NRL Report 5023

MAGNETIC DRUM STORAGE CROSSCORRELATION RADAR

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November 14, 1957

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Washington, D.C.

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ABSTRACT

A radar system has been developed which promises to extend very greatly the range and detection capabilities of future radar sets. The basic concept of this radar, which was developed under Project Madre, employs crosscorrelation techniques coupled with a magnetic drum storage system and a single sweeping filter. The operation of the system is such that it integrates signals over a period of twenty seconds, resulting in a theoretical signal-to-noise ratio improvement of 33 decibels. A group of components is being developed on contract by the General Electric Company following detailed specifications set forth by the U. S. Naval Research Laboratory. These components will form the major portion of a research radar which has been designed to evaluate the underlying concepts involved. Several optimal modes of system operation are provided for by the system.

PROBLEM STATUS

This is an interim report. Work is continuing on all phases of the problem.

AUTHORIZATION

NRL Problem R02-23
Projects NR 412-000 and NR 412-007

Manuscript submitted August 30, 1957

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INTRODUCTION

The problem of detecting aircraft and other airborne targets at great distances has long been one of considerable interest to the Navy and to national defense in general. With the ever-increasing velocity of airborne targets, the time from detection to target-overhead has, in the case of conventional radar, dwindled to the point that there remains insufficient time to take defensive action.

The Radar Division of NRL has for some time been investigating unconventional detection methods for signals appreciably smaller than receiver input noise. The novel techniques can be described as employing crosscorrelation means and, on the basis of theoretical considerations, these offer very appreciable gain by allowing a new concept of minimum detectable signal. In brief, the process consists of multiplying or comparing a noise-free image of the transmitted signal with the small received signal in the presence of a large amount of noise and integrating the product over some maximum length of time consistent with the phase coherence of the received signal and the operational time requirements of a practical system. This approach is not actually new, since various methods have been investigated, to some extent, by workers in other laboratories. Their results have varied from the realization of modest gains to reports of gains insufficient to justify the additional complexity of the systems. In each case, there has been a difference in some important aspect between work of others and the effort of this Laboratory.

Related Studies

Early work on the problem of very-long-range detection at the Naval Research Laboratory was initiated and stimulated by the contribution of Dr. R. M. Page (1). An experimental system was envisioned, and initial work was directed along two lines: the investigation of phase coherence of the echo in an attempt to quantify the target degradation of the return, and the study of electrostatic storage mechanisms for the retention of transmitted information. The former problem initially seemed to be an open question. Expert opinion varied between the extremes, and it became apparent that some experimental boundary determinations were in order. As a first approach (2), the doppler returns of CW radars operating at selected frequencies over a wide range of frequency were analyzed for frequency content. The results of this work showed the return signal to be largely of one frequency, and this led to a study (3,4) of the pulse-by-pulse correlation between transmitted and returned pulses at selected operating frequencies from 400 Mc to 30,000 Mc. The data gathered from this later work were encouraging, since they showed that the correlation was roughly inversely proportional to frequency and that at low frequencies it approached unity sufficiently to promise a successful application of integration techniques. Concurrently with the target return research, the static and dynamic characteristics of the QK245, Graphechon, and Radechon electrostatic storage tubes were studied (5), and associated circuits were developed for the successful storage and readout of transmitted pulses. The stored pulses were to be read out of the storage tube at the frequency of write-in, or converted to another frequency, and on command used for comparison with the corresponding target-return pulses.

Simulated Storage Radar

Based upon the success of, and encouragement from, the foregoing studies, a simulated storage, crosscorrelation radar was built. This system, operating at approximately 2 Mc, was designed to verify experimentally several aspects of the general theory and proposed system concept. For one thing, it permitted evaluation of crosscorrelation techniques without the uncertainties of atmospheric losses and the difficulties due to lack of phase coherence of the returned signal. Means were provided to inject noise into the simulated receiver channel. This feature, along with variable signal power, provided flexibility for studies of dynamic range and threshold of detection. The results of this phase were particularly gratifying, inasmuch as they showed the measured decrease in level of signal threshold to be very close to that prescribed by theory.

Electrostatic Storage Radar

At the conclusion of the work with the simulated storage radar, an experimental radar, to evaluate the proper combination of storage and correlation circuitry, was developed and built to operate on 26.6 Mc. This was visualized as a research model which would contain only the essentials considered sufficient to demonstrate the principles involved. Search in range was limited to a preselected, but adjustable, range gate, although additional storage capacity with more tubes or multiple traces on a single storage tube were known means of providing additional coverage in range, if such was thought desirable. In addition to an indicating meter presentation of target data, the radar was equipped with a supplementary A-scope and conventional detection system for direct system comparison purposes. Operation of this radar over a period of about three years has established certain facts and design parameters which were used in the design of the magnetic storage radar to be described in this report. It was demonstrated with this system that at an operating frequency of 26.6 Mc, the phase coherence of the returned signal was sufficiently satisfactory to allow integration times in excess of 20 seconds to be employed. On the basis of a number of preliminary measurements, it was also determined that the power level of the minimum detectable signal could be lowered more than eighteen db below that of the conventional A-scope by employing crosscorrelation means. This performance could be demonstrated by the detection of commercial and military aircraft at ranges appreciably greater (two and one half times) than those experienced with a conventional A-scope. However, after more than a year of operation, it was experienced that for a relatively large portion of the time, backscatter returns emanating from the earth's surface after one or two ionospheric reflections could produce a saturated receiver condition. These returns were studied and analyzed for frequency spectrum as a function of time and bearing. While the apperance of high-level backscatter required additional circuit complexity to permit discernment of aircraft targets in its presence, the success of the system supports the belief that an ionospheric radar can be built which would be capable of detecting aircraft targets at extreme ranges, possibly up to 1500 to 2000 miles.

The results experienced with these phases of the radar research program were encouraging, and the evaluation of the target tracking performance of the electrostatic storage, crosscorrelation radar system is continuing. Plans for the system include the use of additional storage tubes and storage space on these tubes to provide sufficient range blocks to cover 450 miles. Spectral measurements on long-range fixed targets as well as on additional back-scatter data on increased average power operation are planned.

BASIC CONCEPT OF THE MAGNETIC DRUM STORAGE RADAR

Concurrent with the development and early evaluation of the performance of the electrostatic system, another system, also using crosscorrelation techniques, but in a slightly different manner and coupled with magnetic drum storage, was disclosed (6,7). It was recognized initially that the frequency requirements imposed upon the magnetic storage mechanism of the proposed system were severe and probably beyond the state of the recording art at the time. Nevertheless, the system's storage needs were actively advertised in the hope that a worthwhile detection application would serve as a motivating force to extend the storage art sufficiently to make possible the proposed radar. The details of this disclosure particularly interested two commercial companies, and as a result a development contract and a study contract were let.

The proposed radar system is based on the pulse-doppler principle, wherein short samples of coherent echo pulses are recorded and stored on a high-speed rotating drum. The stored pulses are read off the drum consecutively and analyzed by a single sweeping filter, and the doppler signal information is presented on a velocity-range display. A simplified block diagram of the proposed system is shown in Fig. 1. For convenience, the diagram is divided into three parts: the input, comprising the antenna, switch, delay, receiver, coherent mixer, and filter, the storage, comprising the sampling circuit and the magnetic drum with its record and playback circuits, and the output, comprising the sweeping oscillator, doppler filter, detector, and display unit.

Input Portion

The antenna is not specified beyond prescribing that the transmitted pattern be tailored to the desired surveillance volume and that the received pattern be tailored to the same volume or any desired portion thereof.

The transmitted pulse is at a carrier frequency somewhere between 10 and 40 Mc and has a duration of approximately 250 microseconds. An image of the latter is stored in a recirculating, or equivalent, delay system (D of Fig. 1) with a delay equal to the pulse length. The recirculating pulse, being a replica of the transmitter pulse, provides a noise-free reference signal for correlation with received signals. Comparison of the received and stored pulses is accomplished in mixer X_1, and filter F_1 separates the derived doppler information from the unwanted products of multiplication. Each image from the delay unit establishes one range gate of approximately 20 miles length and thereby sets the limit of range resolution. Each new transmitted pulse replaces the last previous pulse in the recirculating delay.

Storage System

The output of filter F_1 is bipolar video (Fig. 2) which is fed to the sampling circuit X_2. It will be noted that the envelope of these pulses is the doppler frequency imparted to the returning pulses by the moving target that they represent. Figure 2a represents but a single target. The interval between pulses is the pulse recurrence period (τ) of the transmitter, and the duration of the individual pulses is the transmitter pulse duration (δ). Figure 2b shows the same signal over the time of a single transmitter period. Here a 23-range-gate structure is shown, with the transmitter pulse occupying the first range gate and a return pulse occupying an arbitrary position corresponding to its range and proper time delay.

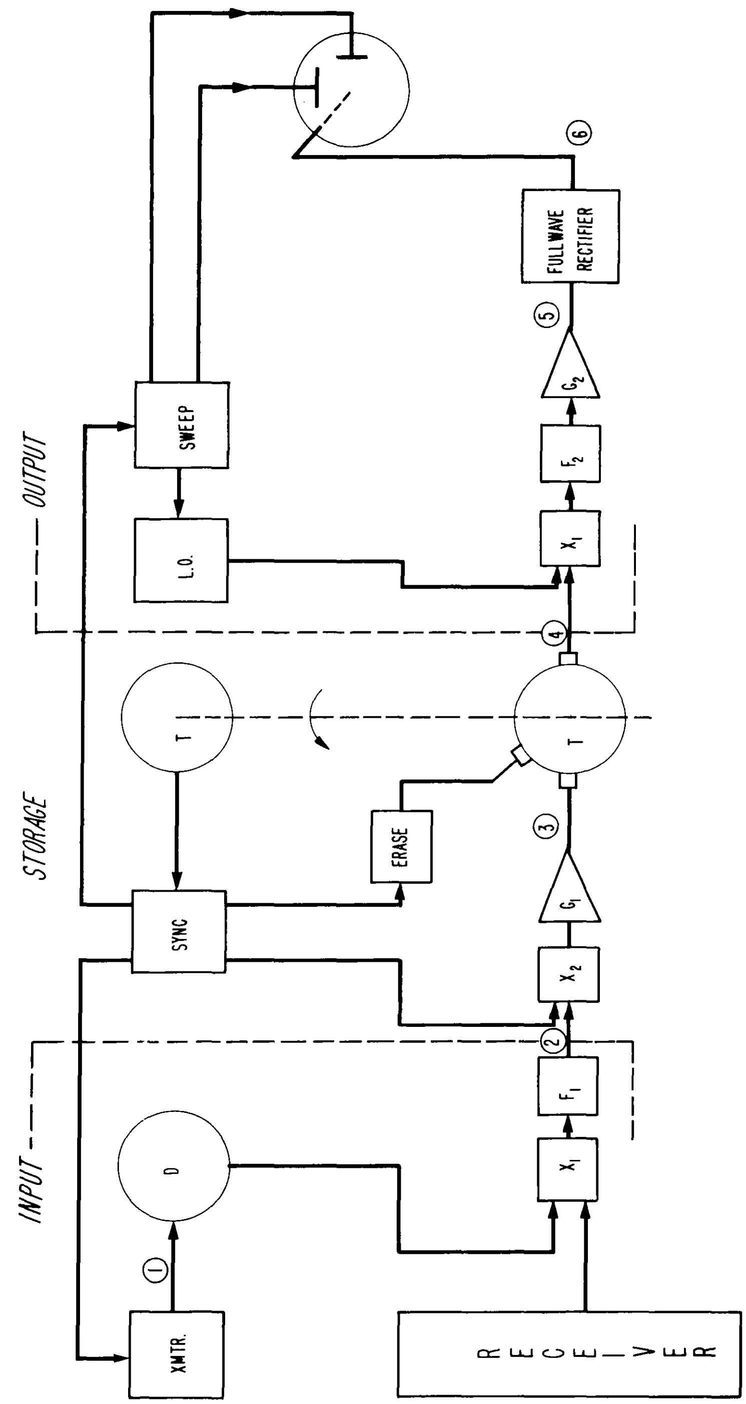
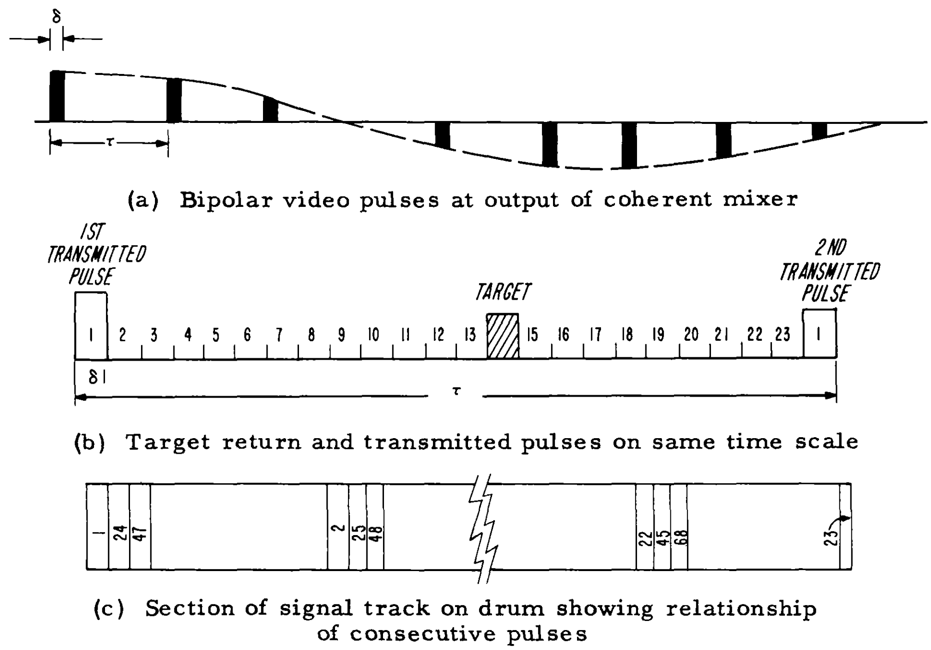


Fig. 1 - Block diagram of system concept



(a) Bipolar video pulses at output of coherent mixer

(b) Target return and transmitted pulses on same time scale

(c) Section of signal track on drum showing relationship of consecutive pulses

Fig. 2 - Time and space relationships of pulses in the system

The sampling circuit is triggered at a rate of 23 times per revolution of the storage drum. The same synchronizing system that drives the sampling circuit triggers the transmitter at the rate of once per drum revolution. As a result, for each firing of the transmitter and each revolution of the drum, each range gate is sampled successively and recorded on the drum, as shown in Fig. 2c. At the end of the first revolution, sample pulses 1, 2, 3, ... 22, 23 are recorded on the drum. The sample duration is 0.075 microseconds, and the synchronous generator drops this amount of time at the end of each revolution; thus sample pulses 24, 25, 26, ... 45, 46 are placed adjacent to the pulses recorded during the previous revolution. The sequence in the first range gate is 1, 24, 47, ... and all other range gates follow in a similar pattern. The sampling process continues until each range gate is full, containing I pulses. At this time, the oldest pulse in each gate is successively erased, and a new one is recorded in its place. The amplitude envelope of the adjacent pulses in any one range gate is at a frequency derived from the doppler shift of the returned pulses. The total number of pulses on the full drum is P, given by multiplying the g range gates by the I pulses in each gate.

Readout of the storage is accomplished by a single magnetic head placed in such a manner as to read the envelope of all the pulses in each range gate each time the drum revolves. Since the pulses recorded over the time of a great many revolutions are read out in one revolution, the doppler frequency extracted by the comparison process is multiplied by a factor m at the output of the playback amplifier.

Output Portion

The pulses stored on the drum comprise a carrier signal on which the doppler signal appears as modulation. Since all the desired information is contained in the modulation, the output from the storage needs to respond only to the modulation envelope. To determine the doppler frequency of the modulation stored in any, or all, of the 23 range sections of the drum, the output of the playback amplifiers is mixed with a signal from a programmed local oscillator (L.O.) in X_3. The coverted frequency output is passed to filter F_2, which has a bandpass of 4 kc. The programming of the local oscillator is such that its frequency is scanned, either continuously or stepwise, throughout the output doppler range at the rate of 4 kc per revolution of the drum. After a sufficient number of revolutions, all doppler signals that might possibly be stored on the drum will be converted and passed through the single analyzing filter. At the filter output, the signal consists of pulses of CW energy at the center frequency of the bandpass filter. This signal is rectified and passed to the data display.

One form of display could be a simple velocity-range presentation. The rectified filter output could be placed on the intensity grid of a cathode-ray tube whose vertical axis represented velocity and whose horizontal axis represented range. The sweep voltage for the vertical scan could be derived from the sweeping local oscillator, and the sweep voltage for the horizontal scan could be derived from the magnetic drum. Azimuth information could be presented on a remote indicator coupled to a rotatable antenna or could be derived by multiple receiving channels and suitable goniometry.

Advantages of Proposed System

As described in this simple review of the basic concept of the proposed radar system, the returned signal has been treated as essentially noise-free. If the returned signal were actually noise-free, the complexity of this equipment would be unjustified. However, in situations where this equipment may be used, a return can be guaranteed at least an order of magnitude smaller, and probably several orders of magnitude smaller than the input receiver noise. In order to understand the system's operation in the presence of noise, it would be well to review briefly the nature of the crosscorrelation process.

If a noisy signal $f_2(t)$ is delayed for a time τ, then mixed with a comparatively noise-free time function $f_1(t)$, and if the subsequent product is averaged over a finite time T, the resulting output is $\phi_{1,2}(\tau,T)$. Symbolically,

$$\phi_{1,2}(\tau,T) = \frac{1}{T}\int_0^T f_1(t)\ f_2(t-\tau)\ dt.$$

This is obviously an "incomplete" crosscorrelation function which approaches a true crosscorrelation function as T approaches infinity. It is well known that, under the previous assumptions, the signal-to-noise ratio of $\phi_{1,2}(\tau,T)$. is enhanced over that of $f_2(t)$. Moreover, the larger T is the greater is the enhancement.

The system performs, in an analogous electronic manner, the mathematical operations indicated in the preceding equation. Consider $f_1(t)$ to describe the image of the noise-free transmitted pulse and $f_2(t-\tau)$ to describe the return pulse, with its doppler shift and large noise component. These two functions are multiplied in mixer X_1, and the doppler component is selected by filter F_1 for further treatment. Equivalent integration is performed by a narrow-band filter F_2 where the integration time T is the reciprocal of the filter's bandwidth.

If the scanning filter system were not employed, filter F_2 would have to be replaced by a large number of narrow-bandfilters, completely covering the doppler frequency range from zero to approximately 90 cycles, each one having a bandwidth of 0.05 cycles. One should stress the fact that the sampling circuit and storage system perform a frequency multiplication, or analogously a time contraction, and provide sufficient time for a more realizable single filter to perform the analysis of each doppler range, one after another. The amount of signal-to-noise improvement, in any application, will depend upon the time available for integration or, in other terms, the degree of effective bandwidth narrowing accomplished by filter F_2.

PROJECT MADRE

Preliminary Activity

As was previously stated, the storage system set forth in the original radar system disclosure imposed some difficult requirements on the state of the art of magnetic recording. Perhaps the most obvious difficulty comes to light when it is realized that the bipolar video pulses from the coherent mixer are sampled for 0.075 microseconds. Using one accepted criteria, the system that records these pulses needs a bandwidth of approximately 15 Mc. Due to the modulated carrier function of these sample pulses, the individual pulses need not be resolved, and the playback bandwidth can be relaxed to that of the highest signal frequency present, 7-1/2 Mc. A second difficult requirement stems from the fact that the overall receiver system is expected to detect signals that are many decibels below system noise, thus imposing severe electronic and magnetic linearity requirements over an unusually large dynamic range. Without a magnetic storage system capable of meeting these special requirements, the complete radar system could not be realized.

After an extensive canvass of the capabilities of the magnetic recording industry, two contracts were negotiated.* The first, with the Radio Corporation of America, consisted of a feasibility study which suggested a possible magnetic storage unit (8). Subsequently, this contractor also disclosed an attractive time multiplex magnetic storage system. The second, with the General Electric Company, provided for the development of a magnetic storage unit along lines suggested by the problem requirements. As the development of this storage unit progressed and the possibility of achieving the required system gradually became more nearly a certainty, the contract was extended to provide a complete magnetic storage radar system, with the exception of an antenna and rf switch. The end item resulting from the latter contract will be a set of radar components conforming to the Naval Research Laboratory's specifications, based on an engineering adaptation of the original disclosure. As is usually the case in most development contracts, the specifications for some of the units were more complete than for others, and some depended upon the actual realization of units without form factor or rigid details. The General Electric Company has an interest in the complete system in which the various units they are constructing will become a part, and thus they consider the overall coordination of the various units they are supplying.

The components that are being developed on this contract will form, along with other elements at hand, a radar suitable for research. Keeping in mind that a chief purpose of the system is to demonstrate the feasibility of magnetic storage crosscorrelation, and to determine the realizable gain in signal-to-noise ratio that one can achieve with the system, it will of necessity possess features not found in operational systems which will add convenience or flexibility as an experimental system. Every effort has been exerted to make the assembly a wide open, uncrowded construction so that adjustments and modifications can be made with ease. Also, several modes of functional operation have been incorporated in some components so that various features can be evaluated.

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*Contract N-onr-1761(00) with the Radio Corporation of America, Camden, New Jersey, and Contract N-onr-1771(00) with the Heavy Military Electronic Engineering Dept. of the General Electric Company, Syracuse, New York.

System Description

As an aid to understanding the system under development, the following parameters are presented, using the notation of Page and George (6). Some of the values used in discussion will be nominal and will be accurate only when the drum is assumed to run at the exact design speed.

f_c	transmitted carrier frequency	26.6 Mc
f_p	pulse repetition frequency	180 cps
τ	transmitted pulse period	5555.5 μsec
δ	transmitted pulse duration	241.5 μ sec
g	number of range gates	23
r_{max}	maximum unambiguous range	455 naut mi
Δr	range resolution	19.8 naut mi
$\dot{r}_{max}$	maximum radial velocity of target	1015 knots
$\Delta \dot{r}$	velocity resolution	0.56 knots
F	input doppler frequency	0-90 cycles
F′	output doppler frequency	0-7.5 Mc
m	frequency multiplication factor	82,800
n	number of resolvable doppler gates	1800
I	total number of pulses integrated	3600
T	total storage or integration time	20 sec
δ_s	duration of sample pulse	0.07 μsec
P	total number of storage positions	82,800
G	system gain in signal-to-noise ratio	35.6 db

The simplest mode of system operation is shown in the block diagram in Fig. 3. The system specifications call for the basic synchronization to originate from a clock track on the magnetic drum. This procedure allows for a degree of uncertainty in the pulse recurrence frequency and certain other parameters of the system but eliminates the troublesome task of slaving the rotational speed of the drum to a more invariant source. By a novel proprietary method developed by the contractor, exactly 5175 cycles of a sine wave are placed on the drum clock track in such a manner that there is no discontinuity where the first wave joins the last wave. The clock track playback reads off these sine waves as a 950-kc signal when the drum is running at the operating speed. This 950-kc signal is quadrupled to 3.8 Mc and passed to the index timer, which produces all of the timing pulses required by the system.

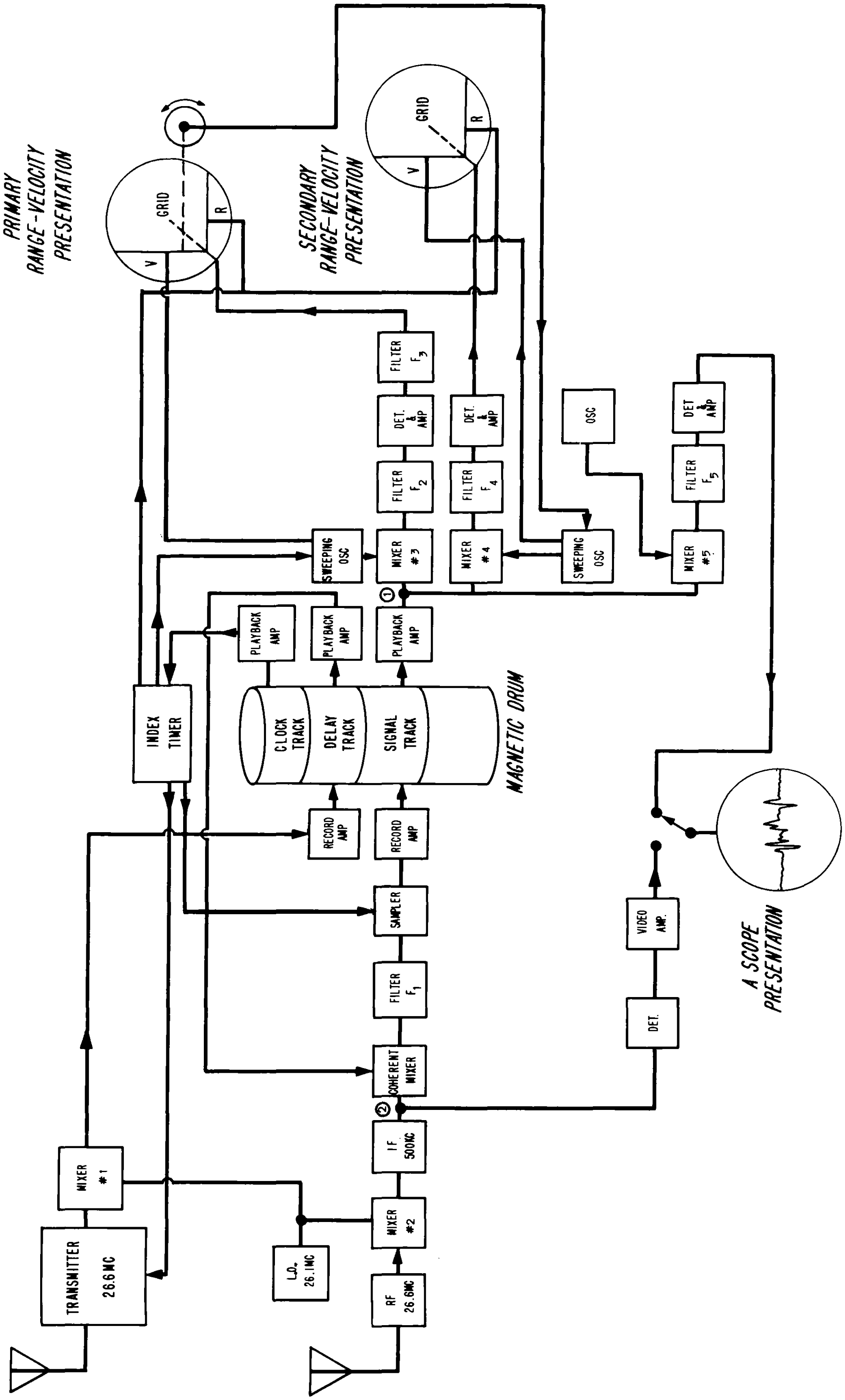

Fig. 3 - Block diagram of single-channel system

The transmitter is triggered by a 180-cps pulse from the index timer, and a 241.5-microsecond pulse of 26.6-Mc energy at a maximum level of 50-kilowatts peak is generated. The exact value of the repetition frequency is of no great importance, but the exactness of the spacing between the pulses over a twenty-second interval is of the utmost importance. The contractor has chosen to meet these stability requirements by gating the low-level output of a continuously running crystal oscillator. The rf pulse is built up by preamplifiers, a driver,and an Eimac 4-5000 tube operating as a single-ended class C power amplifier. The shape of the desired pulse is roughly cosine squared, in order to minimize the side frequencies beyond 8 kc and still maintain as much energy as possible in the carrier. The power amplifier residual output between pulses must be as low as possible in order to facilitate the reception of signals below receiver system noise.

The antenna requirement will vary with mode of operation and is not part of the development contract. In the case of the mode under discussion, it might well be a high-gain rotatable beam that could be pointed in any desired direction. The experimental system does not provide scan in azimuth in the usual sense but looks at some volume in space for at least 3600 pulses or 20 seconds. The usual type of rf switch must be provided with any chosen radiator to allow the transmitter and receiver to time-share the antenna.

The transmitter has a second output which is a low-level sample of the transmitted pulse. This image is fed to mixer 1 (Fig. 3), where it is heterodyned with the signal from a very stable 26.1-Mc crystal oscillator and converted to a pulse at a carrier frequency 500-kc. This image of the main pulse is fed through a record amplifier to 22 record heads operating in parallel. These record heads plus one playback head are placed evenly around the drum, over one track. The pulse duration of 241.5 microseconds is exactly 1/23 of the pulse repetition period and likewise 1/23 of the time of one revolution of the drum. As a consequence of this positioning, the playback head will read out a continuous string of 22 exact images of the 500-kc, converted transmitted pulse. Thus the storage function of a recirculating delay line has been accomplished without incorporating the inherent difficulties.

At some appropriate time after the transmitted pulse goes into space, an echo may return and appear at the input of the receiver. The echo pulse, reduced in amplitude and shifted in frequency by a doppler frequency corresponding to the radial velocity of the target that reflected it, is amplified in the radio frequency portion of the receiver. It then passes to mixer 2, which heterodynes it with a signal from the previously mentioned stable local oscillator used in conjunction with mixer 1, and converts it to a 500-kc pulse. It is further amplified by a conventional intermediate-frequency amplifier, and at this point the signal has built up to a magnitude comparable to the string of transmitted pulse images obtainable from the delay track of the magnetic drum.

Coherent Mixer and Filter

So far, the described receiving process has been conventional. At this point, the process becomes different. The received pulse at a frequency of 500-kc plus or minus the doppler frequency is passed into the coherent mixer. This mixer is a form of a synchronous detector which is capable of multiplying the transmitted and received signals and producing an output containing the doppler frequency, the transmitted spectrum, the received spectrum, and higher order terms. The second input to this detector comes from the magnetic delay in the form of a string of replica transmitted pulses converted to 500 kc and differing from the received pulses only in phase and doppler shift. The phase difference is arbitrary and targets at a certain distance, or a certain position within the range gate, will produce different amplitude outputs in the coherent detector. Since all targets of interest will have a component of motion in the radial direction, they will produce an output varying from maximum to minimum, consistent with the radial velocity of the target.

Filter F_1, Fig. 3, has the primary function of removing the carrier and higher order components from its input. This function is performed by a low-pass filter with a cutoff above 2 kc. The output of such a filter would be bipolar video pulses of 241.5-microsecond duration occurring at a repetition rate of 180 per second whose envelope will be the doppler frequency as shown in Fig. 2a.

As a result of experimentation with the existing electrostatic crosscorrelation research radar, it was found that at certain frequencies a signal due to backscatter could be the limiting factor in detection at any range. The backscatter signals are due to reflection of the transmitted signal from thousands of square miles of the earth's surface after the transmitted signal has been reflected by the inosphere. The range of such an enormous target is much greater than the unambiguous range of a line-of-sight radar, so backscatter is likely to appear over a considerable portion of the range sweep and to be of such amplitude that it may completely obscure any but the largest local targets. Without question, the amplitude of backscatter is great enough at times to overload the magnetic recording process and to introduce a very undesirable nonlinear condition. A detailed study of backscatter shows that the movement of the earth's surface (undulation of water and vegetation) shifts the carrier to generate side frequencies not more than 2 cycles off the 26.6-Mc carrier (9). In the case of the electrostatic radar, a filter is employed to work successfully through backscatter. For the magnetic radar, F_1 will have, in addition to the low-pass characteristics, a comb rejection pattern. Zero to five cycles will be suppressed, and a five-cycle band on each side of 180 cycles and each harmonic within the low pass will be eliminated. While the output from F_1 may be greatly altered from the video pulse structure pictured in Fig. 2a, any pertinent doppler frequency from 5 to 90 cycles will be presented to the sampler.

Sampler

The sampler consists of a pulse-shaping circuit and a diode-sampling circuit. The index timer triggers the sampler at the rate of 23 pulses per revolution of the drum. These pulses are shaped into pulses of 0.07-microsecond duration which actuate the sampling circuit so as to pass to the record amplifier short samples of each range section of the filter output. By this process, noise and possible target information from each range gate are sampled each revolution of the drum. The trigger pulses are delayed one sample duration at the completion of each revolution of the drum, thus causing the sampling process to move progressively across each range gate and the samples to be placed side by side on the signal track of the drum.

Record Amplifier and Bias System

The record amplifier possesses extremely wide bandwidth capabilities and supplies record currents to the toroidal record heads of approximately one ampere. An unusual type of magnetic bias is supplied by this same amplifier. The sampled information is superimposed on unidirectional current pulses of sufficient amplitude to bias the magnetic process to a linear operating point. In addition, an erase pulse is supplied once for each range section for each revolution to remove a few old pulses of each group prior to recording new information. Ideally, only one pulse would be erased at a time, but this feature would impose impossible resolution requirements on the system. The end results of eradicating a few pulses produces a degradation in the ratio of a few pulses to 3600 pulses, which is not particularly damaging.

Drum Details

Physically, the magnetic drum is a 13-1/2-in.-diameter disc machined from 2-in.-thick aluminum alloy plate stock. It is precisely balanced and runs on 30-millimeter bore, double row, ball bearings. The drum drive consists of a belt-coupled 5-horsepower induction motor. It rotates at 10,800 rpm and presents a moderately high Q mechanical system. Experience to date indicates that its speed stability will be sufficiently high to require only secondary automatic control. The cylindrical surface of the drum is coated with an ordinary red iron oxide suspension, and it has space for four signal tracks, the clock track, the delay system track, and at least two spare tracks. The cylindrical frame structure is provided with 23 equally spaced head mounting stations. Each signal track has one record head and one playback head mounted diametrically opposite. The delay track has 22 record heads and one playback head, thus filling all mounting positions over this track. The clock track will have one head mounted in any convenient position.

Readout Process

Readout is accomplished for each signal track by a single magnetic head placed in one of the 23 mounting positions so that it reads all the information on a single track each revolution of the drum. These heads consist of ferrite toroidal cores with a very few turns of wire so that self-resonance is above the useful frequency range. Mounted in very close proximity to the head is a preamplifier consisting of a single tetrode type transistor. At a more remote location, there is a vacuum tube amplifier equalized to provide an output flat from 10 kc to almost 2 Mc and flat, to minus 3 decibels, out to 7-1/2 Mc. It has been stated in the discussion of the general concept that the sampling pulses provide a carrier for the input doppler frequency. In order to read out the doppler frequency, it is necessary to resolve only the envelope of the sampling pulses; thus the maximum output frequency of interest is the maximum doppler of 90 cycles times the multiplying factor of 82,800, or 7-1/2 Mc.

Data Analysis and Indicator System

As described so far, the system has accomplished only a doppler extraction. In order to realize maximum signal-to-noise improvement, the crosscorrelation process must be completed by narrowing the bandwidth with a bank of filters that would contain a very large number of bandpass elements, each of which would respond to a particular narrow range of doppler frequencies. An important feature of the developed system is that it contains a few sweeping, analyzing filters which replace the required multitude of filters. Actually, four different types of analyzing filters are planned, and presentations are also provided for evaluation and comparison of their relative merits.

One presentation has for its filter (F_2) a 40-kc bandpass unit centered at approximately 8 Mc, performing some 23 decibels of predetection signal-to-noise improvement. It is followed by a detector, amplifier, and a 4-kc low-pass filter (F_3) which provides up to ten additional decibels of bandpass narrowing or signal-to-noise improvement. This combination of predetection and postdetection integration is arranged so as to cause little if any loss of signal-to-noise improvement for a practical signal.

The output doppler from the storage drum is presented to one input of mixer 3 while the second input comes from a sweeping oscillator whose frequency changes at the rate of 40 kc per revolution of the drum. The relationship between the two inputs is such that for the first revolution of the drum, after a given time, frequencies from 0 to 40 kc will be converted to the 8-Mc region and will pass through the filter. During the second revolution of the drum, output frequencies from 40 to 80 kc will be converted to the 8-Mc region. This process continues until the drum output frequencies up to 7-1/2 Mc have been converted.and passed through the single filter. At this time the whole process is repeated. By the use of the drum and its multiplying factor, time has been contracted, and there is sufficient time to analyze each doppler range in sequence, thus permitting the use of a simple filter system.

The basic indicator for this research radar system will consist of a cathode-ray tube with the range presented on the horizontal axis, velocity on the vertical axis, and the filter output on the intensity grid. The range sweep will be synchronized from the index timer, and the velocity sweep will be synchronized from the sweeping oscillator so that targets will fall in the proper positions on the two scales. This filter and indicating system has a velocity resolution of 5 knots and a range resolution of approximately 20 nautical miles.

In order to study the relative effectiveness of a 100-percent predetection integration system and to provide greater velocity resolution, a secondary or vernier scan has been incorporated into the indicator system. It possesses a velocity resolution of 1/2 knot and will present a restricted range of velocity gates centered around any target selected from the primary display. To accomplish this, the signal from the playback amplifier, point 1 of Fig. 3, is fed to mixer 4, which is identical to mixer 3. The sweeping oscillator used in this case is similar to the first one, but it sweeps over a range of about 60 kc at the rate of 4 kc per revolution of the drum. It is followed by a 4-kc bandpass filter F_4, which accomplishes the 33 decibels of bandwidth narrowing in one step.

After rectification, the video is presented to a cathode-ray tube in the same manner as for the 40-kc primary scan. The horizontal sweep is synchronized by the index timer to produce one sweep per revolution of the drum. The vertical sweep is synchronized by the restricted-range sweeping oscillator, which is centered about a given target by mechanical adjustment of an index line over the desired target on the primary presentation.

A third presentation is provided in the form of a velocity scan. Mixer 5 also gets a signal from point 1, and a local oscillator signal is provided by a manually tuned, non-sweeping oscillator. The converted signal is passed to filter F_5, which has the same 4-kc bandpass as F_4. The signal is passed through a third detector and to the vertical deflection plates of a cathode-ray tube which gives an A-scope presentation for any given velocity range. The horizontal sweep is derived from the drum at the rate of once per revolution. This presentation will discriminate against noise, because system noise appears irrespective of range and hence will be apparent all along the horizontal sweep. A target appears in but one range gate and therefore has a distinctive shape. If there is some question as to the validity of a target, the approximate velocity range can be searched with this presentation, and the true nature of the target can be assessed.

The fourth presentation is purely auxiliary and is provided for comparison purposes. A signal is taken from point 2 at the output of the 500-kc intermediate frequency amplifier. It is detected, amplified, and by means of a switch placed on the vertical plates of the cathode-ray tube used for the velocity scan presentation. By operating as a conventional radar at the same time that it is operating as a crosscorrelation radar, an estimate of the success attained may be made by noting the maximum tracking range of a receding target as indicated by the two types of operation.

OPTIONAL MODES OF OPERATION

Four-Channel Option

Project Madre was considered in one form to be an all-azimuth, nonscanning system for extended range detection. In this form, it consists of four channels of receivers,

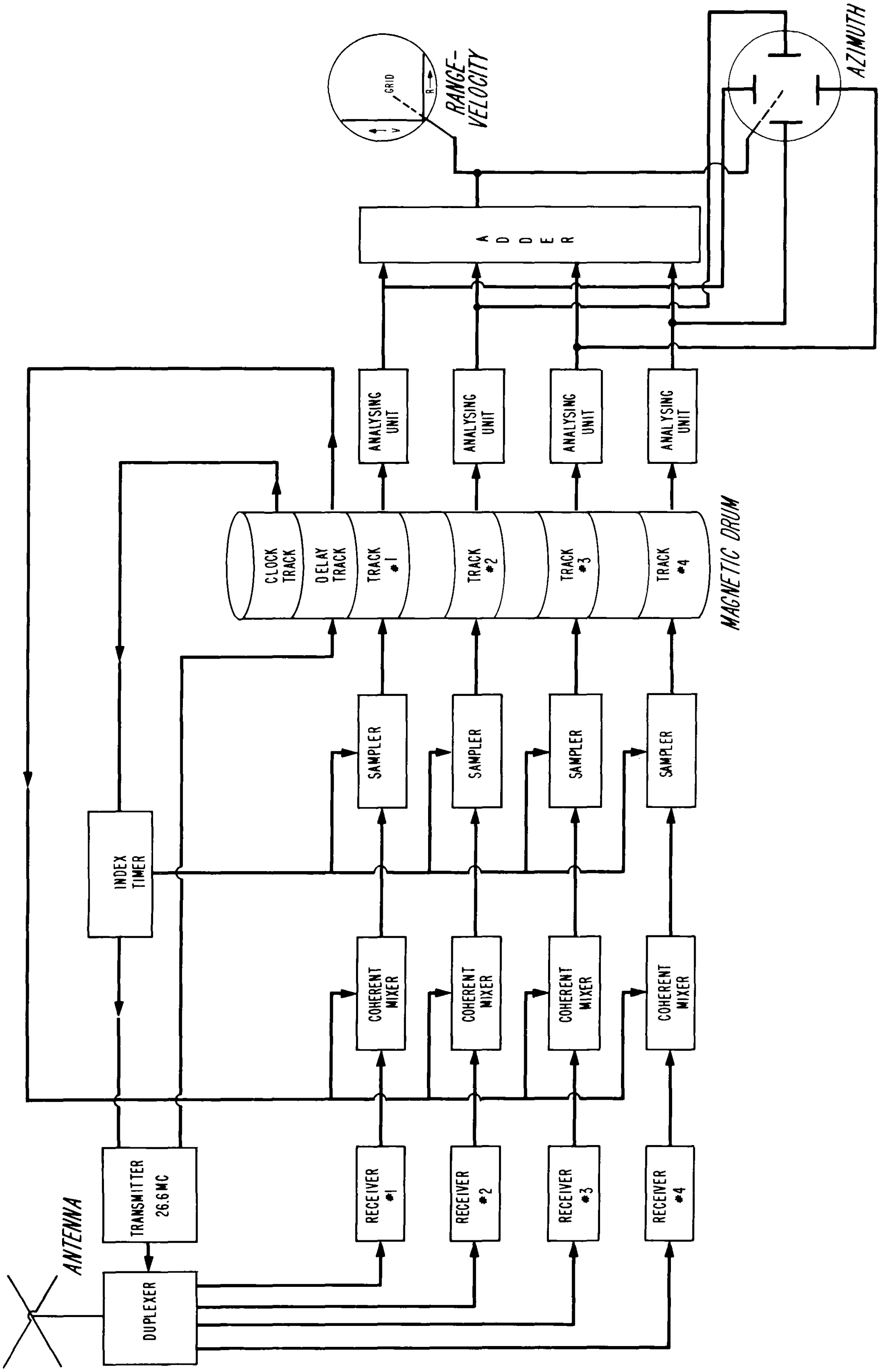

Fig. 4 - Four-channel system

A second method of accomplishing the same end is also incorporated in Project Madre. It consists of a frequency-stepping mode of operation and offers, in addition, some antijam potential. The transmitter is provided with three crystals in the exciter oscillating at 26.6 Mc, 26.6 Mc plus 8 kc, and 26.6 Mc minus 8 kc. The three crystals are gated into the transmitter circuit one after another at the rate of 180 cps, causing successive pulses to be at different frequencies. With this method, three receiver channels are used. The low-pass filter in connection with F_1, Fig. 3, is set so that its cutoff is between 2 and 8 kc; this establishes sufficient selectivity to distinguish between the three transmitted frequencies. The radio frequency portion of each receiver passes all three frequencies, and the comparison signals for the coherent mixers are derived by gating the various oscillators in such a manner that the first channel always receives a comparison signal from the oscillator that caused the prevailing transmitted pulse. The second channel always receives a comparison signal from the oscillator which causes the previous pulse, and the third channel receives a comparison signal from the oscillator which causes the second previous pulse. This allows the first channel to store doppler information from targets in the range of zero to 455 nautical miles, the second in the range of 455 to 910 nautical miles, and the third in the range of 910 to 1365 nautical miles. The system achieves extended range just as the previous mode of operation, and to overcome its loss of average power, it too can be associated with a high-power final amplifier. This method has blank spots on the range scale where the receivers are gated off during the second and third transmitter firings. In addition, if the transmitted spectrum contains appreciable energy beyond 8 kc from the carrier, this energy will appear in the wrong receiver channel and tend to degrade the stored signal. On the other hand, this method presents a more difficult jamming problem, because jamming energy would have to be spread over a wider frequency range; it is considered that this system might profitably be evaluated.

General Antijam Option

The transmitter stability requirements are such that it can wander through a 16-kc band if the comparison signal for the coherent mixer is derived from the stored image of the actual transmitted pulse. If the instability is greater than this, the doppler frequency will fall in the wrong velocity gate and degrade the detection results. With this restriction, it is possible, with any of the modes of operation which use the stored transmitter pulse image, to step the transmitted frequency in a programmed manner through a 16-kc band and require the jammer to spread its energy over the same band to be completely successful. Since this possibility is inherent in Project Madre, this system is also considered an important mode to evaluate.

PROGRESS OF DEVELOPMENT

Magnetic Drum Storage System

Project Madre has progressed through several stages. A single-track magnetic storage system was built to demonstrate the feasibility of recording up to 15 Mc. This first step proved to be successful largely because the high surface velocity of the magnetic media on the face of the drum allowed the recording process to take place at a minimum recorded wave length of approximately one mil. Some of the newer ferrite materials facilitated the production of record and playback heads with satisfactory high-frequency magnetic characteristics and extremely low inductance windings, which allowed head resonances to be placed above the useful frequency range of the system. The initial drum has had some 800 hours of running time and has exhibited no indication of bearing failure. The magnetic surface under the airfilm-supported head has run as much as 300 hours without indication of the approach of the end of useful life.

Data Processing System

The single-channel prototype magnetic storage system was provided with a mixer, sweeping oscillator, and filter, and its preliminary performance was studied while operating with sine wave input. It was demonstrated that frequencies from near zero to 90 cycles could be recorded, stored, and read off in an acceptable fashion.

A simulated radar return signal, complete with variable delay to represent range, was also provided and used for an input signal during the course of evaluation. Random noise of large amounts was injected with the signal, and measurements indicated a signal-to-noise improvement approaching 33 decibels. At certain output frequencies, where small amounts of spurious system noise appeared, the improvement was decreased to approximately 25 decibels. Vibrations occurring in the air-supported head mounts are believed responsible for the spurious response, and the solution of this problem will await assembly of the system around the final four-channel drum. Working mockups of the indicators have been coupled to the analysis circuits and have demonstrated the usability of the proposed range-velocity and velocity scan presentation.

Present Status

At this writing, the development phase is drawing to a close and the construction phase is well underway. The transmitter design has been chosen along well-established lines, and the required components have been procured. A model of the receiver, using push-pull circuitry throughout, has been produced, and it appears to be satisfactory. It has been established that the comb filters will be of the regenerative type, and development is in progress. The contract calls for completion by 15 October 1957, and the General Electric Company expects to make delivery by that date.

Future Program

Upon delivery, the Radar Division expects to assemble the components along with components presently on hand and to evaluate the system as a line-of-sight radar. The many modes of operation indicate an extensive evaluation program. At a later date, depending upon the availability of a very-high-power final amplifier and associated antenna, the extended-range option with its ionospheric reflection possibilities will be investigated.

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