Deep Space Communications

Edited by Jim Taylor

Jet Propulsion Laboratory
California Institute of Technology

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Foreword

The Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO) was established in 1998 by the National Aeronautics and Space Administration (NASA) at the California Institute of Technology's Jet Propulsion Laboratory (JPL). DESCANSO is chartered to harness and promote excellence and innovation to meet the communications and navigation needs of future deep-space exploration.

DESCANSO's vision is to achieve continuous communications and precise navigation—any time, anywhere. In support of that vision, DESCANSO aims to seek out and advocate new concepts, systems, and technologies; foster key technical talents; and sponsor seminars, workshops, and symposia to facilitate interaction and idea exchange.

The Deep Space Communications and Navigation Series, authored by scientists and engineers with many years of experience in their respective fields, lays a foundation for innovation by communicating state-of-the-art knowledge in key technologies. The series also captures fundamental principles and practices developed during decades of deep-space exploration at JPL. In addition, it celebrates successes and imparts lessons learned. Finally, the series will serve to guide a new generation of scientists and engineers.

Joseph H. Yuen
DESCANSO Leader

Preface

This book presents the planetary communications design as developed by the Deep Space Network (DSN) and Jet Propulsion Laboratory (JPL) flight projects. It uses a case study approach and shows the communications link performance resulting from the design. This is accomplished through a description of the design and performance of six representative planetary missions. These six cases illustrate progression through time of the DSN and onboard hardware and software techniques, capabilities, and performance from 1970s technology to the most recent missions.

The first chapter presents an overview of deep space communication capability over the last five decades. It also describes the design process for these links and the current capabilities of the Deep Space Network (DSN). The second chapter gives an overview of the DSN.

In Chapters 3 through 8, from Voyager in the 1970s to the Mars Science Laboratory in the 2010s, the six missions represent all those that have communicated directly with the Deep Space Network. Two of six also communicated from the surface of Mars to orbiting spacecraft that in turn communicated with the Earth.

The Voyager mission was intended as a flyby mission to Jupiter and Saturn, and its X-band communications system was sized for science return from those planets. With improvements in the Deep Space Network, the two Voyager spacecraft continue to return data from beyond the distances of additional flybys at Neptune and Uranus.

The Galileo mission was intended to transmit the majority of its science data from orbit around Jupiter via a high-gain antenna at X-band. When that antenna failed to unfurl properly early in the cruise to Jupiter, JPL mounted a major effort to change the spacecraft's software and the ground stations'

telemetry system to achieve the return of a high amount of science information via a low-gain antenna at S-band.

Deep Space 1 was intended as an in-flight test bed of new capabilities, with an incidental science mission. This spacecraft carried the first Small Deep Space Transponder (SDST) that has been the mainstay of many missions communicating with the DSN since it worked in Deep Space 1. It also carried a solid state Ka-band amplifier to provide the means to test deep space communications at this frequency. Notable also was the development—after a failure in the spacecraft's attitude control system—of an operational workaround using the spacecraft signal and the station to achieve control of the spacecraft antenna pointing during data return.

The Mars Reconnaissance Orbiter, besides having an ambitious science mission that continues today, was intended to serve as a communications relay terminal for surface landers and rovers. For direct communications with Earth, in addition to using the SDST, it has a 100-watt traveling wave tube amplifier at X-band and a large fixed high-gain antenna. For UHF relay communications with the surface, it uses an Electra transceiver and the Proximity-1 communications protocol.

The two Mars Exploration Rovers, Spirit and Opportunity, for surface operations were each equipped with the SDST and two redundant solid state X-band amplifiers for direct communications and UHF transceivers for relay operations with Mars orbiters. Intended for a 90-day mission after landing on Mars, both rovers outdid themselves, and Opportunity is still continuing its exploration.

The Mars Science Laboratory reflects the maturity of the communications systems first operated on Deep Space 1, Mars Reconnaissance Orbiter, and the Mars Exploration Rovers. After landing on Mars in August 2012, this large rover has been communicating via X-band equipment similar to the Mars Exploration Rover, and a version of the Electra transceiver in the rover as well as in the Mars Reconnaissance Orbiter at the other end of the relay link.

Jim Taylor
Pasadena, California
October 2014

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This book presents results of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

As editor and authors, we acknowledge the constant advice, help, comments, and encouragement from Joseph H. Yuen, the editor-in-chief of the Deep Space Communications and Navigations Systems (DESCANSO) series. David J. Bell's thorough review resulted in much improved clarity and completeness of the spacecraft chapters. In addition, they acknowledge the always helpful inputs and advice of Roger V. Carlson, the JPL editor.

Chapter 1, *Telecommunications Link Analysis*, lays out the principles and the statistical mathematical models for the design control table, or "link budget" in much the original form created by its author Joseph H. Yuen in the 1970s. We have retained this form is sections of Chapter 1 basically unchanged from the version as written by Dr. Yuen in the 1982 edition of Deep Space Telecommunications Systems Engineering.

Chapter 2, *the Deep Space Network*, draws extensively from the Deep Space Network (DSN) Telecommunications Link Design Handbook (810-005) as do sections of the other chapters. As the DSN evolved, many people have created and updated the material in the modules of this handbook. For this chapter we are most indebted to Robert Sniffin, the principal author and editor of the handbook for many decades. Some of the modules in 810-005 carry the names of the principal authors of those modules. In addition, numerous individuals, far too many to name, have contributed to the technology that is documented in their papers in the *Interplanetary Network (IPN) Progress Reports*. This technology has gone into the stations and the control centers, the hardware and software development, the thorough testing involved for each

new system or software update, and the continued operation of the network in support of the missions represented in the following chapters.

Each of the remaining chapters describes the telecommunications system aboard a particular spacecraft. Each such subsystem operates in one to three frequency bands and consists generally of multiple antennas and their routing elements, one or more transponders or individual receivers and transmitters, and the command-receiving and telemetry-generating elements. Each subsystem involved the efforts and time of dozens of individuals or teams that developed the technologies, the functional design, the hardware, and the software. Many others performed the integration of the subsystem into the whole spacecraft and the testing before and after integration. The references in each chapter are those project documents, papers, conference proceedings, and websites that the coauthors and editor of this book drew on directly.

In Chapter 3, *Voyager*, much of the telecom design information was obtained from original Voyager prime mission design documentation: the design control document for the telecommunications links, the functional description of the telecommunications system, and the hardware design requirement for the modulation demodulation subsystem. Much of the mission and operational information was obtained from the Voyager Operational Handbook and the Voyager Neptune Travel Guide. The authors are grateful to Dave Bell, Kar-Ming Cheung, and Ed Massey for their Voyager background and development information.

For Chapter 4, *Galileo*, the authors express their appreciation to many individuals in the Interplanetary Network Directorate and the Telecommunications Science and Engineering Division (33) at JPL and other organizations who contributed directly to the success of the Galileo mission. In addition to the papers cited in the references, Richard Brace, Vic Albrecht, Rick Nybakken, and Gordon Wood, as the spacecraft telecom hardware cognizant engineers, oversaw the development and testing of the transponder, the modulation-demodulation subsystem, the antennas, and the ultra-stable oscillator. Prof. Wai-Kuen Cham of the Chinese University of Hong Kong invented the integer cosine transform (ICT) and helped to refine the ICT algorithm that was used as a form of lossy compression mostly for image data after the high-gain antenna (HGA) failed to deploy. The compression reduced the data volume to fit through the smaller bandwidth provided by the low-gain antenna link to Earth. Dr. Andrew Watson and Sherry Chuang at NASA Ames designed the ICT quantization matrix and performed subject tests with Galileo scientists to determine acceptable fidelity with ICT lossy compression. The authors are especially grateful to Eilene Theilig for her project systems perspective and to Steve Townes for his organizational recommendations that carried over to subsequent articles.

For Chapter 5, *Deep Space 1*, the on-board telecom hardware development and testing was overseen by cognizant engineer Sam Valas and the antennas by Joe Vacchione. DS1 carried the first Small Deep Space Transponder, developed by Motorola with Keith Siemsen as the technical lead. Marc Rayman, as DS1 system engineer, added much to the clarity of the DESCANSO article the chapter is based on, as well as the success of the mission. The DS1 software team led by Dan Eldred helped the AutoNav team as it ventured for the first time into the realm of deep-space flight software. Finally, and perhaps most importantly, thanks go to the attitude control system (ACS) team, led by Sima Lisman, and including Tony Vanelli and Steve Collins. Besides their function of keeping the spacecraft pointed correctly, ACS was key to working with Jim Taylor of telecom to develop the HGA pointing workaround after the in-flight failure of the stellar reference unit.

For Chapter 6, *Mars Reconnaissance Orbiter (MRO)*, as well as for the two Mars rover missions (Mars Exploration Rover [MER] and Mars Science Laboratory [MSL]) that conclude the book, Chad Edwards was the Mars Program office sponsor, and Edgar Satorius was the relay link signal processing lead. Key to the technical and managerial success of the Electra relay radio program development was Tom Jedrey. Eric Schwartzbaum was the Electra program manager, Ann Devereaux was responsible for the baseband processor, Ken Peters was responsible for software, and Todd Ely was responsible for radiometrics. The Electra first flew in the MRO and first operated on the surface in MSL. As MRO telecom lead, Stan Butman provided several suggestions and graphics for the article. Ricardo Mendoza conceived and developed the data volume capability file that is fundamental for science data return planning for all the Mars relay missions and inter-project coordination. The authors are grateful to David Bell, Tom Jedrey, and Ramona Tung for the information they contributed to the descriptions of the Electra transceiver and its use in relaying information with landers on the surface. We thank Charles Lee for the surface communications opportunities simulation, James Border for the information on delta differential one-way ranging (delta-DOR), and David Morabito for the discussion of solar conjunction effects on communications and the experiment plans during the MRO solar conjunctions.

For Chapter 7, *Mars Exploration Rover*, the authors express their appreciation to Brian Cook and Peter Ilott for the wealth of information on the heritage, performance, and testing of the X-band and UHF subsystems, respectively. Thanks also to Bill Adams, the Odyssey and MGS Flight Team Telecom lead at Lockheed Martin Aerospace. We also, thank Jan Ludwinski, whose excellent mission plan became an integral part of this chapter. The authors are grateful to Monika Danos, for scripts that made summaries of data from years of MER prime and extended mission flight operations consistent. Ramona Tung and Ricardo Mendoza were key to developing seamless relay

link prediction capabilities involving the geometric intricacies of a roving surface vehicle working with several relay orbiters. Finally, the authors are indebted to Ed Satorius, Sue Finley, Christine Chang, Doug Johnston, Dave Fort, and Sami Asmar for their contributions to the analysis, development, testing, and operation of the Entry, Descent, and Landing (EDL) Data Analysis (EDA) system that enabled the return of the intricate series of signals with their rapidly varying signal levels and frequencies.

For Chapter 8, *Mars Science Laboratory*, the authors appreciate the access to information and documents provided by members of the MSL spacecraft development, test and flight operations teams. Many of those acknowledged for MRO and MER also participated in MSL. Peter Ilott was the telecom cognizant engineer and provided "better art" for many of the graphics in this chapter. Melissa Soriano, Sue Finley, and Polly Estabrook developed the EDA configuration to receive the X-band signal during EDL. Melissa Soriano, Sue Finley, Kamal Oudrhiri, and Daniel Kahan tested and operated the EDA and Radio Science Receiver during EDL. Mazen Shihabi and David Bell adapted telemetry analysis tools, first developed by Brad Arnold and Tom Jedrey, to rapidly process analyses of relay link performance the first month post-landing. This led to the successful "tuning" of the MRO Electra radio to overcome electromagnetic interference from MRO science instruments that degraded the MSL relay link performance. The new adaptive data rate mode, first used on the MSL/MRO return link was also tuned to maximize data return volume. Much of the information on spacecraft configuration, the science payload, and subsystems other than telecommunications came from the excellent project review information in the project's DocuShare library, maintained by Marie-Ann Carroll. We made particular use of material from the Mission Plan, as prepared for the 2009 mission by Bobak Ferdowsi and John Gilbert. Brian Schratz, the lead of the Entry, Descent, and Landing (EDL) mission phase provided the description of the data analysis of X-band and UHF signals received during the "seven seconds of terror" culminating in touchdown on the surface.

October 2014

Contributors

Ana I. Bolea-Alamañac received her undergraduate degree in telecommunications engineering jointly from the Centro Politécnico Superior (Zaragoza, Spain) and the Ecole Centrale de Lille (Lille, France) in 1995, her master's in space studies from the International Space University (Strasbourg, France) in 2001, and her Ph.D. from l'École nationale supérieure de l'aéronautique et de l'espace (SUPAERO), in Toulouse, France in 2004, with her work focused on the implementation of fade mitigation techniques applied to advanced satellite communication systems.

From 1996 to 2000, Dr. Bolea-Alamañac worked as an engineer and manager engineer at Telefónica de España, where she worked in the international network planning and operation. In 2001, to fulfill a master's degree requirement, she did an internship in deep-space communications at the Jet Propulsion Laboratory. Her work focused on the Deep Space 1 mission, especially the Beacon Monitor Operations Experiment (BMOX) and its implications for a Deep Space Network operational beacon monitoring system. After her Ph.D., she continued her work in the area of advanced digital communication techniques with the Research and Development Department of Thales Alenia Space in Toulouse, France. In 2005, she joined the European Space Agency (ESA) Research and Technology Centre (ESTEC), Noordwijk, The Netherlands, as a communication system engineer.

Andrea Barbieri received a degree ("laurea") in Electrical Engineering in 1995 from the University of Padova, Italy.

Mr. Barbieri joined JPL in 1997. He served as lead system engineer for the UHF subsystem on the Mars Odyssey 2001 orbiter and the 2003 Mars Exploration rovers, and was the telecom system engineer for various deep space science projects. As a senior engineer in the JPL Communications Systems and

Operations Group of the Flight Communications Systems Section, he became the telecommunications system engineer for the Mars Science Laboratory project in 2004.

Mr. Barbieri has been with Airbus Defence and Space in the United Kingdom since 2007. He was team leader for the payload validation of the first four Galileo navigation satellites, and he is currently test manager for telecommunications payloads.

Kar-Ming Cheung received his B.S. EE from the University of Michigan, Ann Arbor in 1984; and his M.S. and Ph.D. from California Institute of Technology (Pasadena) in 1985 and 1987, respectively.

In 1987, he joined the Communications Systems and Research Section at the Jet Propulsion Laboratory (JPL). In the earlier part of his career at JPL, he worked on the research and development of error-correction coding, data and image compression, synchronization, and system analysis of the NASA's Deep Space Network (DSN) communications system.

In the mid-1990s, when the Galileo spacecraft lost the use of its high-gain antenna, Dr. Cheung implemented a low-complexity data compression software scheme that increased Galileo's data return by a factor of 10. He also led development of the error-correction coding scheme, which was part of the ground-enhancement effort to further increase Galileo's data return. He received the NASA's Exceptional Achievement Medal for his contribution to the Galileo Project.

Dr. Cheung is currently a principal engineer and technical group supervisor of the Communications Systems and Research Section's Telecom Architecture Group. He continues to support the multi-mission telecom link analysis tools development and to lead a multi-center team on architecture and system engineering trade studies to support the Space Communications and Navigation (SCaN) Office of NASA.

Polly Estabrook received a B.S. in engineering physics and a B.A. in economics in 1975 from the University of California, Berkeley. She received her M.S. and Ph.D. in electrical engineering in 1981 and 1989, respectively, from Stanford University (Palo Alto, California).

Dr. Estabrook is Deputy Section Manager of the Communications Architectures and Research section. Her research interests lie in the areas of signal detection during critical events, deep-space telecom system design, and the application of new communication technologies to space exploration.

Dr. Estabrook joined JPL in 1987 as a member of the technical staff, working on satellite communications. She was the lead telecommunications system engineer for the Mars Exploration Rover (MER) project, responsible for the performance of the entry, descent, and landing telecommunications system and for the overall design and performance of the direct-to-Earth and relay communications system. After the landing of the MER rovers, she worked on

the design of the communication system for NASA's Vision for Space Exploration Program supporting human exploration of the Moon and Mars. From 1992 to 2004, she was supervisor of the Advanced Communications Systems Concepts Group in the JPL Communication Systems and Research Section. Her group provided the telecommunication system engineers for Cassini, Mars Pathfinder, Deep Space 1, Deep Space 2, Space Technology 3, ST-4, 2001 Mars Odyssey, Mars Sample Return, and MER.

Peter Ilott received his B.Sc. in physics and Ph.D. in electrical engineering at McGill University (Quebec) in 1980 and 1988, and he received his MSc in plasma physics at the Université de Montréal in 1982.

Dr. Ilott came to JPL in 2000. He is the telecommunications lead at JPL for Mars Science Laboratory (launching in 2011) which includes the mission design for entry, descent, and landing (EDL). For the Phoenix Mars Lander, he was a telecom design consultant and participated in EDL operations. For the MER mission, he was the UHF relay engineer and worked EDL and surface operations.

At JPL, Dr. Ilott also worked on Odyssey, Mars Reconnaissance Orbiter (MRO), Deep Impact, and CloudSat. Prior to JPL he worked for 12 years at SPAR Aerospace (now part of MDA) and Hughes Space and Communications (now Boeing Space Systems) on telecommunications systems for commercial mobile communications spacecraft such as MSAT, ICO, and Thuraya, and on remote sensing spacecraft such as RadarSat.

Dennis K. Lee earned his B.S. from Case Western Reserve University (Cleveland, Ohio) in 1997 and his MS from Rensselaer Polytechnic Institute (Troy, New York) in 1998, both in electrical engineering.

He joined JPL in 1999 as a member of technical staff in the Digital Signal Processing Research group. He has worked on telecommunications systems development for several JPL missions including the Gravity Recovery and Climate Experiment (GRACE), Dawn, Mars Reconnaissance Orbiter (MRO), Kepler, Phoenix, and the Soil Moisture Active Passive mission (SMAP). He is currently serving as the NASA Rapporteur for the Consultative Committee for Space Data Systems (CCSDS) Radio Frequency and Modulation Working Group, and is also the principal investigator on a research and development task to develop a wideband integrated-array combiner and telemetry receiver for the Deep Space Network. His research interests include bandwidth-efficient and multi-carrier modulations, array signal processing, and ultra-high rate communication systems. Mr. Lee is currently a senior engineer in the Communications Architectures and Research section.

Roger Ludwig received his B.S. in management from Oakland University (Rochester, Michigan) in 1981 and his MBA in finance from California State Polytechnic University, Pomona in 1996. He began his aerospace career in 1981 at Altair Radar, Kwajalein Missile Range, the Marshall Islands where, as

operations director, he conducted radar “skin” tracks of Earth-orbiting objects for the North American Aerospace Defense Command Space Detection and Tracking System.

In 1985, Mr. Ludwig joined the Jet Propulsion Laboratory as a spacecraft mission controller on the Active Magnetospheric Particle Tracer Explorers (Earth-orbiter) mission. He first performed spacecraft telecommunications analysis supporting Voyager Neptune encounter in 1989, followed by Magellan (Venus), Galileo (Jupiter), Mars Observer, the Defense Support Program, and Cassini (Saturn). He returned to Voyager in 2000, assuming system-level responsibilities, and in 2004, he added command sequence integration engineer to his portfolio of Voyager specialties.

Andre Makovsky received his B.S. (1984) and M.S. (1985) in electrical engineering from the Rensselaer Polytechnic Institute (Troy, New York). He joined JPL in January 1986 and has worked in telecommunications system development on Galileo, Cassini, Deep Space 1 (DS1), 2001 Mars Odyssey, Mars Exploration Rover (MER), Deep Impact, and Mars Science Laboratory (MSL). For each project, he developed the telecommunications link performance tools used during preproject, prelaunch, and in-flight. Prior to his retirement in 2014, he was a senior engineer in the Communications Systems and Operations Group of the Flight Communications Systems Section.

Mr. Makovsky did extensive prelaunch system performance tests in the JPL Telecommunications Development Laboratory and with the Deep Space Network’s Compatibility Test facilities at JPL, in a mobile Compatibility Test Trailer at spacecraft contractor sites, and at the Eastern Test Range at Cape Kennedy, Florida. He participated in extensive testing of Small Deep Space Transponders both at the contractor (General Dynamics, formerly Motorola) in Phoenix, Arizona and at JPL for DS1, Mars Odyssey, Space Infrared Telescope Facility, MER, and MSL.

Michela Muñoz Fernández received her M.S. and Ph.D. degrees in electrical engineering from the California Institute of Technology (Pasadena, California) in 2001 and 2005, respectively. She previously earned an M.S. in Space Studies from the International Space University (France), an M.S.E.E., and two B.Sc. degrees summa cum laude in electrical engineering and telecommunications engineering in Madrid (Spain). Her Ph.D. thesis was based on a coherent-optical-array receiver for pulse-position modulated signals under atmospheric turbulence for deep-space communications.

Dr. Muñoz Fernández has been working on flight, payload, instrument operations, telecommunications, and ground systems engineering for NASA and ESA missions (Orion, Juno, SIM, Deep Space 1, ROSETTA) since 1998. She is the principal investigator of the Juno mission-modeling task for NASA HQ, a task manager in the information architecture standards area at JPL, and

also works on DSN related research applied to link complexity and RF/optical communications.

She is a Society of Photo-Optical Instrumentation Engineers (SPIE) Free Space Laser Communications Program Committee member, and she has been a chair of sessions on Free-Space Link Performance. She was selected in 2008 to the first rounds of the European Space Agency's astronaut program. She won two Amelia Earhart Awards in 2002 and 2004 respectively, plus other ESA and NASA awards.

Dongae Seo received a B.S. degree in physics from Chung-Nam National University, Deajun, Korea, in 1991 and a master's in space studies from the International Space University (Strasbourg, France) in 2002.

In 1992, she joined Korea Telecom as an engineer and worked on operations with fixed telephone lines including fiber cable. She transferred to the Satellite Business Center in 1994 and worked on interference analysis and technical coordination between satellite networks, designing communication satellite networks (including meteorological satellites) and the management of satellite and ground control systems (Koreasat). In 2002, for the master's degree requirement, she completed an internship at the Communications Systems and Research Section's Flight Communications Systems Group in the Jet Propulsion Laboratory. The internship, during which she co-authored the DESCANSO article Galileo Telecommunications, was mainly about the Galileo mission and Galileo telecommunication link analysis. She also studied the propagation effects of a cometary environment on deep space communication, with application to the Deep Space 1 mission.

Shervin Shambayati received his B.S. in applied mathematics and engineering from California State University, Northridge, in 1989, and his engineering degree, M.S.E.E., and Ph.D. in electrical engineering from the University of California, Los Angeles, in 1991, 1993, and 2002, respectively. Dr. Shambayati joined the JPL Deep Space Telecommunications Group in 1993. With that group, he participated in the Deep Space Network Galileo Telemetry Receiver (DGT) and the 34-m Arraying Task.

In 1997, Dr. Shambayati transferred to the Information Processing Group at JPL. With that group, he participated in the Mars Global Surveyor Ka-band Link Experiment II (MGS/KaBLE II) and Deep Space 1 in-flight Ka-band tests. Dr. Shambayati was also the principal investigator for the Mars Reconnaissance Orbiter Ka-Band Demonstration. Later on, Dr. Shambayati became a member of Telecommunications Architecture Group at JPL, where his research areas included evaluation of weather effects on the end-to-end performance of the deep-space link; end-to-end link design and spacecraft downlink operations over Ka-band; and the end-to-end performance of optical links.

In 2012, Dr. Shambayati joined SSL in Palo Alto, California. Currently he is a senior systems engineering specialist at SSL with the Digital

Communications Engineering Section. His current responsibilities include design and analysis of telemetry, command, and ranging systems for commercial and non-commercial spacecraft as well as design and analysis of communications systems for hosted payloads onboard commercial satellites.

Jim Taylor received a B.S., magna cum laude, in 1961 and an M.S. in 1962, both in electrical engineering from Stanford University (Palo Alto, California). His career has been in spacecraft communications. At JPL since 1970, he has been centrally involved in planning and assessing communications links between interplanetary spacecraft and the Deep Space Network (DSN). He has pursued a special interest in the effects of solar interference on radio communications between interplanetary spacecraft and their supporting ground stations, starting with Mars Mariner in 1971, and most recently the Mars Science Laboratory (MSL). In 2003 for the Mars Exploration Rover project, Mr. Taylor brought the concept of communications windows to maturity. (Now also on MSL, communications windows are intervals in which the flight receiver, transmitter, and antenna are configured by the flight software from on-board tables rather than by sequenced commands.)

Mr. Taylor is a principal engineer at JPL, working on telecommunications analysis, ground-system implementation, and flight operations for deep-space and Earth-orbiting projects. He was the founding telecommunications member of JPL's Spaceflight Significant Events Group, now called Lessons Learned. He received the NASA Exceptional Achievement Medal in 2000 for innovative use of the DS1 communications systems and the NASA Exceptional Service Medal in 2006 for operational development and support on Deep Impact.

Andrea Gail Thomas received a B.A. from the University of California, Los Angeles (California) in 1981 with a major in music. She began her career at JPL in 1984 in the Parts Reliability Section but soon moved to the Spacecraft Telecommunications Equipment Section, now the Flight Communications Systems Section.

She worked on ground support equipment (GSE) hardware and software for the Cassini telemetry control unit. She more recently worked on the GSE software for the Mars Exploration Rover (MER) and the Mars Science Laboratory (MSL) telecommunications subsystems.

Ms. Thomas began working in MER flight operations as a "data miner" during the MER prime mission, then transitioned to become a telecom analyst during the first MER extended mission in 2004, and most recently became a telecom analyst for Cassini. She has also served as the telecom lead in subsequent MER extended missions through 2007.

Ramona Tung received her B.S. (1992) and M.S. (1994) in electrical engineering from the Massachusetts Institute of Technology (MIT, Cambridge). At JPL in the Communications Ground Systems Section, she did simulations and analysis to support the development of the Block V Receiver and the

Block III Maximum-Likelihood Convolutional Decoder (B3MCD), both of which are standard equipment at the three Deep Space Network sites. In the Communications Systems and Research Section, she did high-level telecommunications systems analysis and led the development of the Telecom Forecaster Predictor (TFP) multi-mission telecom analysis tool. TFP has supported many JPL deep-space projects, including Mars Reconnaissance Orbiter (MRO), MER, MSL, and Deep Space 1.

On the MER telecom operations team, Ms. Tung was one of the two telecom analysts providing the majority of telecom support for Spirit during the prime mission, including the resolution of the Sol 18 anomaly. She has worked closely with telecom system engineers at JPL and Lockheed Martin. On MRO, she was the Mission Operations System/Ground Data System lead for Electra, the next-generation UHF proximity radio for communicating between MRO and the MER and MSL rovers. Now in the Mission Systems and Operations section, she is the Flight Operations Team lead for the Soil Moisture Active Passive (SMAP) Earth-orbiter launching in 2014.

Joseph H. Yuen received his Ph.D. in electrical engineering from the University of Southern California (Los Angeles). He is the Chief Technologist of the Communications, Tracking, and Radar Division, and the Leader of the Deep Space Communications and Navigation Systems Center of Excellence, Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California. He is the Series Editor of two active book series: JPL Deep Space Communications and Navigation, and JPL Space Science and Technology; both by John Wiley and Sons, Hoboken, New Jersey. He published a book, *Deep Space Telecommunications Systems Engineering* (ed.), published by NASA, Washington, D.C., 1982, and later commercially by Plenum, New York, 1983.