NOAA Technical Memorandum ERL WPL-74

A GENERAL PURPOSE CORRELATOR

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NOAA/ERL/Wave Propagation Laboratory
Boulder, Colorado 80303

ABSTRACT

We describe a correlator for general laboratory use that calculates the time-delayed correlation of two electrical signals in real time.

1. INTRODUCTION

The Wave Propagation Laboratory has had a continuing need to measure the correlation of fluctuating signals in real time. The instrument described here is an improved version of a type that has been in use for some time. It computes both the correlation and covariance of input signals as a function of time delay and provides an output for displaying the function on an oscilloscope or a chart recorder.

The particular kind of correlation circuit that has been used in optical remote sensor applications is based upon work by J.A. Van Vleck at MIT Lincoln Laboratory during World War II. He published this work in the open literature somewhat later.[1] A WPL report describes an application of his principles to the design of a correlator circuit.[2] The correlator described here uses newer circuit components and computes a time-delayed correlation function. It is, however, based upon the same technique, and reference 2 forms the basis for the following discussion.

By definition, the correlation coefficient (ρ) of two signals is

$$\rho = \frac{\overline{xy}}{\sqrt{\overline{x^2}\;\overline{y^2}}} \qquad (1)$$

where x and y are the signal deviations from their means. If, however, the signals have a jointly normal amplitude distribution, ρ can be determined merely by measuring the coincidence of the signs of the signals relative to their means. An exclusive or logic element determines the coincidence or noncoincidence of the signs, greatly simplifying the calculation.

Several points must be kept in mind when using a correlator of this type. One is that the output voltage of the circuit is not linear with correlation, but follows the law,

$$\rho = \sin\left(\frac{\pi}{2}\frac{V}{V_{max}}\right) \qquad (2)$$

where ρ = correlation coefficient,

V = output voltage, and

V_{max} = output voltage for $\rho = 1$.

This relation is correct only for signals having Gaussian amplitude distributions. However, useful results can be obtained for signals having other amplitude distributions.[2]

The second point concerns computational efficiency. The accuracy of the estimate obtained is of course less than if the computation was performed according to the defining equation for ρ. Near $\rho = 0$, the correlator requires about 2.5 times as much sample length as would be required by computing ρ directly.[3] As the correlation increases more time is required, approximately 3 times at $\rho = 0.5$, and 6.5 times at $\rho = 0.9$. The standard deviation of the estimate of ρ does, however, decrease with increasing ρ, but not as rapidly as when ρ is computed directly from the defining equation.

The mean time from which the signal deviations are determined is defined by the input RC circuitry. The time constant, τ, (adjustable from .00005 to 5 seconds) forms an exponential window in which present information is most heavily weighted and past information is gradually discounted. It is approximately the length of the time average represented by the bars in equation (1). Considering the circuit as a high-pass filter, the half-power frequency response, f_c, occurs at

$$f_c = \frac{1}{2\pi\tau} \quad (3)$$

and frequencies below this value get less and less consideration in the covariance, according to the 6-dB/octave rolloff law.

The coincidence of signs technique simplifies the calculation of a time-delayed correlation function, since many values of the function can be calculated by processing the digitized signals with shift registers and exclusive or circuits. This technique inherently produces a normalized function. The covariance of x and y is calculated by multiplying the correlation function by the product of $\sqrt{x^2}$ and $\sqrt{y^2}$. Only two multipliers and two root-mean-square modules are necessary, then, to obtain the time-delayed covariance function.

2. OPERATION

The front panel connections and controls have the following functions:

INPUTS -- The correlator accepts input signal levels from 10 mv to 20 volts RMS. The useful frequency range is about 0.2 Hz to 20 kHz.

SIGNAL, NORMALIZED -- The correlation vs. time delay appears at this output. A correlation of +1 gives +10 volts; -1 gives -10 volts. The function is presented sequentially from -64 bits of delay to +64 bits, with a fixed time constant average of 22 seconds. Input A is delayed relative to B, to the left of zero delay; to the right, B is delayed relative to A.

SIGNAL, UNNORMALIZED -- The covariance, ρ_u, vs. time delay appears at this output, and is scaled so that $\rho_u = \overline{xy}/10$, with a ± 10 volt full scale limit.

AUTO CROSS -- If this switch is in AUTO position, the autocorrelation and the autocovariance of input A is computed.

MEAN, SECONDS -- The mean time (τ) over which the correlation or autocorrelation is computed. This control can also be considered as an adjustable high-pass filter with half-power cutoff frequency $f_c = 1/2\ \pi\tau$.

DELAY PER BIT, MSEC -- Input A is delayed relative to input B from -1 to -64 delay intervals (bits); likewise, input B is delayed from 1 to 64 bits relative to input A. This control sets the delay interval, i.e., the time scale of the correlation vs. time function. The maximum delay available is of course 64 times the bit delay.

SYNC -- A positive sychronization pulse appears at this output that corresponds in time to the -64 bit delay.

RING COUNTER CLOCK -- In the fast position the 129 position in time (128 delays plus zero delay) are sampled at a 15 kHz rate (116 sweeps/second) to provide a continuous plot on an oscilloscope. In the slow position they are sampled at 10 Hz (12.9 seconds/sweep) suitable for a chart recorder or computer entry via an analog-to-digital converter.

CALIBRATE -- A voltage corresponding to a correlation of +1 and -1 appears at the signal output with this switch in the + and - positions, respectively. The signal appears at the output in RUN position.

CANCEL -- Pressing this button discharges all signal storage capacitors and removes whatever function is being displayed. A new function will then develop at the 22 second time constant rate from new information being received.

MANUAL START -- If for some reason, the sample pulse is lost from the ring counter, it can be reintroduced by pressing this button, without loss of the stored function. The button is not needed in normal operation, however, as the sample pulse is automatically introduced when the instrument is turned on.

A usual mode of operation when the function is displayed on an oscilloscope is to trigger the scope with the SYNC output and adjust the sweep length to the interval between SYNC pulses. The vertical scale can then be set using the CAL switch. The zero time delay position can be located accurately by switching temporarily to the AUTO position.

Since the DELAY PER BIT (b) setting adjusts the delay shift register clock frequency, it also acts as a low-pass filter which cuts off at the Nyquist frequency (1/2b). In general the signal input frequencies of interest will be well below this limit because the bit length on the abscissa of the displayed function must be short compared to the resolution desired. It is well to keep this limit in mind, however. Also, it is good practice to employ low-pass filters ahead of the correlator when high frequency noise is present above the Nyquist frequency.

3. CIRCUITRY

A simplified block diagram of the correlator is shown in Fig. 1. In the input circuitry, the signs of signals A and B relative to their means are determined. This information is then fed to a bank of exclusive or (ex or) and shift register circuits. The ex or circuits measure the correlation by the coincidence of signs as described earlier. The shift registers progressively delay signal A relative to B and Signal B relative to A to 64 increments of delay. The undelayed ex or and the 128 delayed ex or outputs are individually averaged with 22 second time constants. These 129 averaged outputs are sequentially sampled by FET switches driven by a single pulse circulating in a 129 bit ring counter. The FET switch outputs are all connected to a high impedance input amplifier which conditions and calibrates the output. A trigger pulse for synchronization is obtained from the -64 bit time so that the correlation function can be presented on a scope with zero time delay in the center of the trace. To obtain the covariance, the RMS levels of signals A and B are measured, averaged with a 22-second time constant, and their product is multiplied by the normalized output.

Appendix A contains the detailed circuit diagrams. A correlator module circuit board has been designed that contains the ex or, shift register, averaging, ring counter, and FET circuits required for 8 channels of the correlator. A bank of 16 of these modules completes most of the circuitry required. The remaining circuit cards contain the input, zero delay, shift register and ring counter clocks, and output circuitry.

A ±5 volt supply is used for the digital circuitry and a separate ±15 volt supply powers the analog circuitry. This isolates analog from digital, and also allows the output amplifier to accept the ±4.9 volt CMOS voltages without saturating.

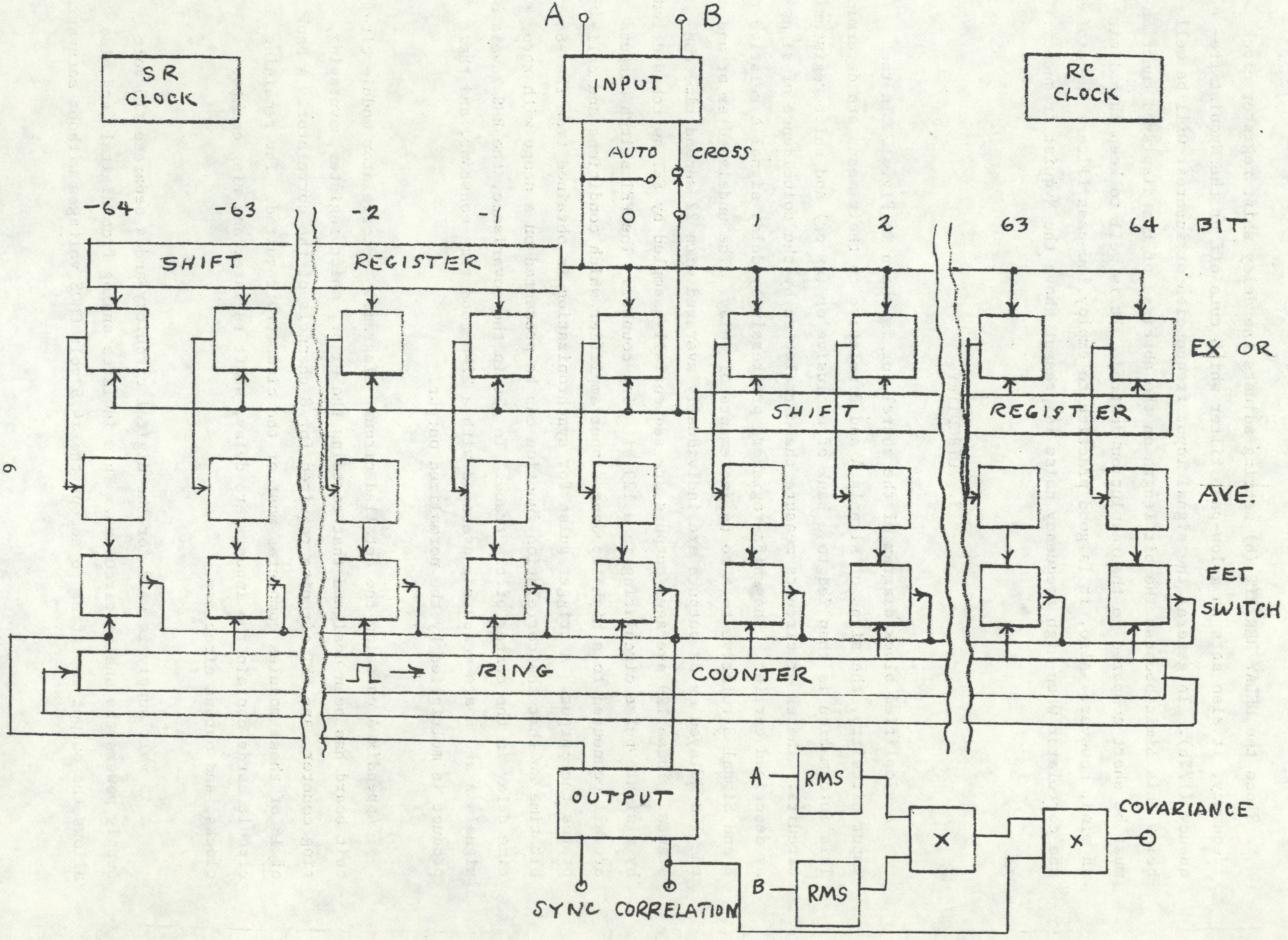


Figure 1. Block Diagram

4. ALIGNMENT

There are no adjustments on the correlator modules, i.e., all the cards in the lower card cage. The input, shift register and ring counter clocks, and the output adjustments are made as follows:

On input card --

A. Ground A1 and adjust pot A for zero volts at pin 6 of associated op amp.

B. Ground B1 and adjust pot B for zero volts at pin 6 of associated op amp.

On floating input and multiplier card --

A. Ground points 23 and 53 and adjust pot A and pot B for 0.000 volts at points A1 and B1 respectively.

B. With the grounds still in place, adjust pot C for 0.000 volts at the SIGNAL, UNNORMALIZED output.

On clock card --

A. With the DELAY PER BIT set at .003 ms, adjust pot A for 333 kHz out at pin 13 of the 2207 oscillator (SR CLK OUT).

B. With the DELAY PER BIT set at .01 ms, adjust pot B for 100 kHz out at pin 13 of the 2207 oscillator (SR CLK OUT).

C. With the RING COUNTER READOUT set at 10 Hz, adjust pot E for 10 Hz out at pin 13 of the 2207 oscillator (RC CLK OUT).

D. With the RING COUNTER READOUT set at 15 kHz adjust pot D for 15 kHz at pin 13 of the 2207 oscillator (RC CLK OUT).

E. Set the CAL switch to +1 and adjust pot C for +10.0 volts at the signal output.

F. With the CAL switch set to -1, check for -10.0 volts at the signal output.

5. REFERENCES

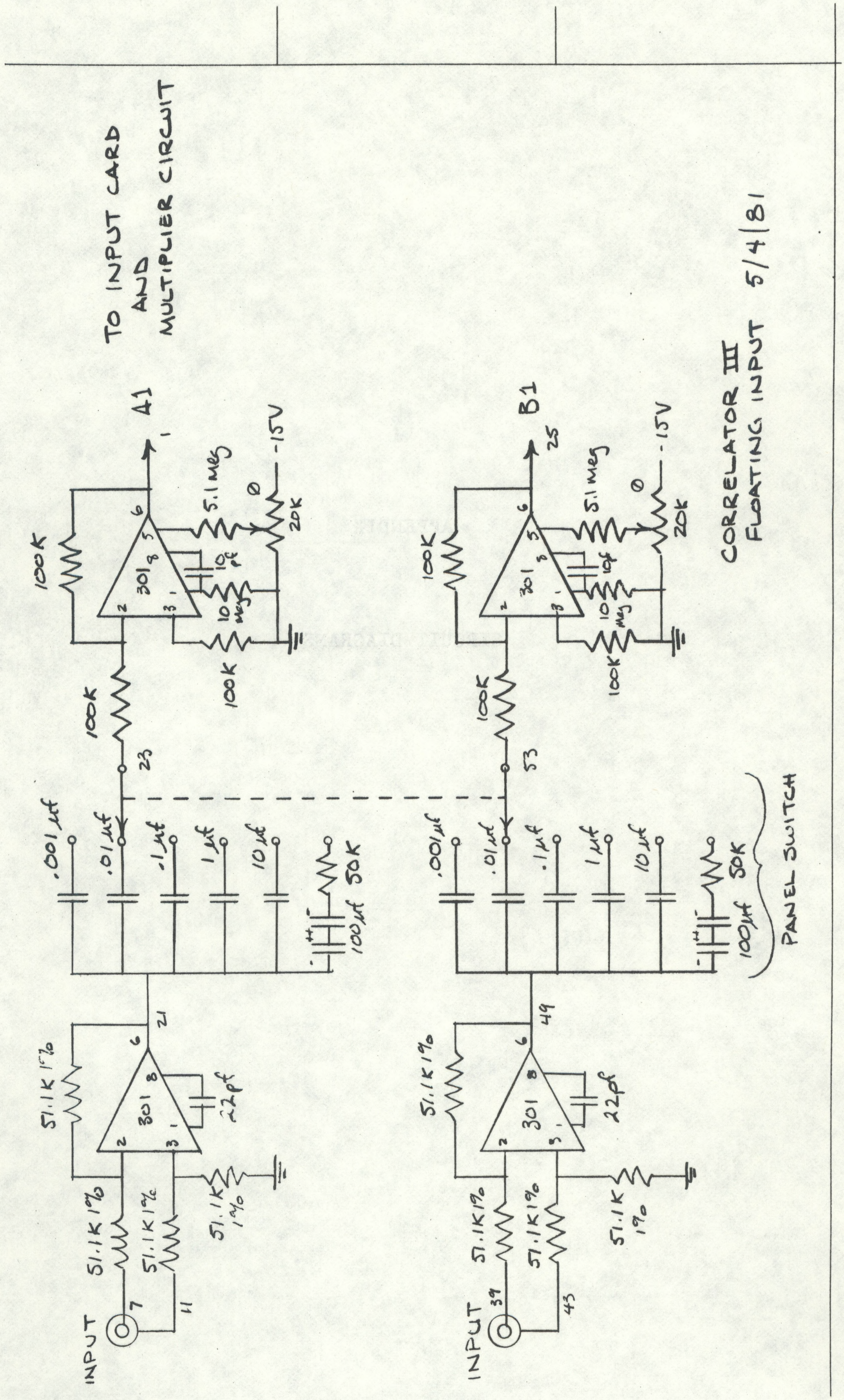
1. Van Vleck, J.H., and D. Middleton (1966), "The spectrum of clipped noise," Proc. IEEE, 54, No. 1, 2-19.

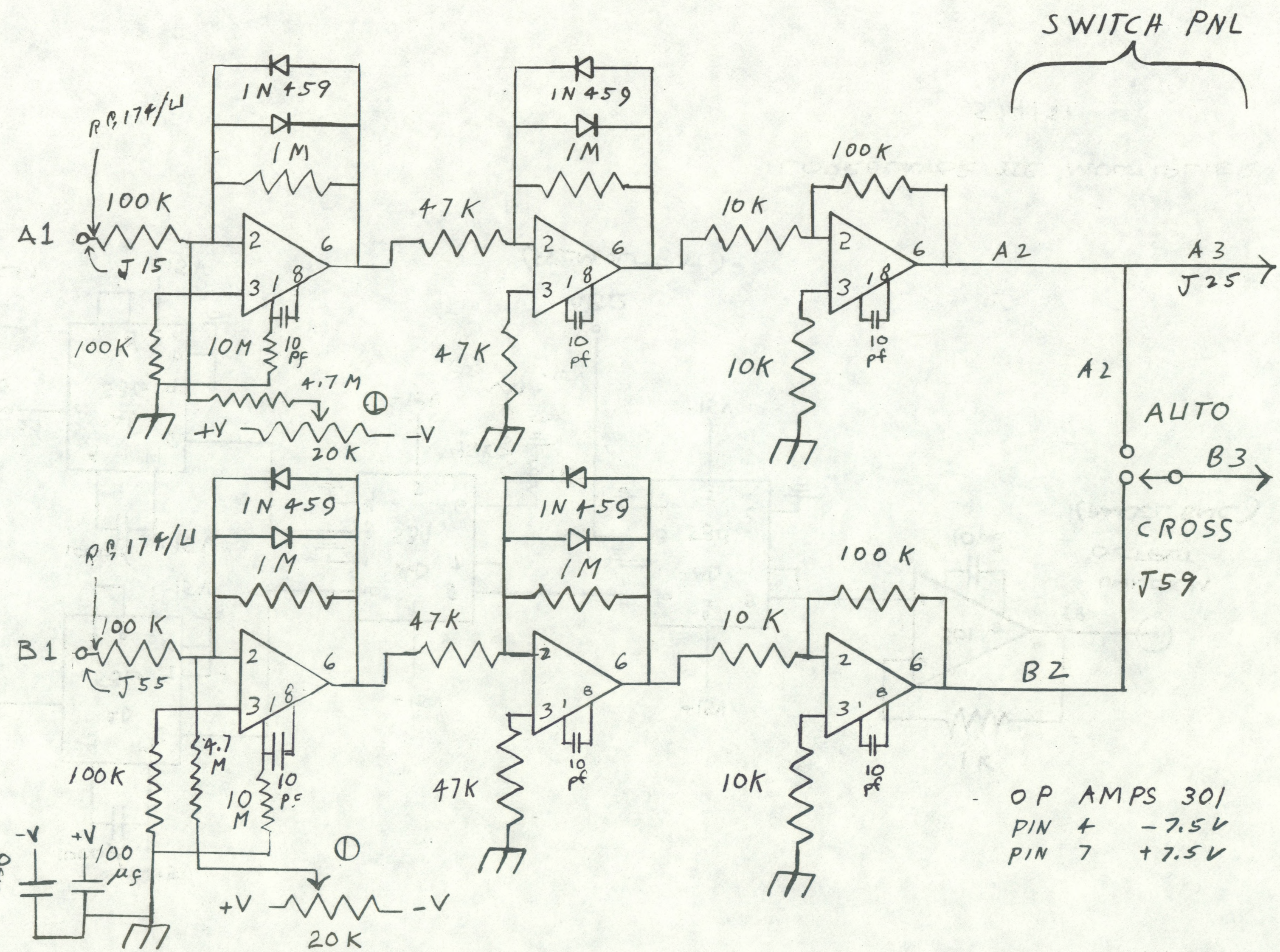
2. Ochs, G.R., "A circuit for the measurement of normalized crosscorrelations," ESSA Tech. Rept., ERL 63-WPL 2.

3. Barber, N.F. (1961), "Experimental correlograms and Fourier transforms," (Pergammon Press, New York).

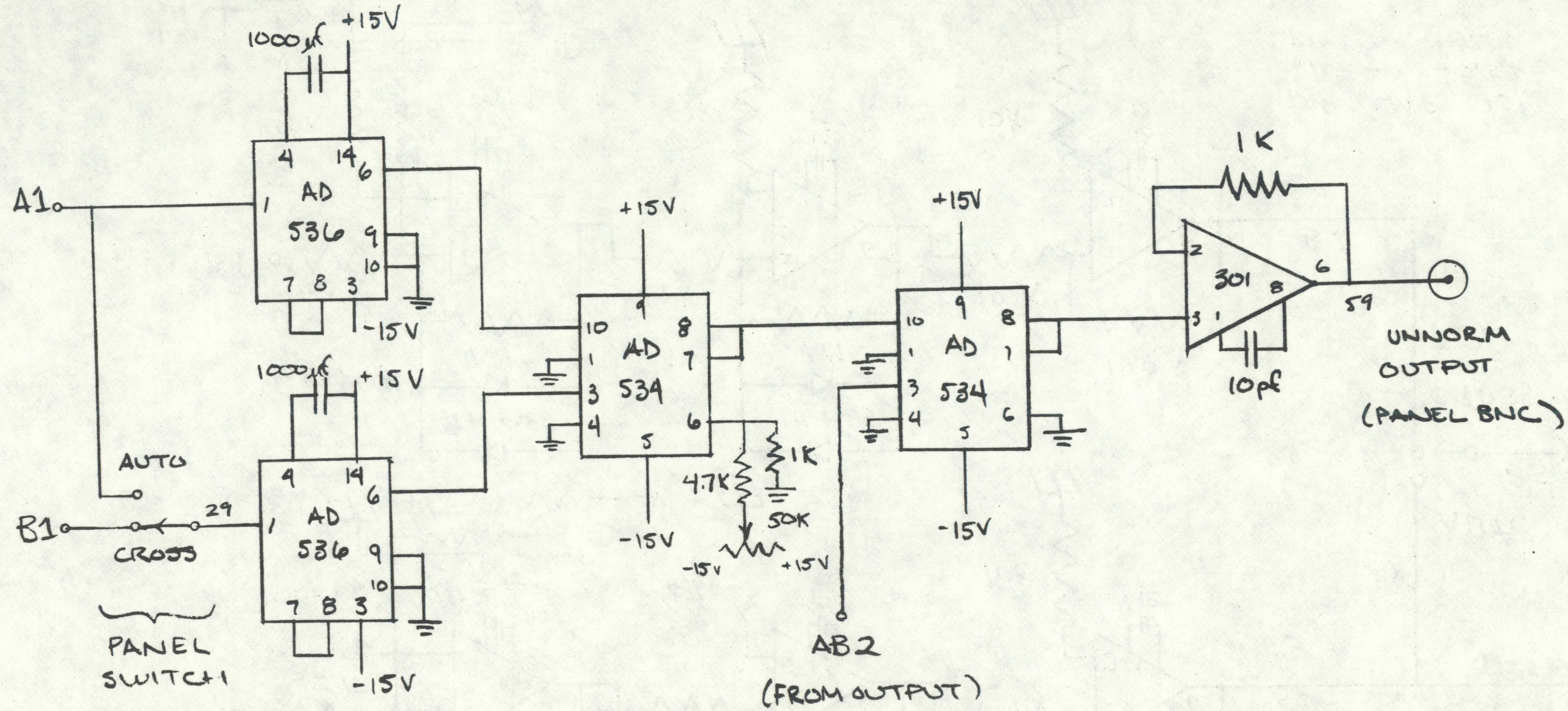
APPENDIX

CIRCUIT DIAGRAMS


TO INPUT CARD
AND
MULTIPLIER CIRCUIT
CORRELATOR III
FLOATING INPUT 5/4/81
PANEL SWITCH
INPUT
INPUT
A1
B1
100K
5.1 meg
10 meg
10 pf
20K
-15V
51.1K 1%
301
22pf
.001µf
.01µf
.1µf
1µf
10µf
100µf
50K

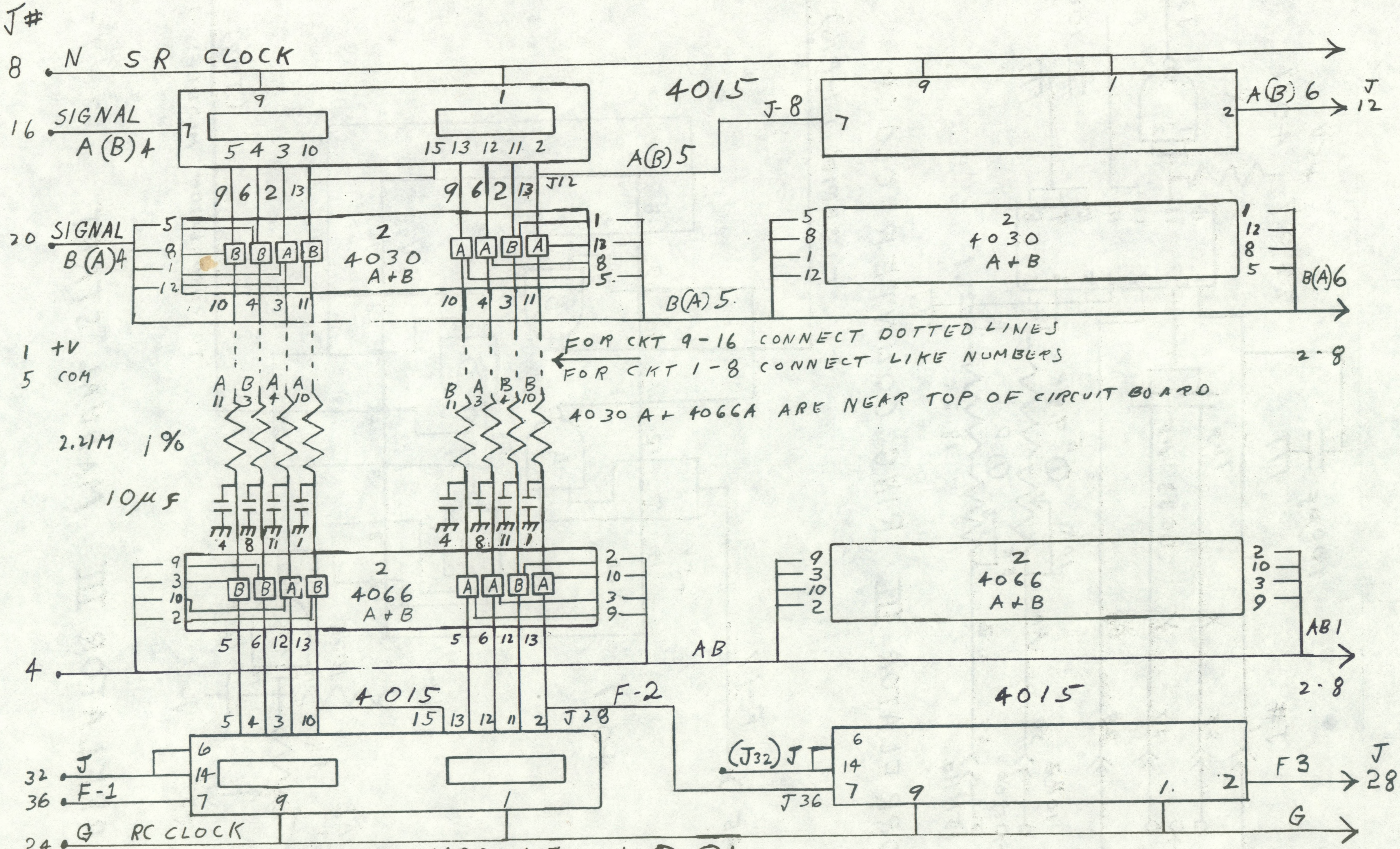


CORRELATOR III INPUT 5/4/81



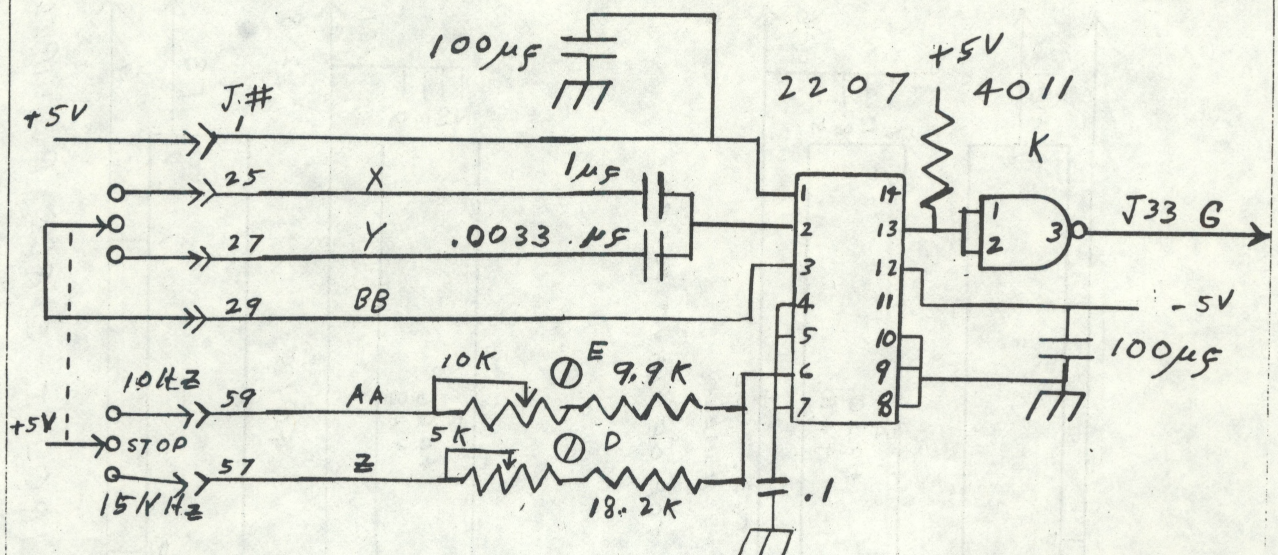
CORRELATOR III MULTIPLIER

5/4/81

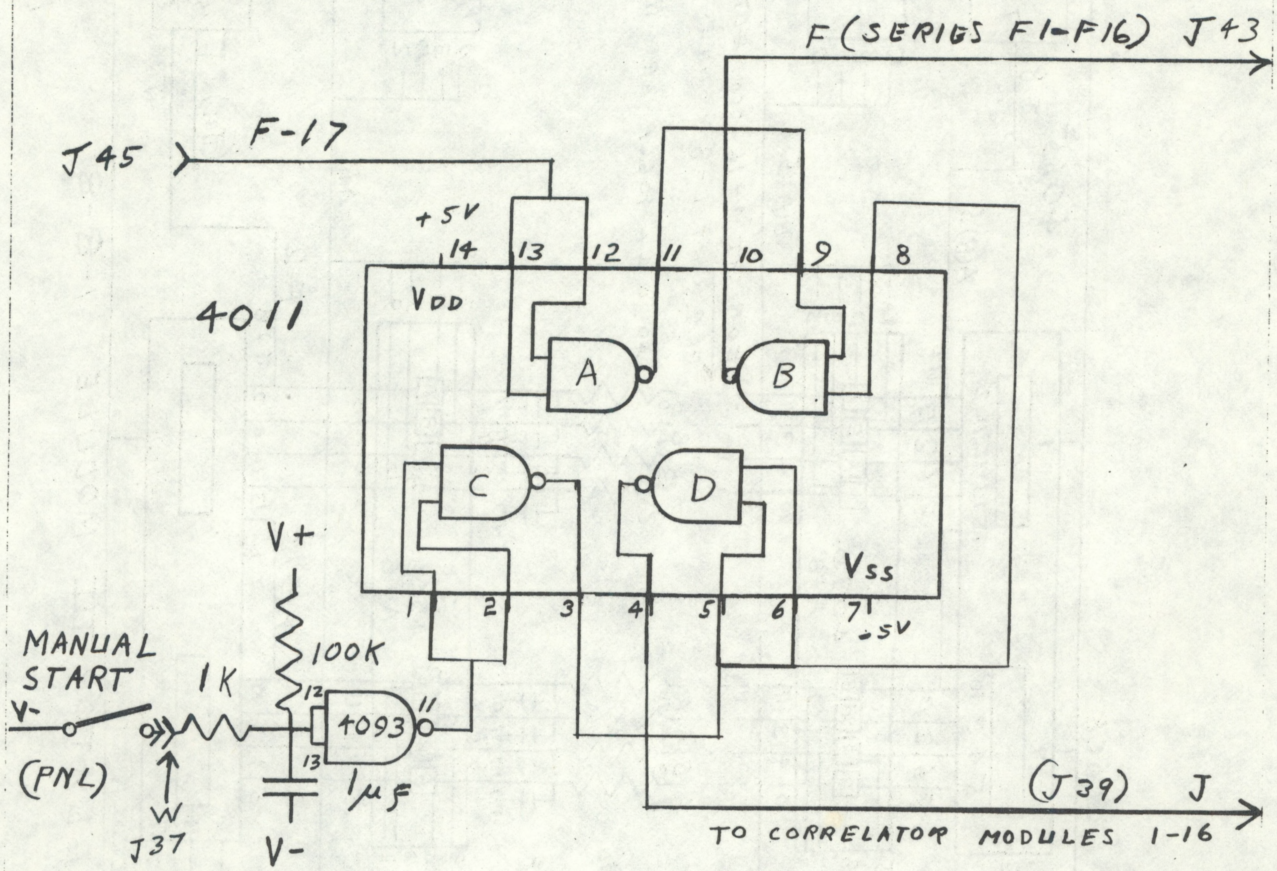


CORRELATOR III MODULE 1-8-81

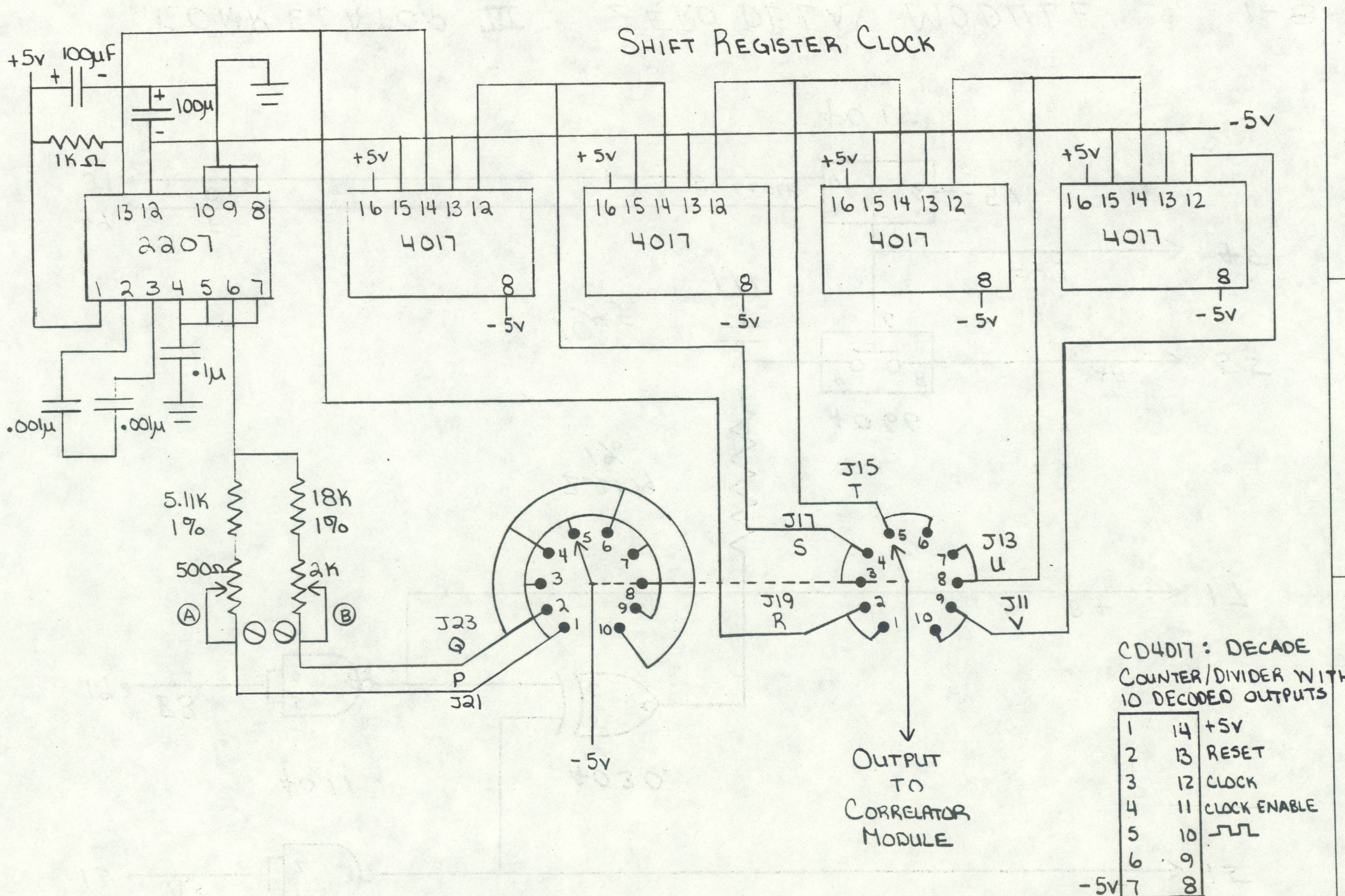
16 CIRCUIT CARDS REQUIRED



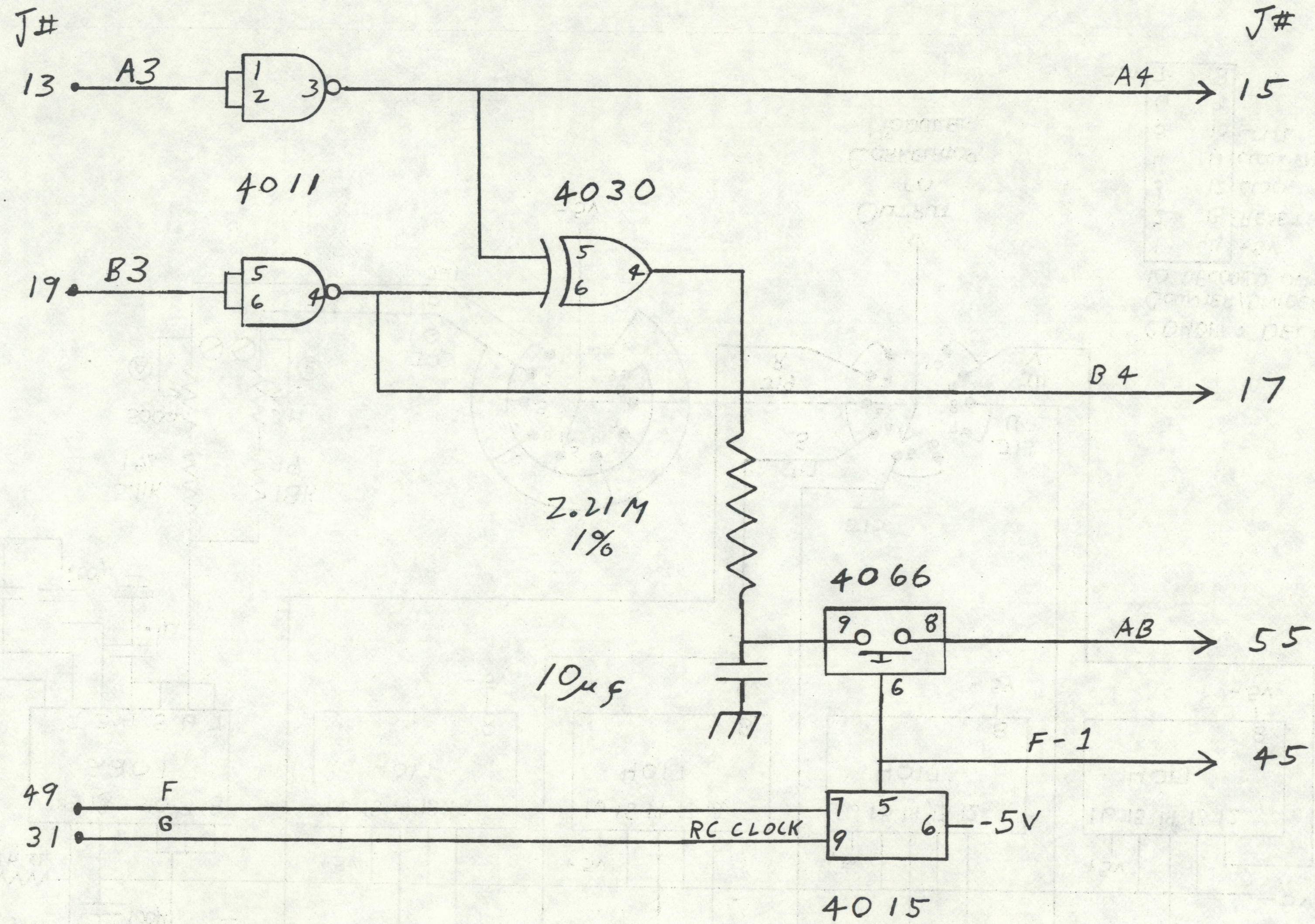
CORRELATOR III RING COUNTER CLOCK



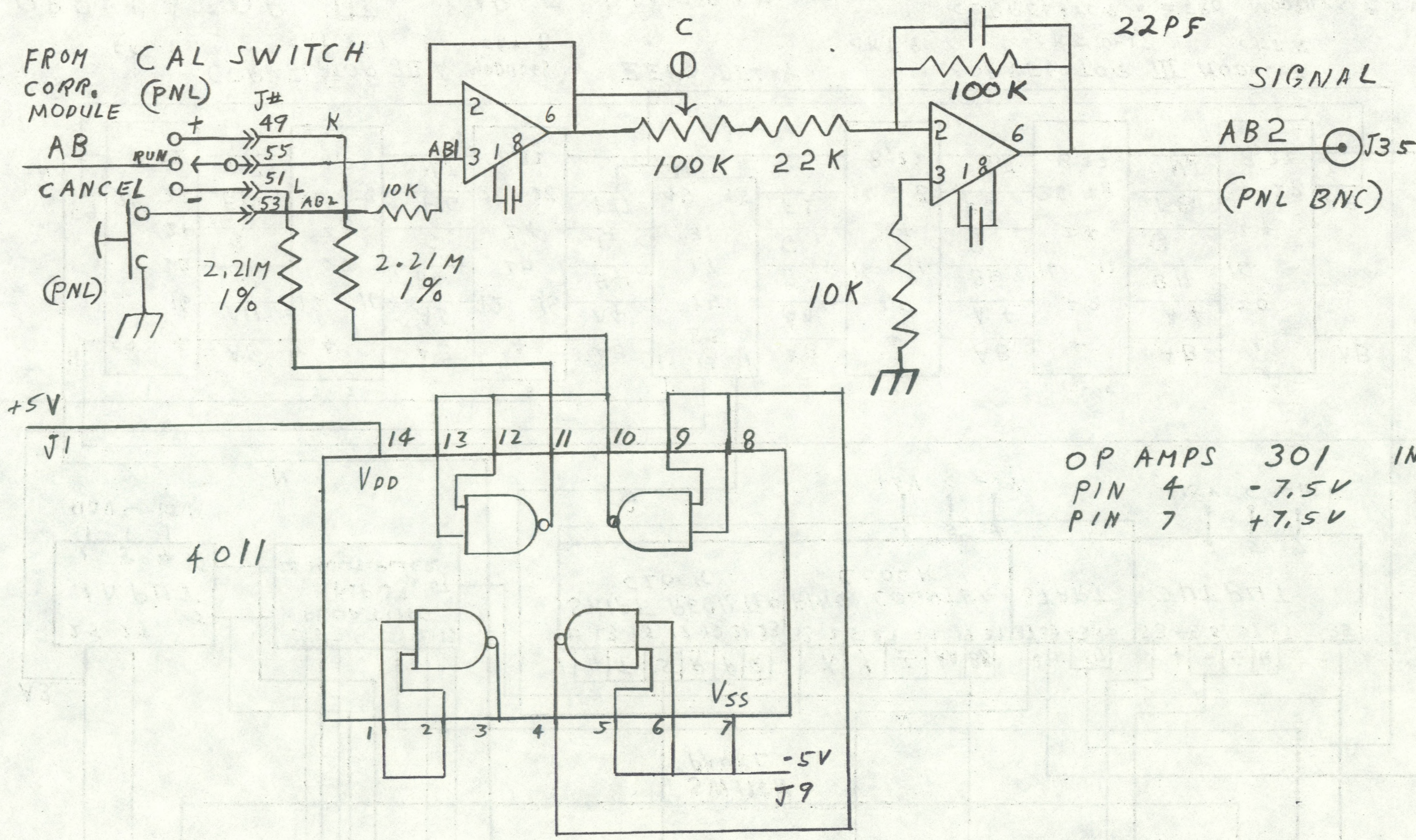
CORRELATOR III MANUAL START 3-9-81



SHIFT REGISTER CLOCK
+5v
100µF
100µ
1KΩ
2207
13 12 10 9 8
1 2 3 4 5 6 7
.1µ
.001µ
.001µ
4017
16 15 14 13 12
8
+5v
-5v
5.11K
1%
18K
1%
500Ω
2K
A
B
J23
Q
P
J21
-5v
J15
T
J17
S
J19
R
J13
U
J11
V
OUTPUT
TO
CORRELATOR
MODULE
CD4017 : DECADE
COUNTER/DIVIDER WITH
10 DECODED OUTPUTS
1 14 +5v
2 13 RESET
3 12 CLOCK
4 11 CLOCK ENABLE
5 10
6 9
-5v 7 8



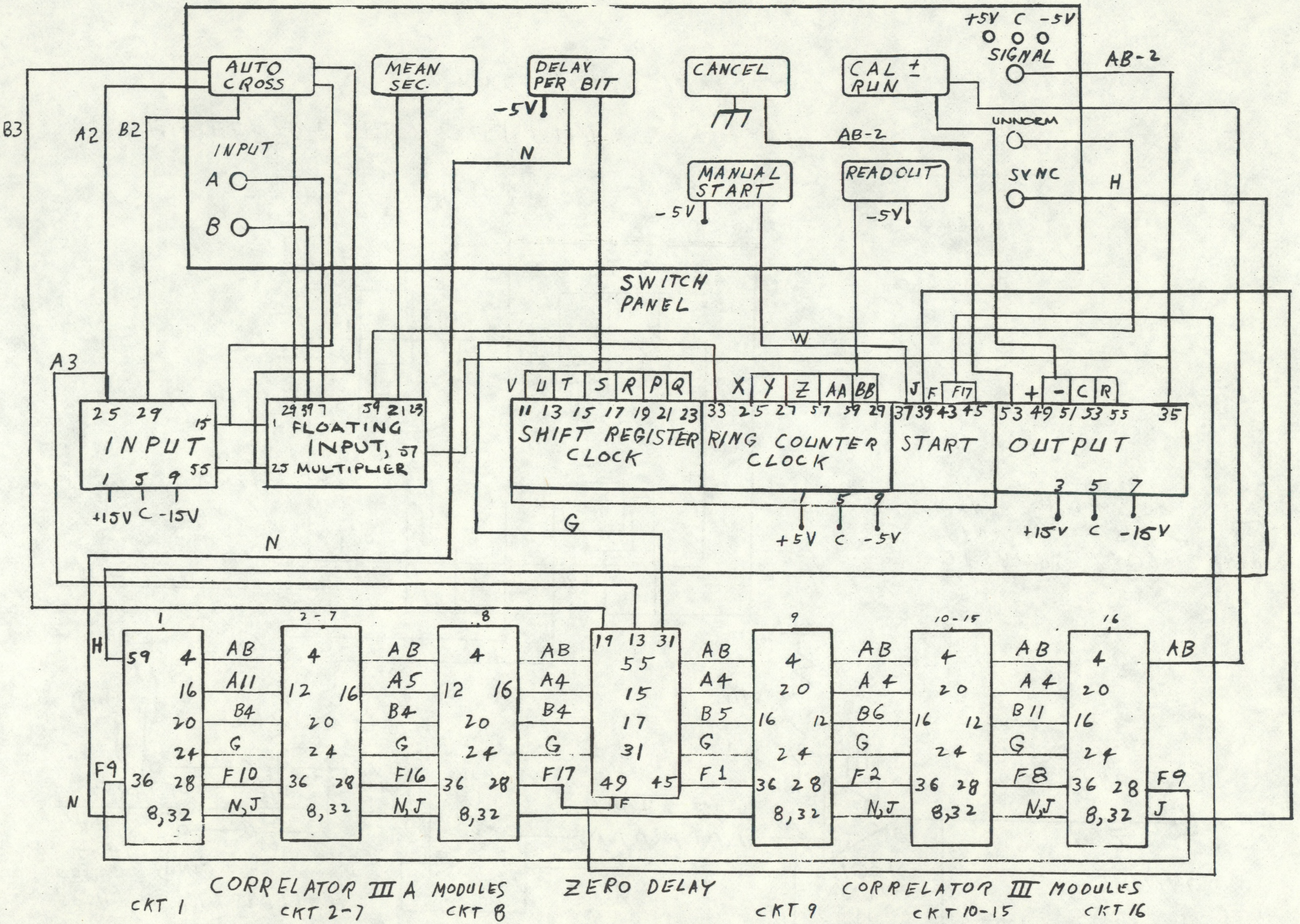
CORRELATOR III ZERO DELAY MODULE 1-8-81



OP AMPS 301 INPUT
PIN 4 -7.5V J7
PIN 7 +7.5V J3

CORRELATOR III OUTPUT 5-4-81

SYNC PULSE INVERSION



CORRELATOR III CABLE DIAGRAM

5-4-81

CORRELATOR + ZERO MODULES ± 5V
NUMBERS INSIDE BLOCKS ARE CONNECTOR NUMBERS