MESSENGER: A DISCOVERY MISSION TO MERCURY

Ralph L. McNutt, Jr.[(1)], Robert E. Gold[(1)], Sean C. Solomon[(2)], James C. Leary[(1)], and David G. Grant[(1)]

[(1)]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, ralph.mcnutt@jhuapl.edu
[(2]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA.

ABSTRACT

NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was launched on 3 August 2004. The mission is designed to answer six fundamental questions about Mercury that are pertinent as well to our general understanding of terrestrial planets. During the 6.6-year cruise phase, MESSENGER will fly by Earth, Venus, and Mercury. Calibration measurements of the Earth and Moon were made during an Earth flyby, one year after launch. The three Mercury flybys in 2008 and 2009 slow the spacecraft sufficiently for Mercury orbit injection in March 2011 and permit mapping of 90% of the planet. All of the seven instruments have now been successfully operated in space. The cruise phase has been used to commission the spacecraft and instruments and to begin the transition to automated operations with on-board, time-tagged commands. A one-year-long observational campaign in a near-polar orbit is planned for the Mercury orbital phase. A 12-hour period and 80° inclination are maintained while the periapsis altitude is readjusted to 200 km every Mercury year. This orbit enables mapping of the entire planet and acquiring detailed elemental and topographical data over the northern hemisphere.

1. INTRODUCTION AND OVERVIEW

1.1 The Discovery Program

The U.S. National Aeronautics and Space administration (NASA) began the Discovery Program as a series of focused, low-cost missions under the direction of a single Principal Investigator. Ten Discovery missions have been selected for flight to date (Fig. 1). MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) is Discovery mission number seven [1].

1.2 Mercury Exploration Issues

While there had been studies of follow-on missions to Mercury after the Mariner 10 mission of the mid-1970's, the advocated missions were complex and expensive [2, 3]. Mercury is difficult to study, either by telescope, due to its proximity to the Sun, or by spacecraft. Heretofore, the planet has been visited only by the Mariner 10 spacecraft, and that only in the course of three brief flybys of the planet in 1974 and 1975. More detailed study, in particular study required to resolve questions only hinted at by Mariner 10, require an orbiter.

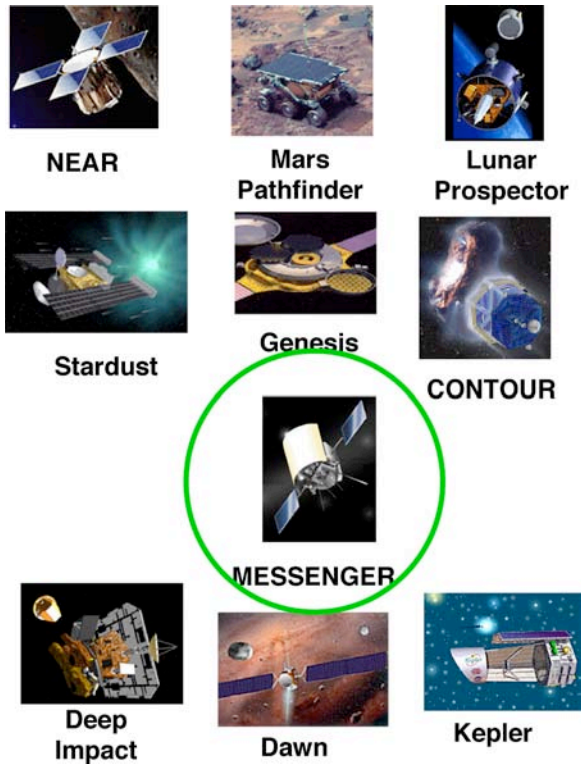

Fig. 1. Discovery missions selected for flight to date. The first three missions have been completed through data analysis.

With Mercury's depth in the Sun's gravitational well, the key to any orbital mission is the use of reverse gravity assists to slow the spacecraft with flybys of Venus and Mercury and decrease the speed change required for orbit insertion to a level commensurate with existing propulsion technology [4-8].

1.3 MESSENGER Science

Mercury is a planet of extremes, including the highest uncompressed density of any planet in our solar system, the highest diurnal variation in temperature, the only solar system object in 3:2 spin-orbit resonance, the planet whose geological history ended earliest among the terrestrial planets, and the smallest planet with a global magnetic field, along with the most Earth-like magnetosphere [9]. Questions associated with the most scientifically pressing issues were formulated for the MESSENGER mission and used to plan its implementation [10].

The guiding science questions, and corresponding measurement objectives, for MESSENGER are

(1) What planetary formational processes led to the high metal-to-silicate ratio in Mercury? – Map the elemental and mineralogical composition of Mercury's surface.

(2) What is the geological history of Mercury? – Image globally the surface at a resolution of hundreds of meters or better.

(3) What are the nature and origin of Mercury's magnetic field? – Determine the structure of the planet's magnetic field.

(4) What are the structure and state of Mercury's core? – Measure the libration amplitude and gravitational field structure.

(5) What are the radar-reflective materials at Mercury's poles? – Determine the composition of the radar-reflective materials at Mercury's poles.

(6) What are the important volatile species and their sources and sinks on and near Mercury? – Characterize exosphere neutrals and accelerated magnetosphere ions.

The MESSENGER mission team, sponsored by NASA's Science Mission Directorate, has been focused since the time of selection on providing a spacecraft [11, 12] and instrument set [13, 14] to answer these questions (Fig. 2).

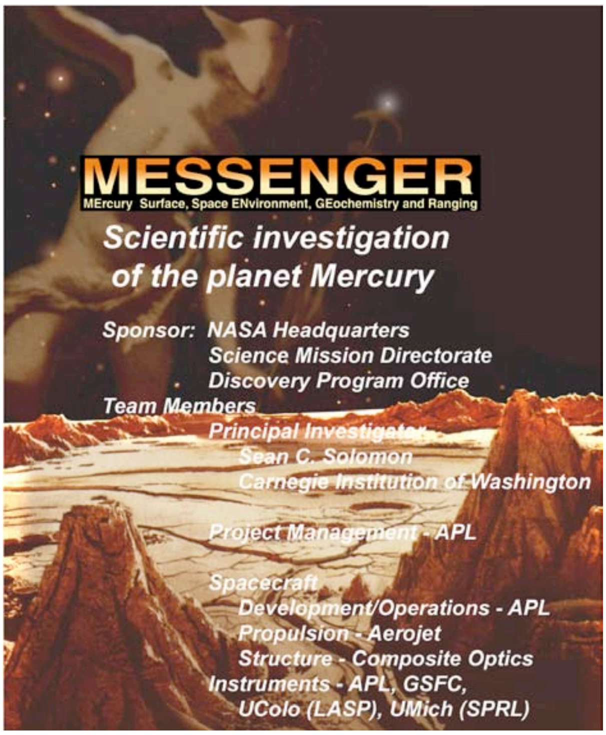

Fig. 2. The MESSENGER team at a glance.

1.4 International Interactions

Although there is no direct, formal international collaboration on MESSENGER, there are ongoing informal international discussions on the exploration of Mercury. In addition to various sessions at scientific meetings on the subject, the core science teams of MESSENGER and BepiColombo (a joint European Space Agency (ESA)/Japanese Aerospace Exploration Agency (JAXA) mission to Mercury) have had, and continue to have, unofficial coordination meetings [15].

1.5 Payload

MESSENGER's comprehensive payload consists of seven scientific instruments plus the telecommunications system for radio science (Fig. 3).

The instruments include: Mercury Dual Imaging System (MDIS), provided by the Applied Physics Laboratory (APL) of The Johns Hopkins University, the Gamma-Ray and Neutron Spectrometer (GRNS), provided by APL, the X-Ray Spectrometer (XRS), provided by APL, the Magnetometer (MAG), a joint APL/Goddard Space Flight Center (GSFC) instrument, the Mercury Laser Altimeter (MLA), provided by GSFC, the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), provided by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado in Boulder, and the Energetic Particle and Plasma Spectrometer (EPPS) consisting of the Energetic Particle Spectrometer (EPS), provided by APL, and the Fast Imaging Plasma Spectrometer (FIPS), provided by the Space Physics Research Laboratory (SPRL) of the University of Michigan.

1.6 Technology Challenges

The spacecraft design faced many technology challenges. The spacecraft will face a severe thermal environment of >14 kW/m^2 thermal input at Mercury with the front of the spacecraft reaching temperatures of greater than 360°C. The most stressing case will occur then the spacecraft is sandwiched between Sun and planet while maintaining a thermal environment that allows use of standard space electronics [16].

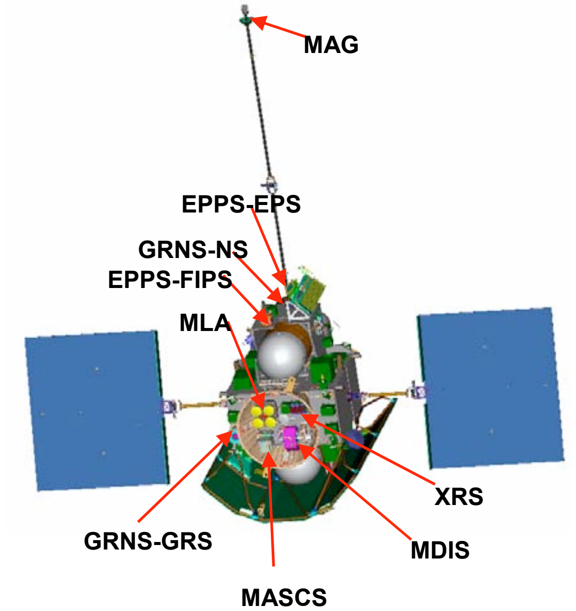

Fig. 3. The MESSENGER instruments.

Greater than 2300 m/s of in-space propulsion is required to insert the spacecraft into Mercury orbit while keeping the overall mass commensurate with the capabilities of a Delta II Heavy launch vehicle (the largest allowed in the Discovery Program).

Power generation at high temperatures as well as at just outside of 1 AU is required for the mission. Once in orbit at Mercury, face-on exposure of the solar panels to the Sun could cause the panel temperatures to reach 270°C. MESSENGER was designed to keep the temperatures below a still high, but acceptable, level by combining optical solar reflectors with the cells and tilting the arrays back at an increasing amount as the spacecraft moves closer to the Sun [17, 18].

Communications reliability at the extreme temperatures to be encountered was also an engineering issue. To keep the antenna and mechanisms from thermal extremes while returning > 75 Gbits from Mercury was approached by implementing two electronically steered phased arrays on the spacecraft [19, 20], eliminating the need for moving parts.

Finally, one of the most challenging engineering tasks is that associated with the gamma-ray spectrometer sensor on the GRNS instrument. It must operate at 80 K while the spacecraft experiences the severe thermal input at Mercury.

Significant mass reductions were required for all payload instruments as well as most spacecraft subsystems [21-25].

1.7 Operations

To provide a spacecraft that can meet these challenges, the operations must be simple yet versatile. This goal was accomplished with a 3-axis, zero-momentum-bias attitude control system [26], robust fault protection, and autonomous operations capabilities [27]. Autonomous software controls the solar array pointing, phased-array antenna steering, and spacecraft momentum build up. Pointing options for the spacecraft are planet-referenced or celestial. The planet-referenced pointing can aim the payload apertures at any given altitude, which includes surface-feature tracking [28]. Pointing accuracy by the attitude control system is better than 1.7 mrad (0.1°) with 350 µrad (0.02°) after-the-fact pointing knowledge, and < 25 µrad/100 ms (0.001°) pointing jitter.

For communication and data handling MESSENGER uses a prioritized file system similar to a PC disk [29, 30]. To maximize the returned data, the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP) is used along with variable downlink data rates (10 bps to 104 kbps) [31, 32].

The spacecraft includes limited one-time deployable items: the magnetometer boom, an acoustic cover on EPS, and a cover on the MASCS instrument; all of these have been operated successfully. With the exception of an external pivot and filter wheel on MDIS and an internal drive in the MASCS instrument, all components and instruments are fixed, with highly miniaturized and mass efficient designs.

1.8 Trajectory and Mission Plans

NASA's MESSENGER spacecraft, launched on 3 August 2004 (Fig. 4), has begun its voyage to the

Fig. 4. MESSENGER launch on 3 August 2004.

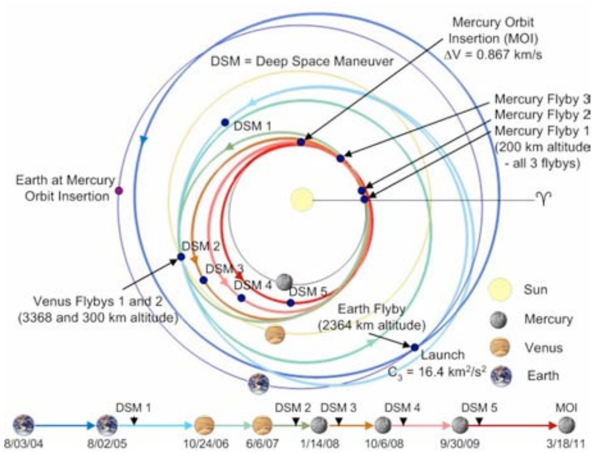

Fig. 5. MESSENGER's cruise trajectory.

innermost planet. Prior to orbit insertion there is a 6.6-year cruise phase, during which MESSENGER will fly by Earth, Venus, and Mercury.

One year after launch an Earth flyby began removing kinetic energy from the spacecraft while enabling calibration measurements of the Earth and Moon. Venus flybys in October 2006 and June 2007 increase the inclination of MESSENGER's transfer orbit to match that of Mercury. The three Mercury flybys in 2008 and 2009, interspersed with deep space maneuvers, will slow the spacecraft sufficiently for Mercury orbit injection in March 2011 (Fig. 5) and permit mapping of 90% of the planet.

The cruise phase to date has been used to commission the spacecraft and instruments and begin the transition to automated use of the instruments with on-board, time-tagged commands. In the Mercury orbital phase, the spacecraft's nominal periapsis latitude of 60° N will gradually drift northward as the periapsis altitude of 200 km gradually drifts upward due to solar gravitational perturbations. The 12-hour period and 80° inclination are maintained while the altitude is readjusted downward to 200 km every Mercury revolution about the Sun. This orbit enables mapping of the entire planet and acquiring detailed elemental and topographical data over the northern hemisphere.

After conclusion of the nominal mission in March 2012, an additional year of data analysis and archiving is planned before the conclusion of the MESSENGER project.

2. CURRENT STATUS

2.1 Earth Flyby

The MESSENGER flyby of the Earth was successfully conducted on 2 August 2005 (Fig. 6). The imager (MDIS) and spectrometer (MASCS) used lunar observations to confirm their calibrations. The magnetometer (MAG) and particle instrument (EPPS) made magnetospheric measurements. The altimeter (MLA) ranged to Earth in May 2005, while GRNS and XRS were not operated.

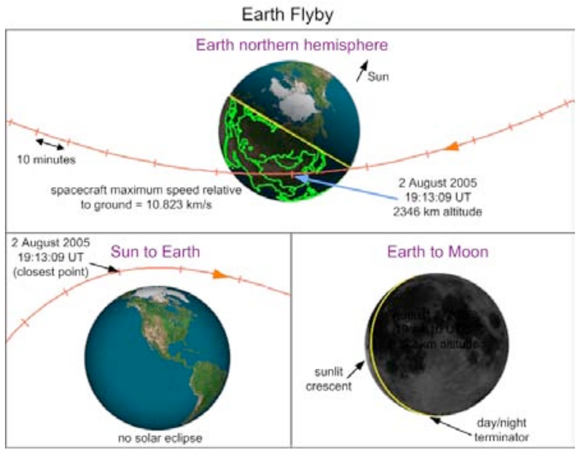

Fig. 6. Geometry of the Earth flyby.

As part of the operational tests and calibrations, images of the Earth and Moon were acquired with MDIS. Fig. 7 shows a false-color image taken prior to closest approach.

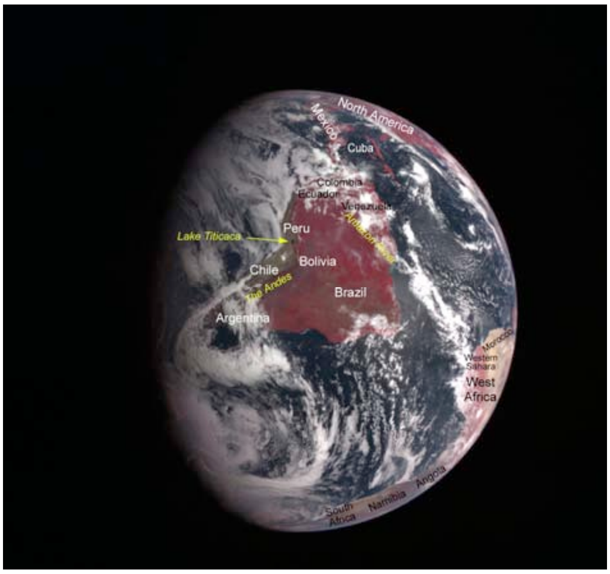

Fig. 7. A false-color image acquired with three exposures using three different filters on the wide-angle camera component of MDIS.

The MASCS instrument used its Visible Infrared Spectrograph (VIRS) to acquire spectra of the Moon for comparison with those to be obtained of Mercury. Following the Earth flyby the Ultraviolet and Visible Spectrometer (UVVS) portion of MASCS was used to probe the Earth's hydrogen geocorona.

The MAG data allowed a detailed comparison with the Earth's magnetic field and verified the alignments and noise level of that instrument.

The radiation belts of the Earth were probed with the EPS sensor to obtain a good calibration of the electron channels, something not possible with Earth-based facilities.

2.2 Other Instrument Calibration Activities

Initial operational/calibration activities have been conducted for all of the other instruments as well. The gamma-ray spectrometer on GRNS has been turned on and cooled to the cryogenic operational temperature for its high-purity germanium detector. Performance was excellent. The nominal energy range is 0.1 – 10 MeV with a measured resolution of 3.5 keV full-width half maximum at1332 keV. The cruise operation shows a range of elements within the spacecraft; the following elements/lines have been identified: H, O, Ne, Na, Mg, Al, K, Ti, Mn, Fe, Co, Zn, Ga, Ge, Cs, Th, U, e^{-}-e^{+} annihilation.

The neutron spectrometer (NS) section of GRNS is sensitive to fast, epithermal, and thermal neutrons. It is also sensitive to gamma-ray bursts (GRBs). In particular, the MESSENGER NS detected the GRB of 1 May 2005 (Day of Year 121 $8^{h}20^{m}5.690^{s}$).

The MLA was exercised with both passive and active ranging prior to the Earth flyby to test separately the transmitter and receiver. A spacecraft passive raster scan of Earth from a range of 29 x 10^{6} km checked MLA internal alignment and the co-alignment with the MDIS imagers. Two-way, active ranging with Earth was conducted at a distance of 26 x 10^{6} km. The MLA downlink laser was detected at both GSFC and the Jet Propulsion Laboratory (JPL), and the uplink laser from GSFC was detected on the spacecraft. This exercise was the longest-range laser communication experiment that has been carried out to date.

The MESSSENGER XRS has been checked out by observing the supernova remnant Cassiopeia A.

Finally, FIPS has been used to measure the solar wind near Earth and has returned solar wind parameters consistent with those observed by the Advanced Composition Explorer (ACE), in a halo orbit about the upstream Earth-Sun L1 point.

2.3 Earth-to-Venus Cruise

The MESSENGER spacecraft is now operating normally on its cruise to Mercury. Initial commissioning and checkout have been completed, with over 100,000 commands and six trajectory maneuvers to date. Numerous instrument calibration activities for the payload have been carried out successfully, and the power, thermal, telecommunications, propulsion, and guidance and control systems are all working well. The spacecraft is now oriented with the sunshade toward Sun. Outside of 0.95 astronomical units from the Sun, the sunshade has been turned away from the Sun to keep the spacecraft within its design thermal range while limiting required heater power. The phased array antennas and CFDP are providing excellent data return.

The next major maneuver, and the first to use the bipropellant propulsion system in space, will occur on 12 December 2005 to target MESSENGER for its first flyby of Venus. That flyby on 24 October 2006 is at a relatively high altitude (3324 km) and near solar conjunction, so there will be no observations with the payload. The second MESSENGER flyby of Venus on 5 June 2007 will be at an altitude of 300 km. Plans are now underway for further instrument calibrations as well as scientific investigations of Earth's "sister planet" at that time. The second Venus flyby will also be used as a dress rehearsal for our first observations of the planet Mercury by MESSENGER during the first Mercury flyby seven months later on 14 January 2008.

3. ACKNOWLEDGMENTS

"The MESSENGER Team" includes hundreds of scientists, engineers, designers, technicians, support personnel, subcontractors, and managers too numerous to list. We also acknowledge the assistance of NASA personnel and others who gave of their time to help review the program and enable MESSENGER to be on its way to Mercury. The current MESSENGER effort is supported by the NASA Discovery program under contract NAS5-97271 at APL and NASW-00002 at the Carnegie Institution of Washington.

4. REFERENCES

1. McNutt R. L., Jr., Solomon S. C., Gold R. E., Leary J. C., and the MESSENGER Team, *Advan. Space Res.*, in press, 2005.

2. Belcher J. B., Slavin J. A., Armstrong T. P., Farquhar R. W., Akasofu S. I., Baker D. N., Catttell C. A., Cheng A. F., Chupp E. L., Clark P. E., Davies M. E., Hones E. W., Kurth W. S., Maezawa J. K., Mariani F., Marsch E., Parks G. K., Shelley E. G., Siscoe G. L., Smith E. J., Strom R. G., Trombka J. I., Williams D. J., Yen C.-W., Mercury Orbiter: Report of the Science Working Team, *NASA Technical Memorandum 4255*, NASA Office of Management, Scientific and Technical Information Division, 136 pp., 1991.

3. Stern S. A., and Vilas F., Future observations of and missions to Mercury, in *Mercury*, F. Vilas, C. R.

Chapman, and M. S. Matthews (Eds.), pp. 24-36, University of Arizona Press, Tucson, AZ, 1988.

4. Yen C.-W., Ballistic Mercury orbiter mission via Venus and Mercury gravity assists, *Proceedings of the American Astronautical Society/American Institute of Aeronautics and Astronautics Astrodynamics Conference, Paper AIAA No. 85-34*6, San Diego, CA, 1985.

5. Yen C.-W., Ballistic Mercury orbiter mission via Venus and Mercury gravity assists, *J. Astronaut. Sci.*, Vol. 37, 417-432, 1989.

6. Yen C.L., New trajectory options for ballistic Mercury orbiter mission, *American Astronautical Society/American Institute of Aeronautics and Astronautics Space Flight Mechanics Meeting, Paper AAS 01-158*, 9 pp., Santa Barbara, CA, February 11-15, 2001.

7. McAdams J. V., Farquhar R. W., and Yen C. l., Improvements in trajectory optimization for MESSENGER: The first Mercury orbiter mission, *Advan. Astronaut. Sci.*, Vol. 109, Part III, 2189-2203, 2002.

8. McAdams J. V., Dunham D. W., Farquhar R. W., Taylor A. H., and Williams B. G., Trajectory design and maneuver strategy for the MESSENGER mission to Mercury*, 15th American Aeronautical Society/American Institute of Aeronautics and Astronautics Space Flight Mechanics Conference, Paper AAS 05-173*, 20 pp., Copper Mountain, Colorado, January 23-27, 2005.

9. Solomon, S. C., Mercury: The enigmatic innermost planet, *Earth Planet. Sci. Lett.,* Vol. 216, 441-455, 2003.

10. Solomon S. C., McNutt R. L., Jr., Gold R. E., Acuña M. H., Baker D. N., Boynton W. V., Chapman C. R., Cheng A. F., Gloeckler G., Head J. W., III, Krimigis S. M., McClintock W. E., Murchie S. L., Peale S. J., Phillips R. J., Robinson M. S., Slavin J. A., Smith D. E., Strom R. G., Trombka J. I., and Zuber M. T., The MESSENGER mission to Mercury: Scientific objectives and implementation, *Planet. Space Sci.,* Vol. 49, 1445-1465, 2001.

11. Santo A. G., Gold R. E., McNutt R. L., Jr., Solomon S. C., Ercol C. J., Farquhar R. W., Hartka T. J., Jenkins J. E., McAdams J. V., Mosher L. E., Persons D. F., Artis D. A., Bokulic R. S., Conde R. F., Dakermanji G., Goss M. E., Jr., Haley D. R., Heeres K. J., Maurer R. H., Moore R. C., Rodberg E. H., Stern, T. G., Wiley S. R., Williams B. G., Yen C. L., and Peterson M. R., The MESSENGER mission to Mercury: Spacecraft and mission design, *Planet. Space Sci*., Vol. 49, 1481-1500, 2001.

12. Santo A. G., Leary J. C., Peterson M. R., Huebschman R. K., Goss M. E., McNutt R. L., Jr., Gold R. E., Farquhar R. W., McAdams J. V., Conde R. F., Ercol C. J., Jaskulek S. E., Nelson R. L., Northrop B. A., Mosher L. E., Vaughan R. M., Artis D. A., Bokulic R. S., Moore R. C., Dakermanji G., Jenkins J. E., Hartka T. J., Persons D. F., and Solomon S. C., MESSENGER: The Discovery-class mission to orbit Mercury, International Astronautical Congress, World Space Congress, *American Institute of Aeronautics and Astronautics, Paper IAC-02-U.4.1.04*, 11 pp., Houston, TX, October 10-19, 2002.

13. Gold R. E., Solomon S. C., McNutt R. L., Jr., Santo A. G., Abshire J. B., Acuña M. H., Afzal R. S., Anderson B. J., Andrews G. B., Bedini P. D., Cain J., Cheng A. F., Evans L. G., Feldman W. C., Follas R. B., Gloeckler G., Goldsten J. O., Hawkins S. E., III, Izenberg N. R., Jaskulek S. E., Ketchum E. A., Lankton M. R., Lohr D. A., Mauk B. H., McClintock W. E., Murchie S. L., Schlemm C. E., II, Smith D. E., Starr R. D., and Zurbuchen T. H., The MESSENGER mission to Mercury: Scientific payload, *Planet. Space Sci*., Vol. 49, 1467-1479, 2001.

14. Gold R. E., Solomon S. C., McNutt R. L., Jr., and Santo A. G., The MESSENGER spacecraft and payload, *International Astronautical Congress, World Space Congress, American Institute of Aeronautics and Astronautics, Paper IAC-02-Q.4.1.02*, 9 pp., Houston, TX, October 10-19, 2002.

15. McNutt R. L., Jr., Solomon S. C., Grard R., Novara M., and Mukai T., An international program for Mercury exploration: Synergy of MESSENGER and BepiColombo, *Advan. Space Res*., Vol. 33, 2126-2132, 2004.

16. Ercol C. J. and Santo A. G., Determination of optimum thermal phase angles at Mercury perihelion for an orbiting spacecraft, *29th International Conference on Environmental Systems, Society of Automotive Engineers, Tech. Paper Ser., 1999-01-21123*, 10 pp., Denver, CO, July 21-25, 1999.

17. Ercol C. J., Jenkins J. E., Dakermanji G., Santo A. G., and Mason L. S., Prototype solar panel development and testing for a Mercury orbiter spacecraft, *35th Intersociety Energy Conversion Engineering Conference, American Institute of Aeronautics and Astronautics, Paper AIAA-2000-2881*, 11 pp., Las Vegas, NV, July 24-28, 2000.

18. Dakermanji G., Jenkins J., Schwartz P., and Kennedy L., The MESSENGER spacecraft power system, *Proceedings of the Sixth European Space Power Conference, European Space Agency SP-502*, pp. 121-128, 2002.

19. Wallis R. E., and Cheng S., Solid-state phased-array antenna system for the MESSENGER deep space mission, *Institute of Electrical and Electronic Engineers Aerospace Conference, Paper 2.0104*, 9 pp., CD Track 2: Space Missions, Systems, and Architecture, Big Sky, MT, March 10-17, 2001.

20. Stilwell R. K., Wallis R. E., and Edwards M. L., A circularly polarized, electrically scanned slotted waveguide array suitable for high temperature environments, *Proceedings of the Institute of Electrical and Electronics Engineers International Symposium on Antennas and Propagation and United States National Committee*, Canadian National Committee, International Union of Radio Science North American Radio Science Meeting, Columbus, OH, June 22-27, 2003 (CD-ROM).

21. Le B. Q., Ling, S. X. Kennedy L. R., Dakermanji G., and Laughery S. C., The MESSENGER power distribution unit packaging design, *21st Digital Avionics Systems Conference (DASC), Paper 9B3*, 8 pp., Irvine, CA, October 27-31, 2002.

22. Ling S. X., Conde R. F., and Le B. Q., A light weight integrated electronics module (IEM) packaging design for the MESSENGER spacecraft, *21st Digital Avionics Systems Conference (DASC), Paper 9B4*, 9 pp., Irvine, CA, October 27-31, 2002.

23. Persons D. F., Mosher L. E., and Hartka T. J., The NEAR Shoemaker and MESSENGER spacecraft: Two approaches to structure and propulsion design, 41st Structures, *Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics, Paper AIAA-00-1406*, 10 pp., Atlanta, GA, April 3-6, 2000.

24. Tam W., Wiley S., Dommer K., Mosher L., and Persons D., Design and manufacture of the MESSENGER propellant tank assembly, *38th American Institute of Aeronautics and Astronautics/American Society of Mechanical Engineers/Society of Automotive Engineers/American Society for Engineering Education (AIAA/ASME/SAE/ASEE) Joint Propulsion Conference and Exhibit, Paper AIAA 2002-4139*, 17 pp., Indianapolis, IN, July 7-10, 2002.

25. Wiley S., Dommer K., and Mosher L., Design and development of the MESSENGER propulsion system, *American Institute of Aeronautics and Astronautics/Society of Automotive Engineers/American Society of Mechanical Engineers (AIAA/SAE/ASME) Joint Propulsion Conference, Paper AIAA-2003-5078*, 20 pp., Huntsville, AL, July 21-24, 2003.

26. Vaughan R. M., Haley D. R., O'Shaughnessy D. J., and Shapiro H. S., Momentum management for the MESSENGER mission, *American Astronautical Society/American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference, Paper AAS 01-380*, 22 pp., Quebec City, Quebec, Canada, July 30 to August 2, 2001.

27. Moore R. C., Safing and fault protection for a mission to Mercury, *21st Digital Avionics Systems Conference (DASC), Paper 9A4*, 8 pp., Irvine, CA, October 27-31, 2002.

28. O'Shaughnessy D. J., and Vaughan R. M., MESSENGER spacecraft pointing options, *13th American Astronautical Society (AAS)/American Institute of Aeronautics and Astronautics (AIAA) Space Flight Mechanics Conference, Paper AAS-03-149*, 20 pp., Ponce, Puerto Rico, February 9-13, 2003.

29. Krupiarz C. J., Burleigh S. C., Frangos C. M., Heggestad B. K., Holland D. B., Lyons K. M., and Stratton W. C., The use of the CCSDS file delivery protocol on MESSENGER, *Space Operations 2002 Conference, World Space Congress, American Institute of Aeronautics and Astronautics, Paper T5-35*, 8 pp., Houston, TX, October 9-12, 2002.

30. Krupiarz C. J., Artis D. A., Calloway A. B., Frangos C. M., Heggestad B. K., Holland D. B., and Stratton W. C., File-based data processing on MESSENGER, *Proceedings of the 5th International Academy of Astronautics (IAA) International Conference on Low-Cost Planetary Missions, Special Publication SP-542*, edited by R. A. Harris, pp. 435-442, European Space Agency, Noordwijk, The Netherlands, 2003.

31. Srinivasan D. K., Vaughan R. M., Wallis R. E., Mirantes M. A., Hill T. A., Cheng S., Bruzzi J. R., and Fielhauer K. B., Implementation of an X-band phased-array subsystem in a deep space mission, *Institute of Electrical and Electronics Engineers (IEEE) Aerospace Conference, IEEEAC paper 1067*, 11 pp., Big Sky, MT, March 5-12, 2005.

32. Srinivasan D. K., Wallis R. E., Royster D. W., Bruzzi J. R., Malouf P. M., and Fielhauer K. B., Spacecraft-level testing and verification of an X-band phased array, *Institute of Electrical and Electronics Engineers (IEEE) Aerospace Conference, IEEEAC paper 1059*, 9 pp., Big Sky, MT, March 5-12, 2005.