Try Living in the Real World: the importance of experimental radar systems and data collection trials

David Greig[1*], Carmine Clemente[2], Michail Antoniou[3], Mohammed Jahangir[3], Darren Coe[4] , Duncan A. Robertson[5], Matthew Ritchie[6]

[1]Leonardo UK Ltd, Edinburgh, EH5 2XS, UK
[2]University of Strathclyde, Glasgow, UK
[3]Univeristy of Birmingham, Birmingham, UK
[4]QinetiQ, Malvern, UK
[5]University of St Andrews, St Andrews, UK
[6]University College London, London, UK
**david.greig@leonardo.com*

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Abstract

While simulations of increasingly high fidelity are an important tool in radar science, experimentation is still needed as a source of validation for simulation, to explore complex phenomena which cannot be accurately simulated and ultimately in turning theory and simulation into a real world system with real world applications. Experimental systems can range from laboratory based, installations on the ground with limited fields of view all the way up to flying demonstrators which may be prototypes for radar products. In this paper we will discuss the importance of experimentation in the development of radar science and radar products with examples of systems used by a sub-set of the members of the UK EMSIG.

1 Introduction

The use of simulation over experiment is attractive in the academic, industrial and government sectors. For universities, laboratories take up a lot of space for a small number of researchers and procuring or making specialised components is more expensive than modelling them. Any RF transmission, even at low power, also requires safety considerations and appropriate licenses. Industry faces similar issues with the added commercial pressure of getting product to market quickly and with the minimum of non-recurring expense (development cost). For government, the cost of flight trials for system validation and verification can be a significant proportion of procurement costs and delay entry into service.

System development has recently focussed on the idea of a “digital twin”; a virtual representation of the physical system which can be used in development of hardware, firmware and software. This idea was defined and popularised by NASA a decade ago to improve spacecraft development. While the approach can be adopted for aspects of a radar system (e.g. prediction of interference from windfarms) the full fidelity of the complex environmental interaction which drives system performance cannot be simulated in real time, if at all.

In radar science, simulation now dominates over experiment. In the schedule for the IEEE Radar 2022 Conference, “field trials” are only mentioned twice in the abstracts of the papers [1]. However, radar remains an experimental science. Radar systems must operate in the real world with all its complexities of clutter and interference, false alarms and false positives, and hardware which may conform to the specifications once integrated into a platform.

The development of radar systems follows the Technology Readiness Levels, from laboratory experiments (TRL 1-3) to controlled field trials (TRL 3-5) to fully functioning prototypes and data collection systems (TRL 6-7). The higher TRL systems are increasingly important as interest grows in machine learning (ML) for radar. ML requires data, and while synthetic data has benefits in initial development (the content is entirely defined and known) ultimately real data must be used in testing to demonstrate that the assumptions made in generating the synthetic data are valid in the real world. Collecting, preparing and labelling the volume of data needed for a ML study requires substantial effort, effort without which ML cannot truly progress.

The Electromagnetic Systems Interest Group (EMSIG) is an organisation within the UK which represents the interests of those working on radar and RF systems in general across academia, industry and government [2]. One of the goals of EMSIG is to encourage experimentation, data collection and sharing of data between members to enable the development of radar capability in the UK. The following section provides examples of radar data collection systems and results.

2 Example Systems and Results

At the Sensor Signal Processing & Security (SSP&S) labs of the University of Strathclyde, COTS and prototype radar sensors have been used to validate algorithms and novel radar concepts/modes. An example is the GNSS based passive radar setup [3, 4] used to demonstrate to acquire real passive radar (Figure 1). The setup used a high gain directive L-band antenna to monitor the surveillance area and an omnidirectional GNSS antenna for the reference signals.

Figure 1 GNSS based passive radar setup (left) and example of acquisition scenario (right).

Another example exploited Software Defined Radio (SDR) to demonstrate a radar concept of joint radar and communication waveform design [5, 6]. The set up is shown in Figure 2 , with the communication receiver, completely independent and separate from the radar, able to decode the information transmitted by the radar performing radar tasks.

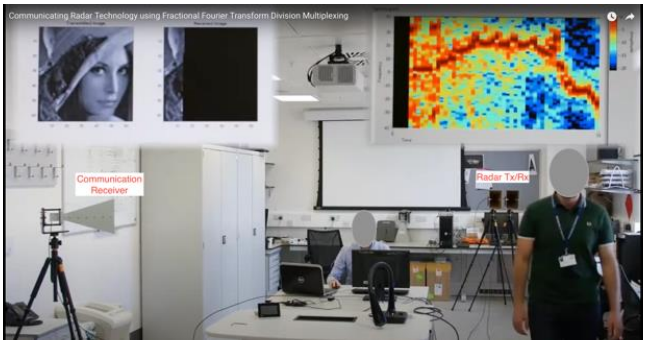

Figure 2 Software Defined Radio based joint radar and communication system

QinetiQ have used SDR in the development of their RF sensor payload for small drones, Figure 3. This has proved a cost effective way to field multiple airborne sensors simultaneously in order to collect the complex data sets necessary to support multi-platform distributed coherent sensing, volumetric imaging, etc. The data collected has enabled advanced algorithmic techniques to be explored, and the fundamental constraints of the capability defined.

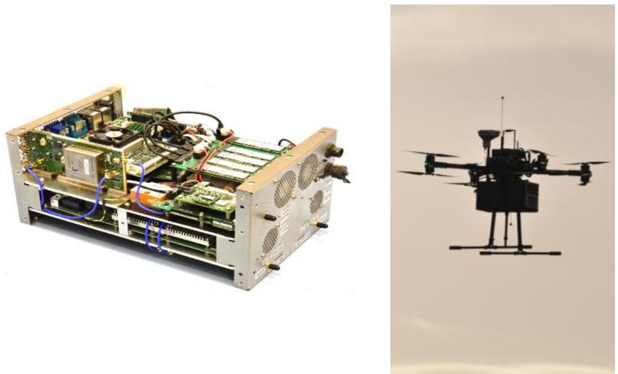

Figure 3 QinetiQ RIBI hardware and flown on <20kg quadcopter

Off-the-shelf short range radars are a good way to gather data in order to demonstrate models and algorithms working in the real world. An example is the system developed by White Horse Radar Ltd and used by the SSP&S team to validate models and algorithms for ballistic missile classification [7], Figure 4.

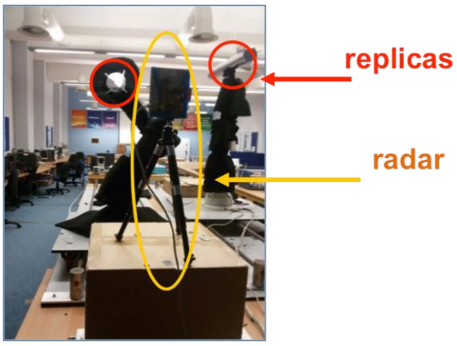

Figure 4 Setup exploiting robotic manipulators and Ballistic Targets replicas to validate radar models and classification algorithms.

The University of Birmingham (UoB) staring radar facility comprises a network of two Aveillant Gamekeeper prototype radars, installed on the rooftop of two buildings at the campus (Figure 5). Each radar has a floodlight beam and employs digital beam-forming on receive with a 64-element array. This architecture allows persistent area surveying, high-Doppler resolution due to increased dwell time on target and fully flexible beam forming which provides for sufficient sensitivity to detect and locate small highly manoeuvrable targets [8].

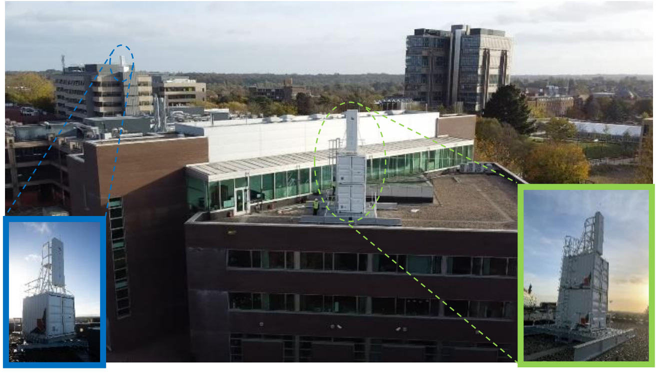

Figure 5 Two L-Band multiple receive beam staring radar installed at University of Birmingham Edgbaston campus.

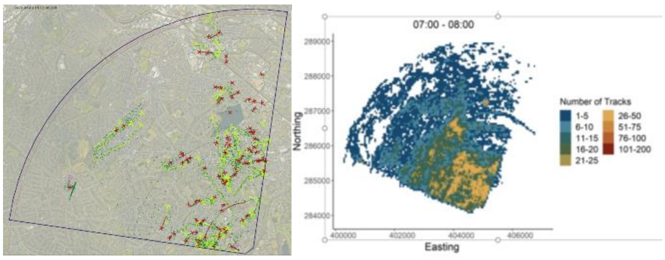

Figure 6 (a) Real-time processor detections and classified tracker output (b) Heatmap plotting track occupancy over a 1-hr duration.

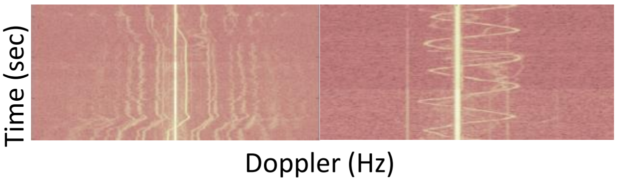

Figure 7 Raw data spectrograms (a) Rotary wing drone (b) Bird

The two radars are separated by ~200 m and are pointing towards an urban environment with an overlapping coverage. A real-time processor generates detection and classified tracker output (Figure 6a). Offline analyses using heat-maps (Figure 6b) is supporting research in long term trends in bird movements within dense urban coincubation [9]. Raw I/Q data can be recorded for all channels to build a vast database of target signatures in realistic clutter conditions (Figure 7& [10]) which is furthering work on machine learning classifier [11] and drone signature modelling [12]. The network configuration will provide a vital facility for multi-static measurements [13]. In due course, both radars will be connected to ultra-low phase noise, ultra-fine stability, Quantum oscillators to establish both the performance limits of monostatic radar in strong clutter and the coherence in the radar network [14]. The degree of phase coherence and timing stability(10^{-18} nominal) is expected to be at least an order of magnitude higher than with a conventional crystal oscillator and will provide for a truly unique fully coherent Quantum-enabled networked staring radar testbed. The data from this facility will be invaluable in optimising detection, tracking and classification algorithms for a host of applications including counter-drone defence, monitoring of future air space usage, aero-ecology etc.

The Millimetre Wave Group at the University of St Andrews has, for the past 20 years, been developing prototype millimetre wave radars up to TRL 6 for applications in security and remote sensing. To date, the group has built 14 experimental radar systems at frequencies of 10, 24, 35, 77, 94, 220 and 340 GHz, most of which are still in operational use. The group's expertise encompasses a whole system approach of radar hardware development (RF/microwave circuit, antenna, data acquisition, mechanical design, power supplies), field deployment, then data processing and analysis.

All the group's projects involve the collection of experimental radar data using in-house developed radar sensors, usually in outdoor field trials, and sometimes in remote locations, as per the following examples. Ground-based, portable, scanning real-beam 94 GHz radars have been used for terrain mapping and topographic change detection through obscuring conditions as applied to volcanology [15] and glaciology [16], Figure 8.

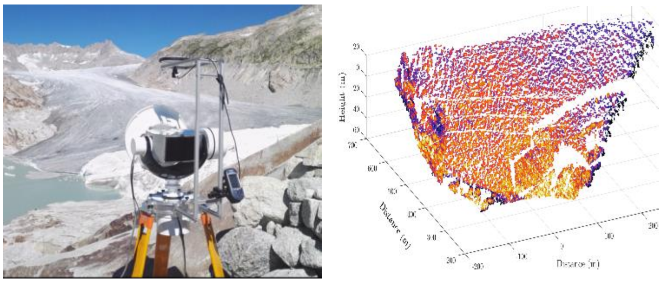

Figure 8 : AVTIS-2 94 GHz radar deployed at Rhône glacier, Switzerland (left) and resulting received power point cloud (right).

High fidelity RCS and micro-Doppler data of drones and birds [17,18], including drones equipped with threat payloads [19,20], have been collected in realistic in-flight scenarios at 24, 77 and 94 GHz, Figure 9. This information has led to the development of dedicated drone detection radar prototypes [21] and classification algorithms capable of distinguishing between drone and birds [22] and between different drone types based on the distinct propeller signatures [23].

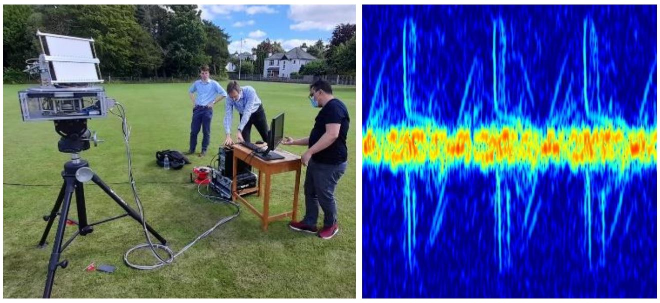

Figure 9 : FAROS-K drone detection radar during trials (left) and 94 GHz CW spectrogram of in-flight drone blade flashes (right).

To address the requirement for future marine autonomous vessels to be able to sense their surroundings and avoid obstacles, the group are collaborating with the University of Birmingham to evaluate sub-THz radar for this application. As there exits virtually no radar data for sea clutter or objects in the sea above Ka-band, a programme of data collection trials is underway, Figure 10. Initial results have gathered data at 24 and 94 GHz from breaking waves in littoral conditions which will yield amplitude statistics [24] and Doppler information which will enable the development of classification algorithms suitable for obstacle avoidance.

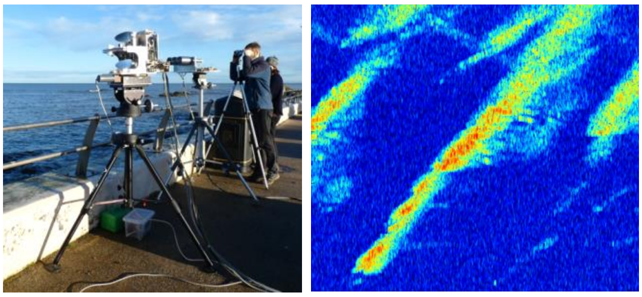

Figure 10 : 94 and 24 GHz radars collecting sea clutter data (left) and 94 GHz range-time-intensity plot of breaking waves (right).

The University College London (UCL) radar group has a strong background in developing real radar systems that are deployed both nationally and internationally. Key systems of note include the NetRAD [25] and NeXtRAD [26-27] multistatic radar systems. NetRAD is a S-band multistatic coherent pulse-Doppler radar system that has been used for drone detection, human micro-Doppler classification, bird signature capture, wind turbine and sea clutter trials. It was originally developed at UCL at by T. Derham and S. Doughty as a short range 3 node 2.4 GHz wired system. This was then upgraded to a enable wireless synchronisation between nodes via a collaboration with the University of Cape Town (UCT) who provided the GPSDO sync solution. Example captures from NetRAD can be seen in Figure 11. The NeXtRAD radar system was developed as a dual band (L and X band), dual-pol, higher power system with more advanced Digital Signal Processing (DSP) capabilities than NetRAD. These systems have been research platforms for multiple PhDs, postdoctoral research projects, as well as providing trials data for NATO and other international collaborations. They represent a strong justification for the development of real experimental radar systems.

These two projects have covered over two decades of research and provided invaluable insight into the real-world challenges of developing coherent multistatic radar. There is a strong current trend in radar research and development towards multistatic RF sensing and without the development of these demonstrator systems the quantification of expected performance would not be possible as modelling the whole system and environment parameters would be too challenging when trying to consider all aspects of the performance.

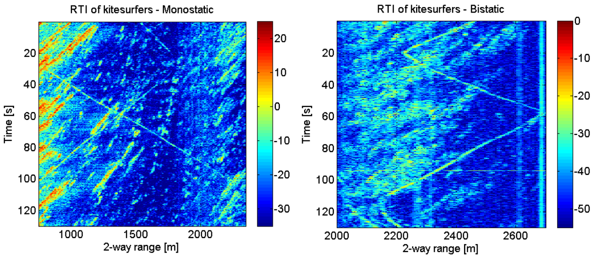

Figure 11 NetRAD Sea clutter and kite surfer data from South Africa Experiments [25]

The Leonardo AEXAR radar was developed initially as a test-bed for the tile-based active electronically scanned antenna (AESA) technology which is now used in the Osprey radar product. AEXAR was retained and maintained as an airborne experimental radar system which has been used both to assist in further product development and for collaborations with UK MoD, NATO research groups and academia. The typical installation of AEXAR in the luggage bay of a helicopter is shown in Figure 12.

Figure 12 AEXAR installed in a Twin Squirrel Helicopter

AEXAR is an X-band system with two channels separated horizontally and electronic steering in both azimuth and elevation giving wide area coverage for a compact, fixed installation. The complete system weights less than 10 kg and operates off the 28 V DC supply on the helicopter. Waveforms can be modified through software, the modes most often used are MTI and SAR. An example of a SAR image captured on a trial for the NATO SET250 research task group is shown in Figure 13.

QinetiQ Ltd undertake research and development on RF sensors, both radar and EW, mainly for military applications. They have spearheaded the UK development of airborne techniques such as SAR, GMTI and target recognition. All of this has been built on a solid foundation of real RF data collected from prototype and experimental systems and dedicated trials activity. QinetiQ works closely with radar manufacturers to develop next generation systems and techniques – this has included the Enhanced Surveillance Radar developed with Leonardo for surface surveillance and the PodSAR with Thales UK for reconnaissance aircraft (Figure 14).

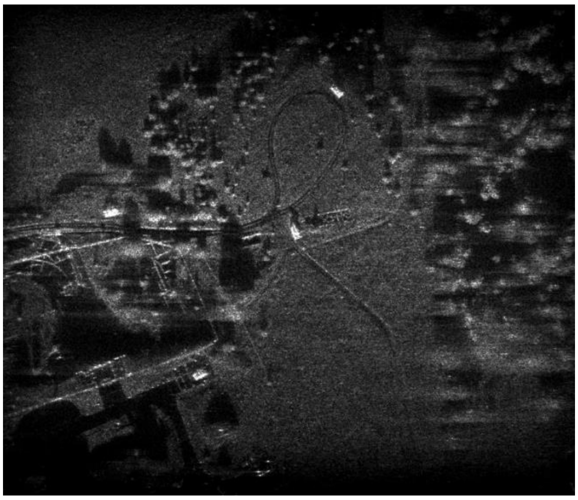

Figure 13 high resolution AEXAR image including vehicles

Figure 14 QinetiQ operated SAR platforms for data collection

Regular RF data collection campaigns have supported the development of practical real world techniques, including clutter modelling for enhanced detection, SAR image formation and autofocus.

SAR imaging and exploitation is a prime example of where collection of real data from experimental systems is essential. QinetiQ have been developing advanced SAR image formation and Automatic Target Recognition (ATR) algorithms for more than two decades, and real data has been vital to this activity. Real world effects like platform motion are critical in understanding the real world problems and designing robust real world solutions.

For ATR development, real world data and simulation work go hand in hand. The vast number of target images necessary for training robust recognition algorithms necessitates signature simulation, but those simulation techniques must be validated initially against real world data. Finally, any recognition solutions developed must demonstrate performance on real world data. Figure 15. In recent years imagery from the Leonardo AEXAR radar has been used to mature SAR ATR.

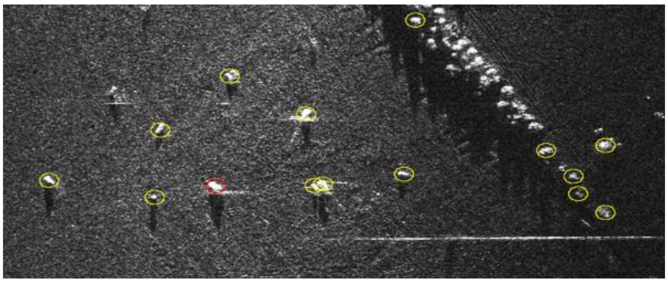

Figure 15 QinetiQ SAR image with target detection

Signals used in high resolution SAR are inherently wideband and may be affected by the crowded RF spectrum issue more than other radar modes of operation. SAR is similarly vulnerable to deliberate jamming, particularly repeater jammers. QinetiQ are working with Leonardo to collect data with the AEXAR radar and QinetiQ transmitters to investigate the mitigation of these effects.

Data collection assets and regular data collection campaigns with accurate ground truth are essential to the continued development of radar and EW techniques for next generation system platforms and capabilities.

3 Discussion

We have presented here examples of experimental radars used by EMSIG contributors from simple laboratory based systems, through ground-based field trial deployments and a large scale data collection system in a fixed position, to a flying system which has been used to develop specific capability with investigation of novel quantum technology included in the mix.

There remain a significant number of experimental radar systems in the UK which form the basis of current and planned research programmes. While the interaction between academia, government and industry is well established and growing, there is more which can be done collaboratively to enhance radar research and development in the UK. In particular, the networking of radar systems, the cooperative use of active and passive systems across the RF spectrum and the exploitation of the vast amount of digitised data these systems will produce present a substantial problem which can only be solved collectively.

Radar systems will always have limitations on power-aperture product and coverage (field of view), both of which can be overcome by networking of multiple radar systems. There are many challenges in building a practical networked radar system – synchronisation, passing data between nodes, centralised fusion and control versus decentralised (distributed processing), security and resilience of network. These can best be investigated by experimentation, connecting two or more of the diverse systems available in the UK.

Co-operative use of different radar systems will also help overcome the problem of the “crowded spectrum”. Passive radar systems can operate in parts of the spectrum occupied by other RF systems. Co-ordination of systems and multi-use waveforms will also be needed to avoid mutual interference problems and to optimally use the available spectrum both of which require examination in the real RF environment.

Having multiple systems operating at the same time will increase the amount of data available for radar development including the application of Machine Learning to problems which cannot reasonably be solved analytically. While Machine Learning on synthetic data can demonstrate the benefits of a certain algorithm the ability to adapt to the real, more complex environment will always need to be demonstrated. To do this, real world data is needed, as has been shown for ATR from SAR imagery. The amount of data required is potentially huge and introduces further challenges on storing and recalling the data, understanding where data may be corrupted and of most important being able to label the contents of data to provide the truth to learn from. Databases containing such information for photographic images are widely used in research and in the development of commercial applications. A similar database for radar is challenging as radar data takes many different forms.

All of these future developments for radar systems will require increased processing power. The volume of data that a radar system produces is not necessarily related to size; multiple small radars or a large multi-channel digital radar will produce data at much higher rates than large analogue systems did 40 years ago. The processing challenge is non-trivial and requires practical investigation in the laboratory and in the field, in particular where the availability of power for the processing is limited (e.g. battery powered commercial drones).

Although presented from a UK perspective these issues span national boundaries, and increased co-operation between partner nations in collaborative trials and sharing of data will be essential to fuel the next stages of radar development.

4 Conclusion

The future of radar systems is not only dependent on the development of technology, but on the ability to exploit that technology in the real world. Real world experimentation and demonstration are expensive and complex, and best enabled through cooperation.

The UK has a strong history in development of real demonstrator and experimental radar systems, and it is vital that this continues and is provided sufficient funding and incentives to do so.

In the future platforms should developed in an open manner to enable collaborative projects, where remote access or algorithm development could be completed in collaboration with multiple institutions, both industrial and academic. The required effort to develop elaborate radar systems necessitates they are exploited as much as possible to provide new research outputs. A strong UK RF role in radar data collection and demonstration will also fuel international collaboration with partners and allies.

The UK EMSIG has a role to play in the brokering of collaboration, as a framework under which the disparate elements of the UK radar industry can meet and discuss future requirements and plan activities.

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