JOURNAL OF RESEARCH of the National Bureau of Standards—C. Engineering and Instrumentation
Vol. 67C, No. 1, January–March 1963

An Automatic Multichannel Correlator

Robert F. Brown, Jr.

(September 25, 1962)

Very early in the Infrasonic Research Program of the U.S. National Bureau of Standards, it became apparent that the only way to differentiate between local meteorological pressure variations and the infrasonic signals from distant sources was through the relative time of arrival of the pressure disturbance at pickups spaced several miles apart. The "Multichannel Correlator" is an analog computing instrument that was designed to detect these infrasonic signals.

At each pickup the pressure variations are converted to FM audio signals which are transmitted over leased telephone lines to the correlator. At the correlator these FM signals are demodulated and recorded on a one-fourth inch per minute multichannel magnetic tape. The recorded data frequency range is 0.02 to 1.0 cycles per second and the pressure range is 0.1 to 50 dynes per square centimeter. Ten-minute blocks of data are read from the tape and amplitude equalized to a constant root mean square value. A programed time-delay device produces the equivalent delays appropriate to a continuous horizontal azimuth search for velocities in the range of 280 to 400 meters per second. The correlator output is a continuous record of the average of the rectified sum of the delayed channel signals.

1. Multichannel Correlator

The multichannel correlator is an analog computing instrument which produces an output proportional to the average of the cross correlations between pairs of its inputs. It was built in an attempt to mechanize signal detection in a noisy environment. The inputs were from several microbarograph pickups located in the Washington area. The only available criterion for the presence of signal was waveform congruence, at an appropriate time delay, between data channels. Experience had shown that within one data channel there was no way to tell signal from noise. Both signals and background noises could show semiperiodic structure or random waveforms. They could occur anywhere in a wide frequency spectrum. They showed both rapid and slow rise and decay of energy levels. Thus a signal waveform was completely unpredictable and looked like the background noise on any one channel. Also, a type of noise associated with weather phenomena could maintain waveform congruence while passing through the area but would have a very low velocity, frequently local wind speed. Therefore, the time delay search range was restricted to include only velocities of 280 to 400 m/sec. The correlator has five operational sections; data storage, sampling readout, time delay, amplitude equilization, and detection.

Figure 1 is a photograph of the complete Multichannel Correlator. The equipment fills most of a three section rack. The left hand section holds the data recorder and readout. The center section holds the delay system and amplitude equalizers. The right hand section holds the detector, output recorder and auxiliary equipment.

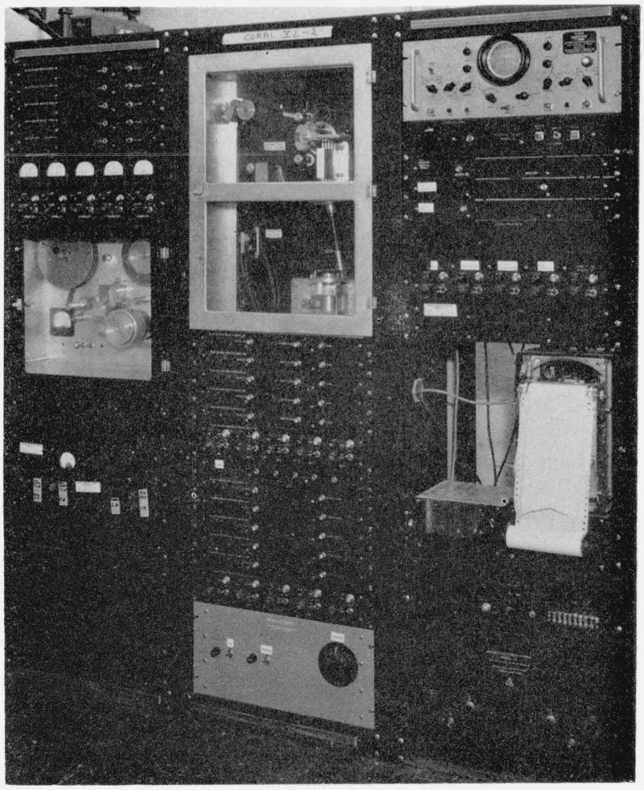


FIGURE 1. *Front view of the automatic multichannel correlator.*

2. Data Storage Section

The correlator has five data inputs and a time input. The data inputs are in the form of frequency-modulated audio carriers. The FM is demodulated and the resulting analog data are recorded on a magnetic tape. The five tracks of data are recorded in parallel on the tape. The range of frequencies of interest is from 0.02 c/s to 1.0 c/s. By using a tape speed of 0.25 in. per minute (about 0.004 ips), the recorded wavelengths on the tape lie between 0.2 in. and 0.004 in. This is the same range of wavelengths as is used in conventional recording. The recording is done using a-c biasing and the bias frequency used is about 80 c/s.

A sixth track on the magnetic tape is used for recording the time signal. The time signal consists of a 1.0 sec pulse recorded every 5 min. The hour pulse is identified by adding another 1.0 sec pulse displaced by 10 sec.

Figure 2 is a photograph of the data storage and sampling readout section. The storage tape travel is from the supply spool, across the writing table, record head, drive capstan, readout heads, and onto the takeup spool.

The tape moves so slowly that it can easily be written on with a brush or a felt ink marker. Thus comments such as local weather conditions, calibration data, or date and time marks can be written directly on the storage tape. The only precaution is that the tape motion across the recording head should not be disturbed. For these reasons the writing table was provided ahead of the recording head. The tape was mechanically isolated from writing disturbances by lateral guides and a friction pad.

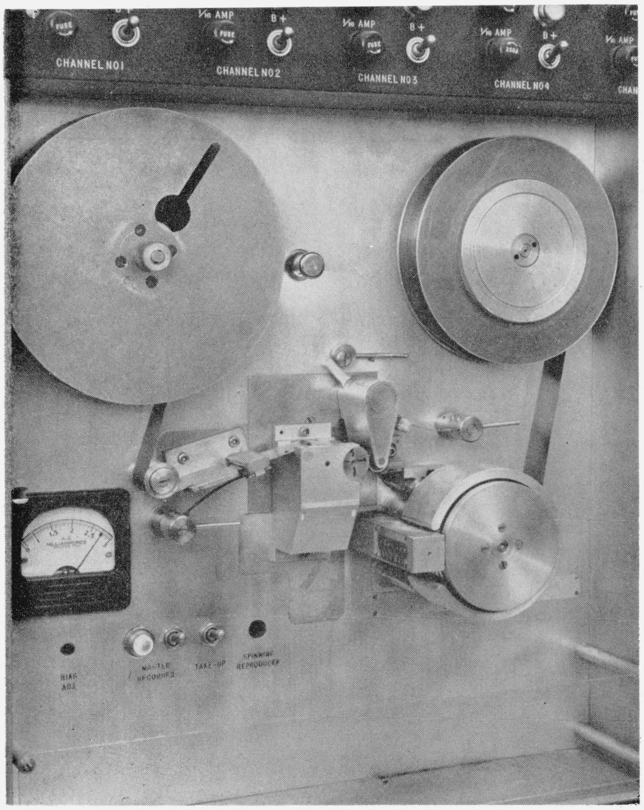


FIGURE 2. *Closeup view of the data storage section.*

The recording head stack is of conventional construction as are the drive capstan and pressure roller.

3. Sampling Readout

The sampling readout occurs at the cylinder around which the tape makes a 90° turn. In this cylinder are mounted four readout head blocks with their gaps accurately located 90° apart. The circumference of the cylinder is 10 in. In operation it revolves counter-clockwise at 3 rps. This makes the playback head-to-tape velocity 30 ips, which gives reasonable head output levels. Each head contacts the tape for $2\frac{1}{2}$ inches, which corresponds to 10 min. of recorded data. The outputs of the four heads sampling a recorded data channel are added in series. Thus, the sampled readout consists of a continuous sequence of data blocks, each containing the equivalent of 10 min. of original recorded signal.

The tape was recorded at 1/240 ips and is read at 30 ips. This high speed readout translates the input frequency spectrum upwards by a factor of 7200:1. Thus the original 0.02 c/s to 1.0 c/s becomes 144 c/s to 7200 c/s. Also, the time delays between channels, necessary to bring the signal waveforms into coincidence, are reduced by the same 7200:1 factor. For example consider two microbarographs placed 10 miles apart. They have about a 48 sec direct line transit delay. The equivalent relative delay needed after sampling is only 6.7 msec.

The data are read out at 12 samples per second. Each head is in contact with the tape for 2.5 in. so that any given datum point on the tape continues to be sampled for 10 min. The effect is to produce 7,200 samples of any given datum point. In the limit this would allow the trial of 7,200 different data computations.

A synchronizing pulse is produced during each sample. This pulse can be phased to correspond with any position along the 10 min sample.

4. Time Delay Section

By means of the tape loop and the map linkage, variable time delays are introduced into each channel corresponding to a systematic search for signal correlation at all azimuths and over a range of velocities appropriate to acoustic signals. Relative time delays are introduced into all five data channels but not the time channel. Figure 3 is a photograph of the time delay mechanism. The time delay is produced by using a tape loop with moveable playback heads. The loop is formed of 40 in. of 1 in. wide magnetic tape. It runs at a speed of 30 ips. The five data outputs from the storage readout are re-recorded in parallel on the tape loop. Each data track has an independently moveable readout head. The heads can be displaced a maximum of $\frac{3}{4}$ in. for a maximum change in time delay of 25 msec. This is the equivalent of 180 sec in the original data time scale.

The time delay is programed by a map and push-rod linkage. The program includes only those time delays appropriate to acoustic phase velocities across the microbarograph array. Plane wavefronts are assumed and no corrections are made for local topography. This program is achieved by the following mechanism. A scale map of the microbarograph sites is mounted in a pair of gimbals with the plane of the map at the gimbal axis. The push-rods operate from the map positions of the sites, and are displaced along their axes when the map is tilted. The push-rods in turn vary the position of the playback heads along the tape loop. In the neutral position, map plane perpendicular to push-rod axes, all playback heads are in line and there is no relative time delay. This corresponds to an infinite horizontal velocity or to a signal which comes straight down form overhead. As the map is tilted away from neutral some heads are advanced and others retarded from the neutral position. This corresponds to searching in the direction of greatest retardation for the presence of signals having a velocity which is a function of the amount of retardation.

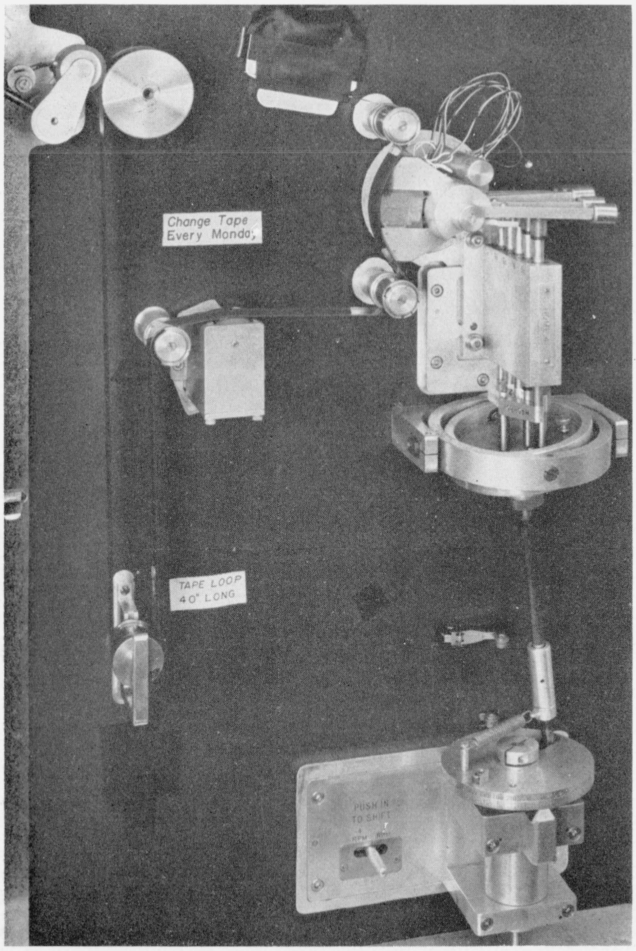


Figure 3. *Closeup view of the time delay mechanism.*

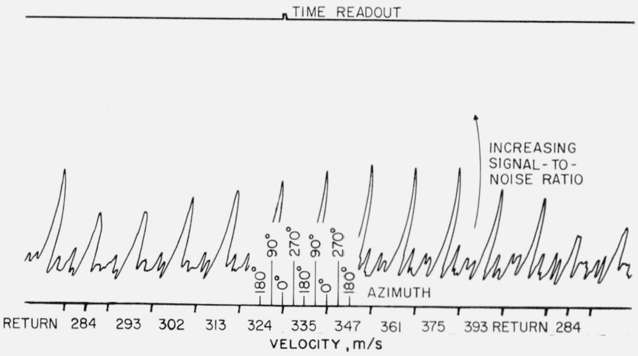


Figure 4. *Sample output record for the correlator.*

Since the map is mounted in gimbals, it can be tilted toward any azimuth; or, at a given tilt, it can be rotated through a complete circle or azimuth sweep. The time delay program rotates the map tilt continuously, taking 15 sec for a complete azimuth sweep. At the same time as it is rotating, the map tilt angle is slowly changing from an angle corresponding to a velocity of 400 m/sec to an angle corresponding to a velocity of 280 m/sec. The total change in tilt angle takes 10 azimuth sweeps or 2.5 min. An eleventh azimuth sweep is used to return the velocity program to its starting point. Figure 4 shows a sample output record for one complete azimuth-velocity search pattern. At the search rate used, any signal in the original recording will yield an output for at least three successive azimuth-velocity searches.

Each azimuth sweep takes 15 sec. At 12 data samples per second there are 180 data samples per azimuth sweep (360°). Ignoring all other factors this gives an azimuth resolution of 2°. In automatic search this resolution is seldom achieved. But the automatic search can be stopped and the mechanism moved by hand to any desired point in the program.

5. Amplitude Equalization

The original input data amplitude range covers over 60 db. Under "quiet" conditions the background may fall as low as 0.1 to 0.2 dyne cm^{-2}. Under "noisy" conditions the background can exceed several hundred dyne cm^{-2}. Since this is recorded as direct analog data on the magnetic tape, the tape's own dynamic range becomes the limiting factor. This has been set at 0.2 to 50 dyne cm^{-2}. To cover this wide range of data levels, automatic amplitude equalization or automatic gain controls were used.

The amplitude of each channel is independently and automatically adjusted to the same rms voltage. This is done by two stages of thermistor controlled feedback amplifiers. One stage is between the sampling readout and the tape loop delay. This stage can reduce a 60 db input amplitude range to a 20 db range. This eases the dynamic range requirement of the delay system. The other stage comes after the delay system, reducing the 20 db delay output range to 0.5 db. As a result all input levels, from the equipment self noise level to tape saturation come out within 0.5 db of the same level. The time constant of the equalizer and the averaging time of the detector are both approximately 10 min, referred to the time scale of the original data.

6. Signal Detection

In an ideal situation the output would be zero at all search points except for the one representative of the signal. This would require that the noise present be completely incoherent at all times and the signal be of such a character as to be incoherent at all search points except that point of full coherence. This ideal situation cannot exist in a practical device since it would require as one prerequisite an infinite sample length. Since the sample length is finite and there are a limited number of inputs, there is also a real probability of correlation in the noise. The output of the correlator is useful, in spite of the nonideal operation, since noise correlations tend to occur at random, while the azimuth is searched. It is this repetitive output for signal that allows it to be identified in the presence of noise.

For the following analysis it is assumed that the map linkage is stopped at the point which introduces the ideal relative time displacements for signal correlation.

Let the correlator have n inputs I_i, each of which is the sum of signal S_i and noise N_i. These inputs are operated on by compressor circuits which equalize all inputs to the same rms level. Therefore the outputs of the compressors are $E_i=C[I_i/(\overline{I_i^2})^{1/2}]$. The channels are added in a resistive adder whose output is $E_A=[1/(n+2)]\Sigma E_i$, this adder being chosen for calibration convenience. The adder output may be detected by a square law rectifier, averaged, and displayed on a graphic recorder. The recorder deflection D is therefore another averaged quantity $D=\overline{E_A^2}$. Combining these several operations gives as a result

$$D=[C/(n+2)]^2\left[n+\sum_{i\neq j}\overline{(I_iI_j)}/(\overline{I_i^2})^{1/2}(\overline{I_j^2})^{1/2}\right].$$

The Pearson correlation coefficient r_{ij} is defined as

$$r_{ij}=\overline{I_iI_j}/(\overline{I_i^2})^{1/2}(\overline{I_j^2})^{1/2},$$

so that the recorder deflection can be written as

$$D=[C/(n+2)]^2\left(n+\sum_{i\neq j}r_{ij}\right).$$

An average correlation coefficient $\bar{r}$ can be defined by

$$\bar{r}=\left[\sum_{i\neq j}r_{ij}\right]/[n(n-1)]$$

resulting in $D=[C/(n+2)]^2[n+n(n-1)\bar{r}]$.

To establish a scale for the output recorder it is necessary to note that removal of all inputs but one results in a constant output of $D=C^2/9$. With $\bar{r}=0$, $D=C^2/[(n+2)^2/n]$; or for $n=4$, $D=C^2/9$ and for $n=5$, $D=C^2/9.8$. Thus, the one input case gives the same deflection as zero correlation for four inputs and is a close approximation for five inputs. The deflection for $\bar{r}=1$ is established by injecting the same signal into all inputs simultaneously. For operational use the constant term was suppressed so that the recorder scale would be direct reading in $\bar{r}$.

Returning to r_{ij} and substituting S_i+N_i for I_i gives

$$r_{ij}=\overline{(S_i+N_i)}\,\overline{(S_j+N_j)}/[\overline{(S_i+N_i)^2}]^{1/2}[\overline{(S_j+N_j)^2}]^{1/2}$$

or, assuming that $\overline{S_iN_i}=\overline{S_iN_j}=\overline{N_iN_j}=0$,

$$r_{ij}=\overline{S_iS_j}/[(\overline{S_i^2}+\overline{N_i^2})(\overline{S_j^2}+\overline{N_j^2})]^{1/2}.$$

The signal-to-noise ratio R_i can be defined as $R_i^2=\overline{S_i^2}/\overline{N_i^2}$ and, if it is assumed that $S_i=S_j$, then $r_{ij}=R_iR_j/[(R_i^2+1)(R_j^2+1)]^{1/2}$. The correlator output is now seen to be a function only of the number of input channels and the signal-to-noise ratio at each input.

If all the input noise levels are approximately the same, then it is convenient to think of an average input signal-to-noise ratio R. The operating recorder output then can be taken as $D\propto R^2/(1+R^2)$ and it is this scale that is used in estimating input signal-to-noise ratio.

The original detector was an approximately square-law device. Although it was an excellent detector, its operating point and range were variable enough to be a maintenance problem. A simple full-wave rectifier has since been used with excellent results. Comparison tests have shown it to be approximately equivalent to the square-law device for detection. Both have detected signals at a signal-to-noise ratio of 1/4, $\bar{r}=1/17$. The linear detector has the disadvantage that the output indication is not calibratable in terms of signal-to-noise ratio as is the square-law detector.

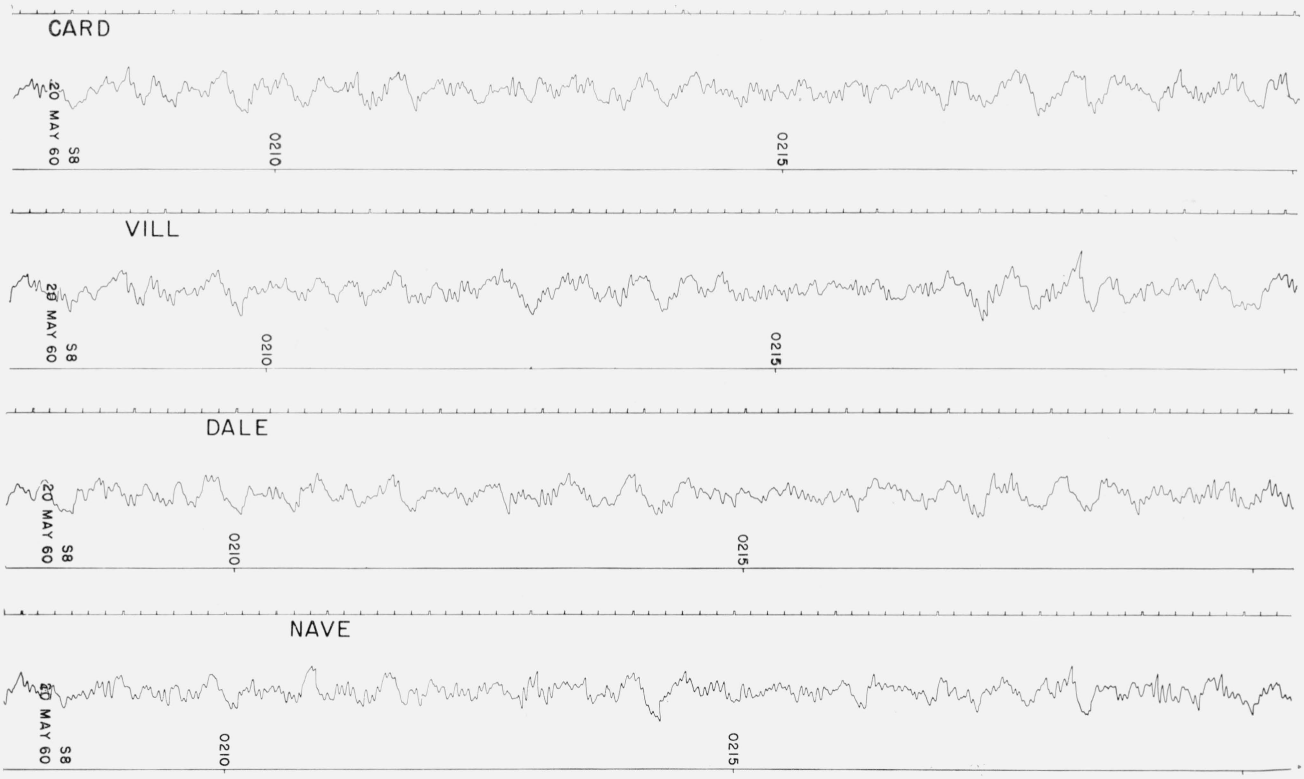
7. Auxiliary Devices

The synchronizing pulse produced with each data sample has been used for three purposes. Originally it was used to generate a blanking pulse to eliminate the overlap region between sample ends. The data samples are taken continuously with the beginning of a sample immediately following the end of the preceeding sample. There is no gap or blank between samples. Thus, when the delay playback heads are displaced to give a relative delay, there is a short region when the leading head is reading the beginning of a sample and the trailing head is reading the end of a sample. This region of nonreal inputs was accordingly blanked from the detector's memory. Subsequent tests showed that the contribution from this region to the output was so small as to be unnoticeable; therefore, the blanking feature was eliminated.

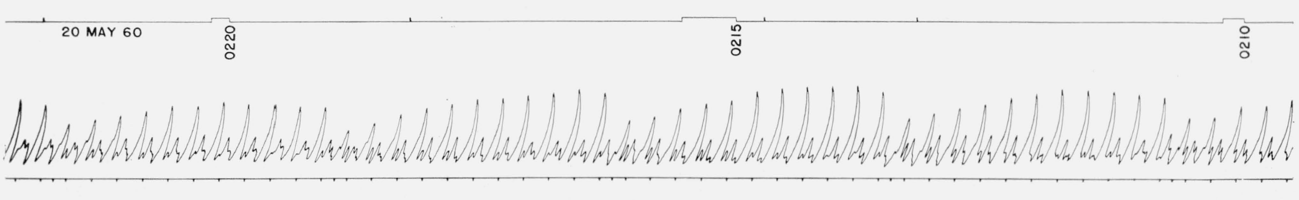
The second use of the synchronizing pulse is in reading out the time pips. The sync-pulse generates a gate about 0.5 msec long. The time pulse reads out as a 0.14 msec pulse. As the storage tape moves through the sampler, the position of the time pulse will pass through the position of the gate. A coincidence circuit is used to compare the position of the time pulse with the gate. The two will show coincidence for about 36 samples or 3 sec. The output of the coincidence circuit throws a time marking pen on the output recorder. Thus, the recorder time track has a 3 sec mark every 5 min. These marks identify the data interval being processed.

The third use of the synchronizing pulse is a recent development. Using it to trigger a gated detector connected to the sampler output allows the creation of a graphic anolog replica of the input data in real time. Divorced from the correlator it forms a gated-readout device for low speed magnetic tape recordings. It is not the same as a flux sensitive readout but can perform essentially the same function.

Another use of the gated readout which has been suggested is in signal enhancement. Once a signal has been detected by the correlator the search mechanism can be stopped and set to the optimum azimuth and velocity. The storage tape can be backed up and rerun through the sampler. Now, if the gated readout is connected to the adder output, it will read out a graphic replica of the "best correlating fit." This improves the signal-to-ratio by $(n)^{1/2}$ over the original data channels. For our 5 channel system this amounts to 7 db. This is not a large increase but, having once identified the presence of a signal, it may allow a better study of the signal's character.



N6 Graphic Records



Multi-Channel Correlator

FIGURE 5. *Graphic records and correlator output for a tornado signal.*

As an example of signal detection by the correlator, figure 5 shows the graphic recordings and correlator output for the May 20, 1960 acoustic signal reported in "Intrasonic Disturbance in the Atmosphere," NBS Technical News Bulletin, December 1960.

(Paper 67C1–117)

The correlator exists as a functional device primarily due to the skill and efforts of the following persons. The basic concepts used in the device were originated by Daniel P. Johnson and the late Peter Chrzanowski. The device was designed and proven out chiefly by Harry Matheson, Irving Levine, and Henry Schmidt.