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CORRELATORS FOR INTERFEROMETRY — TODAY AND TOMORROW

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ABSTRACT History of correlators for radio interferrometer is briefly reviewed. Advantages and disadvantages of various methods are discussed and the most appropriate ways are given for various interferrometers. Challenges to the next generation short-wavelength interferrometer are also discussed.

INTRODUCTION

In early years of the history of radio interferrometers, scientists and engineers started their works with analog correlators. Soon they had become aware of the stability and the repeatability of digital circuits. They studied characteristics and statistics of quantized signal to make a digital correlator which is now called an XF type digital correlator (Weinreb et al. 1963). The VLA correlator is one of those and the one which has the largest bandwidth and the largest number of correlation channels in late 70s.

The progress in mm-wave astronomy raised strong needs for larger bandwidth and more frequency channels. Chikada proposed a new efficient method to have both of them in spectral correlator, and built such a correlator which is called the Nobeyama FX (Chikada 1981, Chikada et al. 1987).

The FX method drastically improved the bandwidth and the frequency resolution of correlators. However, so-called "hybrid XF" method was then proposed by Weinreb and this has also been adopted in the wide band correlators of relatively few element arrays.

One of the purposes of this talk is to discuss the advantages and the disadvantages of those methods, and the other is to show a portion of problems that should be solved in near future.

XF, FX, AND HYBRID-XF

The principles of the XF and the FX method have been discussed in many literature (for an example, Chikada et al. 1987), so very brief description will be given here. In the XF method, a data stream of sampled data from an antenna will be fed into a shift register and each output at each lag will be multiplied by data from another antenna of a pair. The multiplier is usually an Exclusive-OR gate for one bit per sample data. Then the product at each lag will be time-averaged to yield a lag spectrum. The lag spectrum will be Fourier-transformed into a frequency spectrum in case of line observations. On the contrary, in the FX method, the data streams will be transformed into frequency domain by FFT processors first. Then the "Voltage frequency spectra" of an antenna pair will be cross-multiplied to yield a frequency cross-power-spectrum.

The necessary number of operations per second is proportional to:

$$O(N\ B\ log\ n) + O(N^2\ B)\ \ and\ \ O(N^2\ B\ n) \tag{1}$$

in the FX method and in the XF method, respectively, where N, B, and n are number of element antennas, total bandwidth, and number of frequency resolvable points, respectively. Complexities of circuits in the two method are different and in the FX method complexity is higher than the XF because of the necessity of multi-bit (less than ten in usual cases) precision in the Fourier transform. Although there are some factors applied to the equations (1) and (2), it is apparent that the FX method can realize a large array and/or a large number of frequency resolvable points.

In the hybrid-XF method, the signals are divided into several subbands by an analog variable filter bank, and then each output of a filter is fed into an XF. The division into subbands by an analog filter bank makes it m-times easy to satisfy the condition of arithmetic operations per second, where m is the number of subbands which is usually in the range of $10^0 - 10^1$. However, to connect the spectra from the different analog subbands, there is a problem which will be discussed later.

CORRELATORS OF TODAY

The specifications of existing correlators and those under development are shown in the TABLE I-II. Telescopes are picked up from large and non-solar ones, and they are arranged in the table in the order of their completion date.

Very Wide Bandwidth

It can be easily seen from TABLE I that there are strong demands for wide bandwidth. Many correlators employ parallelism in their architecture to expand bandwidth beyond the clock rate. Hybrid XFs, such as OVRO, Ryle, BIMA, and IRAM, have m identical correlators in parallel (m : no. of subbands). On the other hand, division into subbands by an analog filter bank raises a problem in connecting the spectra from the different analog subbands, "But experience has shown that this can be solved by careful engineering of the analog stages preceding the sampler." (Torres 1990).

On the contrary, the "K-4 type 1" VLBI terminal and the VSOP correlator system is going a way to minimize the number of subbands to avoid such problem and to also minimize costs of variable filters. Normal mode of that system will be 1-2 subbands (4 at maximum). However, this does not mean that the VSOP correlator cannot accept MkIII, etc., it accommodates those multiple subband data by dividing the large FFT into smaller FFTs for each subband and also by correlating them to single subband data from the K-4 type 1.

TABLE I Specifications of correlators. Architecture, RF wavelength, number of element antennas, number of subbands, total bandwidth, total number of frequency channels, and number of bits per a sample, versus telescope names. The total bandwidth is the bandwidth that can be observed simultaneously at the coarsest frequency resolution, i.e., the maximum bandwidth of the subband multiplied by the number of the subbands. The total number of frequency channels is that of subband multiplied by the number of the subbands also at the coarsest frequency resolution. The number of frequency channel is larger than the figures when the data is recirculated, etc., to observe spectral lines in narrower bandwidth.

	arch.	RF	elem. ant.	no. of sub-bands	total BW (MHz)	total freq. ch.	bits/ sample
VLA	XF	cm	27	1	50	16	1.5
NMA	FX	mm	6	1	320	1024	3*1)
Haystack	XF	dm	7	14	28	448	1-2
AT	XF	cm	6+5	1	256	32	1-2*2)
OVRO	XF	mm	3	4	512	256	2
Ryle Tel.	XF	cm	8	10	390	40	2
Hat Creek	XF	mm	6	8	800	512	2
IRAM	XF	mm	4	12	960	192	2
VLBA	FX	cm	20	8	128	8K*3)	1-2
GMRT	FX	m	30	4	128	1024	4
VSOP	FXP	mm	20(5)	1-32	128(512)	8K*3)	1-2

Remarks.
*1). Complex sampling. 3 bits for real and 3 bits for imaginary part.
*2). In 2 bits/sample mode, the total bandwidth will be halved.
*3). Actual number of frequency channels is limited by the transfer rate from the cross-multiplier to the successive stages.

Multiple-Bits/Sample

In addition to the wide bandwidth, progress in the scale of integration also allow us to accept multiple-bits-per-sample data. Two-bits/sample mode gives fairly large signal-to-noise ratio (SNR) improvement over one-bit/sample mode. In GMRT, up-to-four-bits/sample will be realized to avoid harmonics and intermodulation by strong interferences which are inevitable in meter wave region.

More bits are needed for single dishes for easy calibration and in interferrometers for precise measurements of system temperature in autocorrelations under the varying atmospheric emission of 300K. Even in VLBI where one-bit/sample mode has the best continuum SNR under the recording bottle-neck in transmission, multiple-bits/sample mode gives us better SNR for narrow line observations (Haystack, AT, VLBA, VSOP in TABLE I).

It is easy for an FX to accept multiple-bit data, but 2-bit data is not much costly to be processed by an XF also. In an FX, all the calculation are done to multi-bit data from time domain to frequency domain. Therefore it is very easy to implement high-precision station-based corrections: fringe rotation and fractional sample correction (fractional delay-bin correction) which allow good closure phase observations.

Full- or Semi-Custom ICs

TABLE II shows that the full- or semi-custom fabrication of ICs has an important role to realize large scale integration of elements of a correlator: correlator cell, counter, FFT butterfly, accumulator, etc. Bos's chip is the one that is presently used in multiple observatories, but it is not clear that every chip has universality under the rapid progress in IC technology.

TABLE II Specifications of correlators (continued). Architecture, RF wavelength, completion date, and IC technology versus telescope names. Telescopes are the same as in the TABLE I.

	arch.	RF	compl. date	IC technology *1),*2) and chip's name	
VLA	XF	cm	'80	ECL,LSTTL	FC
NMA	FX	mm	'83	CMOS	GA
Haystack	XF	dm	'86		MSI
AT	XF	cm	'87	nMOS(XCELL)	FC
OVRO	XF	mm	'90	ECL,CMOS	GA
Ryle Tel.	XF	cm	'90+	CMOS	GA
Hat Creek	XF	mm	'90+	CMOS (BOS)	GA
IRAM	XF	mm	'91	CMOS (BOS)	GA
VLBA	FX	cm	'92	HCMOS(VLBA)	GA
GMRT	FX	m	'93	HCMOS(VLBA)	GA
VSOP	FXP	mm	'93	CMOS	GA

Remarks.
*1). FC: full custom IC. *2). GA: gate array.

What Was Said to be Problems of an FX?

[Van Vleck correction] One of the characteristics which was said to be drawbacks of the FX was that it has sources of quantization errors not only in analog-to-digital converters but also in the FFT and in the cross-multiplication. Therefore it is not so easy to formulate correction of correlation factor – the Van Vleck correction (1966) as in XFs. However, the correction may be measured for each implementation and the resultant correction curve may be applied to the observations. Actually that empirical correction curve of the Nobeyama FX was measured (Fig. 1), but there were no occasions where such correction was needed because in usual observations the sources are not so strong.

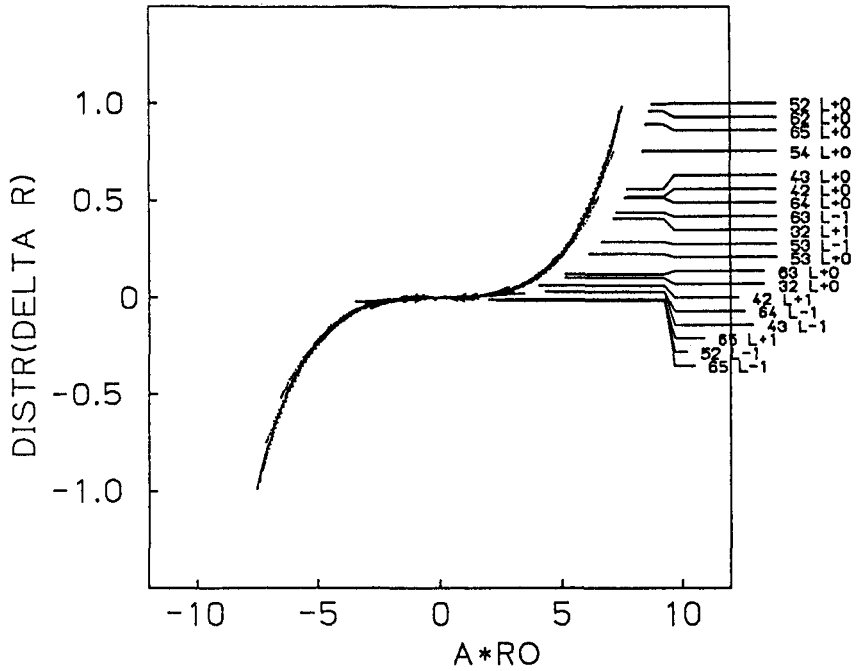

Fig. 1. An empirical correction curves of the Nobeyama FX. Correction (ordinate) and true correlation factor (abscissa) in an arbitrary unit. Curves are plotted for various input levels.

[Cyclic convolution] It is also said that an FFT which is fed signal to its full length yields an output from which no linear (normal) convolution can be recovered. The result of inverse FFT of the output of the X section (cross-multiplier) is aliased to be cyclic convolution. However it is not a problem in continuum observation where only small lag portion of the correlation function is important, because aliasing occurs to a triangular window lag spectrum so that there are no contamination at the peak of the triangle where lag is zero. Similarly, utilizing that the length of FFT can be easily extended with little hardware cost, usual line observation can be done with only the "small" lag portion.

If there is a very sharp line which needs large lag portion and if the line is strong enough to be corrected via "Van Vleck correction", then cyclicity of convolution will be a problem. But in this case, the signal is no more white and the formalism of the Van Vleck correction can not applied and the correction should be measured and applied empirically in either FX or XF.

[Segmentation of the data] It was said that: "To calculate FFTs in an FX, one needs to divide the continuous data stream into segments, and that causes undersampling of 'cross-segment' correlations. This will result in the degradation of the output SNR." However, this is not a problem for the continuum observations and for the line observations where an FX has large enough FFT points and bunching along frequency axis can be done to lessen the weights of the "large lag portion", just as the problem of the cyclic convolution. The degradation by segmentation is also greatly lessen by overlapping of the segments along the time axis.

This segmentation problem also appears in some XFs, for an example, Australian XCELL chip has segmentation scheme to reduce interconnection among correlator cells.

Which Method is the Most Appropriate for Various Interferrometers?

The conclusion is fairly apparent, if mosaicing along the frequency axis is no problem for the Hybrid XF. It is summarized in the TABLE III.

TABLE III Selection of architecture versus application.

application	architecture
Closure phase obs.	FX
Continuum obs.	XF
Line, large array	FX
Line, small array	hybrid XF or FX
Line, RF < 3GHz	XF
RF freq. < 300MHz	FX

CORRELATORS OF THE FUTURE

Phase fluctuation and absorption caused by earth atmosphere must be overcome for the mm and sub-mm astronomy. One solution is to go outside the atmosphere and the other is to built a signal and/or image processor which can search a real fringe and/or image.

Satellite-Born Correlator for Sub-mm

It is a big challenge to built a satellite-born correlator for sub-mm observation at 1000 GHz RF frequency with velocity field-of-view 600km/s and resolution of 2km/s. It should accommodate data from, say, 3 elements and of bandwidth 2 GHz into 300 frequency channels with only 100-300 Watts. Or is it better to have optical down link of the wide bandwidth IF signal?

The necessary arithmetic operations per second will be nearly the size of the IRAM hybrid-XF (24 subbands for 3 baselines needed) or 1/4 of the VSOP

FX (negligible X section compared to the VSOP FX and only 256 channels needed). The estimated power consumption is ten times larger than the above specification with present technologies. However in the next 10 years, it will be surely possible to reduce speed-power product of digital components by a factor of ten.

Post-Detection Processing

What is "detection"? Is it merely integration of the received energy? Our observables change with time, e.g., earth atmosphere, VLBI clock, etc. Can we guess those parameters just as the fringe search in VLBI in the process of "detection"? Can we do something in-between the square law detector and the imaging? To do that, we will have great progress if we have some massively parallel computer after the square-law detector, although it will be necessary to speed-up the processing by an order of 2-3 for an increase of one in the number of parameter to be guessed.

For the VSOP correlator, we are designing a post-detection processor, "P" section of the VSOP FXP, which is planned to have Gbyte GFLOPS capabilities. It will calculate the above "guess" and also multi-field of view, triple product, and usual fringe searching for satellites which have not so good orbit determination.

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