Antenna Arraying Techniques in the Deep Space Network
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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
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Preface

This monograph provides an introduction to the development and use of antenna arraying in the Deep Space Network (DSN). It is intended to serve as a starting point for anyone wishing to gain an understanding of the techniques that have been analyzed and implemented. A complete discussion of the general subject of arraying has not been provided. Only those parts relevant to what has been used in the DSN have been included.

While baseband arraying, symbol combining, and carrier arraying were discussed and developed fairly early in the history of the DSN, it wasn’t until the failure of the main antenna onboard the Jupiter-bound Galileo spacecraft that arraying antennas became more critical. In response to this crisis, two methods were analyzed: full-spectrum arraying and complex-symbol combining. While both methods were further developed, it was full-spectrum arraying that was finally implemented to support the Galileo data playback. This effort was so successful that a follow-on implementation of full-spectrum arraying was begun that provided for much higher data rates than for the Galileo Mission and allowed for arraying of up to six antennas within the Goldstone Complex. In addition to providing a backup to the 70-m antenna, this array (the Full Spectrum Processing Array, or FSPA) allows future missions to use a varying number of antennas as a function of time, and thereby to optimize the use of resources. This capability is also being implemented at the other DSN complexes.

We present here a description of this development, including some historical background, an analysis of several methods of arraying, a comparison of these methods and combinations thereof, a discussion of several correlation techniques used for obtaining the combining weights, the results of several arraying experiments, and some suggestions for future work. The content has been drawn from the work of many colleagues at JPL who have participated in
the effort to develop arraying techniques and capabilities. We are indebted to the large number of scientists, engineers, testers, and operators who have played a crucial role in the implementation of antenna arraying in the DSN. Finally, we acknowledge the primary role of NASA, its Deep Space Network, and especially the Galileo Project in the development of this exciting capability.

David H. Rogstad
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Timothy T. Pham
Acknowledgments

We are especially grateful, and wish to dedicate this work, to George M. Resch (1941–2001) for his untiring support in pursuing the use of very long baseline interferometry (VLBI) techniques and equipment to implement full-spectrum arraying. His encouragement and expertise led to its being developed originally as a technology project and finally as a method to enhance telemetry for the Galileo Project.

We would also like to express our appreciation to the large number of people who have contributed to arraying development in the DSN, and consequently to many parts of this monograph on the subject. While it is not possible to name everyone, certain individuals deserve special mention because of their key contribution to the preparation of the material presented here: Roger A. Lee, Robert Kahn, Andre Jongeling, Sue Finley, Dave Fort, William Hurd, James Ulvestad, Biren Shah, Sampson Million, and Joseph Statman. One individual who deserves special acknowledgment is Sami Hinedi. His work, together with that of one of the authors (Alexander Mileant), provided the basis for much of the receiver and array analysis presented in Chapters 5 through 7.
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Chapter 1
Introduction

As the signal arriving from a receding deep-space spacecraft becomes weaker and weaker, the need arises for devising schemes to compensate for the reduction in signal-to-noise ratio (SNR). With maximum antenna apertures and lower receiver noise temperatures pushed to their limits, one remaining method for improving the effective SNR is to combine the signals from several antennas. This is referred to as arraying, and it has enabled the National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) to extend the missions of some spacecraft beyond their planned lifetimes. A related benefit provided by arraying has been its ability to receive higher data rates than can be supported with a single antenna. As an example, symbol-stream combining was used to array symbols between the Very Large Array (VLA) radio telescope, located in New Mexico, and Goldstone’s antennas, located in California, during Voyager’s encounter at Neptune [1,2]. That technique increased the scientific return from the spacecraft by allowing data transmission at a higher rate. In general, arraying enables a communication link to operate in effect with a larger antenna than is physically available.

Antenna arraying can be employed with any signal modulation format, be it binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), continuous phase modulation (CPM), etc. In this discussion, the NASA standard deep-space signal format will be used to illustrate the different arraying techniques, but the results can be extended to other formats, including suppressed carrier.

This monograph compares the various arraying algorithms and techniques by unifying their analyses and then discussing their relative advantages and disadvantages. The five arraying schemes that can be employed in receiving signals from deep-space probes are treated. These include full-spectrum combining (FSC), complex-symbol combining (CSC), symbol-stream
combining (SSC), baseband combining (BC), and carrier arraying (CA). In addition, sideband aiding (SA) is also included and compared even though it is not an arraying scheme since it employs a single antenna. Combinations of these schemes are also discussed, such as carrier arraying with sideband aiding and baseband combining (CA/SA/BC) or carrier arraying with symbol-stream combining (CA/SSC), just to name a few. We discuss complexity versus performance trade-offs, and the benefits of reception of signals from existing spacecraft. It should be noted here that only the FSC method has application for arraying of signals that are not telemetry. Consequently, all of the analysis and comparisons referred to above are done using telemetry signals. There is no reason to believe that the performance of FSC on non-telemetry signals will not yield similar results.

The most recent implementation of arraying for telemetry within the DSN is the Goldstone array [3], which supports full-spectrum combining of up to six antennas within the complex. Specific techniques that are used in this array are discussed, and results from several experiments are presented. Finally, directions for future research and implementation are discussed.

1.1 Benefits of Arraying

Arraying holds many tantalizing possibilities: better performance, increased operational robustness, implementation cost saving, more programmatic flexibility, and broader support to the science community. Each of these topics is discussed further in the following sections.

1.1.1 Performance Benefits

For larger antennas, the beamwidth naturally is narrower. As a result, antenna-pointing error becomes more critical. To stay within the main beam and incur minimal loss, antenna pointing has to be more precise. Yet this is difficult to achieve for larger structures.

With an array configuration of smaller antennas, antenna-pointing error is not an issue. The difficulty is transferred from the mechanical to the electronic domain. The wider beamwidth associated with the smaller aperture of each array element makes the array more tolerant to pointing error. As long as the combining process is performed with minimal signal degradation, an optimal gain can be achieved.

Arraying also allows for an increase in effective aperture beyond the present 70-m capability for supporting a mission at a time of need. In the past, the Voyager Mission relied on arraying to increase its data return during Uranus and Neptune encounters in the late 1980s. The Galileo Mission provides a recent example in which arraying was used to increase the science data return by a factor of 3. (When combined with other improvements, such as a better
coding scheme, a more efficient data compression, and a reduction of system noise temperature, a total improvement of a factor of 10 was actually realized.)

Future missions also can benefit from arraying. These include the class of missions that, during certain operational phases, require more performance than a single antenna can offer. For example, the Cassini Mission requires only a single 34-m antenna during cruise phase, but upon entering the Saturn orbit, in order to return 4 Gbits/day mapping data, it will need an array of a 70-m and a 34-m antenna [4]. Missions that need to relay critical science data back to Earth in the shortest possible time also are potential beneficiaries. The Stardust Mission, for example, can reduce single-event risk by increasing the data rate for its encounter with the Wild 2 comet in 2004.

1.1.2 Operability Benefits

Arraying can increase system operability. First, higher resource utilization can be achieved. With a single-aperture configuration, a shortfall in the 34-m link performance will immediately require the use of the 70-m antenna, increasing the potential for over-subscription of the 70-m service. In the case of an array, however, the set can be partitioned into many subsets supporting different missions simultaneously, each tailored according to the link requirements. In so doing, resource utilization can be enhanced.

Secondly, arraying offers high system availability and maintenance flexibility. Suppose the array is built with 10 percent spare elements. The regular preventive maintenance can be done on a rotating basis while allowing the system to be fully functional at all times.

Thirdly, the cost of spare components would be smaller. Instead of having to supply the system with 100 percent spares in order to make it fully functional around the clock, the array offers an option of furnishing spares at a fractional level.

Equally important is the operational robustness against failures. With a single resource, failure tends to bring the system down. With an array, failure in an array element degrades system performance but does not result in a service shutdown.

1.1.3 Cost Benefits

A cost saving is realized from the fact that smaller antennas, because of their weight and size, are easier to build. The fabrication process can be automated to reduce the cost. Many commercial vendors can participate in the antenna construction business, and the market competition will bring the cost down further.

It is often approximated that the antenna construction cost is proportional to the antenna volume. The reception capability, however, is proportional to the antenna surface area. For example, halving the antenna aperture reduces the