/97	4+	3	4+	4+	4+	4
Galileo-Energetic Particle Detector (EPD)	10/1/97-10/31/98	4	4	3	4	4	3.8
High Energy Neutral Atom (HENA)	7/25/96-12/31/98	3	3	+	+	+	N/A
ISTP/EPIC MO&DA	10/1/97-9/30/98	4	4	4	4	4	4
Midcourse Space Experiment (MSX)	11/88-7/96	4	4	4	4	+	N/A
Midcourse Space Experiment (MSX)	8/96-9/98	4	4	+	+	+	N/A
Near Earth Asteroid Rendezvous (NEAR)	12/93-7/97	+	+	+	+	+	N/A
Near Earth Asteroid Rendezvous (NEAR)	8/97-9/98	+	+	+	+	+	5
Oscillator for proposed Pluto mission	no dates provided	+	4	4	+	++	N/A
Oscillator for Mars Observer and Cassini	no dates provided	3-4	3	4	4	4	3.75
Polymer Battery Development Program	10/96-9/98	+	4	3	4	+	4.2
Special Sensor Ultraviolet Spectrographic Imager (SSUSI)	3/19/90-9/30/98	3	2	4	4	+	3.6
Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED)	10/96-7/31/97	4	4	4	4	4	N/A
Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED)	8/1/97-12/31/98	3	2	3	2	3	2.6
Telescope for Shuttle Spacelab	1978-1996	4	4	4	4	4	4+
Ulysses HI-SCALE	7/1/97-6/30/98	+	3	4	4	4	4

Table Ap. I-7
Ratings Guidelines*

Summarize contractor performace in each of the rating areas. Assign each area a rating of: 0 (Unsatisfactory), 1 (Poor), 2 (Fair), 3 (Good), 4 (Excellent), or ++ (Plus). Use the following instructions as guidance in making these evaluations. Ensure that this assessment is consistent with any other Agency assessments made (i.e., for payment of fee puposes).

Score	Quality of Product/Service	Cost Control	Timeliness of Performance	Business Relations
	- Compliance with contract requirements - Accuracy of reports - Appropriateness of personnel - Technical excellence	- With budget (over/under target costs) - Current, accurate, and complete billings - Relationship of negotiated costs to actuals - Cost efficiencies - Change orders issue	- Met interim milestones - Reliable - Responsive to technical direction - Completed on time, including wrap-up and contract administration - No liquidated damages assessed	- Effective management - Businesslike correspondence - Responsive to contract requirements - Prompt notification of problems - Reasonable/cooperative - Flexible - Pro-active - Effective contractor-recommended solutions - Effective small/small disadvantaged business subcontracting program
0 (Unsatisfactory)	Nonconformances are compromising the achievement of contract requirements, despite use of Agency resources.	Cost issues are compromising performance of contract requirements.	Delays are compromising the achievement of contract requirements, despite use of Agency resources.	Response to inquiries, technical/service/administrative issues is marginally effective and responsive.
1 (Poor)	Nonconformances require major Agency resources to ensure achievement of contract requirements.	Cost issues require major Agency resources to ensure achievement of contract requirements.	Delays require major Agency resources to ensure achievement of contract requirements.	Response to inquiries, technical/service/administrative issues is marginally effective and responsive.
2 (Fair)	Nonconformances require minor Agency resources to ensure achievement of contract requirements.	Cost issues require minor Agency resources to ensure achievement of contract requirements.	Delays require minor Agency resources to ensure achievement of contract requirements.	Response to inquiries, technical/service/administrative issues is somewhat effective and responsive.
3 (Good)	Nonconformances do not impact achievement of contract requirements.	Cost issues do not impact achievement of contract requirements.	Delays do not impact achievement of contract requirements.	Response to inquiries, technical/service/administrative issues is usually effective and responsive.
4 (Excellent)	There are no quality problems.	There are no cost issues.	There are no delays.	Response to inquiries, technical/service/administrative issues is effective and responsive.
+ (Plus)	The contractor has demonstrated an exceptional performance level in any of the above four categories that justifies adding a point to the score. It is expected that this rating will be used in those rare circumstances when contractor performance clearly exceeds the performance levels described as "Excellent".			

* Taken from "A Guide to Best Practices for Past Performance," Office of Federal Procurement Policy, dated May 1995.

APPENDIX J

INTERNATIONAL AGREEMENTS

Not applicable.

APPENDIX K

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APPENDIX L
ACRONYMS

AAAS	American Association for the Advancement of Science
ACE	Advanced Composition Explorer
ACO	Administrative Contracting Officer
ACT	Applied Coherent Technology
ACTS	Activated Carbon Treatment System
ADCS	Attitude Determination and Control Subsystem
AESP	Aerospace Education Services Program
ALAS	Advanced Liquid Axial Stage
AM	Atmosphere and Magnetosphere Group
AMNH	American Museum of Natural History
AMPTE	Active Magnetospheric Particle Tracer Explorers
AO	Announcement of Opportunity
APL	The Johns Hopkins University Applied Physics Laboratory
APX	alpha, proton, X-ray
ASCS	Atmospheric and Surface Composition Spectrometer
ASIC	Application Specific Integrated Circuit
ATDF	auxiliary tracking data file
AU	Astronomical Unit
BGO	bismuth germanate
BISD	Business and Information Services Department
BMDO	Ballistic Missile Defense Organization
BTC	Burns Telecommunications Center
BWG	beam-waveguide
C&DH	command and data handling
CAD/CAM	computer-aided-design/computer-aided-manufacture
CASE	Carnegie Academy for Science Education
CCB	Change Control Board
CCD	charged-coupled device
CCE	Charge Composition Explorer
CCSDS	Consultative Committee for Space Data Systems
CCSSE	Challenger Center for Space Science Education
CDR	Critical Design Review
CE	Contamination Experiment
CER	Cost Estimating Relationship
CERES	Center for Educational Resources
CERT	Computer Emergency Response Team
CESR	Centre d'Etude Spatiale des Rayonnements
CHEMS	Charge-Energy-Mass-Spectrometer
CIRS	Composite Infrared Radiometer and Spectrometer
CIW	Carnegie Institution of Washington
CMC	ceramic matrix composite
CMX	Cerium oxide doped borosilicate glass
COBE	Cosmic Background Explorer
CoDR	Conceptual Design Review
Co-I	Co-Investigator
COI	Composite Optics Incorporated

COM	Cost of Money
CONTOUR	Comet Nucleus Tour
CORE	Central Operation of Resources for Educators
CoTR	contract technical representative
COTS	commercial-off-the-shelf
CPFF	cost-plus-fixed-fee
CPIF	cost-plus-incentive-fee
CPM	Critical Path Method
CPU	Conceptual Design Review
CPV	common-pressure vessel
CR	Confirmation Review
CRRES	Combined Release and Radiation Effects Satellite
CRs	Cosmic Rays
CTT	Compatibility Test Trailer
DCMC	Defense Contract Management Command
DCN	Drawing Change Notices
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DPCS	Dual Precision Clock System
DPU	Data Processing Unit
DSAD	digital solar aspect detector
DSM	Deep Space Maneuver
DSN	Deep Space Network
DTM	Department of Terrestrial Magnetism
DWG	Data Working Group
E/PO	Education/Public Outreach
E/q	energy/charge
ECR	Engineering Change Request
EDR	engineering design review
EELV	Evolved Expendable Launch Vehicle
EHR	Education and Human Resources
ELV	Expendable Launch Vehicle
EMI/RFI	electromagnetic interference/radio frequency interference
EPAM	Electron, Proton, and Alpha Monitor
EPD	Energetic Particles Detector
EPIC	Energetic Particle and Ion Composition
EPPS	Energetic Particle and Plasma Spectrometer
EPS	Energetic Particle Spectrometer
ERCN	Educators' Resource Center Network
ESA	European Space Agency
ESD	electrostatic discharge
ESOP	Employee Stock Ownership Plan
EUVE	Extreme Ultraviolet Explorer
FAR	Federal Acquisition Regulation
FES	Fine Error Sensor
FFR	fabrication feasibility review
FFT	fast Fourier transform
FIPS	Fast Imaging Plasma Spectrometer
FMEA	failure mode effects analysis
FORTÉ	Fast On-Orbit Recording of Transient Events

FOV	field-of-view
FPA	Focal Plane Assembly
FPGA	field-programmable gate array
FRU	frequency reference unit
FTE	Full-Time Equivalent
FUSE	Far Ultraviolet Spectroscopic Explorer
FUV	Far Ultraviolet
G&A	General and Administrative
G&C	guidance and control
GAS	Get-Away-Special
GC	Geochemistry Group
GDS	Ground Data System
GEOSAT	Geodetic Earth Orbiting Satellite
GG	Geology Group
GLAS	Geoscience Laser Altimeter System
GLAST	Gamma-Ray Large Area Space Telescope
GP	Geophysics Group
GRC	John H. Glenn Research Center at Lewis Field
GRNS	Gamma-ray and Neutron Spectrometer
GRS	gamma-ray spectrometer
GSE	Ground System Engineer
GSFC	Goddard Space Flight Center
HBCUs	Historically Black Colleges and Universities
HEF	high-efficiency
HENA	High Energy Neutral Atom
HFET	heterostructure field-effect transistor
HGA	high-gain antenna
HRG	hemispherical resonator gyroscope
HUT	Hopkins Ultraviolet Telescope
HV	high voltage
I&T	Integration and Test
IA&T	Integration, Assembly and Test
ICD	interface control document
ICESat	Ice, Cloud, and land Elevation Satellite
ICS	Ion Composition Subsystem
IDS	Instrument Data System
IEM	integrated electronics module
IHI	Ishikawajima-Harima Heavy Industries
IMAGE	Imager for Magnetopause-to-Auroral Global Exploration
IMU	inertial measurement unit
INCA	Ion and Neutral Camera
IPSDU	Instrument Power Switching and Distribution Unit
IR	infrared
IR&D	Independent Research and Development
IRR	Integration Readiness Review
ISAS	Institute of Space and Astronautical Science
ISTP	International Solar-Terrestrial Program
IUE	International Ultraviolet Explorer
IV&V	independent validation and verification
JHU	The Johns Hopkins University

JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LAMRC	lossy adaptive multi-resolution compression
LASP	Laboratory for Atmospheric and Space Physics
LEMMS	Low Energy Magnetospheric Measurements System
LGA	low-gain antenna
LRR	Launch Readiness Review
LV	Launch Vehicle
MAG	Magnetometer
MCM	Miscellaneous Contract Materials
MCP	microchannel plate
MDIS	Mercury Dual Imaging System
MEM	MESSENGER Education Module
MEOP	Maximum Expected Operating Pressure
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry and Ranging
MEU	Main Electronics Unit
MGA	medium-gain antenna
MGS	Mars Global Surveyor
MIMI	Magnetospheric Imaging Instrument
MI	Minority Institution
MLA	Mercury Laser Altimeter
MLI	multilayer insulation
MLS	Microwave Limb Sounder
MM	Mission Manager
MOC	Mission Operations Center
MODC	Miscellaneous Other Direct Costs
MOI	Mercury orbit insertion
MOLA	Mars Observer Laser Altimeter
MOLA-2	Mars Orbiter Laser Altimeter
MOS	Mission Operations System
MOSFET	metal-oxide semiconductor field-effect transistor
MOT	Mission Operations Team
MP	main processor
MPA	Mirror Positioning Assembly
MPAe	Max Planck Institute for Aeronomie
MPG	Mission Planning Group
MRDF	Material Review Disposition Form
MRR	Mission Readiness Review
MSE	Math, Science, and Engineering
MSE	Mission System Engineer
MSI	Multi-Spectral Imager
MSU	Montana State University
MSX	Midcourse Space Experiment
MTAC	Mid-Atlantic Technology Applications Center
MTTF	mean-time-to-failure
MU-SPIN	Minority University-SPace Interdisciplinary Network
MUV	Middle Ultraviolet
NA	narrow-angle
NARB	NEAR Anomaly Review Board
NASA	National Aeronautics and Space Administration

NASCOM	NASA Communications Network
NASM	National Air and Space Museum
NEAR	Near Earth Asteroid Rendezvous
NIST	National Institute of Standards and Technology
NLR	NEAR Laser Rangefinder
NMO	NASA Management Office
NMSA	National Middle School Association
NNSS	Navigation Satellite System
NRE	Non-Recurring Engineering
NRTS	Network Resources and Training Sites
NS	Neutron Spectrometer
NSES	National Science Education Standards
NSTA	National Science Teachers Association
NSWC	Naval Surface Weapons Center
ODC	Other Direct Costs
ODF	Orbit Data File
OLS	Orbital Launch Services
OMB	Office of Management and Budget
OMS	orbital maneuvering subsystem
OSDP	Onboard Signal and Data Processor
OSR	optical solar reflector
OSS	Office of Space Science
P/FR	Problem/Failure Report
PAE	Performance Assurance Engineer
PAIP	Performance Assurance Implementation Plan
PCI	Peripheral Component Interconnect
PDR	Preliminary Design Review
PDS	Planetary Data System
PEM	Particle Environment Monitor
PER	Pre-Environmental Review
PI	Principal Investigator
PIDDP	Planetary Instrument Definition and Development Program
PM	Project Manager
PMT	photomultiplier tube
Polar BEAR	Polar Beacon Experiment and Auroral Research
PPT	peak-power tracker
PRI	Proxemy Research, Inc.
Pro-Net	Procurement Marketing and Access Network
PS	Project Scientist
PSD	power spectral density
PSE	power-system electronics
PSI	Pressure Systems, Inc.
PSIA	pounds per square inch absolute
PSR	Pre-Ship Review
QARL	Quality Assurance Requirement Level
RE	Recurring Engineering
REA	Rapid Environmental Assessment
RFI	Request for Information
RFP	Request for Proposal
RIU	remote interface unit

RMIS	Resource Management Information System
RS	Radio Science
RSE	resident subcontract employee
S/C	spacecraft
S/W	software
SAMPEX	Solar Anomalous Magnetospheric Particle Explorer
SAS	Science Analysis System
SBIRS	Space-Based Infrared Surveillance
SBLO	Small Business Liaison Office
SBV	Space Based Visible
SCA	Subcontract Administrator
SCP	spacecraft control processor
SCSE	Spacecraft System Engineer
SD	Space Department
SDB	Small Disadvantaged Business
SDI	Strategic Defense Initiative
SDP	Software Development Plan
SDST	Small Deep Space Transponder
SEU	single-event-upset
SLA	Shuttle Laser Altimeter
SMEX/WIRE	Small Explorer/Wide Infrared Explorer
SNR	signal-to-noise ratio
SOC	Science Operations Center
SOHO	Solar and Heliospheric Observatory
SPICE	Spacecraft, Planet, Instrument, C-matrix, Events
SPIRIT III	Spatial Infrared Imaging Telescope
SPM	Science Payload Manager
SRR	System Requirements Review
SRTM	Shuttle Radar Topographic Mapper
SSC	Science Steering Committee
SSCM	Small Spacecraft Cost Model
SSD	solid-state detector
SSPA	solid-state power amplifier
SSR	solid-state recorder
SSUSI	Special Sensor Ultraviolet Spectrographic Imager
STE	Special Test Equipment
STICS	Supra-Thermal Ion Composition Spectrometer
SWSE	Software System Engineer
TA	true anomaly
TDA	Technical Direction Agent
TEC	thermo-electric cooler
TES	Thermal Emission Spectrometer
TGA	Thermal Gravimetric Analysis
TIM	Technical Interchange Meeting
TIMED	Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics
TIP	Transit Improvement Program
TIU	time interval unit
TMC	Total Mission Cost
TMDC	Total Modified Direct Cost
TML	total mass loss

TMOD	Telecommunications and Mission Operations Directorate
TOF	time-of-flight
TRL	technology readiness level
TSD	Technical Services Department
TUB	Technical University of Braunschweig
UARC	University Affiliated Research Center
UARS	Upper Atmosphere Research Satellite
ULEIS	Ultra Low Energy Isotope Spectrometer
UM	University of Michigan
USO	Ultra-Stable Oscillator
UV	ultraviolet
UVISI	Ultraviolet and Visible Imagers and Spectrographic Imagers
UVS	Ultraviolet Spectrometer
UVVS	Ultraviolet-Visible Spectrometer
V&V	validation and verification
VIRS	Visible-Infrared Spectrograph
VIS	Visible
VLSI	very large scale integration
VMAG	Vector Magnetometer
WA	wide-angle
WBS	Work Breakdown Structure
WOSB	women-owned small business
WotU	Window on the Universe
XGRS	X-ray and Gamma-ray Spectrometer
XRS	X-ray Spectrometer