Coupled-Oscillator Based Active-Array Antennas

Ronald J. Pogorzelski and Apostolos Georgiadis

Jet Propulsion Laboratory
California Institute of Technology

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We dedicate this book to our wives,
Barbara and Ana,
who sustained us in this endeavor.

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—anytime, 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 is a compilation of research results obtained primarily over the past two decades in the application of groups of oscillators coupled in various configurations to the excitation of phased-array antennas. Much of the work was carried out at the Jet Propulsion Laboratory of the California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA) building on the early work at the University of Massachusetts, Cornell University, and the University of California, Santa Barbara. More recent work at several institutions in Spain and especially at the Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), as well as a variety of institutions across Europe and Asia is also described. A motivation for much of this work was the promise of a method of providing beam agility at electronic speed that is simpler than the conventional method of using a phase shifter at each element or module and controlling these phase shifters in a coordinated manner. More generally, however, the effort has focused on the integration of transmitter, receiver, and antenna including the beam-steering function in a single planar package.

The intended audience for the book comprises primarily designers of phased-array antennas and the associated electronics, but the book may also be of interest to those who may, through understanding the principles presented, envision other innovative applications of oscillator arrays such as distribution of timing signals and phase locking in general. In the same way, graduate students may find inspiration for research work leading to theses or dissertations based on extending the work described here.

With regard to the references, as a general rule we have used peer reviewed archival journal articles and not conference presentations in the interest of ease

of access. We have, however, made a few exceptions in this regard in cases of very recent work that, as far as we know, has not yet appeared in the peer-reviewed literature and in one case for the use of figures with proper attribution. We have endeavored to present a comprehensive treatment of the work in this field to date but recognize that we cannot be sure that we are aware of everyone in the world with interest in and contributions to this fascinating area of research. We, therefore, extend apologies to any who feel their work has been slighted in any way. Be assured it was unintentional.

The book begins with a note concerning the early use of coupled oscillators in the field of mathematical biology wherein researchers used them as an artifice in representing the behavior of neurons in what is known as a central pattern generator in a manner amenable to mathematical analysis. The application to phased array antennas owes its origin primarily to Karl Stephan at the University of Massachusetts [1] [2] [3] and to Richard C. Compton at Cornell and his student, Robert A. York. [4] [5] [6] [7] However, the modern emphasis on the study of the dynamics of such arrays was inspired by the interest of James W. Mink of the U. S. Army Research Office [8] in spatial power combining at millimeter wave frequencies. Thus, the presentation continues with a discussion of the utility of oscillator arrays in phased array antennas and a detailed discussion of the mathematical analysis of the dynamic behavior of such arrays. The mathematics is at a level that should be easily accessible to graduate students in the physical sciences. Advanced calculus, linear algebra, complex variables, and Laplace transforms are the primary tools.

The treatment is arranged in two passes. On the first pass in Part I, we formulate the analysis in the simplest possible manner while retaining the essence of the dynamic behavior, the so-called phase model. Most of the results are based on a linearization of the equations valid for small inter-oscillator phase differences. This permits introduction of the key features of array behavior with a minimum of complexity. We then describe a number of experimental demonstrations of this approach to phased array beam agility and validation of the approximate theoretical results in Part II. In Part III, we return for a second pass at the analysis, this time including a more sophisticated theoretical description of the oscillators permitting detailed study of the impact of their nonlinear properties. Much of the contemporary research in this area is focused on these properties and their potential utility in modern physical array implementations with many and varied applications. In Part III the presentation of experimental work is integrated with the theoretical as appropriate.

In preparing material for this book, a number of sign errors, typographical errors, and, in rare cases, errors of substance were uncovered in the references.

Every effort has been made to correct these so that where the book differs from the literature; it is the book version that is correct.

Ronald J. Pogorzelski and Apostolos Georgiadis
Pasadena, California and Castelldefels - Barcelona, Spain
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The work of A. Georgiadis has been supported by the Juan de la Cierva Program 2004, the Torres Quevedo Grant PTQ-06-02-0555, and project TEC2008-02685/TEC on Novel Architectures for Reconfigurable Reflectarrays and Phased Array Antennas (NARRA) of the Ministry of Science and Innovation Spain, and the European COST Action IC0803 RF/Microwave Communication Subsystems for Emerging Wireless Technologies (RFCSET).

Dr. Georgiadis would like to especially acknowledge Dr. Ana Collado for her invaluable contribution in every aspect of the results presented in Part III of this book. Additionally he would like to acknowledge Dr. Konstantinos Slavakis for his contribution associated with beamforming and optimization and for long discussions related to convex optimization. Finally, he would like

to acknowledge Dr. Maurizio Bozzi and Francesco Giuppi from the University of Pavia and Selva Via from CTTC for their contribution in the recent development of coupled oscillator systems using substrate integrated waveguide (SIW) technology.

Lastly, both Dr. Pogorzelski and Dr. Georgiadis would like to acknowledge the tireless efforts of Mr. Roger V. Carlson of JPL in obtaining the permissions to reprint items from the literature and in editing the manuscript to conform to the format required by the publisher.

Authors

Ronald J. Pogorzelski received his BSEE and MSEE degrees from Wayne State University, Detroit, Michigan in 1964 and 1965, respectively, and his PhD degree in electrical engineering and physics from the California Institute of Technology, Pasadena, in 1970, where he studied under Professor Charles H. Papas.

From 1969 to 1973, he was Assistant Professor of Engineering at the University of California, Los Angeles, where his research dealt with relativistic solution of Maxwell's equations. From 1973 to 1977, he was Associate Professor of Electrical Engineering at the University of Mississippi. There his research interests encompassed analytical and computational aspects of electromagnetic radiation and scattering. In 1977 he joined TRW as a senior staff engineer and remained there until 1990 serving as a subproject manager in the Communications and Antenna Laboratory, and as a department manager and the Manager of the Senior Analytical Staff in the Electromagnetic Applications Center. From 1981 to 1990 he was also on the faculty of the University of Southern California, first as a part-time instructor and then as an adjunct full professor. In 1990, he joined General Research Corporation as Director of the Engineering Research Group in Santa Barbara, California. Since 1993, he had been with the Jet Propulsion Laboratory as Supervisor of the Spacecraft Antenna Research Group until 2010. From 1999 to 2002 he was a lecturer in electrical engineering at Caltech. In June 2001 he was appointed a JPL Senior Research Scientist. He retired from JPL in May 2010 and is currently Senior Research Scientist Emeritus at JPL.

Dr. Pogorzelski's work has resulted in more than 100 technical publications and presentations. In 1980, he was the recipient of the R. W. P. King Award of

the IEEE Antennas and Propagation Society for a paper on propagation in underground tunnels. Over the years he has served on a number of symposium committees and has chaired a number of symposium sessions. Notably, he was Vice Chairman of the Steering Committee for the 1981 IEEE AP-S Symposium in Los Angeles, California and Technical Program Chair for the corresponding symposium held in Newport Beach, California in 1995. From 1980 to 1986 he was an associate editor of the *IEEE Transactions on Antennas and Propagation* and from 1986 to 1989 he served as its editor. From 1989 to 1990 he served as Secretary/Treasurer of the Los Angeles Chapter of the IEEE Antennas and Propagation Society, was a member of the Society Administrative Committee from 1989 to 2000, served as Vice President of the Society Administrative Committee in 1992, and was its 1993 president. From 1989 to 1992 he was a member of the Society's IEEE Press Liaison Committee. He has also represented IEEE Division IV on the Technical Activities Board Publication Products Council, Periodicals Council, and New Technology Directions Committee**.** In 1995 he also served as a member of a blue ribbon panel evaluating the U.S. Army's Team Antenna Program in helicopter antennas. He served for ten years as a program evaluator for the Accreditation Board for Engineering and Technology (now ABET, Inc.). Dr. Pogorzelski is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi Honor Societies; and has been elected a full member of U.S. National Committee of the Union Radio Scientifique Internationale (USNC/URSI) Commissions A, B, and D; and he is a past chair of U. S. Commission B. In 1984 he was appointed an Academy Research Council Representative to the XXIst General Assembly of URSI in Florence, Italy, and in 1999 he was appointed a U.S. Participant in the XXVIth General Assembly of URSI in Toronto, Canada, and similarly in the XXVIIth General Assembly of URSI in Maastricht, the Netherlands in 2002. He has been a member of the Technical Activities Committee of U. S. Commission B and has also served on its Membership Committee from 1988 to 2002 serving as Committee Chair from 1993 to 2002. He was appointed to a two year term as Member at Large of the U.S. National Committee of URSI in 1996 and again in 1999. Dr. Pogorzelski is an IEEE Third Millennium Medalist and a Fellow of the IEEE.

Apostolos Georgiadis was born in Thessaloniki, Greece. He received his BS degree in physics and M.S. degree in telecommunications from the Aristotle University of Thessaloniki, Greece, in 1993 and 1996, respectively. He received his Ph.D. degree in electrical engineering from the University of Massachusetts at Amherst, in 2002.

In 1995, he spent a semester with Radio Antenna Communications (R.A.C.), Milan Italy, where he was involved with Yagi antennas for UHF applications. In 2000, he spent three months with Telaxis Communications,

South Deerfield, Massachusetts, where he assisted in the design and testing of a pillbox antenna for local multipoint distribution service (LMDS) applications. In 2002, he joined Global Communications Devices (GCD), North Andover, Massachusetts, where he was a systems engineer involved with CMOS transceivers for wireless network applications. In June 2003, he was with Bermai Inc., Minnetonka, Minnesota, where he was an RF/analog systems architect. In 2005, he joined the University of Cantabria, Santander, Spain as a researcher. While with the University of Cantabria, he collaborated with Advanced Communications Research and Development, S.A. (ACORDE S.A.), Santander, Spain, in the design of integrated CMOS voltage controlled oscillators (VCOs) for ultra-wideband (UWB) applications. Since 2007, he has been a senior research associate at Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Barcelona, Spain, in the area of communications subsystems where he is involved in active antennas and antenna arrays and more recently with radio-frequency identification (RFID) technology and energy harvesting.

Dr, Georgiadis is an IEEE senior member. He was the recipient of a 1996 Fulbright Scholarship for graduate studies with the University of Massachusetts at Amherst; the 1997 and 1998 Outstanding Teaching Assistant Award presented by the University of Massachusetts at Amherst; the1999, 2000 Eugene M. Isenberg Award presented by the Isenberg School of Management, University of Massachusetts at Amherst; and the 2004 Juan de la Cierva Fellowship presented by the Spanish Ministry of Education and Science. He is involved in a number of technical program committees and serves as a reviewer for several journals including *IEEE Transactions on Antennas and Propagation*, and *IEEE Transactions on Microwave Theory and Techniques*. He was the co-recipient of the EUCAP 2010 Best Student Paper Award and the ACES 2010 2nd Best Student Paper Award. He is the Chairman of COST Action IC0803, RF/Microwave communication subsystems for emerging wireless technologies (RFCSET), and he is the Coordinator of the Marie Curie Industry-Academia Pathways and Partnerships project Symbiotic Wireless Autonomous Powered system (SWAP).