Summary of a Workshop on the Future of Antennas

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Norm Haller, Rapporteur; Division on Engineering and Physical Sciences; National Research Council

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Division on Engineering and Physical Sciences

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*Planned or attended the workshop.

Preface

The workshop described in this report is the second in a series of three workshops, held in early 2012 to further the ongoing engagement among the National Research Council's (NRC's) Technology Insight—Gauge, Evaluate, and Review (TIGER) Standing Committee, the scientific and technical intelligence (S&TI) community, and the consumers of S&TI products. A restricted version of this report is available by contacting the Public Affairs Office of the sponsoring agency (Defense Intelligence Agency) directly.

We express our appreciation to the members of the Committee for Science and Technology Challenges to U.S. National Security Interests for their contributions to the planning of this workshop. We are also grateful for the active participation of many members of the technology community in the workshop, as well as to the sponsor for its support. The committee also expresses sincere appreciation for the support and assistance of the NRC staff, including Terry Jaggers, Daniel Talmage, Sarah Capote, Marguerite Schneider, Zeida Patmon, and Dionna Ali. Finally, we would like to thank the rapporteur for this report, Norm Haller, a consultant.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

James Armitage, Potomac Institute for Policy Studies,
Lawrence J. Delaney, Independent Consultant (Titan Corporation, retired),
Gilman Louie, Alsop Louie Partners, and
Al Romig, NAE, Lockheed Martin Aeronautics Company.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the views of individual participants, nor did they see the final draft of the report before its release. The review of this report was overseen by Lou Lanzerotti (NAE), New Jersey Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the author and the institution.

Contents

1
Introduction

The Workshop on the Future of Antennas was the second of three workshops conducted by the National Research Council's Committee for Science and Technology Challenges to U.S. National Security Interests. The statement of task can be found in Box 1-1. The workshop objectives were to:

- Review trends in advanced antenna research and design.
- Review trends in commercial and military use of advanced antennas that enable improved communication, data transfer, soldier health monitoring, and other overt and covert methods of standoff data collection.

The first day's sessions, consisting of five presentations and discussions on antennas and wireless communications and control, were open to committee members, staff, guests, and members of the public. The second day was a data-gathering session addressing vulnerabilities, indicators, and observables; presentations and discussions during this session included classified material and were not open to the public. Appendix A contains biographies of the committee members. The workshop agenda and a list of participants are given in Appendix B. Appendix C gives the biographies of the presenters.

This report has been prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. The committee's role was limited to planning and convening the workshop. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the committee, or the National Research Council. The workshop was not intended to provide a comprehensive review of the state of antenna technology.

This report is organized by topic in the order of presentation and discussion at the workshop. For Day 1 the topics were Future of Antennas, Commercial State of the Art of Wireless Communications and Control, Military State of the Art of Wireless Communications and Control, and Future Trends in Antenna Design and Wireless Communications and Control. For Day 2 the topics were Vulnerabilities of Ubiquitous Antennas, and Indicators and Observables, followed by a wrap-up discussion.

BOX 1-1

Statement of Task

An ad hoc committee will plan and conduct three workshops on the science and technology (S&T) fields noted below that have potential impact on U.S. national security.

- Big Data—The workshop will review emerging capabilities in large computational data to include speed, data fusion, use, and commodification of data used in decision making. The workshop will also review the subsequent increase in vulnerabilities over the capabilities gained and the significance to national security.
- Future of Antennas—The workshop will review trends in advanced antenna research and design. The workshop will also review trends in commercial and military use of advanced antennas that enable improved communication, data transfer, soldier health monitoring, and other overt and covert methods of standoff data collection.
- Future Battlespace Situational Awareness—The workshop will review the technologies that enable battlespace situational awareness 10-20 years into the future for both red and blue forces. The workshop will emphasize the capabilities within air, land, sea, space, and cyberspace.

The committee will design the workshops to address U.S. and foreign research, why S&T applications of technologies in development are important in the context of military capabilities, and what critical scientific breakthroughs are needed to achieve advances in the fields of interest—focusing detailed attention on specific developments in the foregoing fields that might have national security implications for the United States. The workshops will each also consider methodology to track the relevant technology landscape for the future.

Each of the three workshops will feature invited presentations and panelists and include discussions on a selected topic including themes relating to defense warning and surprise. The committee will plan the agenda for the workshops, select and invite speakers and discussants, and moderate the discussions. Each event will result in a workshop summary that will be subject to appropriate institutional review prior to release.

2
First Day (Open)

The presentations were followed by discussion periods during which questions were posed and answered and ideas were exchanged among the participants. Summaries of these discussions sometimes do not follow their specific order of occurrence during the meeting, thus allowing like topics to be synthesized (e.g., discussions of entities engaged in antenna design activities). The first three presentations had one speaker each. The last topic was covered by two speakers.

FUTURE OF ANTENNAS

Lon Pringle, director of the Signature Technology Laboratory at Georgia Tech Research Institute, was the speaker. His key point was that the "future of antennas is now" and that several enabling technologies, most notably the increase in computational power, are combining to make the present an era of dramatic improvements in antenna performance." Signatures dominated 20 years ago, and then technology really started to accelerate. Apertures are solved, but the electronics are still maturing to enable utilization of the future capability of the antenna. Everyone likes low frequency, but big antennas are needed, in his view.

Pringle reemphasized a major element of his key point as follows: the ability to predict the performance of antennas by calculation has taken over the prior slow process of building (by intuition) and testing. The fact that the United States can now model how an antenna is going to perform is really significant and a great breakthrough. Enabling technologies include electromagnetic modeling, speed of computation, and micro-electronics; he affirmed that these tools are enabling design and discovery. He further amplified the importance of computation by noting that the future of antenna design is in a person who understands electromagnetics and works with a computer to design a new antenna (i.e., person plus computer). In 5 to 8 years, fast commercial codes will give most radar houses this capability.

His many other comments included that (1) a computer can tell what values of resistive sheets to place in cavities; (2) some connected arrays have coupling that works for them rather than against them; (3) challenges include getting rid of heat, packaging, wide-band electronics, and beam-formers; (4) optical switches can optimize performance (e.g., switch bands, steer antenna, use several beams or combine them into a more powerful one); and (5) there is a revolution in ground-plane structures—hopefully, with these and active meta-materials, one can build an adaptable antenna, which actually reacts to the environment (e.g., a missile is also the antenna).

Discussion After Presentation[1]

Q: What kind antennas for UAVs? A: Low gain. Small UAVs just can't carry a heavy dish antenna. Larger UAVs have dish antennas.

Q: Will better materials come into play? A: Magnetic and meta-materials. But we must have area, which some say we can get along without—be skeptical.

[1]Unless specifically stated otherwise, the speaker answered all questions.

Q: How about advances in other countries or areas, such as Europe or China? A: If need is there, then the Chinese will go for it. Right now, they need to work on building the infrastructure (e.g., foundries) to support the technology. Regarding ultra-wideband phased arrays, ultra-thin low-frequency antennas, reconfigurable ground planes for low-frequency applications, and reconfigurable antennas, the Europeans are working in these areas. This information is also published, and so we can research where Europeans are going.

Q: Are you seeing really interesting publications and new innovative concepts outside the United States? A (by James Armitage, attendee): When it comes to who is producing the most, then it is China. However, although quantity is high, quality is not there yet. At the same time, the Chinese are catching up and will eventually be at the same level as we are; many Chinese working in this field went to school in the United States. They are going home and applying in China what they learned here. Don't underestimate computing resources outside the United States. The Chinese are building foundries like crazy to feed the auto industry worldwide. It is all money driven and requires large investments.

Q: What countries around the world are doing this type of work—China, India, Russia, Israel, France, Germany? A (by James Armitage and Gilman Louie): We need to watch where the money is going. We have been spending more money, by orders of magnitude, than other countries in developing these types of technologies. Now, when we are not spending as much, and other countries decide to make heavy investments, they will catch up quickly. Most of the professors in China received their PhDs in the United States. Now they are going back to China to teach the next generation of engineers. This also applies to other regions of the world (e.g., Europe and India).

COMMERCIAL STATE OF THE ART OF WIRELESS COMMUNICATIONS AND CONTROL

Sebastian Rowson, chief scientist at Ethertronics, was the speaker. His privately held company manufactures million of antennas per week (e.g., for cell phones, laptops, medical devices). They have moved from simple designs and manufacturing challenges to active, reconfigurable antenna systems defined and optimized for commercial applications. "Active antenna systems technology applies to any wireless device. Mobile device data throughput increased (46 percent increase demonstrated in an access point)." Challenges are numbers of applications supported and very small volumes (e.g., 2 cubic centimeters with active antennas). Ideally, active and reconfigurable antennas can adjust automatically to changes in the environment enveloping the device (e.g., when a hand is on a phone).

For the future, Rowson noted that a goal is to integrate everything inside the phone; the antenna is the link to outside signals. If switching from different base stations can be minimized by optimizing for only one base station, effort and resources can be freed up. Associated challenges involve development of new software to support the antenna. Again, the aim is to design everything together and have elements that adjust "on the fly" so as to achieve more capability with these systems.

Discussion After Presentation[2]

Q: Where have you seen more gain in technology advances? A: Probably in filters. Already a lot of work has been done on power amplifiers, but there are still opportunities for improvement.

Q: How transparent to the user is a change in modes? A: It is very fast; the user does not know it is happening.

Q: Are any of these things dependent on materials? A: Mostly on design, but in some cases they are dependent on new semiconductor technology.

Q: How about jamming? A: The hope is that the FCC is keeping others off these frequencies. We're not looking closely at jamming.

[2]Unless specifically stated otherwise, the speaker answered all questions.

Q: Are there safeguards to limit power coming from antennas? A: The only way to solve this issue is to reduce power.

Q: What's next, most interesting? A: Innovative research and development is done at Ethertronics (e.g., switching) to anticipate what the market is going to look like. However, it is customer driven when it comes to producing new designs for antennas—approximately 200 new designs each year. Medical device drawers (metal) were challenging; each had to have six antennas.

Q: Does Ethertronics have a single point of failure in its process, such as raw materials? A: Not that we can see. The belief is that nothing will really stump Ethertronics; it has such a wide variety of resources.

Q: How about hiring the right engineers to work for Ethertronics; has that been difficult? A: Yes. Now the company hires graduate students and trains them, enabling new employees to fit well into the company environment. Grants help fund these training sessions. There is also recruiting from local colleges (e.g., San Diego State University).

Q: How much does Ethertronics work with international companies? A. The company shows some current and advanced designs to companies in various countries. Technology shared with each country depends on the relationship and on the amount of cooperation that has occurred with that company. Samsung and Ethertronics have a good relationship based on design cooperation and past experience.

General Discussion on Several Topics by Attendees

Individual attendees and speakers then generally discussed several topics and questions. Some participants noted that the future is driven largely by fancier algorithms but that other frequency bands will be needed. NATICK (U.S. Army) is interested in battlefield monitoring. Commercial is going Blue-Tooth (for heart-rate, breathing, skin temperature monitoring). When it comes to physiological monitoring, some participants wanted ubiquity and ease of use. Some participants suggested a need to figure out how to move the data and store it effectively for easy analysis. Some challenges facing the industry: Should data all be on the same network or on different networks? Where should we leverage the infrastructure that exists?

MILITARY STATE OF THE ART OF WIRELESS COMMUNICATIONS AND CONTROL

Robert Newgard, director of Advanced Radio Systems, Rockwell Collins, was the speaker.

Rockwell Collins serves two markets—commercial and military. A publicly traded company, it is there for shareholder value; the commercial side is becoming an early adapter of new technologies. Newgard opened with military radio objectives (i.e., cost-effective capabilities, support for operational needs). More specifically, today's military requires multi-mode, multi-channel, upgradable, networked, remotely configurable, actionable information; broadband; low power, high performance; geo-location (for blue- and red-force tracking); and ultimately, any waveform, any time, any place. He also addressed software-defined radios, noting that any waveform can be loaded.

Newgard also pointed out that an array of technical challenges exist for military systems: today's fielded radios use large radio frequency (RF) front ends and components that can accommodate the worst-case requirements ("corner" cases are difficult). Future designs need adaptable and reconfigurable RF front ends; flexible and dynamic RF performance; real-time optimization and performance; low observability; and the characteristic of being capabilities driven, not requirements driven. He explained how to do more with less. More capability with fewer assets (e.g., we have a lot of capability, but we cannot fix all issues by throwing more hardware at the problem). If one throws hardware or software at a problem, the solution could become too expensive (especially in the software realm).

Discussion After Presentation[3]

Q: Is the point solution going to be cheaper and better than software-defined radio? A: Yes.

Q: Does the manufacturer reconfigure, or does the operator do that? A: The radio does it by itself.

Q: How much red force or outside threats do you factor into your research and development? A: Quite a bit; we try to vector threats into our production and technology and regularly consult with people in the field (engineers in the battle-space) for design. We also have cleared staff that can work on classified projects.

Q: Is there an opportunity for photonics in the front end? A: Yes, small power.

Q: What fraction of radios are software defined? A: Somewhere in the 25 percent range are software defined, and it is not growing fast.

Q: How far behind Android and iPhone are the military? A: Not that far.

Q: What is U.S. technology vulnerability in your field? A: The biggest concern is what the Department of Defense (DoD) is doing to develop requirements. DoD acquisition managers are developing requirements that may not be realistic. Instead of engineers, there are people who lack the technology expertise to develop proper requirements. They have business majors instead of engineers working on this, people who do not have the necessary expertise. People need intuition, knowledge, and experience to create effective requirements.

Q: What percentage of Rockwell Collins engineers are foreign nationals? A: It has no foreign nationals; most of the engineers have projects that involve work requiring a clearance.

Prompted by questions and exchanges among participants, Newgard made the following general comments: Our biggest concern going forward is the skill set, not the technology. It is more about having the engineers who are capable of doing what needs doing, and being passionate about it. Yes, Rockwell Collins is having problems hiring qualified candidates, and now tends to grow its own people (e.g., hire engineers while they are going through college, use internships, and then train them). Also, a large portion of the Rockwell Collins engineering design team is going to retire in the next decade. We need capable engineers who are "committed experts." Regarding the Federal Acquisition Regulatory (FAR) process, there are many problems that involve one hand not talking to another. F-22s don't talk well to legacy systems. The Navy builds systems that do not talk to the Army's. On top of that, the FAR process does not allow a lot of critical thinking to determine effective tradeoffs (make tough calls with limited resources). And when the requirement developers lack engineering experience, it creates a somewhat confusing environment that inhibits innovative thinking.

FUTURE TRENDS IN ANTENNA DESIGN AND WIRELESS COMMUNICATIONS AND CONTROL

Timothy Hancock, assistant group leader, Analog Device Technology, Lincoln Laboratory, MIT, was the first speaker. He was followed by Yahya Ramat-Samii, Northrop Grumman Chair in Electromagnetics at UCLA, who spoke by phone.

Hancock reviewed trends in the use of antennas that enable improved communications, data transfer, soldier health monitoring, and methods of data collection. He briefly described techniques for overt and covert methods of standoff data collection (e.g., reduce transmitted power and energy per bit, mitigate or exploit in-band interference), noting that it would be good to get away from the concept of "that's my band, so don't use it." Turning to multiple-input, mutiple-output (MIMO) wireless systems, he introduced the approaches of spatial multiplexing, diversity coding, and pre-coding and then pointed out several advantages of MIMO (e.g., improved data transfer from or to a disadvantaged transmitter or receiver and mitigating interference). Challenges in implementing MIMO systems include the design of antennas, receivers, and transmitters; much computing power and math are involved.

[3]Unless specifically stated otherwise, the speaker answered all questions.

Rahmat-Samii (using nearly three dozen slides) described novel outside-of-the-box concepts for antennas—from tiny ingestibles to large space antennas. UCLA's antenna research, analysis, and measurement laboratory is organized in five fields: personal communications; medical RFID (RF identification); remote sensing; electromagnetic band gap (EBG), photonic band gap (PBG), nano, and MEMS (microelectromechanical systems); and analyzing, optimizing, and measuring. The laboratory (in cooperation with other institutions) is advancing miniature antenna concepts as well as large antenna concepts. One of his key points was that "we can optimize antennas for almost any need!"

Rahmat-Samii highlighted the many conflicting challenges of miniaturization (e.g., low profile or low volume, with or without ground plane, single frequency or multifrequency, narrow or broad band, single or multiple elements, low or high cost). Approaches for miniaturization included low profiles using EGB, folding structures, incorporating switches, hybridization of the above, and stored energy utilization. He mentioned advances in RFID, including platform-tolerant tag designs, medicine-monitoring RFID systems, and medical diagnostics and sensing. He also covered advances in meta-materials, including double-negative materials, EBG structures, and artificial complex ground planes.

Questions and General Discussion[4]

Q: For wearable textile antennas, where do you see this research going? A: Two fronts, embroidery machines and wearable designs (e.g., communications on clothing, such as for firemen).

Q: In medical applications, are you looking at RFID tags embedded inside the body for medical scans? A: Designing these types of chips, which create the communication link, is a challenge. However, this area of study is emerging, and the UCLA team is examining this application.

Q: International work? A: Europeans are doing interesting work (e.g., research on antennas and establishing a school of antenna engineering for worldwide Ph.D. students). The Far East (e.g., Singapore) is working in areas of miniaturization and multi-band design plus medical applications (biotelemetry). The Japanese are trying to reduce the cost of arrays and are also harvesting electromagnetic energy (e.g., charging cell phones from energy in the environment). Finally, China is doing research and producing various products.

[4]Unless specifically stated otherwise, the speaker answered all questions.

3
Second Day (Closed)

This day included the availability of classified materials. The presentations were followed by discussion periods during which questions were posed and answered. At times during the discussion periods there were also exchanges of ideas among the participants. Again, summaries of these discussions sometimes do not follow their specific order of occurrence during the meeting, thus allowing like topics to be synthesized. The first two topics had three speakers. The last topic was a general wrap-up discussion moderated by a committee member.

Mark Schrote, senior consulting engineer, Northrop Grumman Electronic Systems, was the first speaker. He was followed by Luke Feldner, principal member of the technical staff, Sandia National Laboratories.

Schrote discussed technology trends in active electronically steered antennas (AESAs). He opened by describing the advantages of AESAs (e.g., more power output, higher sensitivity, much faster steering without gimbals) and their heritage from the 1970s. AESAs are used for air, ship, ground, and space applications, and new designs have been appearing about once per year. Trends are moving to more functionality, applications beyond radar (e.g., communications), open architectures, scalability, and digital beam-forming—overall, providing rapidly growing capability and lower cost. Better design tools, also discussed on Day 1, are very helpful as the future multi-mission applications for AESAs evolve and mature.

James Armitage, senior fellow, Potomac Institute for Policy Studies, was the principal speaker. Luke Feldner's material, originally scheduled for this session, was covered in the session summarized above.

Committee member Kenneth Kress, senior scientist for KBK Consulting, Inc., and consultant for Booz Allen Hamilton, moderated the wrap-up discussion. Participants commented about the merits of this kind of workshop and offered statements about key issues. The statements are not necessarily consensus correlations of views expressed at the workshop, but rather were the comments of individuals.

Appendixes

Appendix A
Committee Biographies

J. Jerome Holton, *Chair*, is a senior systems engineer with the Tauri Group, where he supports the BioWatch Systems Program Office within the Office of Health Affairs, Department of Homeland Security (DHS). He provides analysis, advice, and counsel to senior government decision makers on policy, technology, and operations issues related to weapons of mass destruction and their effects on civilian infrastructure, first responders, military forces, and tactical operations. Prior to this, he served in a variety of leadership positions for private-sector companies, spanning the gamut from scientific research start-up to large management consulting firm. Past clients include the Office of the Deputy Assistant to the Secretary of Defense for Counterproliferation and Chemical/Biological Defense, the Chemical Biological Defense Directorate of the Defense Threat Reduction Agency, the Chemical Biological National Security Program of the Department of Energy, and the DHS Science and Technology Directorate. His work extends broadly across the chemical/biological/radiological/nuclear/conventional explosives detection and countermeasures arena. For several years, he focused on the counterproliferation of, counterterrorism/domestic preparedness issues for, and the detection, identification, and decontamination of chemical and biological weapons. Recent accomplishments include fielding information operations tools and enhancing the intelligence, surveillance, and reconnaissance capabilities to detect and defeat improvised explosive devices as well as the development of applique armor solutions to counter explosively formed penetrators. Holton previously served on the NRC's Standing Committee on Defense Intelligence Agency Technology Forecasts and Reviews (TIGER), the Committee for the Symposium on Avoiding Technology Surprise for Tomorrow's Warfighter, and the Committee on Alternative Technologies to Replace Antipersonnel Landmines. He earned his B.S. in physics from Mississippi State University and holds M.S. and Ph.D. degrees in experimental physics from Duke University.

Edward M. Greitzer (NAE), *Vice Chair*, is the H.N. Slater Professor, Department of Aeronautics and Astronautics at Massachusetts Institute of Technology. He received his A.B., S.M., and Ph.D. from Harvard University. Prior to joining MIT in 1977, he was with United Technologies Corporation, and, more recently, he was on leave at United Technologies Research Center as director, Aeromechanical, Chemical, and Fluid Systems. From 1984 to 1996 he was the director of MIT's Gas Turbine Laboratory, and from 1996 to 2002 was associate head, and from 2006 to 2008 deputy head, of the Department of Aeronautics and Astronautics. His research interests have spanned a range of topics in gas turbines, internal flow, turbomachinery, active control of fluid systems, university-industry collaboration, and robust gas turbine engine design; he was the MIT lead for the Cambridge-MIT Institute Silent Aircraft Initiative. He teaches graduate and undergraduate courses in the fields of propulsion, fluid mechanics, thermodynamics, and energy conversion, as well as the department's undergraduate project course. Greitzer is a three-time recipient of the American Society of Mechanical Engineers Gas Turbine Award for outstanding gas turbine paper of the year; in addition, he received the ASME Freeman Scholar Award in Fluids Engineering, the International Gas Turbine Institute Scholar Award, and

publication awards from the American Institute of Aeronautics and Astronautics and the Institution of Mechanical Engineers. He has also received the Aircraft Engine Technology Award from the ASME International Gas Turbine Institute, the U.S. Air Force Exceptional Civilian Service Award, and the ASME R. Tom Sawyer Award. He has been a member of the U.S. Air Force Scientific Advisory Board and the NASA Aeronautics Advisory Committee, and he is an Honorary Professor at Beihang University (Beijing). Greitzer has published more than 70 papers and is lead author of the book *Internal Flow: Concepts and Applications*, published by Cambridge University Press. He is a fellow of AIAA and ASME, a member of the National Academy of Engineering, and an International Fellow of the Royal Academy of Engineering.

Brian Ballard founded and currently serves as the CEO of APX Labs, a software company focused on leading development into wearable augmented reality products at the nexus of computer vision, user experience, and see-through displays. Previously he served as the director of product development and vice president at Battlefield Telecommunication Systems (BTS), where he led the development of defense-oriented augmented reality and biometric data fusion applications. As part of his portfolio, he was also heavily engaged in developing mobile 3G and 4G networks, devices, and applications for tactical military employments. Prior to joining BTS, Ballard served as the CTO at Mav6, where he was involved in the development of emerging networking and embedded systems technologies for intelligence, surveillance, and reconnaissance (ISR) systems and applications in government and military. He is a highly experienced professional in the field of national intelligence systems and computer engineering. Employed for more than 10 years with the National Security Agency, he has dealt with all forms of data collection, dissemination, processing, and visualization. Ballard holds an M.S. and a B.S. in electrical and computer engineering from Carnegie Mellon University, and a master's of technology management from the University of Maryland. He is currently working on an MBA at the University of Maryland.

Kenneth I. Berns (NAS/IOM) is director of the University of Florida Genetics Institute and Distinguished Professor of Molecular Genetics and Microbiology, Medicine. He has served as a member of the Composite Committee of the United States Medical Licensing Examination, chairman of the Association of American Medical Colleges, president of the Association of Medical School Microbiology and Immunology Chairs, president of the American Society for Virology, president of the American Society for Microbiology, and vice-president of the International Union of Microbiological Societies. He is a member of the National Academy of Sciences and the Institute of Medicine. Berns's research examines the molecular basis of replication of the human parvovirus, adeno-associated virus, and the ability of an adeno-associated virus to establish latent infections and be reactivated. His work has helped provide the basis for use of this virus as a vector for gene therapy. Berns's M.D. and his Ph.D. in biochemistry are from the Johns Hopkins University.

Ann N. Campbell is director, Information Solutions and Services, at Sandia National Laboratories. Her organization develops and stewards a broad range of software applications and information systems for both internal (enterprise) and external customers to facilitate the delivery of effective national security technologies. At Sandia, she previously served as senior manager and deputy to the chief technology officer for cybersecurity science and technology (S&T). In that role she was responsible for developing and implementing an institutional strategy for cyber S&T. She was recently acting director for Sandia's Cyber Security Strategic Thrust, leading the lab's activities to expand Sandia's cyber workforce and infrastructure, and strategies to provide increased support for Sandia's national security sponsors' cyber missions. Campbell has also served as deputy for technical programs for the Defense Systems and Assessments Strategic Management Unit (DSA SMU). In that role she advised the DSA vice president regarding the

unit's national security programs, was responsible for strategic planning and the investment strategy for the DSA, and assisted with implementation of the laboratory's cyber strategy. From 2003 to 2007, Campbell led the Assessment Technologies Group in Sandia's Information Systems Analysis Center. She was responsible for development, coordination, and oversight of programs focusing on vulnerability assessments and development of national security solutions in information technologies for multiple government sponsors. From 1999 to 2003 she was manager of the Microsystems Partnerships Department, which assessed and addressed microelectronics vulnerabilities for a variety of government sponsors. In that role Campbell led Sandia's program to support the DoD Anti-Tamper Initiative. She joined the technical staff at Sandia in 1985 and had assignments in the Materials and Process Center and the Microsystems Science, Technology, and Components Center. She conducted research on the microstructure and physical properties of advanced materials, the physics of microelectronics failures, and the development of advanced microelectronics failure analysis techniques. Campbell serves on the National Academies' Standing Committee on Technology Insight–Gauge, Evaluate and Review (TIGER). She is a senior member of IEEE and served as vice president of membership for the IEEE Reliability Society and on the Management Committee and board of directors for the IEEE International Reliability Physics Symposium. She has more than 20 publications and several patents. She holds a B.S. degree in materials engineering from Rensselaer Polytechnic Institute and M.S. and Ph.D. degrees in applied physics (materials science concentration) from Harvard University.

Dean R. Collins recently retired as a deputy director of DARPA's Microsystems Technology Office (MTO); as a chief scientist he was responsible for the monitoring, analysis, and evaluation of research projects directed by MTO program managers and also participated in the concept planning for leading MTO into new programs beyond the current state of the art in electronics, photonics, microelectromechanical systems (MEMS), component architectures, and algorithms. He managed the MTO program on integrated circuit cybersecurity. Prior to joining DARPA, Collins was director for the Advanced Research and Development Activity (ARDA) in information technology. ARDA functioned as a joint activity of the intelligence community and the Department of Defense, addressing high-risk/high-payoff information technology problems that had broad impact across both supporting communities. Collins initiated ARDA's key cyber security effort. He was also a member of the intelligence community Advanced Research and Development Committee and managed the ARDA quantum information science effort. Prior to joining ARDA, Collins was with the National Institute of Standards and Technology (NIST), where he was chief of the High Performance Systems and Services Division, the largest division at NIST. This position focused on information technology with a strong commercial bias, and the topics investigated ranged from biometrics to electronic books. Previously, Collins was with Texas Instruments, as director of the System Components Lab, which was responsible for all research on III-V devices, nanoelectronics, photonics, and neural networks. Prior to that, he was director of the Interface Technology Lab, which was responsible for all sensor and display research, including LCDs, DLPs, and CCDs. Collins is a fellow of the IEEE, a member of the American Physical Society, and a registered professional engineer. He has published more than 40 refereed articles and has 10 issued U.S. patents.

Sharon C. Glotzer is the Stuart W. Churchill Collegiate Professor of Chemical Engineering and a professor of materials science and engineering at the University of Michigan (UM), Ann Arbor, and is director of research computing in the UM College of Engineering. She also holds faculty appointments in physics, applied physics, and macromolecular science and engineering. She received a B.S. in physics from UCLA and a Ph.D. in physics from Boston University. Prior to joining UM, she worked at the National Institute of Standards and Technology. Her research focuses on computational nanoscience and simulation of soft matter, self-assembly and materials design, and computational science and engineering and is sponsored by the DoD, DoE, NSF, and

the J.S. McDonnell Foundation. Glotzer is a fellow of the American Physical Society and of the National Security Science and Engineering Faculty, and she was elected to the American Academy of Arts and Sciences in 2011. She has served on the National Academies' Solid State Sciences Committee; Technology Warning and Surprise study committee; Biomolecular Materials and Processes study committee; Modeling, Simulation, and Games study committee; and Technology Insight–Gauge, Evaluate, and Review (TIGER) Committee. She is involved in roadmapping activities for computational science and engineering, including chairing or co-chairing several workshops, steering committees and pan-agency initiatives, and she serves on the advisory committees for the DOE Office of Advanced Scientific Computing and NSF Directorate for Mathematical and Physical Sciences. Glotzer is also co-founding director of the Virtual School for Computational Science and Engineering under the auspices of the NSF-funded Blue Waters Petascale Computing Project at the National Center for Supercomputing Applications.

J.C. Herz is chief executive officer at Batchtags, LLC. She is also a technologist with a background in biological systems and computer game design. Her specialty is massively multiplayer systems that leverage social network effects, whether on the web, mobile devices, or more exotic high-end or grubby low-end hardware. She currently serves as a White House Special Consultant to the Office of the Secretary of Defense (Networks and Information Integration). Defense projects range from aerospace systems to a computer-game-derived interface for next-generation unmanned air systems. Hertz is one of the three co-authors of OSD's Open Technology Development roadmap. She serves on the Federal Advisory Committee for the National Science Foundation's education directorate. In that capacity, she is helping NSF harness emerging technologies to drive U.S. competitiveness in math and science. Hertz was a member of the National Research Council's Committee on IT and Creative Practice and is currently a fellow of Columbia University's American Assembly, where she is on the leadership team of the Assembly's Next Generation Project. In 2002, she was designated a Global Leader for Tomorrow by the World Economic Forum. She is a member of the Global Business Network; a founding member of the IEEE Task Force on Game Technologies; a term member of the Council on Foreign Relations; and a member of the advisory board of Carnegie Mellon's ETC Press. Hertz graduated from Harvard University with a B.A. in biology and environmental studies, magna cum laude. She is the author of two books, *Surfing on the Internet* (Little Brown, 1994), an ethnography of cyberspace before the web, and *Joystick Nation: How Videogames Ate Our Quarters, Won Our Hearts, and Rewired Our Minds* (Little Brown, 1997), a history of videogames which traces the cultural and technological evolution of the first medium that was born digital and how it shaped the minds of a generation weaned on Nintendo. Her books have been translated into seven languages. As a *New York Times* columnist, Hertz published 100 essays on the grammar and syntax of game design between 1998 and 2000. She has also contributed to Esther Dyson's Release 1.0, *Rolling Stone*, *Wired*, *GQ*, and the *Calgary Philatelist*.

Kenneth A. Kress is a senior scientist for KBK Consulting, Inc., an affilate of Montana State University's Department of Physics, and a consultant for Booz Allen Hamilton, where he specializes in quantum information science and other technical evaluations and strategic planning for intelligence and defense applications. Some of his past clients include DARPA's Microsytems Technology Office, Noblis, Georgia Tech Research Institute, Mitretek Systems Inc., and Lockheed Martin's Special Programs Division. From 1971 to 1999 he worked in a series of positions at the Central Intelligence Agency's Directorate of Operations, Office of Development and Engineering, and finally, Office of Research and Development (ORD); first as a research and development manager, later as a program manager, and finally as an ORD Office senior scientist responsible for management support, the development of technical and strategic plans, and DOD inter-agency coordination for advanced technology. He is the inventor of the solid-state neutron

detector, for which he won an award in 1981. He holds a Ph.D. in physics from Montana State University.

Darrell D.E. Long is the Kumar Malavalli Professor of Computer Science at the University of California, Santa Cruz. He holds the Kumar Malavalli Endowed Chair of Storage Systems Research and is director of the Storage Systems Research Center. He received his B.S. in computer science from San Diego State University and his M.S. and Ph.D. from the University of California, San Diego. His dissertation advisor was Jehan-François Pâris. He is a fellow of the Institute of Electrical and Electronics Engineers and of the American Association for the Advancement of Science. He is a member of the IEEE Computer Society, the Association for Computing Machinery, the American Society for Engineering Education, the Usenix Association, Upsilon Pi Epsilon, and Sigma Xi. He has broad research interests in many areas of mathematics and science, and in the area of computer science including data storage systems, operating systems, distributed computing, reliability and fault tolerance, and computer security. His research has been supported by the National Science Foundation; the Department of Energy (Office of Science and National Nuclear Security Administration); Lawrence Livermore, Los Alamos, and Sandia National Laboratories; the Office of Naval Research; and a number of industrial sponsors that include IBM, Microsoft, NetApp, Symantec, LSI Logic, Samsung, Hewlett-Packard, and Data Domain. He served as the vice chair and then chair of the University of California Committee on Research Policy. He has served on the University of California President's Council on the National Laboratories, and on the Science and Technology, National Security, and Intelligence committees. He currently serves on the Science and Technology committee for both Los Alamos and Lawrence Livermore National Laboratories. He previously served on the National Research Council Standing Committee for Technology Insight–Gauge, Evaluate and Review. He continues to serve on numerous committees and advisory panels for various federal government agencies.

Julie J.C.H. Ryan is an associate professor and chair of Engineering Management and Systems Engineering at George Washington University. She holds a B.S. degree in humanities from the U.S. Air Force Academy, an M.L.S. in technology from Eastern Michigan University, and a D.Sc. in engineering management from the George Washington University. Ryan began her career as an intelligence officer, serving the U.S. Air Force and the U.S. Defense Intelligence Agency. After leaving government service, she continued to serve U.S. national security interests through positions in industry. Her areas of interest are in information security and information warfare research. She was a member of the National Research Council's Naval Studies Board from 1995 to 1998. She has conducted several research projects and has written several articles and book chapters in her focus area.

Janet A. Therianos, a consultant, has 30 years of military experience. She is a U.S. Air Force Academy graduate with an undergraduate degree in aeronautical engineering; an MBA from Harvard Business School; and a masters of arts in air and space power strategy. She was a National Defense fellow and has executive education from Harvard's Kennedy School of government, the Center for Creative Leadership, and the Intelligence Community Senior Leader Program. Therianos has flown several military aircraft and has served as a command pilot, flight examiner, flight instructor, and functional check pilot. She also holds an FAA Airline Transport Pilot rating. Her military career was grounded in operations, but she also had extensive higher-headquarters staff duties, including serving as senior military assistant to the Secretary of the Air Force. Her leadership experiences were threaded throughout her career, including several Commands. Her final military assignment was leading the Air Mobility Command's Directorate of Intelligence, where she was responsible for organizing, training, and equipping the Air Force's

global mobility intelligence units. Operationally she led the Command's daily Threat Working Group, which assessed threat levels for all global mobility flight operations.

Elias Towe is currently a professor of electrical and computer engineering and the Albert and Ethel Grobstein Professor of Materials Science and Engineering at Carnegie Mellon University. He was educated at the Massachusetts Institute of Technology (MIT), where he received B.S, M.S., and Ph.D. degrees from the Department of Electrical Engineering and Computer Science. Towe was a Vinton Hayes Fellow at MIT. After leaving MIT he became a professor of electrical and computer engineering, and engineering physics at the University of Virginia. He also served as a program manager in the Microsystems Technology Office at the Defense Advanced Research Projects Agency (DARPA) while he was a professor at the University of Virginia. In 2001, he joined the faculty at Carnegie Mellon University. Towe is a recipient of several awards and honors that include the National Science Foundation Young Investigator Award, the Young Faculty Teaching Award, and an Outstanding Achievement Award from the Office of the Secretary of Defense. He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Optical Society of America (OSA), the American Physical Society (APS), and the American Association for the Advancement of Science (AAAS).

Alfonso Velosa III is research director for Gartner with a focus on sustainability, business ecosystems, and smart cities. He is also agenda manager for electronic equipment research at Gartner, concentrating on electronics and semiconductor supply chain research, with a particular focus on global trends for manufacturing, consumption, financing, and the key vendors in the market. Velosa has also written extensively about electronics, outsourcing of electronics manufacturing, electronic manufacturing services (EMS), original design manufacturing (ODM), and semiconductor consumption. He previously worked at or consulted for Intel Corporation, NASA Lewis Research Center and NASA Headquarters, Mars & Co., and IBM Research. Velosa graduated from Columbia University with a B.S. in materials science engineering; from Rensselaer Polytechnic Institute with an M.S. in materials science engineering; and from Thunderbird, the Garvin School of International Management, with an M.I.M. in international management.

Eli Yablonovitch (NAS/NAE) is an adjunct professor of electrical engineering at UCLA after having served as a full faculty member until 2007. He is currently a professor of electrical and computer engineering at University of California, Berkeley. He graduated with a Ph.D. in applied physics from Harvard University, worked for 2 years at Bell Telephone Laboratories, and then became a professor of applied physics at Harvard. In 1979 he joined Exxon to do research on photovoltaic solar energy; in 1984, joined Bell Communications Research, where he was a Distinguished Member of Staff and also director of Solid-State Physics Research; and in 1992, joined the University of California, Los Angeles, where he became the Northrop Grumman Opto-Electronics Chair and a professor of electrical engineering. Yablonovitch's work has covered a broad variety of topics: nonlinear optics, laser-plasma interaction, infrared laser chemistry, photovoltaic energy conversion, strained-quantum-well lasers, and chemical modification of semiconductor surfaces. Yablonovitch's research focuses on optoelectronics, high-speed optical communications, high-efficiency light-emitting diodes and nanocavity lasers, photonic crystals at optical and microwave frequencies, and quantum computing and communication.

Appendix B
Workshop Agenda and Participants

AGENDA

Workshop on the Future of Antennas
May 8-9, 2012
Battelle Charlottesville Operations
Charlottesville, Virginia

Future of Antennas
Lon Pringle, Director, Signature Technology Laboratory, Georgia Tech Research Institute

Commercial State of the Art of Wireless Communications and Control
Sebastian Rowson, Chief Scientist, Ethertronics

Military State of the Art of Wireless Communications and Control
Robert Newgard, Director, Advanced Radio Systems, Rockwell Collins

Future Trends in Antenna Design and Wireless Communications and Control
Timothy Hancock, Assistant Group Leader, Analog Device Technology, Lincoln Laboratory, MIT
Yahya Rahmat-Samii, Northrop Grumman Chair in Electromagnetics, University of California, Los Angeles

Vulnerabilities of Ubiquitous Antennas
Mark Schrote, Senior Consulting Engineer, Northrop Grumman Electronic Systems
Luke Feldner, Principal Member of Technical Staff, Sandia National Laboratories

Indicators and Observables
James Armitage, Senior Fellow, Potomac Institute for Policy Studies
Luke Feldner, Principal Member of Technical Staff, Sandia National Laboratories

PARTICIPANTS

Committee

Kenneth Berns, University of Florida College of Medicine
Jerome Holton, Tauri Group
Kenneth Kress, KBK Consulting, Inc.
Julie Ryan, George Washington University
Janet Therianos, Independent Consultant, (USAF, retired)
Alfonso Velosa, Gartner, Inc.
Eli Yablonovitch, University of California, Berkeley

Staff

Terry Jaggers, Lead DEPS Board Director
Daniel Talmage, Study Director
Sarah Capote, Research Associate
Marguerite Schneider, Administrative Coordinator

Speakers

James Armitage, Potomac Institute for Policy Studies
Luke Feldner, Sandia National Laboratories
Timothy Hancock, MIT Lincoln Laboratory
Robert Newgard, Rockwell Collins, Inc.
Lon Pringle, Georgia Tech Research Institute
Yahya Rahmat-Samii, University of California, Los Angeles
Sebastian Rowson, Ethertronics
Mark Schrote, Northrop Grumman Electronic Systems

Guest Affiliations

Defense Intelligence Agency
Department of Defense
National Ground Intelligence Center
United States Navy
United States Army

Appendix C
Speaker Biographies

James Armitage is a senior fellow at the Potomac Institute for Policy Studies. As a former vice president and sector chief technology officer for Northrop Grumman Electronic Systems, he was responsible for the sector's overall technology strategy and development plans. Armitage's career began as a design engineer in the Antenna and Microwave Department at Westinghouse, where he pioneered the development of low observable apertures and active electronically scanned arrays. His technical leadership led to a number of roles in business development and program management. During his 36 years with Westinghouse and Northrop Grumman, he served in a variety of executive and leadership roles. In 1984, Armitage received the IEEE Aerospace Electronic Systems Society Centennial Key to the Future Award as the outstanding young engineer. He also served on the Defense Science Board Global Surveillance Task Force and is a member of the IEEE International Radar Conference Board, having served as treasurer in 1995 and as general chairman for the 2010 Conference. In 1998, he completed the Harvard University General Manager Program. Armitage earned his B.S. degree in electrical engineering from Ohio State University in 1975 and an M.S. in applied physics from Johns Hopkins University in 1980.

Luke Feldner is a principal member of the technical staff at Sandia National Laboratories in the Special Technologies Department of the Systems Assessment and Research Center, where he manages several research and development programs related to U.S. national security interests. As a member of the Department of Energy's Field Intelligence Element at Sandia, he lends technical, analytical, and research support to the federal law enforcement, intelligence, and defense communities. From 2001 to 2006, Feldner worked in Sandia's Electronics Systems Center as an RF/microwave circuit and antenna designer in the Advanced Radar Development Group. He has been actively involved in the analysis, measurement, and design of advanced antenna and RF systems for more than a dozen years and has developed and conducted multiple training exercises for government and military field officers. Feldner is a member of the IEEE Antennas and Propagation, Microwave Theory and Techniques, and Communications Societies, as well as the Center for Strategic and International Studies project on Nuclear Issues. He received a B.S. degree in electrical engineering from the Milwaukee School of Engineering, and the Dipl.-Ing. (FH) degree in electrical engineering from the Lübeck University of Applied Sciences, Lübeck, Germany, in 1999; an M.S. degree in electrical engineering from the University of Wisconsin-Madison in 2001; and a Ph.D. degree in electrical engineering from the University of New Mexico in 2006.

Timothy M. Hancock received a B.S. degree in electrical engineering from the Rose-Hulman Institute of Technology and M.S. and Ph.D. degrees in electrical engineering from the University of Michigan, where he was involved with the development of SiGe integrated microwave components from 6 to 77 GHz. In the past he worked for Conexant Systems on a single-chip GPS receiver and at M/A-COM on a Silicon Germanium 24 GHz automotive radar solution. For 6 years he was a staff member in the Analog Device Technology Group at MIT Lincoln Laboratory, where he was involved with the development of low-power, small-form-factor

wireless devices and reconfigurable and multiple-input-multiple-output (MIMO) communication systems in work focused on integrated circuit design and wireless system design. As assistant leader of the same group since 2011, he has continued to develop programs in the area of MIMO communications and small-form-factor wireless devices as well as technology for radar and ELINT systems.

Robert Newgard is the director of the Advanced Radio Systems within the Advanced Technology Center at Rockwell Collins, Inc. His principal technical responsibilities are in the design and development of airborne communication systems and technologies. Newgard has performed as principal investigator on numerous Defense Advanced Research Program Agency (DARPA)-funded research programs, including the Chip-Scale Atomic Clock (CSAC), Next Generation Spectral Sensor (XG), Analog Spectral Processors (ASP), Dynamics-Enabled Frequency Source (DEFYS), and Chip-Scale Spectrum Analyzers (CSSA). Newgard's department is focused on the development of technologies and systems focused on the high-performance radio frequency (RF) front ends. Included in this focus are antennas, receivers, transmitters, synthesizers, photonics, and frequency standards.

Lon Pringle is the principal research scientist at Georgia Tech Research Institute and is the director of the Signature Technology Laboratory. Pringle's research encompasses infrared phenomenology, advanced infrared measurements and simulations, the detection and tracking of low observable targets in clutter, the management and control of optical energy by active and passive techniques, radiative energy transfer processes in optical color transparencies and prints, adaptive signature control technologies, radio frequency (RF) and infrared (IR) seeker and fuze designs, advanced RF beam forming using phase-only control (as contrasted with amplitude and phase control), and recently a revolutionary new methodology for the design of wideband, multi-function, reconfigurable apertures. This research led to more than 25 technical publications, and two patents and was supported by approximately $18 million in sponsorship, for $9.5 million of which Pringle has served as project director/principal investigator. Of special note has been his successful direction of the DARPA-sponsored reconfigurable aperture program and its follow-on application in the Future Combat System program.

Yahya Rahmat-Samii (NAE) received M.S. and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana-Champaign, and a B.S. degree, with highest distinction, in electrical engineering from the University of Tehran, Iran. Before joining UCLA in 1989, he was a senior research scientist at NASA's Jet Propulsion Laboratory/California Institute of Technology and was a guest professor at the Technical University of Denmark (TUD) in the summer of 1986. He has also been a consultant to many aerospace companies. He served as chair of UCLA's Electrical Engineering Department from April 2000 through June 2005. Since 2007, he has held the Northrop Grumman Chair in Electromagnetics at UCLA. Rahmat-Samii has authored and co-authored more than 750 technical journal articles and conference papers, has written 25 book chapters, is the co-author of three books, and holds several patents. He has made pioneering research contributions in diverse areas of electromagnetics, antennas, measurement and diagnostics techniques, numerical and asymptotic methods, satellite and personal communications, antennas for remote sensing and astronomical applications, human/antenna interactions, frequency selective surfaces, electromagnetic and photonic band gap structures, and the applications of genetic algorithms and particle swarm optimization. On several occasions, Rahmat-Samii's work has been featured on journal covers and in magazines, as well as in several TV newscasts.

Sebastian Rowson is one of the founders and also the chief scientist at Ethertronics, a privately held antenna design and manufacturing company that manufactures primarily embedded antennas

for personal and industrial wireless devices. Ethertronics has annual shipments of about 100 million units to clients that include Samsung, LG Electronics, and Motorola. Ethertronics co-founders Laurent Desclos and Sebastian Rowson started the company in 2000 to commercialize new antenna technology known as IMD (isolated magnetic dipole). Rowson has filed 49 patents with the U.S. Patent and Trademark Office, and 30 of those have currently been issued. He has also served as the director of technology transfer and as a senior engineer at Ethertronics. Previously, Rowson was a research engineer at the University of California, Los Angeles. He earned his M.S. and a Ph.D. at the University of Paris-Sud. Rowson is a member of the Institute of Electrical and Electronics Engineers.

Mark Schrote is a senior consulting engineer with Northrop Grumman Electronic Systems. He received his BSEE, MSEE, and Ph.D. in electrical engineering in 1978, 1980, and 1983, respectively from Ohio State University. Schrote has more than 28 years of experience in active electronically scanned array design, focusing on advanced development systems.