HARDWARE IN THE LOOP RADAR ENVIRONMENT SIMULATION ON WIDEBAND DRFM PLATFORMS

J.J. Strydom, J.E. Cilliers, M. Gouws, D. Naicker, K. Olivier

Council for Scientific and Industrial Research (CSIR), South Africa, jjstrydom@csir.co.za, jcilliers@csir.co.za, mgouws@csir.co.za, dnaiker@csir.co.za, kolivier@csir.co.za

Keywords: DRFM, ECM, Complex Targets, Clutter, HIL, radar environment, simulation.

Abstract

This paper describes the development and testing of a digital radio frequency memory (DRFM) kernel, as well as some of the functionality which has been added to the system to make it a fully-fledged hardware in the loop (HIL) radar environment simulator (RES) system for radar testing and evaluation.

1 Introduction

The testing and evaluation of modern radar systems is becoming increasingly difficult owing to the adaptive nature of such radars [17]. In general there are two approaches to this problem: Firstly the radar developer can design and build specialised test equipment for each radar. Secondly, more generic test equipment can be designed which can be used to test a class of radars. This approach is especially important to organizations, such as defence evaluation and research institutes (DERI) and other government agencies, which specialize in independent review, acceptance testing and optimisation of the operational utilisation of radar systems.

The use of HIL testing during the early stages of a radar's development can also give the radar designers the opportunity to test critical radar functionality before the radar is optimized for size and weight, thus reducing the overall project risk. This should also reduce the required number of measurement trials as well as the cost of developing such systems [13].

The HIL simulator captures the radar's transmit pulse by mixing it down and sampling it with a high-speed analogue-to-digital converter (ADC). In order to simulate a target at a specified range delay, the captured ADC information is transferred into digital memory through a field programmable gate array (FPGA) and re-transmitted at the correct range via a high-speed digital-to-analogue converter (DAC) and RF up-conversion chain. A common local oscillator (LO) is used to guarantee the coherency of the signal. This architecture (illustrated in Fig. 1) is commonly referred to as a DRFM [1, 18].

Recently, DRFM based systems have been employed as the core of such general radar test systems used by independent organizations and research institutes.

This paper is structured as follows: Section 2 describes the design of a high performance DRFM kernel. Section 3 describes the integration of this kernel into a radar environment simulator system. Sections 4, 5 and 6 then present the generation of realistic targets, ECM techniques and synthetic clutter respectively using multiple DRFM kernels.

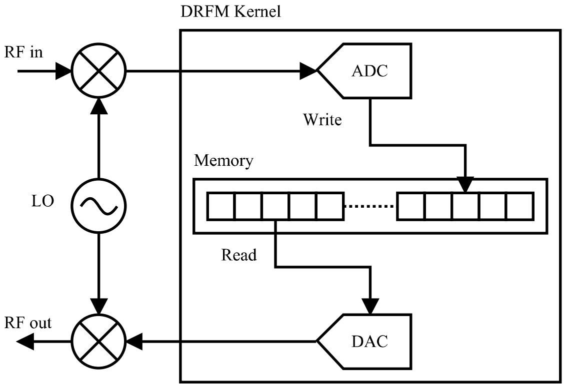

Figure 1: Block diagram of a generic DRFM design.

2 Wideband DRFM Kernel

This section highlights important aspects of the design and architecture of a wideband DRFM on printed circuit board (PCB) implemented using commercial-off-the-shelf (COTS) components.

Modern radars tend to have wide agile bandwidths and thus require simulator systems to have a wide instantaneous bandwidth to capture and recall frequency agile radar signals. The storage and recall of the radar pulse information also needs to exhibit high fidelity in amplitude and phase [8] to provide a reliable return signal to the radar, so the DRFM has to attain the conflicting, wideband and high fidelity, characteristics simultaneously. It is therefore critical to understand the aspects involved in a high-speed mixed-signal design in order to achieve exceptional performance [15].

As operating frequencies of electronic systems increases, the physical size of circuits and devices being used becomes more important [9]. In order to achieve short electrical lengths, circuits in the Gigahertz-domain on PCB, need to be implemented in close proximity to one another, and caution has to be exercised regarding crosstalk. Care was taken during the design to provide low inductance return paths for high frequency signals to reduce the crosstalk [7]. Another important design aspect in mixed-signal design is grounding. This research has shown that partitioning of analogue and digital components in a mixed-signal design along with a moat and bridge approach on a single reference plane as advocated in [16], yields exceptional results. The key to success of this approach is to route all of the signals that cross between the analogue and digital partitions over the bridge as illustrated in Fig. 2.

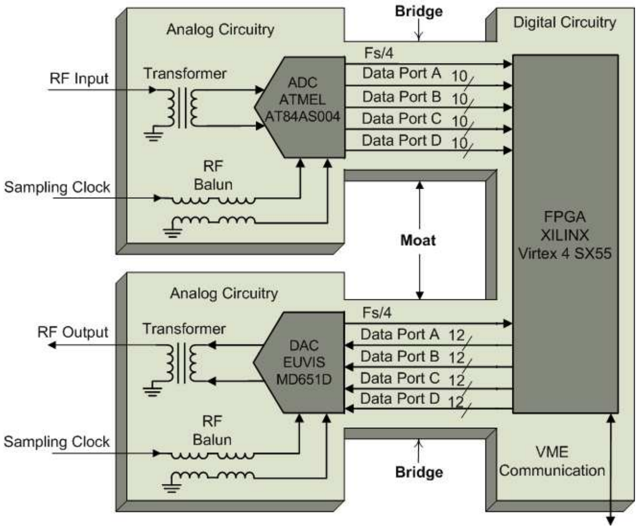

Figure 2: Schematic block diagram of the wideband DRFM showing implementation of the moat and bridge approach on a reference plane (from [15]).

This figure also indicates the specific data converters and field-programmable-gate-array (FPGA) that were chosen for this design. This circuit required an 18 layer, controlled impedance PCB. The DRFM was designed to sample at 2 GS/s and to have a usable bandwidth of 800 MHz.

A good measure of the fidelity of a DRFM is its spurious free dynamic range (SFDR) which is shown in Fig. 3.

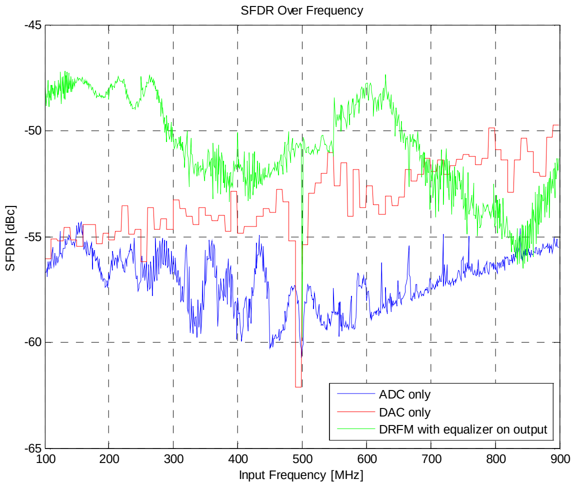

Figure 3: Measured SFDR of the wideband DRFM (from [14]).

The figure shows the measured SFDR of the ADC, DAC and DRFM as individual traces. A worst-case SFDR of -47 dBc was measured over the 100 to 900 MHz band. An analogue equalizer was used on the output of the DRFM to compensate for the sin(x)/x amplitude slope. The DRFM was also tested against an experimental pulse-Doppler radar and its performance against the radar was compared with that of an optical delay line (ODL) which produces a good approximation to an ideal point target for the radar. The results of these comparative tests are shown in Fig. 4 for a range and Doppler cut in the radar's received data.

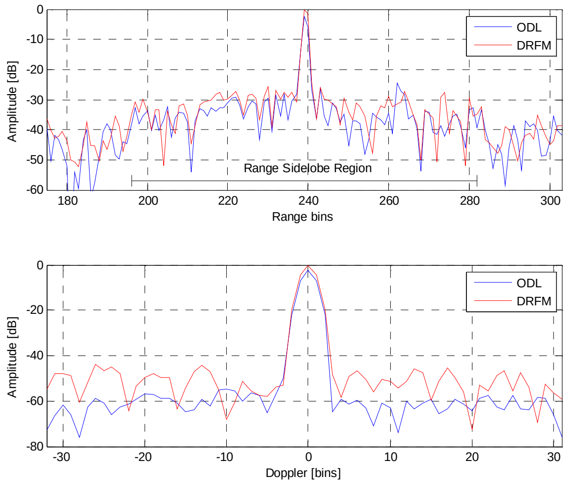

Figure 4: Comparison of the radar's range responses (upper plot) and Doppler responses (lower plot) for the ODL and DRFM target (from [14]).

Having developed a high performance DRFM kernel, additional functionality was added to enable the DRFM to operate as a fully fledged HIL simulator, as described in the following sections.

3 Radar Environment Simulator System

Multiple DRFM's were integrated into a VME based system along with the radio frequency (RF) hardware to mix the DRFM's instantaneous band to any frequency in the 1 to 18 GHz range (Fig. 5).

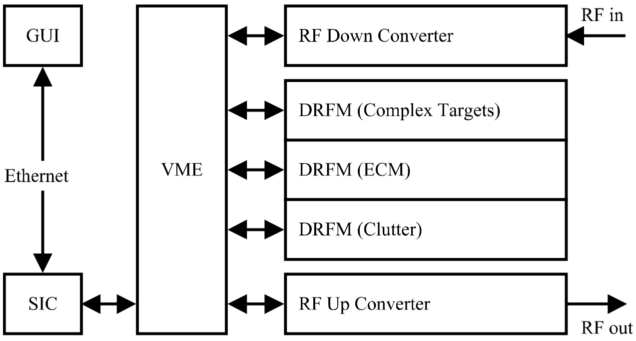

Figure 5: HIL RES system architecture.

The system is controlled locally by a system interface controller (SIC), which receives setup commands from a graphical user interface (GUI) over an Ethernet link, thus allowing remote operation of the system. The three DRFM kernels are implemented using identical hardware. Different firmware configurations are then programmed to realise either a complex target, an ECM technique or radar clutter simulation channel. These sub-components together form the HIL radar environment simulator (RES).

To extend the capability of the system to simulate two independent complex targets, each with their own ECM capability, a second complex target DRFM and a second ECM DRFM module are added into the VME rack. Alternatively the clutter channel can be reprogrammed through the GUI to fulfil one of these tasks. The modular design of the DRFM kernel makes the HIL RES highly configurable.

4 Complex Targets

Modern radars increasingly exploit the detailed characteristics of target returns in an attempt to identify the target. High Range Resolution (HRR) radars can resolve targets into several range bins, so the HIL testing and evaluation of such functionality requires the DRFM to generate much higher fidelity targets, since a single point scatterer can easily be distinguished from the complex return of a skin echo. Fig. 6 depicts an example of the simulated HRR skin echo of a helicopter to illustrate this. Imaging radars require the simulated scatterers to follow a precise dynamic phase progression corresponding to the relative target-sensor range and orientation. It is also required to model modulations due to mechanical vibration or rotation on targets, such as rotor blade modulation. Additionally, it is required to simulate accurate deterministic RCS fluctuations for a specific target/engagement profile, beyond the limited fidelity of standard statistical Swerling models.

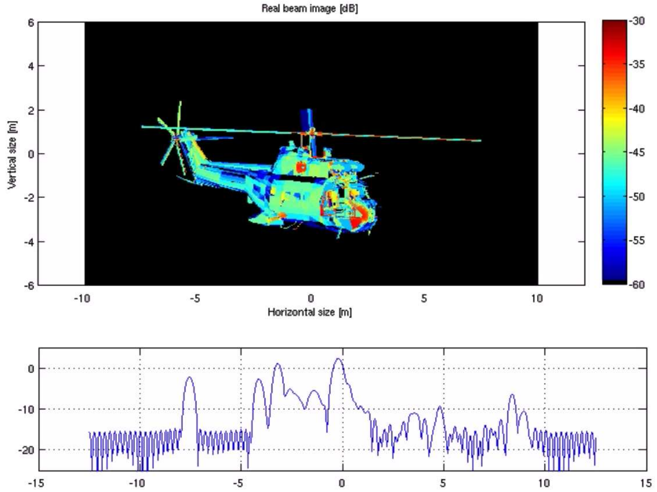

Figure 6: HRR of a helicopter with rotating blades simulated using SigmaHat. The upper frame shows the bright scattering points on the target.

To address these requirements, the DRFM simulates the target as a group of many configurable scatterers. The range, amplitude, phase and Doppler offset of each scatterer may be independently specified. The system supports high update rates (pulse-to-pulse) of all scatterer parameters allowing high-fidelity dynamic simulation. The complex target system was designed for both pulsed and CW radars.

Determining the target scatterer parameter values for high-fidelity simulation of a specific target and engagement profile is a complex problem. This was achieved by the integration of the complex target simulation DRFM with Radar and EW engagement simulation software and a high-fidelity RCS prediction tool (SigmaHat [10, 11]), both of which have been developed in-house. This tool chain pre-calculates high-resolution RCS profiles of the target as it follows a simulated engagement path.

Due to the high complexity of this mode it has only been tested for IBW’s up to 500 MHz. Note that the DRFM’s are responsible for generation of the true target as well as the deception technique.

5 Electronic Counter Measures

ECMs are deception techniques used to counter radar systems so that they are unable to detect and track various types of air, sea or land vehicles. These techniques involve the injection of non-coherent jamming signals into a radar system, or the manipulation of the range, Doppler and amplitude domain of retransmitted copies of the radar’s signals. The radar developer is usually required to develop countermeasures against the ECM’s, or to at least characterise the radar’s performance in the presence of ECM’s.

ECM simulator systems are utilised primarily for testing the effectiveness of a radar system, whereas operational ECM systems (jammers) are used for defence against operational radars. This DRFM was developed primarily as an ECM simulator system, although DRFM subsystems have been integrated into operational ECM systems in the past.

A critical requirement of ECM systems is to provide RF returns to a radar with sufficient fidelity in terms of Doppler, range and radar cross section (RCS), to ensure that the radar interprets the return as a “real” target. Once this is accomplished the ECM system can manipulate these parameters in the testing/jamming of radar systems.

The DRFM based system has an instantaneous bandwidth (IBW) of 800MHz, within which, a Digital Instantaneous Frequency Measurement (DIFM) [5] was implemented for accurate Doppler shift calculation. Doppler processing is implemented digitally within the FPGA of the DRFM subsystem, resulting in reduced system complexity. The system can simulate returns from ranges of 100 m to 1000km. Updating the range delay of an ECM system during the coherent processing interval of a pulse Doppler radar results in phase discontinuities that produce elevated Doppler side lobes [6]. In this design a range update phase correction was implemented digitally to eliminate this problem. The ECM system also maintains phase coherency throughout the RF mixing stages. The system architecture was designed to be fully customizable in terms of amplitude and Doppler modulations as well as ECM techniques.

The DRFM based ECM system can generate both noise as well as deceptive type ECMs.

Noise jamming is accomplished by generating noise data with user specified characteristics. The noise is band limited to any bandwidth within the IBW of the DRFM. Noise data can be provided by the user in file format using the GUI. This data is downloaded into the memory of the DRFM. Noise playback is either continuous or on the reception of a radar pulse. This noise jamming technique is typically employed against search radars.

Deception jamming can present up to 64 false targets to the radar in order to prevent the radar from tracking the “real” target. Range/Velocity Gate Pull Off (R/VGPO) techniques are used to break radar lock on the platform in the range and Doppler domain. Due to the fact that radars can discriminate between true and false targets based on amplitude modulation, the DRFM applies Swerling models (0 to 4), along with range extended targets, comprising of multiple scatterers, to provide close to realistic radar returns.

ECM’s are not the only source of interference a radar system has to contend with. Clutter is a naturally occurring interference source which can cause a large degradation in the radar’s performance. It is thus vital to include this phenomenon during the testing of radar systems.

6 Clutter

Radar clutter simulation recreates the environment surrounding the target for the purpose of radar testing and evaluation. ECM techniques and complex targets simulate the return from a potential threat which occupies a very small portion of the range line, whereas radar clutter could potentially be present along the entire range line. Ground clutter is the main source of interference from the natural environment for a radar system and is thus responsible for a loss in radar performance. The complexity of realistic ground clutter is so high that only a statistical representation thereof is feasible. To simulate realistic ground clutter, the clutter should be temporally correlated, as well as conform to the amplitude statistics described by the probability distribution function (PDF) of the relevant type of clutter and radar platform as shown in Fig. 7. The clutter simulator should also be stable and reliable as the radar adaptively changes between operational modes and waveforms.

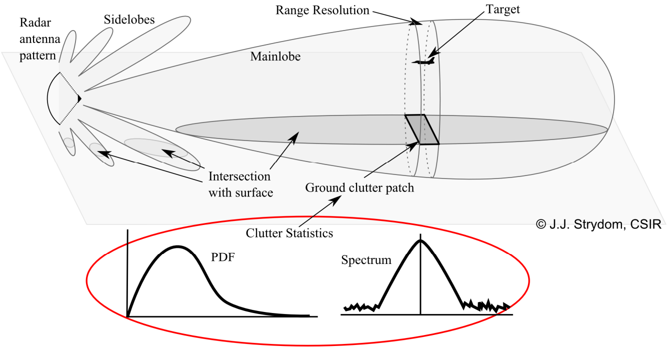

Figure 7: The Radar Clutter scenario showing how the target competes with the ground clutter return within the same range cell. The scattering statistics (PDF and bandwidth) of the ground clutter return within that range cell is shown.

Barton [2] lists the following clutter parameters for radar performance evaluation:

- clutter RCS,
- number of discrete scattering sources,
- spatial extent and distribution of sources,
- velocity extent and distribution (Doppler spectrum),
- wavelength dependence of RCS,
- amplitude distribution (PDF),
- spatial correlation of amplitudes,
- and polarization properties.

Due to this complexity, the clutter had to be simulated statistically. Spatial correlation and extent is controlled by having range segments with similar statistics. The Doppler distribution is simulated by adding correlation, with specified spectral properties, between consecutive clutter returns on a pulse to pulse basis.

For clutter to be present along an entire range line, many independent clutter scatterers have to be simulated, requiring each clutter scatterer to have its own dedicated storage in the DRFM’s memory. The clutter points are stored form pulse to pulse, to allow the temporal correlation to be applied. The memory on the DRFM system is capable of storing more than two million independent clutter scatter points. To the authors best knowledge the digital generation of synthetic clutter on a DRFM kernel was first published in the open literature in 2010 [12, 13].

The upper frame in Fig. 8 shows the range-Doppler map of ground clutter data measured with an X-band measurement radar on the CSIR premises. The lower frame in Fig. 8 shows the recreation of this range-Doppler map by using 8 range segments to drive the statistical behaviour of the clutter points in the range line. Segments were alternated between patches with large clutter returns and patches with little or no clutter return.

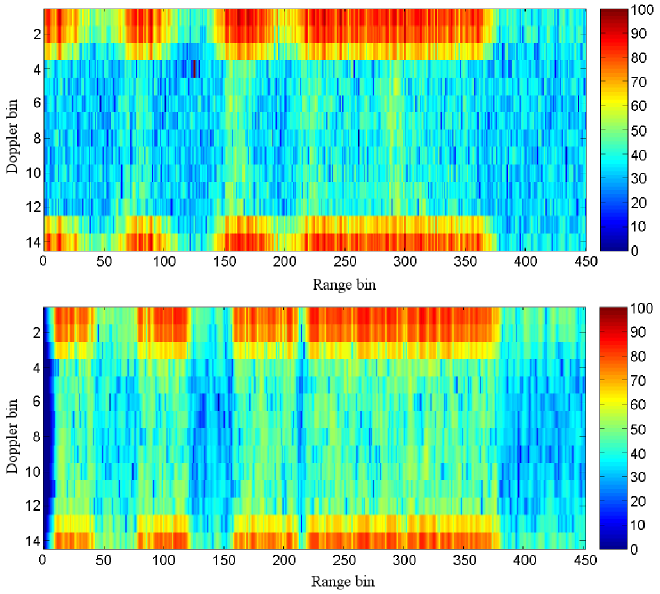

Figure 8: Comparison of clutter range-Doppler maps measured with the CSIR radar (upper frame), and clutter simulated using the DRFM to match the measured clutter statistics (lower frame).

For low range resolution radars, Rayleigh distributed clutter is usually sufficient, but for high range resolution (HRR) radars with narrow beam widths this approximation no longer holds and Weibull, Log-Normal or K-distributions have to be used [4]. The DRFM system is capable of simulating any arbitrary clutter distribution. This is especially useful when data measured with the radar (e.g. [3]) does not match a standard distribution, but the behaviour of the radar has to be analysed for that specific situation.

The DRFM based clutter simulation system is capable of testing a wide range of radar systems. Tests have shown that the clutter sub-system can operate at an IBW of 500 MHz, with input pulse widths up to 300 μs, and PRF's from 1 Hz to 300 kHz.

7 Conclusion

A wideband, high fidelity DRFM was designed and characterised for its SFDR performance as well as tested against a pulse-Doppler radar. The test against the pulse-Doppler radar showed that even though quantisation effects of the DRFM are evident, the spurious levels are low enough that it is unlikely that advanced electronic counter countermeasures (ECCM's) in the radar will be able to distinguish between a physical target return and one generated by the DRFM. This makes DRFM based systems ideal for radar environment simulation.

Using this DRFM as a kernel, a realistic HIL simulation test environment was developed which is capable of simulating standard radar test targets, complex multi-scatterer targets, ECM techniques and ground clutter, for which selected results were presented. The system is thus an excellent platform for the independent testing of radars, as well as research and development of new radar systems.

Acknowledgements

The authors would like to express their gratitude to the Council for Scientific and Industrial Research (CSIR) in South Africa, for providing funding for this research.

The authors would further like to thank the Radar and EW competency at CSIR, DPSS for their support.

References

[1] F. Bandiera, A. Farina, D. Orlando, and G. Ricci, “Detection algorithms to discriminate between radar targets and ECM signals,” IEEE Trans. on Signal Process., 2010, Dec., 58, (12), pp. 5984–5993.

[2] D. K. Barton, Modern radar system analysis, Artech House, 1988.

[3] H. J. de Wind, J. E. Cilliers and P. L. Herselman, “DataWare: Sea Clutter and Small Boat Radar Reflectivity Databases,” IEEE Signal Processing Magazine, Vol. 27, No. 2, March 2010, pp. 145-148.

[4] F. Gini, M. Greco, M. Diani, and L. Verrazzani “Performance Analysis of Two Adaptive Radar Detectors against Non-Gaussian Real Sea Clutter Data,” IEEE Trans. on Aerospace and Electronic Systems , Vol. 36, No. 4, October 2000, pp. 1429-1439.

[5] P. L. Herselman and J. E. Cilliers, “A digital instantaneous frequency measurement technique using high-speed analogue-to-digital converters and field programmable gate arrays,” South African Journal of Science, vol. 102, no. 7/8, pp. 345–348, July 2006.

[6] P. L. Herselman, W. A. J. Nel, and J. E. Cilliers, “Effect of DRFM Phase Response on the Doppler Spectrum of a Coherent Radar: Critical Implications and Possible Mitigation Techniques,” 1st CSIR Biennial Conference, pp. 1, Feb. 2006.

[7] C. L. Holloway, and E. F. Kuester, “Closed-form expressions for the current densities on the ground planes of asymmetric stripline structures,” IEEE Trans. on Electromagnetic Comp., 2007, Feb., 49, (1), pp. 49-57.

[8] T. W. Küsel, M. R. Inggs, and J. E. Pienaar, “A Comparison Between the Spectral Purity of Three Digital Radio Frequency Memory Architectures,” Transactions of the AOC, vol. 1, no. 1, pp. 135-144, October 2004.

[9] R. Schmitt, “Electromagnetics explained: a handbook for wireless, RF, EMC, and high-speed electronics,” Elsevier Science, 2002.

[10] J. C. Smit, J. E. Cilliers, and E. Burger, “Comparison of MLFMM, PO and SBR for RCS Investigations in Radar Applications,” to be published in the IET Radar Conference Proceedings of Sept. 2012.

[11] J. C. Smit, and J. E. Cilliers, “Insights Into Factors Contributing to the Observability of a Submarine at Periscope Depth by Modern Radar: Part 2 – EM Simulation of mast RCS in a realistic sea surface environment,” ICEAA, 2-7 Sept. 2012.

[12] J. J. Strydom, E. Pienaar, J. E. Cillers and K. Olivier, “Advances in the realtime simulation of synthetic clutter for radar testing and evaluation,” 47th Annual AOC International Symposium and Convention, Atlanta, Georgia, USA, 3-7 Oct. 2010.

[13] J. J. Strydom, and J. E. Cillers, “Advances in the testing and evaluation of airborne radar through realtime simulation of synthetic clutter,” 48th Annual AOC International Symposium and Convention, Washington, DC, USA, 13-16 Nov. 2011.

[14] K. Olivier, J. E. Cilliers, “Design Aspects and Characterised Performance of a Wideband DRFM for Radar Test and Evaluation,” to be published in the IET Radar Conference Proceedings of Sept. 2012.

[15] K. Olivier, J. E. Cilliers, and M. du Plessis, “Design and performance of wideband DRFM for radar test and evaluation,” Electronics Letters, Vol. 37, No. 14, 7 July 2011, pp. 824-825.

[16] H. W. Ott, “Partitioning and layout of a mixed-signal PCB,” Printed Circuit Design Mag., 2001, June., pp. 8-11.

[17] S. Watts, H. D. Griffiths, J. R. Holloway, A. M. Kinghorn, D. G. Money, D. J. Price, A. M. Whitehead, A. R. Moore, M. A. Wood, D. J. Bannister, “The specification and measurement of radar performance,” IEE International Conference Radar 2002, 15-18 Oct. 2002, IEE Publication No. 490, pp. 542-546.

[18] W. Zongbo, G. Meiguo, L. Yunjie, and J. Haiqing, “Design and application of DRFM system based on digital channelized receiver,” Int. Conf. on Radar., 2008, Sept., pp. 375–378.