VLB ARRAY MEMO No. 392

California Institute of Technology
VLBA Correlator Memorandum

To: VLBA Memo Series

From: M. Ewing (PHOBOS::MSE) ext 4970 24 Sept., 1984

Subject: Updated VLBA Correlator Information

Changes in the VLBA correlator specifications have been made in recent months. Exclusion of channel sampling rates of greater than 16 Mega-samples/sec (Ms/s) and the selection of the "Mark-III style" recording system have had significant impacts. In the first section of this Memo, the very broadest-scale picture of the correlator is presented according to the new realities. Successive sections present correlator specifications and operating modes. Note that all information is tentative and subject to revision as comments are received and more detailed studies are performed.

OVERVIEW

A general view of the correlator system is presented in Figure 1.

<u>1. DATA PLAYBACK SYSTEM (DPS).</u> Haystack Observatory will supply the playback system based on an upgrade of the Mark III (1-inch longitudinal) recorders. The DPS will include some functions previously considered correlator functions, namely

- Data decoding
- Data quality monitoring
- Tape clock deskewing
- Interferometer delay tracking
- IF channel to correlator input channel mapping.

Geometric and experiment-setup data are provided by the Correlator Control Computer for the DPS to carry out the functions listed above.

2. DPS SELECTION. Extra DPS units are required to function as "buffer" units, allowing off-line tape changing in an orderly manner. They will also be needed as spares in case of DPS failure. How many extra units are required has been discussed previously (VLBA Memo 230). The number selected will depend on operational requirements, but for present purposes we assume 22 DPS units will be available.

Distribution of the 22 DPS outputs among the 19 Correlator Input Channels (CICs) is accomplished by routing all 22 outputs along a "Global Bus," which goes to every correlator rack. Signal Distribution Modules (SDMs) allow each correlator module to accept inputs from any playback station and any IF channel.

3. CORRELATION ASSEMBLY. Physical cross-correlation, lobe rotation, and autocorrelation are all performed in the "Correlation Assembly," consisting primarily of two types of modules: the Cross-Correlation Module (CCM) and the Auto-Correlation Module (ACM).

a. Cross-Correlation Module. The CCM may contain 64 complex correlation channels (128 accumulators), 2 lobe rotators, and switching to permit it to handle either 16 lags in full polarization (P) modes for one IF R/L channel pair or 32 lags in non-polarized (NP) modes for two IF channels. These parameters seem to represent a reasonable balance between correlator capability for the maximum number of antennas (19), the minimization of the number of lobe rotators, and simplicity of interconnections. (However, the CCM size is not definite at this time.) The CCM will likely include sufficient accumulation (in RAM) to allow integrations for up to tens of seconds, although frequently such long integrations will not be possible due to field-of-view problems, etc.

b. Auto-Correlation Module. The ACM is similar to the CCM, except it has no lobe rotator and it calculates real-valued correlations only. The ACM will also contain a phase calibration detector, which in many ways will be similar to the CCM's lobe rotator. The phase-cal detector may be programmed to detect calibration tones at any position in the bandpass. Multiple tones may be detected by time multiplexing the phase-cal detector.

c. Signal Distribution. Signal distribution from the DPS units to the

CCMs and ACMs is rather complicated because the correlator must operate in many modes. One difficulty is in operating the correlator modules in 10-, 14-, and 19-antenna modes. In general each module must accept inputs corresponding to 3 different antenna pairs for each of the 3 major modes. The signal levels and timing must also be maintained as the signals are distributed. The "Global Busing" approach is a proposal to solve this problem by allowing all CCMS and ACMS to select any DPS output.

4. FRINGE PROCESSOR (FP). Requirements for the Fringe Processor have recently been discussed by Benson (VLBA Memo 384). The FP is intended to perform routine calibration and filtering operations before data is recorded on the archive medium. The FP is a specialized computer capable of several times the performance of a VAX-11/780 (= 0.5 MFlop) at cost of about $10,000.

The FP will perform 32-bit floating point operations at a rate of more than 1 million/sec (1 MFlop). Current plans are to use a "board-level" computer with the M68020 32-bit processor and fast floating point hardware. Suitable hardware is being developed by the Caltech/JPL Concurrent Processor project, but commercial alternatives are available.

Programming will be in a high-level language. A similar system, Block II's Tensor processor, is programmed in PASCAL cross-compiled on the VAX control computer; the VRTX "silicon operating system" provides the necessary resource scheduling functions. The VLBA FP language will be selected according to availability of good compilers and compatibility with other VLBA subsystems.

5. ARCHIVE WRITER. Fringe Processor output data is collected by this process (processor) and written to the archive medium-magnetic tape in the current plan. This function may be compatible with the control computer (below), but the data rates can be quite high. Thus a special-purpose processor (similar to the FP) may be more cost-effective.

6. CONTROL COMPUTER (CC). This computer controls and monitors the real-time operation of the entire correlator system. It interfaces with the Monitor & Control system's experiment database, with the DPS, and also with the post-processing system through the Archive Writer. Corre-

lator operators control the correlation process through the CC using an interface that must be similar to that being designed for the M & C system. (The same operator crews must use both.)

The control computer must be capable of effective real-time process scheduling, of "friendly" user interfaces, and of good general-purpose computing support. System development for the FPs, the Archive Writer, and the CC will probably be done on the CC itself. In performing the calibration fringe fitting required to support FP operation, the CC must run AIPS-like software, and in particular it should have an array processor. In addition, the CC must support high I/O rates if it is to handle the archive function.

One of the DEC VAX-11 processors would be suitable for the CC function. Model 750 would probably be adequate if the archive function is handled scparately, while the 780 or 785 may be required otherwise. The VAX family is especially suitable since we are building on the experience gained in the recent Block II correlator project and since it is a leading contender for the Monitor & Control job.

CORRELATOR SPECIFICATIONS
(TENTATIVE)

- **Number of Antennas Supported:** **2-10 (full)**
  11-14 (half)
  15-19 (quarter)

The number of antennas that can be correlated is limited by the number of correlator "lags" that are available, how the lags can be subdivided, and by the number of IF channels supported. Full capability is provided for up to 10 antennas, the number proposed in the the basic VLBA. A break then occurs, and 11-14 antennas are supported in "half" mode, i.e., half the number of frequency channels. This is because the 10 station correlation modules are effectively divided in half. Another break then occurs, and "quarter" mode is supported for 15-19 stations.

- **Number of Frequency Channels per Baseline:**

  512 (full)
  256 (half)
  128 (quarter)

This specification is determined by the needs of spectral line experiments. It determines the following correlator hardware specification.

- **Number of Crosscorrelator "Lags":** **46,592**
- **Number of Crosscorrelator accumulators:** **93,184**

The number of lags is sufficient to allow "half" capability with 14 stations (91 baselines). This is slightly more than necessary for "full" mode with 10 stations or "quarter" mode with 19.

- **Number of Autocorrelator "Lags":** **10,240**
  (equal to number of accumulators)

The number of autocorrelator accumulators is determined by the need for full frequency resolution on 45 baselines (10 stations).

• **Bandwidth: up to 128 MHz**

The interface with each antenna's recording system includes 16 IF channels, each of which corresponds to an 8 MHz band sampled at a 16 MHz rate. The number of channels recorded may be reduced for lower observing bandwidths. For very low recording rates, sample rates below 16 MHz per channel may be chosen; from the correlator standpoint, division of 16 MHz by powers of two is convenient (16, 8, 4 Ms/s, etc.).

The maximum bandwidth, 128 MHz (i.e., sample rate 256 Ms/s), is determined by the DPS (tape recorder) interface. The VLBA specification for recording rate is approximately 128 Megabit/sec (normal) and 256 Megabit/sec (double rate). These correspond to 128/64 and 256/128 Megasamples/sec for 1-bit/2-bit sampling, respectively.

Bandwidth in "quarter" mode (15-19 stations) is limited to 64 MHz (128 Ms/s) by the limited divisibility of correlator lags. Since we have only one lobe rotator per 32 lags (NP modes), there are enough for only about 1456 IF channels, spread over 171 baselines. That is, there are only enough lobe rotators for 8 IF channels per station. (Doubling lobe rotators and signal multiplexing would cost an additional $150,000 according to a very rough estimate.)

• **Sample Quantization: 1 or 2 bits**

Input channels always carry 2-bit data samples, but one bit may be ignored if 1-bit operation is desired. Correlation of 2-bit signals will be performed according to a multiplication table which is not yet decided. The table will be a tradeoff between numerical accuracy and logical simplicity (i.e., limited dynamic range). The quantization thresholds of the IF sampler must be coordinated with the multiplier specifications.

- **Oversampling Factors:** 1 (normal)
  2
  4

Sensitivity of limited-bandwidth observing can be improved by oversampling by the indicated factors.

- **Number of Unrelated Experiments to Correlate Simultaneously:** 2

Two independent experiments involving a total of 10 antennas (including possible duplicated antennas) may be processed in "full" mode. If the total is 11-14, they may be processed in "half" mode; 15-19, in "quarter" mode. In particular, a 10-station and a 12-station experiment could be handled at once. The "Global Busing" method allows up to two 14-station experiments to be handled simultaneously (in "quarter" mode), by straightforward expansion. No additional correlator modules would be required.

- **Polarization (P) processing (compared with NP modes) divides the number of independent IF channels by two, hence divides the maximum signal bandwidth by two. The number of frequency channels is divided by four.**

IF channels may be recorded in in R,L pairs. These paired signals are treated as orthogonal polarization channels at a common RF frequency and sideband. Correlators handling R,L pairs will be grouped physically together, since they will share a common lobe rotator.

To clarify the P/NP cases, consider the following diagrams. Both deal with a minimal polarization correlator module, which can be considered the minimal module of the correlator system. (The actual definition of the "minimal" module is not yet complete.)

POLARIZED (P) MODE

```
                               +---------+---------+
STATION 01 CHANNEL R1 -->      |   RR    |    R    |
                               +---------+---------+
STATION 01 CHANNEL L1 -->      |   LR    |   LL    |
                               +---------+---------+
                                         |       |
               STATION 02 CHANNEL R1             |
                                                 |
                         STATION 02 CHANNEL L1
```

Only one lobe rotator is required for such a group of 4 correlators operating in P mode, since interferometer geometry and frequency are identical for all. Channel-specific (or R/L-specific) delay, phase or frequency offsets can be removed in later processing.

NON-POLARIZED (NP) MODE

```
                               +---------+---------+
STATION 01 CHANNEL R1 -->      | -----  RR   ----  |
                               +---------+---------+
STATION 01 CHANNEL L1 -->      | -----  LL   ----  |
                               +---------+---------+
                                         |      |
               STATION 02 CHANNEL R1            |
                                                |
                       STATION 02 CHANNEL L1
```

NP processing requires no combination of the R and L channels, so double the delay coverage and frequency resolution (per channel) are available compared with P mode. Since R and L channels will generally be from separate IF frequencies, two independent lobe rotators are required.

• Correlator module size: 128 accumulators, 64 complex lags, 2 lobe rotators.

From a cost standpoint, it is desirable to make the basic correlator module (which is replicated many times) fairly large so that (1) the number of lobe rotators can be kept low, and (2) so that the number of interconnections is not excessive. On the other hand, operation with many IF channels and many antennas requires that the correlator lags be distributed in small modules. Polarization processing also requires that modules be divisible in twos or fours.

The tentative modularization is into 64-lag complex (128 accumulator) units corresponding to the two figures drawn above. In P modes, 16 lags (sample delays) would be available in each of the 4 polarization correlators. In NP modes, 32 lags would be available in two IF channels. Two independent lobe rotator circuits would be required for each 64-lag module in NP modes. (P modes require only one.)

This choice of module size rules out 128 MHz bandwidth modes in "quarter" mode, more than 14 stations. These modes are considerably beyond the basic VLBA specifications. They could be handled in the future by expansion of the number of modules. This limitation may be viewed as a consequence of the limited number of lobe rotators in the system or the limited divisibility of the correlators.

CORRELATOR MODE LIST

A summary of correlator modes is presented in Table 1, thanks to T. Pearson. The modes are detailed in the following discussion. Some special modes are not yet fully specified.

1. P Modes. (Full polarization analysis)

a. Maximum bandwidth. In this mode all IF channels are used at their maximum rates. Only 10 antennas are permitted unless optional IF channels are provided. Peak-rate recording is required. ("Double peak rate" if 2-bit sampling is used.) Operation with more than 14 antennas is excluded because of the minimum correlator module size (see above).

RF bandwidth:	64 MHz	
Channel sample rate:	16 Ms/s	
Recording rate:	256 Mb/s (1-bit)	
	512 Mb/s (2-bit)	(a)
No. IF frequencies:	8	
No. antennas:	10 (160 IF channels)	
	14 (224 IF channels)	(b)
Freq. channels/baseline:(c)	128 (10 antennas)	
	64 (14 antennas)	(b)
Lags/channel/baseline:(d)	32 (10 antennas)	
	16 (14 antennas)	(b)

Notes:
- a Exceeds VLBA reference recording rate.
- b Beyond capabilities of "reference correlator", i.e., requires a "positive option" to be implemented.
- c 32 channel/19 antenna mode not allowed due to correlator module size.
- d I.e., the delay range covered in a single channel and baseline (samples).

b. Moderate bandwidth. In this mode half the antenna IF channels are used. The correlator input channels are then sufficient for 20 antennas, although only 19 can be correlated.

Design assumption: Current information is that the DPS will be able to switch any IF signal channel to any correlator input channel (within a single DPS), and, furthermore, that the delay corresponding to any correlator input channel can be set independently of all the others (within the capacity of the DPS' RAM buffer). This capability is used in the correlator to provide higher frequency resolution for lower observed bandwidths.

RF Bandwidth:	32 MHz
Channel sample rate:	16 Ms/s
Recording rate:	128 Mb/s (1-bit)
	256 Mb/s (2-bit)
No. IF frequencies:	4
No. Antennas:	up to 19
Freq. channels/baseline:	128 (10 antennas)
	64 (14 antennas)
	32 (19 antennas)
Lags/channel/baseline:	64 (10 antennas)
	32 (14 antennas)
	16 (19 antennas)

c. Lower bandwidth.

RF Bandwidth:	16 MHz
Channel sample rate:	16 Ms/s
Recording rate:	64 Mb/s (1-bit)
	128 Mb/s (2-bit)
No. IF frequencies:	2
No. Antennas:	up to 19
Freq. channels/baseline:	128 (10 antennas)
	64 (14 antennas)
	32 (19 antennas)
Lags/channel/baseline:	128 (10 antennas)
	64 (14 antennas)
	32 (19 antennas)

d. Lowest bandwidth. Note that this mode places the same IF channels (R and L) into 8 correlator input R/L channel pairs, with suitable delay offsets.

RF Bandwidth:	8 MHz	
Channel sample rate:	16 Ms/s	
Recording rate:	32 Mb/s (1-bit)	
	64 Mb/s (2-bit)	
No. IF frequencies:	1	
No. Antennas:	up to 19	
Freq. channels/baseline:	128 (10 antennas)	
	64 (14 antennas)	
	32 (19 antennas)	
Lags/channel/baseline:	256 (10 antennas)	
	128 (14 antennas)	
	64 (19 antennas)	

2. NP Modes. (No polarization analysis)

a. Maximum bandwidth.

RF Bandwidth:	128 MHz	(a)
Channel sample rate:	16 Ms/s	
Recording rate:	256 Mb/s (1-bit)	
	512 Mb/s (2-bit)	(a)
No. IF frequencies:	16	
No. Antennas:	10 (160 IF channels)	
	14 (224 IF channels)	(b)
Freq. channels/baseline:	512 (10 antennas)	
	256 (14 antennas)	(b)
Lags/channel/baseline:	64 (10 antennas)	
	32 (14 antennas)	

Notes:

a Exceeds VLBA specification.

b Requires positive option (IF channels)

b. Moderate bandwidth.

RF Bandwidth:	64 MHz
Channel sample rate:	16 Ms/s
Recording rate:	128 Mb/s (1-bit)
	256 Mb/s (2-bit)
No. IF frequencies:	8
No. Antennas:	10 - 19
Freq. channels/baseline:	512 (10 antennas)
	256 (14 antennas)
Lags/channel/baseline:	128 (10 antennas)
	64 (14 antennas)
	32 (19 antennas)

c. Lower bandwidth.

RF Bandwidth:	32 MHz
Channel sample rate:	16 Ms/s
Recording rate:	64 Mb/s (1-bit)
	128 Mb/s (2-bit)
No. Antennas:	10 - 19
Freq. channels/baseline:	512 (10 antennas)
	256 (14 antennas)
	128 (19 antennas)
Lags/channel/baseline:	256 (10 antennas)
	128 (14 antennas)
	64 (19 antennas)

d. Lowest bandwidth.

RF Bandwidth:	16 MHz
Channel sample rate:	16 Ms/s
Recording rate:	32 Mb/s (1-bit)
	64 Mb/s (2-bit)
No. IF frequencies:	2
No. Antennas:	10 - 19
Freq. channels/baseline:	512 (10 antennas)
	256 (14 antennas)
	128 (19 antennas)
Lags/channel/baseline:	512 (10 antennas)
	256 (14 antennas)
	128 (19 antennas)

3. Special Modes.

a. Pulsars. The basic requirement for pulsar observations is time gating synchronous with the pulse rate. Some observations will also need some "de-dispersion" capability, which may mean independent gating of IF channels or possibly more elaborate signal processing in the Fringe Processor. (See Bartel, VLBA Memo 367.) In some cases, it will be useful to accumulate independent time bins centered on various pulse phase angles.

b. Geodesy/Astrometry. These modes are "special" in their need to process multiple, non-contiguous IF bands for bandwidth synthesis. This process loads the Fringe Processor with large FFTs that convert from frequency to "synthesized delay" space, but the load may only be comparable to spectral-line processing. Typically geodesy and astrometry now require fewer than 10 antennas per experiment.

c. Multi-Group Correlation. Correlator throughput can be enhanced by simultaneous correlation of independent experiments. The "Global Bus" allows all available DPS units to be distributed between two experiments.

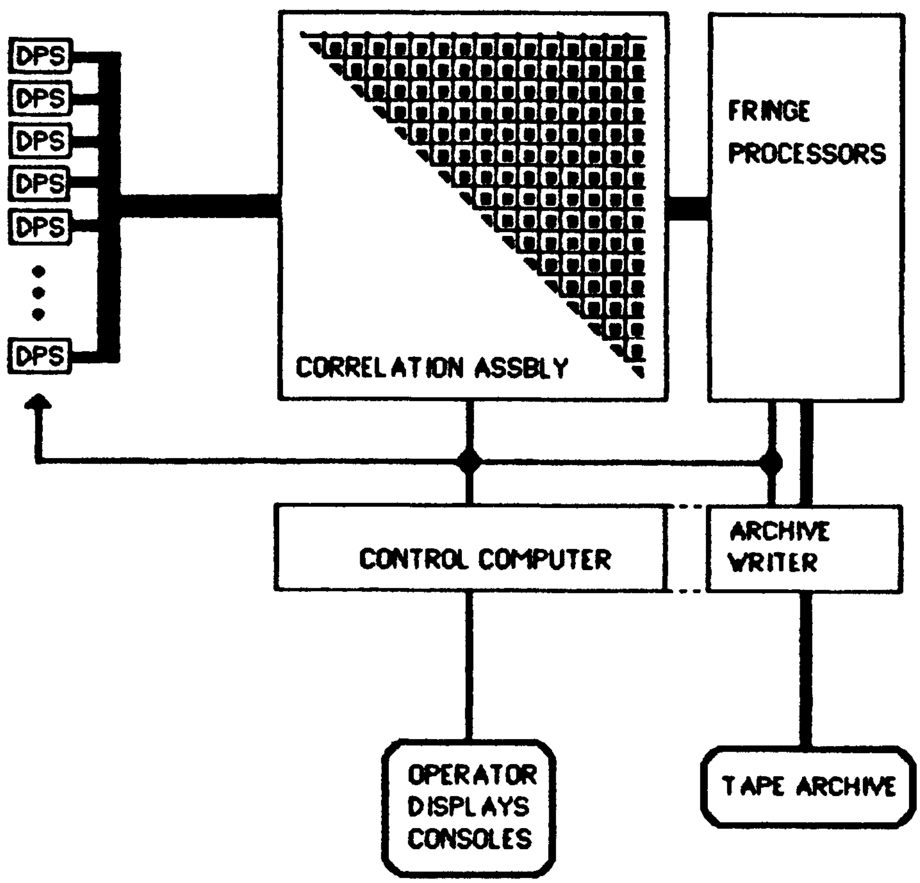

Figure 1. Overall VLBA Correlator System

VLBA Correlator Modes
(excluding lower-bandwidth modes produced by reducing the clock rate)

Antennas	P/NP	Bandwidth RF (MHz)	Channel Sample Rate (Ms/s)	Recording rate 1bit/2bit (Mb/s)	Number of IFs	Number of IF channels	Freq chan /baseline	Lags/chan /baseline
2-10	NP	128	16	256/512	16	160	512	64
	P	128	not permitted					
	NP	64	16	128/256	8		512	128
	P	64	16	256/512	8	160	128	32
	NP	32	16	64/128	4		512	256
	P	32	16	128/256	4		128	64
	NP	16	16	32/ 64	2		512	512
	P	16	16	64/128	2		128	128
	P	8	16	32/ 64	1		128	256
11-14	NP	128	16	256/512	16	224	256	32
	P	128	not permitted					
	NP	64	16	128/256	8		256	64
	P	64	16	256/512	8	224	64	16
	NP	32	16	64/128	4		256	128
	P	32	16	128/256	4		64	32
	NP	16	16	32/ 64	2		256	256
	P	16	16	64/128	2		64	64
	P	8	16	32/ 64	1		64	128
15-19	NP	128	not permitted					
	P	128	not permitted					
	NP	64	16	128/256	8		128	32
	P	64	not permitted					
	NP	32	16	64/128	4		128	64
	P	32	16	128/256	4		32	16
	NP	16	16	32/ 64	2		128	128
	P	16	16	64/128	2		32	32
	P	8	16	32/ 64	1		32	64

TABLE 1.