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ACOUSTOELECTRIC DEVICES: A NEW TECHNOLOGY FOR WAVEFORM-AGILE RA--ETC(U)  
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6 ACOUSTOELECTRIC DEVICES: A NEW TECHNOLOGY FOR WAVEFORM-AGILE RADAR

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ABSTRACT

✓ This paper proposes a waveform-agile radar, analyzes the signal-processing required, and describes the state of the art of two new acoustoelectric devices needed for the agile radar: the memory correlator, which provides electronically programmable matched filtering of individual pulses, and the coherent integrator, which is being developed to provide electronically programmable Doppler processing. The electronic programmability of these compact wideband analog devices gives them unique functional capabilities which may allow future tactical systems to achieve electronic counter measure resistance and low probability of intercept by facilitating the use of continually changing wideband waveforms.

\*This work was sponsored by the Department of the Army.

Presented at the  
AIAA Strategic/Tactical Missile System and Space Sciences Meeting  
Session on Advanced Signal/Data Processor Architecture

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# ACOUSTOELECTRIC DEVICES: A NEW TECHNOLOGY FOR WAVEFORM-AGILE RADAR\*

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## INTRODUCTION

There is a well-recognized need to provide in modern tactical radars a capability against increasingly sophisticated jamming and spoofing threats. This need for electronic countermeasure (ECM) resistance is frequently coupled with a requirement that the tactical radar have the lowest possible probability of intercept (LPI) to avoid detection and negate such threats as antiradiation missiles. A wideband radar with a high degree of waveform agility could potentially satisfy all of these critical requirements. The unique ingredient in such a system would be the use of a number of selectable wideband waveforms to provide a means by which successive radar pulses would be distinguished. Providing signal processing for waveform agility in tactical systems is doubly difficult, because such systems are by nature constrained to use components which are compact, low power, and potentially low cost. Optimum implementation of the sophisticated signal processing demanded by the ECM and LPI requirements discussed above will require integration of new technologies into tactical systems.

This paper proposes a waveform-agile radar, analyzes the signal-processing required, and describes the state of the art of two new acoustoelectric devices needed for the agile radar: the memory correlator,<sup>1</sup> which provides electronically programmable matched filtering of individual pulses and the coherent integrator,<sup>2,3</sup> which is being developed to provide electronically programmable Doppler processing.

## WAVEFORM-AGILE RADAR

The proposed waveform-agile radar is shown schematically in Fig. 1. On each pulse repetition interval, a selected waveform is transmitted, and a small amount of transmitter energy is intentionally coupled into the receiver chain where it is translated to an intermediate frequency by a local oscillator. This translated waveform is stored in the memory correlator as a reference function against which to correlate the subsequent return signal. In this manner the memory correlator automatically accommodates pulse-to-pulse changes in the waveform modulation. In order to achieve Doppler processing, the succession of compressed pulses from the output of the memory correlator is fed into a parallel bank of N coherent integrators, each of which provides one programmable Doppler channel for search and tracking over many range cells. Control of the local-oscillator phase and write-pulse timing selects the desired Doppler hypothesis for each channel. This results in the coherent addition of the compressed subpulses from a target with a velocity which is matched to that channel. When the separate single-pulse autocorrelation outputs of the memory correlator have been overlaid within the selected range

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swath, the range-and-Doppler outputs are then read out in parallel. In the search mode, a large number of coarse Doppler channels could be processed sequentially in groups of  $N$ , while in track just one group of 3 or 4 could be actively programmed to provide well-resolved velocity information. Additional benefits of such a system should be noted. The memory correlator can eliminate the deleterious effects of unintentional variations in waveform parameters (e.g., time and frequency jitter) encountered with tactical millimeter wave sources such as magnetrons and impact-avalanche-and-transit-time (IMPATT) diodes. In fact, because the memory correlator automatically compensates for all phase and amplitude distortions in the transmitted waveform, the device permits the use of relatively inexpensive low-accuracy circuit components. Also the use of changing waveforms solves the familiar range-ambiguity problem.

On the  $n^{\text{th}}$  pulse repetition interval (PRI), the transmitted waveform  $S_n(t)$  of the proposed agile radar has the form:

$$S_n(t) = \psi_n(t - nT - t_n) \exp \{j2\pi(f_c + f_n)(t - nT)\}, \quad (1)$$

where  $f_c$  is the nominal center frequency, the time  $t_n$  and frequency  $f_n$  jitters have been allowed for explicitly, and a random start phase as well as the modulation are contained in  $\psi_n(t)$ .

As the waveform is transmitted, a small amount of the energy is intentionally coupled into the receive chain and translated to an intermediate frequency (IF) by a local oscillator at frequency  $f_L$ . This signal is entered into a memory correlator, a store impulse is applied to the device at a time  $nT + t_i$ , and the resulting stored reference pattern is:

$$\psi_n^* \left( t_i - t_n - \frac{z}{v} \right) \exp \left\{ -j2\pi(f_c + f_n) \left( t_i - \frac{z}{v} \right) - f_L \left( nT + t_i - \frac{z}{v} \right) \right\} \quad (2)$$

where  $z$  and  $v$  are the propagation distance and velocity, respectively, within the correlator structure.

The return signal from a target with round-trip delay  $T_r$  is given by:

$$\psi_n(t - nT - T_r) \exp \{j2\pi(f_c + f_n)(t - nT - T_r)\}. \quad (3)$$

This signal is translated to IF and entered into the memory correlator. The output signal is given by a spatial integral over the length  $L$  of the structure:

$$\int_0^{\frac{L}{v}} \psi_n \left( t - \frac{z}{v} - nT - T_r \right) \psi_n^* \left( t_i - t_n - \frac{z}{v} \right) \exp \{j2\pi(f_c + f_n) \left( t - \frac{z}{v} - nT - T_r \right) - f_L \left( t - \frac{z}{v} \right) - (f_c + f_n) \left( t_i - \frac{z}{v} \right) - f_L \left( nT + t_i - \frac{z}{v} \right)\} d \left( \frac{z}{v} \right)$$

$$= R_{nn}(t - nT - T_r - t_i) \exp \{-j2\pi f_L (t - nT - t_i)\} \quad (4)$$

where  $R_{nn}(t)$  is the autocorrelation function of  $\psi_n(t)$ .

Notice that the peak of the correlation occurs at time equal to  $nT + t_i + T_r$ , as expected for a deterministic pulse, and that the phase shift at that point represents the phase rotation of the LO during the round-trip pulse propagation time, as desired for moving target indicator (MTI) operation. Thus, on a single pulse, the memory-correlator has removed the changing or random features of the waveform.

We now consider the coherent processing of the N-pulse return from a moving target. In the correct Doppler channel, the phase becomes a constant which will be ignored. The waveform resulting from the overlay of the subpulses is the main lobe of the autocorrelation function of the burst waveform.

$$R_{ML}(\tau) = \sum_{n=1}^N R_{nn}(\tau) \quad (5)$$

The memory correlator has allowed elimination of the effects of time jitter, random start phase, and waveform changes. The coherent integrators provide the coherent overlay of the compressed subpulses for Doppler processing.

The principles of operation and experimental results for both the memory correlator and coherent integrator are summarized below. An essential ingredient in these devices is the interaction of electrons in a high-density Schottky-diode array with the evanescent RF electric fields accompanying surface acoustic waves (SAWs) propagating on a nearby piezoelectric delay line.

#### MEMORY CORRELATOR

A programmable acoustoelectric matched filter was first proposed by Stern and Williamson<sup>4</sup> of MIT Lincoln Laboratory, and subsequently the feasibility of such a device was demonstrated with a diode acoustoelectric memory by Ingebrigtsen while at Lincoln Laboratory. The device used in this feasibility demonstration was a gap-coupled structure consisting of a matrix of free-standing Schottky-barrier diodes on a silicon strip in close proximity (~300 nm) to the surface of a  $\text{LiNbO}_3$  delay line. The two-dimensional array of Schottky diodes provides charge-storage sites which have subnanosecond response times in forward bias and multi-millisecond storage times in reverse bias.

Consider the diode array to be at zero bias. As depicted schematically in Fig. 2, a reference waveform  $S_n(t)$  of eq. (1) as shifted to IF launched into the delay line sets up RF electric fields in the air gap. An impulse is applied for a fraction of an RF cycle between the ohmic contact on the back of the silicon strip and the metal contact on the bottom of the  $\text{LiNbO}_3$ , driving the Schottky array into a low-impedance state. Each diode charges in response to the superposition of the strong, uniform impulse and the local RF fields. When the impulse ends, the charge on the diodes serves to self-bias the array in the reverse direction.

In this way, a replica of the phase and amplitude of the reference waveform (eq. (2)) is stored in the form of a depth modulation of the depletion layer behind the diodes. The maximum storage time is determined by the diode leakage current. During this storage time, a return signal (eg. (3)) may be launched into the delay line, wherein the piezoelectric fields of the second signal will interact in the silicon with the electric fields of the spatially varying stored charge pattern of the reference signal. The resulting acoustoelectric voltage induced across the structure is the correlation (eg. 4) between the return signal and the reference wave.

The memory correlator is shown partially assembled in Fig. 3. This device has demonstrated a memory time in excess of 10 ms and can process wideband waveforms of up to 60-MHz bandwidth and 5- $\mu$ s duration. The correlation output observed experimentally for an unweighted linear-FM waveform of 40-MHz bandwidth and 2- $\mu$ s duration is shown in Fig. 4. Performance characteristics of the memory correlator have been reported elsewhere<sup>1</sup>, but only as a matched filter and not in the context of a programmable burst-waveform processor in an agile radar.

A summary of these performance characteristics is given in Table I.

TABLE I Memory Correlator Performance

|                                                            |           |
|------------------------------------------------------------|-----------|
| Center Frequency                                           | 150 MHz   |
| Bandwidth                                                  | 60 MHz    |
| Waveform Duration Time                                     | 5 $\mu$ s |
| Memory Time                                                | >10 ms    |
| Dynamic Range                                              | 50 dB     |
| (above $kTB \times$ noise figure<br>with 23 dBm reference) |           |
| Spurious Levels                                            |           |
| Near-In                                                    | <-32 dB   |
| RMS                                                        | <-35 dB   |

#### COHERENT INTEGRATOR

The coherent integrator is a newer device than the memory correlator, and although it is based on the same gap-coupled acoustoelectric technology it is not yet at as advanced a state of development as the memory correlator. This device is shown schematically in Fig. 5 and partially assembled in Fig. 6.

The structure physically resembles the memory correlator. It consists of a  $\text{LiNbO}_3$  SAW delay line with four transducers (signal and write centered at frequency  $\omega$ , read and bias at frequency  $2\omega$ ) coupled to a high density array of PtSi Schottky diodes on a 30  $\Omega$ -cm n-type strip of silicon. The silicon strip is mounted 350 nm from the delay line surface, close enough to interact with the evanescent RF fields produced by surface waves on the piezoelectric crystal. Nonlinearities in the silicon provide a distributed mixer, with each point on the silicon generating the local product of counterpropagating signal and write waves centered at temporal frequency  $\omega$  and spatial frequency  $k$ . Each diode charges up in response to the local quasistatic component of this product voltage and the

correlation function evolves as a depth modulation of the depletion layer with spatial frequency  $2k$ . Thus a succession of subpulse correlations from the memory correlator, representing target returns, is entered into a  $\text{LiNbO}_3$  delay line. These are coherently overlaid in the Schottky-diode array of the device by means of the counterpropagating train of acoustic storage pulses appropriately timed for the target velocity. After all subpulses are overlaid, the stored charge pattern ( $R_{ML}(\tau)$  of eg. (5)) is read out with an acoustic read waveform, using the same mechanism as in the memory correlator. That is, the electric fields from a subsequent read wave centered at frequency  $2\omega$ , when launched in the delay line, mix in the silicon with the electric fields of the stored charge, and the result is an RF output at frequency  $2\omega$  between the two contact planes. This output is in fact the cross-correlation between the read wave and the stored correlation pattern, and for the special case in which the read wave is an impulse, the output of the coherent integrator provides the desired range-and-Doppler information.

Note that in order to achieve the desired coherent addition of subpulse energy the integration process, which takes place as charge addition in the diode array, must be linear. Such linear integration is achieved by precharging the diode array into uniform reverse bias by means of an RF pulse entered into the bias port. This self-reverse bias stays essentially fixed through the overlay and read modes, and ensures that the propagation and charging conditions are constant for all subpulses of the burst waveform. In the absence of a precharge the first segment of the input waveform would see a smaller depletion depth, which would result in a slowing of the wave and accompanying dephasing relative to later subpulses. An appropriate uniform reverse bias preserves the linearity of the charging characteristic for at least 10 ms. Because of the long storage time of the array, green LEDs were used to erase<sup>6</sup> the memory of both the memory correlator and coherent integrator at the end of the cycle. This allows a fast recycle time without cycle-to-cycle effects.

The device is currently designed to accommodate up to 20-MHz waveforms, with integration times selectable from 0.1-10 ms, and to provide up to 340 range cells over a 17- $\mu\text{s}$  range window in one Doppler channel. Results of coherent summation of gated-CW and 10-MHz phase-shift-keyed bursts in Fig. 7 show the desired linear charging behavior over an integration time of 10 ms.

In a demonstration more like the proposed radar application, Doppler-shifted input waveforms consisting of 2 to 16 3- $\mu\text{s}$ -long gated-CW subpulses having 100- $\mu\text{s}$  intervals were employed. The ambiguity surface of the resultant output is shown in Fig. 8 for 16 subpulses, and is consistent with the number of input subpulses and the subpulse-to-subpulse interval. As expected theoretically, the near-in sidelobe level approaches -13 dB as the number of subpulses is made large. An array of such devices can provide both Doppler and range information in a number of parallel channels, with the Doppler velocity, Doppler resolution, and range swath under programmable control.

A summary of the performance characteristics of this developmental device is given in Table II.

TABLE 11 Coherent Integrator Performance

|                         |            |
|-------------------------|------------|
| Center Frequency        |            |
| Input                   | 100 MHz    |
| Output                  | 200 MHz    |
| Bandwidth               |            |
| Input                   | 20 MHz     |
| Output                  | 40 MHz     |
| Range Window            | 17 $\mu$ s |
| Integration Time        | >10 ms     |
| Dynamic Range           | 25 dB      |
| (set by spurious level) |            |

#### FUTURE DEVELOPMENT

To date the coherent integrator has not been integrated with the memory correlator in a subsystem. The task also remains to fully characterize both devices with pseudorandom waveforms of wide instantaneous bandwidth. Wide spreading of the transmitted pulse spectra is required to achieve good LPI system performance, and the development of the acoustoelectric devices will continue toward that goal.

This paper has focused on two specific devices, the memory correlator and coherent integrator, as examples of how programmable signal processing elements can provide a waveform-agile radar with 30 dB or more of processing gain. Additional devices which were not described here are also under development. These include an integrated surface-wave/charge-coupled structure (SAW/CCD)<sup>7</sup> and a hybrid convolver/binary<sup>8</sup> subsystem. These devices could be utilized in an architecture similar to that described here. It is anticipated that appropriate configurations of the acoustoelectric devices will allow extension of the signal processing gain achievable in radar systems to 50-60 dB.

#### SUMMARY

In summary, waveform-agile radar is appropriate for many tactical applications. The powerful signal processing capabilities of acoustoelectric devices have been explored, with emphasis given to the possibility of exploiting memory correlators and coherent integrators in an agile radar system. Operating principles were presented, performance characteristics of the memory correlator were reviewed, and new data on the coherent integrator were given. The electronic programmability of these compact wideband analog devices gives them unique functional capabilities which may allow future tactical systems to achieve ECM resistance and LPI by facilitating the use of continually changing wideband waveforms.

#### ACKNOWLEDGEMENTS

The authors are indebted to S. A. Reible and I. Yao, for their most recent experimental results on the coherent integrator.

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8. R. P. Baker and J. H. Cafarella, "Hybrid Convolver/Binary Signal Processor Achieves High Processing Gain", unpublished.

### FIGURE CAPTIONS

- Fig. 1 Signal processor for waveform-agile radar.
- Fig. 2 Gap-coupled memory correlator structure.
- Fig. 3 Partially assembled memory correlator.
- Fig. 4 Typical matched filter response of memory correlator.
- Fig. 5 Gap-coupled coherent integrator structure.
- Fig. 6 Partially assembled coherent integrator.
- Fig. 7 Outputs of coherent integrator for burst waveforms, both gated-CW and 10-MHz phase-shift keyed.
- Fig. 8 Output of coherent integrator as a function of Doppler-frequency offset for 16 3- $\mu$ s-CW subpulses with 100- $\mu$ s interpulse period.

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# WAVEFORM-AGILE RADAR

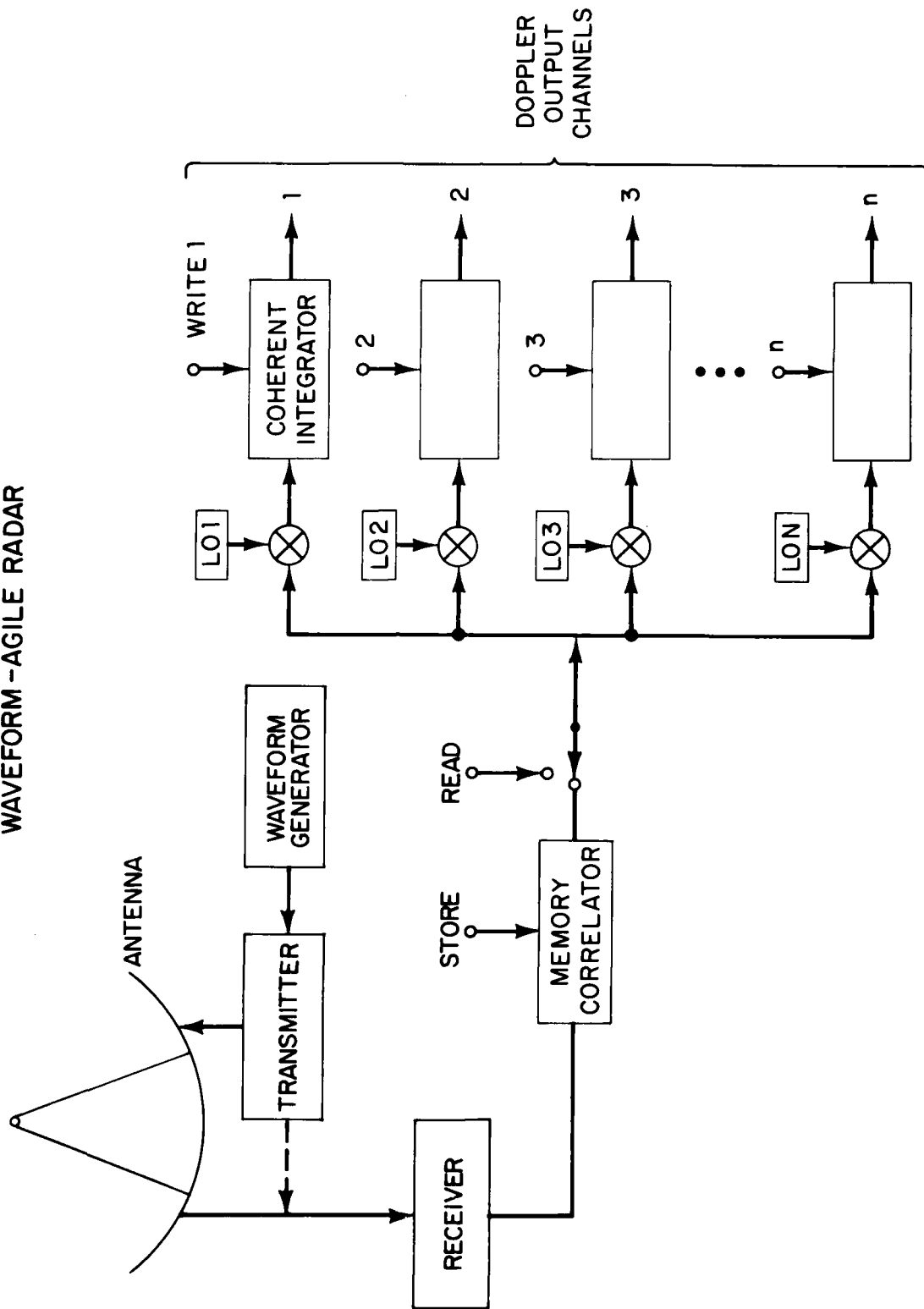


Fig. 1

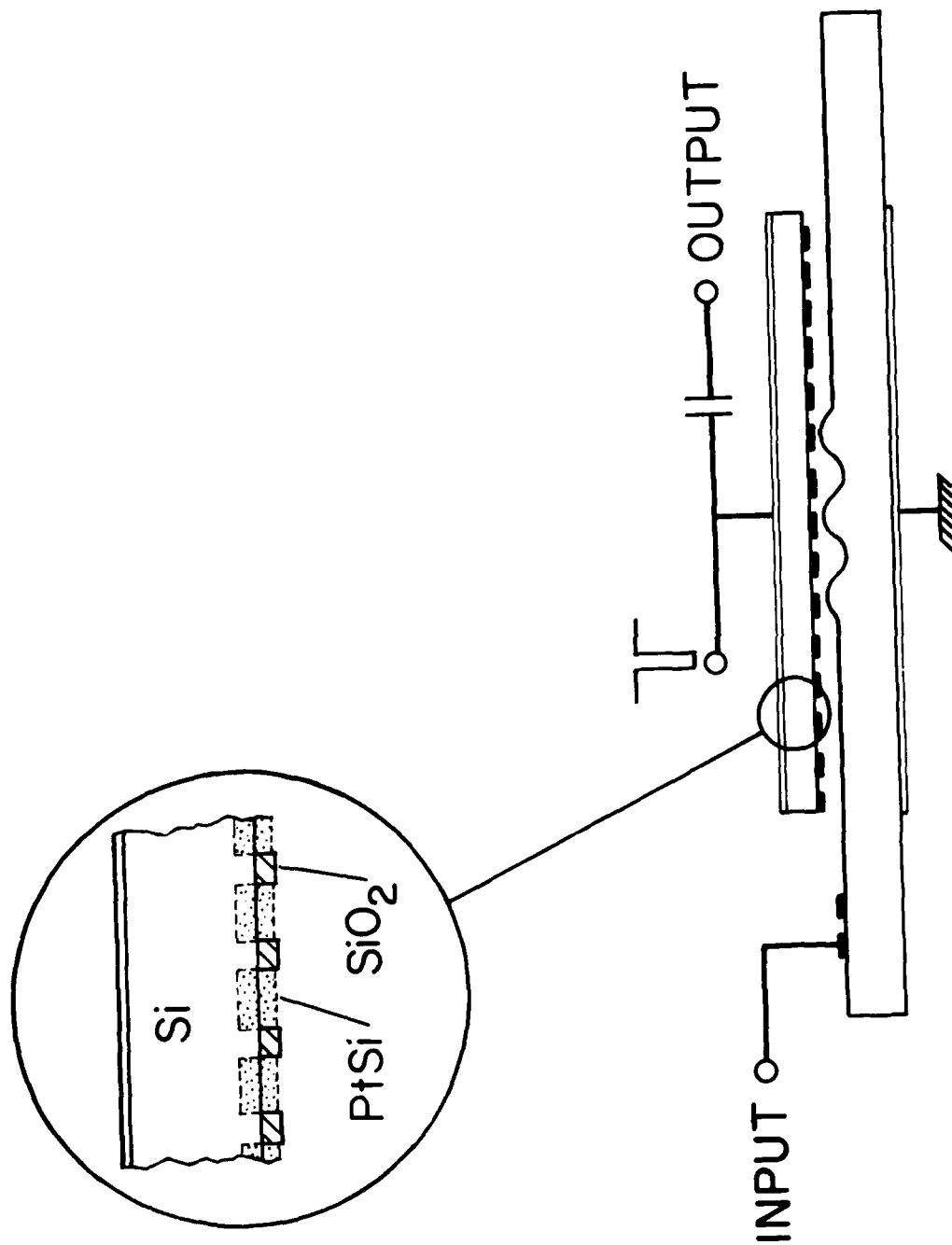


Fig. 2

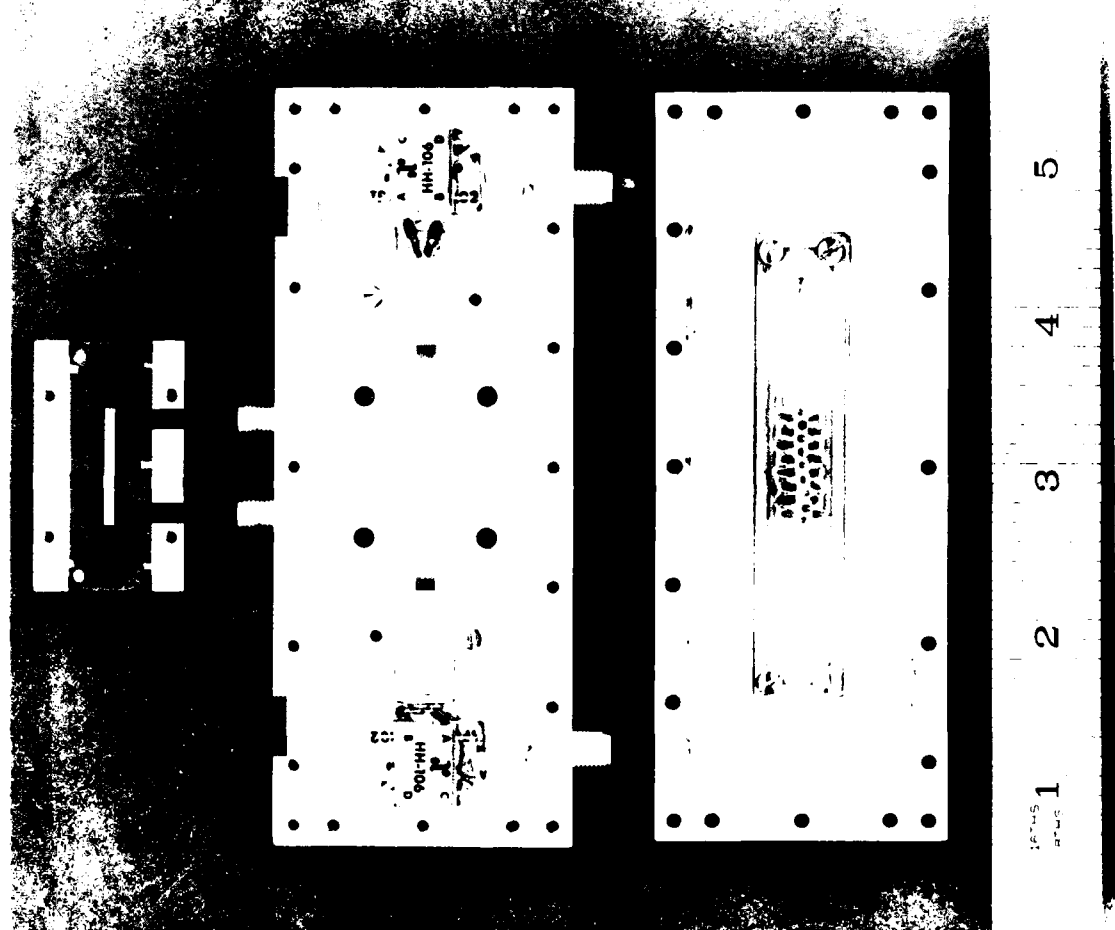


Fig. 3

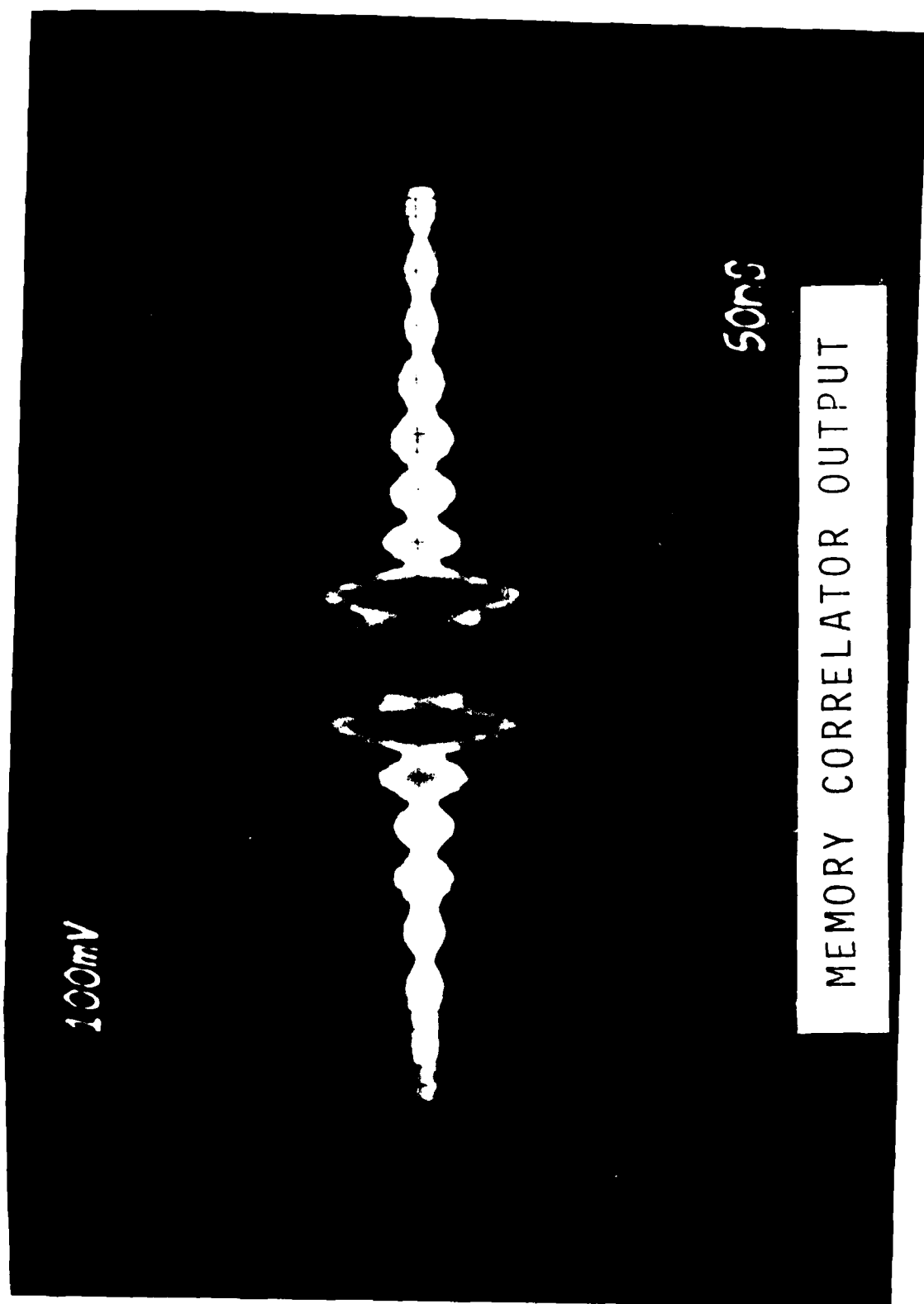
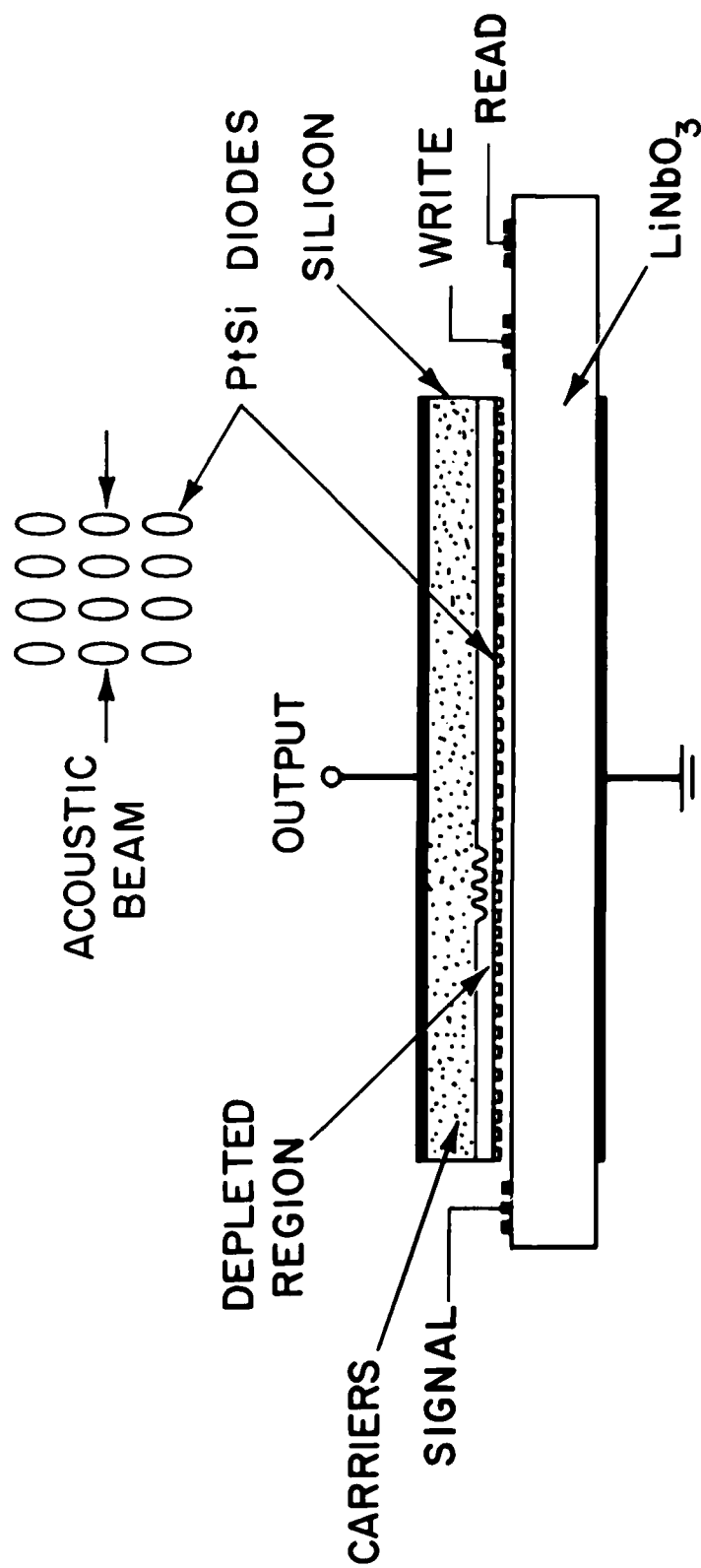


Fig. 4



# COHERENT INTEGRATOR

Fig. 5

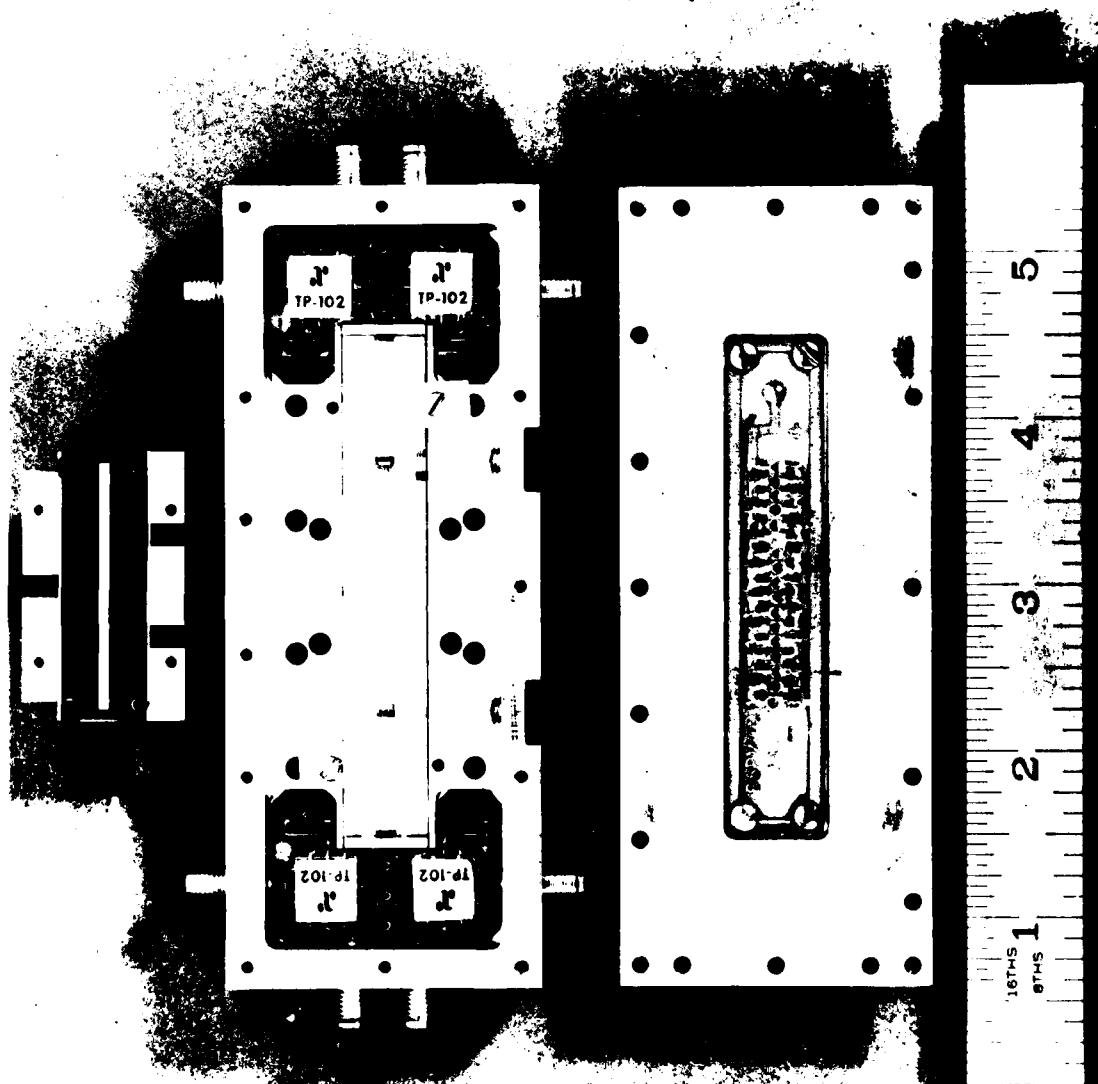
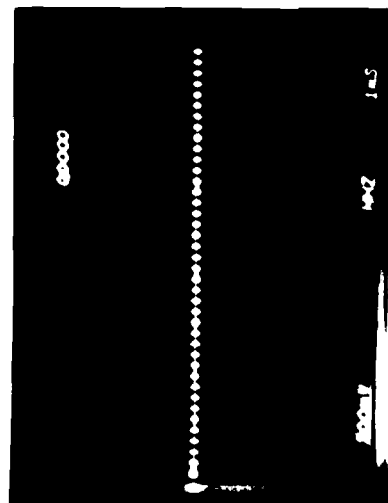
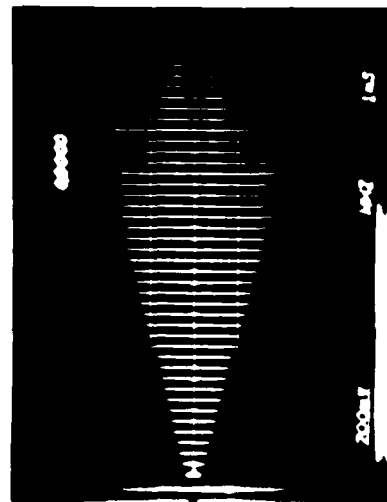


Fig. 6

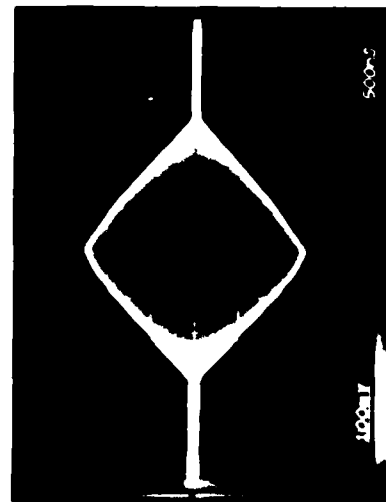
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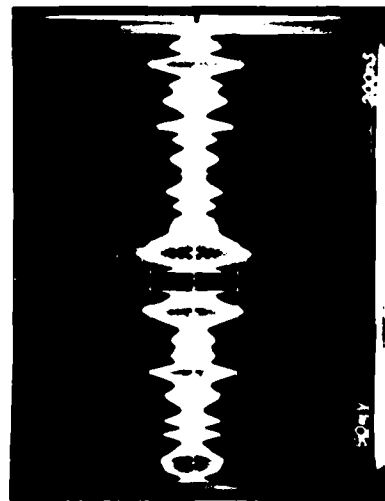
NO SIGNAL



CW PULSE BURST

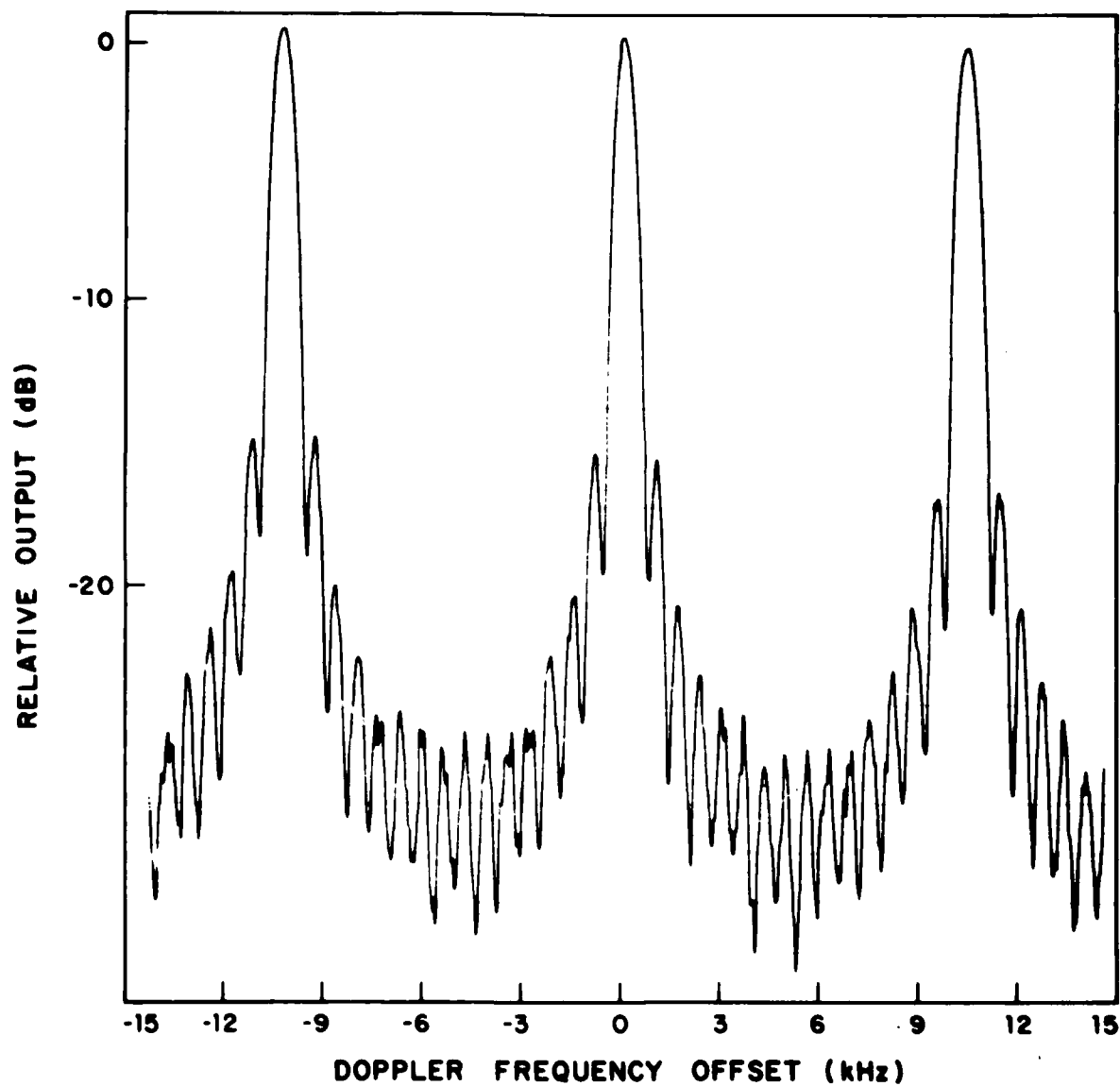


EXPANDED CW-BURST



EXPANDED PSK-CODED - BURST

# OUTPUT OF COHERENT INTEGRATOR AS A FUNCTION OF DOPPLER FREQUENCY OFFSET



INPUT WAVEFORM: 16  $3\mu\text{sec}$  - CW - SUBPULSES CENTERED AROUND  
97.5 MHz WITH  $100\mu\text{sec}$  INTERPULSE PERIOD

Fig. 8