Implementing Correlators for the SKA

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***Abstract*—It is proposed that a new centimetre wavelength radiotelescope (SKA) be built in the next ten years. The astronomical requirements of this telescope require a correlator with enormous computing power. This paper examines possible options for the correlator and describes a design for an FX correlator that provides an economical implementation and satisfies all astronomical requirements.**

***Index Terms*—Correlators, FX, radioastronomy, SKA**

I. INTRODUCTION

The SKA is the next generation centimetre wavelength radiotelescope being considered by astronomers. To achieve desired improvements in sensitivity it will need a total collecting area of one square kilometre. Addional requirement are that the SKA have 10,000 spectral channels and be able to image one square degree at a frequency of 1.4GHz. These latter constraints require the telescope to have a correlator with very high processing capabilities. This paper describes the new approaches needed in correlator design to satisfy these capabilities in the most economical way.

II. THE PROBLEM

The SKA is obliged to operate at many resolutions requiring antenna separations from tens of metres to thousands of kilometres. Thus the SKA will be a synthesis instrument where observations are made by measuring the cross power spectrum between pairs of antennas. Each measurement estimates a Fourier component of the image with the length, in wavelengths, of the vector joining the antennas specifying the spatial frequency.

One way of satisfying the one-degree field-of-view requirement is to use individual antennas with this field of view. This specifies a filled aperture antenna with a collecting area of about 153m^2 or 6,500 such antennas to achieve the one square kilometre area of the SKA. The cross power spectrum must be calculated for each pair of antennas, or baseline, and there are 6,500*6499/2 = 21million baselines. For each baseline a total of 10,000 spectral channels are wanted.

The traditional method of building a correlator (for example VLA[1], AT[2] and BIMA[3]) is to use an XF correlator [4] which directly measures the cross correlation function. An example of an XF correlator for one baseline is shown below. The delay **nD** is needed to allow the measurement of the two sided cross correlation function.

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To generate 10,000 spectral channels the correlator needs 20,000 cross multiply accumulate (XMAC) units where an XMAC consists of a real multiplier and an accumulator.

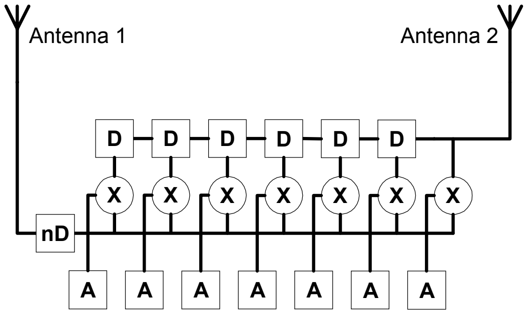

Figure 1 Basic XF correlator, **D** is a delay, **X** a multiplier, and **A** an accumulator

As the total bandwidth of the systems is as high as 4GHz the total processing power is 2.1x10^7 baselines · 20,000 XMACS/baseline · 8x10^9 samples/s · 2 operation/XMAC = **6.7x10^{21} operations/s**.
Even considering that the input to the multiplier is 2 to 4 bits, this amount of processing will not be achievable in the near future.

Using larger antennas capable of multibeaming can reduce the total number of operations. For example using filled aperture antennas with 10 times the area (1530m^2) reduces the number of baselines by a factor of 100. But now 10 beams are need to form a one-square-degree image. Thus the total number operations is reduced by a factor of 10. As most SKA designs have antennas sited at ~300 locations, at best the computational load can be reduced by a factor of 20.

III. FX CORRELATORS

The alternative to measuring the cross correlation function is to directly measure the cross power spectrum. This, for correlators with a large number of baselines, can greatly reduce the computational load. The basic design for this correlator is shown in Figure 2. The data from each antenna is first transformed into the frequency domain and then the cross power in each spectral channel measured to give the cross power spectrum. This type of correlator is called an FX correlator [4,5] because the frequency transformation (F) precedes the cross multiply operation (X). Traditionally, the FFT has been used to perform the frequency transformation (originally the F in the FX nomenclature stood for FFT [5]).

As the FFT is an isomorphism the input and output data rates are identical when the input data is processed as non-overlapping blocks. Compared to XF correlator the input to the single multiplier is now complex but at half the sample rate, the total number of operations per second are:
2.1×10^7 baselines · 1 XMACS/baseline · 4×10^9 samples/s · 8 operation/XMAC = **6.7×10^{17} operations/s**.
The computational load for the cross multiply operations has been reduced by four orders of magnitude.

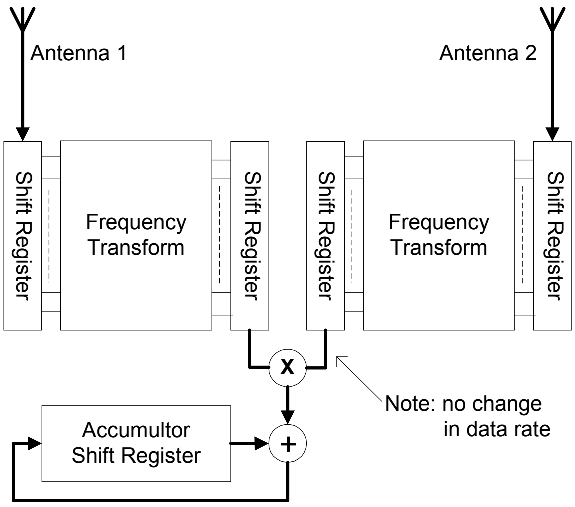

Figure 2 Basic FX correlator

But there is no reduction in the total memory, the total size of the accumulator shift register is identical to the total memory in the accumulators of an XF correlator. In a following section it will be shown how the accumulator memory for an FX correlator can be implemented in off-the-shelf RAM as opposed to the on-chip RAM needed by an XF correlator. This eliminates the accumulator memory as a major cost of the correlator.

The disadvantage of the FX correlator is the cost of the frequency transformation. Assuming ~100 operations per sample to perform the frequency transformation then its computational load is
6500 antenna · 4Gsamples/s/antenna · 100 operation/sample = **2.6×10^{15} operations/s**.
To compare this to the XMAC unit in an XF or FX correlator the computation load must be increased by an order of magnitude because many of the operations of the frequency transformation are full precision multiplies. Multiplies in XMAC units are usually of 2 to 4 bit precision. Even with this added factor the computational cost of the frequency transformation is small when compared to the cross multiplication.

IV. FX CORRELATOR PROBLEMS

It is clear that an FX correlator greatly reduces the computational load of an SKA correlator. But compared to XF correlators current FX correlators suffer from:
(1) higher interconnection cost due to bit and data rate increase[6],
(2) degraded signal to noise performance [7] and
(3) higher implementation costs.
These problems are all solvable and will be addressed in turn in the next three sections

V. BIT RATE INCREASE

In XF correlators a 2-bit sampling of the antenna signal is standard for most applications. This minimises the data transmission cost from the antenna and cabling costs within the correlator; both significant system costs. The crude sampling does reduce the signal to noise ratio [4] but this is more than offset by the increased bandwidth that can be processed. To overcome the non-linear correlation gain changes with input level changes and achieve the best signal to noise ratio the decision levels of the A/D are controlled by the statistics of the sample data (Atomatic Level Control or ALC) [4].

In FX correlators the crude analogue-to-digital sampling has normally been retained but after the frequency transformation the data in each frequency bin is commonly represented by 6 bits[5,8]. This increases the cost of cabling to the XMACs by a factor of 3. The solution to this is to treat each frequency channel of the FX correlator as if it was a narrowband XF correlator [9]. To see how this can be done consider Figure 3 which shows the last frequency selection stage and the quantiser of an XF correlator (a) and the one channel of an FX correlator (b). The down sample and quantise function of the FX system performs a function identical to the A/D in the XF correlator. The added component in the FX correlator is the A/D converter. If this converter has sufficient precision then it introduces no significant non-linearities and little additive noise. The final quantiser can now be implemented so that in performs the same function as the coarse A/D with ALC in the XF correlator. The two systems are now essentially identical and the 2-bit data can be used. For the same total bandwidth, the signal to noise performance and bit rate are identical for XF and FX correlators.

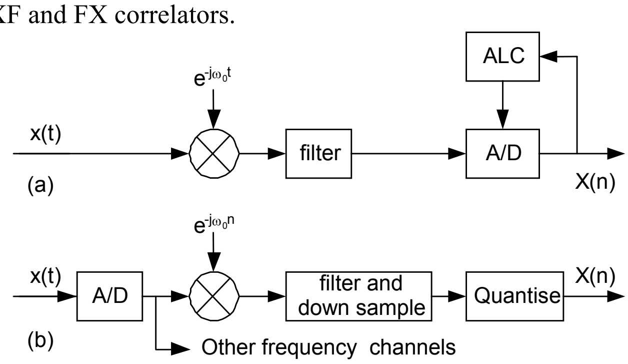

Figure 3 (a) Quantiser in an XF correlator with preceding filter and down converter.
(b) one channel of an FX correlator filterbank with preceding A/D converter and output quantisation.

VI. Data Rate Increase and Signal to Noise Degradation

Current FX correlators use the FFT for the frequency transformation. This causes the FX correlators to suffer from signal to noise degradation or a data rate increase. The FFT has been used because of the efficiency with which it implements the frequency transform but by itself the FFT imposes severe limits on the filter function that can be implemented. When used at its greatest efficiency the FFT processes contiguous blocks of non-overlapping data. This makes the filter frequency response a sinc function, which has a magnitude of 0.6366 at a frequency equal to half the output sample rate of a single frequency channel. This spectrum estimation error causes a decrease in signal to noise ratio for spectral line observations [7], estimated to be a factor of 1.22 [10]. Overlapping data blocks or averaging over adjacent frequency channels can reduce this degradation. The first method increases the data rate and the second method reduces frequency resolution.

A second reason for using overlapped data blocks and increasing the output data rate is to accurately measure narrow band sources. In the extreme case where the source bandwidth is narrow compared to channel bandwidth the source power can vary by a factor of 0.41 as the source moves from the centre to the edge of the channel. When the power in the adjacent channel is added the measured power is in error by a factor of 0.81 when compared to the channel centre estimate. Windowing the data can flatten the channel response. This however, losses sensitivity, for example a Hanning window discards samples at the edge of the widow. The sensitivity is recovered by overlapping the data blocks. For a given correlator performance the increase in data rate causes the cost of interconnections and the number of XMAC units to increase.

What is needed is a channel response that is flat across the passband with a small transition band while at the same time not increasing the data rate. Windowing and oversampling, together with post filtering and decimation can achieve this. A more efficient implementation is the polyphase filter bank where a polyphase filter is used in conjunction with an FFT[11]. The interconnection of the polyphase filter and FFT are shown in Figure 4.

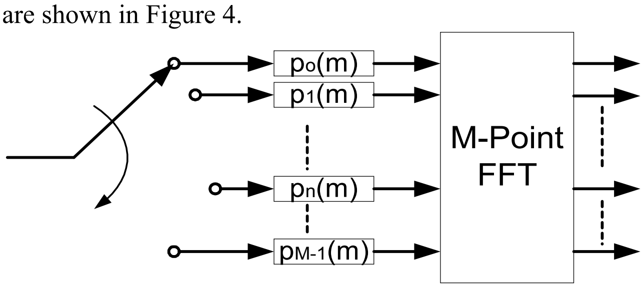

Figure 4 Polyphase filterbank

The polyphase filter preceding the FFT allows the channel impulse response to be longer than the FFT length and thus the channel impulse response can be chosen arbitrarily. An example of the channel response possible is shown in Figure 5, which shows a response where the channel impulse response is twelve times the length of the FFT. In the lower plot the frequency response of the channel is shown together with the response of an adjacent channel, dotted.

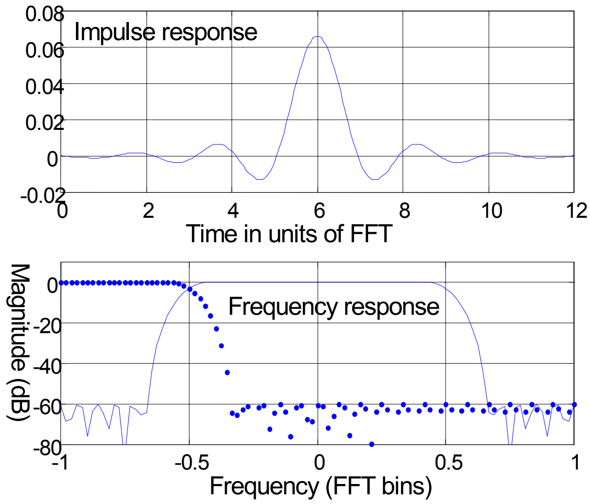

Figure 5 Example of the channel response for polyphase filterbank. Top impulse response, bottom frequency response.

The response has 0.1dB passband ripple and 60dB stopband attenuation. The response of each channel can be made as good or better than any analogue filters with the added benefit that the filter response is absolutely stable. It is seen that there is very little overlap between the two channels. The small amount of aliasing that results from the overlap can be removed by operating the polyphase filterbank in an oversampling mode. However, the filter quality is such that just a 15% increase in sampling frequency is needed to prevent aliasing to any frequency component in the passband (-0.5 to 0.5 FFT bins). With this increase the filter response ensures the measurement of the power of narrowband sources to an accuracy of 0.1 dB. For broadband noise sources the instantaneous aliased noise power is about –40dB leading to a negligible reduction in signal to noise ratio.

Thus, the high quality channel response possible with the polyphase filterbank together with minimal data rate increase ensures that the FX correlator can work to the same level of performance as an XF correlator. In practice the small errors introduced by not oversampling the data will be acceptable for most astronomy application.

VII. Implementation

The main problem with an FX correlator implementation is that correlators for radioastronomy have been built around special purpose ASICs (Application Specific Integrated Circuits), [2] for example, which incur a very high development cost as well as NRE costs during manufacture. For XF correlators a single ASIC design is needed, and this ASIC is very regular. For FX correlators at least one additional ASIC is needed for the FFT function [5]. This ASIC (or ASICs) is a comparatively complex and costly design. In recent years this situation is changing because of the increasing capabilities of Field Programmable Gate Arrays (FPGA). The advantage of these devices is that there is no NRE charge and the implementation need only be approximately correct before it is implemented in hardware. Any faults in the design can then be corrected simply by changing the programming of the FPGAs. This leads to a simpler and faster design cycle that is more forgiving of errors. In contrast, a single error in an ASIC design will result in long delays and a second set of NRE charges. An FPGA design eliminates much of the overhead in implementing FX correlators. This removes one of the obstacles to their adoption for future correlators

As an example of what is possible with current devices the ATNF is designing a 2GHz bandwidth polyphase filterbank based on four XILINX XC2V6000 chips with some smaller device for ancillary functions [12]. At lower bandwidths, FFT cores are available. Mated with an appropriate polyphase filter structure this give a polyphase filterbank with very low design costs.

A second implementation problem that is common to all correlators with a large number of antennas is the cabling to the XMAC units. Consider a design where each XMAC module of the correlator can form correlations between 1/N of the antennas. The signal from each antenna must go to N such modules to ensure correlations are formed between itself and all other antennas. For an SKA correlator N could be large and the cabling cost very large. For an FX correlator the problem has been solved [13]. Make each module process data from all antennas by reducing the total bandwidth processed by each module. Thus each component of the signal from each antenna makes only one connection to the XMAC modules and interconnection cost is minimised.

A final implementation problem for FX correlators is the accumulator shift register associated with each XMAC. If this memory is on-chip it will occupy most of the area of the chip and greatly limit the number of XMAC units on each chip. Instead, this memory needs to reside in off-chip memory. If this is done it is the off-chip memory bandwidth that limits the processing. What is needed is a reduction in the rate at which the XMAC units generate data that needs to be sent off chip. A reordering of the data before it is processed by the XMAC solves this problem[14]. Instead of processing data as it arrives, usually in frequency channel order, store it in a double buffer. While one buffer is being filled the other is being processed with common correlations being processed together. Thus if the data from each frequency channel clocks at 1MHz and the buffers hold 10ms of data there are 10000 common correlations. The XMAC units can accumulate the result of 10000 multiplications before the result needs to be written to external memory. If the XMACs are double buffered and the external memory can be clocked at the same rate as the input data then a single integrated circuit (IC) can hold ~10000 XMACs.

Such a chip requires only 100 input signals which is within the capabilities of current ball-grid-array packages. At 2 operations per XMAC the chip has the processing power of 10^{13} operations/s when running at 500MHz. 67,000 of these chips provide enough compute power for a full one-degree correlator for the SKA based on $153m^2$ antennas. Use of larger antennas can reduce the number of chips to a few thousand.

VIII. Conclusion

The correlator requirements for the SKA require an enormous amount of compute power, mainly for the XMAC operation. It has been shown that an FX correlator minimizes the number of operations and that the design can be implemented with a reasonable amount of hardware.

The limitations of existing FX correlators have also been explored and solutions to the problems have been found. The extra processing needed does not significantly increase the cost of the correlator.

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