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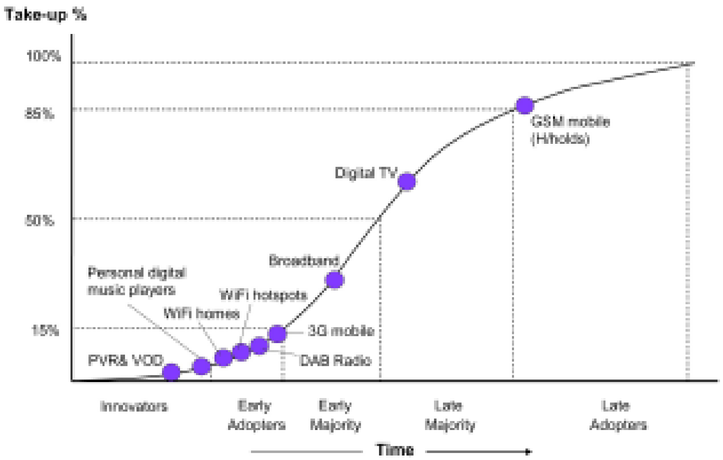
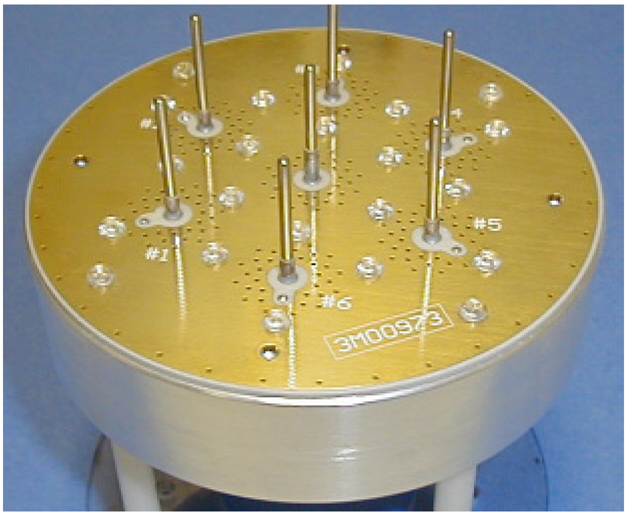
U.R.S.I.





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Contents

Front cover: On top: The technology adoption curve (Source: Ofcom), See the paper by E. Taillefer and J. Cheng (pp. 14-25); Below: A photo of a fabricated seven-element ESPAR antenna operating in the 2.4 GHz band , See the paper by W. Webb (pp.26-35).

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The International Union of Radio Science (URSI) is a foundation Union (1919) of the International Council of Scientific Unions as direct and immediate successor of the Commission Internationale de Télégraphie Sans Fil which dates from 1913.

Editorial

Our Papers

Smart antennas are adaptive-array antennas that adapt their patterns to optimize communication. For example, such antennas can focus a beam on a desired mobile device, while placing pattern nulls on undesired interference – and then dynamically change to adapt to a different desired mobile device, or to the motion of the mobile device. One type of smart antenna is an electronically steerable parasitic-array-radiator (ESPAR) antenna. ESPAR antenna patterns can be controlled via reactances on the parasitic elements. In contrast to more-common multiple-output arrays, ESPAR antennas have a single output port. This makes the signal-processing issues associated with using such antennas rather challenging. In the invited Commission C *Review of Radio Science* in this issue, Eddy Taillefer and Jun Cheng provide a review of current issues associated with such antennas, and how the signal-processing challenges are being met.

The authors begin by providing a very nice and easily readable discussion of how smart antennas in general, and ESPAR antennas in particular, can be used in a variety of applications. They also discuss the tradeoffs between multiple-output and single-output antennas in such applications. They then develop a signal model for the ESPAR antenna. They define reactance-domain signal processing as the ability of an ESPAR antenna to steer a beam and/or a null in the direction of a source. They then show how a variety of adaptive-beamforming results can be obtained using such signal processing. They explain how direction-of-arrival estimation can be done using signal processing with the one-output ESPAR antenna, and they describe a variety of algorithms for accomplishing this.

The efforts of Takashi Ohira, Associate Editor for Commission C, and Phil Wilkinson in bringing us this review are gratefully acknowledged.

Forecasting the future is not usually considered to involve the exercise of much science. However, as William Web demonstrates in his invited General Lecture paper, it can be done scientifically, at least when what is being forecasted is the future of an area of radio science: wireless communications. He looks at the likely state of wireless communications over the next five, 10, 15, and 20 years. The process is as interesting as the results – and I think many will be surprised by the results. He begins with an explanation of why prediction is critical, both to business and to those actually doing the science. He then introduces a series of "laws" that serve as guideposts for predicting scientific and technological progress in key areas. The technologies that are likely to play key roles in determining the future of wireless communications are then introduced, and those that will – and will not – and the reasons why may again surprise you. Economic and social issues, and issues related to the structure of the communications industry, are then examined. Contributions from a series of people who were asked for their predictions are then summarized. All of this is finally synthesized into a set of predictions, and the implications of those predictions are studied.

As noted, this isn't just a matter of predicting the development of technology. It also involves predicting what areas of scientific research are likely to be needed, and what areas are likely to have little impact. Such information can be of critical importance in thinking about future areas of research and development. This paper will form the basis for one of the General Lectures at the XXIXth URSI General Assembly, to be held in Chicago, Illinois, USA, August 7-16, 2008. You should definitely plan on hearing it in person!

The efforts of Gert Brussaard in arranging for this Lecture are gratefully acknowledged.

Our Other Contributions

Peter Watson has assembled a substantial set of dissertation abstracts for this issue. In reading them, you can find out not only what new research has been done, but have an opportunity to experience the ideas of a new crop of radio scientists.

As I reported in this column in the last issue, we learned of the sad death of Dr. A. P. Mitra, Honorary President of URSI, just as that issue went to press. Several of Dr. Mitra's colleagues have given us a warm and moving account of his life in this issue.

We have an interesting letter to the Editor in this issue. It offers some updated estimates for some critical efficiencies in the SPS White Paper that appeared in the June issue.

The XXIX General Assembly of URSI

The URSI General Assembly will be held in Chicago next August. The deadline for submission of papers is January 31, 2008, not too long after you will hopefully receive this issue of the *Radio Science Bulletin*. Information on how to submit a paper is available at http://www.ece.uic.edu/2008ursiga. Information is also available there on the URSI Young Scientist program. For this General Assembly, the local Organizing Committee is sponsoring a student paper competition. While the first-through fifth-place finishers in the contest will receive certificates and monetary awards ranging from US$500 to US$1500, all ten finalists will receive free lodging at the General Assembly headquarters hotel, the Hyatt Regency in downtown Chicago, for the ten-day duration of the General Assembly, based on double-room occupancy. The submission deadlines for the Young Scientist program and for the student paper competition are also January 31, 2008.

I hope to see you all at the General Assembly!

Ross

Letter to the Editor

U.R.S.I.

COMMENTS ON URSI WHITE PAPER ON SPS SYSTEMS

I am a member of Commission E in the field of radio-communication interference. I am very fond of the *Radio Science Bulletin* and of URSI General Assemblies.

I have read with a lot of interest the URSI White Paper on SPS systems [URSI Board, "URSI White Paper on Solar Power Satellite (SPS) Systems," *Radio Science Bulletin*, No. 321, June 2007, pp. 13-27]. However, I have found two items in the June 2007 *Radio Science Bulletin* that may need correction.

On page 18, near the end of the first column, were provided figures for the efficiency of Si cells as 17.3% and GaAs cells as 20%. The quoted reference [reference 7 in the White Paper] for these data is a report from October 1978. Now, in 2007, the figures are significantly better. It will be useful to take as a reference, for instance, the expert papers [1, 2]. Yesterday, I read [3]. The authors mentioned that Si cell efficiency today has grown to 28%, and GaAs to more than 30%.

On page 23, at the bottom part of the first column, it seems that the safety limit for 2.45 GHz is 50 W/m^2, and for 5.8 GHz, the limit is 10 W/m^2. This is not exact. The limits for the lower frequencies have to be stricter (lower), because they are nearer to the radiation resonance absorption frequencies of the human body and head. The correct limits are that above 2.45 GHz, the safety limit power density in the radiation far field does not change significantly with frequency. Its value is 50 W/m^2 for...professional people and 10 W/m^2 for the general public, including children and old people.

For more than 30 years, I have been involved in the field of satellite communication and stratospheric quasi-stationary platforms (SQ-SP), which are called HAPS. This White Paper is the result of many years of research by a great team of very qualified scientists. I am also involved in the activities of COST 297, dealing with HAPS development. This White Paper was very useful for me for making deductions for the design of a rectenna on the HAPS feed, for 5.8 GHz, 24.1 GHz, or 35 GHz from a microwave ground station. There, the separation distance is only 20 km, instead of 40000 km, and the required power on the HAPS is only 150 kW. The HAPS issue is much simpler than SPS, and has to be solved in the next five to 10 years, in comparison to the complex SPS, which may be solved in the next 20 to 40 years.

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2. K. Reed "Ultra Light Amorphous Silicon Cell for Space Applications," March 2007, available at http://www.hapcos.org/papers.php.
3. F. Geyer, B. Caswell, and C. Signorini, "Powering the Future. A New Generation of High-Performance Solar Arrays," *ESA Bulletin*, No. 131, August 2007, pp. 46-49.

In Memoriam

Ashesh Prosad Mitra
1927 - 2007

Dr. Ashesh Prosad Mitra (Figure 1), the doyen of upper-atmospheric research in India and an internationally acclaimed global climate-change scientist, breathed his last on the early morning of September 3, 2007. His contribution to the growth of ionospheric research and climate research in India was immense.

Figure 1. Dr. Ashesh Prosad Mitra

Ashesh was born on February 21, 1927, in Calcutta (now known as Kolkata), West Bengal, India. He was the eighth child of Mr. Ambika Charan and Mrs. Suvarna Prabha Mitra, and was therefore nicknamed Gopal (one of the names of the mythological Lord Krishna). His father was a school teacher and his mother was a homemaker. Ashesh was a brilliant student in his Calcutta school days, always at the top of the class. He joined the "Bangabasi" college in Calcutta for his intermediate classes, because the Principal of that college made it a point to meet Ashesh's father with the request that he join that college. He had great reverence for his teachers, such as Jagdish Bhattacharya (Bengali literature), Promod Kumar Sen (Physics), and the legendary chemistry teacher, Ladli Mohan Miter. Ashesh recalled later in his life that they used to consider the students as their own children. He said that many times, the teachers would wait until he could come to the class.

He completed his BSc in Physics (Honors) from the well-known Presidency College of Calcutta in 1946, and secured the first-class first position. Similarly, he was first in the MSc (Physics) from the Calcutta University in 1948. He was taught by such eminent teachers as Prof. Satyendra Nath Bose (Bose-Einstein condensation), Prof. Meghnath Saha (Saha's ionization equation), and Prof. Sisir Kumar Mitra. Prof. Sisir Mitra – an outstanding ionospheric physicist of India in the early 20th century, whose book *Upper Atmosphere* is considered a classic text – attracted his favored student Ashesh to his subject of radio physics. Ashesh started his PhD work in 1950 under the senior Mitra, who was then the Ghosh Professor of Physics of the Department of Physics of Calcutta University. Sr. Mitra was soon to establish a new department, called the Institute of Radio Physics and Electronics (INRAPHEL). Ashesh was one of the earliest students of Sr. Mitra, even before INRAPHEL was established. As a Research Assistant, along with other scholars like Mrinal Dasgupta (who later became a well known radio astronomer), he assisted the Senior Mitra in preparing his famous treatise, *The Upper Atmosphere*.

Ashesh managed to complete his PhD thesis within a year, and went to Australia under the Colombo plan. In Sydney, he collaborated with Dr. Alex Shain to develop a riometer, which could measure cosmic radio-noise absorption in the D region due to flares emanating from the sun. This collaboration resulted in well-cited papers in *JATP* in 1953 and 1954.

Prof. K. S. Krishnan, an outstanding physicist and a collaborator of Prof. C. V. Raman in the discovery of the Raman Effect, was the Director of the National Physical Laboratory (NPL) at that time. He noticed the young Mitra during the 10th General Assembly of URSI at Sydney, Australia, and invited him to join NPL. Under the leadership of Prof. Krishnan, Mitra got involved in the very successful program of the 1957 International Geophysical Year (IGY). Dr. Mitra served NPL as the Head of the Radio and Atmospheric Science Division until 1982, as Director of NPL until 1986, and as Director General of CSIR until 1991. He was later associated with NPL as Scientist of Eminence, until his death. Dr. Mitra's activities covered the atmospheric environment, radio communication, ionospheric physics, atmospheric chemistry, global climate change, and space research.

Dr. Mitra's pioneering work on the use of cosmic radio noise for studies of the upper atmosphere resulted in a series of well-cited papers on ionospheric and solar physics, and cosmic rays. He was the driving force behind the Indian program of the IGY (1957-1958), as mentioned earlier. Mitra carried out comprehensive studies on the ionospheric effects of solar flares. He introduced new techniques for detecting solar flares, including the use of cosmic radio noise. At the NPL he set up a radio-flare system that in the sixties was one of the most extensive anywhere in the world. He introduced new techniques for analysis of flare effects of the atmosphere and, in pioneering work, showed that atmospheric chemistry changes during a flare. These works resulted in a comprehensive book, *Ionospheric Effects of Solar Flare*, (Riedel, 1974). He developed an atmospheric model from observations of satellite drag, and initiated new D-region rocket experiments. Mitra's work on ion and neutral chemistry in the upper atmosphere, and especially on the minor constituent nitric oxide, provided the basis for much of our present knowledge of the lower ionosphere. At the NPL, he introduced a method of ionospheric prediction that has been the basis of radio forecasts for HF and MF communication systems. In early 1970, he set up a school on tropospheric monitoring and propagation systems, and on microwave radiometry. He provided a reference database for radio communication over frequencies from VLF to microwaves. He developed a scientific base for troposcatter design and performance analysis, and for the estimation of radar target errors. He established an International Radio and Geophysical Warning Centre, serving India, the Middle East, and Southeast Asia.

By introducing tropospheric radio research in India in the 1970s, Mitra contributed in an important way to major improvements in radio-communication capabilities in India. He helped the Indian Air Force's radar-communication systems, which gave them superior detection capability in difficult hilly terrain in the early 1970s. In the late seventies, his group introduced for the first time in India an acoustic radar (SODAR: Sonic Detecting And Ranging), and carried out work on atmospheric ducting, pollution, and instability. Under his leadership, NPL started satellite radio beacon monitoring, and satellite-, rocket-, and balloon-borne in-situ measurements for ionospheric and middle- and lower-atmospheric studies. With this expertise, during the 1990s, NPL was able to send the first aeronomy satellite payload onboard the Indian satellite SROSS-C2 for upper-ionospheric studies. In 1979, he was awarded the prestigious Jawaharlal Nehru Fellowship, using which he undertook new work on the changing environment, both from natural and human influences. He brought out a monograph on *Human Influences on Atmospheric Environment* (1980).

In the eighties, Dr. Mitra led the very extensive middle-atmosphere program in India as part of IMAP (International Middle Atmosphere Programme). A major aim was to evolve a first-order reference middle atmosphere over India. This was achieved through the use of over a hundred rocket experiments, and establishment of new facilities (such as the Laser Heterodyning Facility at Delhi, the scientific expedition to Antarctica, and the setting up of a 96 GHz radiometer for ozone measurement there). Of the minor constituents, measurements of ozone were the most comprehensive, providing several key results: low ozone content at equatorial regions, and anomalies associated with passing weather disturbances.

The areas in which Dr. Mitra made outstanding contributions since the 1990s include (a) the first effort to examine global change signals over the entire atmospheric environment, from the surface to 1000 km; (b) the pioneering measurements of methane emission from paddy fields, which reduced the Indian contribution of the carbon budget to one-tenth of the initial estimates made by the US EPA (Environmental Protection Agency); and (c) the INDian Ocean EXperiment programme (INDOEX). Mitra's initiatives have made an impact on the global discussions about the responsibility of various countries with regard to greenhouse-gas inventories, current emissions, and likely future scenarios. He also played a key role in setting up some large national and international level facilities, such as the MST Radar at Tirupati; the Free Air Carbon Dioxide Enrichment (FACE) facility at the Indian Agriculture Research Institute, New Delhi; and the Bose Institute of High Altitude Centre for Astro-particle Physics and Space Science at Darjeeling. By training his sharp focus on global environmental changes, Mitra provided a very insightful analysis of the Kyoto protocol. He showed how the different categories of pollutants have an impact on India's environment and health, and on the biosphere. He brought into focus the Asian brown cloud problem, and helped formulate the Indian response to climate change. His contributions to the ozone problem, to atmospheric chemistry, to the measurement of greenhouse gases of India, and to global environmental chemistry have had international impact. Since he was leading the global-change science program in India and south Asia and the INDOEX in India, he became the driving force from India behind the International Geosphere Biosphere Programme (IGBP) from the 1990s onwards. These contributions led URSI to nominate him as an Honorary President of URSI in 2002.

In a unique honor to Indian science, Mitra was chosen to lead investigating teams of several international global-change-related programs in recent years. He became instrumental in developing both institutional and individual capacities across the south Asian region in this area of research. He was the Chair of the South Asian START (SysTem for Analysis, Research and Training) COMmittee (SASCOM) during the 1994-98 period, but continued as the Director of the South Asian START Regional Centre (SAS RC), located at NPL, until his death. More recently, in April 2007, he set up a new "Regional Facility on Radio Science" (RFRS) at NPL for the promotion of radio science along the lines of URSI in India, as well as in neighboring countries, including SAS-COM countries. Just a week before his death, a memorandum of understanding of cooperation with URSI was signed by him, as Chair of RFRS. His last scientific article, "The Importance of Earth

Figure 2. (l-r) Prof. Kristian Schlegel, then President of URSI; Dr. A. P. J. Abdul Kalam, then President of India; and Dr. A. P. Mitra, Honorary President of URSI, at the 2005 URSI General Assembly in New Delhi, India.

Observations in the Assessment of Malaria, Respiratory and Ocular Diseases in South Asia," was sent for publishing in the GEO Summit Publication "The Full Picture," and is to appear soon.

Honors and awards came to Dr. Mitra as a natural consequence of his intense work in diverse areas. He was the President of URSI during 1984-87, the first Indian and second Asian to be elected to this high office. He was a member of the General Committee of the International Council of Scientific Unions (ICSU, now the International Council of Science), 1984-88; served COSPAR in various capacities; was Chair of the National Committee for IGBP (1991-94); Chair of START-SASCOM and Director, SASCOM-RRC; Chair, Indian Advisory Committee on Space Sciences; Chair, Governing Council of Science Museums; and many more. He had many awards to his credit, including the Shanti Swarup Bhatnagar Award for Physical Sciences (1968), the Sir K. S. Krishnan Memorial Lectureship of INSA (1975), the C. V. Raman Award of UGC (1982), the FICCI Award for Physical Sciences (1982), the Jawaharlal Nehru Fellowship (1978-80), the Om Prakash Bhasin Award for Physical Sciences (1987), the Padma Bhushan by the President of India (1989), the Meghnad Saha Golden Jubilee Award of the Indian Association of Science (1991), the Sir C. V. Raman Birth Centenary Medal by the Indian Science Congress Association (1991), CSIR Distinguished Scientist (1991), the Modi Science Award (1992), the Meghnad Saha Medal by the Asiatic Society (1994), the S. K. Mitra Centenary Medal by the Indian Science Congress Association (1995), Senior Homi Bhabha Fellow (1996-98), and the Vasvic Award on Environmental Science and Technology (2002). He was a Fellow of the Royal Society of London; a Fellow of the Indian National Science Academy, of the Indian Academy of Sciences, and of the National Academy of Sciences; a Fellow of the Third World Academy of Sciences, and of the International Academy of Astronautics. He a past President of the National Academy of Sciences, and Secretary, INSA (1979-82), and an INSA Council Member (1994-95).

He published more than 150 papers, and wrote and edited several books and monographs. Examples included: *Advances in Space Exploration* (1979), *Ionospheric Effects of Solar Flares* (Reidal, 1974), *Human Influences on Atmospheric Environment* (1980). He was also on the editorial board of several scientific journals, including the *Journal of Atmospheric and Terrestrial Physics*, *Space Science Reviews*, *Indian Journal of Radio and Space Physics*, and *Mausam*.

Dr. Mitra was a very kind-hearted person, who tried to help every one. His former younger colleague and a distinguished radio astronomer, Prof. Mukul Kundu of the University of Maryland, said,

> Ashesh was an extremely kind person. He tried to take advantage of everybody's best qualities. He never spoke ill of anybody; he saw good traits in everybody. For this

reason, he was able to help a large number of people. To me he was a great friend....

After my DSc from Sorbonne (Paris) in 1957, I needed a job; so I wrote to APM [A. P. Mitra]. He instantly offered me a senior fellowship of CSIR on a small stipend. In Delhi's Karolbagh, I lived with some friends (2/3) to share the expenses. These friends were all from Kolkata – either from radio physics or pure physics. In the evening, our place became the meeting place – APM and his wife used to come to our place – we drank tea, ate pakora/luchi, played bridge, practically every evening.That was my best time in Delhi. I still fondly remember those wonderful days, and APM was fully involved as a full participant in those Bengali-style social activities.

The first author (SA), who comes from the same alma mater as Mitra and has known him for over three decades, was amazed at his energy while recently working with him, in connection with the 2005 URSI General Assembly, which Mitra was instrumental in organizing on a very grand scale in India's capital, New Delhi (Figure 2). Prof. Govind Swarup, who founded the radio astronomy group at the Tata Institute of Fundamental Research in 1963, said that he had quite close interaction with Mitra over the last 50 years, discussing many scientific problems and particularly the growth of the field of radio science in India. Mitra was always passionately involved, not only in his own research, but also in supporting and nurturing young research workers and new research centers in India. Mitra also played an important role in nurturing a group in the field of radio astronomy at NPL. Later, two members of the NPL group, N. V. G. Sarma and M. N. Joshi, joined as early members of the radio astronomy group in 1964. They played a very significant role in building the Ooty Radio Telescope, conceived by Swarup (SA, too, joined as a graduate student of Swarup, in 1966). Prof. Kundu was with the group from 1965-1968. Later (1984 onwards), the radio astronomy group went on to create the now-famous Giant Meterwave Radio Telescope, in which SA had the good fortune of being deeply involved, along with Profs. Govind Swarup, Vijay Kapahi, and other colleagues.

Similarly, the second author (KKM) joined Mitra in 1959, and had a 48-year-long association with him. He was the first student to get his PhD under Mitra's supervision. Mitra always treated his students like his friends, and quite a few of them remained his family friends throughout his life. KKM feels that the greatest humane quality of Mitra was that he never talked ill of anybody. He trusted and helped everyone.

The third author (SCG) too joined Mitra in 1969 at NPL, and was his close associate for the past 38 years. He says that Mitra had the exceptional quality of being able to remember vast amounts of both scientific and literary works, which he could recall when needed at the right time. This enabled him to take quick and correct decisions, and made him a good scientist as well as a good administrator. SCG says that Mitra was a very tough taskmaster, expected his colleagues to deliver, and could be unrelenting in getting the goals completed. While he could be a bully, banging his fist on the table, he was also kind-hearted and considerate. These qualities endeared him to his colleagues, and earned him a very high degree of respect. Dr. Mitra was also constantly involved in encouraging young scientists and in popularizing science. He played a key role and was the chair for the creation of the Calcutta Science City. He had presented numerous public lectures at places such as Ram Krishna Mission, as well as having published several articles on popular-science topics in publications such as *India Today* and the Bengali weekly *Desh*.

Dr. Mitra also had an artistic side to his personality. He was not only a voracious reader of science, but also widely read Bengali literature, mysteries, and English classics. He used to pen poems, which were published during his young days. He loved music, and always had something playing in the background, and supported his wife and daughters, who are dancers.

Dr. Mitra was married to Sunanda Mitra, his long-term companion and advisor. Their two daughters are Anasua and Patralekha (Dr. Mila Mitra), who are now an architect and astrophysicist, respectively. He encouraged them to excel, as well as pursue their dreams.

Acknowledgments

The authors are grateful to many persons for help in writing this in memoriam. In particular, they wish to thank Dr. B. R. Chakraborty of NPL for his free translation of an article by Mr. Pathik Guha in the Bengali newspaper, *Desh*; to Dr. Mila Mitra for sharing some aspects of her father's childhood; to Dr. Vikram Kumar of NPL for his help and advice; and to Profs. Mukul Kundu and Govind Swarup for their contributions.

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XXIX General Assembly
of the International Union of Radio Science
Union Radio Scientifique Internationale (URSI)

August 07-16, 2008
Hyatt Regency Chicago Hotel on the Riverwalk
151 East Wacker Drive, Chicago, Illinois 60601, USA

Call for Papers

The XXIX General Assembly of the International Union of Radio Science (Union Radio Scientifique Internationale-URSI) will be held at the Hyatt Regency Chicago Hotel in downtown Chicago, Illinois, USA on August 07-16, 2008.

The XXIX General Assembly will have a scientific program organized around the ten Commissions of URSI and consisting of plenary lectures, public lectures, tutorials, invited and contributed papers. In addition, there will be workshops, short courses, special programs for young scientists and graduate students, programs for accompanying persons, and industrial exhibits. More than 1,500 scientists from more than fifty countries are expected to participate in the Assembly. The detailed program, link to electronic submission site, registration form and hotel information will be available on the General Assembly Web site:

www.ece.uic.edu/2008ursiga

Submissions: All contributions must be submitted electronically via the link provided on the General Assembly Web site. The site will open in July 2007 and will close on January 31, 2008.

Submission Deadline: January 31, 2008.

Authors Notification: Authors will be notified of the disposition of their submissions by March 31, 2008. Accepted contributions will be scheduled for either oral or poster presentation.

Contact: For any questions related to the XXIX General Assembly, please contact the Chair of the Local Organizing Committee:

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XXIX General Assembly of URSI, Chicago, Illinois, USA – August 07-16, 2008

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UNION RADIO-SCIENTIFIQUE INTERNATIONALE

INTERNATIONAL UNION OF RADIO SCIENCE

AWARDS FOR YOUNG SCIENTISTS

CONDITIONS

A limited number of awards are available to assist young scientists from both developed and developing countries to attend the General Assembly of URSI.

To qualify for an award the applicant:

1. must be less than 35 years old on September 1 of the year of the URSI General Assembly;
2. should have a paper, of which he or she is the principal author, submitted and accepted for oral or poster presentation at a regular session of the General Assembly.

Applicants should also be interested in promoting contacts between developed and developing countries. Applicants from all over the world are welcome, also from regions that do not (yet) belong to URSI. All successful applicants are expected to participate fully in the scientific activities of the General Assembly. They will receive free registration, and financial support for board and lodging at the General Assembly. A basic accommodation is provided by the assembly organizers permitting the Young Scientists from around the world to collaborate and interact. Young scientists may arrange alternative accommodation, but such arrangements are entirely at their own expense. Limited funds will also be available as a contribution to the travel costs of young scientists from developing countries.

The application needs to be done electronically by going to the same website used for the submission of abstracts/papers. This website is **http://www.nss-mic.org/ursi**. The deadline for paper submission for the URSI GA2008 in Chicago is 31 January 2008.
A web-based form will appear when applicants check "Young Scientist paper" at the time they submit their paper. All Young Scientists must submit their paper(s) and this application together with a CV and a list of publications in PDF format to the GA submission Web site.

Applications will be assessed by the URSI Young Scientist Committee taking account of the national ranking of the application and the technical evaluation of the abstract by the relevant URSI Commission. Awards will be announced on the URSI Web site in April 2008.

For more information about URSI, the General Assembly and the activities of URSI Commissions, please look at the URSI Web site at: http://www.ursi.org. If the information you are looking for is not on this site, please contact:

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APPLICATION FOR AN URSI YOUNG SCIENTIST AWARD

I wish to apply for an award to attend the XXIXth General Assembly of the International Union of Radio Science in Chicago, Illinois, USA, on 9-16 August 2008.

Name: Prof./Dr./Mr./Mrs./Ms. ....

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Academic qualifications, with date(s) obtained: ....

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Title of abstract submitted: ....

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Type of session preferred: ☐ in an oral session ☐ in a poster session

The subject of the paper is relevant to URSI Commission ……….session (leave blank if uncertain).

I hereby certify that I will be less than 35 years old on September 1, 2008.

Date:............................Signed: ....

For applicants from developing countries only:
I estimate the cheapest return fare to the URSI meeting is EURO...

2008 URSI General Assembly

August 7-16, 2008 – Chicago, Illinois, USA

Student paper competition

Eligibility

Any full-time university student from any country, who is the first author and presenter of a paper (oral or poster) at the General Assembly (GA) can be a candidate.

Requirements

A full paper in the format specified by *Radio Science* must be submitted on the GA website by the specified deadline. An application by the student and a certification by the student advisor are needed. Both documents are to be submitted electronically, concurrently with the paper submission.

The ten finalists will receive free lodging at the GA headquarters hotel, Hyatt Regency in downtown Chicago, for the ten-day duration of the GA, based on double-room occupancy. Students must check into the hotel on Thursday, August 7, 2008 and present their contribution orally in a special session on Friday morning, August 8. They will also have to present their contribution in a regular session (oral or poster).

All ten finalists will have free access to a workshop or short course of their choice on either Friday afternoon, August 8 or Saturday, August 9. All ten finalists are required to attend the official banquet where winners will be announced.

Procedure

The ten URSI Commission Chairs will constitute the Panel of Judges. Each Judge will obtain three peer reviews for each student paper submitted through his/her Commission. The competition Chair will forward the top papers from each Commission along with their reviews to all ten Commission Chairs for ranking, to arrive at the names of the ten finalists. Process must be completed by June 1, 2008.

Awards

The ten URSI Commission Chairs (or their Vice Chairs, if the Chairs cannot attend) will be the judges at the competition among the ten student paper finalists on August 8.

The five non-winning finalists will receive a certificate identifying them as a finalist at the assembly banquet. The five winners will receive prizes as follows at the banquet:

1^{st} prize:	a certificate and a check for $1,500.
2^{nd} prize:	a certificate and a check for $1,250.
3^{rd} prize:	a certificate and a check for $1,000.
4^{th} prize	a certificate and a check for $750.
5^{th} prize:	a certificate and a check for $500.

Financial obligation

The $5,000 in prizes, the cost of preparing award certificates, and other expenses related to the student competition will be funded by the US National Committee of URSI as a contribution to the GA.

Contact

The person who will conduct the student paper competition is Prof. Steven Reising at Colorado State University, Fort Collins, USA. He may be contacted by e-mail at: steven.reising@colostate.edu

Reactance-Domain Signal Processing for Adaptive Beam-forming and Direction-of-Arrival Estimation: An Overview

E. Taillefer
J. Cheng

Abstract

This paper gives an overview of reactance-domain (RD) signal processing with electronically steerable parasitic-array-radiator (ESPAR) antennas. ESPAR antennas are single-port-output smart antennas, which can be controlled through reactances loaded on surrounding parasitic elements. Reactance-domain signal processing refers to the ability of the ESPAR antennas to electronically steer beams and nulls in the directions of sources. Employed in hand-held-device receiver applications, the single-output property of the ESPAR antennas offers lower power consumption and more effective cost than conventional multi-output array antennas. However, due to the single-port limitation, the implementation of the signal-processing algorithm part of the applications becomes a hot topic. This overview presents some fundamental algorithms that allow designing adaptive-beamforming and direction-finding applications with ESPAR antennas. This overview gives an appreciation of the signal-processing issues met in the use of ESPAR antennas in smart-antenna applications.

1. Introduction

Adaptive arrays have gained a lot of interest in commercial wireless applications, because they allow improving the performance of radio systems by increasing the channel capacity and spectrum efficiency. Adaptive arrays can provide great coverage area, allow using communication scenarios such as a decentralized ad hoc network, etc. For example, in an ad hoc network with multiple nodes they can focus the radiated electromagnetic energy on one transmitter node while rejecting unwanted interfering nodes, or perform node-position location by estimating the node direction-of-arrival (DoA) angles. A common implementation of an adaptive array is a digital beamformer (DBF), which consists of several antenna elements with one receiver per element. For each antenna element, the receiver will consist of down-converting the antenna analog signal into a baseband signal, following by analog-to-digital conversion. The adaptation or DoA estimation is then carried out in a digital-signal-processing (DSP) chip by applying specific algorithms to the digitalized signal data. However, most of the hand-held devices or mobile terminals utilizing wireless technology require small electronic part sizes and low power consumption for effective portability and battery life. Adaptive arrays implemented with a digital beamformer do not satisfy these requirements, since they exhibit a complex receiver structure, where power consumption and effective size grow upwards with the number of antenna elements [1, 2].

As a kind of adaptive array, switched parasitic antennas were proposed for cellular communications [3-7]. Compared to a digital beamformer, which needs as many active radio receivers as antenna elements, a switched parasitic-array antenna needs only one single active radio receiver. Therefore, the use of a switched parasitic antenna is an interesting alternative for adaptive-array implementation that can provide compact effective size, low cost, and low power consumption for the receiver. The switched parasitic antenna forms beams by using parasitic antenna elements that serve as reflectors when shorted to ground. Thus, a number of directional patterns can be achieved by switching the short circuits of the passive elements using PIN diodes [7]. Switched parasitic antennas are known to allow improving communication capacity in wireless communication systems [8]; to perform high-resolution DoA estimation [9], such as for personal locating services; and to provide antenna diversity [3, 4] for adaptive communication systems.

The electronically steerable parasitic-array-radiator (ESPAR) antenna, a kind of reactively controlled antenna [10], was first proposed for low-cost user-terminal

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This is one of the invited *Reviews of Radio Science* from Commission C.

applications [11]. Compared with simple switched parasitic antennas, the ESPAR antenna exhibits greater ability to control steering by means of its electronically controllable reactances, and a more complex system for controlling the reactances [12]. Indeed, the parasitic element is connected to the ground by means of a reactance made with a reverse-bias varactor diode, which can be controlled through the loaded voltage. Thus, the parasitic element can variably act as a reflector or a radiator, as a function of the reactance value [13]. The continuous variability of the loaded reactance of the ESPAR antenna makes it more flexible than switched parasitic antennas, because the number of possible directional patterns becomes greater [12]. For example, such a feature could be successfully employed in adaptive beamforming, which involves forming beams and nulls. The radiation pattern of an ESPAR antenna with a beam-pointing direction in the desired signal direction and nulls in the interference directions is obtained by optimizing the loaded reactances [14].

Because the ESPAR antennas exhibit only one output port, performing beamforming with such an antenna cannot consist of simply applying optimum beamforming algorithms available for conventional digital-beamformer antennas. In the case of an ESPAR antenna, beamforming consists of searching for the optimum reactance values. During the optimum search, the reactance values are electronically updated before receiving the block of symbols. Then, a specific criterion is used to decide whether or not the reactance values are optimum. If the reactance values are not optimum, the update-receive-and-decide process has to be iterated until the optimum reactance values are reached. However, in the case of a digital beamformer antenna, only one block of symbols is required. Because all the element output information is independently and simultaneously observable, and because digital weights are used instead of reactances, the beamforming can be entirely performed in the digital processor.

Another issue is that the digital-beamformer output can be achieved by linearly combining all of the element outputs, whereas the ESPAR antenna's output is an analog, highly nonlinear mixture of the parasitic elements with the active element. In the case of linear combining, optimum-combining factors (weights) can be directly derived by using Weiner-Hopf filter theory [15], for example. However, in the case of nonlinear combining, other optimization methods have to be considered or designed. Many approaches have been proposed for adaptive beamforming of an ESPAR antenna [13]. For most of these methods, the problem was to find the best suitable reactance values that maximize the output signal-to-interference-and-noise ratio (SINR). Moreover, beamforming was considered in the cases of both trained beamforming, where a known reference signal is available, and blind beamforming, where only the antenna's output is observable.

Regarding DoA-estimation applications with an ESPAR antenna, an earlier method was proposed to develop a hand-held microwave DoA finder for locating transmitters [16] after an avalanche [17], for example. This method was based on a simple algorithm that switched twelve directional-beam patterns by means of reactances, and then chose as the DoA estimate the beam-pointing angle of the pattern that provided the highest antenna output-amplitude gain. Therefore, this method could only provide estimation for one impinging signal DoA, with a coarse precision of 30° [16, 17]. An alternative that used antenna output-amplitude gain with pre-measured directional patterns was proposed for high-precision DoA estimation of one impinging signal [18]. The method was called the Power Pattern Cross Correlation (PPCC). As its name suggests, it is based on the correlation between the pre-measured power radiation patterns and the power outputs of the antenna.

To use more-enhanced DoA-estimation algorithms, featuring high resolution and precision, which are available for a conventional digital beamformer, a correlation matrix of the output of the antenna elements is required. In the case of the ESPAR antenna, since the beamforming is performed in the analog domain, only one output port is observable. However, by using a vector composed of this output-port's complex gain, measured sequentially for different directional patterns, a technique called the *reactance-domain* (RD) technique can be adopted to create a correlation matrix for the ESPAR antenna. Consequently, based on this technique, the multiple-signal classification (MUSIC) [19] subspace DoA estimator was proposed [20] and experimentally verified [21] with a seven-element ESPAR antenna.

Aiming at further reducing the computational cost of DoA estimation, the reactance-domain estimation of signal parameters via rotational-invariance techniques (ESPRIT) algorithm [22] was also proposed and experimentally verified [23, 24]. By transmitting the same information as many times as the number of directional patterns used, the reactance-domain technique could be implemented [21]. Although such a data-transmission scheme decreases the transmission rate, it is still sufficient in applications such as terminal-position location, a hand-held DoA finder, or when DoA estimation is needed from time to time for such tasks as forming a node-position location table in an ad-hoc network where the nodes do not frequently relocate. Another interesting possibility for obtaining the reactance-domain output information without decreasing the transmission rate is to sample the received signal with different radiation patterns. This technique of over-sampling is common in many communication systems, but here it needs to be considered as spatial-temporal over-sampling, since beam-pattern switching implies spatial diversity.

In this paper, we give an overview of reactance-domain signal processing with an ESPAR antenna. First, we present the single-port ESPAR antenna. Second, trained and blind adaptive-beamforming approaches with an ESPAR antenna are presented. Third, DoA estimation methods, allowing high precision and resolution estimation of an incoming source, are explained.

2. ESPAR Antenna Signal Model

The ESPAR antenna is a reactively controlled array antenna that consists of an active monopole element, located at the center of a ground plane and connected to the receiver. The active monopole element is surrounded by M parasitic controllable monopole elements, equally spaced around a circle. Each element is a quarter-wavelength long, and the inter-element separation is d. Each parasitic element is loaded by an adjustable reactance [11].

Figure 1 shows an $(M+1)$-ESPAR antenna with $M=6$, an inter-element spacing of d, and a working wavelength of λ. Small spacing (i.e., $d<\lambda/2$) between elements involves mutual coupling between the elements, and thus allows antenna beamforming; a small d also allows reduction of the total antenna's size. The model formulation of the beamformer *equivalent radio-frequency (RF) weight vector* is given by [13, 25]

$$\mathbf{w} = 2z_s\left(\mathbf{Z}+\mathbf{X}\right)^{-1}\mathbf{u}_0, \qquad (1)$$

where z_s is the receiver's input impedance, $\mathbf{Z}$ is an $(M+1)\times(M+1)$-sized mutual-impedance matrix, and $\mathbf{u}_0$ is an $(M+1)$-dimensional vector, taken as $J(\mathbf{x})$. The superscript $(\cdot)^{\mathrm{T}}$ is the transpose operator. The diagonal matrix $\mathbf{X}=\mathrm{diag}\left\{z_s, j\mathbf{x}^{\mathrm{T}}\right\}$ is called the reactance matrix, with $\mathbf{x}\equiv\left[x_1,\ldots,x_M\right]^{\mathrm{T}}$ as the vector containing the reactance values applied to the parasitic elements.

The response of the antenna to a unit signal from direction θ_q is modeled by the complex $(M+1)$-dimensional steering vector ,

$$\mathbf{x}^{(n+1)} = \mathbf{x}^{(n)} + \mu\nabla J, \qquad (2)$$

where

$$\psi_m\left(\theta_q\right) = \frac{2\pi d}{\lambda}\cos\left(\theta_q - 2\pi\frac{m-1}{M}\right) \qquad (3)$$

and $m=1,\ldots,M$.

The Q complex signal components at time t, $s_q(t)$, $q=1,\ldots,Q$, are collected in the vector $\mathbf{s}(t)=\left[s_1(t),s_2(t),\ldots,s_Q(t)\right]^{\mathrm{T}}$. The ESPAR antenna output $y(t)$ is then expressed as

$$y(t) = \mathbf{w}^{\mathrm{T}}\left[\mathbf{a}(\theta_1),\ldots,\mathbf{a}(\theta_Q)\right]\mathbf{s}(t)+n(t) \qquad (4)$$

$$= \mathbf{w}^{\mathrm{T}}\mathbf{A}\mathbf{s}(t)+n(t),$$

where $n(t)$ is a complex white Gaussian noise component. Changing the value of the reactances allows us to control $\mathbf{w}$, and thus the antenna's radiation pattern.

3. Adaptive Beamforming of the ESPAR Antenna Based on Reactance-Domain Search

As a preliminary step, a performance analysis of the ESPAR antenna's beamforming functionality as regards the port-impedance deviation and frequency bandwidth was conducted [27]. The beam- and the null-forming

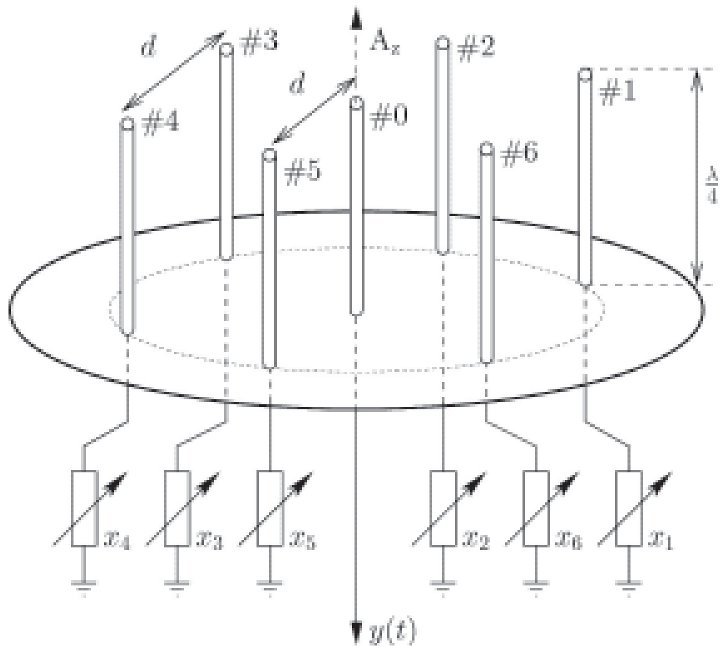

Figure 1. A diagram of the seven-element ESPAR antenna.

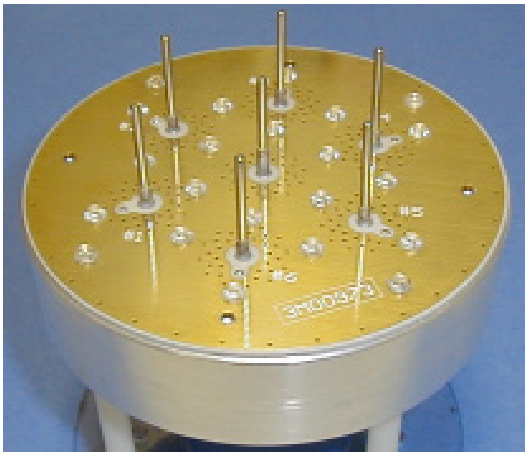

Figure 2. A photo of a fabricated seven-element ESPAR antenna operating in the 2.4 GHz band [47].

performance was analyzed with views of independently forming a beam or a null, simultaneously forming a beam and a single null, and simultaneously forming a beam and multiple nulls. The results of this analysis could motivate undertaking research on optimum adaptive beamforming with an ESPAR antenna.

The reactance-domain refers to the reactance space, which embodies all of the possible M-size reactance-vector values. In this section, an overview is given of beamforming methods that consist of searching for an optimum set of reactances from among the reactance-domain values. The optimization aims to find the best suitable reactance values that maximize the SINR at the antenna's output. For convenience, these methods are separated into trained and blind beamforming methods. Trained and blind beamforming methods differ with regard to the availability (or lack thereof) of a reference signal, $r(t)$, (or, of a training sequence) for which the sequence information is known or fed back to the receiver device. The reference signal is one of the signal's coming into the ESPAR antenna. It follows that $r(t)$ is equal to $s_d(t)$, with constant d such that $1 \le d \le Q$.

Most of the trained beamforming approaches are based on the steepest gradient. Compared with general optimization methods, such as the genetic algorithm (GA) [28], particle-swarm optimization (PSO) [29], or the Nelder-Mead algorithm (Simplex) [30], the steepest gradient converges drastically faster. However, unlike the GA, PSO, or Simplex algorithms, which are optimal algorithms, the steepest gradient can converge to a local optimum, and therefore is a sub-optimal algorithm.

The optimization by the steepest gradient of the antenna reactances is an iterative process, which consists of the following recursive relation:

$$\mathbf{x}^{(n+1)} = \mathbf{x}^{(n)} + \mu \nabla J, \tag{5}$$

where $\mathbf{x}^{(n)}$ denotes the reactance vector at the nth iteration, and $\mu > 0$ is a real-valued constant corresponding to the iteration step size. The vector ∇J is the gradient vector of the real-valued cost function $J(\mathbf{x})$ (also called the criterion). The mth component of the gradient vector, $[\nabla J]_m$, is usually obtained by calculating the forward approximation of the first derivative of $J(\mathbf{x})$ along its mth component, as

$$[\nabla J]_m = \frac{\partial J(\mathbf{x})}{\partial x_m} \approx \frac{J\left[\mathbf{x} + \mathbf{f}^{(m)} \Delta x_m\right] - J(\mathbf{x})}{\Delta x_m}, \tag{6}$$

where $\mathbf{f}^{(m)}$ is an $M \times 1$ single-entry vector having 1 in its mth entry and zero elsewhere. Δx_m is the perturbation size.

Prior to practical adaptive beamforming involving several signals, the ESPAR antenna's beamforming capability of steering one beam or one null in the direction of a desired signal was experimentally studied [31]. Examples of single-source beam- and null-steering are shown in Figure 3.

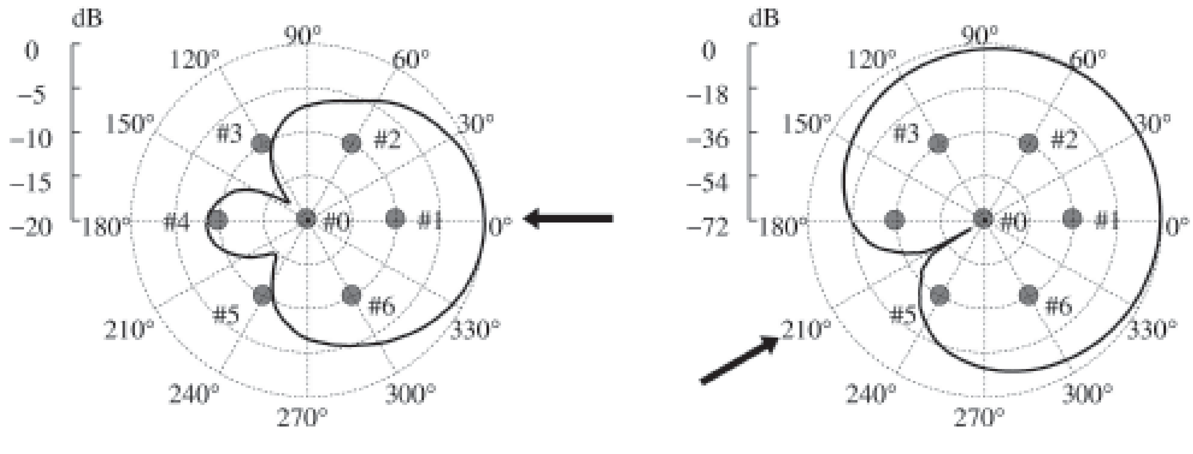

Figure 3. Examples of measured null- and beam-forming patterns after adaptive forming. The desired signal is towards 0° and 210° for the upper and lower patterns, respectively

3.1 Trained Beamforming

Adaptive beamforming of an ESPAR antenna based on the steepest-gradient algorithm was first proposed in [32]. The cost function (criterion) was computed as the cross-correlation coefficient (CCC), ρ_n, between the antenna's output and a training sequence. For the nth iterative block, this cost function is expressed as

$$J^{(n)} = \rho_n = \frac{\left|\mathbf{y}^{\mathrm{H}}(n)\mathbf{r}(n)\right|}{\sqrt{\mathbf{y}^{\mathrm{H}}(n)\mathbf{y}(n)}\sqrt{\mathbf{r}^{\mathrm{H}}(n)\mathbf{r}(n)}}, \qquad (7)$$

where the training-sequence, $\mathbf{r}(n)$, and the antenna-output, $\mathbf{y}(n)$, vectors are K-dimensional vectors that are discrete time samples of the reference, $r(t)$, and the antenna-output, $y(t)$, signals. These vectors represent the nth consecutively measured block of K samples.

The cross-correlation coefficient was chosen as the criterion because it is closely related to the output $\mathrm{SINR}^{(n)}$, which can be approximated by

$$\mathrm{SINR}^{(n)} = \frac{|\rho_\mathrm{n}|^2}{1-|\rho_\mathrm{n}|^2}. \qquad (8)$$

Moreover, since the estimated $\mathrm{SINR}^{(n)}$ converges toward the true output SINR with the number of samples per block, K, the cross-correlation coefficient is an efficient criterion for adaptive control. One can notice that since the estimation of the gradient vector, ∇J, needs the antenna reactances to be changed $M+1$ times, one computation of $J^{(n)}$ requires $(M+1)\times K$ output samples. It follows that when the beamforming needs to be performed frequently, this required number of samples becomes a critical issue.

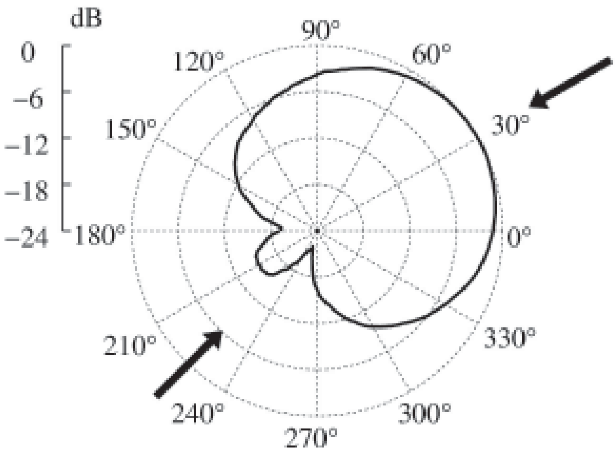

Figure 4. The normalized measured beam pattern of a trained adaptive beamforming experiment. The cost function employed was Equation (7). The DoAs of the desired signal (and also, of the reference signal) and the interference signal were 30° and 225°, respectively.

As an improvement of the beamforming convergence performance, an adaptive control algorithm for an ESPAR antenna based on stochastic approximation theory has been proposed [33, 34]. In this approach, the adaptive beamforming of the ESPAR antenna was considered to be a nonlinear spatial filter that had variable parameters. The beamforming was thus performed by using the normalized mean square error as an objective function and its minimization via a stochastic-descent technique, in accordance with stochastic approximation theory. In this approach, the cost function $J_{\mathrm{NMSE}}^{(n)}$ was taken as the normalized mean square error (NMSE) of the output, $y(t)$, relative to the reference signal, $r(t)$, where

$$J_{\mathrm{NMSE}}^{(n)} = 1 + |\rho_n|^2. \qquad (9)$$

Moreover, a "search then converge" learning rate schedule was adopted, where the iteration step and perturbation sizes converged together with the reactances as

$$\mu(n) = \frac{\mu}{1+\frac{n}{\tau}}, \qquad (10)$$

$$\Delta x_m(n) = \frac{\Delta x_m}{(n+1)^\gamma},$$

where μ, τ, and $\gamma > 0$ are user-selected constants [33]. To obtain a more-accurate gradient vector, central approximation was preferred instead of forward approximation for the calculation of $[\nabla J]_m$.

To further improve the beamforming-convergence performance and to reduce the number of samples necessary to compute the gradient vector, fast beamforming of the ESPAR antenna, based on a simultaneous perturbation stochastic approach, was proposed [14]. In this approach, one computation of the gradient vector requires $2K$ samples, and therefore only K samples for a consecutive gradient-vector computation. For each gradient-vector computation, the perturbation sizes Δx_m, $m = 1,2,\ldots,M$ were chosen to be Bernoulli distributed. Their values were either -1 or 1 with a probability of $1/2$. The cost function was the same as Equation (9), and a "search then converge" approach, similar to as Equation (10), was also adopted.

Figure 4 shows an experimental example result of an ESPAR antenna radiation pattern after beamforming adaptation.

3.2 Blind Beamforming

A high-order maximum-moment criterion (MMC) has been proposed for blind aerial beamforming [35]. This criterion was heuristically defined for $m$ary PSK modulated signals by

$$J_m(y) = \frac{\left|\mathrm{E}\left[y(t_s)\right]\right|^m}{\mathrm{E}\left[\left|y(t_s)^m\right|^2\right]}, \quad (11)$$

$$\mathrm{E}\left[y(t_s)\right] = \frac{1}{K}\sum_{s=1}^{K} y(t_s),$$

where $y(t_s)$ is the antenna's output signal observed at time t_s, and $\mathrm{E}[\cdot]$ is the expectation operator. It was also shown that this criterion converges in a time of sampling K when the antenna output is considered to be the sum of an uncorrelated signal, $s(t_s)$, and noise, $n(t_s)$, $y(t_s) = s(t_s) + n(t_s)$,

$$\lim_{K\to\infty} J_m(s+n) = \frac{1}{\sum_{k=0}^{m} \frac{m!^2}{(m-n)!^2\, k!}\left(\frac{\sigma_S^2}{\sigma_N^2}\right)^{-k}}, \quad (12)$$

where $\sigma_S^2 = \mathrm{E}\left[\left|s(t_s)\right|^2\right]$ and $\sigma_N^2 = \mathrm{E}\left[\left|n(t_s)\right|^2\right]$. The equation above shows that the criterion in Equation (11) is a monotonic function of the SNR, σ_S^2/σ_N^2, which is an indispensable functionality to be used in blind beamforming. As a further improvement, optimum adaptive beamforming based on the combining of several high-order blind criteria has also been proposed [36]. Adaptive beamforming employing the maximum-moment criterion with the steepest-gradient algorithm was verified through experiment in an anechoic chamber [37]. An example beam pattern of experimental blind beamforming with the maximum-moment criterion is given in Figure 5.

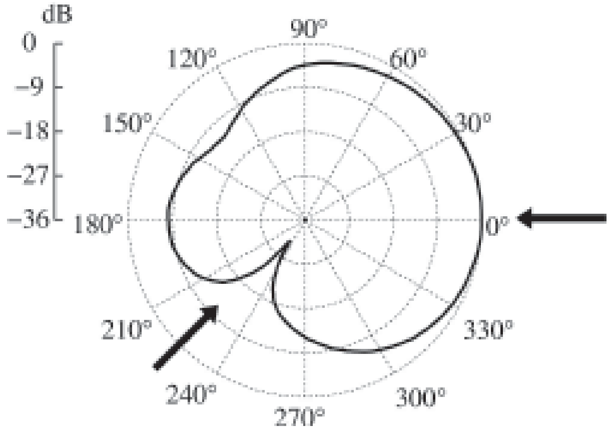

Figure 5. An example of a normalized measured beam pattern obtained after blind beamforming adaptation. The desired (and also, reference signal) and interference signals came from 0° and 225°, respectively.

4. DoA Estimation with an ESPAR Antenna Using Reactance-Domain Processing

Due to its single-port design and the presence of tunable reactances, the ESPAR antenna seems dedicated only to applications requiring adaptive beamforming. However, the ability to control $\mathbf{w}$ through the reactances fed still allows DoA estimation by exploiting reactance diversity to recreate output diversity. The output diversity can be directly exploited to perform DoA estimation, or to construct a (time-) reactance-domain correlation matrix. The reactance-domain matrix is thus used to apply high-resolution DoA estimation methods.

The motivation of DoA estimation with an ESPAR antenna is the availability of many methods for direction finding using conventional digital-beamformer antennas [38, 39]. Moreover, since wireless-communication application systems may require high-performance DoA estimation capabilities for the receiver, efforts for developing a high-performance DoA finder for an ESPAR antenna had to be made, despite of the difficult hardware limitation due to the single-output structure. In the following, an overview is given of three DoA estimation methods based on the reactance domain. The first method uses a cross-correlation-coefficient approach for performing high-precision DoA estimation, whereas the other two methods employ a correlation-matrix approach that allows applying the well-known MUSIC and ESPRIT algorithms to the ESPAR antenna [19, 22]. The cross-correlation approach has the advantage of a low computational complexity and robustness against impinging signal-phase fluctuation. However, this method has limited multiple-signal resolution capability. The correlation-matrix approach allows applying most of the high-resolution DoA-estimation algorithms available for conventional adaptive-array antennas to an ESPAR antenna.

In the following methods, the number of incoming signals, Q, is assumed to be known or estimated, as a preliminary step. The number of signals, Q, can be estimated by using the AIC or MDL criteria [40].

4.1 Power-Pattern Cross-Correlation Algorithm

The power-pattern cross-correlation (PPCC) method is based on the computation of the correlation between N *pre-measured* power radiation patterns and N power outputs of the antenna, measured at each estimation time. A suitable selection of pattern shapes, which was derived directly from the principle, shows that with four single-peaked directive patterns, the method can efficiently achieve DoA estimation of an unknown signal. Moreover, since only the amplitude of the power output is used, the method exhibits robustness against arrival signal data-phase fluctuation. Another advantage is the low computational cost, allowing the power-pattern cross-correlation algorithm to be employed in many applications requiring direction finding. However, N pattern data need to be measured and saved in

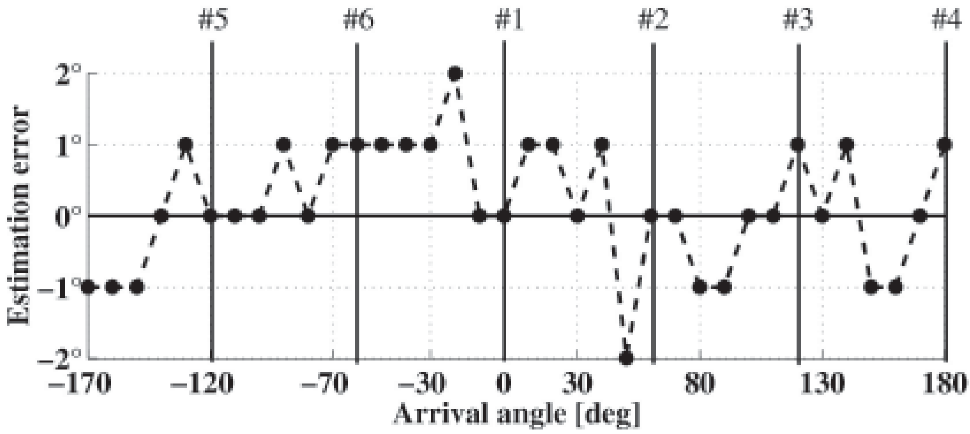

Figure 6. The results of a DoA estimation experiment using PPPC with six directive beam patterns.

order to apply the method practically, which can be costly in terms of measurement equipment.

We consider one signal impinging on the antenna at the unknown DoA, θ_{sig}. The power-pattern cross-correlation principle is explained as follows: for a given set of N antenna power patterns, corresponding to a set of N reactance vectors $\left\{\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \ldots, \mathbf{x}^{(N)}\right\}$, the correlation coefficient between the output power of the antenna for each corresponding reactance vector $\left\{Y\left[\mathbf{x}^{(1)}\right], Y\left[\mathbf{x}^{(2)}\right], \ldots, Y\left[\mathbf{x}^{(N)}\right]\right\}$ and the antenna power-pattern set is the highest at the signal DoA angle. Here, according to Equations (1) and (4), the antenna's output power can be modeled by

$$Y\left[\mathbf{x}^{(k)}\right]$$

$$= E\left[\left|s(t)\right|^2\right]\mathbf{w}_k^{\mathrm{T}}\mathbf{a}\left(\theta_{sig}\right)\mathbf{a}^{\mathrm{H}}\left(\theta_{sig}\right)\mathbf{w}_k^{*} + E\left[\left|n(t)\right|^2\right], \quad (13)$$

where

$$\mathbf{w}_k = 2z_s\left[\mathbf{Z} + \mathrm{diag}\left\{z_s, j\left[\mathbf{x}^{(k)}\right]^{\mathrm{T}}\right\}\right]^{-1}\mathbf{u}_0. \quad (14)$$

The superscript $(\bullet)^{\mathrm{H}}$ is the conjugate transpose operator. The part $\mathbf{w}_k^{\mathrm{T}}\mathbf{a}\left(\theta_{sig}\right)\mathbf{a}^{\mathrm{H}}\left(\theta_{sig}\right)\mathbf{w}_k^{*}$ in Equation (13) represents the power of the antenna's radiation pattern toward θ_{sig} for antenna parasitic elements loaded with reactance values $\mathbf{x}^{(k)} = \left[x_1^{(k)}, x_2^{(k)}, \ldots, x_6^{(k)}\right]$. The power-pattern cross-correlation method can be summarized in the follows four steps:

First, choose N different sets of reactances, $\left\{\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \ldots, \mathbf{x}^{(N)}\right\}$. Then, measure the antenna power pattern for each set. The antenna power-pattern value at angle θ corresponding to the ith set is denoted $P\left[\mathbf{x}^{(i)}, \theta\right]$. Note that the first step is performed only one time.

Second, for each set of reactances, $\left\{\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \ldots, \mathbf{x}^{(N)}\right\}$, measure the corresponding antenna output power, $\left\{Y\left[\mathbf{x}^{(1)}\right], Y\left[\mathbf{x}^{(2)}\right], \ldots, Y\left[\mathbf{x}^{(N)}\right]\right\}$.

Third, for θ from 0° to 360º, compute the correlation coefficient, $\Gamma(\theta)$, defined as

$$\Gamma(\theta) = \frac{\sum_{n=1}^{N} P\left[\mathbf{x}^{(n)}, \theta\right] Y\left[\mathbf{x}^{(n)}\right]}{\sqrt{\sum_{n=1}^{N} P\left[\mathbf{x}^{(n)}, \theta\right]^2 \sum_{n=1}^{N} Y\left[\mathbf{x}^{(n)}\right]^2}}. \quad (15)$$

Fourth, the DoA estimate, $\hat{\theta}_{\mathrm{sig}}$, is taken to be the maximum value of Equation (15).

To speed up the estimation calculation, a *pre*-decision on the search range of the maximum value of Γ can be performed. Indeed, employing an adaptive-beamforming algorithm [13, 33], it is possible to provide a set of reactances corresponding to a directive beam pattern for each of the Q regular directions of the azimuth plane (e.g., for $Q = 6$, form beams at 0º, 60º,..., and 300°). Then, within this Q *pre*-calculated reactance set, we look for the angle $\theta_C \in \left[0^\circ, 60^\circ, \ldots, 300^\circ\right]$ providing the highest gain value. The angles before θ_C and the angle after θ_C become the limits of the search range of the maximum of the function Γ. Experimental results for the DoA-estimation precision achieved with power-pattern cross-correlation over the full azimuth are given in Figure 6. The directive beam patterns employed were those shown in Figure 3.

4.2. Reactance-Domain Correlation and Signal-Subspace Matrices

In a conventional array antenna, the correlation matrix is obtained from the measurement of the signals at each element of the antenna. For a single-port output device such as the ESPAR antenna, the spatial diversity of a conventional array antenna is recreated by periodically changing the reactance values while measuring the antenna's output.

First, the reactance-domain complex output vector, $\mathbf{y}(t) = \left[y(t_1), y(t_2), \ldots, y(t_N) \right]^{\mathrm{T}}$, is formed by choosing N different sets of reactance values $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N$. Then, for each reactance set $\mathbf{x}_m$, the output, $y(t_m)$, of the antenna ($n = 1, \ldots, N$) is obtained:

$$\mathbf{y} = \begin{bmatrix} \mathbf{w}_1^{\mathrm{T}} \mathbf{As}(t_1) \\ \mathbf{w}_2^{\mathrm{T}} \mathbf{As}(t_2) \\ \vdots \\ \mathbf{w}_N^{\mathrm{T}} \mathbf{As}(t_N) \end{bmatrix} + \begin{bmatrix} n(t_1) \\ n(t_2) \\ \vdots \\ n(t_N) \end{bmatrix}. \quad (16)$$

It is assumed that the same signals are repeated N times, i.e., for $n = 1, \ldots, N$, $\mathbf{s}(t_m) = \mathbf{s}$. Thus, $\mathbf{y}$ can be rewritten as

$$\mathbf{y} = \begin{bmatrix} \mathbf{w}_1^{\mathrm{T}} \\ \mathbf{w}_2^{\mathrm{T}} \\ \vdots \\ \mathbf{w}_N^{\mathrm{T}} \end{bmatrix} \mathbf{As} + \begin{bmatrix} n(t_1) \\ n(t_2) \\ \vdots \\ n(t_N) \end{bmatrix} = \mathbf{W}^{\mathrm{T}} \mathbf{As} + \mathbf{n}, \quad (17)$$

where $\mathbf{W}^{\mathrm{T}}$ is called the RF equivalent weight matrix or the reactance-domain weight matrix.

Then, assuming that the noise for different times and the incoming signals are not correlated with each other, the reactance-domain correlation matrix, $\mathbf{R}_{yy}$, thus has the following structure:

$$\mathbf{R}_{yy} = \mathrm{E}\left[\mathbf{y}\mathbf{y}^{\mathrm{H}} \right] = \mathbf{W}^{\mathrm{T}} \mathbf{A} \mathbf{P}_s \mathbf{A}^{\mathrm{H}} \mathbf{W}^* + \sigma_n^2 \mathbf{I}_N, \quad (18)$$

where $\mathbf{P}_s = \mathrm{E}\left[\mathbf{s}\mathbf{s}^{\mathrm{H}} \right]$ is the signals' correlation matrix, σ_n^2 is the noise variance, and $\mathbf{I}_N$ is an $N \times N$ sized identity matrix.

In practice, instead of Equation (18), a sample reactance-domain correlation matrix, $\hat{\mathbf{R}}_{yy}$, based on $N \times K$ observations (snapshots) of the antenna's output, $y_n[k]$, ($n = 1, \ldots, N$), is computed as

$$\hat{\mathbf{R}}_{yy} = \frac{1}{K} \sum_{k=1}^{K} \left[\begin{Bmatrix} y_1[k] \\ y_2[k] \\ \vdots \\ y_N[k] \end{Bmatrix} \left\{ y_1^*[k] \quad y_2^*[k] \quad \cdots \quad y_1^*[k] \right\} \right]. \quad (19)$$

The eigen-decomposition of the reactance-domain correlation matrix estimate, $\hat{\mathbf{R}}_{yy}$, has the following form:

$$\hat{\mathbf{R}}_{yy} = \hat{\mathbf{E}}_s \mathbf{\Lambda}_s \hat{\mathbf{E}}_s^{\mathrm{H}} + \hat{\mathbf{E}}_n \mathbf{\Lambda}_n \hat{\mathbf{E}}_n^{\mathrm{H}}, \quad (20)$$

where

$$\hat{\mathbf{E}}_s = \left[\mathbf{e}_1, \ldots, \mathbf{e}_Q \right],$$

$$\hat{\mathbf{E}}_n = \left[\mathbf{e}_{Q+1}, \ldots, \mathbf{e}_N \right],$$

$$\lambda_1 \geq \cdots \geq \lambda_N,$$

$$\mathbf{\Lambda}_s = \mathrm{diag}\left\{ \lambda_1, \ldots, \lambda_Q \right\},$$

and

$$\mathbf{\Lambda}_n = \mathrm{diag}\left\{ \lambda_{Q+1}, \ldots, \lambda_N \right\}.$$

In the case of conventional array antennas, the space spanned by the columns of $\mathbf{E}_s$ is often referred to as the signal subspace, and $\mathbf{E}_n$ is called the noise subspace. However, in the case of reactance-domain signal processing, the signal-subspace correlation is performed by means of the reactance-domain weight matrix, $\mathbf{W}^{\mathrm{T}}$, as can be seen in Equation (18).

It should here be noted that the reactance-domain technique could be performed with more or less than $M+1$ reactance sets, as in [20, 21], where it was performed with M reactance sets. However, in the case of the ESPRIT algorithm, which requires that a translational invariance be designed into the array-element geometry, the reactance-domain correlation matrix must have the same dimension as the number of array elements.

4.3 RD-MUSIC Algorithm

According to the reactance-domain technique, the antenna-steering vector, $\mathbf{a}(\theta)$, will result in a modified steering vector, $\mathbf{W}^{\mathrm{T}} \mathbf{a}(\theta)$ [20]. The RD-MUSIC algorithm thus consists of computing the following modified MUSIC DoA spectrum:

$$P_{MUSIC}^{RD}(\theta) = \frac{1}{\mathbf{W}^{\mathrm{T}} \mathbf{a}(\theta) \hat{\mathbf{E}}_n \hat{\mathbf{E}}_n^{\mathrm{H}} \mathbf{a}^{\mathrm{H}}(\theta) \mathbf{W}^*} \quad (21)$$

for $0° \leq \theta \leq 360°$.

The DoA estimates $\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_Q$ correspond to the values of θ at the maxima of $P_{MUSIC}^{RD}(\theta)$.

4.4 RD-ESPRIT Algorithm

The ESPRIT algorithm fundamentally requires that the signal-subspace matrix be computed from the elements' correlation matrix, and that translational invariance be designed into the array-element geometry. Consequently, the reactance-domain subspace matrix, $\hat{\mathbf{E}}_s$, needs to be

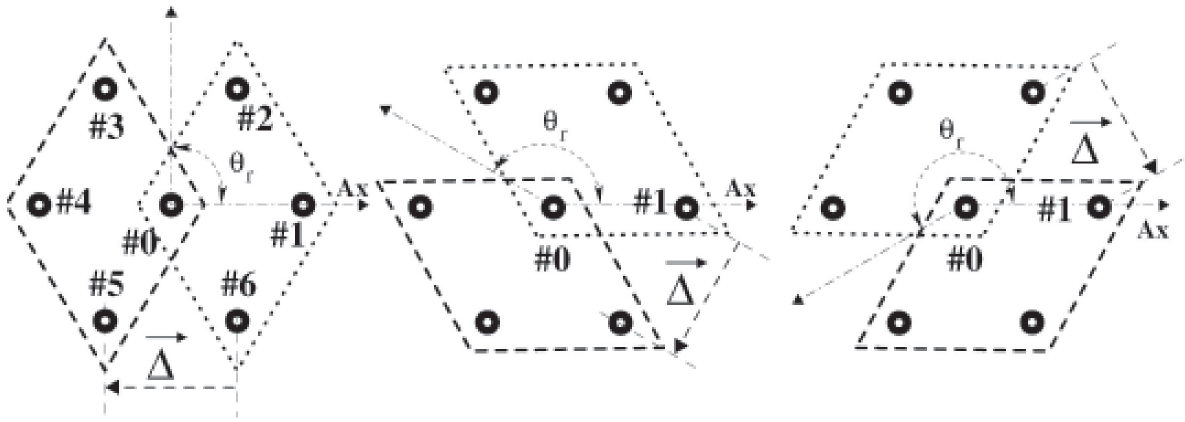

Figure 7. Translational invariance configurations designed into the seven-element ESPAR antenna. Subarrays 1 and 2 were drawn with dotted and dashed lines, respectively.

processed before employing any subspace-based method that requires the element signal subspace. The element signal subspace can thus be obtained as follows:

$$\tilde{\mathbf{E}}_s = \left(\mathbf{W}^{\mathrm{T}}\right)^{-1} \hat{\mathbf{E}}_s . \quad (22)$$

Thanks to the hexagonal shape of the seven-element ESPAR antenna, three configurations showing translational invariance could be heuristically found. The configurations are shown in Figure 7, where $\vec{\Delta}$ characterizes the translational invariance between the two subarrays.

The spatial delay between subarrays 1 and 2, due to displacement invariance $\vec{\Delta}$, leads to a phase delay, φ_q, on the incoming signal, $s_q(t)$. This phase delay is expressed as

$$\varphi_q = \exp\left[j\frac{2\pi\Delta}{\lambda}\sin\left(\theta_q - \theta_r\right)\right], \quad q = 1,2,\ldots,Q , \quad (23)$$

where $\Delta = \left\|\vec{\Delta}\right\| = d$, and θ_r is a constant angle value that depends on the translational invariance axis, with $\|\bullet\|$ as the norm operator. The ESPRIT algorithm aims at estimating the phase delays, φ_q.

Therefore, the total-least-square (TLS) ESPRIT algorithm applied to one of the three configurations can be summarized as follows [22]:

1. Decompose $\tilde{\mathbf{E}}_s$ into $\tilde{\mathbf{E}}_{s1}$ and $\tilde{\mathbf{E}}_{s2}$ by using the selection matrices $\mathbf{J}_1$ and $\mathbf{J}_2$, which pick up the elements of subarrays 1 and 2, respectively:

$$\tilde{\mathbf{E}}_s \equiv \begin{bmatrix} \tilde{\mathbf{E}}_{s1} \\ \tilde{\mathbf{E}}_{s2} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_1\tilde{\mathbf{E}}_s \\ \mathbf{J}_2\tilde{\mathbf{E}}_s \end{bmatrix}. \quad (24)$$

2. Eigen-decompose (with eigenvalues in decreasing order)

$$\begin{bmatrix} \tilde{\mathbf{E}}_{s1}^{\mathrm{H}} \\ \tilde{\mathbf{E}}_{s2}^{\mathrm{H}} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{E}}_{s1} & \tilde{\mathbf{E}}_{s2} \end{bmatrix} \quad (25)$$

to obtain its eigenvectors, and then form the matrix, $\mathbf{E}$, containing these eigenvectors.

3. Decompose $\mathbf{E}$ to form the $Q \times Q$ sized matrices $\mathbf{E}_{12}$ and $\mathbf{E}_{22}$, as follows:

$$\mathbf{E} \equiv \begin{bmatrix} \mathbf{E}_{11} & \mathbf{E}_{12} \\ \mathbf{E}_{21} & \mathbf{E}_{22} \end{bmatrix}. \quad (26)$$

4. Calculate the eigenvalues, $\hat{\phi}_q$, (also called phase factor estimates) of $\mathbf{\Psi} = -\mathbf{E}_{12}\mathbf{E}_{22}^{-1}$, $q = 1,\ldots,Q$.

5. Calculate the DoA estimates from

$$\hat{\theta}_q = \arcsin\left\{\frac{\lambda}{2\pi\Delta}\arctan\left[\frac{\Im m\left(\hat{\phi}_q\right)}{\Re e\left(\hat{\phi}_q\right)}\right]\right\} + \theta_r , \quad (27)$$

where $\Im m(\cdot)$ and $\Re m(\cdot)$ are the imaginary- and real-part extraction operators, respectively.

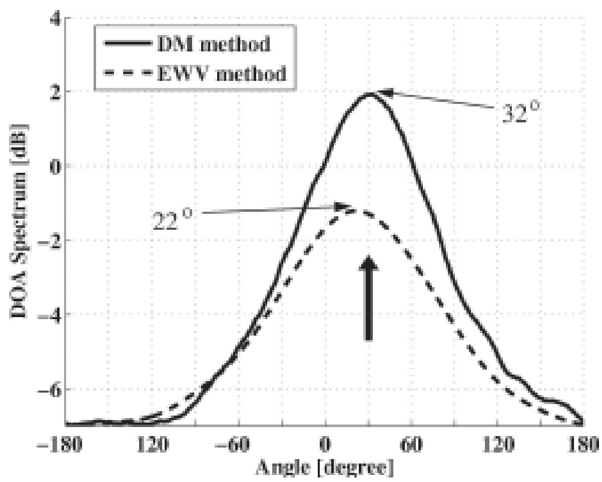

Figure 8. Measured RD-MUSIC spectra exemplifying the DM and EWV methods for signal DoA toward 30°.

4.5 Calibration Methods for Practical Implementation of DoA Estimation with RD Processing

For the implementation of these methods in direction-finding applications, the problem is how to obtain the required unknown matrix, $\mathbf{W}^{\mathrm{T}}$. Two practical methods, the equivalent-weight vector (EWV) and direct-measurement (DM) methods, aiming at estimating the reactance-domain steering vector, $\mathbf{W}^{\mathrm{T}}\mathbf{a}(\theta)$, were first proposed [21]. The two methods differ in the way the reactance-domain steering vector is obtained. A third method, based on least-square calibration and allowing more-efficient estimation of $\mathbf{W}^{\mathrm{T}}$ with less measurement cost was then proposed [41].

4.5.1 Equivalent Weight Vector (EWV) Method

The reactance-domain steering vector, $\mathbf{W}^{\mathrm{T}}\mathbf{a}(\theta)$, is computed by simply using the formulation of the current vector given in Equation (1). To be precise, for each set of reactances $\mathbf{x}^{(l)} \equiv \left[x_1^{(l)},\ldots,x_N^{(l)}\right]$, the corresponding RF equivalent weight vector, $\mathbf{w}^{(l)}$, is calculated from Equation (1). The matrix $\mathbf{W}^{\mathrm{T}}$, used for computing the RD-MUSIC spectrum, is formed after repeating the process for the N sets of reactances.

Notice that in this method, the computation of the RD-MUSIC spectrum is led by the estimation of the impedance matrix, $\mathbf{Z}$, and the relationship used to obtain the equivalent reactances. Therefore, these parameters have to be calibrated. This critical problem of calibrating the impedance parameters used in the ESPAR antenna's output model can be avoided by using a more-direct method.

4.5.2. Direct Measurement (DM) Method

In the previous method, for a given ESPAR antenna we need to estimate the matrix $\mathbf{Z}$ and the relation between the voltage and reactance. The accuracy of the MUSIC-ESPAR spectrum obtained strongly depends on these estimations. In the direct-measurement method, the DoA spectrum is calculated using *only directly measured data*.

The method is based on the idea that for one constant impinging signal, $u(t) = K = 1$, arriving toward θ with a noise-free assumption, and for a given reactance set, $\mathbf{x}$, the ESPAR antenna's output is expressed by

$$y(t) = \mathbf{w}^{\mathrm{T}}\mathbf{a}(\theta)u(t) = \mathbf{w}^{\mathrm{T}}\mathbf{a}(\theta), \quad (28)$$

which can be estimated by measuring the phase and power outputs of the antenna. The current-steering vector data,

$$\mathbf{W}^{\mathrm{T}}\mathbf{a}(\theta) = \left[\mathbf{w}_1^{\mathrm{T}}\mathbf{a}(\theta), \mathbf{w}_2^{\mathrm{T}}\mathbf{a}(\theta), \ldots, \mathbf{w}_N^{\mathrm{T}}\mathbf{a}(\theta)\right]^{\mathrm{T}},$$

for a given θ is obtained by measuring the power and phase of the antenna's output for each of the N sets of reactances. Then, the RD-MUSIC spectrum in Equation (21) is computed using this data.

Notice that for a given number N of sets of reactances and, for example, angles $\theta = 0°, 1°, \ldots, 359°$, $P_{MUSIC}^{RD}(\theta)$ is formed with $\hat{\mathbf{E}}_n$ and the measurement of N patterns having 360 points each. In addition, to perform several estimations of the same impinging signal at different DoAs, the N patterns are measured only one time.

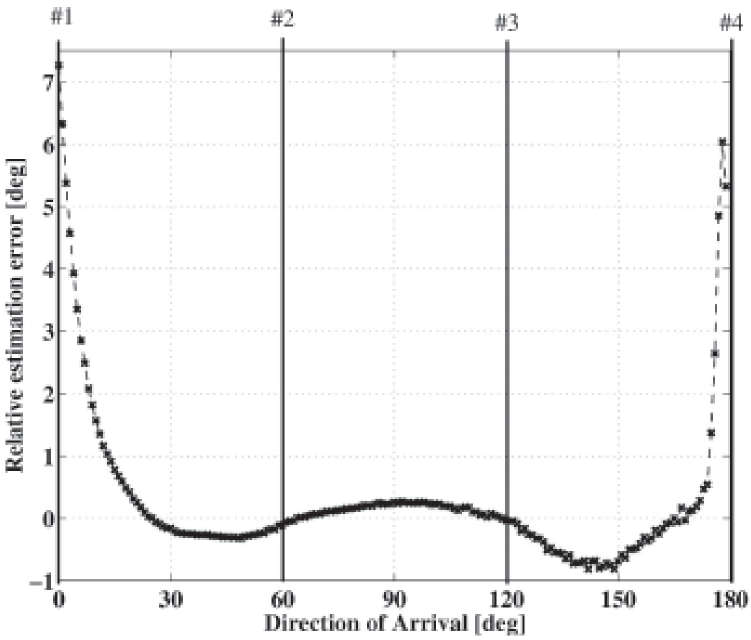

Figure 9. Single-source DoA-estimation experimental results employing RD-ESPRIT.

4.5.3 Least-Square-Based Calibration Method

Because of the unknown element gain, phase, element misalignment causing mutual-coupling errors, and reactance flaws of the real antenna, which could not be considered in the antenna model, the $\mathbf{W}^{\mathrm{T}}$ parameter directly calculated from the analytic model in Equation (1) may not be suitable for practical DoA estimation [21]. In this case, a calibrated estimate of $\mathbf{W}^{\mathrm{T}}$ should be considered.

The chosen calibration method is based on an array manifold calibration [42, 43]. In the case of the ESPAR antenna, this calibration procedure follows these steps [41]:

1. Choose N sets of reactances, $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N$.
2. Choose P different values for angles θ_p, $p = 1, \ldots, P$, with $0° \le \theta_p < 360°$ and $P \gg N$.
3. For one signal impinging on the antenna toward θ_p, form $\hat{\mathbf{R}}_{yy}$ from Equation (19). Then, eigen-decompose $\hat{\mathbf{R}}_{yy}$ to obtain the eigenvector, $\mathbf{e}_1^{(p)}$, corresponding to the highest eigenvalue, $\lambda_1^{(p)}$. Carry out the same procedure for all θ_p, with p from 1 to P, and form the matrix $\mathbf{E}_c = \left[\mathbf{e}_1^{(1)}, \mathbf{e}_1^{(2)}, \ldots, \mathbf{e}_1^{(P)}\right]$, which collects all of the computed eigenvectors.
4. Form the matrix $\mathbf{A}_c = \left[\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_P)\right]$, which contains the steering vector for each of the chosen θ_p.
5. Finally, the RF weight-vector estimate, $\hat{\mathbf{W}}^{\mathrm{T}}$, is given by the total least-square solution of $\hat{\mathbf{W}}^{\mathrm{T}} \mathbf{A}_c = \mathbf{E}_c$.

For better performance the N sets of reactances employed during the calibration procedure should be the same as the reactance sets used during the DoA estimation.

An example of DoA estimation using RD-ESPRIT with RF equivalent weight matrix $\mathbf{W}^{\mathrm{T}}$ obtained from least-square-based calibration is given in Figure 9.

5. Conclusions

This paper gave an overview of reactance-domain signal processing with ESPAR antennas. ESPAR antennas are single-port-output smart antennas that can be controlled through reactances loaded on surrounding parasitic elements. Reactance-domain signal processing refers to the ability of the ESPAR antenna to electronically steer beams and nulls in the directions of sources. Employed in hand-held-device receiver applications, the single-output design of the ESPAR antenna offers lower power consumption and lower effective cost than the conventional multi-output array antennas. However, due to the single-port limitation, the implementation of the signal-processing algorithm part of the application becomes a hot topic. In this overview, we focused on the adaptive beamforming and DoA estimation methods designed for an ESPAR antenna. Although many algorithms are available in the literature, they are however all based on the reactance-domain processing approach. Moreover, the overview given of the fundamental algorithms permits appreciation the processing burden that results from the use of an ESPAR antenna in array-antenna (smart-antenna) applications.

On the one hand, trained and blind adaptive beamforming with steepest-gradient-descent iteration were applied by using heuristically proposed criteria based on the maximization of the SINR. Adaptive beamforming with an ESPAR antenna turned out to be costly in term of the required antenna-output data. To reduce this cost, criteria and an algorithm featuring very fast convergence have to be employed. On the other hand, DoA estimation methods already available for conventional multi-port array antennas could be applied by using a reactance-domain correlation matrix to reconstitute the ESPAR antenna's element output. DoA estimation using a reactance-domain correlation matrix required a calibration step to estimate the matrix $\mathbf{W}^{\mathrm{T}}$, which embodies the antenna's physical parameters correlated to the reactance values. A least-square-based calibration approach allows reducing the measurement burden required by the estimation of $\mathbf{W}^{\mathrm{T}}$.

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Wireless Communications: 2020

W. Webb

There are no shortages of predictions as to what the mobile phone, or communicator device, will be capable of in the future. Many of these center around the phone becoming a "personal butler" or "remote control on life," and guiding an individual through an increasingly frenetic and complex world with ease and intelligence. However, we have had these predictions with us for over a decade: indeed the ability to dial home and turn on the air conditioning was postulated by AT&T in the 1960s. Is now the time that they really will emerge, or will wireless communications twenty years from now look much like it does today? The predictions reported in this paper are based on a more detailed book published in 2007 [1].

Some History to Start With

My first prediction of the future was made in 2000 [2]. It was based on a mix of deduction and contributions leading to predictions for 2005, 2010, 2015, and 2020. When we reached 2005, I analyzed how accurate my predictions had been [3]. In that paper, I concluded that

> The predictions I made appear almost exactly right. In some cases I was unsure about which technology would transpire, for example whether WLANs or cellular picocells would predominate, but the overall direction was correct. Interestingly, in overall terms I predicted little change of substance between 2000 and 2005, and that is exactly what transpired. This was not based on an expectation of hard times ahead for the wireless industry, but more on an understanding of how long it would take for technologies to be developed and reach mass-market penetration levels.

One of the key messages, then, in predicting the future of wireless, is that contrary to popular opinion, wireless is not an incredibly fast-moving world. New technologies can readily take a decade or more to emerge. This makes wireless a readily predictable field – as long as the key drivers and constraints are well understood. This was taken into account when developing the ideas discussed here.

Why Prediction is Essential

Almost all activities in the world of wireless communications require a forward-looking assessment. Operators who are deciding whether to buy spectrum at auction need to assess the likely services and revenue they can expect over the lifetime of their license – often, 20 years or more. Manufacturers need to decide on which areas to focus their research activities, and which technologies and devices to develop into products. Academics and other researchers need to understand which areas will require the greatest advances, and hence be most amenable to research. With the development of standards taking five to ten years from inception to commercial product, those developing the standards need to predict what type of products will be needed, and the technologies available during the lifetime of their standard. There are many examples of poor forecasting – for example, Iridium over-forecast the number of users who would be prepared to pay for an international satellite phone – and some examples of excellent forecasting, such as Vodafone's decision to enter the mobile communications marketplace when it was in its infancy. Getting these forecasts right is one of the most critical factors in building a successful business.

There are many forecasts. A raft of consultancies, analysts, brokers, and others provide predictions for growth in particular markets – almost all showing a "hockey stick," predicting dramatic growth. However, these typically fail to look at the bigger picture and understand how sectors will evolve over decades. There are also a few books providing "visions" or similar. These tend to explore a range of different scenarios and predict what might happen under each scenario, but they rarely reach a single conclusion, and are often excessively optimistic. Hence, the reason why I completed this forecast: I felt it would be valuable to have a single clear assessment of how the world of wireless communications will evolve over the next twenty years, based on data provided by expert contributors and assembled by an experienced forecaster with a track record of previously accurate prediction.

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Understanding Technological Progress

One of the key drivers of the future is technological change. Understanding how technology might evolve over the next two decades is therefore one of the key components of making any prediction. Equally, though, it is easy to get carried away. Just because something is technically possible does not necessarily mean that it will happen: video calling has been technically possible for decades, and yet is still very rarely used. In essence, a new service cannot happen until it is technically viable, but it must also be economic and become socially accepted. For example, controlling the home heating system remotely from a cell phone is technically simple, but the cost of installing wireless heating-control systems is currently much higher than the utility many would perceive to get from moving from the current systems to one that can be remotely controlled. Video calling is both technically possible and, for users with broadband connections and PCs, inexpensive, but has not yet become socially acceptable, and hence is not in widespread use. Economics and social issues are discussed in later sections, but firstly there is a need to understand what technology will offer.

There are two key ways to predict technological progress. One is through broad trends, making use of physical and empirical laws, such as Moore's law. The other is to look at specific technologies that are currently in the research stage, and to ask how long it will take for them to become commercial propositions and what impact they might have. Both approaches are discussed below.

The Laws

Shannon's Law [4, 5]. This is more of a physical limit than an empirical law. It sets out the capacity of a single channel in the presence of noise. While directly applicable to wired connections, it cannot be easily applied to wireless systems where frequencies can be reused in neighboring areas. Much work is underway to estimate the maximum capacity of a wireless network with a given spectrum allocation and number of cells, and results vary depending on the approach taken. However, it seems likely that we are within a factor of 10 of the maximum we can achieve, and may well be much closer than that in practice – perhaps as close as a factor of three. Hence, there is little room for technological breakthroughs that dramatically increase the capacity per cell. However, as will be explained shortly, this can be circumvented simply by increasing the number of cells.

Moore's Law [6]. Easily the most well-known of the empirical laws, this predicts that the number of transistors that can be placed on a chip will double every 12-18 months (in practice, it has been doubling every 24 months). The implications of this for wireless are mixed. It does imply that handsets will continue to increase in memory and processing power. However, as we approach the limits of what is possible over wireless channels, massive increases in processing are needed for even small gains in capacity.

Cooper's Law [7]. This is a most intriguing prediction that notes that the number of wireless voice channels in the world doubles around every 30 months, and has done so since 1901. What is most interesting is that of the million-times improvement that has occurred since 1950, roughly 15 times was the result of being able to use more spectrum (3 GHz versus 150 MHz), and five times was from using frequency division, that is, the ability to divide the radio spectrum into narrower slices (25-kHz channels versus 120-kHz channels). Modulation techniques (such as FM, single sideband, time-division multiplexing, and various approaches to spread spectrum) can take credit for another five times or so. However, the lion's share of the improvement – a factor of about 2,700 – Cooper suggested was the result of effectively confining individual conversations to smaller and smaller areas by spatial division or spectrum reuse. Again, this gives us a pointer that smaller cells may well be more important in the future than any "wonder" technology.

Edholm's Law [8]. Edholm pointed out that data rates over wired and wireless networks increase over time. Wired networks typically support data rates about two orders of magnitude (i.e., a hundred times) greater than wireless. While wireless improves steadily over time, so does wired, making convergence between them unlikely. This suggests that wireless will not replace wired networks where high speed is needed, although it may form a short "tail" on the end of a high-speed wired connection.

Hard disk size [1]. There has been a very interesting trend in hard disk size. Since 1980, the average hard disk size on a mid-range PC has increased by an order of magnitude every six years. Of course, all trends of this sort come to an end eventually, but if this were to continue, then hard disks 18 years from now would have 1,000 times the capacity of hard disks today. If this also applies to portable devices, then the sort of hard disks currently found within iPods and similar devices – which currently have a capacity of around 20 GB – could store 20 TB by 2025 or thereabouts. This suggests that storage capacity on mobile devices over the next two decades will, for most people, become effectively unlimited.

Technologies

There are many technologies in various stages of development that have yet to become commercial reality. Technologies can take many years to make it out of the lab and into the hands of consumers. For example, OFDM was a research topic in the 1960s, but not a product until around 2000. More recently, ultra-wideband (UWB) was being aggressively developed by start-ups from around 1998, but will not be commercially available until 2008. and will possibly take another three to five years to become widespread. 3G standardization started around 1992, but 3G still does not have as many customers as 2G.

So, there is a long lead time on many technologies. Just by looking at those currently under development, it is possible to be near-certain that anything likely to materialize in the next decade has been considered – and, indeed, most things likely to turn up in the next 20 years. The key emerging technologies are discussed below.

Software defined radio [9]. Many future visions of wireless communications involve multi-modal devices connecting to a wide range of different networks, such as 2G, 3G, WiFi, and Bluetooth. They may even involve devices modifying their behavior as they discover new types of networks, or as home networks add additional functionality. At present, this is achieved by incorporating the chipsets from each of the different standards into the handset, e.g., 3G and Bluetooth. While such an approach works, it is relatively inflexible. An alternative is for communication devices to be designed like computers, with general-purpose processing capabilities and different software for different applications. Such devices could then call up, or download, the appropriate software for the particular communications requirement currently in use. The underlying architecture needed to achieve this is termed software-defined radio (SDR).

In practice, the benefits of software-defined radio appear relatively minor compared to the downsides. The current approach of multi-modal devices works well, and will likely always be less expensive than a general-purpose software-defined radio. Further, since new network technologies are generally introduced much less frequently than users replace handsets, there is little need for a handset to download a new standard when this can more readily be embedded in the handset during production. Because of this, we do not expect "true" software-defined radios that can change their radio behavior to be implemented during the next two decades. However, we do expect handsets to be able to download a wide range of new applications and software patches.

Smart antennas/MIMO [10]. Smart-antenna technology has the potential to significantly increase the efficient use of spectrum in wireless-communication applications. Through intelligent control of the transmission and reception of signals, capacity and coverage in wireless networks could be improved. Various smart-antenna techniques may be used. These include:

- Antennas that form narrow beams that are steered towards the user, called "smart" or "directive" antennas. These result in a stronger signal received by the user and reduced interference to others. However, larger arrays of antennas are needed to form beams, and tracking moving users can be problematic.
- Multi-antenna diversity schemes, such as multi-input multi-output (MIMO) approaches. MIMO systems work by having a number of antennas at the base station and a number at the subscriber unit. A different signal is transmitted from each antenna at, say, the base station, but all transmissions are at the same time and same frequency. Each antenna at the subscriber unit will receive a signal that is the combination of all the transmissions from the base station, modified by the parameters of the radio channel through which each passes. In a diverse environment, each radio path might be subtly different. If the characteristics of each radio channel from each transmitting antenna to each receiving antenna are known, then a "matrix inversion" operation can be used to deduce what data was transmitted from each antenna.
- Semi-smart antenna schemes, such as those that decrease the size of a cell with heavy loading and increase the size of neighboring cells to compensate. This can be achieved with mechanisms such as antennas with variable down-tilt. These schemes have lower potential gains than the schemes described above, but are cost effective and simple to implement, and do not require antenna arrays.

These approaches are complementary, some being most appropriate for large, costly infrastructure systems, others working best in certain propagation environments, such as where multipath is prevalent. However, both the smart-antenna and MIMO approaches have significant costs associated with them, in the form of additional antennas, additional hardware, extra space on masts, and so on. They both also have difficulties in realizing all their gains in practical environments where the transmission channels are constantly changing their parameters as the mobile moves, or as vehicles or people move in the vicinity.

In summary, while smart antennas and MIMO have strong potential, we do not expect to see them make a significant impact in wide-area networks over the next 10 to 20 years. This is because most schemes are difficult to implement, do not always bring gains, and require arrays of antennas at base stations at a time when environmental concerns are high. Comparatively, installing smaller cells brings much greater capacity gains for a smaller cost and lower risk.

Mesh networking [11]. A wireless mesh network utilizes other users in the network as nodes to relay information. In this way, information can be transmitted from one user to a distant user via multiple hops through the other users. Many advantages are claimed for mesh networks, including a limited need for infrastructure, reducing deployment and ongoing operational costs; increased capacity because each node acts as a mini-base station; and increased coverage due to the ability to hop around corners.

However, a significant body of research casts doubts on these claims. Unless a node is connected via backhaul to the core network, it cannot effectively generate capacity. Instead, it needs to relay any communications that it receives. There are some gains due to the lower power that can be used for multiple short hops compared to one long hop, but these are outweighed by inefficiencies, such as signaling protocols, and the fact that the short hops are unlikely to align well with the single "long hop," and so power requirements increase.

Our view is that wireless mesh networks will not make a significant difference to high-volume wireless communications. Mesh networks may have niche applications, such as working alongside existing networks to fill in areas of poor wireless coverage; in areas where conventional networks are uneconomic, such as the provision of broadband services to rural communities; or in deploying sensor networks.

Multi-user detection/interference cancellation [12]: Interference cancellation (sometimes termed "multi-user detection") is a technique whereby a receiver analyses the complete set of all signals it receives and attempts to remove those that are considered to be interference. Its operation is most readily understood at a CDMA base station. The base station will be receiving the signal from all the mobiles in the sector. It can extract the signal from a particular mobile using the correlation of CDMA codes. However, for weaker signals, this may be difficult. The base station could decode the strongest signal and then subtract this decoded signal from the overall set of received signals. It could progressively do this, reducing the interference on the weaker signals until they can be decoded. As well as doing this sequentially, it could in principle be performed in parallel using an optimal detector, although in practice the complexity of these is normally too high to be implemented.

There are many other situations where interference cancellation could be used. For example, a fixed link could have a separate antenna pointing at an interfering link. The signal from this antenna, suitably modified, could be subtracted from the signal on the main link.

For cancellation to work, the interfering signal must be accurately characterized. If this does not occur, then an inaccurate version of the signal may be subtracted, potentially worsening the error rate. This has proved to be somewhat difficult in practice, with the result that interference cancellation is not widely deployed. The cost of the systems also tends to be high, due to the need for additional processing, in some cases additional antennas, and possibly the need to send additional information such as the codes in use.

Our view is that in many cases the cost and impracticalities of interference cancellation outweigh any potential benefits, and we only expect to see simple versions in widespread use in wireless communications systems of the next 10 to 20 years.

Cognitive radio [13]. Although there are many different definitions of what is a cognitive radio, the basic concept is of a device that, on arriving in a new environment, can "understand" the usage of the radio spectrum and adapt its behavior accordingly. So, for example, a cognitive radio might detect that the emergency-service frequencies were currently lightly used – perhaps because there were few emergencies taking place. It might then move to these frequencies and make a series of short transmissions, checking after each one that the frequencies were still free. If not, it might then move to other frequencies, perhaps those used by broadcasting, for example, which were essentially unused in the area.

There are many problems with cognitive radio, including an inability to be certain that the spectrum is not being used, and hence that transmissions might cause interference. Even if all the problems could be overcome, there is still a question as to what the cognitive radio transmits. A network of base stations that is able to scan all frequencies for possible transmissions would be expensive and hugely risky to construct. Locating other terminals to transmit directly to is also difficult, and suffers the problems associated with mesh networks.

Another issue is that there is little need for this additional capacity generated in this manner. 3G operators in 2007 were still typically only using 50% of their spectrum allocation. Additional 3G spectrum was promised at 2.5-2.7 GHz and at UHF after the analogue TV switch-off. Hence, we believe that cognitive radio will struggle to find an application where its more-expensive handsets can be justified. It will not make a significant impact on our predictions for the future.

Fiber radio. If fiber were widely available, then some have suggested the deployment of a technology known as "fiber radio" or "direct radio." This is a concept where – in its purest form – the base-station antenna supplies its received signal to an electrical-to-optical converter. This is then connected to a fiber-optic cable, taking the signal back to a network node where the wanted signals are extracted and routed as appropriate. Transmission works in the converse manner.

Proponents claim a range of advantages for such a concept. In particular, each antenna would, in principle, be able to receive signals spanning a huge range of frequencies, and equally could transmit across this range. As a result, almost "the entire spectrum" would be available in each cell, allowing massive capacity. The antenna unit would also be very compact and cheap, potentially allowing widespread deployment of very-high-capacity small cells. Some researchers have even considered passive electrical-to-optical converters, such that the antenna unit would not require power. However, this does limit the range to around 10 m.

However, there are many problems with such an approach. Firstly, such a device could not use the entire spectrum: some would remain reserved for a range of other applications, such as satellite transmission and cellular systems. In the worst case, the device might not have available to it any more spectrum than a standard multi-band cellular base station. Secondly, while the antenna unit may be cheap, this approach places maximum requirements on the backhaul, which is more likely to be at a cost premium than using the radio spectrum. Indeed, each antenna unit needs its own dedicated fiber connection going all the way back to the network node. If there were a dense array of antennas, this might require a massive upgrade in fiber deployment. Thirdly, there is little need for a solution of this sort. A standard WiFi base station will provide enough capacity for the foreseeable future, is low cost and simple to deploy, and can be connected to a wide range of backhaul options.

So, while we see fiber radio as an interesting architectural concept, there do not seem to be sufficient drivers to overcome the substantial disadvantage of requiring dense fiber deployment.

Summary of Technological Progress

All these observations suggest that there is no wonderful technology, or technical trend, that on its own is going to revolutionize wireless over the next decade, and with all likelihood, over the next twenty years. Hence, there seems little rationale for a completely new "4th generation" of cellular, as 3G reaches the limits of what is possible in a radio channel. Fixed wireless access is unlikely to succeed – even with the advent of WiMax technology.

Despite the lack of promise of new technology, we can expect increased capacity and data rates almost entirely as a result of smaller cells. These might be a mix of cellular networks continually reducing cell sizes in urban areas, and the increasing deployment of WLANs, in some cases providing coverage across entire cities.

However, different problems emerge. The key cost element for small cells, particularly those offering high data rates, soon becomes the "backhaul:" that is, the connection of the cell into the core network. Other costs include site rental and power, but for small cells in urban environments, these costs are typically low. While backhaul of any required data rate can be provided through the deployment of appropriate copper or fiber cabling, this can be uneconomic for small cells serving only a few customers. Indeed, we can go as far as to say that since small cells are the key route to increased wireless data rates and capacity – and since backhaul is the key constraining factor in the deployment of small cells – that the biggest challenge facing wireless is fixed communications.

Economics and Social Issues

Even if the "perfect" service is introduced, the entire population does not rush out to buy the service immediately. Instead, as is well chronicled, the service is first adopted by a particular type of individual: the early adopter. Depending on their reaction, it may then become adopted more widely.

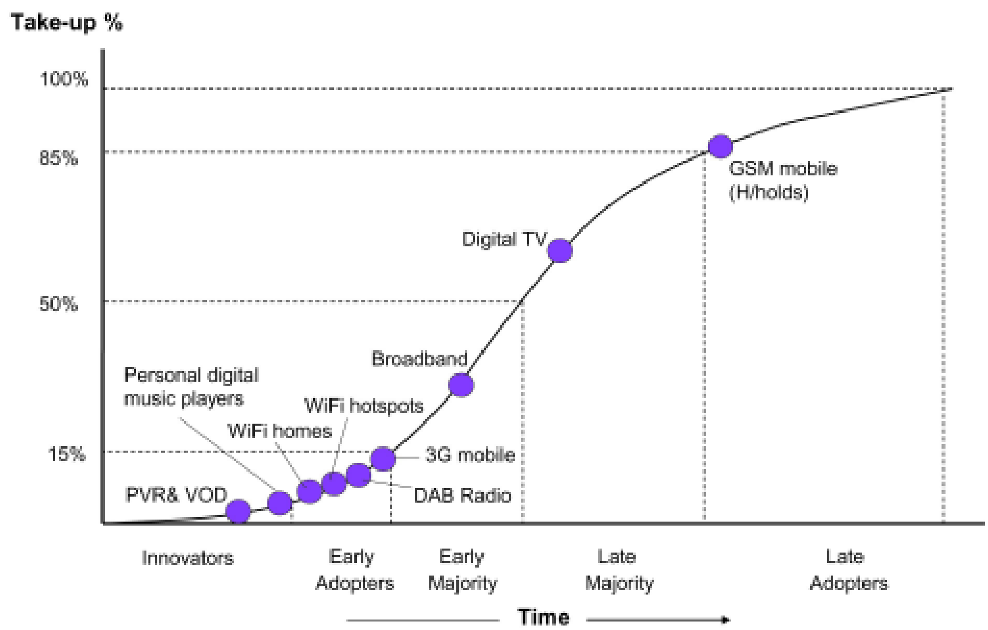

Figure 1. The technology adoption curve (source: Ofcom)

This is shown graphically in Figure 1, with some examples of various levels of device penetration in 2005 [14].

There are many complex dynamics here. The majority will typically only take up the service if the experiences of the early adopters are good. They will rely on word-of-mouth, reviews, and wide-scale promotion to convince them that the technology is worthwhile and mature. Initially, pricing is often high, as manufacturers seek to recover development costs and before economies of scale become important. It then starts to fall, as penetration increases. For technology products, many now wait for falling prices as a signal to buy, having experienced situations in the past where they have bought products, only to find the same or better products available for less shortly afterwards.

There are two important implications:

- Much can go wrong. If the early adopters do not like the product, if the price is not set correctly, if the distribution chains do not champion it, if the consumers perceive a risk of early obsolescence, and so on, then the launch of the product will fail.

- The process will take some time. Regardless of how wonderful is the product, the majority will not adopt it until they feel enough time has passed for the product to become proven, for the price to stabilize, and for it to be an acceptable thing for them to own.

History shows that a new service or product might take anything between four and 10 years to reach mass adoption, even if the service is perfect in every respect and there is a strong user demand for it. Services for which the benefits are less familiar to the end user will take longer. Add five years for the standardization and development of a new technology, and it might take 15 years from conception to large-scale success. This is the truth of "the fast moving world of telecommunications" which is often not widely understood.

Structural Issues

It is worth discussing the current structure of the communications industry. This varies around the world, but has a similar model in most developed countries. The communications industry has developed predominantly in specialized "verticals." For each type of service – such as cellular or fixed – there are one or more companies that have built the network, run the network, deliver the customer service and billing, maintain a brand, etc. These companies might include:

- A fixed operator (typically, the old "post and telecommunications" entity). In the US, the single provider was split into multiple regional providers, who are now recombining in various ways.
- One or more cable-network operators.
- One or more terrestrial TV broadcasters.
- Typically, a single satellite broadcaster.
- Multiple cellular-network operators.
- Multiple WLAN hotspot providers.

There have been some attempts to change this. Mobile virtual network operators (MVNOs) act as service providers on top of "network pipes." Some operators are outsourcing the building and maintenance of their networks so they can concentrate on service provision, taking the first steps towards disaggregation. Some cellular operators have also become hotspot providers, and third parties have emerged who build hotspot networks and then sell capacity to service providers, such as cellular operators.

Nevertheless, the industry structure is still predominantly one of vertical silos, with different communications technologies competing with each other at the edges. Such a structure makes the provision of consolidated services – such as phones that work in the office, home, and wide area – rather difficult. If network provision was separated into "pipes" and "services," then a service provider could buy bulk capacity from a range of network operators, and offer a consolidated service to end users. Instead, consolidated services can only be offered if operators reach agreement among themselves. This is often difficult to do, and can restrict the offering to a subset of available operators.

It seems unlikely that change will happen soon. Companies rarely choose to split themselves apart. This could be a significant impediment to the provision of consolidated services in the future.

The Contributors

A key part of the forecasting exercise was to solicit input from experts around the world providing their views of the future. This provides different insight and a clear indication of those areas where there is agreement and those where there is doubt. The key insight from these contributions includes:

- Consideration of the future evolution of displays by Joel Pollack, CEO of Clairvoyante, who predicted brighter and lower-power displays, but that foldable or "rollable" displays would prove very difficult.
- A look at how people will interact with mobiles and computing devices in the future by Tom MacTavish, from Motorola's research laboratories, who predicted that devices will be built into clothing or building fabric, providing a range of ways of interaction.
- An essay on the development of speech recognition by William Meisel, President of TMA Associates, who suggested that network-based speech recognition would soon become an important tool in interacting with devices and transcoding messages.

- A detailed assessment of the likely development in the military use of wireless by Paul Cannon and Clive Harding, from Qinetiq, who noted that a number of technologies will be developed by the military that could then be used in the commercial sector, including mesh networks, high-altitude platforms, and on-body networks.
- A look at possible "stage left" surprises in the future from Peter Cochrane, head of Concept Labs and renowned futurologist, who predicted that wireless devices would become very widespread, providing sensor networks in the home and office, automating logistics and transport, and dramatically changing our lives.
- An analysis of how mesh networks might play a major role in the evolution of wireless communications by Gary Grube and Hamid Ahmadi, senior wireless architects and general managers at Motorola, who predicted widespread deployment of mesh networks for a range of applications such as disaster relief, sensor communications, range extension, and more.
- A look at how changing regulatory policy could make a significant difference in wireless access from Dennis Roberson, now with the Illinois Institute of Technology and previously CTO at Motorola, who suggested that more liberal spectrum policies, such as allowing cognitive radio, could providing a large increase in capacity, driving a wide range of wireless developments leading eventually to immersive wireless experiences.
- A wide-ranging and thoughtful prediction of the future from Simon Saunders, CTO of Red M, who predicted that wireless would pass through a turbulent period as a range of new technologies were trialed, but would settle into a configuration where any system could use almost any spectrum and air interface, resulting in ubiquitous wireless devices, taken for granted by all.
- An analysis of the likely future for cellular technologies and cellular operators from Stephen Temple, senior strategist at Vodafone, who predicted that there would not be a 4th generation cellular technology, but that there were a number of chaotic and unpredictable factors that could shape how cellular technology was used in the future.

There is a much agreement across all these contributions. Equally, there were some areas of disagreement, such as the extent to which MIMO would succeed, the likelihood of unlicensed spectrum becoming overwhelmed by usage, the value of cognitive and mesh wireless, and the possibility of fiber radio emerging.

The Predictions

Table 1 provides a summary of my predictions for 2011, 2016, 2021, and 2026, across a number of specific areas. First, let's consider how the overall user experience might change.

Between now and 2011, the key change for the end user will be the convergence between home and wide-area phones. Users will gradually stop using their home phone, reserving it for those times that their cell-phone batteries are low. This will lead to a gradual understanding of the problems of convergence, such as the difficultly in separating work and business calls, and the emergence of filtering solutions to deal with this. Wireless homes will offer a range of capabilities to control the home that users will increasingly come to rely on. This will be the period in which many will make their first video call, and will start to appreciate that there are times when video calling is advantageous. Users will appreciate higher data rates to the home and in the wide area, but will not yet have any new applications that take advantages of these. They will also become accustomed to the mobile phone being a multi-purpose device, with camera functionality acceptable for most, and music capabilities sufficient to displace iPods and similar devices for many.

Moving on to the period from 2011 to 2016, change will have become more of a continuum than a specific event. Building on the change of the previous five years, users will now become completely comfortable with convergence. The home phone will be relegated to a cupboard "just in case." Users will understand how to structure their communications in such an environment, and when to use video calls. Users will perceive a significant revolution in broadcasting: no longer will many use TV guides. Users will also expect wireless control of all electrical devices in the home and office, including the ability to remotely interrogate home appliances from devices such as the cell phone.

By 2021, users will become increasingly familiar with their new converged world. They will perceive increased value in personalized services, allowing their service provider, via their phone, to make all sorts of decisions and provide suggestions for them. This will be the end of a journey: little more will change between 2021 and 2026.

Based on these ideas, it seems likely that the key technologies will be mesh, RFIDs [15], UWB [16], low-cost sensors, and enhanced software. However, equally, developments will be held back by slow progress in backhaul and battery technology. Major growth areas will include ever-enhanced handsets, home wireless networks, intelligent software, and service provisioning. Manufacturers will need to increasingly focus on handsets, operators will need to prepare for a move from vertical integration to horizontal, service providers will need to build competence and credibility, and academics will need to switch research from wireless technology to intelligent software.

It is interesting and instructive to compare these predictions with those made in 2000. As might be expected (and hoped), there is much alignment. Where there is a difference, it is almost always that the latest predictions are delayed compared to the 2000 predictions, showing how

Table 1. The predictions.

Area	2011	2016	2021	2026
Fixed Networks	IP cores, ADSL2+ in access network	Fiber deployment to the home underway around the world	Fiber deployment mostly complete in developed world	Little further change
Broadcasting	PVRs starting to build individual programs, high definition used for films and sports events	Majority now use intelligent PVRs to assemble content and distribute to appropriate devices	Little true broadcasting, instead PVRs assemble content from a range of providers and channels	Little further change
Wide Area Wireless	Little change	Some mesh extension of coverage	Cell sizes decrease in some areas	Little further change
Short Range Wireless	Massive increase in indoor WLAN deployments leading to a range of converged services	Indoor wireless coverage ubiquitous, outdoor widely available (but not covering entire cities), many appliances now wireless enabled	Little change in technology, but large growth in home control services	Little further change
Handsets	Storage capacity grows, speech recognition improves	Better displays, increased functions integrating other personal devices	Incremental improvement in most areas	Further incremental improvement
Services	Mobile TV emerges	Broadcasting becomes a personal service integrated into wireless devices, contextually aware and personalized services widely used	Growth in personalized services providing "remote control on life"	Ever wider range of personalized and general services built on top of stable wireless platform
Convergence	Huge growth in single phone for home and wide area, and increasingly office.	Broadcasting well on the way to converging with telecoms, telecoms completely converged	Complete – the time when different devices were used for different services will seem old-fashioned	Now fully converged
Industry Structure	Little changed	Change from vertical to horizontal integration	Stable in the new horizontally integrated form	Pipe providers remain stable but change in service providers

slowly many things develop in the world of wireless and how easy it is to over-predict change – which goes some way toward explaining why we do not yet have the remotely controlled air-conditioning that AT&T predicted in 1960!

Implications

In this section, we consider what the changes predicted here might mean for different groups of stakeholders.

For manufacturers, this forecast presents a picture of two halves. In the early years, there will be considerable deployment of new technology, including 3G networks, mobile TV networks, and core IP networks. Sales of handsets, WLAN routers, and BlueTooth devices will grow considerably. However, between 2011 and 2016, networks will become stable and little additional rollout will occur. Of course, there will continue to be upgrades, replacement of faulty and obsolete equipment, and filling in additional cell sites, but the days of complete network builds will be over.

Handset manufacturers are likely to see continued growth, with handsets developing ever-increased capabilities and better human interfaces. There will need to be ongoing research across a wide range of areas to improve capabilities such as displays, batteries, and speech recognition.

For operators, too, this is a future with two distinct periods. In the first decade or thereabouts, for most operators this will be a period of stability and profitability. No major change in plans will be needed from any operators. Perhaps operators might use this time to focus on reducing costs, improving networks, and building portfolios of new services. Then, at some point, the industry structure will shift. Operators will undergo major and painful splits, with a subsequent period of mergers and acquisitions. This will distract the operators for some time, but once over this period, there will be a strong growth in service offerings, potentially requiring enhancements to core networks.

Pure service providers will continue to find it difficult to operate profitably until the industry structure changes as described above. At this point, there will be a host of service providers created from existing operators. Many new service providers will also likely enter this new market. There is probably little that the existing service providers can do in the interim.

There are surprisingly few implications for regulators. Concerning spectrum regulation, there is little additional demand predicted for spectrum in our view of the future. Pressure will likely increase on unlicensed spectrum, and there may be opportunities to reduce this pressure through a combination of additional spectrum and "rules," such as politeness protocols, which have been proven to increase capacity. Concerning competition regulation, little will change from today's position. It may be that some partnerships to provide convergence are judged anti-competitive. However, after the change in industry structure, there should be increased competition, and hence less need for regulation.

Concerning academics and the research community, our predictions suggest that the key areas where advances will be needed are:

- Handset technology including batteries, displays, man-machine interface, processing power, and storage.
- Software capable of providing contextual information, and eventually leading to automated diary management and environment control.
- Systems that can handle the complexity of a large number and wide range of wireless devices, e.g., in the home, but present a simple plug-and-play interface to the user.
- Backhaul systems that will facilitate the rapid and inexpensive deployment of cells.

This agenda is somewhat different from the current research profile. At present, there is still significant effort expended on faster air interfaces or means to provide more efficient throughput. This includes research into MIMO and smart antennas, complex OFDM approaches, and mesh networks. Our predictions suggest that much of this work is unnecessary. There is also much work on enhancing the interaction between different layers in a system to optimize across multiple layers. This may be more appropriate as a low-cost mechanism to gain capacity.

Concerning developed and developing countries, it is clear that most of the developments predicted here are primarily aimed at developed countries. It is here that there is generally the greatest need for increased capacity, the largest appetite for new services, and, critically, the greatest ability to pay increased monthly fees in order to fund the new development. Historically, there has been a trend for new wireless technology to be deployed in the developed world first, and to then progress to the developing world as economies of scale bring down costs. Broadly, we expect this trend to continue, so that the new services and applications predicted here might reach the developing world perhaps a decade or so later, depending on the cost of the service.

However, as applications platforms are developed and the communicator devices become more flexible, there is an increased possibility of applications emerging specifically tailored at developing countries. For example, these might be semi-automated wireless trading solutions, allowing simpler sale of commodity goods in an agricultural community. Indeed, it is likely that the enhanced communicator device will make a greater change to the lives of those in developing countries than in developed. This is because in developing countries, it might enable completely new ways of working, whereas in developed countries, it seems likely to enhance productivity but broadly maintain the same working patterns. In summary, the future wireless communicator will take longer to reach the developing countries, but may have a greater impact when it finally arrives.

Summary

This paper has set out why it is possible to predict the next 20 years of wireless with reasonable certainty. For the user, the next 20 years will see a very substantial but steady change. Users will come to rely on their handset as a single device to manage their communications and, indeed, much of their life. It will truly become a "remote control on life," with massively enhanced capabilities, including huge storage, advanced methods of user interaction such as speech recognition, and many in-built tools, such as cameras, music players, wallet, keys, etc. Users will cease to differentiate between different communications channels, and instead see the world as one large communications network, able to provide them whatever content they need wherever they are. Users will also no longer see broadcasting and communications as separate, and indeed, the concept of broadcasting will change dramatically to one of content provision that is sought out by users: more like the publishing model of today. Users will perceive their lives becoming more convenient, both in the home and wider area. At home, their home wireless systems will automate a range of tasks and provide new capabilities, such as suggesting menus based on the contents of the refrigerator. Out of the home, their devices will book and alter travel according to conditions, manage diaries, and ensure appropriate information is available.

Achieving all of this will require little in the way of change for wireless technology, which is already capable of delivering more-than-adequate data rates and services if deployed with sufficient density – and indeed, no further significant advances in wireless technology are expected. As a result, no new generations of wireless network or widespread network deployments are predicted, although existing networks will be much enhanced. However, there will be substantial progress in the intelligent systems that use context to configure devices appropriately, control interaction with the handset, and control home and office networks in a simple, yet intelligent manner. Battery and backhaul will remain areas where substantial progress would make a significant difference, but the barriers will be such that only steady improvements can be expected.

Overall, the future is marked by an initial period of stability, as 3G and broadband networks are built out, followed by a short period of upheaval, as the industry structure changes dramatically and new services and service providers emerge: this is the point at which convergence truly happens. Beyond this, the underlying wireless-communications infrastructure will become a slow-changing utility, similar, for example, to railways or, increasingly, the core Internet infrastructure, but with substantial excitement and growth around the services provided on top of this wireless platform.

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Radio Science Doctoral Abstracts

Robert C. Moore, ***ELF/VLF Wave Generation by Modulated HF Heating of the Auroral Electrojet***, Department of Electrical & Electronic Engineering, University of Stanford, March 2007; E-mail: robert.moore@gmail.com.
Relevant Commission: B

Abstract

The generation of electromagnetic waves in the extremely-low-frequency (ELF, 3-3000 Hz) and very-low-frequency (VLF, 3-30 kHz) bands by modulated high-frequency (HF, 3-30 MHz) heating of the auroral-electrojet current system is investigated experimentally, and observations are compared against the predictions of a theoretical model.

Experimental evidence is presented to demonstrate the regular occurrence of ELF/VLF amplitude saturation as a function of peak HF power level. The observed ELF/VLF amplitude saturation is examined as a function of modulation frequency and as a function of time of day. For modulation depths less than 100%, the dependence of ELF/VLF amplitude on average HF power is investigated, yielding an optimal average HF power level that maximizes the observed ELF/VLF amplitude. Observations of ELF/VLF amplitude saturation under a large range of geomagnetic conditions indicate that the identified saturation process occurs on a regular basis. Furthermore, observations indicate that the spatial distribution of the modulated ionospheric conductivity can be remotely sensed using ground-based measurements of the horizontal component of the generated ELF/VLF magnetic-flux density. Each of these experimental observations is interpreted in the context of an HF heating model that accounts for the Earth's magnetic field and for the altitudinal variation of several ionospheric constituents. This model indicates that the variation in ELF/VLF amplitude at low HF power levels is dominated by the HF self-absorption process, whereas the variation in ELF/VLF amplitude at high HF power levels results from the competition between the electron energy losses associated with the rotational excitation of molecular nitrogen and the vibrational excitation of molecular oxygen.

Cesar O. Noguera, ***Development of Two New Ionospheric Indices***, Department of Physics, Utah State University, 4415 Old Main Hill, Logan, UT 84322-4415, USA, April 2007; E-mail: cnoguera@cc.usu.edu.
Relevant Commission: G.

Abstract

The solar terrestrial environment presently is characterized by a suite of indices that represent the system dynamics and indicate the degree of space-weather effects. These indices have extended heritage, based on measurements that are well calibrated and readily available. Examples of these are the solar radio flux at 10.7 cm (F10.7), magnetospheric currents inferred from ground-based magnetographs (Dst), and the auroral electrojet, also based on ground-based magnetograms (AE family of indices). At the present time, the ionospheric dynamics and response to space weather are not characterized by a "true" ionospheric index. However, because ionospheric plasma variability is a major adverse effect on mankind's space technologies, the creation of such an index may be appropriate. The major adverse effects are associated with radiowave propagation, either communication or navigation, through the ionosphere. Over the past decade, thousands of ground-based dual-frequency GPS receivers have been deployed, each of which measures ionospheric total electron content (TEC) continuously in multiple directions. Hence, with the standardized formatting of these measurements and their relatively real-time nature, a unique ionospheric data stream exists from which indices can, in principle, be developed. This study is an initial exploration of how purely an ionospheric index could be derived from these GPS-TEC data. Regional versus global issues are addressed, as well as diurnal issues.

Gopi Krishna Seemala, ***Studies on Spatial and Temporal Characteristics of TEC and L-Band Scintillations and their Possible Impact on GPS-Based Navigation Systems in the Indian Sector***, Space Physics Laboratories, Department of Physics, Andhra University, Visakhapatnam, India, April 2007; E-mail: toyoursgopi@yahoo.com.
Relevant Commission: G

Abstract

In recent times the behavior of the ionosphere and plasmasphere – particularly during space-weather-related events such as geomagnetic storms and ionospheric scintillations – have gained importance, owing to applications in satellite-based navigation and such other transionospheric communication systems. In the context of the proposed implementation of the GAGAN (GPS-Aided Geo-Augmented Navigation) project in India, similar to that of WAAS (Wide-Area Augmentation System) in the United States, a detailed investigation of the spatial and temporal behavior of the total electron content (TEC) and

L-band scintillations (GPS), and geomagnetic activity related studies, have become important. For the first time, a comprehensive, simultaneous, and coordinated set of measurements of TEC and L-band scintillations from a network of 18 GPS receivers, located in different parts of India during the period 2004-2006, have been carried out. The various results are presented in a total of six chapters in this thesis.

Eliana Yepez, ***Prediction of Single and Multi-User Downlink Channel Capacities Based on Multiple Antenna Propagation Measurements***, Department of Systems and Computer Engineering, Ottawa-Carleton Institute for Electrical and Computer Engineering, Faculty of Engineering, Carleton University, Ottawa, ON, Canada, May 2007;
E-mail: elianayepez@gmail.com.
Relevant Commissions: C, F

Abstract

In this thesis, we develop methods to analyze the capacities of multiple-antenna channels based on a limited number of radio-propagation measurements. The results can be applied to the deployment of high-speed fixed Internet wireless services. We design and build a multiple-antenna broadband channel sounder to measure the radio channel. In our measurements, the four-antenna base station (BS), located at the rooftop of a building, transmits to four non-line-of-sight users. Each user, also equipped with four antennas, is located inside a different building. Our objective is to compare the downlink channel capacity of an orthogonal space-division multiplexing (OSDM) scheme, where the BS transmits simultaneously to all users, with that of a time-division multiplexing (TDM) scheme, where the BS transmits to each user in a different time slot. We select these schemes because they exploit the channel differently. At each channel use, the spatial sub-channels in OSDM are orthogonal by means of transmit-receive spatial processing, but they may be unbalanced due to largely separated users. The spatial sub-channels of each user in TDM are balanced but they may not be orthogonal, due to the nearly co-located antennas of each user. Initially, we analyze the data to predict the capacities of the single-user channels. We find that a significant amount of shadowing on the measured channels, which causes variations in the mean power for each receive sub-area, can severely affect their capacities. The importance of this analysis is the connection we make between channels with shadowing and their capacities. We extend this analysis to multi-user channels and find that they are mainly affected by variations in the mean received powers for each user due to different transmitter-user separations. We show that compared to TDM, the capacity of OSDM is more sensitive to these power variations.

Dongson Zeng, ***Pulse Shaping Filter Design and Interference Analysis in UWB Communication Systems***, The Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Falls Church, Virginia, USA, September 2005;
Email: dongsong.zeng@honeywell.com,
Relevant Commission: C

Abstract

Ultra-wideband (UWB) is a promising technology for short-range and high-speed wireless communications, such as home entertainment, wireless video downloading, wireless LAN, wireless USB, and so on. This dissertation investigates several critical aspects of UWB technology, such as UWB pulse selection, pulse-shaping filter design, UWB RAKE receiver, etc. Its findings and novelties are summarized as follows.

First, a two-stage optimal UWB pulse-shaping filter-design procedure is proposed, which not only satisfies the FCC transmission spectral masks, but also suppresses the multiple-access interference (MAI). The major advantages of the proposed joint optimization method are that (1) it has superior MAI suppression capability, and that (2) it can achieve the best system performance by jointly optimizing transmitting and receiving filters. Second, a pulse-shaping optimizer is proposed to achieve the best received signal-to-noise ratio (SNR). Since the objective function of the SNR optimization has multiple maxima, genetic algorithms are adopted in this all-pass filter optimization. Third, a novel analytical method of assessing the narrowband performance degradation due to UWB interference is proposed. This method models the UWB interference as a composite signal of white Gaussian noise and jamming tones. Finally, a RAKE receiver simulation model under a realistic UWB channel is proposed, and numerical results are presented. Overall, this dissertation not only studies several important issues in the real-world application of UWB technology, and but also provides valuable insights into the role of UWB technology in the evolving course of wireless communications.

Call for Submissions

In order to encourage dialogue with young radio scientists, the *Radio Science Bulletin* publishes the abstracts of relevant doctoral dissertations or theses in the fields of radio science as soon as they are approved by universities or other degree-awarding institutions.

We thus call upon supervisors or research-group leaders to bring this opportunity to the attention of recently qualified doctoral graduates, asking them to e-mail their abstracts to the address given below. The date of publication should be given, with full details of the address of the awarding institution, and also an e-mail address for the author. It would also be helpful to indicate which URSI Commissions relate most closely to the doctoral work.

Peter Watson, University of Bath
E-mail: rsbursi@bath.ac.uk

CONFERENCE REPORT

Rarotonga Energetic Particle Workshop 2007

Rarotonga, Cook Islands, 6 - 10 August 2007

A small but focused workshop was held in Rarotonga, the Cook Islands, supported by URSI Commission H. The Rarotonga Energetic Particle Workshop (REPW) 2007 built upon a series of informal workshops which have taken place over recent years, targeted at active researchers in the field of energetic particle dynamics in the inner magnetosphere. The workshop was organised by Craig Rodger (Univ. Otago, New Zealand) and Anthony Chan (Rice Univ., USA), and follows on from their earlier International Space Environment Conference (ISEC) held in Queenstown, New Zealand, in 2001. The organisers were keen to keep the link to New Zealand, our home country, but move away from the winter climate. For these reasons REPW was held in the Cook Islands, a self-governing parliamentary democracy in free association with New Zealand.

The URSI support to our workshop enabled a PhD student to come to REPW and to interact with the scientists assembled there.

Presentations focused on the dynamics of electrons in the Earth's radiation belts, and particularly the impact of geomagnetic storms and electromagnetic waves upon the belts. Our colleagues reported on data analysis, modelling or theory of the acceleration, transport and loss of these particles. Participants made full use of the time available in the programme, and also of the workshop nature of the meeting, with long discussion sessions during talks.

Looking back at recent workshops in this area, there has been strong disagreements as to the relative importance of differing mechanisms which lead to energisation of radiation belt electrons to relativistic energies. Two classes of mechanisms are thought to be especially important for relativistic electrons: (1) Local acceleration and loss by cyclotron-resonant interaction with VLF/ELF waves, and (2) radial transport by drift-resonant interaction with electromagnetic perturbations in the ULF frequency range. However, at REPW we saw evidence of a growing consensus in the community, with both local acceleration by cyclotron-resonance and radial transport playing a role. Most participants accepted that relativistic electrons observed in the heart of the radiation belts were produced by cyclotron-resonant local acceleration processes, but that radial transport plays a vital role in providing the seed population of electrons and in re-distributing locally-accelerated particles. In addition, the waves which dominate the cyclotron-resonant interaction are still to be established. While most speakers in this area focused upon acceleration by various types of ELF/VLF, one example of localised acceleration by ULF waves was also presented. Speakers also described important loss processes, and the significance of the ring current and EMIC waves in controlling radiation belt dynamics.

A full listing of abstracts can be found at: http://www.physics.otago.ac.nz/space/REPW_files/REPW_2007_Abstracts_Listing.pdf

Craig J. Rodger, Anthony Chan

REPW 2007 group photo at the edge of The Rarotongan's hotel complex.

URSI CONFERENCE CALENDAR

February 2008

ICRS 2008 - International Conference on Radio Science
Jodhpur, India, 25-29 February 2008
cf. Announcement in the Radio Science Bulletin of June 2007, p. 56.
Contact : Prof. O.P.N. Calla, Director ICRS, OM-NIWAS, A-23 Shastri Nagar, Jodhpur 342003, Rajasthan, India, Fax +91 291-2626166, E-mail : opncalla@yahoo.co.in , E-mail : http://radioscience.org/default.html

March 2008

MicroRad 2008 - the 10th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment
Florence, Italy, 11 -14 March 2008
cf. Announcement in the Radio Science Bulletin of September 2007, p. 55 -56
Contact: Dr. Simonetta Paloscia, CNR-ITAC, Via Madonna del Piano, 10, 50019 Sesto Fiorentino, Firenze, Italy, Fax: +390 55 5226467, Email: info@microrad2008.org, Web: htpp://www.microrad2008.org

May 2008

META'08, NATO Advanced Research Workshop:Metamaterials for Secure Information and Communication Technologies
Marrakesh, Morocco, 7 - 10 May 2008
cf. Announcement in the Radio Science Bulletin of June 2007, p. 57.
Contact: Prof. Saïd Zouhdi, Laboratoire de Génie Electrique de Paris (LGEP-Supélec), Plateau de Moulon, 91192 Gif-Sur-Yvette Cedex, France, Tel: +33 1 69851660, Fax: +33 169418318, Email: said.zouhdi@supelec.fr, Web site: http://meta.lgep.supelec.fr

9th International Workshop on Finite Elements in Microwave Engineering
Bonn, Germany, 8 - 9 May 2008
cf. Announcement in the Radio Science Bulletin of September 2007, p. 55.
Contact: FEM2008 Secretariat, c/o Theoretische Elektrotechnik, Saarland University, Building C63, P.O. Box 151150, D-66041 Saarbrucken, Germany, Tel: +49 681 302 2551, Fax: +49 681 302 3157, Web: http://www.lte.uni-saarland.de/fem2008

IES2008 - 12th International Ionospheric Effects Symposium
Alexandria, Virginia, USA, 13-15 May 2008
Contact : JMG Associates Ltd., IES Symposium Managers, 8310 Lilac Lane, Alexandria VA 22308, USA, Fax: +1-703-360-3954, Web : http://www.ies2008.com/index.html

ISEA-12 - 12th International Symposium on Equatorial Aeronomy
Crete, Greece, 18 - 24 May 2008
Contact: Christos Haldoupis, Physics Department, University of Crete, Heraklion, Crete 71003, Greece, Tel: +30 2810 394222, Fax: +30 2810 394201, Email: isea12@physics.uoc.gr, chald@physics.uoc.gr, Web: http://isea12.physics.uoc.gr/

July 2008

COSPAR 2008 - 37th Scientific Assembly of the Committee on Space Research and Associated Events "50th Anniversary Assembly"
Montreal, Canada, 13 - 20 July 2008
cf. Announcement in the Radio Science Bulletin of March 2007, p. 58.
Contact : COSPAR Secretariat, c/o CNES, 2 place Maurice Quentin, 75039 Paris Cedex 01, France, Tel: +33 1 44 76 75 10, Fax: +33 1 44 76 74 37, E-mail : cospar@cosparhq.cnes.fr, Web : http://www.cospar2008.org

EUROEM 2008 - European Electromagnetics
Lausanne, Switzerland, 21-25 July 2008
Contact : EUROEM'08, EPFL-STI- LRE, Station 11, CH-1015 Lausanne, Switzerland, Tel : +41-21-693 26 20, Fax : +41-21-693 46 62, E-mail: information@euroem.org, Web : http://www.euroem.org

August 2008

URSI GA08 - XXIXth URSI General Assembly
Chicago, IL, USA, 9-16 August 2008
Contact : URSI Secretariat, c/o INTEC, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium, Tel. : +32 9 264 3320, Fax : +32 9 264 4288, E-mail : info@ursi.org

September 2008

EMC Europe 2008
Hamburg, Germany, 8 - 12 September 2008
Contact: EMC Europe 2008, Harburger Schlossstrasse 6 - 12, 21079 Hamburg, Germany, Tel: +49 40 76629 6551, Fax: +49 40 76629 6559, Email: info@emceurope2008.org, Web: http://www.emceurope2008.org

URSI cannot be held responsible for any errors contained in this list of meetings

News from the URSI Community

BOOK PUBLISHED BY AN URSI RADIOSCIENTIST

Seismo-electromagnetics and related phenomena: History and latest results

By O.A. Molchanov and M. Hayakawa, Terra Scientific Publishing Company (TERRAPUB), 2007, 190 p., Hardcover, ISBN 978-4-88704-143-1

About this book

This monograph is devoted to essential aspects of recent activity in a rather new field of research known as Seismo-Electromagnetics and Related Phenomena (SERP). This field becomes firmly established since early nineties of 20th century and it differs both in methods and ideology from its predecessor which was known long time as nonseismic precursors of earthquakes (hereafter EQs).

About 15 years ago a conceptual breakdown happened in seismology. It was discovered that conventional models of EQ preparation were not valid and doubts were appearing as to the possibility of successful EQ prediction using purely seismic observations. Heterogeneity and nonlinearity in seismic processes in a state of the so-called self-organized criticality causing unpredictable behavior of tectonically activated regions after some time of consideration (limited "memory" of the system) have been understood. At the same time ideas on new alternative field methods with a particular emphasis on radio-physical sounding and even satellite observation were emerged. They gradually took the place of traditional studies on the quasi-steady electric and magnetic fields, resistivity, magneto-telluric impedance, geodetic changes, which were found to be inefficient. By that stage enthusiastic groups in several countries had already shown some evidence of seismo-electromagnetic phenomena. An example is discovery of ULF seismo-magnetic emissions in USA and Russia.

Unless we launch a concentrated interdisciplinary effort, we shall always be surprised by next major EQ. This vision is in close agreement with our present point of view except one important detail: even at present scientific community is not ready to suggest any prediction scheme. So this book is not about EQ prediction or EQ precursors. It is concerned with electromagnetic and other nonseismic phenomena which accompany a large EQ shock. Based on the results of recent prominent projects in Japan and Russia we believe that non-seismic events are not only helpful to work out the real strategy (scientific basis) for future probabilistic EQ forecast but also they indicate mechanisms of preseismic and postseismic processes. In addition a problem of lithosphere-atmosphere-ionosphere coupling due to seismicity arises as a result of application of radio-physical and satellite recording methods.

Because of numerous publications on the subject we need to constrain our statement of contents. Firstly, we consider only short-time events, i.e. phenomena with temporal scale from a few weeks before to a few weeks after the EQ date and in nearby zones of the EQ epicenter. From seismological point of view it is a frame of so-called foreshocks-main shock- aftershocks sequence. Secondly, we do not discuss events, which were revealed in a case study, but not checked afterwards by reliable statistics. The third, we pay main attention to the events that can be explained by understandable physical mechanisms and can be computed in modeling up to observation values. Justification of these constrains and of our selection is presented in the Introduction chapter. Finally, due to the book volume limits we concentrate on the results during recent 10-12 years when we have been actively involved in such a research.

The shock and sorrow following the great Kobe EQ in Japan (17 January, 1995) motivated the Japanese government to establish the special research programs to investigate short-term (at least) EQ forecasting. It was driven by a general demand from the Japanese population for warning of such disastrous events. These programs included the Frontier/RIKEN and Frontier/NASDA projects, which investigated the electromagnetic effects associated with seismicity. The similar program under aegis of ISTC (International Science Technology Center) is now being conducted in Russia, where a special complex observatory in Kamchatka peninsula is operating since 2000. Thus, it is no surprise that a large proportion of this book contains Japanese and Russian results. However, many valuable inputs have also been provided by groups from China, France, Italy, Greece, USA, Ukraine, Mexico, Taiwan, Israel, and India. This demonstrates the international scope of the research activity.

The main reason for writing this book is to systematize a lot of material on the topic, which is spread out now in about 100 original papers published by the authors during the last 12 years. Another motivation is to prepare a supplementary guidebook for the students and young researchers. At last we are going to present state of art of this fast-developing multi-disciplinary science that, in our opinion, only recently overcomes a semi-professional level and is necessary in distinguishing from overoptimistic and almost amateur reports.

The book has a potential to be useful for students and researchers who are interested in the modern problems of the Earth physics and radio-physics. It will be especially attractive to scientific community in different countries, which are vulnerable to seismic hazard and to whom new approaches to EQ prevention are a subject of not only academic interest. We try not to overburden the book by complicated mathematics, so that the necessary relations are put in Appendices and captious persons can find details in the original papers.

Table of Contents

About the Authors

O. A. Molchanov works now at Institute of Physics of the Earth, Russian Academy of Sciences, Russia. He has been strongly affiliated with URSI, and he has been and is co-chair of many sessions in the URSI.

M. Hayakawa works at The University of Electro-Communications, Chofu Tokyo Japan. He was the Japanese URSI Commission E chair and was also the URSI Commission E chair (1996-1999). He has been chairs of URSI Commission E working groups and he is now co-chair of URSI Joint Commission (E, G, H) working group on Seismo Electromagnetics.

International Geophysical Calendar 2008*

	S	M	T	W	T	F	S
JANUARY			1	2	3	4	5
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FEBRUARY	3	4	5	6	7 N	8	9
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31	1	2	3	4	5	6	SEPTEMBER
7	8	9	10	11	12	13	
14	15 F	16	17	18	19	20	
21	22	23	24*	25*	26	27	
28	29 N	30 +	1 +	2 +	3	4	
5	6	7	8	9	10	11	OCTOBER
12	13	14 F	15	16	17	18	
19	20	21	22*	23*	24	25	
26	27	28 N +	29 +	30 +	31	1	
2	3	4	5	6	7	8	NOVEMBER
9	10	11	12	13 F	14	15	
16	17	18	19*	20*	21	22	
23	24	25	26	27 N	28 +	29 +	
30 +	1	2	3	4	5	6	DECEMBER
7	8	9	10	11	12 F	13	
14	15	16	17	18	19	20	
21	22	23	24*	25*	26	27 N	
28	29	30	31	1	2	3	2009
4	5	6	7	8	9	10	JANUARY
11 F	12	13	14	15	16	17	
18	19	20	21*	22*	23	24	
25	26 N	27	28	29	30	31	
S	M	T	W	T	F	S	

15 Regular World Day (RWD)

16 Priority Regular World Day (PRWD)

12 Quarterly World Day (QWD) also a PRWD and RWD

2 Regular Geophysical Day (RGD)

10 11 World Geophysical Interval (WGI)

\+ Incoherent Scatter Coordinated Observation Day

N NEW MOON   F FULL MOON

7 Day of Solar Eclipse: Feb 7(annular) and Aug 1 (total)

9 10 Airglow and Aurora Period

8* Dark Moon Geophysical Day (DMGD)

This Calendar continues the series begun for the IGY years 1957-58, and is issued annually to recommend dates for solar and geophysical observations, which cannot be carried out continuously. Thus, the amount of observational data in existence tends to be larger on Calendar days. The recommendations on data reduction and especially the flow of data to World Data Centers (WDCs) in many instances emphasize Calendar days. The Calendar is prepared by the International Space Environment Service (ISES) with the advice of spokesmen for the various scientific disciplines. For some programs, greater detail concerning recommendations appears from time to time published in IAGA News, IUGG Chronicle, URSI Information Bulletin and other scientific journals or newsletters. For on-line information, see **http://www.ises-spaceweather.org.**

The definitions of the designated days remain as described on previous Calendars. Universal Time (UT) is the standard time for all world days. Regular Geophysical Days (RGD) are each Wednesday. Regular World Days (RWD) are three consecutive days each month (always Tuesday, Wednesday and Thursday near the middle of the month). Priority Regular World Days (PRWD) are the RWD which fall on Wednesdays. Quarterly World Days (QWD) are one day each quarter and are the PRWD which fall in the World Geophysical Intervals (WGI). The WGI are fourteen consecutive days in each season, beginning on Monday of the selected month, and normally shift from year to year. In 2008 the WGI are March, June, September and December.

2008 Solar Eclipses:

a) **February 27, 2008, annular eclipse**, up to 2 m 12 s, visible only over Antarctica, the part south of South America. Partial phases include eastern Australia and New Zealand.
b) **August 1, 2008, total solar eclipse**, beginning in the northern Canadian islands, continuing over Greenland, and descending through Russia's Siberia (maximum totality of 4 m 29 s, with totality including Novosibirsk with 3 m), and then western Mongolia and China (near Xian). The partial phases will be visible through much of Europe (northeast of southern France and mid-Italy) and most of Asia (though excepting Japan and southern Malaysia and Indonesia).

Information provided by Jay M. Pasachoff, Chair, on behalf of the International Astronomical Union Working Group on Eclipses based on calculations from Fred Espenak, NASA's Goddard Space Flight Center, and information from Jay M. Pasachoff, Peterson Field Guide to the Stars and Planets; see http://www.eclipses.info.

Eclipse References:

- Fred Espenak, Fifty Year Canon of Solar Eclipses: 1986-2035, NASA Reference Publication 1178 Revised, July 1987.
- Leon Golub and Jay M. Pasachoff, The Solar Corona, Cambridge University Press, 1998. http://www.williams.edu/Astronomy/corona
- Jay M. Pasachoff and Alex Filippenko, The Cosmos: Astronomy in the New Millennium, Brooks/Cole Publishers, 2004. http://info.brookscole.com/pasachoff Brooks/Cole Publishing, 2002. http://www.williams.edu/Astronomy/jay
- Leon Golub and Jay M. Pasachoff, Nearest Star: The Exciting Science of Our Sun, Harvard University Press, 2001. http://www.williams.edu/astronomy/neareststar
- Jay M. Pasachoff, The Complete Idiot's Guide to the Sun, Alpha Books, 2003, http://www.williams.edu/astronomy/sun.

Meteor Showers (selected by P. Jenniskens, SETI Institute, Mountain View, CA, pjenniskens@mail.arc.nasa.gov):
*****Preliminary – based on 2007 input*****

a) Meteor outbursts are unusual showers (often of short duration) from the crossing of relatively recent comet ejecta. Dates for year 2008:

- Apr 28, 17:28 UT, alpha-Bootids (RA = 219º, Decl. = +19º): possible encounter with 1-revolution (1-rev) dust trail of unknown parent comet;
- Aug 12, 22:42 UT, Perseids: encounter with the 1479-dust trail of 109P/Swift-Tuttle; Aug 13, about 04h UT: possible encounter with older Filament debris of 109P/Swift-Tuttle;
- Sep 1, 11:37 UT: Aurigids (RA = 90º, Decl. = +39º) outburst (possible storm) from 1-rev trail of comet C/1911 N1 (Kiess);
- Nov 18, 23:03 UT, Leonids: encounter with the 1932 dust (2-rev) ejecta of comet 55P/Tempel-Tuttle; also possible older Filament encounter at about Nov 19 00:19 UT.
- Dec 21, 03:40 UT: alpha-Lyncids (RA = 138º, Decl. = +44º): possible encounter with 1-revolution dust trail of unknown parent comet;
- Dec 22, about 20h UT, Ursids: possible outburst from Filament of comet 8P/Tuttle.

b) Regular meteor showers: The dates (based on UT in year 2008) for regular meteor showers are: Jan 1-6, peak Jan 04 03:22 UT (Quadrantids); Apr 16-25, peak Apr 23 01h UT (Lyrids); Apr 19-May 28, peak May 05 09h UT, broad component peaks at May 07 23h UT (Eta-Aquariids); May 22-July 02, peak Jun 07 23h UT (Daytime Arietids); May 20-July 05, peak Jun 09 22h UT (Daytime Zeta-Perseids); Jun 05-July 17, peak Jun 28 21h (Daytime Beta-Taurids); Jul 8-Aug 19, peak Jul 29 04h UT (S. Delta-Aquariids); Jul 17-Aug 24, peak Aug 13 09:57 UT (Perseids); Sep 26-Oct 03, peak Oct 02 01h UT (Daytime Sextantids); Oct 02-Nov 07, peak Oct 22 12h UT, bright meteors peak at Oct 18 09h UT (Orionids); Oct 31-Nov 23, peak Nov 17 23h UT (Leonids); Nov 27-Dec 18, peak Dec 14 13:56 UT (Geminids); Dec 17-26, peak at Dec 23 08h UT 2007 (Ursids).

Meteor Shower Websites:

- Shower activity forecast for given location (Peter Jenniskens): http://leonid.arc.nasa.gov/estimator.html
- International Meteor Organization: http://www.imo.net
- Institut de Mécanique céleste et de calcul des éphémérides: http://www.imcce.fr/page.php?nav=en/ephemerides/phenomenes/meteor/index.php

References:
Peter Jenniskens, Meteor showers and their parent comets. Cambridge University Press, 2006.

The occurrence of **unusual solar or geophysical conditions** is announced or forecast by the ISES through various types of geophysical **"Alerts"** (which are widely distributed by telegram and radio broadcast on a current schedule). Stratospheric warmings (STRATWARM) are also designated. The meteorological telecommunications network coordinated by WMO carries these worldwide Alerts once daily soon after 0400 UT. For definitions of Alerts see ISES "Synoptic Codes for Solar and Geophysical Data", March 1990 and its amendments (http://ises-spaceweather.org). Retrospective World Intervals are selected and announced by MONSEE and elsewhere to provide additional analyzed data for particular events studied in the ICSU Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) programs.

Recommended Scientific Programs (Final Edition): (The following material was reviewed in 2007 by spokesmen of IAGA, WMO and URSI as suitable for coordinated geophysical programs in 2008.)

- **Airglow and Aurora Phenomena**. Airglow and auroral observatories operate with their full capacity around the New Moon periods. However, for progress in understanding the mechanism of many phenomena, such as low latitude aurora, the coordinated use of all available techniques, optical and radio, from the ground and in space is required. Thus, for the airglow and aurora 7-day periods on the Calendar, ionosonde, incoherent scatter, special satellite or balloon observations, etc., are especially encouraged. Periods of approximately one weeks' duration centered on the New Moon are proposed for high resolution of ionospheric, auroral and magnetospheric observations at high latitudes during northern winter.
- **Atmospheric Electricity.** Non-continuous measurements and data reduction for continuous measurements of atmospheric electric current density, field, conductivities, space charges, ion number densities, ionosphere potentials, condensation nuclei, etc.; both at ground as well as with radiosondes, aircraft, rockets; should be done with first priority on the RGD each Wednesday, beginning on 2 January 2008 at 0000 UT, 9 January at 0600 UT, 16 January at 1200 UT, 23 January at 1800 UT, etc. (beginning hour shifts six hours each week, but is always on Wednesday). Minimum program is at the same time on PRWD beginning with 16 January at 1200 UT. Data reduction for continuous measurements should be extended, if possible, to cover at least the full RGD including, in addition, at least 6 hours prior to indicated beginning time. Measurements prohibited by bad weather should be done 24 hours later. Results on sferics and ELF are wanted with first priority for the same hours, short-period measurements centered around the minutes 35-50 of the hours indicated. Priority Weeks are the weeks that contain a PRWD; minimum priority weeks are the ones with a QWD. The World Data Centre for Atmospheric Electricity, 7 Karbysheva, St. Petersburg 194018, USSR, is the collection point for data and information on measurements.
- **Geomagnetic Phenomena.** It has always been a leading principle for geomagnetic observatories that operations should be as continuous as possible and the great majority of stations undertake the same program without regard to the Calendar.
  Stations equipped for making magnetic observations, but which cannot carry out such observations and reductions on a continuous schedule are encouraged to carry out such work at least on RWD (and during times of MAGSTORM Alert).
- **Ionospheric Phenomena.** Special attention is continuing on particular events that cannot be forecast in advance with reasonable certainty. These will be identified by Retrospective World Intervals. The importance of obtaining full observational coverage is therefore stressed even if it is possible to analyze the detailed data only for the chosen events. In the case of vertical incidence sounding, the need to obtain quarter-hourly ionograms at as many stations as possible is particularly stressed and takes priority over recommendation (a) below when both are not practical.
- For the **vertical incidence (VI) sounding program**, the summary recommendations are:

(a) All stations should make soundings on the hour and every quarter hour;
(b) On RWDs, ionogram soundings should be made at least every quarter hour and preferably every five minutes or more frequently, particularly at high latitudes;
(c) All stations are encouraged to make f-plots on RWDs; f-plots should be made for high latitude stations, and for so-called "representative" stations at lower latitudes for all days (i.e., including RWDs and WGIs) (Continuous records of ionospheric parameters are acceptable in place of f-plots at temperate and low latitude stations);
(d) Copies of all ionogram scaled parameters, in digital form if possible, be sent to WDCs; (e) Stations in the eclipse zone and its conjugate area should take continuous observations on solar eclipse days and special observations on adjacent days. See also recommendations under Airglow and Aurora Phenomena.

- For the **incoherent scatter observation program**, every effort should be made to obtain measurements at least on the Incoherent Scatter Coordinated Observation Days, and intensive series should be attempted whenever possible in WGIs, on Dark Moon Geophysical Days (DMGD) or the Airglow and Aurora Periods. The need for collateral VI observations with not more than quarter-hourly spacing at least during all observation periods is stressed.

Special programs include:

CAWSES – Climate and Weather of the Sun-Earth System, (S. Avery – susan.avery@colorado.edu.

CEDAR — Coupling, Energetics & Dynamics of

Atmospheric Regions (http://cedarweb.hao.ucar.edu/);
GEM – Geospace Environment Modeling (http://www-ssc.igpp.ucla.edu/gem/);
MST – Studies of the Mesosphere, Stratosphere, and Troposphere — Coordinated D- and E-region campaigns focusing on lower altitudes, with JRO in high resolution MST mode – gravity wave momentum fluxes (G. Lehmacher – glehmac@clemson.edu);
C/NOFS: Communications/Navigation Outage Forecasting System (Odilie de LaBeaujardiere – Odilie.delaBeaujardiere@hanscom.af.mil)
Stratospheric Warmings = Dynamics and temperature of the lower thermosphere during sudden stratospheric warming – ten days of observation in February (L. Goncharenko — lpg@haystack.mit.edu);
Synoptic – Wide coverage of the F-region, augmented with topside or E-region measurements – broad latitudinal coverage (W. Swartz – wes@ece.cornell.edu).
TEC Mapping = ISR/GPS Coordinated Observation of Electron Density Variations (Shun-Rong Zhang — shunrong@haystack.mit.edu);
TIDs Quasi-Periodic Medium-Scale = Latitude dependence of the F-Region plasma variations during the passage of medium-scale Traveling Ionospheric Disturbances (MSTIDs) – continuous vertical power profiles through E/F regions (100-800 km) with best time resolution possible (5 minutes or better) (J.D.Mathews — JDMathews@psu.edu)
International Polar Year continuation of year-long observations with Jicamarca, Poker Flat, EISCAT Svalbard ISRs (Tony van Eyken — Tony.van.Eyken@eiscat.se)
AO — Arecibo Obs (http://www.naic.edu/aisr/olmon2/omframedoc.html);
JRO – Jicamarca Radio Observatory (http://jro.igp.gob.pe/english/radar/operation/real-time_en.php).

Special programs: Dr. Wesley E. Swartz, 316 Rhodes Hall, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA. Tel. 607-255-7120; Fax 607-255-6236; e-mail: wes@ece.cornell.edu; URSI Working Group G.5.
See http://people.ece.cornell.edu/wes/URSI_ISWG/2008WDschedule.htm for complete 2008 definitions.

- For the **ionospheric drift or wind measurement** by the various radio techniques, observations are recommended to be concentrated on the weeks including RWDs.
- For **traveling ionosphere disturbances**, propose special periods for coordinated measurements of gravity waves induced by magnetospheric activity, probably on selected PRWD and RWD.
- For the **ionospheric absorption program** half-hourly observations are made at least on all RWDs and half-hourly tabulations sent to WDCs. Observations should be continuous on solar eclipse days for stations in eclipse zone and in its conjugate area. Special efforts should be made to obtain daily absorption measurements at temperate latitude stations during the period of Absorption Winter Anomaly, particularly on days of abnormally high or abnormally low absorption (approximately October-March, Northern Hemisphere; April-September, Southern Hemisphere).
- For **back-scatter and forward scatter programs**, observations should be made and analyzed at least on all RWDs.
- For **synoptic observations of mesospheric** (D region) electron densities, several groups have agreed on using the RGD for the hours around noon.
- For **ELF noise measurement**s involving the earth-ionosphere cavity resonances any special effort should be concentrated during the WGIs.

It is recommended that more intensive observations in all programs be considered on days of unusual meteor activity.

- **Meteorology.** Particular efforts should be made to carry out an intensified program on the RGD — each Wednesday, UT. A desirable goal would be the scheduling of meteorological rocketsondes, ozone sondes and radiometer sondes on these days, together with maximum-altitude rawinsonde ascents at both 0000 and 1200 UT.
- During **WGI and STRATWARM Alert Intervals**, intensified programs are also desirable, preferably by the implementation of RGD-type programs (see above) on Mondays and Fridays, as well as on Wednesdays.
- **Global Atmosphere Watch (GAW).** The World Meteorological Organizations (WMO) GAW integrates many monitoring and research activities involving measurement of atmospheric composition. Serves as an early warning system to detect further changes in atmospheric concentrations of greenhouse gases, changes in the ozone layer and in the long range transport of pollutants, including acidity and toxicity of rain as well as of atmospheric burden of aerosols (dirt and dust particles). Contact WMO, 7 bis avenue de la Paix, P.O. Box 2300, 1211 Geneva, Switzerland.
- **Solar Phenomena.** Observatories making specialized studies of solar phenomena, particularly using new or complex techniques, such that continuous observation or reporting is impractical, are requested to make special efforts to provide to WDCs data for solar eclipse days, RWDs and during PROTON/FLARE ALERTS. The attention of those recording solar noise spectra, solar magnetic fields and doing specialized optical studies is particularly drawn to this recommendation.
- **CAWSES (Climate and Weather of the Sun-Earth System).** Program within the SCOSTEP (Scientific Committee on Solar-Terrestrial Physics): 2004-2008. Its focus is to mobilize the community to fully utilize past, present, and future data; and to produce improvements in space weather forecasting, the design of space- and Earth-based technological systems, and understanding the role of solar-terrestrial influences on Global Change. Contact is Susan Avery (susan.avery@colorado.edu), Chair of CAWSES Science Steering Group. Program "theme" areas are:

Solar Influence on Climate – M. Lockwood and L. Gray (UK); Space Weather: Science and Applications – J. Kozyra (USA) and K. Shibata (Japan); Atmospheric Coupling Processes – F. Luebken (Germany) and J. Alexander (USA); Space Climatology – C. Frolich (Switzerland) and J. Sojka (USA); and Capacity Building and Education, M.A. Geller (USA). See http://www.bu.edu/cawses/.

- **IHY (International Heliophysical Year) 2007-2009** – International effort to advance our understanding of the fundamental heliophysical processes that govern the Sun, Earth, and Heliosphere — http://ihy2007.org/. See also the IPY (International Polar Year) — http://www.ipy.org/; IYPE (International Year of the Planet Earth) — http://www.yearofplanetearth.org/, and eGY (Electronic Geophysical Year 2007-2008) — http://www.egy.org/ — all celebrating the 50th Anniversary of the IGY (International Geophysical Year 1957-58) — http://www.nas.edu/history/igy/.
- **Space Research, Interplanetary Phenomena, Cosmic Rays, Aeronomy.** Experimenters should take into account that observational effort in other disciplines tends to be intensified on the days marked on the Calendar, and schedule balloon and rocket experiments accordingly if there are no other geophysical reasons for choice. In particular it is desirable to make rocket measurements of ionospheric characteristics on the same day at as many locations as possible; where feasible, experimenters should endeavor to launch rockets to monitor at least normal conditions on the Quarterly World Days (QWD) or on RWDs, since these are also days when there will be maximum support from ground observations. Also, special efforts should be made to assure recording of telemetry on QWD and Airglow and Aurora Periods of experiments on satellites and of experiments on spacecraft in orbit around the Sun.
- **Meteor showers.** Of particular interest are both predicted and unexpected showers from the encounter with recent dust ejecta of comets (meteor outbursts). The period of activity, level of activity, and magnitude distributions need to be determined in order to provide ground truth for comet dust ejection and meteoroid stream dynamics models. Individual orbits of meteoroids can also provide insight into the ejection circumstances. If a new (1-2 hour duration) shower is observed due to the crossing of the 1-revolution dust trail of a (yet unknown) Earth threatening long-period comet, observers should pay particular attention to a correct determination of the radiant and time of peak activity in order to facilitate predictions of future encounters. Observations of meteor outbursts should be reported to the I.A.U. Minor Planet Center (dgreen@cfa.harvard.edu) and International Meteor Organization (visual@imo.net). The activity curve, mean orbit, and particle size distribution of minor annual showers need to be characterised in order to understand their relationship to the dormant comets among near-Earth objects. Annual shower observations should be reported to national meteor organizations, or directly to the International Meteor Organization (http://www.imo.net). Meteoroid orbits are collected by the IAU Meteor Data Center (http://www.astro.sk/~ne/IAUMDC/Ph2003/).
- The **International Space Environment Service (ISES)** is a permanent scientific service of the International Union of Radio Science (URSI), with the participation of the International Astronomical Union and the International Union Geodesy and Geophysics. ISES adheres to the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) of the International Council of Scientific Unions (ICSU). The ISES coordinates the international aspects of the world days program and rapid data interchange.

This Calendar for 2008 has been drawn up by H.E. Coffey, of the ISES Steering Committee, in association with spokesmen for the various scientific disciplines in SCOSTEP, IAGA and URSI and other ICSU organizations. Similar Calendars are issued annually beginning with the IGY, 1957-58, and are published in various widely available scientific publications. PDF versions of the past calendars are available online at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/IGC_CALENDAR.

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Additional copies are available upon request to ISES Chairman, Dr. David Boteler, Geomagnetic Laboratory, Natural Resources Canada, 7 Observatory Crescent, Ottawa, Ontario, Canada, K1A 0Y3, FAX (613)824-9803, e-mail dboteler@NRCan.gc.ca, or ISES Secretary for World Days, Ms. H.E. Coffey, WDC for Solar-Terrestrial Physics, Boulder, NOAA E/GC2, 325 Broadway, Boulder, Colorado 80305, USA FAX number (303)497-6513; e-mail Helen.E.Coffey@noaa.gov.

The calendar is available on-line at http://www.ises-spaceweather.org.

* **Please note that this Calendar is a draft version, the final version can be found within some time on the website as described above.**

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Note: an alphabetical index of names, with coordinates and page references, is given on pages 56-71.

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