Advances in affordable Digital Array Radar

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Introduction

Electronically scanned phased array radar technology comprising several thousand RF T/R modules and associated RF beamforming is employed in the present generation of high performance military radars. In some cases these radars are further enhanced by a level of digital beamforming at subarray level. The present number of subarrays, and thus digitisers, is of the order of 1% of the number of elements (e.g. 20 digitisers with a 2000 element array). This level of digitisation can provide a number of advanced spatial processing features such as adaptive digital beamforming, adaptive angle estimation and space-time processing against clutter.

For total flexibility of spatial processing, the desire has been recognised for 100% digitisation i.e. digitisation at element level. However, this demands thousands of digital receivers (or transceivers) per array face. This dream remains but has a number of key challenges that make it unrealisable at present. The first is the cost of thousands of digitisers, another is processing the huge data rate that would come off of such an array and another is the distribution of thousands of local oscillator feeds.

The middle ground then is to employ, ‘high levels of digitisation’. Here several 10’s or hundreds of small subarrays are employed providing a level of digitisation of some 5-10% of the number of elements. ‘High levels of digitisation’ allows extra spatial digital processing capabilities such as multiple beam clusters and wideband LFM waveform processing. At this high level of digitisation the array aperture is sampled adequately to achieve acceptable low sidelobes for offset beams and LFM beam correction.

This paper firstly reviews the issues and benefits of various levels on digitisation in a DAR (Digital Array Radar) as discussed above. It then focuses on the key technology of high levels of digitisation; that of low cost, high performance, small and modular digital receivers. This paper presents current UK R&D employing low cost COTS components to enable this to be realised. Present S Band and X Band digital receiver designs are used as examples of state of the art modular hardware.

DAR level of digitisation

![Digital Array Radar diagram](image-url)

Figure 1. Element level, small array and subarray level digitisation

The possible levels of digitisation are illustrated in Figure 1.
Element level digitisation (on the left) provides for total flexibility of digital beamforming. It would provide for any number of simultaneous multiple beams to be formed in any desired look direction. It also provides for considerable flexibility of beam shape. No RF phase shifting is required to ‘steer’ beams as all beamforming is provided within the DSP. Such complete flexibility is, however, not generally an essential requirement for a radar. Apart from anything else, if the transmit energy is shared over a number of simultaneous beams, then the power per beam is proportionally less.

The central diagram of Figure 1 illustrates small array digitisation where the number of small arrays is circa 5-10% of the number of elements. In this architecture we need RF modules with phase shifters to provide the basic electronic steering of the array. A discussion later in this paper outlines the benefits and rationale of this level of digitisation.

It is worth noting that both the element level and small array level diagrams show a box called ‘digital subarray beamform’. This intermediate stage of digital beamforming reflects that some digital beamforming processes like adaptive beamforming are difficult to implement with large numbers of subarrays (large numbers of degrees of freedom). Hence this intermediate fixed beamforming provides a ‘degrees of freedom reduction’ DOFR prior to the fully adaptive spatial processing.

Finally the third diagram of Figure 1 shows ‘large subarray’ digitisation. This may be of the order of 1% of the number of elements.

The prospective level of digitisation is further illustrated in the planar array diagrams of Figure 2. The array to the left illustrates the element level lattice with approximately 2500 elements. In this example the elements are combined as vertical ‘quad packs’ as the minimal line replaceable unit and RF building block. The second diagram illustrates an array partition with some 64 small arrays and the third diagram an array partition with 16 subarrays. The small arrays and subarrays are deliberately chosen to have a random distribution of phase centres, this helps to break up the grating lobes caused as a result of not Nyquist sampling the array aperture.

An alternate subarraying technique to avoid grating issues is to use overlapping subarrays but this in not covered in this paper.

**Benefits of high levels of digitisation**

As discussed above, for total flexibility of spatial processing (digital beamforming) one would desire element level digitisation. In practice, however, the majority of Radar beamforming requirements can be provided from a digitisation of small arrays where the number of small arrays is some 5-10% of the number of elements.

The benefits provided by a high level of digitisation are as follows:

1) An increased level of digitisation provides for increased dynamic range (SNR) and increased SFDR. Theoretically the maximum SNR should increase by $10\log N$ as should the SFDR. Practical measurements on multiple receivers have illustrated improvements near to this figure. In relation to SFDR improvement the assumption is that spurs are decorrelated between channels which is true for many of the spurs.
2) An increased level of digitisation improves receiver generated phase noise. It is seen that ADC phase noise is decorrelated between channels and a 10logN improvement in this phase noise should be realised.

3) An increased level of digitisation reduces the need for high tolerance analogue components for a particular level of error sidelobes or beam-pointing accuracy. Errors are spread across more channels. The digital aspect, of course, allows for precise digital broadband equalisation and matching of the channels employing a chirp calibration signal. This equalisation comprises adaptive FIR filters in each small array channel.

4) The digital beamforming provides the ability to generate a cluster of beams. With a single narrow beam a radar mode such as horizon search can take too long. By scanning with a cluster of beams and simultaneously processing each beam provides an appropriate speed improvement. This mode does of course suppose that an appropriately broad transmit beam is employed to cover the beam cluster. Although this results in less transmit power per beam, some radar modes are time limited rather than power limited.

5) The digitised array can be used for wideband LFM (stretch) operation without the need for analogue RF time delay units. In present wideband LFM radars, RF TDU’s are employed at a small array level to prevent the beam from squinting with the LFM sweep. RF TDU’s are large and expensive items. By digitising at small arrays it is possible to provide an LFM correction in the DSP. It provides, in affect, a changing beamsteer to counter the array squint with frequency.

6) Provides the ability to employ complex spatial angle estimation techniques e.g. adaptive monopulse, superrresolution and maximum likelihood algorithms. These angle estimation techniques are also protected from jamming by adaptive beamforming. Removes the need for analogue beamformers to form sum and difference beams.

7) Provides for the ability to implement complex adaptive digital beamforming to remove multiple jammer threats. This jamming can be in the sidelobes or within the main beam. In truth adaptive beamforming is likely to be implemented at sub array level because the complexity of adaptive beamforming calculations are proportional to N^3 where N is the number of degrees of freedom. The high level, small array, digitisation does, however, give flexibility of choice of the small array to sub array mapping provided in a degrees of freedom reduction DOFR process. Figure 3 illustrates an example of the DOFR programmed to form a set of subarrays for adaptive beamforming.

8) Provides the ability to provide adaptive spatial filtering (or space-time filtering) against clutter. In the Doppler radar example this is particularly useful and is called STAP for space-time adaptive processing. The nulling of clutter can be provided at all angles and Doppler frequencies other than those of the target signals.
Low cost COTS digitising solutions

The above presents a considerable number of capabilities that can be provided by a digital array radar employing a high level of digitisation. The challenge then is to provide low cost, high performance digitisation of array radar such that many 10’s or 100’s of digitised small arrays can be supported. The photograph of Figure 4 shows a realisation of such receivers for an S Band radar.

Figure 4. Realisation of many 10’s of digital receivers employing COTS components.

These high performance receivers are realised by employing COTS components wherever possible within the design. The radar world must thank the world of cellular radio and other emerging communications systems that are providing the stimulus to develop these state of the art microwave components, A to D converters, DSP devices etc.

A more detailed appreciation of some similar S Band receivers is shown in Figures 5 and 6 below from a receiver design of 2005.

Figure 5. RF component side of an S Band digital receiver module

The receivers illustrated here comprise a two sided construction. One side provides all the RF and IF circuitry (analogue functions) and the other side houses the A to D and digital functions.
This constructional method provides for good screening isolation between the analogue and digital functions. The RF enters on the left via a standard SMA connector. The RF switch provides a path for a chirp calibration signal to support receiver equalisation. This is followed by a 1dB step RF attenuator to provide the first level of gain control. RF image rejection filtering is then provided prior to the first mixer. The 1st IF is at 1140MHz. Further step attenuation control is provided at 1st IF prior to 2 stages of filtering and subsequent mixing to a 2nd IF of 60MHz. After appropriate IF filtering the signal is passed through the central web in the milled housing and on to the A/D converter.

Figure 6. Digital side of receiver module with ADC, FPGA processing and optical data transfer

The A/D converter provides IF sampling at 80 MSPS. The FPGA down converts this to I,Q baseband and adds header information. It also provides a phase and amplitude correction of the receiver analogue attenuators. Finally this data is converted into a 2.5GBPS serial bit stream for transport over fibre optics.

By employing the COTS component approach outline above it is possible to manufacture digital receiver modules for a few thousand pounds each.

In addition to the realisation of affordable receivers a further complexity to be solved is the distribution of large number of clocks, local oscillators and calibration signals.

Figure 7. Multi-receiver units and associated LO and clock distribution.

To provide this high level of interconnect a number of blind mate RF connectors are employed on the edge of the receiver modules. The modules then plug down into a multi-channel, microstrip, distribution board. A view of this distribution can be seen in the left hand photograph of Figure 7 above. Each mother assembly accommodates 8 receives plus a single LO and BITE module. It
also provides all the power conditioning and digital interface circuitry. The right hand photograph of Figure 7 shows a fully filled mother assembly with its 8+1 LRU’s.

Figure 8. X Band digital receiver with a single layer construction (RF in, Digits out)

An alternative constructional technique is shown in Figure 8. In this example a single layer has been employed for all circuitry for both RF and digits, which results is a very slim unit. This receiver has been designed for an X Band DAR but although some of the RF components are somewhat specialised the receiver is again using extensively COTS components. By the careful use of screening, RF gaskets and good layout it possible to realise this very high performance digital receiver within a single sided housing.

A feature of this design is to employ two different final IF’s with two different bandwidths and two different A/D converters. A multifunction radar may be required to support both relatively narrow bandwidths (a few MHz) and wider bandwidths (a few 10’s of MHz). To optimise the A/D converter for dynamic range and bandwidth the receiver employs two different ADC’s, a 16 bit device for the lower bandwidth and a 12 bit converter for the higher bandwidth. The ADC’s feed the FPGA which selects the appropriate bit stream for the radar mode required. In this example the FPGA provides internal serialisation of its data and outputs over 2x2.5GBPS streams to support the high data rate, wideband mode.

Conclusions

Electronically scanned, active, phased array radar technology provides the present generation of advanced military radars. We have now, however, entered the new era of Digital Array Radar. A key challenge is to develop affordable digitisation modules and subsequent advanced digital spatial processing. It is hoped that this paper provides more insight into the viable realisation of this class of radar and of the considerable benefits that DAR can provide.

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