DIGITAL STEREO ENHANCEMENT TO THE TIGER RADAR SYSTEM

Jim WHITTINGTON[(1)], John DEVLIN[(2)], Minh NGUYEN[(3)]

[(1)]Department of Electronic Engineering, La Trobe University, Bundoora Campus, Victoria, 3086, AUSTRALIA
E-mail: J.Whittington@latrobe.edu.au

[(2)] As (1) above, but E-mail: J.Devlin@latrobe.edu.au

[(3)] As (1) above, but E-mail: M.Nguyen@ee.latrobe.edu.au

ABSTRACT

The Tasman International Geospace Environment Radar (TIGER), which is part of the global SuperDARN network, is a dual HF radar system with overlapping footprints designed to map ionospheric motions by detecting ionospheric scatter. The stereo SuperDARN radar concept is an interesting new innovation that effectively enables two radars to operate from the one site, sharing expensive infrastructure items, such as antennas and RF transmitters. Although improvements continue to be made to the SuperDARN radar concept, its operation remains centered around 20 year old analogue technology. The opportunity to provide enhanced operations through the implementation of a digital SuperDARN radar system has been identified. This paper presents current state of work being undertaken on the development of a Digital SuperDARN Radar and explains the proposal to firstly implement the digital radar as a digital channel in a hybrid analogue/digital stereo radar system, with the ultimate aim being the construction of fully a digital stereo radar.

INTRODUCTION

HF ionospheric radars have long been used to study the ionosphere by detecting signals returned to Earth either as a result of ionospheric refraction (internal reflection) or Bragg scatter from ionospheric irregularities. HF radar, with its ability to survey a large region of the ionosphere from a single site, is an extremely valuable tool for monitoring the state of the high latitude ionosphere and studying the processes that control its behaviour. Of particular importance is the fact that most high-latitude, *F*-region irregularities move with the convection velocity of the background ionosphere driven largely by the solar wind/IMF interaction with the magnetosphere. At any instant in time the detailed structure of the ionospheric convection pattern across the entire polar cap/auroral ionosphere indicates much of the immediate terrestrial impact of space weather. Thus observing the details of this convection is essential to unraveling the complexities of solar wind-magnetosphere-ionosphere coupling, and to improving our ability to predict the impact of space weather on the operation of, for example, satellite, navigation and communications systems.

Greenwald et al. [1], [2] developed the concept of the Super Dual Auroral Radar Network (SuperDARN) capable of monitoring significant portions of the auroral and polar cap ionospheres. The concept is based on the development of a network of dual radars. A radar pair utilises two widely separated radars that have overlapping footprints so that, for a common echo source, each radar determines a different velocity component due to its different viewing direction. This arrangement is capable of providing quite a detailed description of ionospheric convection within the common area of the footprints. Currently SuperDARN (SD) consists of 6 radars in the southern hemisphere and 9 in the north, deployed by scientists from 7 countries [3].

In developing the Tasman International Geospace Environment Radar (TIGER) the aim has been to extend the SD network in the southern hemisphere, but with the important difference of extending coverage to the sub-auroral region. This provides opportunity to observe new phenomena and to improve the coverage of auroral phenomena during magnetic storms when the aurora expands equatorward of the footprints of the other radars in the SD network [4], [5]. The Tasmanian component, located on Bruny Island, began operation in December 1999, while the New Zealand radar, to be located near Invercargill, is under construction and planned for commissioning in 2004.

There is great advantage in using a common hardware and software platform in a radar network and SD has largely followed this principle. However, since its inception in 1991 the SD network has continued to develop, and is still expanding. Improvements to software and hardware continue to be made, although the basic principles of operation remain the same. Significant engineering improvements were made by University of Leicester in developing the

CUTLAS system [6]. The first TIGER radar was built principally to the Leicester design, with improvements to the transmitters, power supplies and micro-controllers.

The basic specifications of the TIGER radar are listed in Table 1. The radar operates as a fixed-frequency sounder, choosing a suitable frequency in the 8-20 MHz band. The frequency selected is that providing the greatest amount of ionospheric scatter (signal return or echo) across the radar footprint. The 16 antennas make up the main array. A phasing network is used to scan the main beam of the array over 52^{O} of azimuth in 16 steps or beams. TIGER is a pulse radar enabling the main antenna array to be used for transmission and reception. An auxiliary receiving array of 4 antennas forms an interferometer to measure the elevation angle of arrival. In the most common modes of operation TIGER completes a full azimuth scan in 1 or 2 minutes [7].

Since its inception, four years ago, the TIGER Tasmania radar has rapidly gained a glowing reputation for the quality of its data and its ability to observe new ionospheric phenomenon, such as, an Auroral Westward Flow Channel [8], the first, and so far only radar to do so.

Table 1. TIGER Radar Specifications

Frequency Band:	8 – 20 MHz
Antenna Arrays:	Tx/Rx Array: 16 horizontally polarised log-periodics
	2nd Rx Array: 4 horizontally polarised log-periodics
Beam Widths:	Horizontal: 4^{o} at 10 MHz, 3^{o} at 14 MHz, 2^{o} at 18 MHz
	Vertical;:50^{o}
Lobe Levels:	< -14 dB for both back and side lobes
Transmitters:	16 x 600 W (one per antenna in Tx/Rx array)
Total Peak Power:	9.6 kW
Mean Power:	200 W
Radiated Power:	12.5 W in main beam direction
Tx signals:	Pulse pattern repetition rate: 50 or 100 ms
	Pulse width: 300 μ s
	Bandwidth: 10 kHz at –20 dB
	Duty cycle: 2.1%
	Carrier frequency stability better that 10^{-8} per day
Range:	180 km to 3330 km

STEREO SUPERDARN RADARS

An interesting recent innovation, pioneered by the University of Leicester is the stereo SuperDARN radar. A stereo radar, shown in figure 1, is effectively two radars, each of which transmits and receives independent signals, although they share common computers, RF transmitters, antennas and control circuitry which synchronises and interleaves the transmissions. Radar pulses from each channel are differentiated by their operational frequency, and it is necessary to use separate signal generation, beam forming and receivers in each of the two channels. As the common components constitute the major capital cost within a SD radar, a stereo radar is significantly cheaper than two independent radars.

The Leicester Stereo radar design was developed to improve the temporal resolution of the SuperDARN radars by adding a second beam direction to the conventional single beam configuration. The Stereo aspect relies on the capability of the transmitters in the SuperDARN radars to operate at duty cycles of at least twice that required for normal SuperDARN operation (i.e. 7.2% compared to 3.6%) [9]. The TIGER consortium has decided to adopt the stereo concept into its future developments. The TIGER New Zealand Radar (nominally termed the Unwin Radar) is the first expansion of the TIGER radar network. This new radar is being constructed as a stereo radar.

The stereo enhancement has no impact on the ability of radar pairs to generate crossed beams and hence provide detailed velocity information. At any given time each channel of a stereo radar must be operating at differing frequencies, they may operate on the same beam or a different beam, as required. Chosen frequencies and beams are under the full control of the operating software and can be specifically set, when required, by the investigating team.

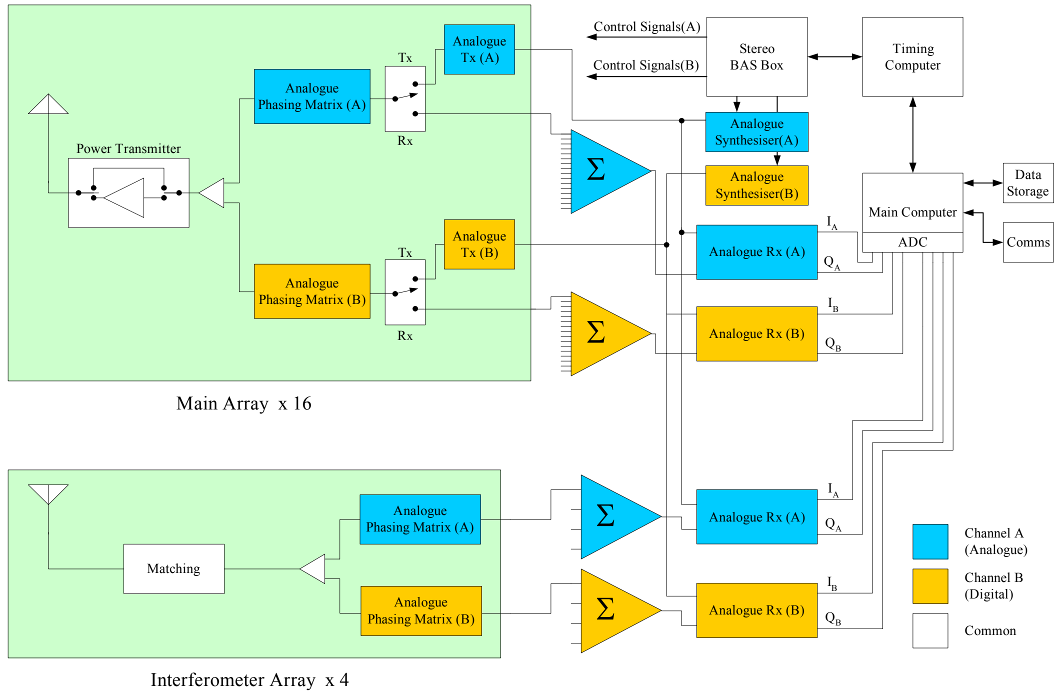

Figure 1: Analogue Stereo SuperDARN Radar - block diagram

DIGITAL RADARS

The application of digital techniques to radar systems dates back to the 1960's and 70's. While the benefits of replacing analogue technology with digital were clear, the resulting systems were far too costly for all but military applications [10]. The 1990's saw wider interest in the application of Digital Signal Processing (DSP) to radar systems. Reported improvements in performance include: reduced cost, power, size and weight; greater reliability and life-cycle; signal-to-noise (SNR) and dynamic range improvements; higher range accuracy and resolution; and increased flexibility, including, multiple radar applications and arbitrary control of waveforms and beamforming [11,12,13,14]. In recent years Field Programmable Gate Array (FPGA) technology has rapidly improved and adopted structures suitable for high bandwidth DSP [15]. This has lead to their adoption as a core element in a number of digital radar systems [14,16,17].

Field Programmable Gate Arrays are specialised integrated circuits that contain a sea of generic components, which can be configured and connected to one another in an enormous variety of ways. In most FPGAs the configuration and connection information is stored in static RAM. This type of FPGA can be re-programmed with a new design in a matter of seconds. This fast design turn around time makes FPGAs ideal for prototyping. It also means that FPGAs can be used to produce reconfigurable hardware - where the same piece of hardware performs different functions at different times (by simply re-programming it's on board FPGA(s)).

The current transmitter and receiver implementation of the SuperDARN radars are based on 20 year old analogue technology. While this implementation has performed well, a number of issues/limitations have become apparent. These include: size and cost of parts; the considerable calibration effort required to setup consistent time delays between various transmitter and receiver pathways; component failures (e.g. analogue switches used for differing delay and gain settings) requiring significant ongoing maintenance effort/cost; time delays that vary with gain settings; and limited flexibility – for example, antenna phasing is performed by switching in set time delays.

There are several reasons for implementing a digital SD radar. The initial (projected) lower cost and "no-maintenance" issues make the digital system very appealing. The extra flexibility provided by a digital radar will make it a valuable research platform for upper atmospheric physics.

The digital radar will have additional performance over the current radar including:

- increased sensitivity (x10) due to digital phasing rather than lossy analogue time delay phasing;
- different mission capability through reconfigurablity;
- x16 temporal resolution;
- the option to employ sweeping beams, as opposed to 16 selectable fixed beams - improved azimuth resolution;
- full scan across field of view;
- possibility of multiple channels increased from the current two available in stereo mode;
- ability to move easily from mono to stereo or beyond.

DIGITAL TIGER DESIGN

Overview

When designing the digital TIGER radar our aim has been to combine the latest digital technology and techniques into a viable system that meets or exceeds the current (analogue) specifications. Current high end FPGA devices, such as the Xilinx® Vertex II family, have been specifically designed to accommodate high speed DSP hardware, and are thus ideally suited for this application. High speed analogue to digital conversion (ADC) is an essential element of our receiver design. Ideally, 16 bits at 125MHz is required but unfortunately, this level of performance is still a few years away. However, a receiver with an equivalent level of performance to the current analogue system can be constructed using readily available 12 bit at 125MHz devices.

A key feature of the proposed design is synchronised Direct Digital frequency Synthesisers (DDS) with initial phase offset inputs for antenna phasing. Frequency synchronisation across all transmitters and receivers is essential for maintaining correct phase delays. A general block diagram of the digital transmitter is shown in figure 2 The basic function of the transmitter is to provide a 290ms modulated Gaussian pulse at the required carrier frequency, following an activation of the pulse start input. Appropriate phasing is introduced to steer the beam. Using a digital Gaussian pulse will result in a transmission pulse with a lower interference profile (i.e. side lobes) than that provided by the current system. The initial sample rate of 125MHz is set by the requirements of the receiver and need for synchronised frequency synthesizers (DDSs). Although, by setting the output sample rate (250MHz) much higher than the maximum transmission frequency (20MHz) the specifications for the multirate digital filter and analogue reconstruction filter are fairly relaxed. This will result in size savings in both cases, however more importantly, in the case of the analogue reconstruction filter less complexity results in improved phase tolerance [18].

A general block diagram of the digital receiver is shown in figure 3. The receiver is required to produce inphase and quadrature outputs, summed from all 16 signals at the chosen transmission frequency, after the effects of antenna phasing have been removed. An RF sampling receiver design has been chosen as this moves almost all of the receiver function into the digital domain. Over-sampling the input, in this case at 125MHz, further relaxes the requirements on the analogue sections that remain (i.e. anti-aliasing filter). By minimising the analogue circuitry we can eliminate post construction tuning and vastly improve receiver phase tolerance [19].

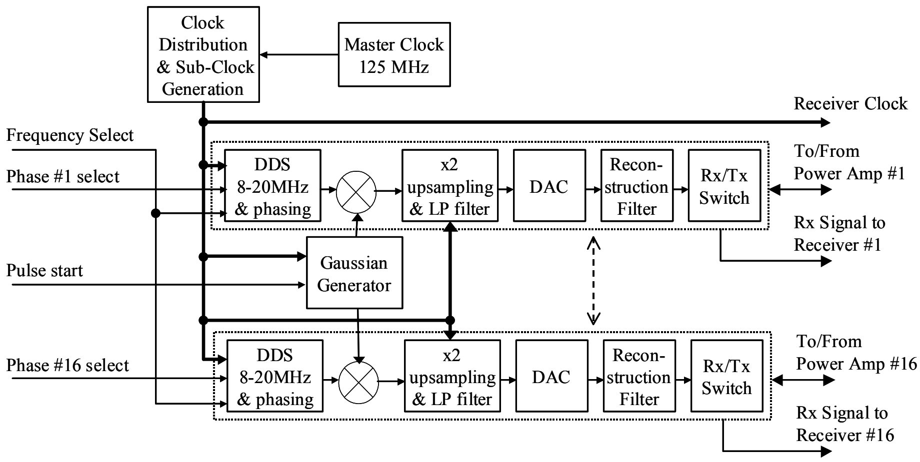

Figure 2: Digital SuperDARN Radar Transmitter – single channel

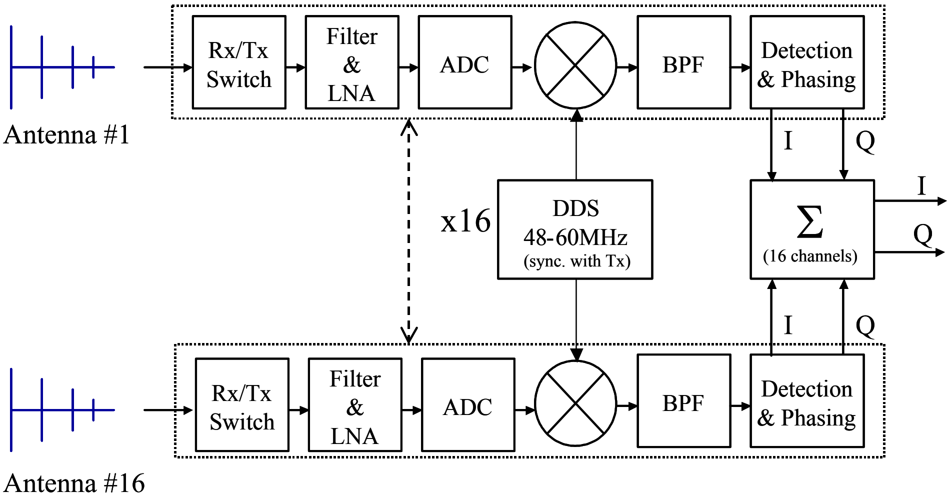

Figure 3: Digital SuperDARN Radar Receiver –single channel

A complete channel consists of 16 transmitters and 20 receivers. A fully digital stereo radar will of course require twice as many modules. A block diagram for a complete digital stereo radar is shown in figure 4. The initial implementation will be to add a digital channel to the existing mono analogue radar, which is discussed in more detail later. Proof of concept studies have demonstrated the feasibility of the proposal [18,19,20,21,22]. At present the design is being completed and prototype hardware constructed.

Design entry and verification has been carried out using *Xilinx System Generator for DSP*^{TM}. This high level modeling and implementation tool sits above the *Simulink*® and *Matlab*® simulation environments, and provides direct links between system level blocks and Intellectual Property (IP) cores that have been specifically designed for implementation in Xilinx® FPGAs. This enables the development and evaluation of bit and cycle accurate models that are readily transferable to hardware [15].

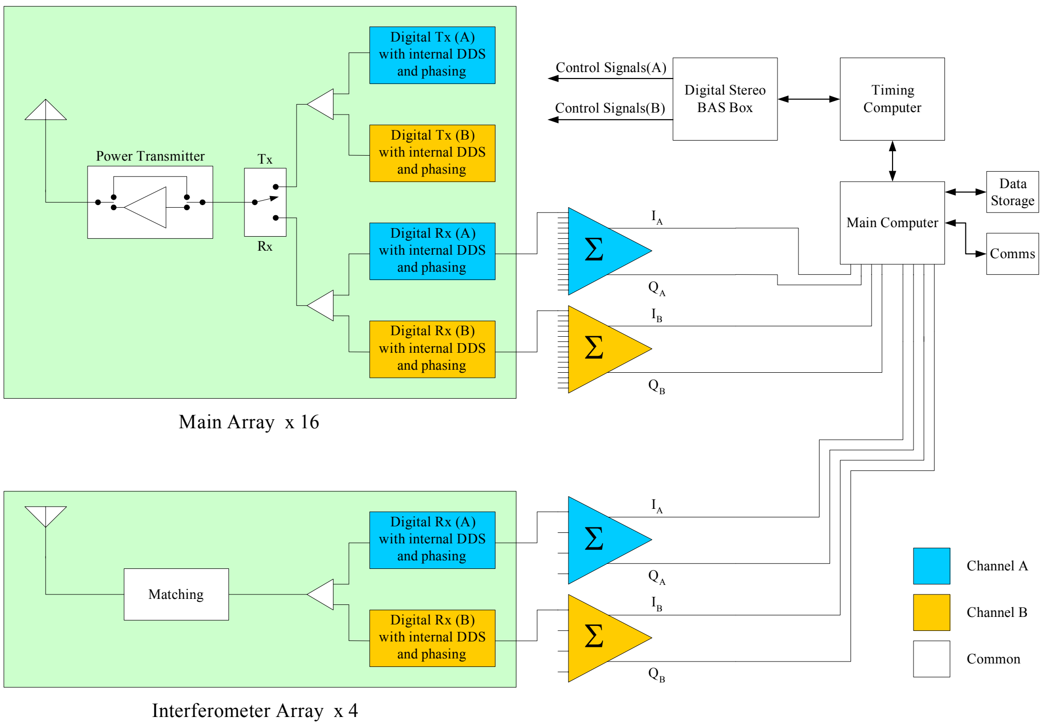

Figure 4: Digital Stereo SuperDARN Radar - block diagram

Digital Transmitter Design

Key components the transmitter design are: a Guassian pulse generator, common to all elements in a single channel; then within each element: a very low noise DDS, which can be loaded with phase increment and phase offset values; a high speed multiplier (mixer) and a 2 times upsampling polyphase filter. The Guassian Pulse Generator, shown in figure 5, is basically a lookup table addressed by a counter, to save space only half of the Gaussian pulse shape is stored.

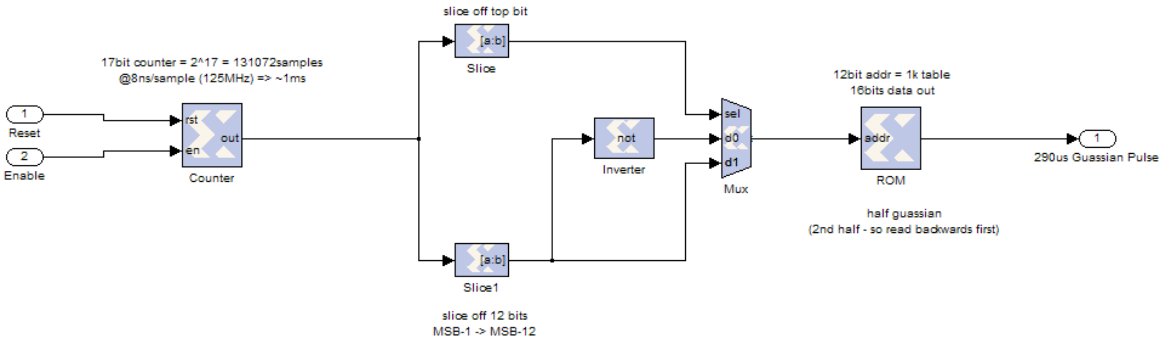

Figure 5: Gaussian Pulse Generator

Within each transmitter element, shown in figure 6, the DDS is loaded first with a common phase increment value, which sets the current transmission frequency, and secondly with a phase offset value, which generates the appropriate phase delay for the current beam. The DDS output is mixed with the common Gaussian pulse, then 2xupsampled and filtered by the polyphase filter. As there is a large gap between the maximum transmission frequency (20MHz) and the final output Nyquest frequency (125MHz) the requirements on the polyphase filter are fairly relaxed (the minimum upsampling image frequency will be at 105MHz).

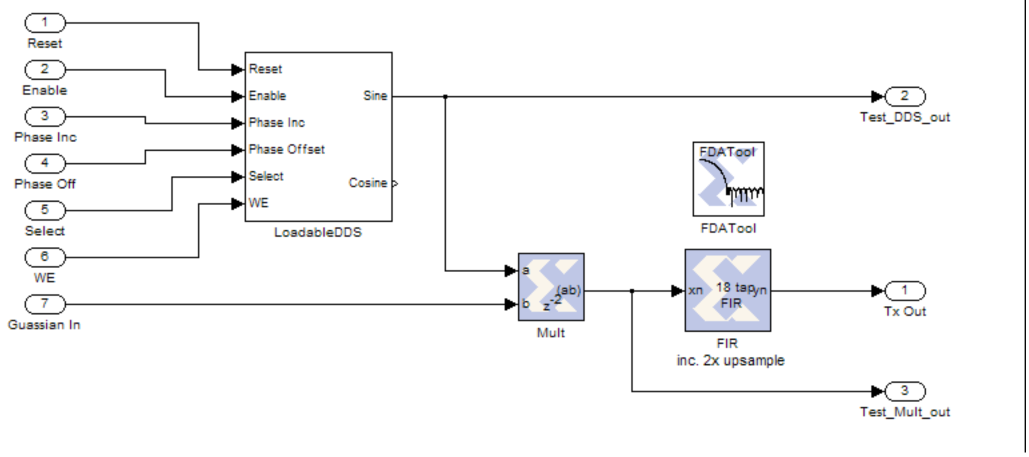

Figure 6: Single Element Digital Transmitter

To better illustrate how all the transmitter elements fit together, a four element array is shown in figure 7. The common phase increment value, which sets the transmission frequency, is expressed in cycles (of the master clock – 125MHz)/sample point. In the example given, 0.1 represents a transmission frequency of 12.5MHz. Each transmitter element can be loaded with a different phase offset value, as required to steer the beam. The phase offset values are expressed in fractions of the transmission frequency cycle (i.e. phase_offset*2π). In the example shown, the phase offset values are set widely apart (at 0, $\pi/2$, π, and $3\pi/2$) to better illustrate the phase delay effect. In an operating system the phase value used will be depended on both the transmission frequency and the beam angle.

The Simulink® simulations shown in figures 8 and 9 demonstrate the operation of this circuit. Figure 8 provides a time domain view of the transmitter output, showing first 8(a), the pulse output from a single element; and secondly 8(b), the expanded view of the transmitted waveforms from the four elements, where the different phase delays can be clearly seen.

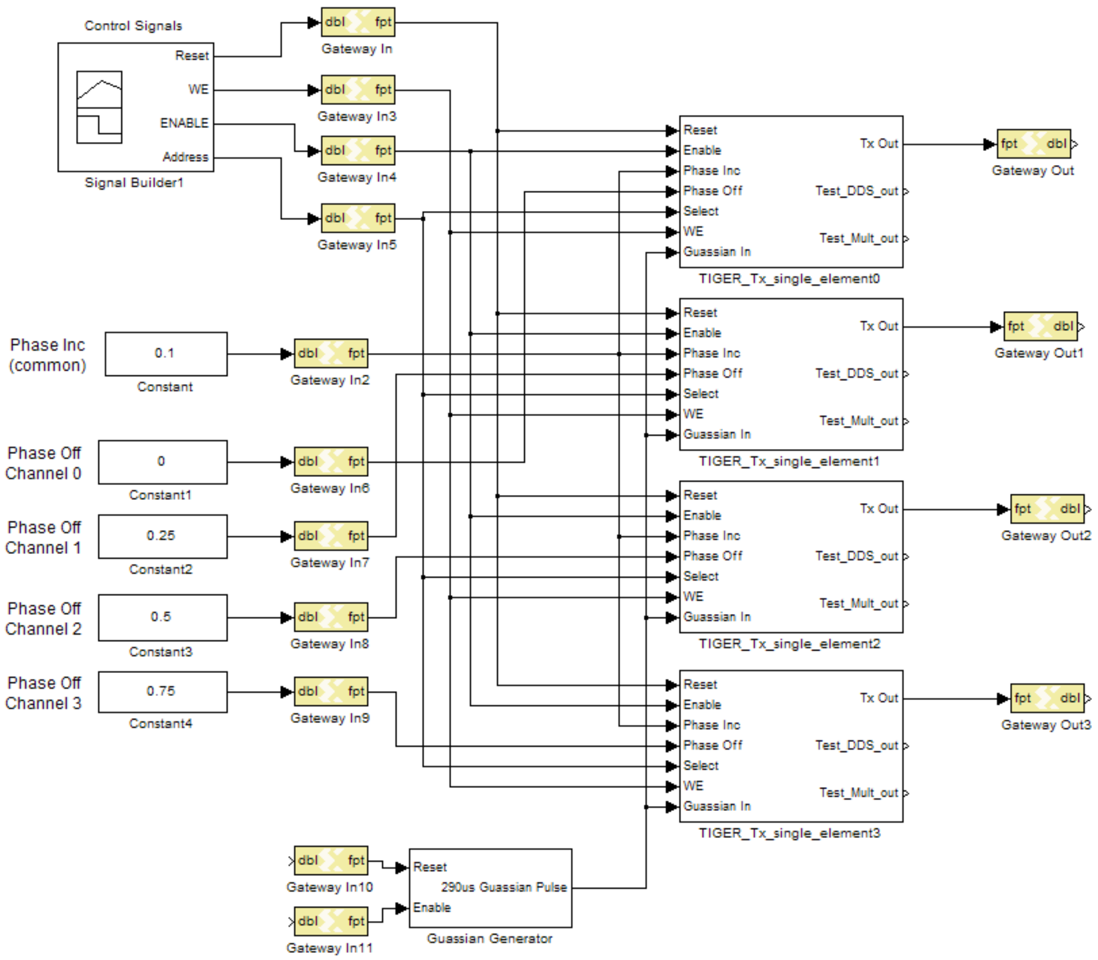

Figure 7: Four Element Digital Transmitter Array

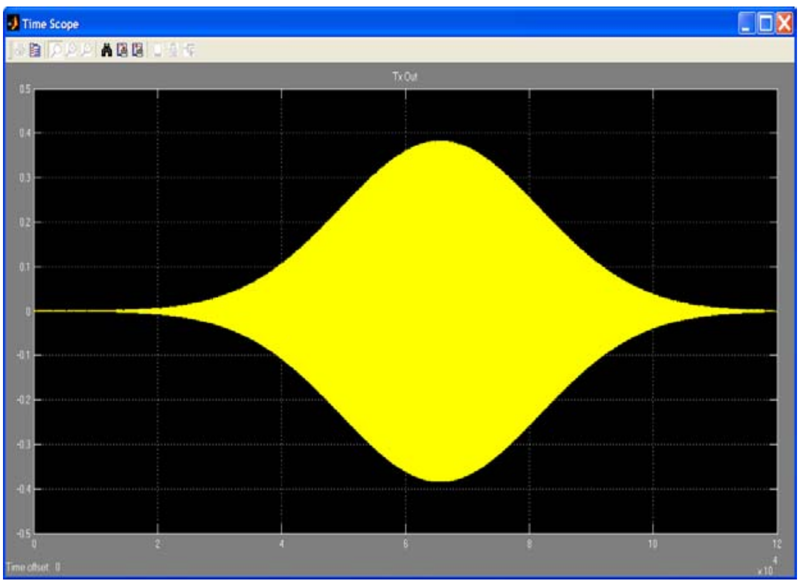

Figure 8(a): Single Element Transmitter Output - time domain

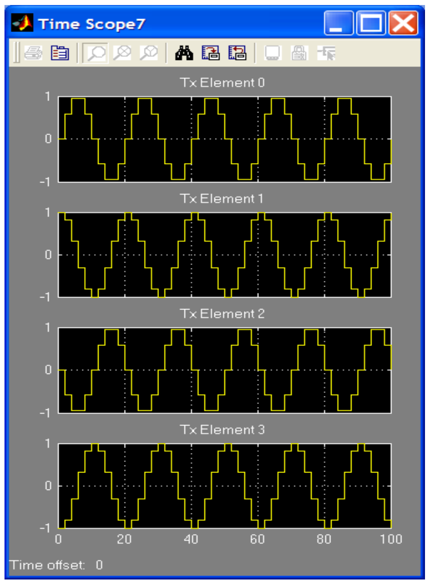

Figure 8(b): Four Element Transmitter Output - time domain, expanded view

Figure 9 shows two frequency domain plots, where the frequency axis is normalized with respect to the maximum sampling frequency – 250MHz. The mixer output is shown in Figure 9(a), with the frequency spike situated at 12.5MHz (0.05*250). The transmitter output spectra are displayed in figure 9(b), with the smaller spike being the upsampled image at 112.5MHz (125-12.5).

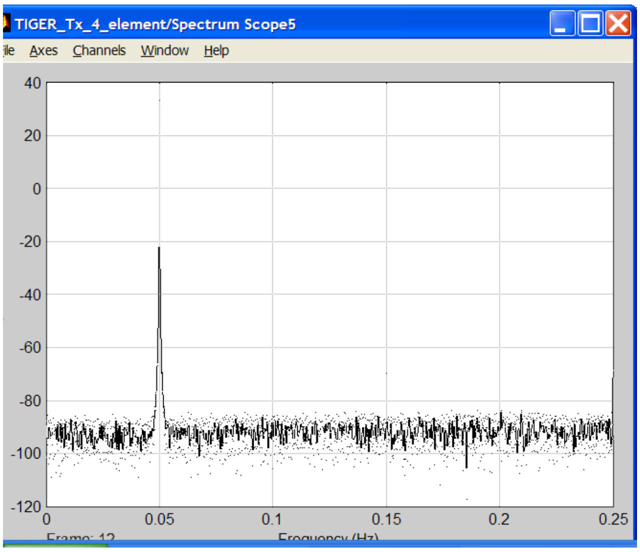

Figure 9(a): Mixer Output - frequency spectra

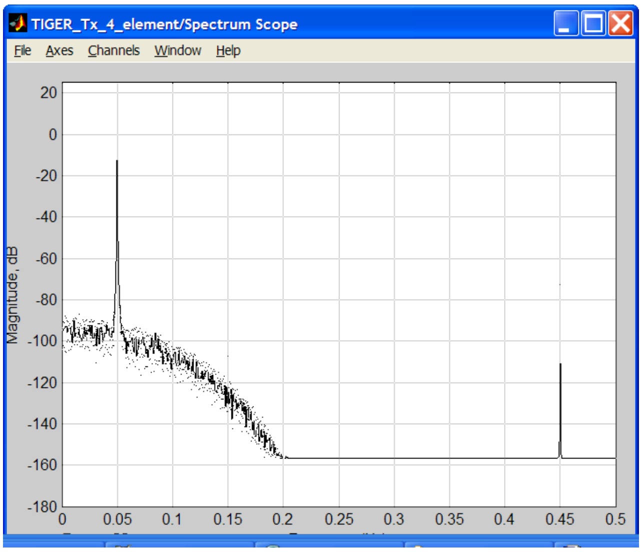

Figure 9(b): Transmitter Output - frequency spectra

Digital Receiver Design

In the digital receiver, shown in figure 10, the sampled signal is first mixed with a LO to produce a 40.625MHz IF signal. The LO is produced by a DDS loaded with a phase increment value to produce frequencies between 48.625 and 60.625, there is no phase offset as phasing is performed at the next stage. Image frequencies will be in the range 56.625MHz to 80.625MHz, however, due to the 125MHz sampling frequency, the images will fold back into the range 44.375MHz to 62.5MHz (Nyquest frequency). A lowpass FIR filter is then used to filter out the image components.

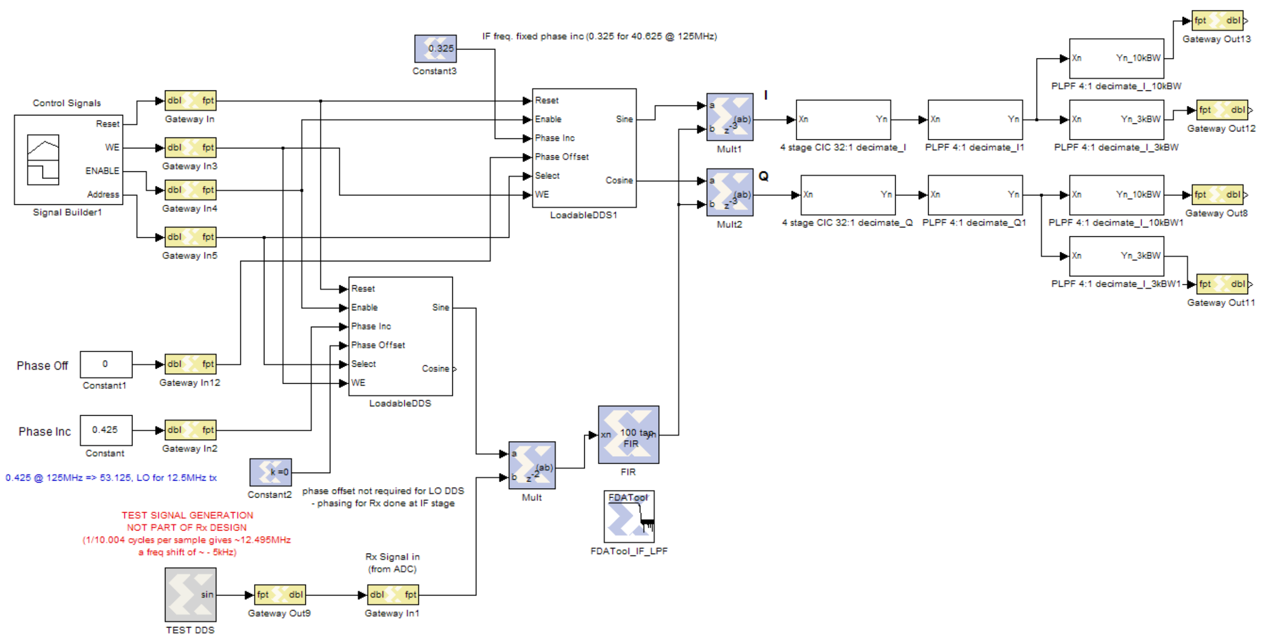

Figure 10: Single Element Digital Receiver

In the next stage the signal is quadrature translated down to the complex baseband by mixing it with sine and cosine output of a DDS operating at the IF frequency (40.625MHz). Phasing is performed at this point, as the mixing frequency is fixed, and so only 16 different phase offset values will be required per receiver element to generate the 16 beams. Following the quadrature mixing stage an image frequency will exist at 43.75MHz (2*IF or 81.25MHz folded over the Nyquest frequency). The following three cascaded filter stages filter out image elements as well as decimating the signal, by 32:1, 4:1 and 4:1 to bring the final sample rate down to ~244kHz. The receiver provides the option of two bandwidth outputs 6kHZ and 20kHz.

To demonstrate the operation of the digital receiver a special 12.495MHz test input signal was generated, this represents a -5kHz frequency shift from the nominated transmission frequency of 12.5MHz. The spectra of the test signal as it progresses through the digital receiver are shown in figure 11. As is expected, the spectra of the receiver outputs, figures 11(e and f) clearly show a 5kHz tone (0.02*250/1000 = 0.005MHz). Finally, the time domain I and Q receiver outputs are presented in figure 12, showing the 5kHz output, but with a 90^{o} phase difference between the I and Q channels, as expected.

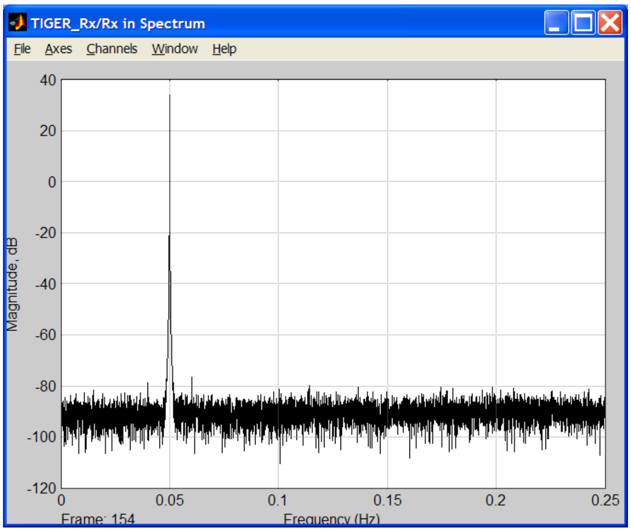

Figure 11(a): Rx in - frequency spectra

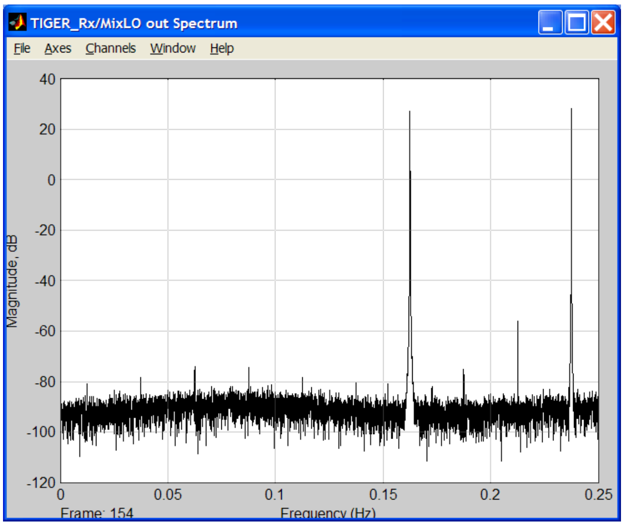

Figure 11(b): LO Mixer output - frequency spectra

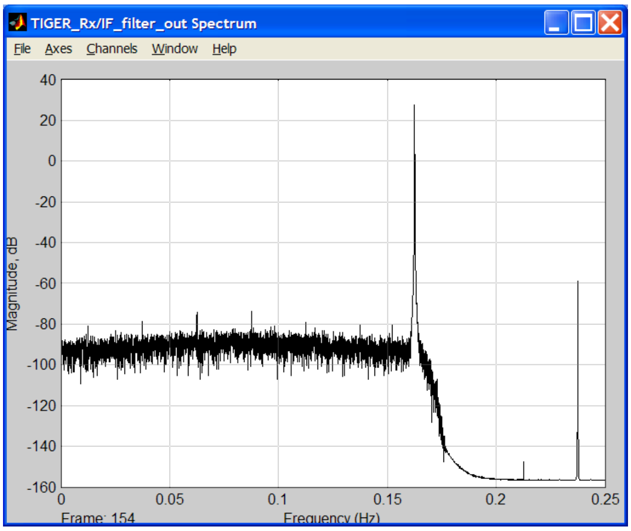

Figure 11(c): IF Filter output - frequency spectra

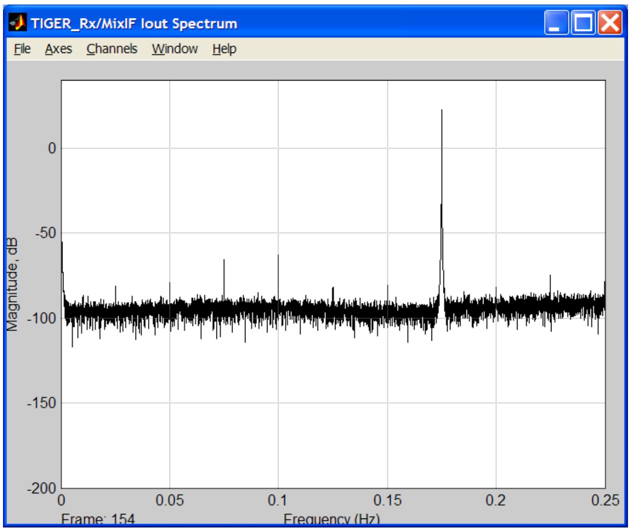

Figure 11(d): IF Mixer output - frequency spectra

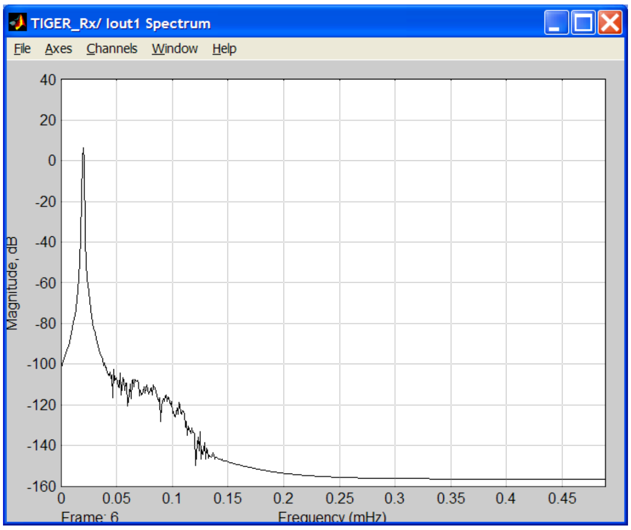

Figure 11(e): Receiver output – 20kHz BW

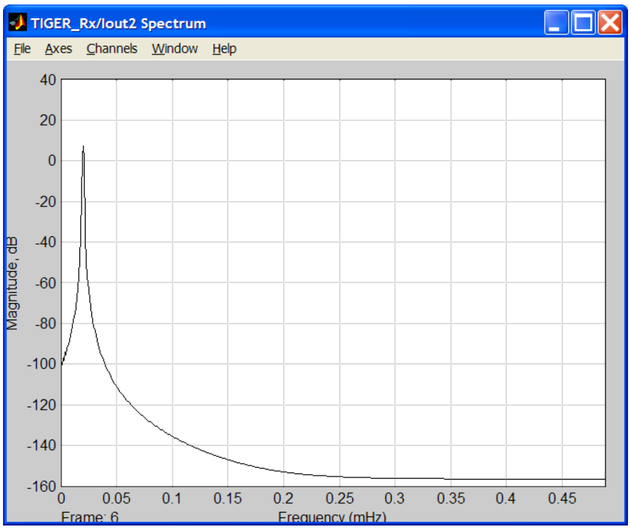

Figure 11(f): Receiver output – 6kHz BW

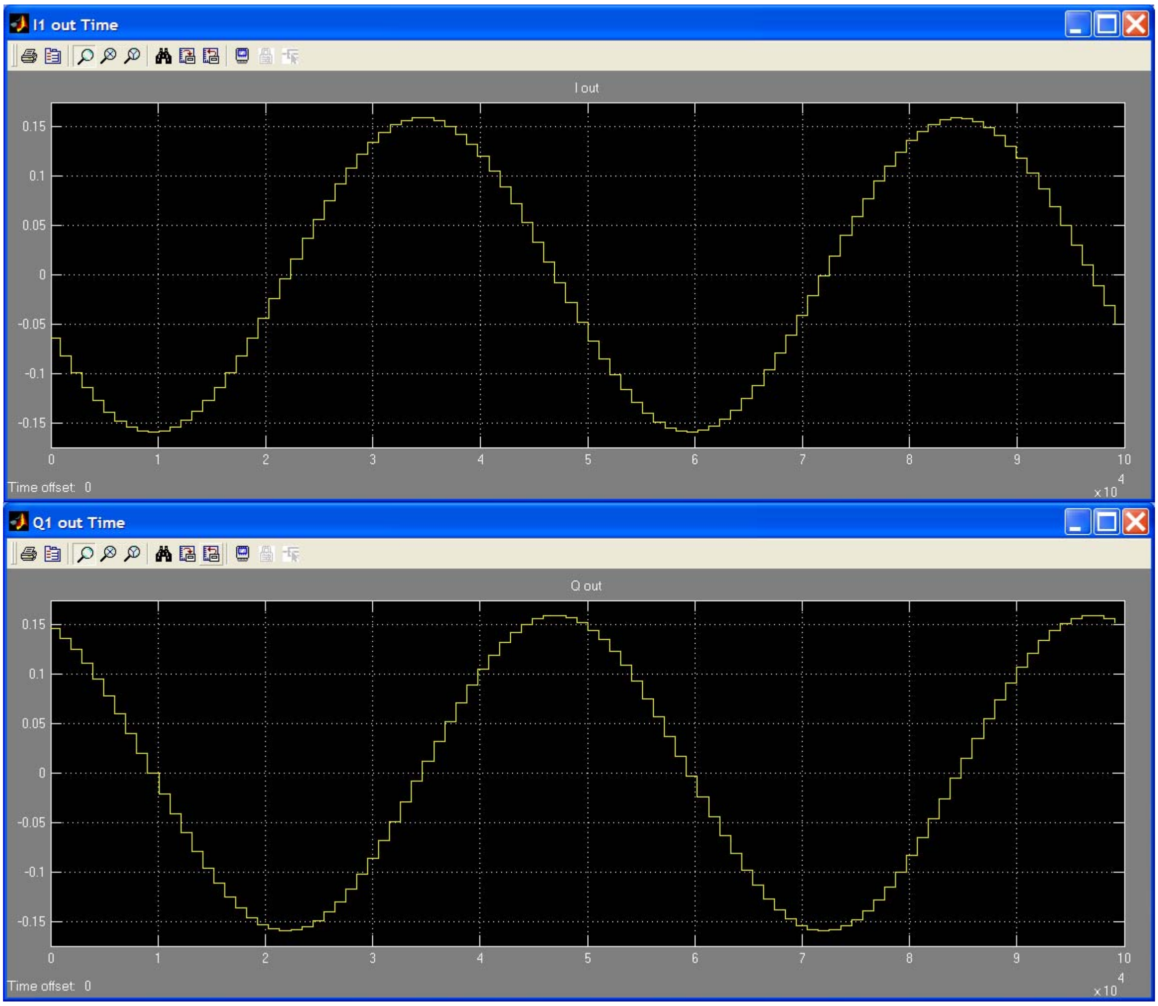

Figure 12: I and Q Receiver Outputs – time domain

HYBRID ANALOGUE/DIGITAL STEREO RADAR

For the initial rollout of the Digital TIGER Radar is proposed that a hybrid Analogue and Digital system be implemented. A second digital channel will be added to the existing TIGER analogue radar at Bruny Island. This minimizes the development effort and cost by allowing a second channel to be added to an existing radar. It also minimizes the risks, as the existing radar will continue to operate and continue to provide the excellent data set we have seen over the past four years. A block diagram for the hybrid analogue/digital stereo radar is shown in figure 13.

The digital channel will operate independently to, but synchronised with, the existing radar. The interface with the existing radar will be based on the approach taken by Leicester with their stereo radar, but will differ significantly in its implementation. The very nature of the hybridisation of the radar requires significant effort in interfacing to the existing system without compromising its operation. For example, the digital radar will naturally have a digital output signal. In the normal course of events this would be passed to the main computer and taken through the normal radar processing routines. In the hybrid design, the quadrature digital output of the digital radar will, by necessity, be taken through a pair of D to A converters and fed to a second pair of A to D converters (in the main computer) to be read along side the current analogue channel. This duplication and interfacing, although cumbersome and redundant, is deemed essential to ensure the operation of the current analogue channel is not compromised during the testing of the digital system. Once testing is complete, a fully digital system can be implemented, eliminating the redundancy of the hybrid system.

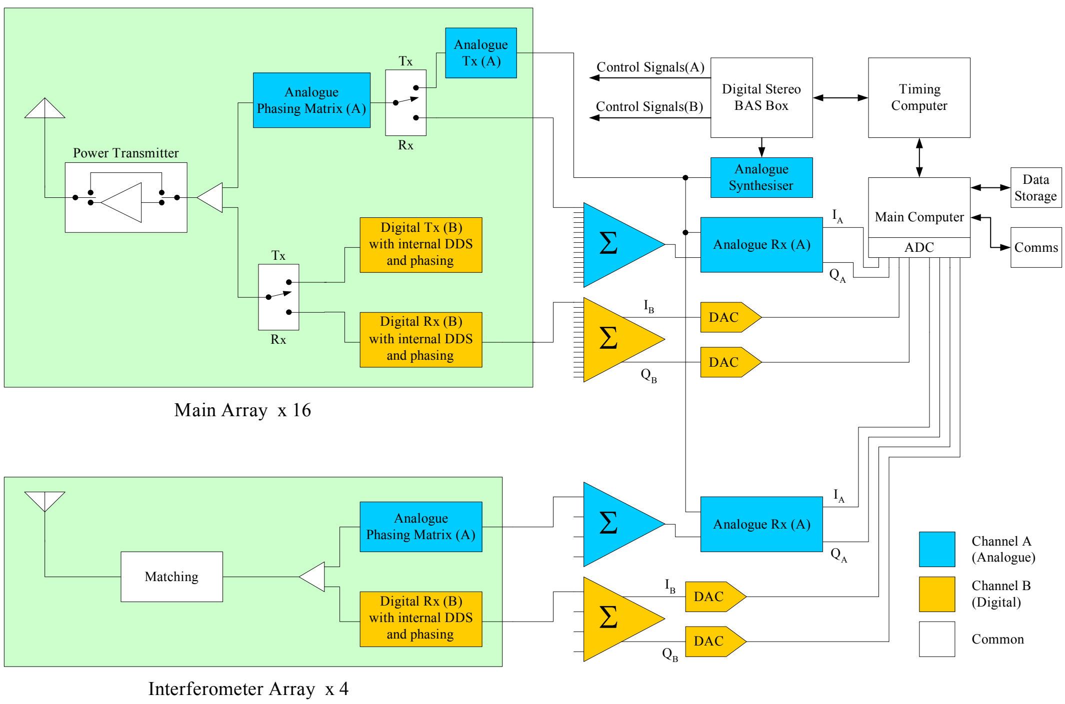

Figure 13: Hybrid Analogue/Digital stereo TIGER Radar - block diagram

SUMMARY

The TIGER radar has proven to be a valuable addition to the SuperDARN network. Improvements to SD radar systems continue to be made, an interesting recent innovation has been the stereo SuperDARN radar concept pioneered by the University of Leicester. However, the core function of all current SD radars is based on 20 year old analogue technology. Moving to a full digital implementation offers many benefits, such as, lower cost and maintenance; although even more appealing is prospect of a more flexible, higher performance radar, providing a significant advance in instrument capability over the current analogue system. A digital radar marries well with the stereo radar concept, in the longer term a fully digital radar with two or more channels is being proposed. However, for the initial implementation and onsite testing a hybrid analogue/digital stereo radar will constructed by adding a digital channel to the existing mono analogue radar in Bruny Island.

A fully digital transmitter and RF sampling receiver has been designed and verified using the Xilinx System Generator for DSP™/Simulink®andMatlab® design, simulation and implementation environment. The design is presently being evaluated, with prototype hardware, based on Xilinx Vertex II FPGAs presently under construction.

REFERENCES

[1] Greenwald, R.A., K. B. Baker, R. A. Hutchins, and C. Hanuise. "An HF phased-array for studying small-scale structure in the high-latitude ionosphere", *Radio Sci*., 20, 63-79, 1985.

[2] Greenwald, R. A., K. B. Baker, J. R. Dudeney, M. Pinnock, T. B. Jones, E. C. Thomas, J.-P. Villain, J.-C. Cerisier, C. Senior, C. Hanuise, R. D. Hunsucker, G. Sofko, J. Koehler, E. Nielsen, R. Pellinen, A. D. M. Walker, N. Sato, and H. Yamagashi. "DARN/Super-DARN: A global view of the dynamics of high-latitude convection", *Sp. Sci. Rev.*, 71, 761, 1995.

[3] SuperDARN Home Page. http://superdarn.jhuapl.edu/index.html.

[4] P. L. Dyson, and J. C. Devlin, "The TIGER Radar - An Extension of SuperDARN to Sub-auroral Latitudes," *WARS'00 (Workshop on Applications of Radio Science) Proceedings,* (Eds. Dyson and Norman), La Trobe University, pp. 9-31, 2000.

[5] P. L. Dyson, and J. C. Devlin, "The Tasman International Geospace Environment Radar," *The Physicist (The Australian Institute of Physics),* vol. 37, pp. 48-53, March/April, 2000.

[6] CUTLASS Home Page http://ion.le.ac.uk/cutlass/operations.html

[7] TIGER Home Page http://www.tiger.latrobe.edu.au/

[8] M. L. Parkinson, M. Pinnock, H. Ye, M. R. Hairston, J. C. Devlin, P. L. Dyson, R. J. Morris, and P. Ponomarenko. "On the lifetime and extent of an auroral westward flow channel (AWFC) observed during a magnetospheric substorm", *Ann. Geophysicae*, In Press, 2003.

[9] STEREO CUTLASS Web Page http://ion.le.ac.uk/cutlass/stereo/stereo.html

[10] Radant, M.E., **"**The evolution of digital signal processing for airborne radar**",** *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 2, pp.723 -733, April 2002.

[11] Adler, E.; Clark, J.; Conn, M.; Phuong Phu; Scheiner, B., "Low-cost technology for multimode radar ", *IEEE Aerospace and Electronics Systems Magazine*, vol. 14, no. 6, pp. 23-27, June 1999.

[12] Rabideau, D.J.; Howard, L.C., "Mitigation of digital array nonlinearities"**,** Proceedings of the 2001 IEEE Radar Conference, pp. 175-180, 2001.

[13] Yuanbin Wu and Jinwen Li, "The design of Digital Radar receivers", *IEEE AES System Magazine,* vol. 13 No. 1 pp.35-41, 1998.

[14] Cantrell, B.; de Graaf, J.; Willwerth, F.; Meurer, G.; Leibowitz, L.; Parris, C.; Stapleton, R., "Development of a Digital Array Radar (DAR)", *IEEE Aerospace and Electronics Systems Magazine* , Vol. 17, no. 3, pp. 22-27, March 2002 .

[15] Xilinx Xtreme DSP web page: http://www.xilinx.com/

[16] Tuan, T.; Figueroa, M.; Lind, F.; Zhou, C.; Diorio, C.; Sahr, J., "An FPGA-based array processor for an ionospheric-imaging radar", 2000 IEEE Symposium on Field-Programmable Custom Computing Machines, pp. 313 –314, 2000.

[17] Moeller, T.J.; Martinez, D.R., "Field programmable gate array based radar front-end digital signal processing"**,** *Proceedings of the Seventh Annual IEEE Symposium on Field-Programmable Custom Computing Machines, FCCM '99,* pp. 178 –187, 1999.

[18] J. Whittington, J. Devlin and T. Salim. "Evaluation of Digital Generation and Phasing Techniques for Transmitter Signals of the TIGER N.Z. Radar", *WARS02 (Workshop on Applications of Radio Science) Proceedings*, (Ed. P. Wilkinson) National Committee for Radio Science, Australian Academy of Science, Paper G12, pp 1-9, 2002.

[19] Nguyen M., Devlin J., Whittington J., "The model design and simulation of an all-digital receiver for TIGER radar." *Fourth International Conference on Modelling and Simulation, MS'02,* 11-13 November 2002.

[20] Salim T., Devlin J, Whittington J. "Investigation of multirate techniques for digital generation of Transmitter signals for TIGER Radar", *Proceedings of 5th IEEE International Multi-Topic Conference 2001*, Lahore, Pakistan, 2001.

[21] Nguyen M., Devlin J., Whittington J., "Investigation of different digital implementation methods for the TIGER radar receiver." WARS02 (Workshop on Applications of Radio Science) Proceedings, (Ed. P. Wilkinson) National Committee for Radio Science, Australian Academy of Science, Paper G8, pp 1-4, 2002.

[22] Salim, T., Devlin J., Whittington J., "Digital Beamforming for HF Radar using Polyphase Filters. " *Fourth International Conference on Modelling and Simulation, MS'02,* 11-13 November 2002.