Spaceborne Antennas for Planetary Exploration

Edited by

William A. Imbriale
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

Spaceborne Antennas for Planetary Exploration traces the development of the Jet Propulsion Laboratory (JPL) spacecraft antennas from the very first Explorer satellite in 1958 to the present. It primarily deals with the radio frequency (RF) design and performance of the antennas although it includes material on environmental and mechanical considerations. It describes all the new designs and technological innovations introduced throughout their evolution. There is also a thorough treatment of all the analytical and measurement techniques used in the design and performance assessment. This monograph can serve as an introduction to newcomers in the field as well as a reference for the advanced practitioner. The technical terms in the text assume that the reader is familiar with basic engineering and mathematical concepts as well as material typically found in a senior level course in electromagnetics.

This book is complementary to Large Antennas of the Deep Space Network\(^1\) published in 2002, which describes all the ground antennas used in support of the spacecraft. Taken together, these books completely describes all JPL antenna technology and is in keeping with the JPL Deep Space Communications and Navigation Series to capture the many technological innovations that helped make significant improvements in deep-space telecommunications over the decades.

As with most Spacecraft antennas, many people contributed to the success of the project, and it would be impossible to include everyone’s name on the Chapter. Indeed, this is not the proper place. Proper credit is given by completely and thoroughly citing all the references and sources from which the material is derived. The only person’s name on the chapter is the one who

\(^{1}\) William A. Imbrieale, John Wiley and Sons, Inc.
actually wrote the contribution and followed it through the editing process, not that they necessarily did the work described. It also allows someone who was not even involved in the actual design to write or coauthor a chapter. For completeness, this is sometimes required in this type of endeavor. That is because the people who actually did the work may not be available or even be alive, as in the case with some of the very early spacecraft.

William A. Imbriale,
Editor
January 2006
Acknowledgments

I would like to express my appreciation to Joseph H. Yuen for his continued support that made possible the writing of this manuscript. I am also deeply indebted to Cynthia D. Copeland for her typing, Roger Carlson and Pat Ehlers for their editing of the manuscript, and Judi Dedmon for typesetting the monograph in its final form. I would like to thank the authors who contributed chapters or portions of chapters. Each contributing author is identified in the Chapter headings. I would also like to thank Paul W. Cramer, Jr. for supplying much of the material used in Chapters 2 and 3 as well as his review of the chapters, Raul Perez for the Cloudsat data, and Daniel J. Hoppe, Vahraz Jamnejad, and David J. Rochblatt for their careful reading and helpful suggestions on several of the chapters.

William A. Imbriale
January 2006
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Gregory L. Davis holds a PhD in mechanical engineering from Rice University (Houston, Texas). Dr. Davis holds both a BS and an MS in physics from the University of Akron (Akron, Ohio). Dr. Davis has worked for the past 16 years as a member of the technical staff in mechanical engineering at JPL, and is currently the lead technologist for the Mechanical Systems Division. Prior to that, Dr. Davis was the supervisor of the Advanced Deployable Structures Group, which has interests in developing novel, lightweight structures for space applications. Previously, Dr. Davis served as the mechanical systems engineer for cruise, entry, descent, and landing on the Mars Exploration Rover (MER) Project.

Mark S. Gatti received his BS in electrical engineering from New Mexico State University (Las Cruces, New Mexico) in 1980 and his MS in electrical engineering from California State University, Northridge (Northridge, California) in 1986. Mr. Gatti joined JPL in 1981 working in spacecraft radio frequency (RF) systems and in antenna design, analysis, and test. Mr. Gatti has held management positions within the Deep Space Network (DSN) and was the deputy section manager of the Communications Ground System Section. Most
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Richard E. Hodges received his BS in electrical engineering from the University of Texas at Austin, his MS in electrical engineering from California State University, Northridge, and his PhD in electrical engineering from the University of California, Los Angeles. Dr. Hodges’ previous work experience includes Hughes Aircraft Company Radar Systems Group, Rantec/MDM (Chatsworth, California), and Raytheon Antenna/Nonmetallics Technology Center (Los Angeles, California). Dr. Hodges has been at JPL from 1988 through 1993 and from 2001 to the present. Dr. Hodges is the group supervisor for the Spacecraft Antennas Group.

Daniel J. Hoppe received a BS and an MS in electrical engineering from the University of Wisconsin Madison in 1982 and 1983, respectively. Dr. Hoppe received a PhD in electrical engineering from the University of California, Los Angeles (UCLA) in 1994. In 1984 Dr. Hoppe joined JPL, where he is currently a principal engineer. At JPL Dr. Hoppe has developed software for the solution of a number of electromagnetic scattering problems, has designed microwave components for the large antennas of the DSN, and has designed antennas for spacecraft applications. Most recently Dr. Hoppe has focused on diffraction modeling of large space-based telescopes.

John Huang received electrical engineering degrees of BS from Michigan Technology University (Houghton, Michigan) in 1970, MS from the University of California at Berkeley in 1971, and PhD from the Ohio State University (Columbus, Ohio) in 1978. Dr. Huang worked six years at the Naval Weapons Center, China Lake, California. Dr. Huang has been with JPL since 1980, where his research activities involve microstrip antennas, mobile vehicle antennas, antenna miniaturization techniques, spacecraft antennas, phased arrays, reflectarrays, and inflatable antennas.

William A. Imbriale received a BS in engineering physics from Rutgers, the State University of New Jersey (New Brunswick, New Jersey) in 1964; an MS in electrical engineering from UCLA in 1966; and a PhD in electrical engineering from the University of Illinois at Urbana-Champaign in 1969. Dr. Imbriale joined JPL in 1980 and is a senior research scientist in the Communications Ground System Section. Dr. Imbriale has led advanced technology developments for large ground-station antennas, lightweight spacecraft antennas, and millimeter-wave spacecraft instruments and is currently principle investigator on a NASA technology contract. Dr. Imbriale also served as the assistant manager for microwaves in the Ground Antennas
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Roberto Mizzoni received his PhD in physics from the University of Rome, Italy, in 1984. Before joining Alenia Spazio (Rome, Italy) in 1987, Dr. Mizzoni worked on two-dimensional radars and three-dimensional phased arrays at Selenia S.p.A. (Rome, Italy) and on broadband direction finding/electromagnetic compatible antennas at Elettronica S.p.A. (Rome Italy). Dr. Mizzoni has extensive experience in the design and development of space antennas for telecommunication, Earth observation, navigation and science. Dr. Mizzoni is co-holder of three patents and is head of the antenna electrical design unit at Alcatel Alenia Space (Rome, Italy).

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Joseph Vacchione received electrical engineering degrees of a BS from Northeastern University (Boston, Massachusetts) in 1985, an MS from the University of Illinois at Urbana-Champaign, and a PhD from the same institution in 1990. Dr. Vacchione joined JPL in 1990 where he has worked on design and development of antennas for space-flight applications. Dr. Vacchione has extensive experience in antennas used for both deep-space telecommunications purposes and for antennas used as part of remote sensing science instruments. Dr. Vacchione is currently the antenna lead for an Earth-orbiting science instrument.
Chapter 1
Introduction

William A. Imbriale, John Huang, and Mark S. Gatti

Spaceborne Antennas for Planetary Exploration traces the development of the antennas used on JPL Spacecraft from their inception on the very first United States Explorer Mission in 1958 to the present. To completely cover all types of spacecraft antennas would be a daunting task indeed, and is not the intent of this monograph. Rather, the focus is only on antennas that have flown on Jet Propulsion Laboratory (JPL) spacecraft or were used for JPL scientific instruments that have flown on other spacecraft. The monograph primarily deals with the RF design and performance of the antennas and associated front-end equipment, but it also includes a chapter on mechanical development. It describes all the new designs and technological innovations introduced by JPL. There is also a thorough treatment of all the analytical and measurement techniques used in the design and performance assessment. This monograph can serve as an introduction to newcomers in the field or a reference for the advanced practitioner. The technical terms in the text assume that the reader is familiar with basic engineering and mathematical concepts including material typically found in a senior-level course in electromagnetics.

This book is complementary to [1], which describes the JPL ground network antennas. However, whereas the ground antennas are primarily for telecommunication, the antennas on spacecraft can serve the dual purpose of a science instrument and/or a means of communicating the science and telemetry data to Earth. JPL’s support of the National Aeronautics and Space Administration (NASA) space program has several distinct eras. The very first mission was an Earth orbiter, quickly followed by unmanned exploration of the Moon in preparation for NASA manned flight to the Moon. Missions to the
Moon included the Ranger series that captured pictures of the surface as it flew into the Moon, and the Surveyor spacecraft that successfully landed on the surface of the Moon. The first interplanetary spacecraft were flybys, initially targeting the inner planets of Venus, Mercury, and Mars. The flyby era concluded with the “Grand Tour” Voyager Mission that flew by Jupiter, Saturn, Uranus and Neptune. The next phase of space exploration was planetary orbiters that collected data at Venus, Mars, Jupiter, and Saturn. Probably, the most challenging and exciting missions to date have been the Mars landers, and several of these missions are currently ongoing. In the planning stage are sample-return missions. In addition to planetary exploration missions, there have been a number of missions that have explored planet Earth, including synthetic aperture radar (SAR) missions that have mapped the entire planet.

This monograph is organized around the various eras and has contributions from many of the engineers involved in the development of the missions. The contributors are all identified in the title of the section. Chapter 1 gives a brief introduction and presents the methods of analysis, with supporting mathematical details of the various antenna types described throughout the remainder of the monograph. It also describes some design and measurement techniques. John Huang contributed the sections on microstrip antennas, and Mark Gatti provided the section on near-field measurements. Chapter 1 combined with the first chapter of [1] gives a very thorough reference on spacecraft and ground antenna analysis techniques, and it could be used in a graduate course on electromagnetics.

Chapter 2, “The Early Years,” describes some of the antennas used on the very first Earth-orbiting and Moon missions, such as the Explorer, Pioneer, Ranger, and Surveyor spacecraft.

Chapter 3, “The Planetary Flybys,” describes the antennas used on the first missions that flew by the planets. It includes the Mariner series of spacecraft that flew by Mars, Venus, and Mercury, as well as the Grand Tour Voyager Mission.

Chapter 4, “The Mars Missions,” by Joe Vacchoine, is a comprehensive chapter that covers all the Mars missions including the early orbiters and landers, as well as the more recent orbiters, landers, and rovers. It includes a complete description of the antennas on the Mars Exploration Rover (MER) landers.

Chapter 5, “The Orbiters,” with contributions from Roberto Mizzoni and Mark Gatti, describes the antennas on the past and current orbiter missions (not including the Mars Missions) such as the Magellan (Venus Radar Mapper), and the Jupiter and Saturn orbiters. It describes the failed deployable mesh antenna.

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1 In 1965 Gary Flandro proposed that, due to a once-per 175-year alignment of planets on one side of the Sun in the 1970s, a multi-planet “Grand Tour” opportunity existed to allow a single spacecraft to explore the four outer planets of the Solar System.
on the Galileo Spacecraft as well as the complicated four-frequency combined radar and communications antenna on the Cassini spacecraft.


Chapter 7, “Instrument Packages,” by Richard Cofield, describes antennas used on various instrument packages for science spacecraft. It includes antennas used on scatterometers and radiometers. Richard Hodges contributed the section on the Wide Swath Ocean Altimeter. There is some overlap in subject material with Chapter 6 as a SAR antenna is also a science instrument, but each chapter has a slightly different perspective and describes different instruments.

Chapter 8, “Mechanical Development of Antenna Systems,” by Greg Davis and Rebekah Tanimoto, discusses the various mechanical aspects of spacecraft antenna design. It also discusses the test program necessary to qualify a spacecraft antenna.

Chapter 9, “Miscellaneous Other Antennas,” describes a few unique antennas that did not readily fit into the other chapters. Included is the Solar Probe antenna and the Deep Impact antenna by Dan Hoppe.

Finally in Chapter 10, John Huang discusses future spacecraft antenna research and development.

1.1 Technology Drivers
William A. Imbriale

Antennas on board JPL spacecraft are used for telecommunications, as science instruments, or for both purposes. Technology required for science instruments is dictated by the specific science objectives and tends to be mission specific. Technology drivers for deep-space telecommunications are more universal and apply to all missions. The following discusses the main requirements for deep-space telecommunications antennas.

The communication links to deep space are asymmetric, with considerably more data on the downlink (space to Earth) than on the uplink (Earth to space) because the downlink contains the science, and telemetry data and the uplink is primarily used for commanding the spacecraft. The key element of the telecommunications-link performance is the ground-received power signal-to-noise ratio (SNR), which is given by

\[
\frac{S}{N} = \frac{P_T G_T G_R}{4\pi R^2 N} = \frac{4\pi P_T A_T A_R}{\lambda^2 R^2 kBT_s}
\]

(1.1-1)

where

- \(P_T\) = spacecraft transmit power
- \(G_T\) = transmit gain
- \(G_R\) = receive gain
Chapter 1

\[ R = \text{distance to the spacecraft} \]
\[ N = \text{total noise} \]
\[ A_T = \text{the effective area of the transmit (spacecraft) antenna} \]
\[ A_R = \text{the effective area of the receive ground antenna} \]
\[ T_s = \text{receive system-noise temperature} \]
\[ \lambda = \text{wavelength} \]
\[ k = \text{Boltzman's constant} \]
\[ B = \text{bandwidth} \]

Thus, data rate is proportional to the spacecraft effective isotropic radiated power (EIRP), or the product of antenna gain and radiated power. High-power spacecraft transmitters and large-aperture antennas are a priority for increasing direct-to-Earth telecommunications performance. Hence, a design that makes the maximum use of the transmit antenna area (high efficiency) is desired. However, not only should the antenna have high gain, but it must be pointed in the right direction. In theory, the main beam pointing could be accomplished electronically or mechanically. But to date, JPL has not used electronic beam pointing, but has relied on mechanically pointing the beam either by gimbaling the antenna or, in the case of a fixed body-mounted antenna, by pointing the entire spacecraft. The necessity to point a high-gain antenna in the proper direction gives rise to the need for antennas that will work when it is not possible to accurately point the antenna. Thus, there is also the need for omni type antennas (antennas that have almost complete spatial coverage) for times when pointing may be completely unknown (emergency situations) or for medium gain (broader beamwidth) when precise pointing may not be available.

There are also a number of environmental factors that must be considered in spacecraft antenna design. The antenna must operate in the vacuum of space and over wide temperature ranges. Sometimes, as in the case of the Solar Probe antenna (Chapter 9), the extreme temperatures dictate the materials that can be used in the design. The antenna must also survive the launch without damage. This includes the launch loads, vibration, shock, and acoustic conditions. Weight and power consumption are at a premium; hence the requirement for light-weight materials. Size is also a major consideration, as the antenna must fit inside the launch-vehicle shroud. For antennas that are too large to fit in the shroud, it is necessary to fold and stow the antenna for launch and deploy it for use.

There are many cases where a direct-to-Earth link, as described above, is not feasible. These applications include small in-situ landers, microprobes, and aerobots as currently in use or planned for Mars missions. These surface or atmospheric probe missions are characterized by their small size (<100 kg) and highly constrained energy budgets (<200 W-hr/sol). Typically, they cannot afford the mass and energy required for any meaningful data return directly over a deep-space link. Rather, these missions require, and are enabled by,
energy-efficient relay communications commonly referred to as proximity links [2,3]. Choice of frequency band is largely dictated by whether directional or omni links are envisioned. For omni-to-omni links, lower frequencies perform better, and the 400-MHz UHF links currently being utilized represent a compromise between communications performance and radio frequency (RF) component size.

1.1.1 Frequency Bands Allocated to Deep-Space Communications

The International Telecommunication Union (ITU) has allocated frequency ranges for use in deep-space and near-Earth research. These ranges are listed in Table 1-1.

1.1.2 Frequency Bands Recommended for Proximity Links

In addition to the formally allocated space-to-Earth links, the Consultative Committee for Space Data Systems (CCSDS) provides a recommendation for space data system standards in the area of proximity space links [4]. Proximity space links are defined to be short-range, bi-directional, fixed, or mobile radio links, generally used to communicate among probes, landers, rovers, orbiting constellations, and orbiting relays. These links are characterized by short time delays, moderate (not weak) signals, and short, independent sessions. The ultrahigh frequency (UHF) frequency allocation consists of 60 MHz between 390 to 450 MHz. The forward frequency band (portion where the caller transmits and the responder receives) is defined from 435 to 450 MHz. The return band (portion where the responder transmits and the caller receives) is defined as from 390 to 405 MHz. There is a 30-MHz deadband between them.

<table>
<thead>
<tr>
<th>Band</th>
<th>Deep-Space Bands for Spacecraft Farther Than 2 Million km from Earth</th>
<th>Near-Earth Bands for Spacecraft Closer Than 2 Million km from Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uplink(^a)</td>
<td>Downlink(^b)</td>
</tr>
<tr>
<td>S</td>
<td>2.110–2.120</td>
<td>2.290–2.300</td>
</tr>
<tr>
<td>Ka</td>
<td>34.200–34.700</td>
<td>31.800–32.300</td>
</tr>
</tbody>
</table>

\(^a\) Earth to space.

\(^b\) Space to Earth.
1.2 Analysis Techniques for Designing Reflector Antennas
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Reflector antennas have existed since the days of Hertz. They represent one of the best solutions for high gain and lightweight, easily stowable antenna systems. The use of physical optics (PO) analysis provides the required performance estimate accuracy. Almost all of the spacecraft reflector antennas were either designed or analyzed using PO, and the measured performance is within a few percent of the calculated values.

In addition to PO, there are many other techniques required to completely design and characterize the antenna system. Accurate programs to design and analyze the feed horn, and transform far-field patterns to near field for use in the PO analysis are required. Synthesis programs are used to determine the reflector shape for maximum gain. The sections on PO analysis, Feed Horn analysis, Spherical-Wave Analysis and Dual-Reflector Shaping are covered in [1], but these concepts are so fundamental they are also included in this reference for completeness. Tools to design and analyze frequency-selective surfaces are also needed for use in multi-frequency systems. And, programs to characterize the effect of a mesh surface for a lightweight deployable antenna are also required. The basic mathematical details of each of these techniques are given in this section with examples of their use sprinkled throughout the book.

1.2.1 Radiation-Pattern Analysis

Physical optics (PO) is by far the most important analytical tool, and it is used to calculate the scattered field from a metallic reflecting surface—in this case, a reflector antenna. Electrical currents, which excite the scattered field, are induced on the conducting surface by an incident wave assumed to be of a known amplitude, phase, and polarization everywhere in space (from a feed or other reflecting surface, for example). The PO approximations to the induced surface currents are valid when the reflector is smooth and the transverse dimensions are large in terms of wavelengths. The closed reflecting surface is divided into a region $S_1$, which is illuminated by direct rays from the source ("illuminated region") and a region $S_2$, which is geometrically shadowed ("shadowed region") from direct rays from the source (Fig. 1-1). The PO approximations for the induced surface current distribution are

$$
J_s = \begin{cases} 
2(\hat{n} \times H_{inc}) & \text{on } S_1 \\
0 & \text{on } S_2 
\end{cases}
$$

(1.2-1)

where $\hat{n}$ is the surface normal and $H_{inc}$ the incident field. The expressions are then inserted into the radiation integral [5] to compute the scattered field.