MILLIMETER ARRAY
MEMO NO. 66

MMA Correlator

Some Design Considerations

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I. Introduction

The intention of this memo is to continue the correlator discussion which began at the April meeting in Socorro. Many points were raised at that meeting. Most comments involved pushing the specifications to include more capability. Naturally, increased capability translates into greater cost. So a happy medium must be reached that gets the most bang for the buck. This paper will roughly address some of the costs associated with increased capability. On a related topic, I will initiate a discussion on the possibility of using a fiber optic system to implement the delay network.

II. Specifications

For reference, I've repeated the design specifications of the MMA correlator:

1. Number of telescopes	: $N = 40$
2. Maximum total bandwidth per antenna; two polarizations of 1 GHz each	: $BW = 2$ GHz
3. IF frequency agile separation of bandwidth, i.e., at least 500 MHz pieces of passband	: $J \geq 4$
4. Spectral frequency resolution at max. BW	: $b = 2.0$ MHz
5. Cross polarization mode possible at reduced capacity of BW,b or N^2	
6. Sideband separation mode (if necessary)	

III. Full Cross-Polarization

The proposal as written, specifies cross-polarization but only at reduced capacity. Some people felt it was inappropriate to force cross-polarization observations to suffer reduced capacity. Naturally, building a full-bandwidth cross-polarizing correlator will increase the size and cost of the correlator. How much additional expense is justified for this technique is a question for the astronomical community. I'll summarize some of the tradeoffs.

First, let me mention the correlator, as originally proposed, that would be operated at reduced capacity for cross-polarization. When the correlator is not performing cross-polarization, each of the polarizations from the telescope are treated like another frequency band. The difference between a single-polarization system and the proposed two-polarization system is roughly double, regardless of implementation technique. A reduced capacity cross-polarization mode does not affect the number of operations per second figure-of-merit, however, it does increase cabling and multiplexing hardware. The proposal lists several parameters which could be reduced in order to implement the cross-polarization mode. If the correlator were required to handle any tradeoff possibility, it would greatly increase the interconnection capability. It would be beneficial to limit the tradeoff possibilities.

Naturally, to provide a full capacity cross-correlating system would increase the complexity of the system. The following table lists some of the possible configurations and the effective number of baselines that must be processed by the correlator system. This table also includes the consequences of including a total power mode which operates simultaneously with the spectroscopy mode (i.e., measuring the auto power spectra of each telescope, all the time). Note the baseline value includes these autocorrelations. This is not completely appropriate, but will be discussed in greater detail in the next section.

Table 1. Correlator Options

Fixed Parameters: 40 Antennas

1. Standard Spectroscopy, One Polarization, No Total Power Mode

This is the classic calculation of baselines, with only one polarization measured (or both polarizations combined).

Baselines = 40 x 39 / 2 = 780

2. Standard Spectroscopy, Two Polarizations, No Total Power Mode

This is the instrument sketched by the MMA proposal. Information about polarizations is separated, but cross polarizations are only available in a reduced capacity mode.

Baselines = 2 x 40 x 39 / 2 = 1560

3. Standard Spectroscopy, Two Polarizations, Total Power Mode.

Includes a continuous measurement of total power spectra, along with the cross power calculation.

Baselines = 2 x 40 x 39 / 2 + 80 = 1640

4. Standard Spectroscopy, Two Polarization with Full Cross Polarization, No Total Power.

Essentially this is the same as 80-station cross correlation with 40 missing baselines, i.e., the cross polarization of the same telescope.

Baselines = 2 x 2 x 40 x 39 / 2 = 3120
[or (80 x 79 / 2) - 40]

5. Standard Spectroscopy, Two Polarizations with Full Cross Polarization, plus Total Power AND Cross Polarization from same telescope.

   Essentially a full implementation of every possible distinct cross and auto correlation.

   Baselines = 80 × 80 / 2 = 3200

The follow-up question to the previous discussion of options is how they affect the size of the correlator. Well, for the two-cent answer: more baselines translate into a bigger, more expensive correlator. There are two components to consider. First, increasing the number of baselines increases the operations per second required of the digital logic. This effect is different for FX and XF type correlators. This effect is fairly easy to quantify. The other less obvious effect is in complexity. In this application, I'll use the word complexity to indicate how different modes increase the need for more hardware interconnections. This does not appear in the operations per second, but more cables and multiplexing mean greater cost and complexity.

First, the simple problem of operations per second. The XF correlator does calculations on a per baseline basis. Cross correlations cost the same as autocorrelations. Therefore, the number of operations per second will be directly proportional to the number of baselines, as defined in Table 1.

The FX correlator is not so simple. First, the FX correlator does its frequency conversion on a per station basis. In one respect, this gives the total power spectra for free. It is calculated automatically and does not require any additional hardware. In truth,some additional storage is required, but this should be a nominal increase in hardware.

Conversely, increasing the cross-polarization will increase the operations per second. However, the effect will be isolated to the cross-multiplication circuitry. The number of Fourier transform engines will not be affected. The operations per second can be quantified with the following expression [2]:

$$r_{FX} = r_{F(X)} + r_{(F)X} = r_0\,[n_S\, n_P\, 2 \log_2(n_T) + (n_X - n_A)]$$

where:

r_0 = Input sample rate (total).
n_S = Number of antennas
n_P = Number of polarizations per antenna
n_T = Number of frequency samples required
n_X = Total baselines as given in Section I.b.
n_A = any "Auto" baselines, i.e., total power spectra.

Note: *the equation does not account for separation into frequency bands, which is a proportionality constant.*

The fact that total power mode is relatively free is indicated by subtracting n_A from the baselines. The effect on correlator size of adding cross polarization will depend on whether the cross-multiplier or Fourier engine dominates the size of the spectrometer. By inserting some realistic numbers for the MMA as proposed, the addition of cross-polarization will increase the correlator size about 1.5 times. This compares to 2 times for the XF case.

Given:

$n_S = 40$
$n_P = 2$
$n_T = 1024$
$n_X - n_A$ (proposed) = 1560
$n_X - n_A$ (full cross) = 3120

Then

r_{FX} (full cross) / r_{FX} (proposed) = 1.49

The question of complexity is more difficult to quantify. But in some ways this would tend to lean towards a full cross-polarization correlator. This seems counter-intuitive, but relates to the reduction of different operating modes. Building a correlator that operates in only one mode is simpler to construct, than a fully configurable system. This is especially relevant at the operating frequencies that might be required to construct the MMA correlator. Quantifying the effects of different operating modes will be an important result of more detailed design study.

IV. Separate Wide Bandwidth Continuum Correlator

At the meeting in April, there was interest in extremely wide-bandwidth continuum observations. Building the continuum correlator into the spectroscopy correlator (like the VLA) has some nice features. However, if extremely wide bandwidths are required, it might be easier to build a separate continuum correlator.

Several things must be considered before making a determination on this issue. First, increasing the bandwidth to handle a wide-bandwidth continuum correlator has a strong influence on the IF system and receivers. Also, will the resulting continuum correlator require some minimum frequency resolution, or could a single channel analog correlator suffice?

V. Delay Lines

During my recent visits to OVRO and BIMA, I was intrigued by their delay subsystem. In both cases they use a very simple coax delay network. For their next generation of arrays, both sites are considering a delay system built on fiber optic delay networks. It is essentially identical to the coax network, but replaces the coax with fiber. It has some nice features, and we should at least consider a similar technique for the MMA.

Some rough numbers:

Maximum delay should be related to the geometry of the telescope,about 3000 m. Conversely, the smallest delay should be around the sampling period of the AD conversion. (Shorter delays will be handled in the correlator). This gives a minimum delay period of 0.5 nsec (for 2 GHz sampling, i.e., 1 GHz bandwidth per polarization). [1]

Assume a fiber optic material with n = 1.5. Therefore, 0.5 nsec translates into about 0.1 meters of cable. If we ignore the switches required to change the delay, the MMA would need a 14-section delay line matrix.

1 = 0.1 m
2 = 0.2 m
4 = 0.4 m
8 = 0.8 m
16 = 1.6 m
32 = 3.2 m
64 = 6.4 m
128 = 12.8 m
256 = 25.6 m
512 = 51.2 m
1024 = 102.4 m
2048 = 204.8 m
4096 = 409.6 m
8192 = 819.2 m
16384 = 1,638.4 m

Minimum delay = 0.5 nsec
Maximum delay = 16.4 usec

A fiber optic delay line does not remove the need for a fractional sampling correction, but it does take care of the really long delays that would be difficult to buffer at the sampling rates required of the MMA correlator. Also, if a hybrid system is built, the digital delay circuit would be repeated for each sampler, and not each telescope like a fiber optic delay system. A fiber optic delay system could be built as an extension to the signal transmission system. If suitable switches can be obtained, the signal does not even need to leave the light domain.

Another interesting bonus of this system is it might simplify the addition of a wideband continuum correlator. It is possible that a fiber delay network could be built with plenty of bandwidth to satisfy its needs, without much additional effort. However, this would depend on several systematic questions, like the method of signal transmission.

Naturally, the big unknown in this scheme is the stability and linearity of the fiber and switches. To its favor, many of these questions must be answered for the signal transmission issue, so the two problems can be addressed together. Also, we can gain experience on the problems from the new efforts at OVRO and BIMA. I see this as an area for positive application of joint cooperation.

VI. Sampling Frequency

There has always existed a gray area in digital circuitry (roughly between 20 MHz and 80 MHz) where it was inconvenient to build large digital systems. This zone was between the competing techniques of TTL logic and ECL logic. Building a circuit within the grey area either meant pushing TTL beyond its limit or using the costlier and more power hunger ECL at a relative crawl.

During recent discussions with several correlator builders, in particular Steve Padin at OVRO, it appears another grey area might exist at a higher frequency range. The frequency range in question is not a problem for available chip technology, instead for connector technology. For systems below about 150 MHz, it is possible to use high density, fairly simple connectors. It is even possible to use edge connectors for short jumps. However, above this point, the connectors must revert to more traditional coax techniques such as SMA, etc. On circuit boards, the signals must be impedance matched to give a good 50-ohm transmission line.

Naturally, all these arguments are dependent on the distance the signal must travel. To a certain point, increases in chip level integration will improve the situation. However, within the limits of present integrated chip design, it is difficult to use simple connector techniques above 150 MHz.

The consequence of this situation is to affect the operating clock rate of the correlator. The clock rate should be held below 150 MHz to take advantage of the simpler technology. Conversely, if the clock rate is to be above this value, it should be pushed higher to take advantage of the circuit gains associated with higher operating speeds. In other words, it might be better to use a 500 MHz sampling speed over 250 MHz. Once the difficulty of a high sampling rate is accepted, the maximum benefit should be engendered.

VII. References:

[1] Thompson, et al. *Interferometry and Synthesis in Radio Astronomy*, Section 7.3, page. 200, "Delay Setting-Tolerances"

[2] Romney, Jonathan, VLBA Correlator Memo 60, "Introduction to the Spectral-Domain ('FX') Correlator", May 5,1986.