News & Information

VECTORS in Radar Technology

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INTRODUCTION

In mid-November 2015 a two-day event took place at University College London (UCL), intended to be the first of a new type of professional meeting. The motivation was a realization that most of the conferences and events that we currently organize are inherently retrospective – that is to say, they are reporting on work that has already been performed. There seemed, therefore, to be a niche for an event that encourages participants to look forward, to speculate and even to argue on the advances that will need to be made over the next ten, twenty years or even further into the future, and what the key challenges might be. This should be more than an academic exercise, of course – the results would be of interest to many parties, including governments, funding agencies, and research program managers.

The resulting workshop was made possible by a generous grant from the U. S. Office of Naval Research (Global) and the U. S. Air Force Office of Scientific Research International Office, which enabled a total of some eighty participants, by invitation, from thirteen different countries, to converge on UCL for the event. These included some of the 'big names' in radar research from all over the world, with clear ideas and strong opinions. A poster event on the first evening was kindly supported by the Australian High Commission in London, also with support from the IEEE AES Society.

Musical entertainment during the poster session.

The format of the event consisted of eight individual sessions, with themes addressing current hot topics in radar research. Each session was led by a keynote speaker whose brief was to identify and explain the challenges, but the bulk of the time was devoted to discussion. And there was no shortage of that – in all cases the discussions had to be curtailed in order to keep the event on schedule.

The program was as follows:

Waveform Diversity

Shannon Blunt, University of Kansas, USA
Antonio de Maio, University of Napoli, Italy

Compressive Sensing

Bernie Mulgrew, University of Edinburgh, UK
Naser Yorouzi, Amirkabir University, Iran

Bistatic and Networked Radar

Chris Baker, Aveillant, UK
Mike Cherniakov, University of Birmingham, UK

Cognitive Radar

Alex Charlish, FKIE, Germany
Simon Haykin, McMaster University, Canada

Multifunction RF Systems

Alfonso Farina, UCL, UK
Alex Yarovoy, Technical University of Delft, Netherlands

High-resolution Imaging and NCTR

Dan André, Cranfield University, UK
Børge Torvik, FFI, Norway
Marco Martorella, University of Pisa, Italy

Phenomenology

Stuart Anderson, University of Adelaide, Australia
Simon Watts, UCL, UK

Biologically-inspired Processing

Alessio Balleri, Cranfield University, UK and with posters from:

Dai, Wei, Imperial College, UK
Gordon Oswald, Aveillant, UK
Albert Huizing, TNO, Netherlands
Tony Gillespie, UCL, UK
Karl Woodbridge, UCL, UK
Feng Li, Beijing Institute of Technology, China
Carmine Clemente, Strathclyde University, UK
David Stupples, City University, UK
Andy Stove, University of Birmingham, UK
Pietro Stinco, University of Pisa, Italy
Francesco Fioranelli, Matt Ritchie, UCL, UK
Mike Inggs, Daniel O'Hagan, University of Cape Town, South Africa

RADAR TECHNOLOGY

The development of technology is not the only driver in the acquisition of new radar systems. If we consider that a piece of military equipment should have an in-service lifetime of at least twenty years, it is likely that the requirements will change significantly over this time, so there will be both 'technology push' and 'requirements pull'. In addition, there will be the inevitable constraints of cost, and of Size, Weight And Power (SWAP), and – of increasing importance – of spectral purity.

As an example to set the scene, it was pointed out that 2015 marked the fiftieth anniversary of Gordon Moore's famous publication [1], in which he observed that computing power (as measured by the number of transistors on a processing chip) essentially doubles every eighteen months. This relationship has been found to hold for many decades. His paper considered the implications of this result, and includes a cartoon of people standing in line to buy a 'personal computer'. To have predicted that more than fifty years ago is surely remarkable! Perhaps less well known is that the final paragraph of the paper considered the implications for radar, and in particular phased array radar. In this way it showed an extraordinary ability to predict the future, and should serve as an inspiration for the meeting.

Hugh Griffiths and Alfonso Farina.

DISCUSSION

The following paragraphs summarise the presentation and discussion under each of the eight topics. However, a first comment is that radar may be regarded in some quarters as a 'mature' technology, which tends to imply that all the important work has already been completed and that future advances will be incremental. That is far from the case, of course, but it suggests that we should instead use the term 'RF sensing', which encapsulates networked, cognitive and passive techniques which represent so much more than conventional approaches, and also acknowledges the common ground with electronic warfare.

Waveform Diversity: Modern digital signal processing now allows us to generate precise, wide bandwidth radar waveforms and to vary them, potentially on a pulse-by-pulse basis – and this is the foundation of waveform diversity. In the future it will be possible to generate radar signals with precisely-controlled spectral characteristics, and this will be critical as the problem of spectrum congestion becomes ever more severe. Indeed, the classical tool for evaluating the performance of radar waveforms – the ambiguity function – says nothing about the spectral properties of the signal. As well as this, we can generate waveforms with ultra-low range sidelobes, but it is important to appreciate and to take into account the distinction between the *code,* which is the sequence of phase values, the *waveform*, when it is modulated onto a carrier with real phase transitions between each code element, and the *emission*, which is subject to the distortions introduced by transmitter and receiver.

Electronic warfare is a key driver for waveform diversity, both to prevent detection/identification and then to mitigate the effects of hostile electronic attack.

A significant amount of work has been accomplished on waveform design and associated adaptive receive processing based on optimization according to a wide range of different mathematical structures and metrics; however, it has been only relatively recently that mechanisms for subsequent physical implementation/application of these waveforms and processing schemes have emerged. There was discussion of the requirements for physical implementation of advanced waveforms and waveform-domain receive processing, providing various examples, and then discussed possible avenues for research moving forward including bio-mimetic approaches, waveform/transmitter co-design, and the coupling of different waveform domains.

Bistatic radar techniques have been around since the very earliest days of radar, but it is only recently that they have properly come of age. This is partly because there are now applications where bistatic operation offers a genuine advantage, and partly because technology now permits things which were previously very difficult. Passive radar techniques have now attained a level of maturity that means that they are now seriously considered for mainstream applications such as Air Traffic Management, especially with ever-increasing pressure on spectrum [2]. A defense business website estimates that the civil and defense market for passive radar will be worth more than US$10 billion over the next ten years [3]. Key advances will need to be made in geolocation and synchronization techniques (especially in GPS-denied environments), in communication between platforms, and in resource management techniques for radar networks. Bistatics and Networked Radar offer both challenges and opportunities. Networked radar – also known variously as distributed radar, netted radar, MIMO, and multiple bistatic radars – is a topic that has been around for some time but is still relatively immature, and definitions are imprecise, even where they exist at all. There are essentially two forms of MIMO radar: in *statistical MIMO*, spatially separated transmit and receive antenna elements form a distributed radar; in *coherent MIMO,* the antenna elements radar are constrained within a single manifold and the radar uses orthogonally-coded waveforms from each transmitter to provide multiple simultaneous transmit-receive paths. Separation of transmitters and receivers brings new design freedoms but also adds technical and logistical challenges.

Compressive sensing has become something of a hot topic in recent years. It involves a digital signal processing technique that provides for efficiently acquiring and reconstructing a signal, by finding solutions to underdetermined linear systems. It stands to reason that signals or images that are 'sparse' over part of their domain do not need to be sampled uniformly, but there remain some rather important questions, particularly about its applicability to real-world problems. Compressive sensing is based on the principle that, through an optimization technique, the sparsity of a signal can be exploited to recover it from fewer samples than required by the Shannon-Nyquist sampling theorem. The presentation posed a number of questions which are listed here. Has compressive sensing delivered on its original promise to significantly reduce sampling rate ? Does this not lead to a drop in detection performance ? Was Nyquist a pessimist ? Surely the radar community has been dealing with sparse/non-uniform sampling for many years under the heading of Array Processing? What if the signal is off-grid or the dictionary is not correct ? Is greed really good or should we iterate to avoid indigestion? Does compressive sensing give us a fundamentally new way of addressing radar signal processing challenges that throws off the shackles of approximate orthogonality and allows us to forget sidelobes and even the ambiguity function? The presentation threw some more light on some of these questions through the illustration of a simple example that is indicative of both airborne pulsed-Doppler GMTI and SAR image formation. The conclusion is probably unsurprising – that the technique has much to offer provided that the signal or image is suitably sparse.

Cognitive Radar represents an exciting and potentially far-reaching set of techniques [4]. A general objective for cognitive radar research is to transition the cognitive processes that are currently performed by an operator into automated processes in a radar system. Consequently, cognitive radar can reduce the operator's cognitive responsibilities by acquiring and intelligently exploiting knowledge on the situations that the radar may encounter; however, to achieve this objective, it is necessary to overcome a number of technological challenges. Even if these technological challenges can be overcome, the development of cognitive processes may be limited by practical limitations, such as legal constraints or new types of drawbacks associated to cognition. Although it is relatively new, the ideas behind the concept can be identified in research and operational systems that pre-date the concept by at least a decade. As well as the advantages, potential drawbacks should be considered in cognitive radar system design, and these may limit the potential applications. A key enabler of cognitive radar is the *a priori* information made available to the radar to allow this novel processing, and the DARPA KASSPER (Knowledge Aided Sensor Signal Processing and Expert Reasoning) program was a key trailblazer in this respect.

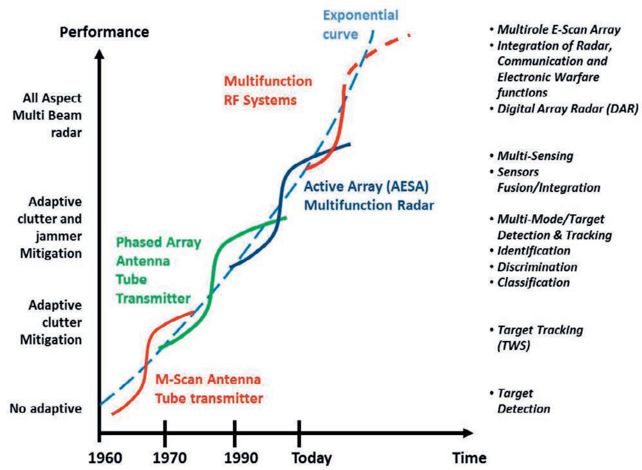
Adoption of cognitive techniques will be easiest for capabilities that a human cannot do or does badly. Automating capabilities that humans are good at will be slower to adopt and potentially limited by legal or trust concerns. In addition, cognitive radar research must draw on other disciplines, such as robotics, convex optimisation, machine learning, information fusion, control, and operations research. Finally, a system view of a cognitive radar system should be taken, where modules may not be cognitive in isolation but contribute to cognitive behaviour of a complete system.

Multifunction RF Systems depend critically on the evolution of the active electronically scanned array (AESA) and the associated enabling technologies, and on new operational needs of radars, and particularly air defence systems. These are made possible by new technologies such as photonics and Gallium Nitride (GaN) semiconductor devices. We may now consider multifunctional RF systems which integrate radar, communications, electronic support measures, electronic countermeasures and electronic attack in a single system and antenna aperture. The new systems can be installed on land, naval, and air platforms (including drones and remotely piloted vehicles).

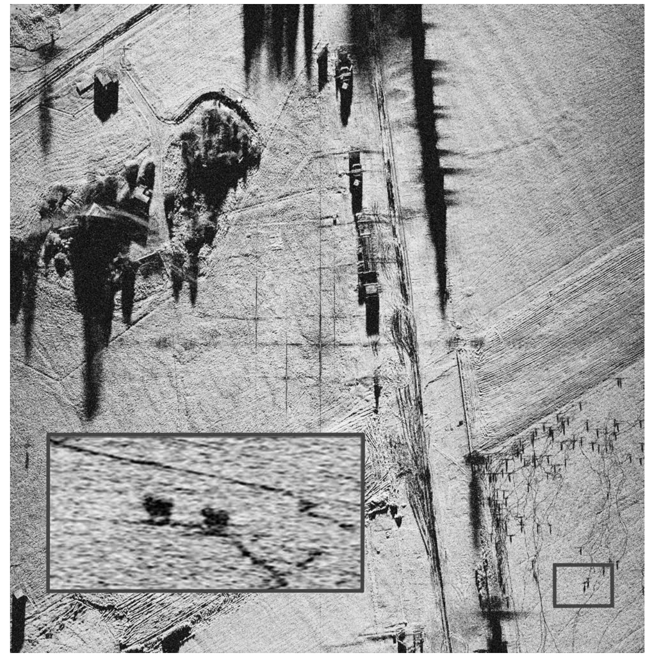
A study of the evolution of such technologies [5] shows that they often take the form of a series of S-curves. This indicates that research and development effort may need to be harnessed over several decades in order to deliver clear benefit, and this should be approached strategically. Bringing down the cost is another major factor; in the telecommunications market the investment to make such advances are justified by the huge production volumes, but in military radars this is much more difficult.

Looking to the future, important issues are identified as:

- Wide spectrum of applications for multifunction RF systems,
- Open architecture and standardization,
- Exploitation of commercial technology development (e.g.: COTS) without redoing the system architecture,
- Management of legacy systems,
- Dual-use,
- New methodologies of conception, design, prototype, program management, production, tests, training, maintenance (virtual reality, …), remote logistics (3D printing, …), porting of functionalities (produced data and C^2) on Android devices,
- SWAP-C (Size, Weight, and Power – Cost) just one development for more system applications,
- DARPA program: Arrays at Commercial Timescales (ACT). "How do we reduce the NRE (Non-recurring engineering) cost of array development?"



Technology advances often take the form of a series of S-curves [5].



Ultra-high resolution Coherent Change Detection SAR image from the Thales BRIGHT SPARK Synthetic Aperture Radar (SAR) sensor. The inset shows two sheep, and their tracks in a field. BRIGHT SPARK is a Dstl Experimental SAR system designed, built and operated by THALES UK. It is a Ka-band sensor providing unprecedented resolution and was used as a technical demonstration of the 'art of the possible'.

SAR and ISAR imaging has reached the stage where extremely high resolutions can now be obtained, both from airborne and satellite platforms, and techniques such as radar polarimetry, interferometry, and coherent change detection (CCD) all provide information that can be used to help classify and identify targets. High resolution Synthetic Aperture Radar (SAR) and its coherence products have been found to be of great utility in both identifying targets and detecting changes that occur on the ground. Detectable changes of interest include vehicle tracks, water flow, and small scale subsidence. The coherent change detection procedure involves performing repeat pass radar collections to form the coherence product, where ground disturbances such as tire tracks can induce detectable incoherence. Currently, SAR imagery of between 10 cm and 30 cm resolution is considered to be high resolution, allowing some success in target identification and in the detection of subtle changes on the ground.

It is interesting to consider what the physical limits may be on resolution and coherence. If such radar modes were available, how could we best profit from them? The CCD SAR image on the top right is a spectacular example of what is now possible. This is a Ka-band image in which dark areas indicate a low degree of coherence between the two images – in other words, areas that have changed. The inset area at the bottom right has been expanded and foreshortened, showing two sheep and their tracks.

Key to this technology, though, is to understand the physics of the interaction of the radar signal with the target, including the effects of multipath reflections, target motion and vibration. This may allow the important information to be extracted and interpreted in the right way.

Radar Phenomenology may be defined as the study of the physical processes of propagation and scattering. It might be imagined that these are by now adequately understood, since they have been studied since the earliest days of radar, and the physics has not changed. This is not the case, however, both because of advances in radar technologies, and because of the application of radars to sensing in ever more complex environments.

In the former category we can note the development of signal sources with extremely low phase noise, the advances in processing power, the evolution of sophisticated signal processing techniques, the availability of GPS and geographical information systems, access to real-time high-bandwidth communication services, the remarkable miniaturisation of components and circuits, and the invention of new materials with unprecedented mechanical and thermal behaviour, and novel electromagnetic properties with startling implications.

The second category embraces such applications as through-the-wall radar imaging, formation of images through turbulence in the atmosphere and the ionosphere, surveillance in the heavily built-up urban environment, mounting of radars on constellations of airborne or spaceborne platforms. We should also recognise the challenges posed by camouflage, concealment, and deception.

To address such missions, and to take full advantage of the enormous improvements in radar technologies, the phenomenological models we employ to describe propagation and scattering must be of commensurate fidelity. In practice this means that the structural and dynamic properties of the propagation media must be characterised in great detail wherever they impact on either the radar signal or the behaviour of the target object. Transformation of signal properties by mechanisms such as dispersion, polarisation transformation, and decoherence cannot be ignored. Equally, the electromagnetic properties of the candidate targets - which may include nonlinearity, inhomogeneity, anisotropy, and so on - must be accounted for, along with any multiple scattering processes. Further, we must not overlook the physical impact of the target on its environment and the associated perturbations to the scattered field.

These phenomenological considerations impact on radar design, choice of frequency and waveform, optimum siting, network design, and signal processing, so it is essential that radar development is accompanied by comprehensive experimental programs to measure and archive all relevant material and environmental parameters

Biologically-Inspired Processing: Finally, a study of how processing in natural systems such as bats and dolphins has benefitted from optimization through millions of years of evolution can teach us some valuable lessons. The acoustic signals that some species of bat use to identify, track, and intercept their prey are sophisticated, and make use of intelligent, cognitive processing [6]. Different species of bat inhabit different environments and feed on different prey, and the waveforms reflect this diversity; some are long, CW-type waveforms, some are shorter and impulsive, and some even include harmonics. In some species the frequency of the emission is adaptively lowered as it moves forward, so that the Doppler-shifted echo from the target scene is still at the peak of the frequency response of the bat's ear [7]. Even more impressive is the way in which the waveforms are adaptively varied through the different phases of the pursuit of insect prey, and evaluation of the ambiguity functions at each stage show the difference in information acquired [8]. One species of bat (*Noctilio leporinus*) feeds on fish, which it detects using echolocation of the perturbation of the water surface caused by the fish under the surface. Are there clues here that might help us with radar detection of submerged objects such as submarines ?

CONCLUSIONS

So what did we learn? Firstly, that this is a really useful meeting format, which should be more widely applicable. It depends on being able to bring together the right people and encouraging them to express their opinions in an honest and unfettered way. It is important that the participants understand that the purpose is to look forward rather than back. Secondly, that it is important to be able to capture the discussion in a form that is usable and useful – and this article forms part of that, of course. Thirdly, that academia, industry, and government labs each have their own perspectives and priorities, and to make genuine progress it is necessary to harness all three in the right way. Fourthly, that there is strong support to repeat the event. Opinion is divided on the appropriate timescale: a repeat interval one year is certainly too frequent, but two or three years seems about right. ◈

ACKNOWLEDGEMENTS

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