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Toward Optimizing OTH-System Performance Through the Use of Digital Techniques for Data Handling and Processing

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ABSTRACT

This report describes the need for implementing advanced concepts of OTH-system performance capabilities in a research and development environment prior to the design of an operational OTH radar system. Specifically the improvement of data-handling and digital signal-processing techniques are discussed. The benefits of increasing the digital capabilities of the Madre system include an automated methodology for target-track synthesis, real-time optimum operational frequency utilization, transmission of covert messages to the Quiet Task Force (QTF), improved probability of detection of ships through reduction of resolution cell size, and improved probability of detection of small targets such as antiship missiles. The hardware needed to accomplish this system performance is described in detail. Emphasis is placed on the impact of OTH technology on naval applications.

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TOWARD OPTIMIZING OTH-SYSTEM PERFORMANCE THROUGH THE USE OF DIGITAL TECHNIQUES FOR DATA HANDLING AND PROCESSING
[Unclassified Title]

INTRODUCTION

The Naval Research Laboratory has recognized the need for continued research and development to enhance the state-of-the-art capabilities of over-the-horizon (OTH) radar systems. NRL is cognizant that before the feasibility of implementing current concepts of a modern OTH radar system can be demonstrated, the system performance of the Madre radar needs to be upgraded. The utility of this system improvement is in its potential impact on future OTH system design for CONUS defense or for naval applications of OTH radar such as fleet air defense (FAD). The Madre system has demonstrated its flexible capabilities in the detection of aircraft, missiles, and ships at over-the-horizon ranges. To optimize the Madre radar performance, however, a system upgrade of the data-handling and signal-processing capabilities is needed.

Conceptually OTH technology has many potential naval applications. Through the implementation of the data-processing techniques discussed in this report many of these concepts can be demonstrated prior to the design of an operational system. A detailed study [1] concerning the potential utility of OTH radar technology as applied to the FAD problem has recently been completed. These concepts can be demonstrated through the hardware modifications to be discussed in later sections of this report. Specifically the improvements to be incorporated include:

- Automated techniques for operator designation of target parameters to the computer and computerized formulation of target tracks.

- Automated determination of the optimum operating frequency, thereby improving system performance.

- Digital clutter filtering to maximize the probability of detection of small targets such as the antiship missile.

- Linear frequency modulation of the transmitted waveform, which decreases cell size and increases resolution, thereby maximizing the probability of detection of slow moving ships; this capability allows not only detection of enemy ship movements but also monitoring the movement of friendly ships which are operating under emission control and cannot transmit their location to shore-based activities.

- Encoding of one bit of information (such as coordinate information of hostile targets) in each transmitted radar pulse for covert communication with the quiet task force (QTF) operating under emission control.

The following section of this report will briefly describe the digital signal-processing capabilities currently incorporated in the Madre OTH system, and it is followed by a detailed discussion of the need for improved data-handling capabilities. The later sections discuss the hardware modifications necessary to improve data-handling capabilities and increase system performance as outlined above.

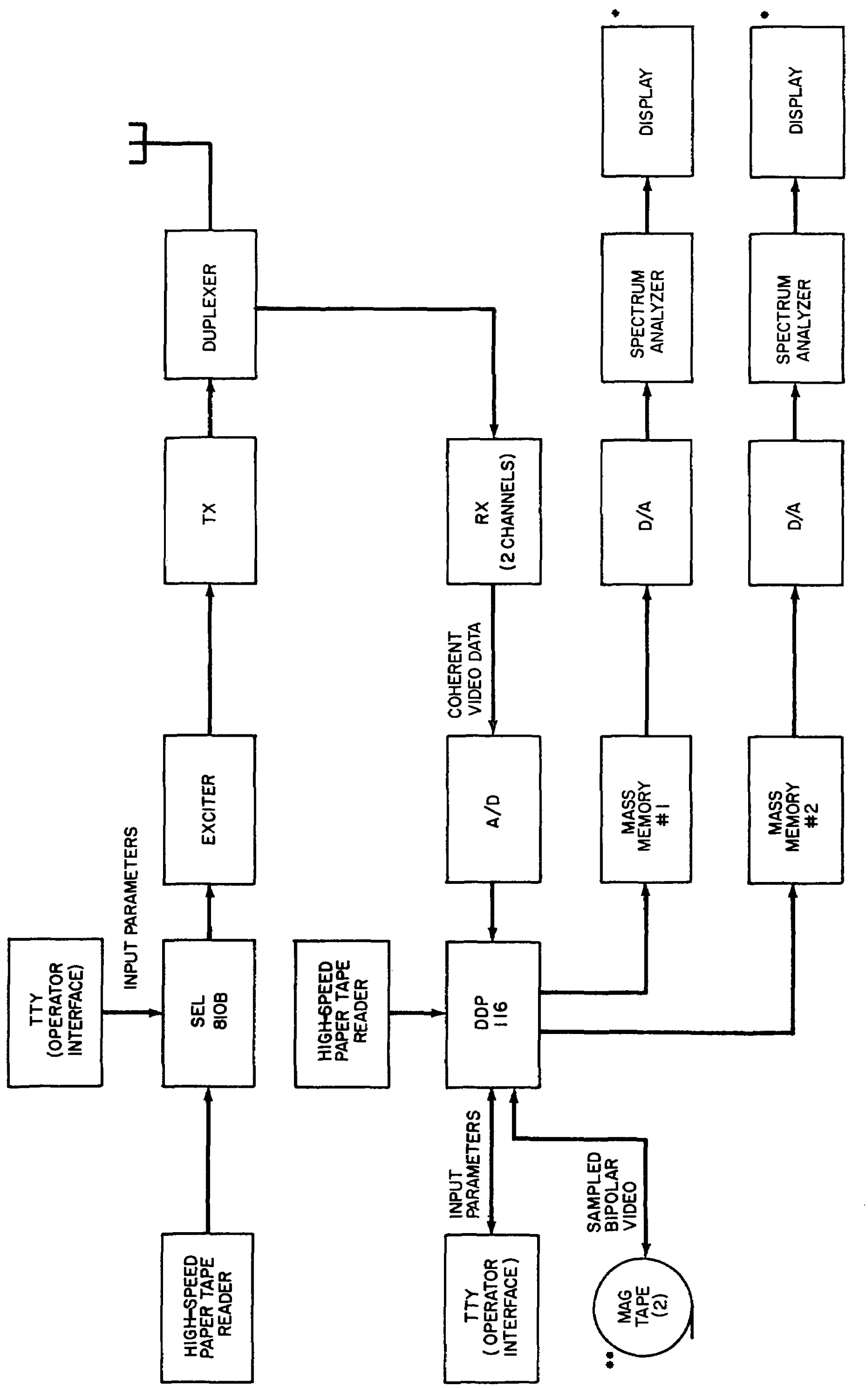
CURRENT DIGITAL COMPUTATIONS IN THE MADRE SYSTEM

Two small-scale general-purpose digital computers are currently incorporated in the Madre OTH system. The first to be installed was the DDP-116 computer, a 16-bit-word machine (Appendix A). This computer is used primarily for process control. Specifically its functions are: time compressed reading out of the mass memory for input into the spectral analysis equipment, controlling the scanning oscillator frequency, selecting the analysis filter bandwidth, and recording the digitized raw video data onto magnetic tape. This computer is the heart of the 60-dB signal processor in use on the Madre system since 1966. A detailed description of this signal-processing system may be found in Ref. 2.

The second digital computer currently part of the Madre system is the SEL 810B, a 16-bit-word machine having an 8k, 1-microsecond core memory. The primary function of this computer is to control the exciter using parameters which are put into the system from a TTY. These parameters including operating frequency, pulse repetition interval, and modulation mode (for example, CW, pulse, or chirp) are used by the control program residing in the SEL 810B to synthesize the pulse waveform for the exciter. A digital image of the modulation waveform is computed and stored in the computer memory. Digital in-phase and quadrature samples of the video waveform are transformed in separate eight-bit D/A converters. Figure 1 shows a simplified block diagram of the present Madre system including the DDP-116 and SEL-810B interfaces with other elements of the system.

The DDP-116 and SEL-810B computers are not capable of supporting additional data-processing functions in the Madre system because of core-memory and timing constraints. The real-time process-control program run on the DDP 116 uses virtually all of the 16k words of memory available, and in addition the amount of processing time used by this software leaves little processing time available for other functions.

The exciter control software developed for the SEL-810B computer does not fully use the processing time available. The machine is in an idle loop in the time interval between pulse synthesis of successive transmitter pulses. However, because of the small memory (8k), additional memory modules would be required in order to use this computer for additional functions. This is not considered to be cost effective, because the SEL 810B is a second-generation computer which has a relatively expensive core memory (approximately $19,000 for an 8k-word module). An additional constraint that would be imposed on the use of this computer for additional functions is that during the time needed for pulse synthesis any other program would have to be interrupted.



*DISPLAYS MAY BE SET UP TO PRESENT VELOCITY/RANGE, VELOCITY/TIME, A-SCOPE, OR AMPLITUDE/FREQUENCY INFORMATION

**TAPED DATA MAY BE PLAYED BACK FOR OFF-LINE PROCESSING AT REAL-TIME RATES

Fig. 1—Present Madre system (timing and control lines are not shown; only data lines are shown)

CONCEPTUAL IMPROVEMENTS IN DATA HANDLING

Target Inventory and Track Synthesis

The Madre OTH system depicted in Fig. 1 is a very capable system for the collecting and processing of radar signals. However the human operator of this system is unable to fully digest in real time all of the information being presented to him. Though visually detecting and recognizing target signatures is easy for a well-trained operator, the operator cannot track these targets in range and azimuth in real time with the current system. At present a range-versus-time plot is obtained as follows: A tape containing raw video data is played back off-line at real-time rates. After the tape is moved forward over 10 seconds of data, the tape is stopped and the doppler/range information of each of the targets appearing on the radar display is recorded. Because of the time required to place the doppler and range strobes on the target, it is likely to take the operator 5 to 10 minutes to record the information for one frame when as many as 10 to 15 targets are appearing. After processing each frame, the tape is moved forward over 10 seconds of data and then halted for processing of the next frame. The data are then keypunched for input into a computer program developed for the CDC 3800 which creates a plot of range versus time.

The procedures as described involve much tedious manual effort in order to analyze data that should be processed dynamically in real time. The acquisition of a small-to-medium-scale, third-generation computer would result in a capability to process this data in real time as well as provide other enhancements to the Madre system.

Ionospheric Propagation Assessment and Optimum Frequency Prediction

Another function that should be handled automatically in real time is that of assessing ionospheric propagation in order to predict the optimum frequency. Though the ionosphere is too dynamic to allow radar operation on the optimum frequency at each instant of time, the system should provide to the operator the necessary information for him to decide when ionospheric conditions have deteriorated to the extent that a change in frequency and/or elevation angle is imperative.

Digital Clutter Filtering

To increase the probability of detecting small targets (such as the 1-square-meter target presented by the antiship missile), a clutter-rejection capability must be added to the present system. This clutter filter should be a digital filter in order to increase system flexibility. A digital filter implemented on a general-purpose digital computer would make it feasible to change the type of filter (elliptic, Chebyshev, Butterworth, etc.) through changes in computer software.

Ship Detection and Ocean Surveillance

OTH radar can have a distinct role to play in surveillance of the ocean. It has been demonstrated [3-6] that OTH radar can detect ships at sea. To see small ships and those that are slow moving, the size of the resolution cell will be reduced such that the target signal strength will compare favorably with the clutter amplitude. The cell size can be reduced by incorporating a chirp/dechirp capability into the system. The SEL-810B computer has the capability of synthesizing a linear frequency-modulated waveform. A later section of this report will describe in detail a method proposed for the dechirp function.

Convert Communications with the Quiet Fleet [Secret heading]

Another function that an OTH radar can perform bearing on naval applications of OTH radar is the encoding of messages into the transmitted pulse for transmission to fleet units operating under emission control [7]. In a typical scenario wherein a task force is under emission control, the task-force commander has no means of detecting approaching hostile forces. An OTH radar could illuminate the task force and a wide area surrounding it, thereby providing ship-surveillance and fleet-air-defense (FAD) capabilities. The OTH system would detect approaching hostile ships and aircraft, compute their latitude and longitude and/or the range and bearing from the task force, and encode this information in the transmitted radar pulses. The mechanism used for message encoding is a phase reversal or no phase reversal of the signal. Thus one binary bit of information would be encoded into each transmitted pulse. This is a sufficient information transmission rate even for low PRF's for the quantity of information to be communicated to the ships at sea. This scheme obviously would require the installation of additional equipment aboard ship for receiving and detecting the encoded information and printing the message on a teletype. A conventional Navy HF receiver that has been modified to adapt a modem would be used for receiving the transmitted pulse.

The system described has a distinct advantage over the other systems that could be used for communication of this information. The advantage is that the target parameters can be transmitted to fleet units in real time and covertly.

REAL-TIME TARGET-TRACK SYNTHESIS

Detection and Tracking Algorithm

The system should be designed such that the target is detected by the operator, leaving the computer with the function of target-track synthesis. Target detection is best performed by the human rather than the machine because it involves a subjective judgment. Target intensity compared to the surrounding clutter, appearance in terms of size and shape, and partial obscuration of target returns by meteor or auroral returns or clutter are all factors taken into consideration by the operator in making his decision.

Existing computer programs have proven the feasibility of track synthesis by automated methods. A Fortran program has been developed by NRL personnel which plots target tracks in range versus time. The computer need only be given the target parameters in terms of doppler frequency and range and the time at which the parameters were recorded. Each candidate for a track is compared with previous candidates. The doppler of the new candidate must be within a specified tolerance in order for the point to be accepted as a valid point on a track. Additionally the range coordinate must be within a specified tolerance of the range coordinate predicted based on the radial velocity and time elapsed since the previous point for the track was taken. If the new candidate is not within the tolerance limits for any of the previously synthesized tracks, it is stored for possible use as a point in a new track. If other candidates for this new track are not found within a specified interval of time elapsed since the mismatched point was recorded, it is dropped from the target inventory. A more detailed description of the algorithm used in the target-track synthesis program will be described in a future report by other members of the Radar Techniques Branch.

Computer Hardware Requirements

The software described is anticipated to be the basis for the real-time synthesis of target tracks. The main requirements for hardware to realize this function is a computer having sufficient storage and processing speed to enable real-time data handling and an interactive method for designating the target coordinates (doppler and range) to the computer. The DDP-116 and SEL-810B computers previously mentioned do not have sufficient capacity for the target-inventory and track-synthesis functions. These functions will require the acquisition of an additional small-to-medium-scale computing system. The exact characteristics of this computer will be deferred to a later section after all the other functions which will be implemented on it have been described.

Interactive Devices

There are a number of possible alternatives as to how the operator could interactively designate a target to the computer. One requirement of the system is that it enable the operator to designate from five to ten targets in one integration period (typically 10 seconds) with minimum operator fatigue. This speed requirement would definitely rule out the joystick and rolling-ball type of cursors for target designation [8]. The light pen is an interactive device which would meet the speed requirements without causing undue operator fatigue. Another approach could be the use of a conductive glass overlay which is capable of providing digital coordinates of the point at which the glass is touched by a pen or a person's finger. These two approaches would have to be analyzed in terms of cost effectiveness and reliability.

In considering a display having an interactive-light-pen capability a number of decisions need be made regarding the type of CRT (refreshed display or storage tube), necessary point writing speed, number of intensity bits, vector and character generators, and cost. In the specific application of interest here it is important to consider whether the display should change dynamically or should remain static for the entire frame time (integration period).

In a dynamic display such as shown in Fig. 2 the display would appear much the same as the present doppler-versus-range display with the exception that there would be no visible sweep from top to bottom. This could be disadvantageous to the operator, because he would not know when one frame time ended and the next began. The sampling rate of the video signal is predicated on the use of a 256-by-256 display matrix and a frame time of 10 seconds. The frame time or integration time should remain flexible, so that the sampling rates shown are for illustration only. The 256-by-256 display

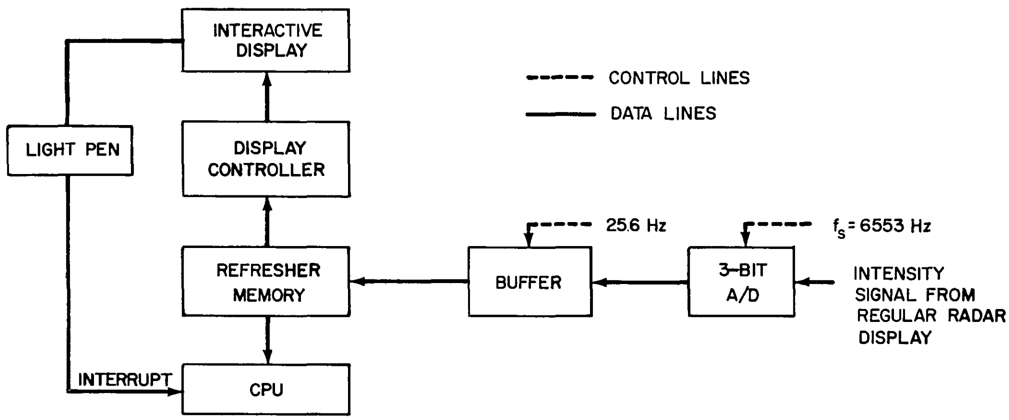


Fig. 2—Dynamic interactive display (with examplary sampling rates based on a 10-second frame time)

matrix would give a range resolution of 1.2 n.mi. if a 300-n.mi. range sector were being displayed and give a doppler resolution of 0.12 Hz for the 30-Hz unambiguous doppler corresponding to a PRF of 60 Hz. The sample rate then is:

$$f_s = \text{number of samples/frame time}$$

$$= (256 \times 256)/10 = 6553 \text{ Hz.}$$

The buffer should be of sufficient size to hold one display line of data, namely, 256 samples. The buffer would be filled 256 times in one frame time and would be dumped into the refresh memory at a 25.6-Hz rate. It is anticipated that a three-bit A/D converter is sufficient, because the maximum number of intensity levels available on most displays is eight. It is unlikely that a mass storage device could be used, because of the data transfer rates required. It will be necessary to run some simulation tests to determine the exact configuration necessary.

The operator will point the light pen at a target and press a switch interrupting the computer. The coordinates of the target will then be transferred to the computer. Because the operator is unlikely to point exactly at the center of the target, the coordinates transferred to the computer will only be approximate. The computer will then have to search for the exact center of the target using the information available in memory, which contains intensity data for each of the 256 times 256 points in the display matrix. Figure 3 shows pictorially the intensity pattern of a typical target. Most targets appear on the present displays in the Madre system as an oblong shape varying in length from 10 to 20 n.mi. and in width from 0.1 to 0.5 Hz. The numbers in Fig. 3 represent intensity levels. Typically the intensity is the greatest at the centroid of the target and decreases toward the edges. The centroid is considered to be the point in doppler-range space at which the target is located. Since the operator will likely place the light pen on the target at some point other than the exact center, a search algorithm must be implemented on the computer that will use the coordinates provided by the light pen as a starting point for searching the intensity pattern to find the centroid of the target return. It was for this reason Fig. 2 shows that the central processor unit (CPU) as well as the display controller must have access to the refresh memory. This memory then has

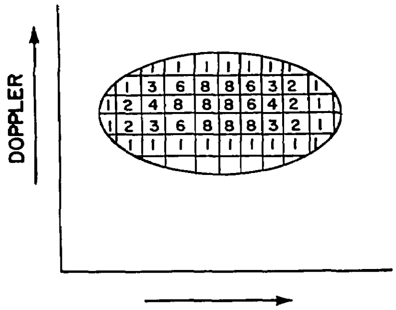


Fig. 3—Target intensity pattern. The numbers within the target outline indicate relative intensity.

a dual purpose: for refreshing the CRT display and for use by the CPU in finding the center coordinates of the target. There will be three bits of information to be stored for each point in the 256-by-256 (64k-point) matrix. The exact format in which these data will be stored will be depend on the CPU and interactive display selected.

As mentioned, there may be some disadvantages to the dynamic display because the operator is unaware of the start and end of a frame time. As an alternative approach a static display is being considered which would eliminate this problem. In the static display configuration the digitized intensity-modulation information is dumped into a memory or other storage device separate from the refresh storage. At the end of each frame time the information in the separate memory is dumped into the refresh storage, which remains unchanged for the next frame time. Thus the display will remain static for the entire frame time. The static-display method has the advantage of the operator knowing when the frame time ends but has the distinct disadvantage of requiring twice as much storage as the dynamic method. All other factors would remain the same for the use of the light pen and the computer for implementing the search algorithm to determine the centroid of the target and add these coordinates to its target inventory.

In both the dynamic- and static-display configurations the use of a refreshed CRT rather than a storage-tube CRT has been assumed because of the slow point-writing speeds of most storage-tube devices. Clearly the storage-tube display cannot be considered for the dynamic configuration, because storage-tube devices cannot be selectively updated [9]. In the static configuration, assuming that it is desirable to change the entire display within 1 second, the point-writing speed required would be

$$1\ \mathrm{s}/256^2\ \text{points} \approx 15\ \mu\mathrm{s}/\text{points}.$$

Storage tubes do not have this capability. The Tektronix Model 4002A graphic display for example is a storage-tube device having a point-writing speed of 82 microseconds. Thus regardless of whether a static or dynamic configuration is chosen, a refresh display will be required.

For a refresh display the refresh rate needed to eliminate visible flicker is from 30 to 60 Hz depending on the phosphorous on the CRT. As an example assume that the refresh rate is 40 Hz. This means that all 256^2 points in our matrix must be refreshed in 1/40 second (25 milliseconds). Kreitzer and Fitzgerald [10] have demonstrated a core-refreshed video display system having 800,000 picture elements, 32 intensity levels per point, and a refresh rate of 30 Hz.

A third method for interactively designating target coordinates to the computer is through the use of a conductive glass overlay placed on top of the present radar display (Fig. 4).

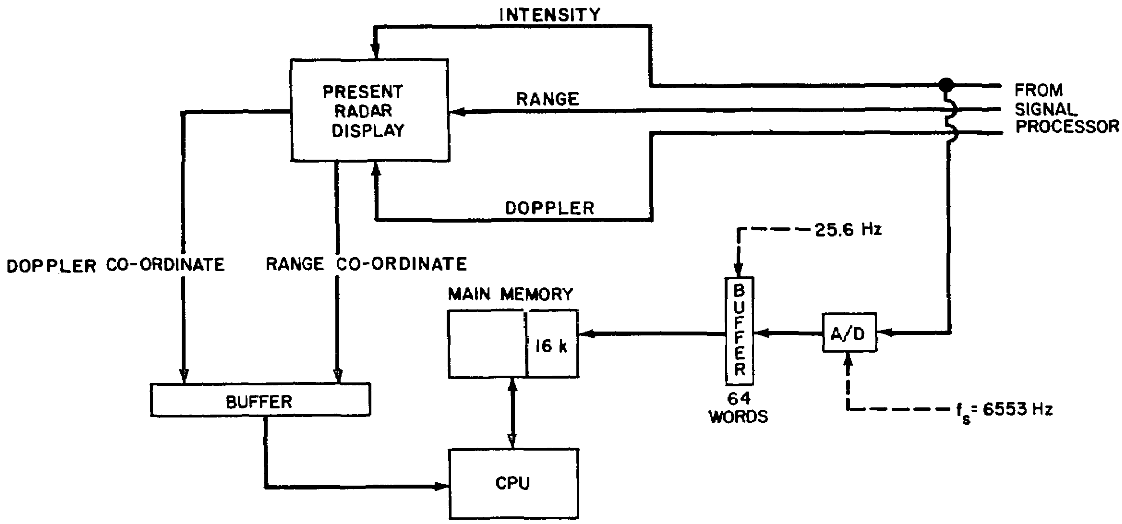


Fig. 4—Target-designation subsystem using a conductive glass overlay

Several manufacturers have developed conductive glass that is sensitive to the touch of a special pencil or pen that will digitize the coordinates at which the pencil or pen touched the conductive surface. This technique has been used in other systems, usually with inadequate results due to poor reliability [11, 12]. The conductive surface has been too susceptible to scratches and abrasions by the pen itself as well as by poor usage by inadequately trained personnel [11, 12]. However a new glass plate has been developed by Instronics Incorporated which is touch sensitive to a finger. Basically it works on a pulse echo-ranging technique. Pulse-modulated high-frequency surface waves are generated by transducers located along two sides of the digitizing surface. Any object contacting the surface of the glass reflects the surface wave back to the source. The digitized coordinates are obtained by measuring the elapsed time between the transmission and reception of the pulse. Since the device is activated by a finger rather than a pencil or probe, the surface would be less susceptible to surface damage.

If a conductive glass overlay can be found that is adequately reliable, this approach is likely to be the most economical device for digitizing the target coordinates. An interactive display, although probably more expensive, would have several inherent advantages over a conductive glass overlay however.

One advantage is that it would have an alphanumeric capability which could be useful in labeling targets. The labeling of targets has been found to be useful when manually recording target coordinates in order to avoid recording the same target on successive frame times. It has been found that there is an uncertainty of 2 to 3 n.mi. in placing the range strobe in the center of the target. In a 10-second frame time a target moving with a radial velocity of 600 n.mi./hr would move a distance of only 1.6 n.mi. Thus the inaccuracy in placing the strobe is greater than the distance most targets could move in one frame time. Therefore it has been found unnecessary to record the coordinates of a given target more than once every 30 seconds. To determine which targets have been taken in the previous two frame times, it is necessary that the target be labeled with some symbol indicating when its coordinates were recorded. The operator must look at the scan every frame time to avoid missing the weak targets that appear infrequently due to target fading. For these reasons it is highly desirable that an interactive display have an alphanumeric capability. The use of a conductive glass overlay rather than a separate display would eliminate the possibility of having an alphanumeric capability.

Another advantage of an interactive display with a light pen over the conductive glass is that the interactive display could be used for other purposes. The display could be used alternately as a method of looking at the backscatter to determine the optimum operating frequency. This procedure will be discussed in detail in the next section.

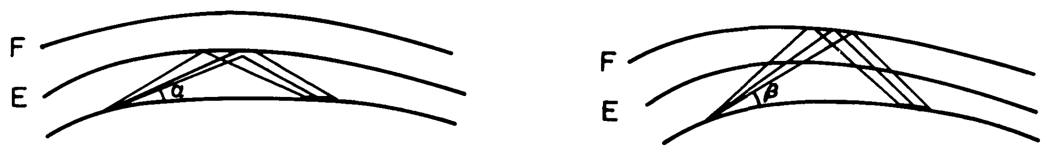
Regardless of the method used for digitizing the target coordinates the function of the computer in implementating the algorithm for searching for the centroid of the target, in creating target inventories, and in synthesizing target tracks will be the same. Only the method of obtaining the initial target coordinates differs.

In addition to the possible use of an interactive display for target designation, there is a need for a large-screen display. Conceptually this would be a command situation display wherein filtered data would be presented. The format of the data could be velocity vs range, velocity vs time, or range vs time. An example of the use of such a display is to provide to the officer in tactical command (OTC) information required in real time. It would present to the commander all information available from OTH radar concerning friendly and hostile forces in his theater of operations. Conceivably information from OTH radar as well as other sensors such as NTDS sensors could be integrated on the same situation display.

OPTIMIZING SYSTEM PERFORMANCE BY REAL-TIME PROPAGATION PREDICTION

Need for Selecting the Optimum Frequency and Ray Takeoff Angles

To optimize the performance of an OTH system in detecting missiles, ships, and aircraft, the radar operator must make proper decisions in regard to frequency management. This is necessary because the vagaries of the ionosphere are such that the optimum operating frequency for one day may be far from optimum on the following day. Current procedures in operating the Madre system include monitoring the earth backscatter on an oscilloscope and deciding from this information what the transmitting frequency should be. This method gives only an approximate estimate of the optimum frequency, because all of the factors affecting the choice of frequency cannot be considered manually in real time. The optimum frequency may be defined as that frequency which not only enables the area of interest to be illuminated but which also minimizes the path loss, decreases the probability of multipath returns, and enhances the doppler integrity of the returned signal.



(a) Reflection from the E layer (b) Reflection from the F layer

(U) Fig. 5—Reflection of rays

Figure 5 illustrates the illumination of approximately the same area on the earth's surface by transmitted signals of either of two frequencies. This figure is a simplification in that it depicts ionospheric reflection rather than refraction of the propagated energy. Assume that in Fig. 5a the transmitted frequency is f_1 and the angle α represents the takeoff angle of the lowest ray in the vertical plane. Other rays of the beam have angles greater than α and are also refracted from the E layer provided they do not exceed some critical angle for the existing ionospheric conditions and the chosen operating frequency f_1. In Fig. 5b the operating frequency is f_2 and the takeoff angle of the lowest beam is β. The takeoff angle for the Madre system can be changed through proper phasing of the phased array antenna. Which mode of transmission and therefore which frequency is to be used in illuminating a given area then is a decision that must be made by the radar operator. This decision should be based on knowledge of the path loss for each of the acceptable frequencies, on multipath assessment, and on doppler-integrity considerations.

If both the E layer and F layer support illumination of the target area but one of the paths has significantly higher path losses, the mode having the lower path loss should be chosen. It should not be inferred however that the operator always has the choice of propagation modes. One or the other of the modes possibly may not support illumination of the target area at all.

The choice of an optimum operating frequency is further complicated in that usually for a specific frequency and takeoff angle energy may be returned by both the E layer and the F layer. Because the main beam has a beamwidth of several degrees in the vertical plane the upper rays may have exceeded the critical angle for refraction from the E layer and be refracted from the F layer for a particular operating frequency while the lower rays are being refracted from the E layer. This problem is further compounded if the antenna pattern has multiple lobes in the vertical plane. The upper lobes may have takeoff angles greater than the critical angle for the E layer for the operating frequency being used while the lower lobes do not. The difference in takeoff angles of rays in the main beam or of different lobes in multilobed antenna patterns can cause multiple-mode (E-layer and F-layer) propagation of transmitted energy. This results in a backscatter return as shown in Fig. 6. The energy distribution may appear differently than depicted,

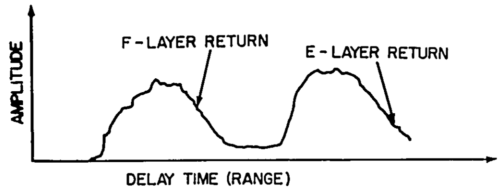


Fig. 6—Backscatter vs delay time for multimode

depending on existing conditions. For example the leading edge of the E-layer return can overlap the trailing edge of the F-layer return. The operating frequency should be chosen such that these simultaneous multipath returns from the same area via both E mode and F mode are minimized. It should be noted that displays of backscatter amplitude vs range as in Fig. 6 include the effects of peaks and nulls in the vertical plane of the antenna pattern.

A further consideration to be made when choosing the optimum frequency is maintaining doppler integrity. Under certain conditions the F layer can cause the radar return to be spread in doppler frequency. Large spread in doppler means a large degree of uncertainty regarding the velocity of the target. It is therefore highly desirable to avoid if possible the choice of any frequency that would use a propagation path that loses doppler integrity.

Automatic Propagation Prediction for Determining the Optimum Frequency

A technique of propagation prediction will be described that will enable a computer to automatically pass to the operator information necessary for frequency management. As a basis for this proposed technique a computer program has been developed [13, 14] which computes virtual-height ionograms and uses these ionograms to compute and plot the ray paths of the HF signal. The program then uses the radar equation to calculate the signal-to-noise ratio for each ray path and then generates the area-coverage plot of backscatter amplitude versus time delay (slant range). This program could be modified for use in real time for automatic determination of the optimum operating frequency.

This program uses an input tape containing median ionospheric data for each month of the year for the E, E_s, F_1, and F_2 layers. Parameters such as month, sunspot number, operating frequency, noise interference level, and radar-location coordinates are entered via input data cards. The program uses this information to compute the virtual-height ionogram, ray paths, absorption losses, and area coverage. The antenna pattern is a known quantity that is included in the area-coverage plot of backscatter amplitude versus range. This is included because the peaks and nulls in the vertical pattern obviously can grossly affect the appearance of the area-coverage plot. Chambers and Davis [15] have shown the effects of removing the antenna pattern of the Madre system from the backscatter return.

In adapting this program for real-time propagation prediction, the approach taken would be to start with the average or predicted ionospheric conditions and iteratively adjust the virtual-height ionogram until the calculated area coverage is a close approximation to the observed area coverage. After each iteration through the program both the calculated backscatter and the observed backscatter would be displayed for comparison on a computer-driven graphic display. When the calculated and observed backscatter are closely correlated, the existing ionospheric profile for that instant is nearly the same as the theoretical virtual-height ionogram. The program can then calculate the path absorption loss for each of several frequencies until the optimum frequency in terms of minimum path loss has been determined.

Because of the diurnal changes in the ionosphere it will be necessary to repeat the process described above periodically. During sunrise and sunset it is especially important that propagation conditions be examined at frequent intervals. Conceivably the computer system on which the propagation prediction program resides could have a real-time clock set to generate an interrupt at some specified interval. When this interrupt occurs, the computer would stop executing any task it was working on and call in the propagation-prediction program from a high-speed disk. The program would then determine the optimum frequency as previously described and provide the radar operator with a printout on either a TTY or a printer which gives the recommended frequency, path losses, and area coverage. Having finished this task the computer would then resume execution of whichever task was being processed prior to the interrupt.

It has been shown [13, 14] that the technique discussed is a viable approach for optimum frequency management. The task that remains is to demonstrate this capability in real time using an on-line computer. The increased performance of the OTH system operating on an optimum frequency will result in higher probabilities of detection for small targets, more efficient illumination of the target area, and increased accuracies in the determination of target velocity and range. Increased accuracy in the determination of velocity is the result of being able to select a frequency that minimizes spread in doppler frequency. This doppler spread can result when operating at a frequency which uses the F layer while spread-F anomalies are in effect [16]. Increased accuracy in range determination is the result of choosing a frequency that minimizes the possibility of multipath returns.

CLUTTER REJECTION AND LINEAR FREQUENCY MODULATION

CSP-30 Digital Clutter Filter

As mentioned previously the need for being able to detect small targets such as antiship missiles by OTH radar is the basis for adding a clutter filter to the Madre system. The linear frequency modulation of the pulse is necessitated by the need to reduce the resolution cell size in order to detect slow moving ships and/or ships having small ($<10^3$ square meters) radar cross sections. A CSP-30 (Computer Signal Processors Incorporated) computer is available for performing these functions. Since it is a prototype model, it is necessary for it to be refurbished by Computer Signal Processors Incorporated. To implement the clutter filter and linear-frequency-modulation (LFM) functions on it, there are additional needs for increasing the core memory from 16k to 24k words and for acquiring an FFT box. The details of the CSP-30 computer, which may be characterized as an extremely fast minicomputer designed for signal processing applications, are presented in Appendix B. Figure 7 is a block diagram for the accomplishment of the digital clutter-filter and dechirp functions.

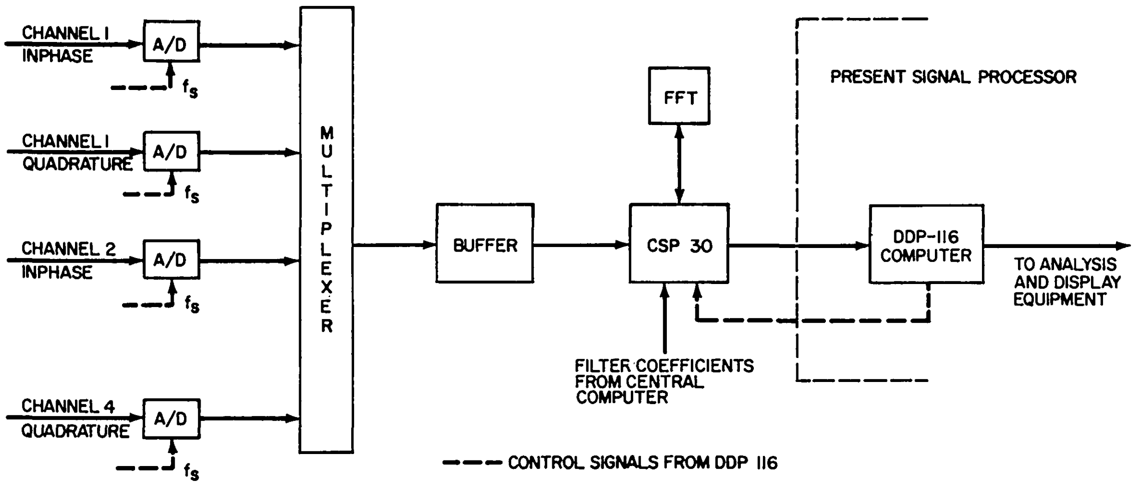


Fig. 7—Preprocessor

The input into the A/D converters in Fig. 7 is the bipolar video. The inphase and quadrature components for each channel are to provide amplitude and phase information for range processing. The digitized signals are multiplexed into a buffer and transferred into the CSP 30 under interrupt control. The clutter is then filtered in the time domain using a recursive digital filter technique that is the equivalent of an analog comb filter. The advantage of using digital rather than analog filters is in the added flexibility of being able to change the impulse response of the digital filter through software modifications of the filter coefficients. Hsiao [17] has developed a computer program which will calculate the poles and zeros of elliptic, Butterworth, and Chebyshev comb filters. The program is given parameters such as attenuation in the stop band, ripple amplitude in the passband, and cutoff frequency in the passband. This particular program could be quite useful in our proposed system. Though the program could not reside in the CSP 30 because of core constraints, it could be used with a larger central computer which would calculate the filter coefficients and pass them to the CSP 30. Thus the operator sitting at a keyboard on the central computer could by specifying filter parameters change the filter response of the digital filter on the CSP 30.

FFT Linear-Frequency-Modulation Dechirp

After clutter filtering, the LFM dechirp capability is implemented in the frequency domain using fast-Fourier-transform techniques. The results of the FFT are multiplied by stored sample values of a filter function matched to the linearly frequency modulated pulse. An inverse FFT function is then performed. To implement this concept, it is necessary that the FFT box be able to directly address the CSP-30 memory without having to interrupt the CSP-30 arithmetic unit. This requires that a multiport or direct-memory-access [18] (DMA) capability be added to the CSP-30 system available at NRL. Conceptually the CSP-30 arithmetic unit will be performing the clutter filter function on the latest digitized input samples concurrently with the FFT box performing the dechirp function on samples that have been previously clutter filtered. This concept of operations will of course require a dynamic usage of core memory and also will require simultaneous access by the CSP-30 arithmetic unit and the FFT box to different memory modules. By dynamic usage of memory is meant that one section that contains the digitized samples x_i for the current input into the recursive filter will have the x_{i1} samples for the next frame time and x_{i2} for the following frame time.

CSP-30 Interfaces

An interface will be necessary between the CSP 30 and SEL-810B (which drives the exciter) to communicate the sense of the linear frequency modulation. There will also be a need for an interface between the CSP 30 and the central computer for communication of the coefficients for the digital clutter filter. The overall system configuration and interfaces between the various computers will be described in more detail in a later section of this report.

FLEET-MESSAGE GENERATION AND ENCODING

As mentioned previously it is highly desirable to have the capability of surreptitiously transmitting to fleet units coordinate information of hostile forces. This concept is important because, first, it would enable our fleet to operate under emission control and thus possibly escape enemy detection without loss of our own capability for detecting enemy ships, aircraft, and missiles and, second, it would give our fleet extended area coverage and advance warning time beyond the capabilities of conventional shipboard line-of-sight radars.

This information could be encoded into the transmitted pulse by the presence or absence of a phase reversal in the transmitted signal. An alternate method of bit encoding would be through the change of sense of the LFM ramp. An up ramp for the pulse could indicate a "1." for example, and a down ramp for the pulse would indicate a "0." Both the phase reversal and the up-rame/down-ramp encoding techniques are now extant on the SEL-810B computer. Work is in progress by others at NRL to construct the necessary equipment aboard ship for reception and detection of the signal. The actual encoding of the pulse then would be by the SEL-810B computer which drives the radar exciter. The generation of the data to be transmitted such as the latitude/longitude of the approaching hostile force, the speed of advance, the number and type of vehicles, or other necessary data are probably beyond the capabilities of the SEL-810B computer. The generation of these data would be on the medium-scale central computer, which would pass it on to the SEL 810B for encoding.

The data rate that could be supported using this scheme is one binary bit per radar pulse or 60 bits per second for a PRF of 60 Hz. The code to be used is a standard seven-element telegraph code [19]. The first element is 1, followed by five elements indicating the character to be transmitted, and the last element is 0. Thus seven bits are required to encode a character. In 1 minute at a 60-Hz PRF for example 3600 bits or 514 characters per minute could be transmitted. If three digits of information are required for each of the target parameters such as range, bearing, and heading and four digits for velocity (13 digits total), the data transmission rate of 514 characters per minute appears to be sufficiently high for the amount of information anticipated. Even considering that the data rate is reduced to 257 characters per minute when the PRF is reduced to 30 Hz, the target parameters of nearly 20 targets (13 characters per target) could be transmitted in 1 minute.

The advantages of this system of transmitting target parameters to the ships at sea are: target information can be communicated in real time, which is imperative in a hostile environment, and the transmission of the information is surreptitious, thus denying knowledge of its existence to the enemy.

The need for a real-time communication system was demonstrated during a fleet air-defense exercise [20] conducted with the *USS Independence*. The Madre radar provided surveillance of the CVA-62 as she transited the eastern Atlantic. Warning messages of approaching noncooperative aircraft were passed to the ship as follows. After three consistent points establishing a track were obtained, the latitude, longitude, and velocity of the target were calculated manually. This information was then encoded in the NATO code, and the message was passed via land line to the Atlantic Fleet Operation Control (OpCon) center at Norfolk. The message was then screened by OpCon-center personnel and relayed to the *USS Independence* via satellite. An average of 10 minutes elapsed during the calculation of target latitude, longitude, and velocity parameters, message encryption, establishment of land-line communications, and passing of the message to the OpCon center. Additional delay was encountered during the handling of the message by OpCon-center personnel and relay to the ship.

The average delay of more than 10 minutes is certainly too long to provide adequate warning to the fleet against high-performance aircraft. All of the functions connected with the calculation of target parameters and message formulation and transmission should be automatic by computerized methods. Endocing target information into the radar pulse would allow passing the information from the OTH radar to the fleet commander in a few seconds rather than many minutes using other communication channels.

PROPOSED SYSTEM CONFIGURATION

Figure 8 shows schematically the interconnections of the computer previously discussed. As previously described the functions of the CSP-30 computer are digital filtering for clutter rejection and LFM dechirp using FFT techniques. The functions performed by the DDP-116 remain unchanged from those performed in the present Madre system. The SEL-810B system is used as a waveform synthesizer as it is in the present system. In the proposed system the SEL 810B will have the additional functions of message encoding in the synthesized pulse and LFM chirp.

The central computer has an interface with each of the other computers. One of the functions of the central computer is to keep track of which target has had the longest time elapse since the last azimuthal update. This is necessary because with the monopulse capability being added to the Madre system only one target can be selected for azimuthal readout per frame time. The central computer could automatically designate the target for azimuthal readout to the DDP 116.

The central computer also has an interface with the CSP 30 to pass digital filter coefficient information for use in the clutter filter. This computer would also interface

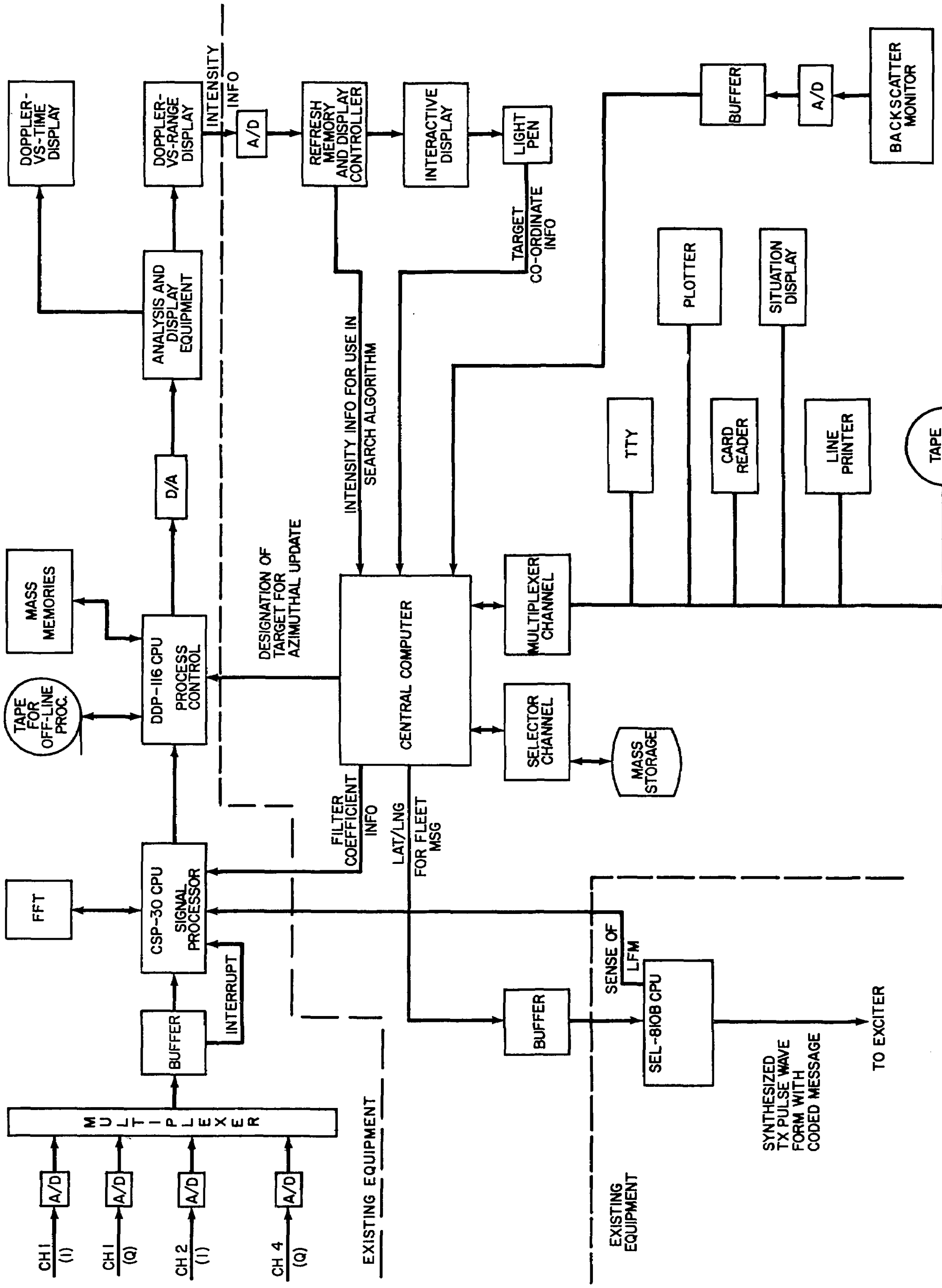


Fig. 8—Configuration of the proposed system

with the SEL 810B for passing the latitude and longitude of hostile targets or other messages for surreptitious transmission to the quiet fleet.

In addition to passing control information to other computers in the system, the central computer has the additional functions of target inventory maintenance, track synthesis and plotting, and real-time propagation prediction as previously described. The tasks to be implemented on this computer have already been described in detail. The exact system requirements in terms of amount of core and number and kind of peripherals although not definitized would likely be 64k to 128k words of memory, and as a minimum the system would have those peripherals shown in Fig. 8. Though the DDP 116, CSP 30, and SEL 810B each have their own TTY input terminals, it would seem logical in the proposed system to have only one input console as a convenience to the operator. Input parameters entered on the TTY would be transmitted as necessary from the central computer to any of the other computers in the system.

The system as proposed in Figure 8 has the minor disadvantage that the data tape created by the DDP 116 for playback would not contain raw data as it does in the present system. In the proposed system the video signal has already been through the digital clutter filter in the CSP 30 prior to entering the DDP 116. This could be remedied by the insertion of a digital recorder prior to the CSP 30.

Also highly desirable in the central computer would be interactive terminals for use in a time-sharing environment. Time sharing is desirable from the programmer's viewpoint in that program development and debug time is minimized. The operating system software of the central computer should feature concurrent time-sharing, real-time, and batch operations. The hardware of the central computer system should include several levels of priority interrupts, an optional number of real-time clocks, floating-point arithmetic, direct memory access, two- or four-way interleaved memory, and a memory cycle time of 1 microsecond or less.

No mention has yet been made of the type of computer to be used as the central computer in our proposed system. Because of the availability of applicable software previously developed on the Xerox Data Systems Sigma 5 computer in support of the FPS-95 project, it would be logical to acquire a Sigma series computer (Sigma 5, 6, 7, 8, or 9) for use as the central computer in our system. (The Sigma series computers are described in Appendix C.) Such an acquisition could conceivably result in savings on software development cost that would match the purchase cost of the hardware. It is recognized that not all of the FPS-95 programs would be applicable to our system and that our system has some unique requirements that would make additional program-development necessary. However much work has already been done at the FPS-95 site in the areas of off-line signal processing, propagation prediction, target tracking, and track plotting. It is these programs that would be invaluable to use in our system.

Most of the program development for the previously mentioned software systems was in the Fortran programming language, and all systems of the size we are addressing have Fortran compilers which meet American National Standards Institute (ANSI) standards. However most computer-system manufacturers add special nonstandard capabilities to their Fortran compilers [21]. If the programmer in developing his software systems uses only those capabilities incorporated in the Fortran ANSI standards, his program could be comparatively easily translated from the computer of one manufacturer to that of another. However most programmers frequently use some of the additional features of their unique Fortran compiler. It is the use of these nonstandard features that frequently makes the translation of Fortran programs from one machine to another time consuming and expensive.

A far more serious problem would be encountered in an attempt to implement some of the programs developed for the FPS-95 on a computer other than an XDS Sigma series computer. Many of the signal processing routines perform data-handling operations that involve manipulations of individual bits in the data word. This type of operation would be handled differently on different machines depending on the computer's word length. For this reason a complete reprogramming effort would be required for these routines that perform this type of operation.

In summary the following functions will be implemented on the specified computer:

- Central computer—real-time target inventory,
  —real-time target track synthesis and track plotting,
  —real-time message formulation,
  —digital filter coefficient calculation,
  —target designation for azimuthal readout,
  —real-time propagation assessment;
- CSP 30—digital clutter filter,
  —linear-frequency-modulation dechirp;
- DDP 116—process control,
  —data handling;
- SEL 810B—transmitter waveform synthesis,
  —encoding of information into the radar pulse.

This division of functional responsibilities describes conceptually how the system could be organized. A later report will expand on this conception and address the problems of computer sizing and interfacing in more detail.

COST CONSIDERATIONS

In the proposed system depicted in Figure 8 the central computer represents the major fiscal hurdle in the implementation of the proposed concept. If a Sigma 5 computer of the same configuration of that used in the FPS-95 system were to be acquired, the purchase price would be in the neighborhood of $1,200,000. However it is likely that this figure could be trimmed considerably by eliminating some peripheral devices used in the FPS-95 system which would not be essential in the Madre system. In addition to the purchase cost, consideration should also be given to site preparation costs (special flooring, power requirements, air conditioning, etc.) and to maintenance costs.

All of the other computers in the proposed system are already government owned. However the CSP 30 would need to be refurbished and its memory capacity upgraded by 8 words. Also a FFT box (either from the manufacturer of the CSP 30 or from some other source) must be acquired.

The cost of software development has previously been described, and the advantages of acquiring a Xerox Sigma series computer discussed.

CONCLUSIONS

There are many potential benefits to be accrued by increasing the performance of the digital data-handling and signal-processing system of NRL's Madre radar. These benefits include demonstration of current concepts of modern OTH radar system performance in a research and development environment prior to the design of an operational system and the demonstration of the utility of OTH technology for naval applications. Naval applications of OTH radar include but are not limited to fleet air defense (FAD), covert communications to the quiet task force (QTF), long-range detection of antiship missiles and low-altitude targets, detection of hostile ship movements, and monitoring of friendly ship positions in an emission-control environment. This report has discussed conceptually the system requirements necessary for the Madre radar in order to fully realize the potentiality of OTH for naval applications. These benefits can be realized for a relatively small expenditure for system hardware and software.

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Appendix A [Unclassified]
HONEYWELL DDP-116 COMPUTER SYSTEM

The DDP-116 computer is a 16-bit-word machine having a memory expandable from 4k to 32k words.* Memory addressing features indexing and indirect addressing. The memory cycle time is 1.7 microseconds. Most internal operations can be performed in two cycle times including instruction access and execution time. Thus the addition or subtraction operations may be performed in 3.4 microseconds. Multiplication requires 255 microseconds if implemented in software and 9.5 microseconds maximum if the optional hardware implementation is used.

The DDP 116 has a fully parallel machine organization. The following optional hardware is available: high-speed arithmetic capability, memory parity, direct multiplexed channel, real-time clock, and a variety of peripheral equipment including a high-speed printer, card reader, card punch, TTY. magnetic tape units, and paper-tape reader and punch. Standard software includes a symbolic assembler and diagnostic and utility routines.

The input/output system includes a word-parallel I/O bus system, 256 priority interrupt lines, and ten external function lines. The following I/O modes are featured: single-word transfer, single-word transfer with priority interrupt, and a direct multiplexed-channel (DMC).

*Honeywell, Inc., "Honeywell DDP-116 Programmers Reference Manual."

Appendix B [Unclassified]
CSP-30 COMPUTER

The CSP 30 is a 16-bit, high-speed (100-nanosecond cycle time) minicomputer.* Core memory size is from 4096 words to 32,768 words expandable in 4k blocks. In addition to the core memory the CSP 30 has a 100-nanosecond-cycle-time integrated-circuit memory. The IC memory features nondestructive readout and has a size of from 512 to 2048 words. Because of the volatility of the solid-state memory when power to the computer is lost, the contents of the IC memory may be transferred to core memory as well as IC memory. For this reason the IC memory is assigned addresses beginning at zero and masks the core memory with the same addresses.

The CSP 30 has an instruction repertoire of 291 instructions. The adding of the contents of a direct-memory address to the contents of the accumulator requires only 500 nanoseconds, and the multiplication of the contents of the accumulator by the contents of a direct-memory address requires only 1.2 microseconds. This timing assumes that the instruction and all direct-memory references are in the high-speed IC memory. These times are typical of the execution times for all instructions in the repertoire and are indicative of the high-speed capabilities of the machine.

The input/output system consists of up to four I/O channels, one of which is capable of multiplexing up to eight low-speed I/O devices. A priority interrupt system allows the use of up to 55 priority interrupt levels.

The optional direct-memory-access system allows the high-speed transfer of blocks of data between external devices and either the IC or the core memory independently of any control by the arithmetic unit.

Numerous I/O devices are available for use with the CSP 30 including a high-speed line printer, magnetic-tape cartridge units, disk storage, CRT display, A/D and D/A converters, and a fast-Fourier-transform module.

The software provided with the CSP 30 includes a text editor for preparing and maintaining symbolic source coding, an assembler language processor, a loader, a keyboard debugging package, diagnostic and maintenance routines, tape copy and dump utilities, and a tape-verify program.

*Computer Signal Processors, Inc., "Computer Signal Processor-30 Programmers Reference Manual."

Appendix C [Unclassified]
XEROX DATA SYSTEMS SIGMA SERIES COMPUTER

The XDS Sigma series computers are third-generation computers capable of supporting concurrent batch, real-time, and time-sharing operations.* General system characteristics are listed below:

- 950-nanosecond memory cycle time (900 nanoseconds for Sigma 8 and Sigma 9).
- Word-oriented memory (32 bits plus parity). Memory is addressable by bytes (eight bits), halfword, word, and doubleword.
- Memory capability is expandable from 8k to 128k (512k for Sigma 9) in 8k-word increments.
- Two- and four-way memory interleaving.
- Two memory ports are standard. Optionally six additional memory ports may be added (ten additional for Sigma 8 and Sigma 9).
- Direct addressing of the entire memory.
- Indirect addressing capability.
- 16 general-purpose registers (expandable to 256 registers)
- Fixed and floating point arithmetic operations (floating point is standard on the Sigma 8 and Sigma 9 computers and optional on the Sigma 5, Sigma 6, and Sigma 7).
- Memory write protection.
- Real-time priority interrupt system with up to 224 interrupt levels.
- Two real-time clocks (two additional real-time clocks optional)
- Optional input/output processors (IOP).

The nonfunctional or systems software available for the XDS Sigma series of computers consists of several operating systems, three assembler language processors, two Fortran compilers as well as other high-level language processors, and various utility and library programs.

*Xerox Data Systems, "Sigma 5 General Information Digest."

The operating systems available are the Real-Time Batch Monitor (RBM), the Batch Processing Monitor (BPM), Batch Time-Sharing (BTM), and the Universal Time-Sharing Monitor (UTS). Of primary concern in the choice of the appropriate operating system is the tradeoff of increased system capabilities vs increased core requirements for the more comprehensive operating systems.

The most basic monitor for real-time operations is the Real-Time Batch Monitor. RBM is a disk-oriented monitor system providing concurrent real-time and batch processing capabilities on a minimal Sigma 5 through 8 computer. RBM occupies approximately 6k of resident core storage depending on the I/O handlers used.

The Batch Processing Monitor is a disk-oriented system that was designed primarily for closed-shop batch operations. BPM also supports real-time processing on a concurrent basis. Minimum core requirements for this system is 8.5k, which would be increased depending on the I/O devices for the specific hardware configuration.

The Batch Time-Sharing Monitor unlike the RBM and BPM systems supports time-sharing operations. BTM will accommodate concurrent time-sharing, real-time, and batch processing. The time-sharing capability allows remote terminal users to create, compile, execute, and debug their programs concurrently with normal batch and real-time operations on the computer. BTM requires approximately 18k words of core.

The Universal Time-Sharing System permits time sharing and a multiprogramming batch to operate concurrently on a Sigma 6, 7, or 9 computer. This system provides most of the services of both BPM and BTM. A multiprogramming batch provides for up to 16 simultaneous batch partitions.

The language processors are the following (not all of which are available with all operating systems): Symbol assembler language, Macro-Symbol assembler language, Meta-Symbol assembler language, Basic compiler language, extended Fortran IV-H, extended Xerox Fortran IV, ANSI Cobol, FLAG compiler language, TEXT compiler language, APL compiler language, and EASY compiler language.

The utility and library programs available include such features as sort/merge, a math library, linear programming systems (FMPS and Gamma III) and several simulation languages (SL-1, GPDS, DMS, and CIRC).

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13. ABSTRACT

This report describes the need for implementing advanced concepts of OTH-system performance capabilities in a research and development environment prior to the design of an operational OTH radar system. Specifically the improvement of data-handling and digital signal-processing techniques are discussed. The benefits of increasing the digital capabilities of the Madre system include an automated methodology for target-track synthesis, real-time optimum operational frequency utilization, transmission of covert messages to the Quiet Task Force (QTF), improved probability of detection of ships through reduction of resolution cell size, and improved probability of detection of small targets such as antiship missiles. The hardware needed to accomplish this system performance is described in detail. Emphasis is placed on the impact of OTH technology on naval applications.

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