The Tasman International Geospace Environment Radar (TIGER) – Current Development and Future Plans

Peter L. Dyson, Dept. of Physics, La Trobe University, VIC 3086 Australia (e-mail: p.dyson@latrobe.edu.au).
John C. Devlin, Dept. of Electronic Engineering, La Trobe University, Bundoora, VIC 3086 Australia (e-mail: j.devlin@ee.latrobe.edu.au).
Murray L. Parkinson, Dept. of Physics, La Trobe University, VIC 3086 Australia (e-mail: m.parkinson@latrobe.edu.au).
J. S. Whittington, Dept. of Electronic Engineering, La Trobe University, VIC 3086 Australia (e-mail: j.whittington@ee.latrobe.edu.au).

Abstract—**The Tasman International Geospace Environment Radar (Radar) is a dual HF radar system with overlapping footprints designed to map ionospheric motions by detecting ionospheric scatter. The first radar was set up on Bruny Island, Tasmania at the end of 1999 and development of the second radar to be placed near Invercargill, NZ, has begun. TIGER is part of the Super Dual Auroral Radar Network (SuperDARN) which currently consists of 15 radars deployed in the northern and southern hemispheres. TIGER is located more equatorward than other SuperDARN radars enabling it to observe new phenomena, such as Auroral Westward Flow Channels (AWFCs). This paper describes TIGER's capabilities and presents examples of observations, including an AWFC. Plans to develop digital transmitters and receivers are discussed as is a proposal to extend the network to even lower latitudes by deploying two additional radars.**

Index Terms—**aurora, HF radar, digital radar, ionosphere, ionospheric convection, magnetosphere.**

I. 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. From the early work of Appleton et al. [1] it was recognised that the auroral phenomenon can be a source of radio echoes. Many early studies used VHF and Bates pioneered the use of HF to study the radio aurora [2]. In fact the entire auroral and polar cap regions of the ionosphere are often rich in ionospheric irregularities with varying characteristics influenced by corresponding magnetospheric processes. Hence 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 con-vection 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 unravelling 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. [3], [4] 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. Each 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 [5].

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 [6], [7]. As Fig. 1 shows the TIGER footprints cover the lower latitude portion of the

Manuscript received January 31, 2003. This work was supported in part by the Australian Research Council, the Australian Antarctic Science Advisory Committee, the Antarctic Foundation, and the Victorian Partnership for Advanced Computing. It was also supported by members of the TIGER Consortium: La Trobe University, Australian Antarctic Division, IPS Radio and Space Services, ISR Division DSTO, Monash University, RLM Systems Pty Ltd, University of Newcastle, and British Antarctic Survey.

auroral oval and the ionospheric trough. 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 is expected to be commissioned in 2004.

This paper describes the basic characteristics of TIGER, presents examples of results obtained using the first radar component, and describes future plans, including extension of the TIGER network to lower latitudes.

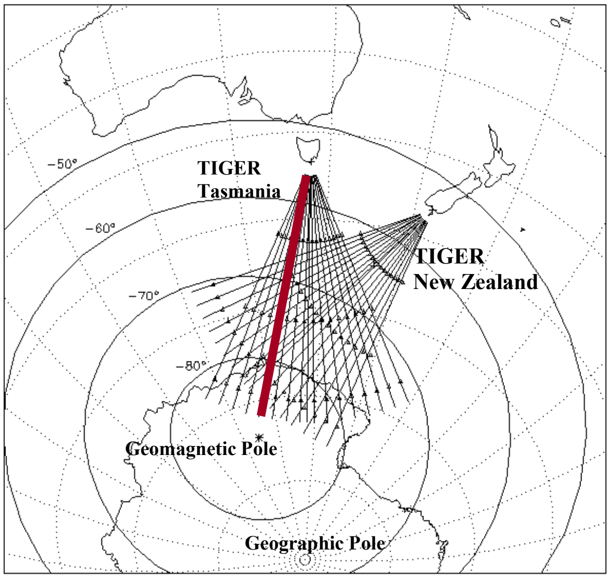


Fig. 1. Field of view of the TIGER radar. The straight lines represent the 16 azimuthal directions scanned by the ~3° azimuthal beam of each radar. Beam 4 of the Tasmanian radar, (red) points along the geomagnetic meridian. The solid curved lines are contours of geomagnetic latitude and dotted lines contours of geographic latitude and longitude.

II. Radar Characteristics

There is great advantage in using common hardware and software in a radar network and this principle has been largely followed by SD. However, since its inception in 1991 the SD network has continued to develop, and is still expanding. Important improvements have been made since the first SD radars were developed by Greenwald et al. [4], although the basic principles of operation remain the same. Significant engineering improvements were made by University of Leicester in developing the CUTLAS system [8]. The first TIGER radar was built principally to the Leicester design, with improvements to the transmitters, power supplies and micro-controllers. All SD radars use common basic operating software which can readily be adapted by each radar group for special operations or new modes which may later be adopted by the entire radar network.

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 across the radar footprint and which, due to ionospheric motions, has a significantly larger Doppler shift than sea or ground backscatter. Once an operating frequency is chosen by the radar it is usually used for at least several hours unless the range extent of ionospheric scatter falls below a specified threshold. Frequent changes in operating frequency would make it difficult to separate temporal variations of ionospheric and magnetospheric phenomena from propagation changes caused by changes in operating frequency.

The transmitting antenna consists of 16 log-periodic, 10 element, horizontally polarised antennas supported by 15 m towers (Fig. 2). Each antenna is fed by its own 600 W power amplifier and a phasing network is used to scan the main beam

TABLE I

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° at 10 MHz, 3° at 14 MHz, 2° at 18 MHz
	Vertical;:50 °
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

Fig. 2. TIGER Antenna Array and Instrument Hut (Courtesy D. Ratcliffe).

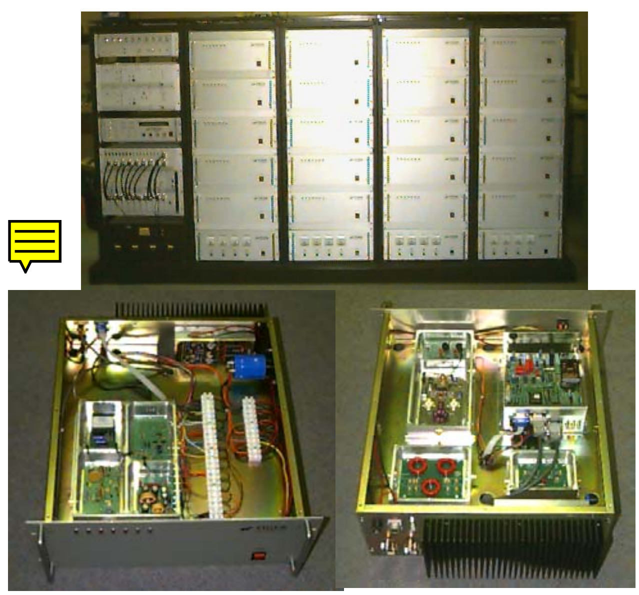


Fig. 3. TIGER Hardware. Top panel is a view of the front of the radar racks showing, on the right, the 20 transmitter modules above 4 power supplies. The receivers and phasing matrix are on the left. The bottom panels show views of a transmitter module chassis from the top (left) and bottom (right).

of the array over 52^{O} of azimuth in 16 steps. The antenna horizontal beamwidth varies with frequency and pointing direction but is ~3^{O}. A much broader vertical beamwidth (~50^{O}) facilitates the detection of echoes with ranges as small as 180 km and as great as 3330 km. TIGER is a pulse radar enabling the same 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. The radar hardware is shown in Fig. 3.

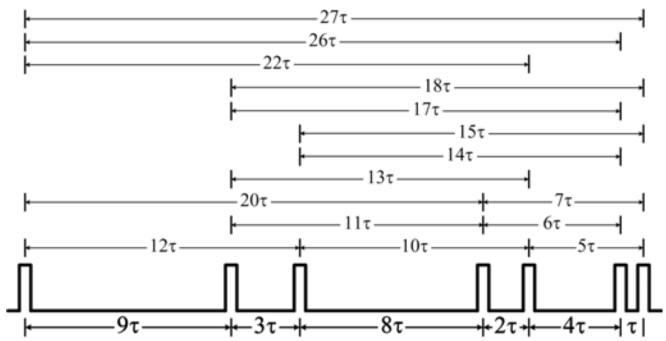


Fig 4. SuperDARN Pulse sequence showing the various lags at which the autocorrelation function can be determined.

A major consideration in designing an ionospheric radar is the choice of a strategy to minimise range-Doppler ambiguities. On the one hand, the lower the pulse repetition frequency (prf), the greater the range to which echoes can be identified unambiguously. On the other hand, a low prf, will cause aliasing of the Doppler spectrum and ambiguity in the determination of echo velocities. The SD approach to this problem is to transmit a sequence of pulses at different spacings that are multiples of a minimum spacing (⓿). This enables the autocorrelation function of echoes at each range to be calculated and the Doppler spectrum of the echo signal is then obtained by Fourier transforming the autocorrelation function [4]. The current SD pulse sequence is shown in Fig. 4. The pulse set length is ~100ms and integration times of 3s and 7s are commonly used. Usually the antenna beam is stepped across the 16 azimuthal directions in either 1 or 2 minutes.

III. Propagation Characteristics

Fig. 5 illustrates typical HF ray paths giving rise to backscattered echoes observed by TIGER. Rays launched from the transmitter are refracted towards the horizontal and backscatter from field-aligned irregularities occurs if and when the rays become perpendicular to the magnetic field lines. Due to the roughness of the ground or sea, backscatter echoes can also occur for rays reflected by the ionosphere back to Earth. Since these echoes travel through the ionosphere, their characteristics are indicative of ionospheric conditions near the midpoint and in fact these ionospheric effects quite often produce larger Doppler shifts than sea-waves at the surface backscatter point. These processes repeat at greater ranges for multiple hops.

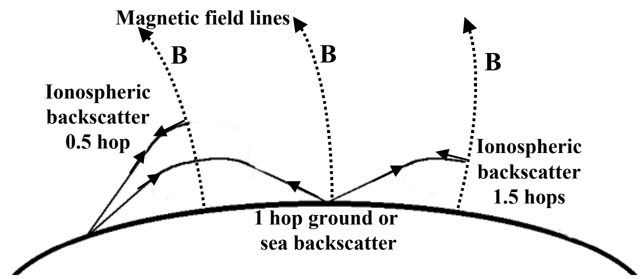


Fig. 5. Schematic ray paths showing 0.5 and 1.5 hop ionospheric scatter and one hop ground or sea scatter.

Rays launched at different elevation angles propagate to different distances giving the radar extensive range coverage when operating at a single frequency. Of course the range coverage varies with frequency and ionospheric conditions and hence the need to search for a suitable operating frequency. TIGER typically operates near 14MHz during daytime and 12MHz at night.

TIGER is capable of swept-frequency operation and the example shown in Fig. 6 illustrates that when irregularities are widespread throughout the ionosphere, the radar detects ionospheric and sea scatter over much of its range window and over a broad band of frequencies.

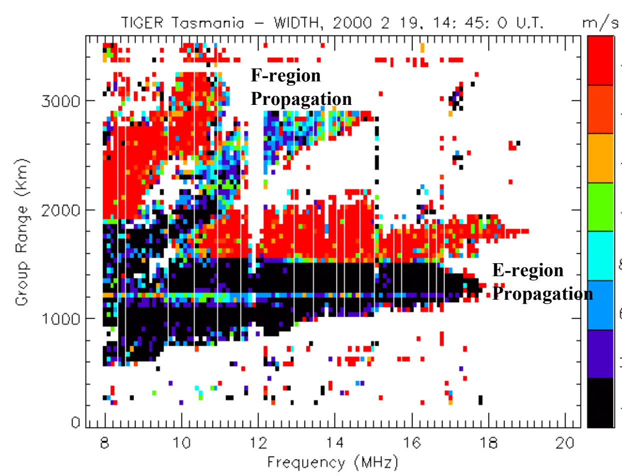


Fig. 6. Swept-frequency backscatter ionogram obtained along the magnetic meridian (beam 4). Echoes have been colour coded according to the Doppler spectral width and slow-speed, one-hop sea echoes are clearly differentiated from the high-speed 1.5-hop ionospheric scatter.

IV. Observations Of Geophysical Phenomena

Ionospheric irregularities are often generated as a consequence of magnetosphere-ionosphere coupling and the backscatter echoes detected from these regions have characteristic Doppler shifts and spectral widths indicative of the particular magnetospheric processes impacting on the ionosphere. Fig. 7 is an example of a single radar scan in which the differing echo patches that occur with increasing range give, respectively, the probable locations of the main ionospheric trough, the auroral and polar cap ionospheres.

Because of the large amount of multi-dimensional data obtained by the radar, a standard way of examining the observations is by presenting summary plots of derived echo parameters versus group range and UT recorded on a single beam.

Fig. 8 is an interesting example showing (a) the backscatter power relative to noise, (b) the line of sight Doppler velocity, and (c) the Doppler velocity spread (or "spectral width") recorded on TIGER beam 15, recorded 08 - 13 UT, 17 August, 2000. Magnetic latitudes of 65°S and 70°S are superimposed in each panel, and a magnetic local time scale is also included at the bottom of the figure. The plots consist of routine 2 minute resolution observations in the pre-magnetic midnight sector. Sea echoes automatically identified from their low Doppler velocity characteristics have not been included in the plot.

This example is important because it reveals an Auroral Westward Flow Channel (AWFC) [9], a new phenomenon closely related to Sub-Auroral Ion Drift Events (SAIDs) [10]. In part (b), the AWFC corresponds to the narrow channel of large approaching Doppler velocity to >480ms^{-1} centred on –64° magnetic and ~2° wide in latitude during ~0906 to 1048 UT. The subsequent scatter spreads out as the zonal flows decreased. Lower Doppler velocities of ~60ms^{-1} persisted until ~1228UT, and correspond to the Subauroral Polarisation Stream (SAP) [11], also thought to occur in association with the main ionospheric trough.

In part (a), power enhancements to >23dB occurred during the AWFC, and then again later during the interval of trough-like scatter, 1128 - 1228 UT. The spectral widths were variable but moderate, ~150ms^{-1}, during the AWFC, and subsequently became small, <50ms^{-1}. The variations in power are related to variations in irregularity production, and the variations in spectral width to instabilities and plasma waves.

Beam 15 becomes a magnetic eastward beam at furthest ranges and so is very sensitive to the detection of narrow zonal flow channels. An analysis of the Doppler shifts recorded on all 16 beams of the radar is consistent with a westward (and slightly poleward) flow channel with speeds >1 km s^{-1} overlapping the equatorward edge of the auroral oval.

Ground-based magnetometer observations recorded nearby at Macquarie Island showed the onset of a substorm occurred at 0900UT, with the peak expansion phase at 0917UT. Geosynchronous spacecraft measurements on board LAN-L 1989-046 showed a dramatic increase in the flux of hot protons near ~0900UT which gradually decayed during ~0920 to 1050UT. Hence the start of the AWFC was similar to previous observations of SAIDs in that it mostly occurred during the recovery phase. However, the AWFC was closely sychronised to substorm onset. In fact, TIGER beam 4 observations suggest the AWFC may have commenced as early as ~0850UT, so there is a possibility it was part of the substorm trigger.

To date AWFCs have only been identified in TIGER SD data, probably due to TIGER's lower latitude. Typically 1 to 6 clearly defined AWFCs per month are identifiable in TIGER data. There are often signatures of convection vortices, ULF waves, and gravity-wave like signatures radiating equatorward from these events. The crossed beams of TIGER NZ radar will permit us to specify the true 2-D structure of non-uniform flows associated with the AWFCs, as well as provide a more comprehensive description of associated ULF and gravity-wave activity.

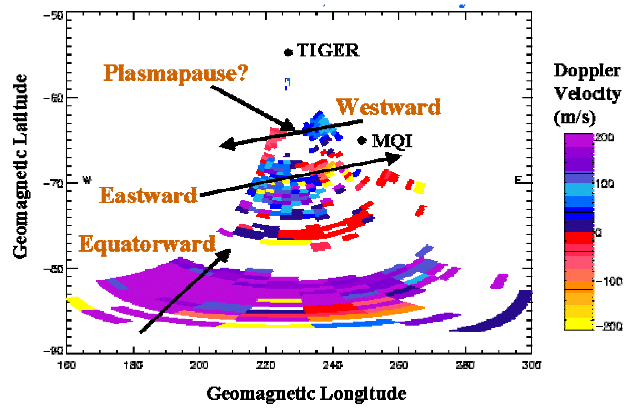
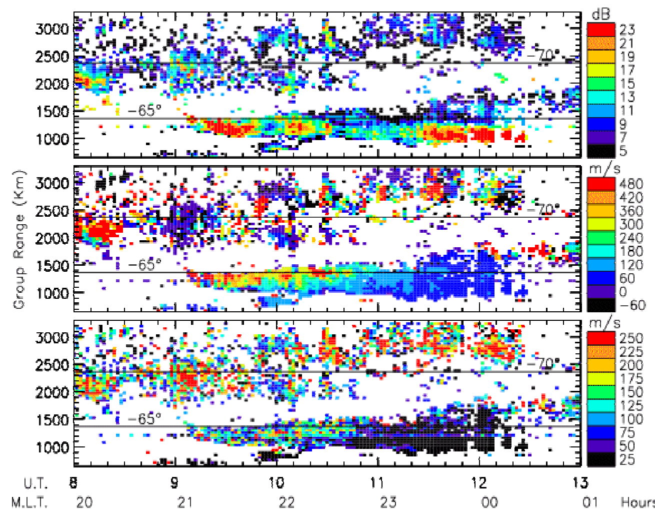


Fig. 7. TIGER scan showing scatter characteristic of several different ionospheric regions. Either another example should be used or this diagram improved to use the space better.



V. FUTURE RADARS

The first component of TIGER has been operating successfully since December 1999 and funds are available to build the second radar during 2003 and to install and commission it in New Zealand in 2004. Results being obtained with the first TIGER component show that having SD radars at sub-auroral locations enables new phenomena, including AWFCs and ULF waves in the plasmasphere, to be studied. Completion of the TIGER dual system with the second radar in NZ will provide important new details on, for example, the east-west flow of ionospheric plasma in the sub-auroral region, which currently is inadequately described by the first TIGER radar that looks primarily southward.

TIGER's new results raise the question of whether additional radars, even more equatorward, would be of value. Undoubtedly the answer is 'yes'. While TIGER does partly cover the sub-auroral region, this is mostly at close range where there is less overlap of the two radar beams (Fig. 1). In earlier studies [12], [13] an ionosonde located north of Melbourne at Beveridge (-49^{o}S geomagnetic) was converted to a simple oblique, south-looking radar using a rhombic antenna. Back-scatter echoes were often detected approaching the station from the south, particularly before dawn. In fact the onset of photoionisation causing a rapid increase in ionisation tended to remove the irregularities just before they reached Beveridge. This indicates that coverage down to less than 50^{o}S geomagnetic latitude is needed to provide complete coverage of the polar cap/auroral/sub-auroral response to solar wind/magnetospheric influences. Fig. 9 shows an example of a useful extension of TIGER lower latitudes, based on two additional radars, one at Invercargill and one in NSW.

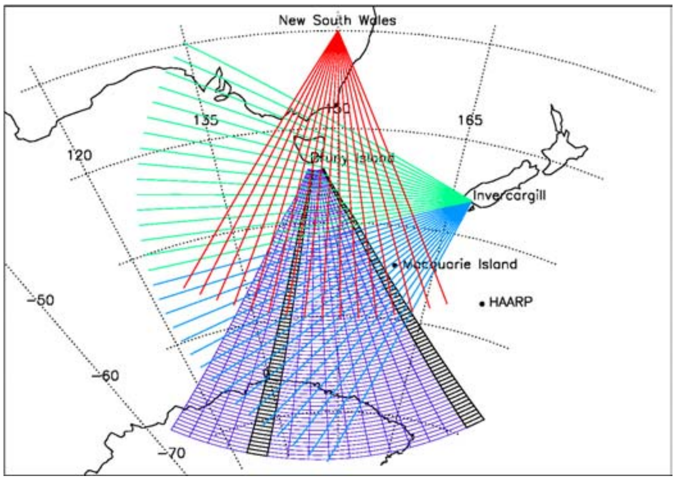


Fig. 9. Additional radars in NSW and NZ giving coverage to lower latitudes

VI. Digital Radars

The current transmitter and receiver implementation of the SD 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.

We are currently designing a digital transmitter and receiver for TIGER. Just as the digitisation of consumer products, such as mobile phones, has lead to enhanced features and flexibility, a digital SD radar will offer improved performance, greater adaptability and new features providing benefits to ionospheric research. Key enabling technologies for the implementation of a digital SD radar are: digital signal processing (DSP); field programmable gate arrays (FPGAs); and analog to digital conversion (ADC). Digital signal processing (DSP) has become an integral part of wireless communication systems. Increasingly, traditional analog sections of transmitter and receiver circuits are being replaced by more efficient DSP solutions. Not only are DSP solutions well placed to take every advantage of the rapid advances in Integrated Circuit technology, but we can also employ DSP techniques in ways that have no direct analog counter part [14]. To implement DSP algorithms a hardware platform is required. An FPGA is an integrated circuit that contains 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 its on board FPGA(s)). 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 analog to digital conversion (ADC) is an essential element of our receiver design. Ideally, 16bits at 125MHz is required but unfortunately, this level of performance is 3-5 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.

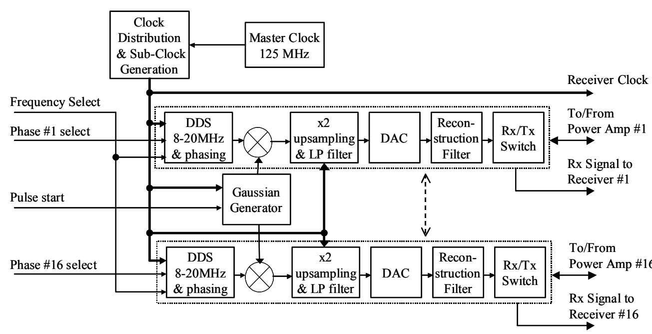


Fig. 10. Block diagram for proposed digital SuperDARN radar transmitter

A key feature of the proposed design is synchronised Direct Digital frequency Synthesisers (DDS) with initial phase inputs for antenna phasing. Frequency synchronisation across all transmitters and receivers is essential for maintaining correct phase delays. A proposed block diagram of the digital transmitter is shown in Fig. 10. The basic function of the transmitter is to provide a 290µs 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 [15].

A proposed block diagram of the digital receiver is shown in Fig. 11. The receiver is required to receive at the chosen transmission frequency, and produce inphase and quadrature outputs, summed from all 16 signals at the chosen transmission frequency, and produce inphase and quadrature outputs, summed from all 16 receivers 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 [16].

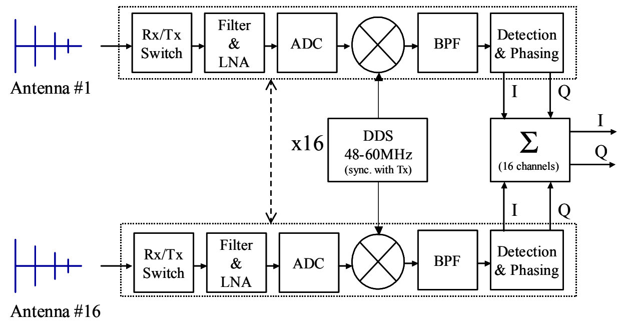


Fig. 11. Block diagram for proposed digital SuperDARN radar receiver

We plan to have a digital radar operational in 2-3 years. Immediate benefits should be radar hardware that requires less space, is easier/cheaper to build and maintain, while at the same time producing a higher quality result. For example, pulse shapes and time delays can be readily fixed in the digital domain and digital receivers do not require special tuning. Longer-term benefits are harder to define, but are most likely to centre on the reconfigurable (flexible) nature of the hardware. It would be possible (and most likely common place) to use the same hardware to produce different scan modes, generate arbitrary waveforms etc. An obvious benefit is that the system configuration can be tailored to suit any particular mission since their is infinite control over the receiver bandwidth. Another possible enhancement could be recording and storing data directly from individual receivers, rather than summing the receiver outputs first, as is done in the current system - although a draw back would be 16 (or 20) times the data rate and storage. Post-processing beam forming and interpolation within beams would then be performed. Furthermore, if the transmitter section was altered (and increased in power) to illuminate the entire field of view, the radar could then receive scatter from multiple azimuth positions at the same time and beams could be positioned anywhere within the antenna's field of view. There are many other possibilities, the main point is that the hardware of a digital SD radar can grow and evolve along with the ideas of the community who use it. In the future researchers may be able the change and adjust the radar hardware in the same way that the software is today.

VII. Summary

TIGER is an important addition to SD, extending the network to lower latitudes and also providing a significant longitude extension in the southern hemisphere. New ionospheric phenomena have been discovered using just the first component radar operating in Tasmania. Further new discoveries can be expected when the second component radar, to be located in NZ, is commissioned in 2004. Development of a digital radar system offers advantages for future radar operation, as does the extension of SD by the deployment of new radars at even lower latitudes.

References

[1] E.V. Appleton, R. Naismith, and L.J. Ingram, "British radio observations during the Second International Polar Year," *Phil. Transact. Royal Soc.* vol. L, A236, pp. 191-259, 1937.

[2] H. F. Bates, "Direct HF backscatter from F-region", *J. Geophys. Res*, vol 65, pp. 1933-2002, July, 1960.

[3] 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.

[4] 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.

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

[6] 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.

[7] 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.

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

[9] 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.

[10] P. C. Anderson, R. A. Heelis, and W. B. Hanson. The ionospheric signatures of rapid subauroral ion drifts, *J. Geophys. Res*., 96, 5785–5792, 1991.

[11] J. C. Foster and W. J. Burke. SAPS: A new categorization for sub-auroral electric fields, *EOS Transactions*, 83, 393-394, 2002.

[12] P. L. Dyson, M. L. Parkinson, A. Quach, P. R Smith, and D. P. Monselesan. Radio studies of the southern hemisphere high latitude ionosphere, *Adv. Space Res.*, vol 16, pp. 103-112, 1995.

[13] M. L., Parkinson, P. L. Dyson, and A. T. D. Quach. Arrival of Ionospheric Troughs and Oblique Spread-F in the Wake of Large-Scale Travelling Ionospheric Disturbances During the Intense Auroral Storms of August 22 and 23, 1990, *J. Geomag. and Geolec.*, vol 48, pp. 1381-1405, 1996.

[14] f. harris, "Signal Processing in Next Generation Digital Receivers and Transmitters", *DSP World Spring Design Conference*, 1999, Santa Clara, CA, USA.

[15] 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.

[16] M. Nguyen, J. Devlin, and J. Whittington. The model design and simulation of an all-digital receiver for TIGER radar. *Proceedings of the 4th International Conference on Modelling and Simulation, Melbourne*, (Ed. A. Zayegh) pp 143-147, 2002.