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DEFENSE OF NORTH AMERICA

Final Report

of

Project Lamp Light

VOLUME II

of 4 volumes

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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of 320 pages, 750 copies.

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Massachusetts Institute of Technology

Defense of North America

Final Report

of

Project Lamp Light

15 March 1955

Volume II

of 4 volumes

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COMMUNICATIONS

CHAPTER 6

COMMUNICATIONS

INTRODUCTION

The Systems Groups of Project Lamp Light have spotlighted a number of communication problems that must be solved if reliable defense systems are to be created. These include establishing highly reliable ground-to-air and air-to-ground communications within line-of-sight and beyond, ship-to-shore and ship-to-ship communications, and ground-based point-to-point relays.

The Data-Processing Group has made an intensive study of the communication requirements of data-processing systems for fleet units integrated into the air defense system and for other fleet activities such as antisubmarine operations. These studies have indicated that communication facilities currently available to the fleet are not adequate to permit proper operation of the integrated data-processing systems.

Proper application of new techniques and better utilization of existing facilities can provide adequate communications for the tasks considered by Lamp Light.

The new scatter modes of propagation such as meteor forward scatter, ionospheric scatter and tropospheric scatter provide means of solving the beyond-the-horizon transmission problem that are much more reliable than the usual ionospheric reflected signals.

The present short-range communication system does not provide an adequate number of interference-free channels nor does it have adequate range. A new system of multiplexing by means of time-sharing, called Centipede, is proposed. This system will provide voice and data transmission for a large number of networks on a single radio-frequency channel.

COMMUNICATION CIRCUIT REQUIREMENTS

Regardless of the method of propagation employed, it is costly to transmit large quantities of information. The faster information must be transmitted, the more power is required in a system.

The bandwidth requirements normally encountered can be segregated into three categories:

> Narrow band, meaning data rates of less than a hundred bits per second and requiring bandwidths of the order of 100 cycles per second. Such a circuit is adequate for: teletype information, the data that must be passed in the Phase 1 naval data-processing system (see Chapter 7), control information for

aircraft or missiles, and some forms of facsimile transmission. Narrow-band information is the easiest to handle, and can be transmitted by any of the means of propagation to be discussed.

Voice Band. By this is meant information bandwidths of 2000 to 10,000 cps. Such information might be actual voice signals, slowed-down video (SDV) data from a radar, information from a data-processing system, high-speed code or facsimile information.

Wide Band. In this category fall those signals having bandwidth requirements in excess of 10,000 cps and extending upwards to several megacycles per second. Such signals can normally be transmitted only by means of the ultra-short waves, i.e., carrier frequencies greater than approximately 100 Mcps.

The reliability of most communication links can be improved by transmitting proper kinds of data. Teletype circuits will operate under conditions where voice circuits would fail; SDV data can be transmitted much more efficiently than the raw video, digitalized data are less affected by noise than analogue data, etc.

A detailed discussion of the naval communications problem is contained in a later section of this chapter.

Table 6-I is a compilation of the communication tasks studied by the Communications Group and the various means ofpropagation that may be employed to meet them. The data rates that are possible, the frequency of operation, and the path lengths over which the method can be used are given, as well as comments regarding the reliability of the propagation mechanism. The statements regarding equipment requirements can be interpreted as follows:

Modest: 100 watts or less radiated power,
Moderate: 100 to 1000 watts radiated power,
Heavy: Greater than 1000 watts.

COMMUNICATIONS REQUIREMENTS IN NAVAL OPERATIONS

Navies cannot operate, under modern conditions, without good communications. As life, including naval operations, gets more complicated, the need for high-quality communications increases, since more and more data of all types are required for assimilation and use by the human beings who must make decisions if those decisions are to be correct. The use of increased amounts of data is forced on us not only by the size and complexity of modern naval organizations but also by the constantly increasing threat of hostile weapons of all types, which make speed and flexibility a prime consideration. In example consider the disappearance of the conventional battleship, which can not cope with either heavy air attack or determined torpedo attack, while its heavy guns have no suitable targets any more save in the case of shore bombardment.

As the nature of threats and targets changes, so do the formations and tactics employed by fleet units at sea, and the equipment required by them. For instance, nuclear weapons are forcing wide dispersal of ships in a formation. This in turn makes it more difficult to screen the formation against the rapidly improving submarine and forces the production of detection devices and counter-weapons having greatly improved performance.

Another modern innovation is the combined use of ships and aircraft in naval operations. While this is obvious in the case of Fleet Air Defense, it is not so obvious but equally important in other types of operation. For instance, antisubmarine operations now depend largely on both fixed and rotary-wing aircraft for search and detection because of their mobility, while employing the dogged persistence of the ship to hunt to exhaustion. Likewise, an amphibious operation must have fighter aircraft to control the air while supporting ground forces with tactical support aircraft. It is perfectly reasonable to assume that, in the future, aircraft and submarines will work together in closely coordinated operations.

One of the major advantages of a naval force is its mobility, together with the implied ability to disappear and reappear in some unexpected place. Surprise is often extremely important; under such circumstances, the use of any form of communications that may disclose the position of the force is suicidal. This again means that the form of organization adopted must not necessitate the use of continuous communications. However, communications must be instantly available when the tactical situation dictates.

Within a naval formation, it is generally true that ships in a position to support each other when under attack require a higher rate of communication than those not so placed, e. g., a task group under air attack requires rapid passage of orders and target information in order to make the maximum use of weapon potential, to avoid overkill of some targets while allowing others to go unharmed, to coordinate weapons of various types, to perform rapid maneuvers and to avoid confusion. A distant picket, whose function is to warn the task group of impending attack, need not pass nor receive nearly so much information. Distant stations, such as High Command ashore or other forces not in the area of engagement, require even less information.

Many types of traffic may be delayed indefinitely; logistic and administrative traffic often may and should be held up until clear of a danger area or even until shortly before arrival in port.

From the foregoing, some general requirements may be derived:

Flexibility	The nature of an operation must not be constrained by inadequacies of communications. The communications systems must not have to operate continuously.
Adequacy	The communications systems must make possible the integration of ships, aircraft and submarines. The systems must have high enough data rates to permit virtually instantaneous passage of vital information.
Dependability	It must be possible to establish contact, when required, with a minimum of delay. This involves selection of the correct frequency, use of sufficient power, etc. Once contact has been established, it must be maintained without interruption. This is expecially important when the terminal equipments are machines rather than men, and becomes more so as transmission rates increase.
Security	Disregarding cryptography, the systems used must be as secure as possible against (a) interception and direction finding, and (b) jamming. In general, this involves the use of very high frequencies and an organization that does not require transmission for receipting purposes where it can be avoided. Diversity of communications methods is very important.

The following methods of communication exist in the Navy: Flags, flashing lights, infrared, sonar, and radio. Of these, the first four are limited in range and in transmission rate. They can be extremely useful, however, under conditions of radio silence. Flags are the most secure method of transmission and are much used in daylight. Recent improvements have increased their range of visibility considerably (*vide* recent work on fluorescent flags). Nondirectional lights are also useful in daytime, having a range greater than that of flags. Directional lights are used for point-to-point transmission by both day and night. Infrared is used at night in close formations. Sonar is chiefly used for communication to submarines, but may also be used for station-keeping at night under conditions of radar silence. However, radio is the most versatile means of communication and must be used when high rates or long ranges are required.

The use made of radio falls naturally into two classes:

> Organization circuits (including High Command, administrative, logistics, etc.); used at long, medium, and short ranges.
>
> Tactical circuits (e. g., maneuvering, aircraft control, inter-CIC, hunter-killer, etc.); used at medium and short ranges.

One of the basic reasons for this classification is, perhaps, that traffic on organization circuits is mostly intended to be recorded, distributed, referred to and acted upon over long periods of time, whereas tactical traffic may or may not be recorded but is almost invariably the cause of immediate action of a somewhat drastic nature. It follows, therefore, that a delay of some minutes, or even hours, which might be acceptable from time to time on an organization circuit, is quite intolerable in the tactical case (this applies to both the initiation time of a message and the transmission time).

The effort to reduce delay on tactical circuits has led to the fitting on ships of a multiplicity of equipment. The situation is further aggravated by the fact that most circuits use voice transmission, which is very wasteful of time when employed to pass information of a stereotyped nature – e. g., position, course, and speed of targets. The flow of such information is further impeded by the limitations of human operators, who are incapable of coping in any sense with a high rate of flow of information, The realization of this has led to the design of various automatic and semiautomatic data-handling systems, such as those described in Chapter 7. However, in order to use the data-handling system efficiently, the requirements of speed and reliability placed on the tactical communications system will be greatly increased.

The delays and inaccuracies afflicting the organization circuits would not be so serious except for one fact: a large naval operation generates a tremendous amount of traffic. Since the chief interest of a naval commander at sea is in the tactical situation (indeed, it may well be his only reason for being there at all), neither the equipment nor the manpower required can be diverted to organization traffic, with the result that a backlog rapidly accumulates. What is required here is something of the nature of a reliable high-speed radiotelegraph, operating at 750 or 1000 words a minute. The introduction of such equipment would greatly increase the amount of traffic that could be handled on any one frequency and would greatly decrease the number of operators needed. At the same time, reliable communications (in the sense of always being able to raise and talk to the desired station) are an urgent requirement.

Since the communications required depend on the tactical situation, and tactical possibilities may well depend on the communications fitted, it is not possible to state an absolute figure for any tactical communications system. What is necessary, however, is to ensure that sufficient communications are available, as economically as the state of the art will permit, to do anything that can be reasonably imagined. This involves several types of improvement, among which are:

> Making the best use of existing equipment, both by better organization and improved maintenance,
>
> Designing new terminal equipment that will permit present bandwidths to be more economically employed,
>
> Developing new types of communications methods that will increase both capacity and reliability of operation.

An order-of-magnitude improvement in existing capacity and reliability can be achieved, we believe, by following the recommendations contained in this chapter and that on data processing, and by implementing the recommendations of the Cosmos report. This should make a good start toward achieving the flexibility that is so vital.

CONCLUSIONS

In this section are listed the main conclusions arising from the detailed work undertaken by Project Lamp Light and fully described in the Appendices to this chapter. The following section lists all the recommendations derived from the various communications studies we have made.

Communications within Line-of-Sight

At the present time, short-range communication is principally by means of AM transmission in the UHF region from 225 to 400 Mcps. Because of the mutual-interference problem, only a very limited number of circuits is available from one location, such as a ship. The Cosmos project communications group has studied this problem in great detail and has made a number of recommendations for improving this situation. We concur in these; however, even after they have been carried out, there will not be adequate numbers of channels available for many contemplated operations.

A time-division multiplexing system (named Centipede by its originators) is proposed to overcome the difficulties of the present frequency-multiplex system. This system, described in Appendix 6-A, is designed so that only one transmitter in a complete communication network, such as would be used to link a fleet together, is transmitting at a time. By this means, all danger of self-jamming and adjacent-channel interference is eliminated.

The Centipede system can be used with scatter propagation, as described in Appendix 6-G, to enable transmission beyond the line-of-sight, and can be used with an airborne relay to obtain increased range and to provide protectection against jamming, particularly beyond line-of-sight.

If desired, the timing pulse of the Centipede system can be used to provide navigation information.

Communications Beyond the Horizon

Low-Frequency Communication:– Low frequencies provide reliable communication over long ranges, especially over the oceans. They are not subject to interruptions during ionospheric disturbances. At high latitudes, where high frequencies are often blacked out, because the noise level is relatively low, low frequencies are particularly useful.

Modern engineering techniques and information theory have been insufficiently applies ? to low-frequency communication. In particular, bandwidth and power requirements can be greatly reduced and range and reliability increased. (See Appendix 6-B.)

High-Frequency Sky-Wave Communication:– High-frequency sky-wave propagation carries the bulk of long-range communication. However, high-frequency sky-wave propagation is very variable and is subject to distortion, disturbances and blackout, especially at high latitudes. (See Appendix 6-C.)

Optimum-frequency prediction services have been developed to circumvent the variability of high-frequency propagation. These have been highly successful in predicting hourly optimum frequencies on a monthly mean basis. Short-term forecasts of day-by-day variations and disturbances are still inadequate. The next step forward should be direct and frequent measurement of the optimum frequency for each circuit.

The system of frequency allocation to individual circuits requires revision. Greater flexibility to allow use of optimum frequencies is desirable. This might be attained by the allocation of frequencies in blocks to a group of circuits under centralized control.

Blackouts and disturbances, particularly at high latitudes, are frequently localized. Alternate-path relay circuits should be available to avoid disturbed regions.

Considerable improvement in the reliability of high-frequency sky-wave communication is possible by developing highly stable equipment for use in single-sideband, multichannel teletype net operation and by using frequency diversity.

High-Frequency Ground-Wave Communication:– Over the ocean, high-frequency ground-wave signals offer a means of obtaining reliable ship-to-ship, ship-to-shore and air-to-ground communications to a distance of several hundred miles. Such operations would be in the frequency range 2 to 10 Mcps. As in the situations previously discussed, full utilization of modern techniques, such as the use of equipment having good frequency stability, single-sideband operation to permit the use of narrower-bandwidth circuits, the design of noise-reducing circuits, etc., will greatly improve this mode of operation.

Ionospheric-Scatter Communication:– Scattered radio energy from the E-layer of the ionosphere has been employed to get extremely reliable communications in the 25 to 50 Mcps frequency band for distances ranging from 600 to 1200 miles. In the past, this has been accomplished using high-powered transmitters and large antenna systems. It appears that narrow-band data such as teletype information can be transmitted using the moderate powers and antenna systems that would be practical on board ship. (See Appendix 6-E.)

Meteor Communication – JANET:– Reflections from highly ionized trails of very small meteors at a height of 60 miles provide a new, reliable means of communication out to a distance of about 1000 miles. The frequency range available is between about 30 and 60 Mcps.

Transmission is in high-speed bursts spaced 30 seconds to 2 minutes apart, each lasting a second or more. Ordinary teletype may be transmitted, storage facilities being provided at each terminal to make the transition between the interrupted high-speed transmissions and the uninterrupted more slowly operating teleprinters.

Low power (100-watt) and small antennas (5-element Yagis) should provide reliable teletype at 60 words per minute over the range of 1000 miles. Message delays of the order of a minute or two will occur, but ionospheric disturbances will not interrupt communication.

Information rates suitable for data transmission or facsimile appear feasible, but voice transmission appears impractical because of the random delays – of the order of a minute.

Fixed point-to-point teletype applications are now under development or test, and techniques have been suggested that appear suitable for mobile omnidirectional communication from ships, submarines or aircraft.

Meteor communication has considerable promise against jamming or interception. Signals can only be intercepted relatively near to the receiver because only meteor trails suitably oriented for the circuit carry information. Likewise, jamming would be feasible only near the circuit.

However, considerable basic research and development must be carried out before the possibilities and limitations of meteor communication can be reliably assessed.

Tropospheric Scatter Communication:– Tropospheric-scatter techniques have provided reliable communication in the UHF band to distances of approximately 300 miles. Such systems can be designed to have intelligence bandwidths of several megacycles per second. From existing data, it appears that voice-bandwidth circuits as much as 500 miles long should be practical. Single voice-circuit or teletype operation to distances of 200 miles should be possible with modest equipment. (See Appendix 6-G.)

Omnidirectional scatter circuits, while not proven experimentally, look practical for fleet operation to distances of 100 to 150 miles.

CHAPTER 6 RECOMMENDATIONS

A. *Within Line-of-sight*

Near Term

1. We recommend that the Cosmos recommendations be carried out to improve on a short-term basis the present UHF communication systems.

Long Term

2. We recommend exploration of the feasibility of utilizing tropospheric scatter with omnidirectional antennas for fleet operation and UHF. This can either be done with relatively narrow bands utilizing a single net, or it can be explored with regard to Centipede (recommended below), or both.

3. We recommend that the Centipede time-division voice-communication system be developed for possible use in the region 225 to 400 Mcps. We list the following specific recommendations:

- *(a) Develop one or more promising accordions*
- *(b) Develop transmitters, receivers and relays of high peak power and appropriate bandwidths for Centipede*
- *(c) Develop appropriate synchronizing systems*
- *(d) Develop appropriate clocks having the necessary accuracy for Centipede*
- *(e) Develop data-handling converters for Centipede for converting radar data into Centipede transmission bursts*
- *(f) Develop equipment for handling discrete-address and reply circuits on Centipede*
- *(g) Develop circuits for putting teletype on Centipede*
- *(h) Develop communications authentication devices for Centipede use*
- *(i) Investigate the possible use of appropriate synchronized scramblers as anti-jamming aids for Centipede use*
- *(j) Investigate the possible use of Centipede with IFF in navigation schemes*

(k) Evaluate the modulation methods best suited operationally for Centipede

(l) Develop appropriate airborne relay equipment

If tests prove favorable in a reasonable number of the above categories, for both surface and air use, we recommend that the frequency assignments now employed from 225 to 400 Mcps be reallocated to permit Centipede use on an operational basis. We also recommend that present frequency-division receivers and transmitters be phased out wherever replacements are warranted by phasing the Centipede into use.

B. Beyond the horizon

1. Low Frequency

(a) The utilization of stable transmitters and receivers designed for low-frequency teletype net operation at optimum bandwidth is recommended.

(b) We recommend that small receiving loops be developed for use at low frequencies.

(c) We recommend that special attention be given to efficient design of low-frequency transmitting antennas, particularly with respect to top loading, ground screens and insulation.

(d) We strongly recommend that the development of single-channel noise-modulation systems be pushed and, in particular, that the application of this technique to low-frequency communication be encouraged.

2. High-Frequency Sky Wave

(a) We recommend that an investigation be made of the feasibility of developing and using simple equipment for ship and aircraft installation for rapid, on-the-spot, measurement of the optimum usable frequency.

(b) A reassessment of methods of frequency allocation is recommended. Assignment of frequencies to groups of circuits, controlled centrally, rather than to individual circuits, may allow more flexible use of available allocations.

(c) We recommend that the use of high-frequency alternate-path relays be extended.

(d) *We urge that stable transmitters and receivers for mobile use be developed that will allow single-sideband, multichannel teletype net operation.*

(e) *We strongly urge that frequency diversity be used with sky-wave single-sideband teletype.*

3. *High-Frequency Ground Wave*

(a) *We recommend the design and use of proper antenna systems for shipboard and aircraft.*

(b) *We recommend the design and use of stable-frequency, single-sideband equipment in the frequency range from 2 to 10 Mcps.*

(c) *We recommend the use of teletype or narrow-band letter facsimile such as Infomax instead of voice where the nature of the operations will permit.*

(d) *We recommend the design and use of noise-reducing receivers if testing proves that this is practical.*

4. *Ionospheric-Scatter Communication*

We recommend experiments to test the possibility of using ionospheric scatter with narrow-band low-power transmissions.

5. *Meteor Communication – Janet*

(a) *We recommend a research program specifically aimed at determining meteor parameters controlling communication.*

(b) *We recommend accelerating and extending present fixed point-to-point meteor teletype development programs.*

(c) *We strongly recommend the development of meteor communication for mobile use on ships, submarines and aircraft.*

6. *Tropospheric Scatter Communication*

(a) *We recommend a program to test the feasibility of using scatter propagation in omnidirectional fleet communication at UHF.*

(b) *We recommend that experiments be conducted to obtain propagation data for path lengths of 300 to 800 miles.*

(c) *We recommend that high-stability, low-power equipment be developed for voice and teletype use with the general-surveillance system.*

APPENDICES TO CHAPTER 6

APPENDIX 6-A

COMMUNICATIONS WITHIN LINE-OF-SIGHT

PRESENT SHORT-RANGE COMMUNICATIONS

At present, short-range communications within line-of-sight (surface-to-air, air-to-air, and surface-to-surface) are provided in the UHF spectrum from approximately 225 to 400 Mcps. The channel allocations call for 100-kcps channel spacings, although in some instances 200 kcps is used. In general, AM voice transmission is utilized. It would be expected that 1750 voice channels could thus be accommodated in the 175 Mcps provided. However, in fact, the number of transmissions that may be made simultaneously from a small area such as a ship is drastically limited to much less than this 1750 figure. The limitation is a result of spurious radiations from the transmitters and spurious responses of the receiver, as well as of receiver bandwidth limitations, and intermodulation introduced in non-ohmic conducting media between the transmitters and receivers. It would be expected that at present about 15 to 20 channels of the 1750 theoretical channels could be utilized simultaneously from a ship, if all equipment were in tip-top shape. Because of inadequate maintenance or other difficulites, in practice generally less than 10 channels are simultaneously available from one ship at UHF. Moreover, the present communications system requires in general very nearly two antennas for each transmitter and receiver, and one transmitter and one receiver are required for each net* which is utilized simultaneously.

This difficulty has been studied by the Cosmos project at Bell Telephone Laboratories and RCA. They have recommended certain improvements which are heartily endorsed for the near-term program. These improvements are of component details and system operation rather than new systems concepts. The Cosmos recommendations include a reallocation of antenna locations, including separation or shielding between transmitting and receiving antennas aboard the same ship. They have also included a decrease of the 200-kcps wide receiver bandwidths, plus a recommendation for a better distribution of frequency allocations among the three Services to permit better choice of net frequencies from each ship, and the use of peak clipping, voice AGC and other similar measures. They have also proposed an improved maintenance program. By these means, it is their belief that on the order of 50 or so transmissions could be made from one ship on UHF.

---

*Netting communications rather than private line communications are generally employed throughout the fleet. Nets are assigned, for example, such that one particular carrier frequency is utilized for simplex transmission and reception by all antiaircraft batteries, another carrier frequency by the CIC, another by the logistics and supply group, another for Command, and so on. Each net employs a separate carrier frequency.

However, it is becoming apparent that the needs for short-range communications are far in excess of the 50 channels that might be provided by this measure. Furthermore, it is apparent that 50 channels provided this way would require at least 50 transmitters and 50 receivers, plus a nearly equal number of antennas, and this imposes considerable complication aboard the ship. The need for passing data around, and for directing aircraft, plus the demands of joint Army, Navy and Air Force operations, impose further limitations and increase of channel capacity requirements over that now employed for strictly Navy operational and logistical messages. Furthermore, anti-jamming considerations would generally call for an increase of transmitter power by at least 10 times, and this, with present techniques, will make the intermodulation and receiver desensitization problems even worse.

PROPOSED CENTIPEDE SYSTEM – GENERAL

In an effort to reduce the equipment complexity currently required for UHF transmission, and in an effort to simultaneously provide for a vastly increased channel capacity, it has become the conclusion of Project Lamp Light that short-range communications should be provided at UHF not by frequency division but by time division. More particularly, it is proposed that under most traffic conditions in any one geographical area of perhaps a 400-mile diameter circle (see Fig. 6A-1) only one transmitter is to be on the air at a time. In this way, all the difficulties of intermodulation and spurious emanations and receptions disappear. We have found that a system* can be devised with this restriction which can be adapted for voice transmission. On the order of 100 separate voice transmissions can be made on each RF channel assigned, and all this from a single transmitter and receiver utilizing but a single antenna. This represents about an order of magnitude more communications capability than at present, with an equal reduction of complexity. Maintenance will obviously be better because of the reduction of numbers of transmitters and receivers.

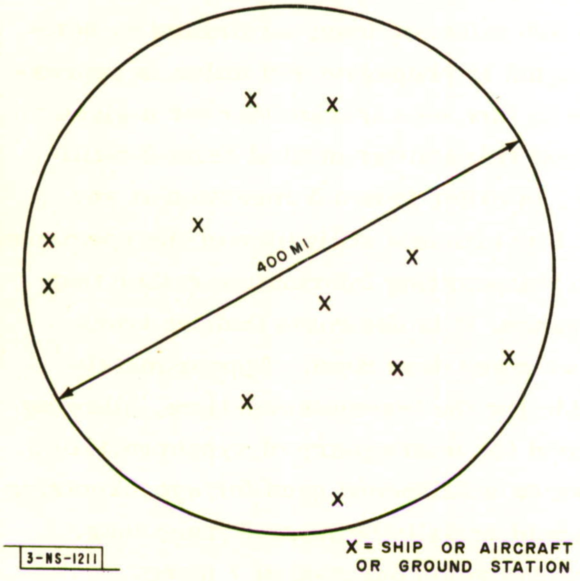

Fig. 6A-1. Short range geography.

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*This system is hereafter referred to as "Centipede".

Each receiver-transmitter will appear as in Fig. 6A-3. By adding extra transmitters and receivers to the single ones required for 100-net capacity, more than one RF channel may be employed simultaneously, but with a limitation on the number of RF channels equal to that currently permitted by the present frequency-division systems. About 35 RF channels could be provided for Centipede use throughout the currently assigned UHF spectrum. However, it would not be expected that more than 2 or 3 of these RF channels would need to be used from a single ship at any one time. Hence, the system would provide for 100 or more voice-transmission channels from a single ship or control center, or an enormously larger number of data-handling or discrete-address channels. Specific methods whereby this may be accomplished are described subsequently.

Derivation of Specific Operating Parameters

CENTIPEDE SYSTEM – DETAILS

In order to use time sharing in the manner described above – that is, in such a manner that only one transmitter will be on the air in a given area at any one instant of time – it is necessary that allowance be made for the time of transmission from the transmitter to each of the variously located receiving points. We shall assume that the propagation distance will in general be 400 miles or less, as limited by horizon and transmitted power. The time for the signal to propagate 400 miles is approximately 2 milliseconds. Therefore, if we were to turn on a transmitter for a given burst of intelligence, we must not turn on the next transmitter until at least 2 milliseconds after cessation of the first transmitter, in order to avoid reception at any location of two transmissions simultaneously. For efficient utilization of the spectrum, it is desirable that most of the time be spent in transmitting information rather than in keeping transmitters turned off. For this reason, it is desirable that the transmission time be substantially longer than the two msec dead time. Approximately 7 msec out of every 10 msec would be reasonable for the transmission time, allowing 2 msec propagation time, and another millisecond for misregistry of synchronization. In practice, it will probably turn out that this extra millisecond used for synchronizing will not be needed, so that each transmission could actually be made 8 msec long. However, in what follows we shall assume a transmission duration of 7 msec.

By thus letting the transmitter go on the air for 7 msec, and allowing 3 msec dead time, a time interval of 10 msec is allocated for each transmission burst (see Figs. 6A-2(b) and -2(c) for timing sequences). One is then faced with the choice of how many separate transmitters or nets one would like to accommodate. If we assume this number is 100 per RF channel, then each transmitter may go on the air once every second to emit its burst. This one-second time delay between bursts is also compatible with other parts of the communications problem, since it does not appear excessive for voice communications, data handling, or aircraft guidance. Thus, with each transmitter on for 7 msec, 100 separate transmitters may be employed to emit messages each second. The amount of information that may be emitted from any one transmitter during its assigned time is dependent upon the bandwidth utilized for transmission (see Fig. 6A-2(a) for a typical waveform of one transmission intelligence burst). As a compromise between several conflicting factors, it is concluded that a bandwidth of intelligence of about 0.5 Mcps would be desirable during transmission. This compromise is based upon the ease with which the transmitter and receiver may be made, the capture ratio available in FM reception, and upon the ease with which "accordion" devices (to be described later) can be developed. It is also based in part upon the requirements for the amount of information (voice, data, or discrete address) that might be employed in any given net.

With 0.5 Mcps of intelligence to be transmitted from a transmitter during the time that it is on the air, the question then arises as to what type of modulation shall be used. In the interests of providing high transmitter power, of simplicity, of providing easy netting operations despite signal-level changes, and of easing the multipath problem, it would appear as though FM modulation with a deviation ratio of about two would be desired.* Thus the transmitted spectral width would be on the order of 3 Mcps plus some small guard bands. One could therefore assign RF channels approximately 5 Mcps apart to carry this 0.5 Mcps of video burst intelligence. This would then permit the assignment of 35 separate RF channels for the Centipede. This sort of RF channel spacing is also very compatible with using a high degree of preselection in the receivers, so that in actual practice transmitters could be spaced only 5 Mcps apart on a single ship platform if necessary.

---

*Of the other conventional forms of modulation, double-sideband AM would appear to be less desirable from a multipath standpoint, and single-sideband AM would appear to require excessive transmitter complexity for a power output necessary to provide the same range as FM. However, single-sideband AM would have certain advantages for multipath on sped-up unscrambled voice from the accordion, since the ear can readily interpret in the presence of short echoes. Each multipath radio propagation path causes on single-sideband a clear echo as though a reflecting wall were located some distance from the observer. The equivalent distance to the wall is about one acoustic foot per mile of radio range difference, due to accordion at the receiver. Thus multipath will generally be equivalent to listening in a room of less than 100 feet linear dimensions. This advantage of single-sideband could be properly weighed only in field trials of single-sideband and FM simultaneously.

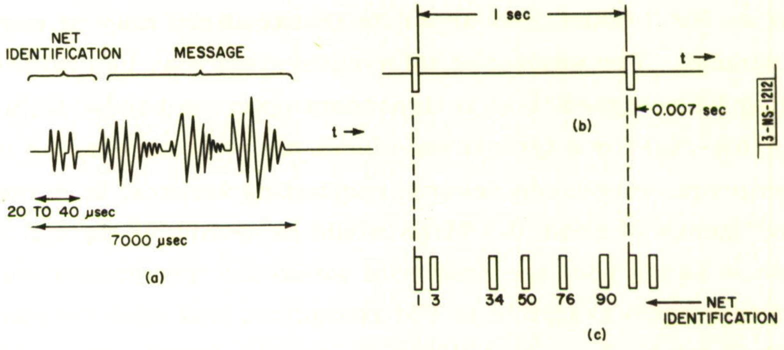

Fig.6A-2. (a) Details of single burst on net 1, (b) succession of bursts on net 1, (c) six nets operating simultaneously from one transmitter.

Anti-Jamming Considerations

In proposing a new communication system, such as Centipede, jamming has been one of the primary factors considered, in view of the vulnerability of an entire defense system to failure of communication channels. This matter is discussed in general in Chapter 9. However, particularly as applied to Centipede, the following considerations are pertinent.

First, if we consider the problem the enemy would have in trying to jam all one hundred nets, compared to his problem of jamming a hundred nets with standard UHF communications, it is apparent that his average jammer power would have to be about the same as the jammer power necessary to jam a hundred standard nets, assuming we employed an average power on each net of Centipede equal to the average power we would employ with each net of standard communications. However, it is apparent that Centipede is extremely well adapted to permit high transmitted powers, since it does not cause trouble to adjacent receivers, and since the transmitter need not have its final stages particularly linear. This is true whether the transmission is voice or data. This contrasts sharply with certain types of data-transmission systems such as the frequency division FM subcarrier system being considered now by the Services.

It will become evident in what follows that in fact transmitter powers capable of providing for tropospheric scatter to about 100 miles range appear feasible. These transmitters have about 55 db more power than would be required for line-of-sight communications at 100-mile range. Therefore it would be expected that jamming of communications that are within line-of-sight distance of each other would be extremely difficult from an airborne platform, in view of the 55 db extra signal that is available above noise at a 100-mile range from the transmitter. The jamming could be effective of course when the jammer is within line of sight of the receiver and when the desired transmitter is utilizing scatter for propagation.

However, as will be evident later, it is possible to utilize an airborne relay with Centipede so that reliance on scatter will not be necessary.

It may turn out that certain communications nets are more important for the air battle than other nets. In this instance, the bomber has a strong incentive to jam only these particular communications nets. In the case of the Centipede, in order for the enemy to select certain nets, he would have to find their time of operation. This requires a certain degree of intelligence aboard the bomber and necessitates listening to the transmissions. If we give the enemy credit for utilizing such listening gear, then we must improvise means that make any one net sound like any other net. Though this can be done with fair ease on voice, it is not easily possible to make the discrete address nets look like voice nets or vice versa. However, such measures may prove worth while. One such simple measure is to scramble the sequence in which the several nets occur after a master synchronizing identification mark or after some arbitrary one-second timing.pulse. This net time position jumping would follow some prescheduled code known only to our own communication centers.

Additional security against jamming is provided if the RF channel used for carrying an entire Centipede net is randomly moved from one part of the spectrum to another part of the spectrum. The random motions must be programmed ahead of time so that they are known to us but not to the enemy.

An additional and important anti-jamming measure is insuring that a received message is authentic. Measures that insure that a received message is indeed a valid one are discussed in Chapter 9. These methods in general reduce the rate at which information can be transmitted, but when it is received it can be truly determined whether or not an enemy has caused part of the message to be misleading.

Transmitter Power Requirements

The transmitter power required is strongly dependent upon operational needs. For example, when line-of-sight paths exist, the peak power requirements are vastly less than when tropospheric scatter must be used. Moreover, it will be apparent that the

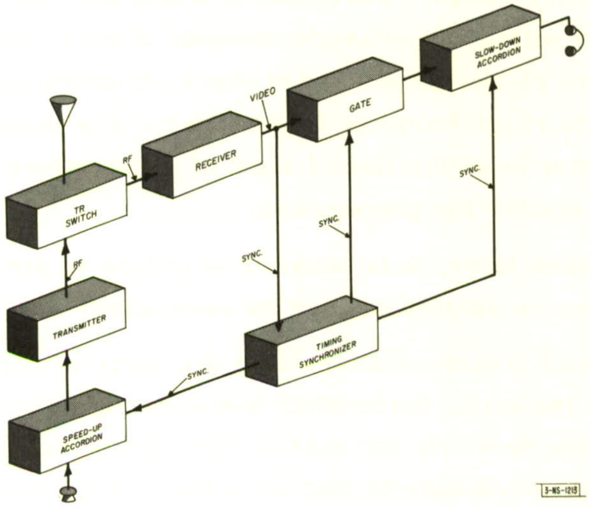

Fig.6A-3. Basic Centipede voice transmitter-receiver.

average power required of a transmitter goes up linearly with the number of nets that must transmit from that transmitter. Thus a minesweeper, which might require only a single net, would employ a transmitter having an average power of only 1/100 its peak power. However, an aircraft carrier or a fighter direction center might employ perhaps 50 nets from a single transmitter, and hence require an average power that is one-half the peak power utilized.

Let us first consider a transmitter capable of providing tropospheric communication over 100-mile range. If we employ an antenna approximately 15 feet high, it will have a gain at 300 Mcps of 10 db in the vertical direction, but be omnidirectional in azimuth. For ship-to-ship use, we can employ such an antenna on each ship so that we would have a net antenna gain of 20 db for both the transmitter and receiver. Under these conditions, the space loss including the antenna gain would come out to be about 103 db at 100-mile range. Scatter communication will add on the average about 55 db more to this. Thus, the total space loss for 100-mile scatter communication would come out to be about 158 db. If we employ a transmitter of 100-kw peak power during the 7-millisecond burst period, then the received signal would be 78 db below a milliwatt. Since the receiver bandwidth will be on the order of 3 Mcps, this received signal will be about 32 db above thermal noise, or about 25 db above the noise of the receiver.

Thus a transmitted power of about 100 kw will provide a margin due to fading, systems degradation, and all other causes of about 15 db (to still yield a 10 db signal-to-noise ratio at IF) for beyond-line-of-sight communications to 100-mile range.*

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*Operational tests may show that a somewhat greater safety margin should be employed. This can be achieved by a reduction of advertised range, or an increase of transmitter power.

Powers on the order of 35 to 45 kw average ought to be obtainable by straightforward development utilizing a pair of tubes such as the 6448. The power that could be obtainable on a pulse basis of a 50 per cent or lower duty cycle ought to be in excess of this value. The mode of transmission (FM with on-off pulsing) appears particularly suitable for the use of several tubes in parallel or in sequence, so that the 100-kw peak power would seem readily attainable in the near future.

For line-of-sight communications, air-to-air, at 400 miles, the transmitter peak power required remains at about 100 kw, if no antenna gain is employed either horizontally or vertically; reasonable antenna gains (5 db on transmitter and 5 db on receiver) lower this to 10 kw peak required. This figure is deemed reasonable, since the average power required would be only 100 watts per net used simultaneously by the aircraft.

Voice Transmission

In order to transmit voice on any one net during the 7-msec burst, the voice signal is recorded continuously on, for example, a magnetic tape or drum. Once each second the tape is read, but at a frequency speed-up of 140 to 1. Thus the full one-second voice transmission is compressed into one 7-msec transmission period. The compression device which thus compresses time is called an "accordion." A companion accordion at the reception end is utilized to stretch out the 7-msec received burst information into the normal one second of audio. Several possible techniques for making an accordion are described in Annex 6-A-1.

By thus utilizing a compression accordion at the transmitter and an expansion accordion at the receiving site, the listener hears the voice just as it is transmitted, except for certain inherent defects believed to be tolerable in a military communications system. These defects include a possible tick, which occurs once per second due solely to the receiver or transmitter alignment errors. Also there is a time delay between the time of the speaker's voice until the listener hears this voice. This time delay will be one second or longer, depending upon the type of accordion employed.

The big question with the accordion is not whether it will work, but rather which type of accordion will be most practical for ship, ground, and/or air use.

Synchronization in the Centipede System

In the Centipede system, it is necessary that each receiver and each transmitter know relative time to within about one-half millisecond, in order to have an approximate indication of the time at which it will be desired to transmit or record information. More-exact synchronization is preferably provided by the actual address code put on the beginning of each transmission.

In order to obtain synchronization within about a half-millisecond, it will be desirable that each transmitter-receiver carry a crystal-controlled clock, which should be good to about 1 part in 10^7. This is apparently feasible at present, and no need is foreseen immediately for the molecular resonance clocks with regard to synchronizing for strictly communicational purposes. As will be pointed out later, however, a molecular-beam clock would be useful if it is desired to provide navigation or high-security IFF with the aid of the Centipede system (see Annex 6-A-2).

The crystal clock will drift from the correct time by about a half-millisecond every 1-1/2 hours. Therefore, it is necessary that, somewhere within the short-range communications group of about 400-mile diameter assumed for the Centipede system, one particular crystal clock be considered the master, and that information from this clock be delivered to each of the other receiving and transmitting sites at least as often as once every 1-1/2 hours. Under conditions of nominal radio silence, this might be achieved by transmission of the synchronizing pulse only at very infrequent intervals, the limiting interval being once per 1-1/2 hours, but perhaps a more practical interval being once every quarter-hour.

The synchronizing information could, for example, be in the form of an identification code starting at the beginning of the time burst for net 1, as shown in Fig. 6A-2(a). A ship somewhere in the center of the task group would be assigned the job of emitting these synchronizing pulses, even though it had no intelligence to emit on net 1. Net 1 might be reserved for emission solely from this ship. The synchronizing information need only take a few per cent of the total 7-msec burst. If we assume that there are to be up to a thousand possible nets which might wish to take the air at any one of the one hundred possible net timing intervals, then we shall need a 10-bit pulse code designation for each net, which will take only 20 to 40 microseconds. Hence it is concluded that the synchronization of a Centipede system will not be a problem, once established. Initial establishment of synchronization will take some time. Consideration will have to be given to this problem, particularly in the case of an aircraft flying from one Centipede system to a second system, not synchronized with the first. The problem here is that of establishing synchronization with the new Centipede in a very short time, rather than after a minute of waiting. It is believed that this problem is readily soluble, in the absence of jamming, simply by letting the aircraft decoder listen to each net identification, and clearing the decoder at the end of each transmission burst. When the decoder hears its net signature, it can then initiate impulsive synchronization, and AFC can be allowed to take over later.

The time occupied by transmission of the synchronizing information (net identification) would therefore be on the order of 20 to 40 μsec out of the total of 7000 μsec utilized for intelligence transmission during each burst. This much time allows a 10-bit identification (one in 1028 nets).

Ships within range of the central transmitter can synchronize their clocks directly by the timing pulses emitted on net 1. Ships outside this range will have to rely on relaying of appropriate timing information, generally on a different net than net 1. Such relaying can be assigned by doctrine to other geographically dispersed ships in the fleet, which are each synchronized by net 1 from the central ship, and each of which transmits other synchronizing information at the start of another net to the more remote ships. By some doctrinal procedure, one of these relay ships could take over the master synchronizing function if the master synchronizing ship emission fails.

In times of continuous communication - that is, when there is no radio silence – the synchronizing pulses from the master ship and from the relay stations would be emitted once per second in general.

More exact synchronization than the half-millisecond provided by the clocks at each receiving site is then obtained by listening at the receiver site to the net designation, which occurs at the beginning of each transmission burst. A block diagram is given in Fig. 6A-4. A gate at the output of the receiver will be open for approximately 10 msec each second to insure that a transmission made on the net will pass through this gate. This gate will then have its output fed to a decoder which will interpret whether or not the intelligence coming through the gate at the time includes the code corresponding to the net to which this particular receiver is to listen. If that code is received, then it is known that the message will start at a predetermined time interval after the last pulse of the code. At the start of the message, the accordion will be put into action, if voice transmission is being received, to store the sped-up voice message for subsequent slow-down. Thus, the accordian could be synchronized with an accuracy of a microsecond or so in principle, despite variations in transmission distance that might account for one or two milliseconds' differences in timing between successive transmissions on the same net as received at a given site.

This accuracy would be sufficiently high that an audible effect due to misregistry of transmit and receive accordions would be undiscernible.

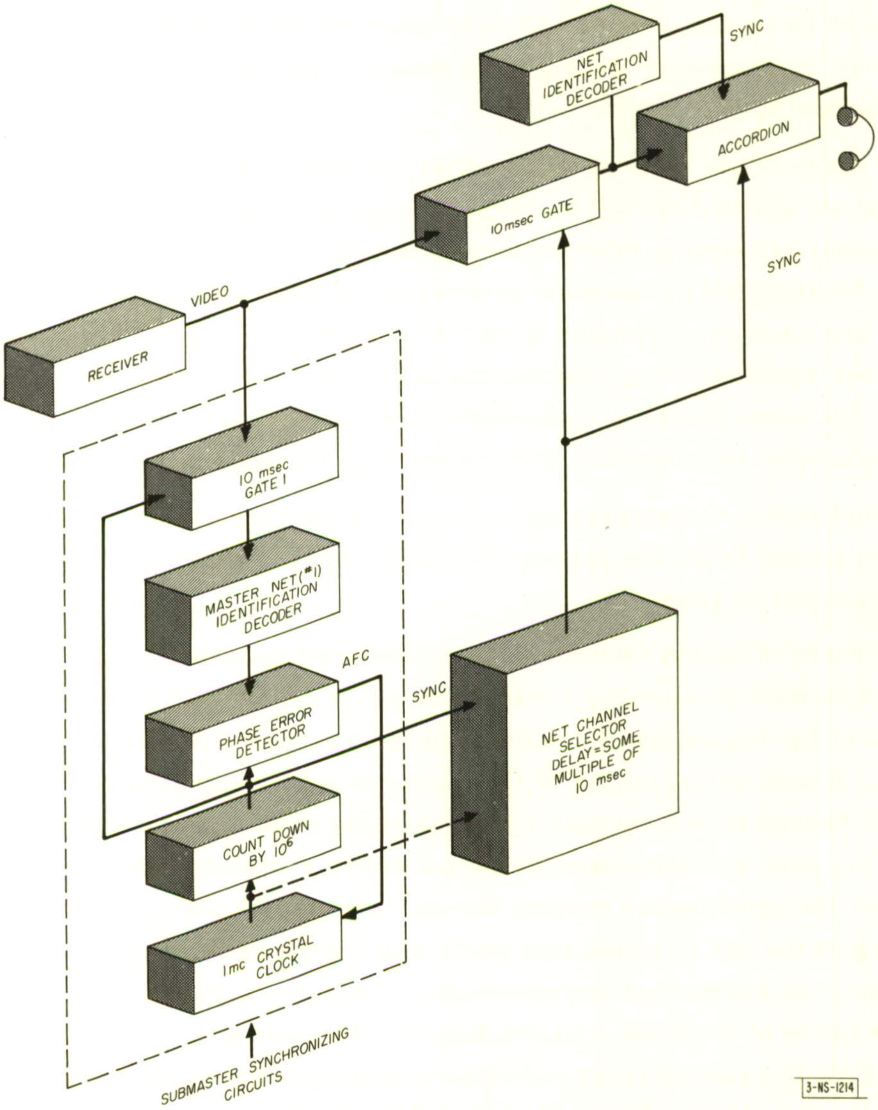

Fig.6A-4. Details of synchronization to master station.

In some instances it may be desirable to put memory into the exact time intervals at which the accordion is to record the incoming information. Such memory would insure recording at exact one-second intervals even though the synchronizing information happened to be jammed or otherwise obstructed at the start of each reception period. Such memory can be incorporated in the AFC circuits shown in Fig. 6A-4.

Netting Operations

The Centipede system may be used to provide communications on any one of a hundred nets, or on all hundred nets simultaneously. Moreover, it can be utilized with switching to accommodate transmission to a hundred nets simultaneously out of a total of, say, a thousand possible nets.

For example, if we are to operate the Centipede so that only a hundred nets are to be utilized, and provision is to be made for utilizing any or all of these simultaneously, then the time of transmission after the master synchronizing net pulse is used is an indication of which net is on the air. Thus, if one chooses to transmit information to all parties on net 30, he will start his transmitted pulse 300 msec after the master synchronizing pulse. If someone else is coupled into net 31, his transmission will start 310 msec after the master synchronizing pulse. A single transmitter will be used to transmit information from all nets utilized from a single platform, and hence the average power of this transmitter will go up linearly with the number of nets simultaneously on the air from that platform.

All parties in the task group that are required to listen to a particular net have their receivers tuned to the required RF channel utilized by the entire task group, and the output of each receiver is gated so as to pass signals only at the time intervals occurring once per second at which the given net is expected to come on the air. Thus, if a particular party is to listen to net 30, his receiver will be gated so that its output can be accepted only in the time interval from 300 μsec to 310 μsec after the master timing pulses. The output of this gate will include a short address whenever a transmitter is on net 30. This short address will give exact synchronizing information indicating when the receiver accordion is to start recording the subsequent information coming out during the 7-msec transmission burst, as described earlier. The information stored in the accordion is then read out slowly to provide continuous voice throughout the one-second interval between successive recordings.

If several parties desire to listen to a corresponding number of different nets at any given receiving site, then the receiver output is fed to a corresponding number of gates and accordion devices, each gate and accordion device being set to respond at the proper time interval after the master synchronizing pulse.

We may now consider the problem when more than one hundred nets are to be provided with communication, but no more than 100 simultaneously on a given RF channel. In this instance, there are two modes of operation having their respective advantages and disadvantages. In one mode of operation, there are 10 possible nets assigned to each of the 100 transmission net time intervals. Thus, the time interval of 300 to 310 μsec after the master timing pulse could be assigned to any one of 10 possible nets. Each of these 10 possible nets when it wishes to go on the air would utilize the same time of transmission. However, each receiver would be activitated only when the particular net designation which was then on the air was appropriate for the receiver indicated. Thus, each listening station would include a radio receiver with its video output gated to permit passage of signals for the appropriate 10-msec time interval. When the output of this gate is a series of pulses that match the code for the particular listening net, then the transmitted information is recorded in the accordion and used to activate the party's headset.

Under the alternative mode by which more than 100 nets can be accommodated, but no more than 100 simultaneously, any one net when it wishes to go on the air takes any free time of the 100 possible free times to emit its signal. In order to do this, it uses a time finder similar to a line finder on telephone switching systems. That is, it looks for some vacant time when no transmission is taking place, and then emits its message during 7 msec of the 10-msec blank space. The first part of this message includes the identification as to which net it is a member of. All receiving parties desiring to listen to this net must therefore have a receiver that continuously looks in each of the possible 100 times of transmission to see whether a signal is being received having a code designating its particular net at the beginning of the transmission.* Whenever such designation is received, the information is stored in the accordion and slowed down in the usual fashion. This second mode of operation is described

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*It is nonetheless possible that more than one party get on the air simultaneously. Such a possibility is a result of time delay in signal propagation (which would permit two parties to grab a single time burst, whether or not they are members of the same net.) Also, variation of signal strength, due to propagation over assorted ranges, may cause one party to think a time of transmission is unused, even when a remote transmitter is on the air. This condition can cause different members of a single net to simultaneously use two or more of the 100 different time bursts. Since this possibility will be difficult to prevent, each receiver should perhaps keep its decoder examining all possible 100 burst times for its own net identification, even when one burst time is being used at the receiver. This would lead to the need for more than one accordion per net at each receiver, and would tend to reduce reliability of usual netting concepts.

primarily to point out that it is full of operational difficulties and hence likely to be less reliable than the method described in the paragraph immediately above for accommodating more than 100 possible nets.

Airborne Relaying

The Centipede is particularly adaptable to beyond-line-of-sight communications within a task group by utilizing an airborne relay. An airborne relay would normally not be required for communications out to 100 miles ship-to-ship. However, in the presence of jamming, this distance cannot be bridged ship-to-ship without it. Therefore, provision should be made for an airborne relay when required.

There are two methods that appear attractive for making an airborne relay for the Centipede system. One of these systems utilizes a shift of the incoming information to a new carrier frequency, and the other system utilizes a shift of the incoming intelligence to a new time.

In the first method of operation, the airborne relay would include a receiver which listened to all transmissions on a given RF channel, and which retransmits all these transmissions as soon as received by modulating them upon a different RF channel. A simple heterodyne repeating operation would be all that would be required, and the signal need never be demodulated to video. The aircraft would be high enough to insure line-of-sight communications to the entire task group. For this purpose, the aircraft should be at an altitude of perhaps 20,000 feet or more. Care must be taken that the transmitter does not interfere with the receiver, but this should be a soluble problem despite the power-level difference between the transmitter and receiver – that is, this problem is no worse than that of obtaining two UHF channels on present UHF frequency-division systems allocations from a single platform. Likewise, when this method of relaying is used, it is necessary that each ship be capable of simultaneously receiving information on two RF channels. This is also a soluble problem, since at present up to 7 RF channels can be received simultaneously, and the Cosmos recommendation, if followed out and applied to the Centipede, would increase this number to something close to the full 35 channels which Centipede would permit.

In the second method by which an airborne relay may be provided, the surface units would utilize only even nets for their emissions, for example nets 0, 2, 4, 6, etc. The airborne receiver (see Fig. 6A-5) would listen to all these emanations from the surface, delay them 10 msec and then retransmit them on the same frequency. Thus all relay channels will come out at time intervals corresponding to net 1, net 3, and so on.

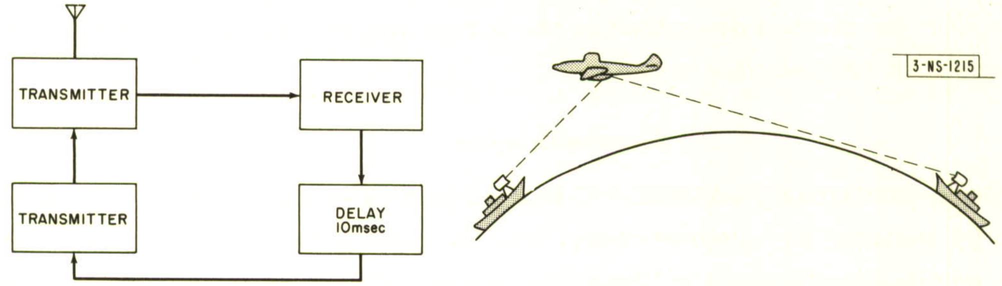

Fig.6A-5. Centipede airborne relay.

In this manner, the number of nets that can be handled is reduced from 100 to 50 on each RF channel, but there is then no problem at all either in the airplane or in the surface ships of receiving information at the same time it is desired to transmit.

Control of Aircraft via Centipede

Control of aircraft may be considered in two classes. In one class, information may be transmitted to the airplane only about once every 10 seconds. In the other case, for example in landing, information must get to the airplane about once every second.

In the first case (that is, for vectoring the aircraft toward the target area), a single Centipede net from the control center could transmit separate control messages to 350 or more individual planes. In order to do this, the single net time interval of 7 msec may be used on a time-sharing basis as follows. First, the 7 msec is divided into 70 time intervals each 100 μsec long. Each of these 100-μsec time intervals is used to address an individual aircraft. It is therefore possible to address 70 aircraft on the given net once each second. Since each individual aircraft needs be addressed only once every 10 seconds, then 700 aircraft may be individually addressed during each 10 seconds. Alternatively, since it is ordinarily not desired to individually direct 700 aircraft from a single platform, it would seem desirable to address perhaps only 350 and repeat each message twice during this time interval, thereby insuring somewhat better communications despite possible jamming or propagation difficulties. The 100 μsec allocated for each message transmission would include bits occurring about 2 μsec apart. In this fashion, about 50 bits of information could be transmitted per message. Of the bits, some 14 would be used to identify the particular aircraft involved (permitting private address for each of about 16,000 different planes) and the remaining 35 would be used to convey the desired message. This system is similar in principle to the discrete-address system currently under development. However, the transmission bandwidth is very much wider than that of the present discrete address system, and since the transmitter is only on the air one per cent of the time for the direction of these aircraft, the other 99 per cent of the time is available for other information.

The problem of permitting an interceptor to go from one communication zone to the next has, in the past, been a considerable one. It is believed that the Centipede will make such a problem relatively simple. We may, for example, utilize the same RF channel in several adjacent ground areas. However, the several ground sectors would utilize different time-division nets on the same RF channel instead of different RF frequencies for their control. The airborne equipment would then include a single RF receiver tuned to the appropriate RF channel in use for the several areas over which the plane is going to fly, with the video output of this receiver fed into several decoders. One decoder listens to those transmissions emanating in one particular region corresponding to the time-division net for that region, while another decoder listens for transmission from another region. The decoders are relatively simple, and as many of them could be used as the number of ground-control areas the interceptor was expected to pass in its total flight. The circuitry associated with each one of these decoders would be so arranged that the amplitude of the RF signal strength received during the time that messages were sent into the decoder would also be known to the apparatus. The apparatus then selects the output of the particular decoder that had the strongest input at the moment, since the decoders have output only from messages addressed to the particular plane in which they are carried. In this fashion, the pilot can fly along without having to do any switching as he goes from one control region to another.

By thus using the Centipede to carry the discrete-address information, we have removed the need for utilizing several closely spaced transmitter RF carriers aboard the single platform, and have hence continued to avoid the intermodulation problem currently experienced.

When it is desired to land aircraft and messages must be transmitted to each aircraft once per second instead of once per 10 seconds, then a 7-msec net different than the 7-msec net utilized for vectoring information should be employed. This second 7-msec net may thus simultaneously address about 70 aircraft to give them landing instructions at the rate of one address per second. In this instance, the 100 μsec utilized for transmission to each aircraft would include, first, the 14-bit identification of the aircraft, and then the landing instruction information for the remaining 36 bits. It is believed that 70 represents an adequately large number to be addressed for landing, and hence we have utilized only two nets out of the total 100 provided by the Centipede for providing all instructions to aircraft both for vectoring information and for landing.

Communications from Aircraft to Ground or Ship

It is deemed desirable, particularly by the Navy, that aircraft have communications back to the ground or ship. It is possible to provide such communications in the Centipede system by any of a number of possible methods, each differing somewhat from the single-net surface-to-air discrete address concept described above.

Of course, if desired, air-to-surface replies could be by the standard Centipede netting operation, with several aircraft sharing a single 7-msec net. However, it would appear desirable to provide instead a method whereby each plane could reply to a controller on his own private channel. If there are a hundred or more planes in the area at a time, this would utilize an entire Centipede RF channel for such replies.

However, it is possible that replies from the aircraft to surface be achieved in a more economical fashion, one of which is to assign one 7-msec Centipede net for voice communications to each group that is operating in the area. Hence perhaps two or three nets would be utilized for voice air-to-surface or air-to-air. In addition, a few more nets of the Centipede would be utilized for data transmission for air-to-surface. In crude fashion and most simply, these data nets could be utilized as follows. In general, it is necessary that the air communicate with the ground with data only about once every 10 seconds. Hence, each Centipede net could be used on a time-sharing basis so that 10 aircraft could share the same 7-msec net. To do this without interference, a round-robin type of transmission would be used in which each aircraft has an adjacent time interval differing from its predecessor by one second. Even more, the 7 msec allowed for transmission is much more than is necessary to get all the data required for the data link for air-to-surface. Hence, each aircraft need utilize only a very small fraction of this, for example, 100 μsec, to transmit a 50-bit message. Thus, we may place at least 3 aircraft on a given Centipede net in each second, or a total of 30 aircraft may then transmit in a 10-second repetition period on a given net. The 3 aircraft would have times of transmission assigned at the beginning, middle, and end of the 7-msec time interval, and 10 such groups of aircraft would then share the single 7-msec Centipede net at a 10-second repetition period. Each aircraft would start its message with its own identification, and then continue with the rest of the message. The control center would then sort each message by utilizing the information at the beginning of the transmission telling it which aircraft was the originator. By thus staggering the times of transmission, no two transmissions would be received simultaneously at the control site from any of the 30 aircraft on the given net. Hence all the usual intermodulation difficulties are avoided.

If it is desired that more than 30 aircraft transmit information to the control center simultaneously, then, in this simple scheme just described, more nets must be used for the data link. If 300 aircraft must be so individually treated, it would be reasonable to assign 10 nets for the data linking for air-to-ground.

A somewhat more elegant scheme for air-to-surface data is possible, which would permit 350 or more aircraft to occupy a single 7-msec Centipede net, but would involve more equipment complexity. In this system, each aircraft would use a 100-μsec burst once every 10 seconds, as above. However, each aircraft would now make its time of transmission such that at the surface control center all the aircraft transmissions would be appropriately staggered in time. Thus, each aircraft must know his distance from the control center. For this purpose either Tacan or Centipede navigation might be employed, or any other type of suitable navigation including dead reckoning. For example, if the pilot knows his distance to within an accuracy of perhaps 2 miles from the control center, then his transmission, which might take 100 μsec, could be centered with an accuracy of about 10 μsec as it arrived at the control center. In order to accomplish this, the aircraft apparatus must take into account the distance from the aircraft to the control center and must advance the time of transmission from the nominal time of reception by the propagation time of the radiation from the aircraft to the control center.

By this method, each aircraft is assigned a particular 100 μsec out of every 10 seconds in which to have his message received. The control center then continuously listens during this 7 msec assigned for air-to-surface data, and receives once-per-second transmissions from 70 aircraft, and, after 10 seconds has elapsed, it receives transmissions from up to 700 aircraft. When fewer than 700 aircraft are contemplated, then one aircraft may utilize several successive time intervals for transmissions thereby utilizing redundancy to make up for possible systems shortcomings such as enemy jamming.

Teletype Transmission on Centipede

For the same reasons that it is desirable to utilize the surface-to-air communications on Centipede, it is also desirable to transmit short-range teletype on the Centipede system rather than on separate UHF carriers as at present, since these have the mutual interference problem that Centipede avoids. When the Centipede is applied to teletype on short range, it is apparent that the bandwidth provided on each net is far in excess of that which present teletype systems can handle efficiently, that is, the effective bandwidth is about 500 kcps during the time the transmission is on (which is about 0.7 per cent of the time), so that the average bandwidth which the teletype would have to keep up with is something on the order of 3500 cps. Present teletype equipment is only capable of following at the rate of 150 cps. Hence the utilization of any single one of the hundred possible Centipede nets for a single teletype channel is wasteful of bandwidth, since each should be able to accommodate on the order of 20 or more teletype channels. However, if desired, it would be possible to utilize a single teletype channel on a single Centipede net and take advantage of the redundancy which could be enabled thereby to provide extremely reliable teletype transmission. An accordion would still have to be used at the transmitting and receiving end to make the system compatible with the existing teletype coders and decoders.

Alternatively, it would be perfectly practical to time-share from a single transmission site 20 separate teletype messages on a single 7-msec Centipede net. This would be done in a manner similar to the surface-to-air discrete address described above, that is, the 7 msec would be split into 20 easily distinguished time intervals each 350 μsec long. Twenty separate specialized accordions would be required at the transmitter and at the receiver in order to accommodate the 20 teletype channels simultaneously on each Centipede net.

NAVIGATION BY THE CENTIPEDE SYSTEM

The Centipede system utilized with three surface stations of known location can provide navigation information to any aircraft or ships listening to transmissions from these three Centipede transmitters. Such navigation would be somewhat similar to Loran, but would have a much wider bandwidth available and hence permit more precise determination of location. The possibilities of navigation by this technique are described in Annex 6-A-2. It is apparent that each aircraft or ship that is to navigate by listening to these three transmissions is also able then to set its clock to an accuracy of perhaps a microsecond, since his location is known and since his reception of the incoming information is known to about this accuracy. Such a navigational accuracy is useful not only for general navigation, station keeping, etc., but also useful in providing clock-setting data for a secure IFF system as described in Appendix 8-A.

SUMMARY OF ADVANTAGES OF CENTIPEDE

It is thus apparent that the Centipede has extreme flexibility as to the mode of setting operations that may be employed. Up to 100 voice nets may be accommodated simultaneously on one RF channel. Up to 35 RF channels may be utilized in the presently assigned 225 to 400 Mcps UHF band. Each of the 100 Centipede nets per RF channel may be subdivided into up to 350 surface-to-air discrete address channels, with 2:1 redundancy. Each one of these channels would be private. Likewise, a single one of the 100 Centipede nets can easily be subdivided into 30 or more air-to-surface private data channels, and, with more equipment complexity, each net can provide for more than 350 air-to-surface data links. Likewise, each Centipede net can be subdivided into 20 teletype channels from a single platform to any number of platforms. The Centipede is also well adapted to airborne relaying of surface messages so as to provide strong defense against countermeasures, particularly for communications which would be beyond line-of-sight without the relaying. Ship relaying can also be used with relative ease. The Centipede is also an aid to navigation, and, when properly integrated, can thereby set clocks well enough to provide secure IFF.

Despite these advantages of flexibility and enormous information-handling capability, the complexity of the Centipede system appears less than that of present UHF equipment.

D. Sunstein

ANNEX 1

INTRODUCTION

Set forth in this Annex are certain techniques believed applicable to subsequent development of accordion devices for use in the Centipede burst-communications system.

These devices have in general been divided in accordance with the mechanism used for storage of the data. Usually, in what follows, the speed-up accordion is described; in most instances, the companion slow-down accordion is obvious.

SUMMARY

In summary, at least three storage techniques appear attractive for further exploration. Since a very substantial improvement in the over-all communications systems of the Armed Services would be envisioned by utilizing the Centipede, it would seem worth while to produce through the breadboard state at least two or more of these potential systems of accordion speed-up and slow-down. The two most likely candidates appear to be one or more of the many magnetic forms, and one or more of the storage-tube forms. Additionally, promise is certainly shown by the delay-line techniques. Further evaluation is obviously required before a decision can be made as to which particular accordion technique can be recommended for service use.

MAGNETIC-STORAGE SYSTEMS

A great number of magnetic-storage systems have been proposed. Some of these use intermittent motion of parts, and others use continuous motion of parts.

Magnetic Drums with Continuous Motion Heads:– Two types of drum systems have been proposed. One is a system in which stationary heads are used on a single drum or disk, and in which the recorded data are interlaced around the periphery of the drum. In this system, speed-up is accomplished by sampling the received incoming audio by a sampler operating at perhaps 8 kcps and recording the output of the sampler on a drum which rotates at about 140 rps. In this manner, each successive sample taken over a 1-second interval is recorded at a different position on the periphery of the drum. Read-out is then via a single head.

Other drum and disk systems have been proposed in which the recording head operates at a different speed, relative to the drum, than the read head. In these systems, recording is done on opposite sides of the drum or disk (this is particularly easy on a disk which is spinning at high speed and which tends to maintain itself stiff even though very thin). One of the heads moves relative to the disk at a speed of perhaps 2 inches per second, and the other head moves relative to the disk at a speed of perhaps 300 inches per second.

Yet another arrangement in which both the high-speed and the low-speed heads are on the same side of the recording medium has been proposed. Interference from the high-speed head banging the low-speed head is avoided by having the two heads displaced axially parallel to the axis of the drum. When recording is done, it is done in one track along the periphery of the drum; and when reading is required, the two heads are moved axially so that the reading head is shoved into a position to read the recently recorded information. The heads are in this way jostled axially between read and write positions.

Magnetic Tapes or Belts:- Still other magnetic systems are based on endless belts or continuously moving belts. These again may be divided into two types in accordance with whether or not the reading and writing operation is done with continuously moving tape or whether a differential speed is achieved by intermittently changing tape speed between the reading and writing operations.

One straightforward technique is to record audio information on the tape at two inches per second, the tape being continuously pulled at 2 inches per second by a capstan located at the recording-head location or directly beyond it. About two inches after the recording head is a reading head. Immediately in front of the recording head is a loop of tape having a slop of at least two inches. When it is desired to read the information just recorded, the loop located just ahead of the recording head is suddenly relocated to occur just after the read head. This may be done by an egg beater-type action in which a shoe suddenly transfers in 7 msec the loop from ahead of the write head to beyond the read head. To accomplish this, slippage takes place at the capstan.

Other sudden-motion devices have been suggested in which the tape is suddenly moved by a claw similar to that used in a movie projector or camera. The difficulty with tape life which might be expected with movie film has been suggested to be not important in this case, since the tape could be made of steel rather than of plastic film.

Suggested also are other belt or tape arrangements in which the tape is suddenly clutched either by an electrostatic clutch operating over a continuously revolving high-speed capstan, or by a magnetic clutch operating in conjunction with an high-intertia motor.

Another accordion has been proposed by W. Buhl, which would use continuously moving magnetic tape. This magnetic tape would be drawn over two 6-inch wheels. These wheels might be on 10-inch centers. Drive would be on wheel A at 12.7 rpm. As close as possible to wheel B would be mounted a magnetic writing head on the side the tape enters the wheel. Similarly on the outgoing side would be a reading head. Both these heads would contact the tape. Inside wheel B are mounted two flying heads which rotate at 1800 rpm opposite to the rotation of wheel B. These heads ride as close as possible to the tape through a slit in the rim of wheel B. For compression, the message is written on the tape by the head where the tape enters wheel B. The message is scanned by the flying heads 140 times as fast as it was written. By proper commutation of the flying heads, the message is accepted only during a particular 0.007 second each second. The commutation is adjustable to put this gating anywhere within the second.

The flying heads are gear-driven from the tape drive which makes compression independent of drive speed. Variations in speed should be held to rates less than 0. 1 per cent per second if overlap or gaps are to be prevented. Commutation can be done mechanically if the commutation is driven from an oscillator locked into the one-second synchronizing pulses emanating from the master transmitter. This may be done more easily by electronic commutation which is triggered each second by the synchronizing pulse.

Message expansion is done by writing with the flying head and reading the message with the head on the tape where it leaves wheel B.

Another arrangement has been suggested by R. Garwin in which a single rocking arm has magnetic tape on its periphery. The arm first rotates slowly in one direction for a one-second time duration and is then suddenly accelerated in the opposite direction. A single head is used, first for recording during the slow motion of the rocker arm, and then this head is used for read-out during the rapid motion of the rocker arm. The rocker arm may be driven by a constant-speed drive of some sort, and when it gets to the end of its travel, or when read-out is desired, the rocker arm is suddenly hammered with a mass moving at a particular velocity. This mass is arranged to be of such value that the mass just comes to rest after imparting all its energy to the rocker arm. The mass had previously been accelerated by a spring, when released from a catch activated from the synchronizing information. Thus the rocker arm is caused to move backward by suddenly changing direction in a time well under a millisecond during the time of impact. After the rocker arm travels its full distance at high speed in the reverse direction, it is arranged to hit a second mass of the same critical value, so that the rocker arm comes to rest while the mass is accelerated rapidly out of the field of interest. The energy imparted to this second mass may be either recovered to re-cock the first spring, or it may simply be dissipated through a viscous damper. The power requirements for operating this reciprocating device need be only on the order of a few watts, since the mass of the rocker arm may be made very low. The rocker arm need have a periphery of only about two inches of recorded information.

An alternative arrangement to the rocker arm is a similar reciprocating device in which motion is linear rather than rotary. In this case, a tape is carried in a little carriage along a track somewhat analogous to a high-speed lathe bed. The tape is drawn at a constant speed in one direction for a time interval of one second, and suddenly the carriage is hammered in the opposite direction by a previously accelerated hammer. The hammer comes to rest and the tape then proceeds at high speed in the opposite direction until it hits another mass, where the energy of the moving carriage is transferred to that second mass. Thereafter, the carriage is again carried in the forward direction at slow speed. Again, only a single recording head need be used, serving the function of both recording and playback. Needless to say, the message that is transmitted from such an accordion comes out backward in time, but this appears to be no disadvantage.

It appears that many of the above magnetic systems hold definite promise. They all involve, primarily, a relatively straightforward mechanical development program. The problem of obtaining video to a half-megacycle from magnetic tape has been solved previously by several contractors in experimental models, and this is not contemplated as a major obstacle to the development of magnetic systems requiring speed-up of only 140 to 1.

STORAGE TUBES

Storage-tube systems are generally characterized by having no moving parts. Since on the order of 8000 bits must be stored, it has been suggested but ruled as impractical at present to store the entire data on a single line or a single circumferential sweep around a single storage tube. Instead, storage has been considered on the basis of a scanning raster. In one arrangement, the storage tube is made to scan at a very slow rate taking almost a full second for its full scan, scanning a raster perhaps 80 lines high in a fashion that is otherwise similar to television, but perhaps having no sudden flyback but rather a triangular scanning waveform. When it is desired to read the storage tube, the beam traces the same path, but at a speed perhaps 150 times faster. Barrier grid-storage tubes appear to be applicable for this purpose.

Other storage-tube systems have been suggested, in which the difficulty of registering a fast sweep and a slow sweep on top of each other is avoided to some extent by providing writing along one raster and reading along a raster rotated 90° with respect to the writing raster.

These possible storage patterns are shown in Fig. 6A-6(a), (b), and (c), pattern (a) being deemed impracticable in view of present storage-tube resolution, but patterns (b) and (c) being believed perfectly practical.*

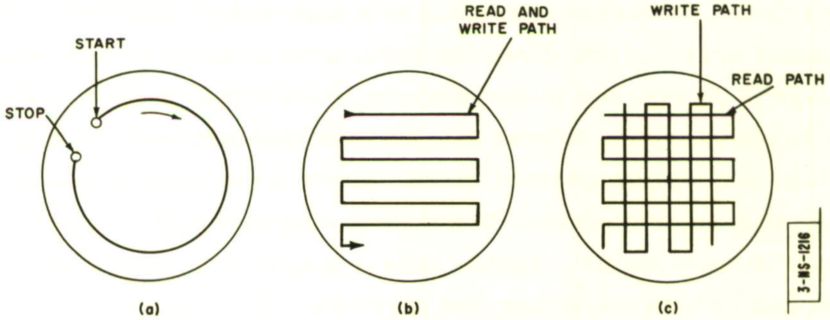

Fig. 6A-6. Storage tube rasters.

In addition to the barrier grid-type storage tube for this application, it is possible that flying-spot scanner techniques could be used with long persistence phosphors which are read by vidicon cameras. The problem of registration and erasure in this instance may be somewhat greater than with a single-gun storage tube.

MECHANICAL-OPTICAL SYSTEMS

Mechanical-optical systems include all those in which the intelligence is recorded optically, and in which mechanical scanning of the optical images is provided. In order to provide speed-up, the intelligence may be recorded as a variable-width modulation in a film track, arranged by mechanical vibration of a triangular stylus in a vertical direction. The variable-width track is arranged to be carried over a glass cylinder at slow speed. Inside the cylinder, a mirror mounted on a 45° angle is rotated at high speed, so that light may be reflected from one spot at a time on the tape to a photocell. In this manner, the photocell may scan the tape at a speed of about 150 times the speed with which the tape is pulled. This system appears practical for the speed-up part of the accordion, but lacks a simple recording method for the slow-down portion. Actually, photographic film could

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*In fact, pattern (c) has had preliminary testing for accordion use at the University of Illinois.

be used to achieve storage for slow-down, since video could be written on it by a short-persistence phosphor, but the development process is believed to be relatively impractical for very widespread use.

An alternative arrangement utilizing a similar mechanical-optical scanning system, but recording images differently, has been proposed. In this instance, it is suggested that the image be recorded xerographically on a slowly rotating drum or disk. The light source for recording the xerographic image can come from a flying-spot scanner or intensity-modulated glow tube. The xerographic recording so produced is then scanned by a rotating mirror in a manner similar to that of Rayfax. Both speed-up and slow-down may be achieved by this xerographic technique.

NUCLEAR RESONANCE (MAGNETIC OR ELECTRIC-QUADRUPOLE)

Theoretical and experimental work at the Watson Scientific Laboratory of International Business Machines Corporation has demonstrated that the spin-echo* method presents a practical memory device for the storage of either digital or continuously varying modulation. The work is to be published in the Journal of Applied Physics,** but some points may be of interest for accordion use.

One may store, in a one-cubic centimeter sample of water in a magnetic field of 7,000 gauss, about 10^4 pulses of information at high reliability. The permanent magnet may weigh about 30 pounds. The number of pulses that can be stored increases linearly with sample volume, as does the magnet weight, eventually.

One has, for magnetic resonance, an ensemble of protons in water, for instance, situated in a magnetic field of average value H_{OZ} and space-carrying part H_{GZ} which may, for instance, be a linear gradient over the water volume. The carrier (gyromagnetic) frequency for protons is 30 Mcps at 7000 gauss H_O. An RF magnetic field is supplied by a coil surrounding the sample and is amplitude-modulated with the information to be stored (frequency modulation is also feasible). After storing the information, a large RF pulse is applied, and the information returns (as voltages induced in the resonant coil) as an exact mirror image of the information reflected in the large "recollection pulse." If now the magnetic field is separable into a strictly homogeneous part H_O and a space-varying part AH_{GZ} of controllable magnitude A, then the rate at which information pulses return, after being called by the recollection pulse, is (A+/A-) times the insertion rate. The carrier frequency remains the same.

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*E.L. Hahn, Phys. Rev. 80, 580 (1950).

**Anderson, Garwin, Hahn, Horton and Walker.

If 3-kcps bandwidth information is to be stored on a carrier, then a bandwidth of 6 kcps is required. This is a field differential over the sample of 1.5 gauss (of 7000 total). If the inhomogeneous part AH_{GZ} is now multiplied by –100 at the end of the information-storage interval, then no recollection pulse is required, and the information returns at 100 times the rate (and at hundredfold greater bandwidth than the form in which it was stored). Unhappily, for this to be true the uncontrollable inhomogeneity must be less than 10^{-4} gauss. This is a region homogeneous to one part in 10^{7} – a very difficult task to accomplish. In the usual spin-echo memory, one either does not change the H_{GZ} or changes it only for short periods, and in this case the spin-echo memory is very stable and convenient.

To store one second of speech at good signal-to-noise ratio will require, at 7000 gauss, a sample volume $\sim$20 cc and a magnet of considerable weight, unless further tricks are invented.

DELAY-LINE STORAGE

Suggestions have been made for utilizing either single or multiple delay lines to provide the proposed speed-up and slow-down (J. E. DeTurk and R. L. Garwin have been most helpful in this connection). Such operation is similar to one form of Redap used for radar data processing at Philco. In one form of such a system, the input signal is first sampled at perhaps every 151.125 μsec with a sample duration of less than 0.5 μsec. The samples are fed into a regurgitating delay line having a delay time of 1.125 μsec less than the sampling interval (about 150 μsec). About 133 samples may thus be taken before the delay line is full. Under these conditions, it will take 20 msec of audio to fill this 150-μsec delay line. Once the delay line is full, its output intelligence is suddenly (150 μsec) dumped into another regurgitating delay line of about 6616-μsec duration. It will then take 44 successive dumpings of the short delay line to stuff the long delay line full of information. Thus, a total listening time of about 0.88 second is required to fill the long delay line. Since the long delay line may be read out in 6.6 msec, the desired speed-up is achieved. This type of speed-up does not necessarily result in output signal coming out in the same sequence as the input signal,* but for some forms of transmission this may not be too bad. A companion unit will provide the anti-scrambling necessary to restore the original 1-second voice to its original value. When scrambling is used, synchronization must be maintained between speed-up accordion and play back accordion to an

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*Actually, for the delay intervals chosen above, no scrambling takes place, but other delay-line lengths that might be used for a full-second storage might cause scrambling.

accuracy of perhaps one microsecond or better. Means have been suggested for achieving this synchronization accuracy, so this may not be a problem.

The biggest problem of delay-line type accordions is in obtaining practical delay lines of 5000 μsec or greater length. Delay times of this order of duration can be achieved by feeding a signal through a shorter delay line more than once. For example, a 2500-μsec delay line may be used, with the signal first going through the delay line on one carrier frequency, and then going through the delay line later on a second carrier frequency heterodyned from the first. These techniques have been found practical in the past. However, there is still a question as to the practicability of sending the signal around the line the several hundred times that are required to obtain a time delay of almost one second with a delay line having a delay time no greater than 2500 μsec, when cascaded with another delay line of only 150 μsec; that is, on the order of several hundred round trips around delay lines will be required before the original transmitted signal is heard in the playback end of the system. The use of FM techniques in the delay line may permit faithful rendition after this many passages, but experimental verification would certainly be required.

STATIC COMPUTING STORAGE ELEMENTS

It has been suggested that conventional computer techniques utilizing magnetic cores or electrostatic elements could be utilized in the required speed-up and slow-down. Although this is perfectly possible, in order that a reasonable dynamic range be provided for voice, it would appear relatively impractical. This statement is based on the fact that about 8000 samples of information are required, each sample preferably being quantized into 16 or more levels. If too few levels are used in the quantization, the ability to recognize the speaker's voice is lost even though full intelligibility is maintained. The size package necessary to store the several tens of thousands of bits of data required, if one is to include a reasonable dynamic range, would appear prohibitive utilizing normal storage techniques such as electrostatic or magnetic cores or flip-flops.

D.E. Sunstein

ANNEX 2

NAVIGATION BY CENTIPEDE

General

This annex describes a means for providing accurate navigation through the use of the Centipede communications system. In summary, it appears that, by utilizing the Centipede communications system, one can ascertain his coordinates to a precision of one-third mile, providing he is within communications range of 3 transmitters which will be called master transmitters. This is achieved by using no separate navigation receivers or transmitters, but only a computer or indicator comparable to that now employed in a Loran receiver.

By virtue of this accurate navigation, each aircraft or ship is also able to set its clock to an absolute time, taking into account the time of propagation from the master synchronizing station to this receiver. Thus each clock throughout an entire area may be synchronized with an accuracy of perhaps a microsecond or better. This absolute timing accuracy is of importance for certain types of secure IFF systems which are described in Appendix 8-A.

General Navigational Principle

Imagine that three Centipede transmitters all on the same RF channel are within propagation range of each other. These transmitters may be either aboard three ships at sea, or they may be ground transmitters. At least one of these transmitters (the Master) should know where he is accurately. At least one of the other stations should know his true bearing from the Master station. The Master should also be considered for the time being a master timing generator, although this timing generator may in turn be synchronized by intelligence received from an entirely different geographical area through any appropriate timing synchronizing methods.

Thus, we have three reference transmitters shown at positions 1, 2 and 3 in Fig. 6A-7. Let us ensure that all three transmitters transmit on three different nets of the Centipede communications system. The messages transmitted will start with the identification of the separate nets. Two of the transmitters listen to the master transmitter and delay their transmission

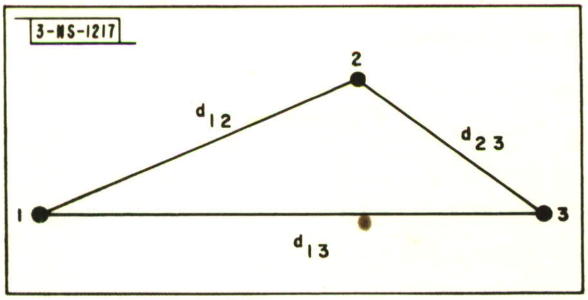

Fig.6A-7. Centipede Navigation Geometry.

a predetermined time after receipt of the master transmission. For example, the master transmitter 1 may be on net 1, reference station 2 on net 2, and reference station 3 on net 3. Reference station 2 receives bursts from the master station 1 and delays these exactly 10 milliseconds before emitting his own pulse designated net 2, and likewise reference station 3 receives master synchronizing signals from station 1 and delays them exactly 20 msec before transmitting them on net 3.

The master reference station 1 may then listen to stations 2 and 3 and by noting the time of arrival of the received signals from these stations, he may accurately compute the distance D12 and the distance D13. After having determined these distances to the other two reference stations, he transmits this distance information out on net 1 along with his original net identification signal as his message or at least a part of his message.. Likewise, reference station 2, by listening to transmissions from station 1 and 3 may then determine the distance between stations 2 and 3, since the distance from station 1 and 3 is already told to him by station 1. A bit of redundant information can then be computed by station 3; namely, station 3 in listening to transmissions from stations 1 and 2 can again compute the distance D23. Stations 2 and 3 will then transmit on the air the distance D23 as part of their messages.

Thus, the triangle determined by the location of the three ships is fixed as to the length of its sides. The only remaining question to fix the location of the three transmitters is to determine the orientation of the triangle in space, that is, the orientation with respect to north, since the location of at least one of these stations was assumed to be known by other navigational means. The orientation of the triangle in space may be determined by DF measurements aboard one or more of the stations.

Needless to say, other surveying means than the Centipede itself may be used for locating the station positions, particularly if the reference stations are ground-based.

Once each of the three reference stations shown in the above triangle has determined its position, it automatically transmits this coordinate information as a part of its message on its own net. Then, any other person using a receiver and listening to transmissions from the three stations is enabled to tell his coordinates by a technique very similar to Loran – that is, by comparing the time of arrival of two of the signals, he fixes his location on one set of hyperbolic coordinates, and by listening to the time of arrival of two other signals he fixes his coordinates on another set of hyperbolas. A computer would be advantageous, since the transmitter locations are mobile, though known.

Since the bandwidth of the Centipede receiver is on the order of 3 Mcps, the computer can easily match rise times to much better than a 1/3 microsecond, and hence compute its location to an accuracy of perhaps 1000 feet or better. The hyperbolic data used in the computer should take into account altitude, since the time delay is of course dependent on altitude for any given aircraft location.

Clock Setting

Each receiving site now having determined its location with respect to the three reference transmitters is then in a position to set its clocks to agree with them, on an absolute basis; that is, if we assume that transmitter 1 is the master transmitter, each receiver in the area has determined its range to receiver 1, and may then set its clock to cause its time "zero" to agree with the time when the message was first emitted from the master station 1 rather than the time when it was received from the master station 1.

We may thus ensure that each clock in the area is set with an accuracy of about one microsecond to a common master.

Different areas utilizing different reference transmitters as masters will, of course, have to have their clocks agree, too, in time.

D. E. Sunstein

APPENDIX 6-B

LOW-FREQUENCY COMMUNICATION

INTRODUCTION

Low frequencies, in the range from 30 to 300 kcps, have the considerable advantage of remaining useful for communication, even in the worst magnetic storms or sudden ionospheric disturbances, when all high-frequency communication may be blacked out. In the Arctic, where high-frequency interruptions caused by auroral-zone magnetic storms are frequent, noise levels are much lower than at temperate latitudes. For these reasons, low-frequency communication is particularly useful at high latitudes.

Low-frequency communication has had limited use for two reasons. The available spectrum space has been very restricted, and large antennas and high-power transmitters have been required. Both these limitations can be relaxed considerably by proper use of modern techniques.

GROUND-WAVE PROPAGATION

Low frequencies are propagated long distances by ground wave, especially over sea water. At a range of 1000 miles over sea water, at 100 kcps, the field is only 20 db below free space; over poorly conducting ground, as found in the Canadian Arctic, it is 40 db below free space [see Fig.6B-1(a)]. This ground-wave field is steady and unaffected by magnetic storms or ionospheric disturbances.

SKY-WAVE PROPAGATION

The sky-wave field depends on the frequency, the distance, and the time of day and season. Figures 6B-1(a) and -1(b) show this dependence for 100 kcps and for different frequencies in summer-day conditions. It is seen that attenuation is greatest in the daytime, at the higher frequencies, and at short range. The figure does not show the sky-wave field beyond 1200 miles, which is the maximum possible distance for single-hop reflection.

Low-frequency sky waves go through a large phase change near sunrise and sunset. At night they are reflected at a height near 54 miles (90 km), and in the day near 45 miles (75 km). Large phase changes may also occur during sudden ionospheric disturbances and for several days after magnetic storms. During such disturbances, however, except at short range at the higher frequencies, the sky-wave amplitude increases.

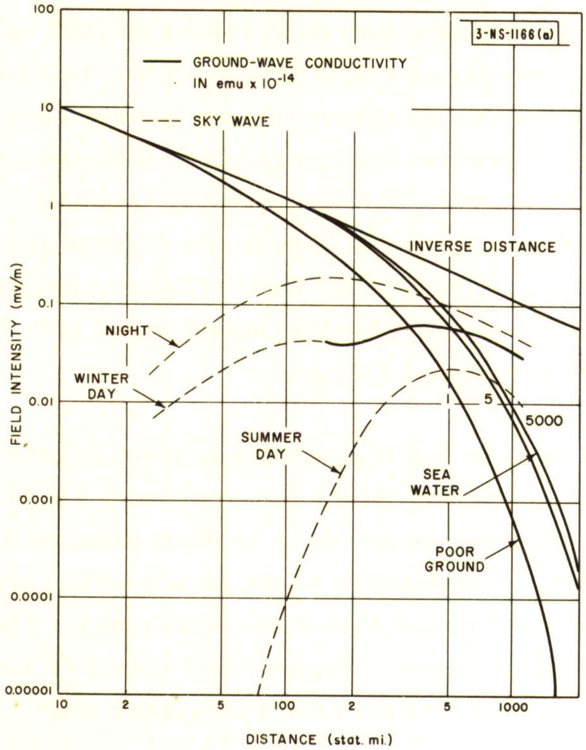

Fig.6B-1(a). Sky-wave field intensity under varying conditions.

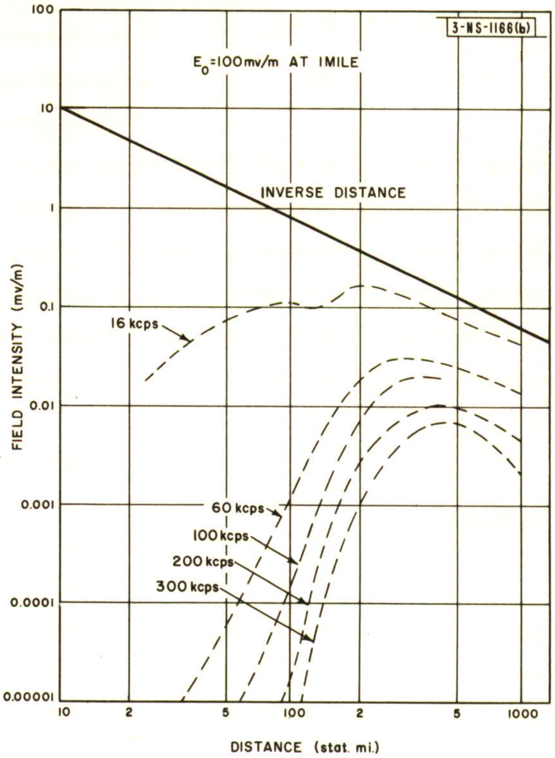

Fig.6B-1(b). Sky-wave field intensity under varying conditions.

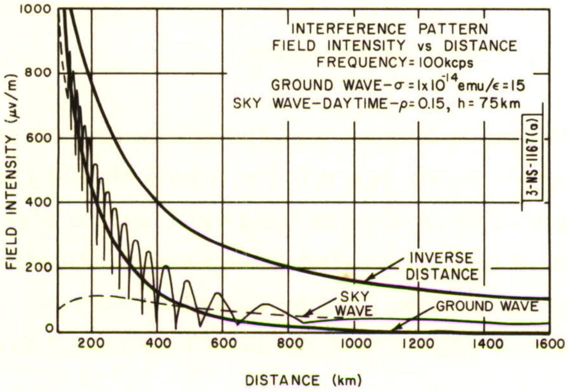

Fig.6B-2(a). Interference pattern (daytime).

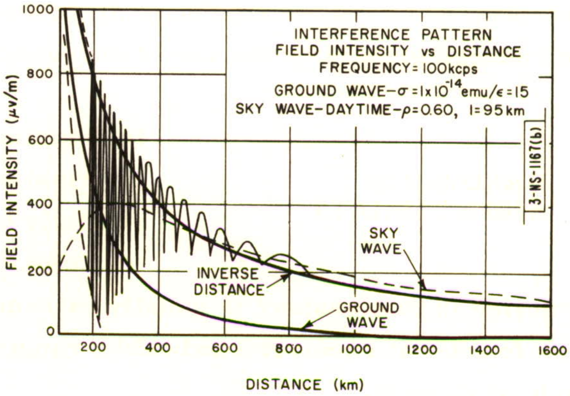

Fig.6B-2(b). Interference pattern (nighttime).

GROUND-WAVE – SKY-WAVE INTERFERENCE

Because of phase variations in the sky wave, reliable low-frequency communication up to ranges of 1000 miles depends upon a proper choice of frequency for the path. A frequency should be so chosen that the ground wave and sky wave are not of about equal amplitudes; serious fades may occur if the two modes of propagation are equal. Figures 6B-2(a) and -2(b) illustrate the resultant field caused by interference as a function of distance, at 100 kcps in the daytime and at night. These interference patterns have been calculated for fixed reflection heights and reflection coefficients. It is clear that a change of reflection height would shift the interference pattern across the receiver with consequent fading.

NOISE

Atmospheric noise at low frequencies is much greater than at high frequencies. In the low-frequency range, atmospheric noise increases about 16 db at noon, and 5 db at midnight for a doubling of the wavelength. Also, the noise may be 35 db higher at night and in the summer than in the winter day. The noise level, however, decreases greatly at high latitudes. Figure 6B-3 indicates the variation of the atmospheric noise amplitude at high latitudes for a frequency near 150 kcps.

Atmospheric noise is propagated long distances from regions of intense thunderstorm activity in the tropics. In addition, local thunderstorms will contribute a spiky component to the background of white noise. Another source of noise is precipitation static produced either by the impact of charged snow, hail or dust on the receiving antenna, or by corona discharge from sharp points nearby. Precipitation static may be reduced greatly by the use of screened-loop receiving antennas.

BANDWIDTH AND STABILITY

Information theory indicates that the transmission of information at 60 words per minute (wpm) should theoretically be possible in 25-cps bandwidth with a signal-to-noise ratio of one. Low-frequency communication practice in this respect is usually extremely inefficient. In one Canadian survey, it was found that receiver bandwidths ranging from 1/2 to 13 kcps were being used for code at 20 wpm.

ANTENNAS

Loop receiving antennas, when properly screened, reduce the effects of precipitation static. In addition, because of their directional properties, they can often be used to discriminate against atmospheric noise sources in the tropics, or against man-made noise or jamming.

Because atmospheric noise levels at low frequency are relatively high, the efficiency of quite small loop antennas can be made high enough to insure that the signal-to-noise level is determined by atmospheric noise and not by antenna and receiver thermal noise. Thus, the use of larger receiving antennas does not improve the signal-to-noise ratio.

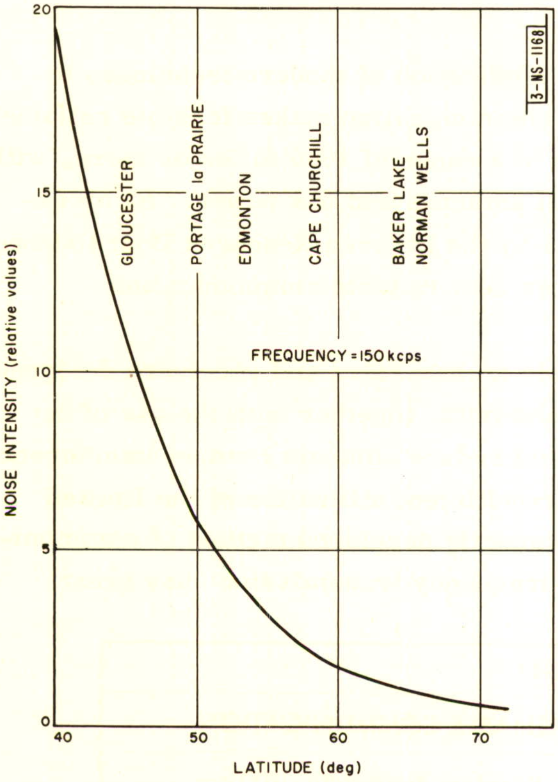

Fig. 6B-3. Variation of noise intensity with latitude.

Four-foot-square loops have been designed with sufficient sensitivity to give optimum performance under the lowest atmospheric noise fields found in the Arctic. Experiments indicate that optimum-performance loops of much smaller size can be designed using low-loss ferromagnetic cores.

Transmitting antennas at low frequency are normally inefficient radiators because of their small size in terms of the wavelength. Vertical dipoles with capacitive top loading to increase the electrical length — and thus increase the radiation resistance — are the most practical form.

Two requirements determine the antenna design: the required radiated power, and the required bandwidth.

Since the radiation resistance is small, it is most important that losses, particularly ground losses, be kept to a minimum. Where feasible, good ground screens are very desirable. It is also very important that antenna insulation be very good, especially in narrow-band systems; otherwise, leakage in bad weather will result in serious antenna detuning.

The antenna bandwidth required is determined by the information rate. At low frequency, increased bandwidth is obtained at the expense of radiation efficiency; consequently, the use of low frequency is impractical for information rates much greater than needed for teletype operation.

The antenna bandwidth is given by the ratio of the frequency to the antenna Q. Any meteorological conditions that affect the electrical properties of the antenna will change the Q and, consequently, the bandwidth. It is most important that sufficient bandwidth be allowed to permit reliable operation in all weather conditions.

POWER AND RANGE

The intelligent application of modern techniques to low-frequency communication makes feasible reliable communication to a range of 1000 miles or more, with relatively small antennas and low power. As an example, computations and tests made in Canada by the Defence Research Board showed the requirements listed in Table 6B-I for 99 per cent reliable communication.

SPECTRUM UTILIZATION AND JAMMING

The use of stable transmitters and receivers designed for optimum bandwidth, together with the use of net operation, should reduce adjacent channel interference and permit more efficient utilization of the limited low-frequency spectrum. However, another recently developed method of communication which is particularly applicable to low-frequency transmission has great

TABLE 6B-I

REQUIREMENTS FOR 99 PER CENT RELIABLE COMMUNICATION

Latitude, 60°N
Morse, 20 wpm
Frequency, 150 kcps

Receiver Bandwidth, 100 cps
Required Field, 1 μv/m
Ground Conductivity, 1×10^{-14} emu

Distance (stat. mi.)	Radiated Power (w)	Antenna Height (ft)	Transmitter Power (w)
50	0.0003	20	3
100	0.003	35	3
200	0.07	65	7
400	3.1	100	52
800	3.6	100	60
1200	8.1	100	135

possibilities, both for saving of spectrum space and for security against jamming. This is the use of single-channel noise modulation.

The block diagram in Fig. 6B-4 illustrates one application of the principle. Noise from the source N, at frequency f, is heterodyned with oscillator frequency δf or $\delta f'$ for mark and space. The noise within bandpass W at f_2 is amplified and transmitted.

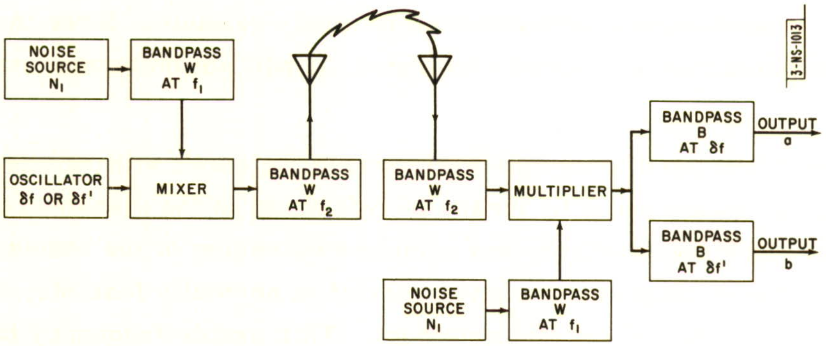

Fig. 6B-4. Single-channel coherent noise-modulation system.

An exactly similar noise source at the receiver is synchronized with the noise N_1 at the transmitter. Noise from this source at f_1 is multiplied with noise received in bandwidth W at frequency f_2. The output is the heterodyne oscillator frequency δf for mark and $\delta f'$ for space. This output is passed through narrow-bandpass filters B at a and b for mark and space.

It has been shown that such a system will provide reliable communication at a signal level many decibels below the ambient noise level. The minimum signal-to-noise level is given by one-half the ratio of the information bandwidth to the receiver bandwidth. Consequently, by transmitting noise in a band much larger than the information bandwidth, communication is feasible at a very low signal level.

It is clear that such a system operated at higher power will be very difficult to jam. In addition, it has also been shown that a single-channel noise-modulation system allows for a great saving in spectrum space. Uncorrelated noise from other transmitters, using the same frequency, produces no interference, but merely adds to the ambient noise level.

It is strongly recommended that the development of single-channel noise-modulation systems be pushed and, in particular, that the application of this technique to low-frequency communication be encouraged.

J.C.W. Scott

APPENDIX 6-C

HIGH-FREQUENCY SKY-WAVE COMMUNICATION

HIGH-FREQUENCY PROPAGATION

Propagation of high frequencies beyond the horizon is either by ground wave or by sky wave. Ground waves at HF are diffracted around the curved surface of the earth to only a few hundred miles range. Within this range, however, ground-wave communication is highly reliable. Since the subject of ground-wave communication is treated elsewhere, it will not be further considered here.

Sky waves may be propagated to any distance around the earth with relatively simple, cheap equipment. Propagation is by means of refraction in the ionosphere which, unfortunately, is an extremely variable and complicated region of the atmosphere. As a consequence, communication over a given circuit is normally feasible, at any one time, only in a narrow band of the HF spectrum. This usable frequency band depends on the location and length of the circuit and on the time of day, season, and period of the sunspot cycle. Moreover, communication may become unreliable or impossible for hours or days at a time, particularly for circuits passing through or near the auroral zone.

To circumvent the variability of sky-wave propagation, optimum-frequency prediction services have been developed. These services have been highly successful in predicting the optimum frequency for any hour of the day on any circuit, months or years ahead; but these predictions are only for mean conditions taken over a month. Attempts to predict daily variations and disturbances have not as yet had marked success.

The practical utilization of optimum-frequency prediction services is handicapped by the scarcity of available spectrum space. Frequencies are allocated on a world-wide basis under the supervision of the International Telecommunications Union. National control bodies, such as the Federal Communications Commission, assign a set of fixed frequencies to each circuit or net. Owing to the limited spectrum and the great demand for communication circuits, it may happen that frequency assignments on a given circuit are too few to permit efficient use of frequency predictions.

In the main, the ionosphere consists of three ionized regions or layers — the F-region at a height of about 300 kilometers, the E-region at 100 kilometers, and the D-region at about 80 kilometers (see Fig. 6C-1).

The F-region is usually the most highly ionized. Because of this and its height, it is the most important layer for long-range communication. However, it is also the most variable, the ion distribution in height changing in a complicated manner with time and location.

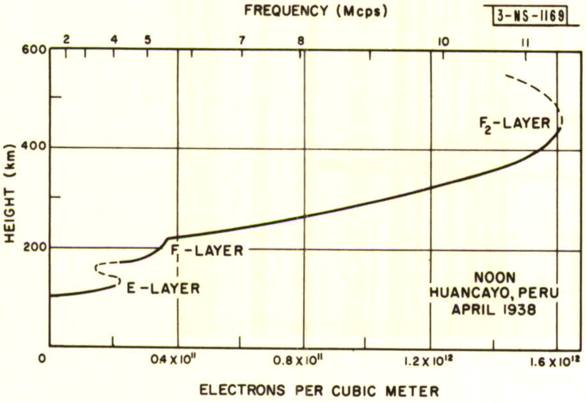

Fig.6C-1. Distribution of ion density with height.

The E-layer, at ordinary latitudes, is much more regular. Its normal electron density rises and falls with solar elevation in a predictable way. However, especially at high latitudes, it is complicated by clouds of intense ionization whose occurrence cannot be predicted. This layer is important to daytime communication out to 2000 kilometers.

The D-layer also rises and falls in ionization with the solar angle, disappearing completely at night; but its maximum electron density is too low to reflect frequencies above 2 Mcps. Nevertheless, the D-layer is a most important factor in HF communications because, due to its low height and relatively high gas density, it is highly absorbing. As a consequence, ionospheric absorption is maximum at noon and, except in the auroral zone, practically disappears at night.

The maximum frequency reflected in any region of the ionosphere is proportional to the square root of the electron density. The maximum frequency is also nearly proportional to the secant of the angle of incidence at the layer, measured with respect to the vertical. Consequently, the maximum frequency that will be reflected back at a given distance depends only on the density of ionization and the height of the reflecting layer.

Higher frequencies will penetrate the layer to higher regions of the ionosphere or into space. But at greater angles of incidence, higher frequencies may be reflected back to earth at longer range; hence, for any frequency, there is a skip region within which it will not be received.

Frequencies lower than the maximum usable frequency (MUF) may reach the receiver by two or more reflections in the ionosphere. The requirement is merely that the electron density at each point of reflection be high enough to support reflection at the

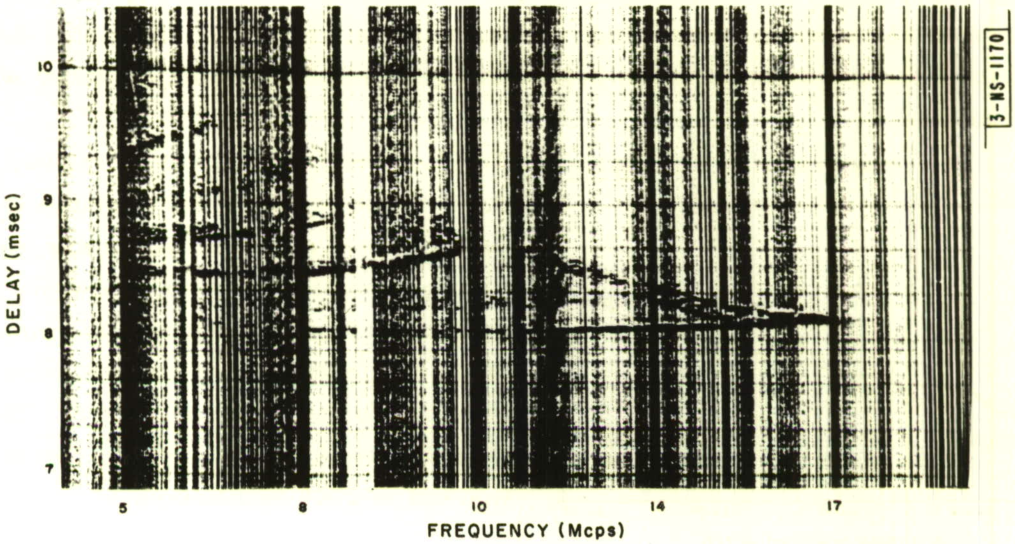

Fig. 6C-2. Multipath propagation as a function of frequency.

lower angle of incidence. Such multipath propagation at frequencies below MUF produces serious signal distortion. Figure 6C-2 illustrates modes of propagation in the ionosphere.

The band of useful frequencies for a given circuit at a given time is limited, on the one hand, by MUF just considered. It is limited, on the other hand, by the lowest useful frequency. One very important lower limit has just been mentioned; that is, the frequency at which multipath propagation produces intolerable distortion. Multipath distortion is worst at short range and least serious at about 4000 kilometers, increasing again at longer distances. To avoid such distortion at short range, a frequency very close to MUF must be used, especially when the transmission rate is high (see Fig. 6C-3).

If communication is by F-layer reflection, the lower E-layer is penetrated on the way up through the ionosphere. As the frequency is reduced, a frequency will be reached which will no longer penetrate the E-layer; instead, it will be reflected back to earth by the E-layer at shorter range. This E-penetration frequency places a lower frequency limit at which F-layer communication is cut off. This phenomenon may modify multipath propagation by cutting off one or more F-layer modes.

Finally, absorption in the D-layer may determine the lowest useful frequency. Absorption varies inversely as the square of the frequency, and is proportional to the density

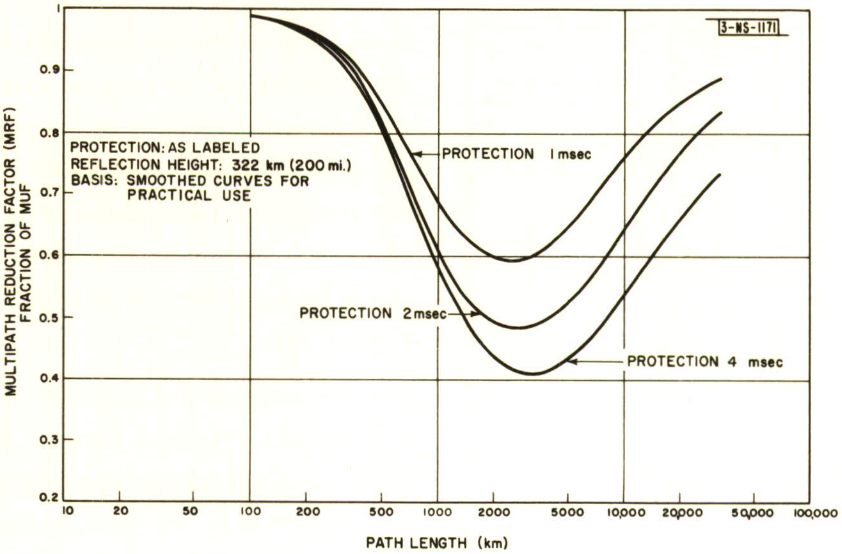

Fig.6C-3. Multipath reduction factor as a function of path length.

of electrons and their collision frequency with the surrounding air. In addition, in the auroral zone, very intense absorption may occur in an unpredictable manner.

Ionospheric disturbances are of two kinds: sudden ionospheric disturbances, lasting from a few minutes to an hour, which black out all HF communication on the sunlit side of the earth; and magnetic storms, which may last hours or days and which may partially or completely black out HF communications in the daytime or at night.

Magnetic storms are most frequent in the auroral zones, which are rings, of about 20° radius, encircling the geomagnetic poles. In these belts, local magnetic storms occur daily; but the larger storms affect communication circuits at low latitudes.

Magnetic storms affect communication both by lowering MUF, due to great diffusion of the F-layer, and by raising the lowest useful frequency, due to increased ionization in the D-layer and consequent increased absorption. The occurrence of total blackouts in the northern latitudes is illustrated in Fig. 6C-4.

The sky-wave field strength at any point, owing to a transmitter at a given location, can be calculated for undisturbed conditions by methods that take into account the modes of propagation and the attenuation. However, to determine the required field at the receiver, the noise level must also be known. Unfortunately, the noise level in the HF spectrum is as variable as the propagation conditions.

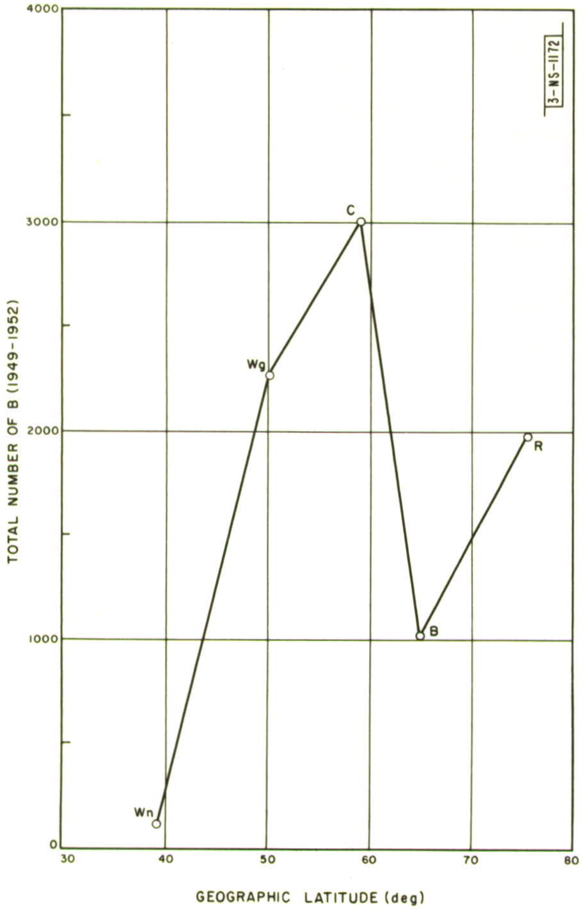

Fig.6C-4. Occurrence of blackouts as a function of latitude.

The limiting noise, below 10 or 15 Mcps, is usually of thunderstorm origin; above 15 or 20 Mcps, it may be cosmic noise. Thunderstorm noise is propagated by the ionosphere from regions of frequent thunderstorms found in the tropics. Consequently, there is a tendency for the noise level to be low at high latitudes (see Fig. 6C-5).

Just as with useful signals, noise can be propagated only in a band of frequencies limited on the upper side by the ionization density or skip frequency, and on the lower side by absorption. Theoretical calculations of noise-field distributions have not yet been established sufficiently by measurement.

As has been said, reliable methods of predicting optimum frequencies, for any hour, for any circuit, are available on a monthly mean basis. These predictions are essentially predictions of MUF. Multipath effects, E-layer penetration effects and absorption all increase as the frequency is reduced below MUF. The noise level also often increases as the frequency is reduced, although in the daytime, at high latitudes, the noise may be maximum near 10 Mcps. Because of all these factors, the optimum working frequency is usually as near MUF as is permitted by deviations from the mean (see Fig. 6C-6).

The greatest variations from the monthly means are caused by disturbances. Sudden ionospheric disturbances cannot as yet be predicted. Large magnetic storms are associated with large sunspots, and tend to occur a day or two after the spots pass the solar meridian. They also tend to recur at the 27-day rotation period of the sun. Consequently, by solar observation, it has been possible to forecast large magnetic storms with fair success (see Fig. 6C-7).

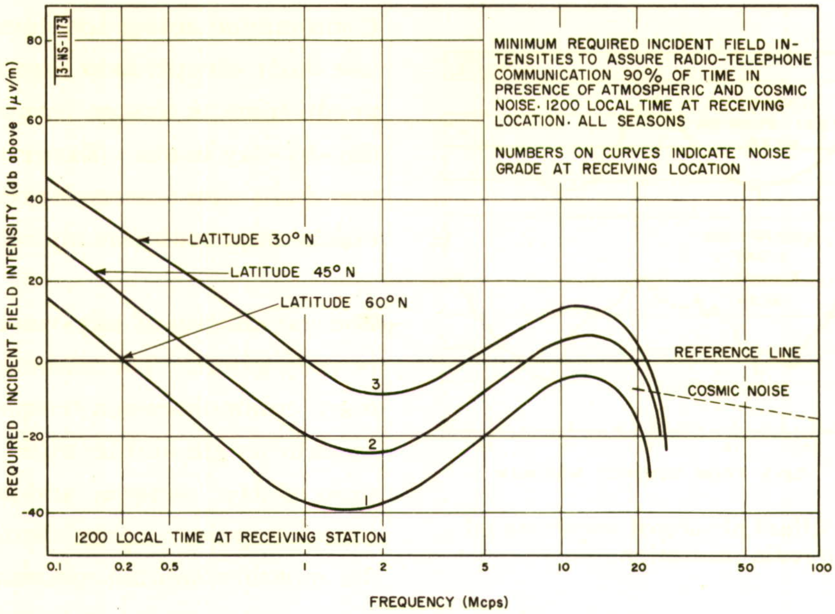

Fig.6C-5. Minimum required field intensities to assure R/T communication.

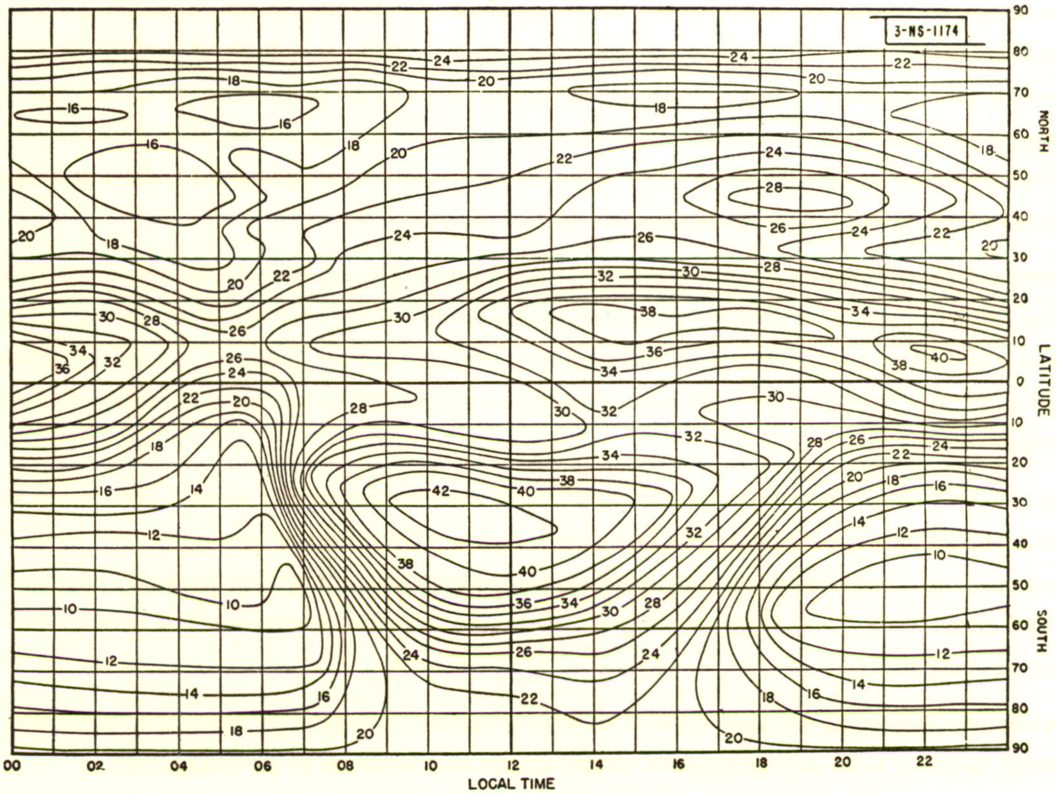

Fig.6C-6. Maximum usable frequency for the F-layer in the western zone.

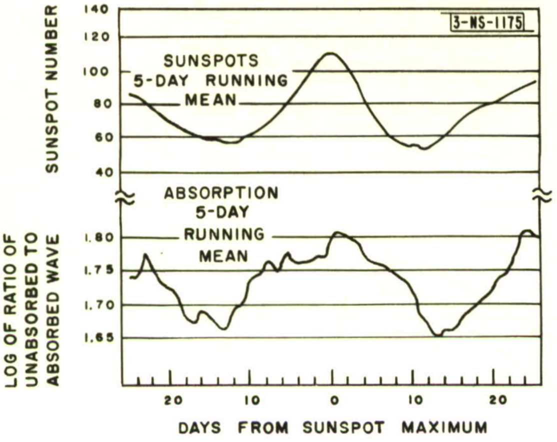

Fig.6C-7. Effect of sunspot variations on variations in radio absorption.

Commercial telegraph companies now use daily circuit data together with solar predictions to assign frequencies on a day-by-day basis. Experience has shown that such short-term forecasting appreciably improves circuit reliability.

The variability of sky-wave propagation is very great. The monthly median optimum communication frequency depends on path length and location, as well as on time of day, season, and period of the sunspot cycle. Large deviations from the monthly median optimum frequency may persist for hours or days. These disturbed conditions are very frequent on circuits passing close to the auroral zone.

Reliable predictions of monthly median optimum frequencies are available, but predictions of daily variations are as yet unreliable. The problem of utilizing optimum-frequency predictions is particularly difficult in mobile operation in which the optimum frequency changes with location and distance. The efficient use of frequency-prediction services is also handicapped by the scarcity of spectrum space and the consequent assignment of insufficient frequencies to a circuit.

Determination of Optimum Frequency:— An investigation should be made of the feasibility of developing and using simple equipment for ship and aircraft installation for rapid on-the-spot measurement of the optimum usable frequency. Such equipment might be of the "cozi" type, which records the skip distance on a number of frequencies by ground backscatter.

On the other hand, the equipment might be of the transponder type. An initiating pulse (or tone) triggers a return pulse (or tone) at the other end of the circuit. This is done at a number of fixed frequencies across the spectrum. The frequency returned with greatest amplitude free from multipath distortion is the optimum frequency for that circuit at that time.

Frequent on-the-spot measurement of the optimum frequency appears to be the only practical way to take advantage of short-term variations in propagation.

Frequency Allocation:– A reassessment of methods of frequency allocation should be undertaken. Assignment of frequencies to groups of circuits controlled centrally, rather than to individual circuits, may allow more flexible use of available allocations. More efficient methods of determining the optimum frequency will be of little use if a frequency near the optimum is unavailable for use.

Relay Operation– The use of high-frequency alternate-path relays should be extended. Local regions of ionospheric disturbance in the auroral zone can often be avoided by using a relay path avoiding the disturbed locality. Reliable ground-wave relays can often be substituted for sky-wave circuits during disturbances.

HIGH-FREQUENCY COMMUNICATION EQUIPMENT

Keeping in mind the great variability of sky-wave propagation, it remains true that considerable improvement in high-frequency communication can be achieved by the use of better equipment. The following discussion is based, to a considerable extent, upon some of the investigations of Project Comos, as detailed in the Interim Report issued by the Bell Telephone Laboratories in May 1954.

It is urged that stable transmitters and receivers be developed for mobile use that will allow single-sideband multichannel-teletype net operation. The requirement is for a transmitter and receiver each having a stability of ±10 cps which will permit a keying speed of 60 wpm, with channel bandwidth of 250 cps, channel spacing of 340 cps, and shift of 170 cps. Automatic frequency control at the receiver would not be required, and is not recommended because of its susceptibility to jamming or interference, and its unsuitability for net operation.

In order to obtain this stability, frequency synthesizers having an absolute error of less than ±10 cps per week, and frequency standards with long-term drift of less than 0.16 per million should be developed for mobile use.

Single-Sideband Modulation:– The advantages of single-sideband communication are many. By suppressing the carrier and one sideband, a 9-db power gain is achieved and the bandwidth requirement is reduced by half. The RF band required is simply the audio bandwidth.

Voice communication on single sideband is more reliable than on double sideband, because multipath effects and selective fading are greatly reduced. This is because the suppressed carrier is replaced by a stable demodulating carrier at the receiver which, of course, is free from fading and phase changes.

Radioteletype and data transmission is made more reliable by the facility to use frequency diversity within the audio band. The single sideband can be packed with a number of teletype channels giving increased traffic capacity. Eight audio channels of 250-cps width and 340-cps spacing can be accommodated in a 3.5-kcps RF band.

The receiver discrimination against adjacent channel interference is much better than in double sideband, due to the fact that it is the audio channel, rather than the IF stage, that determines the selectivity. This permits narrow channeling of low-speed telegraph with consequent improvement of signal-to-noise ratio.

Single sideband with suppressed carrier allows break-in on voice nets without carrier interference. Thus, two persons can be heard intelligibly at once, permitting group conversations.

Finally, single sideband is extremely flexible. Any desired service – such as voice, facsimile, single or multichannel RATT, single or multichannel data, radio-teletype transmission and manual CW – can be provided simply by the addition of suitable radio terminal equipment.

Diversity:– Sky waves are subject to fading of a complicated kind caused by variations in multipath, polarization, absorption, skip and (at short range) ground-wave interference. Under ordinary conditions, the signal amplitude approximates a Rayleigh distribution. By using diversity, under these conditions, a gain of from 10 to 30 db is achieved on teletype circuits.

With single sideband, teletype operation diversity is easily obtained by using frequency diversity. By pairing audio channels, spaced 1360 cps apart, 4 teleprinters can be accomodated in a single RF channel of 3.5-kcps width with adequate diversity. It is strongly urged that frequency diversity be used with sky-wave single-sideband teletype.

Teleprinter Keying Speed:– Multipath delays in the ionosphere are commonly of the order of 4 msec, and can be avoided only by working close to MUF. On circuits shorter than 500 kilometers, multipath delays of 4 msec will occur unless the working frequency is within 80 per cent of MUF.

Start-stop teleprinters will not tolerate delays greater than 35 per cent of the bit duration, but synchronous teleprinters will tolerate multipath delays up to 66 per cent of the bit duration. In addition, synchronous systems will not make repeated errors (as do start-stop printers) as a result of one bit produced by propagation delays. For these reasons, synchronous telegraph systems are recommended for sky-wave operation.

The Navy AN/FGC-5 synchronous time-division multiplex system has a bit duration of 6.7 msec when operated on 4 channels, and of 13.3 msec when operated on 2 channels for a keying speed of 60 wpm per printer. The corresponding permissible multipath delays are 4.45 and 8.9 msec, respectively. It is clear that this equipment will be subject to multipath errors when operated on 4 channels on short paths or on very long paths, unless the working frequency is held close to MUF (see Fig. 6C-3).

Multipath errors will be held to a minimum by keeping the keying speed down to 60 or 100 wpm. Increased traffic can best be handled by multiplexing the narrow audio channels in single-sideband transmission instead of increasing the keying speed.

J. C. W. Scott

APPENDIX 6-D

HIGH-FREQUENCY GROUND-WAVE COMMUNICATION

INTRODUCTION

High-frequency ground-wave-propagated radio signals over water in the 2- to 20-Mcps region can be used for reliable radio communication over distances of several hundred miles, the maximum range being a function of the geographic location, time of day, and system design.

In the area of Newfoundland, the Pan-American and Trans-Canada Airlines have been operating an experimental aircraft-to-ground radio telephone with a high degree of reliability over distances of several hundred miles. They believe that during the daytime, when the atmospheric noise level is low, reliable service can be achieved to a distance of 530 to 600 nautical miles, while night-time service ranges of from 250 to 400 miles can be obtained. Details of these experiments can be obtained from reports published by the two airlines.[1, 2] It is believed that these ranges can be increased considerably by the design of proper aircraft antenna systems and the use of new and better receiving equipment.

The Cosmos report on improved radio communication between ships,[3] prepared by the Bell Telephone Laboratories, examines the possibility of using HF ground wave for ship-to-ship communication and contains an excellent review of this problem. Under noise conditions similar to those indicated above, the Cosmos data predict performance comparable to the experimental data cited above. During part of the day, single-hop sky-wave signals will be received in addition to the normal ground wave. Except when the sky wave and ground wave are of comparable amplitude, no really serious problem will result from the presence of the sky wave; when it is stronger, the communication will be via sky wave, otherwise it will be via ground wave.

CHOICE OF OPERATING FREQUENCY

Propagation

Attenuation of ground-wave radio signals is due principally to losses because of the finite conductivity of the sea water, and so the attenuation of the signal is an exponential function of distance. For the same reason, the signal attenuation increases exponentially with frequency. Figure 6D-1, reproduced from the Cosmos report,[3] shows the path loss over water as a function of both frequency and distance between transmitter and receiver.

The loss of earth is much greater than that of sea water and, consequently, for even the highest conductivity soil, the losses are so great that the useful transmission range at these frequencies is very short over land.

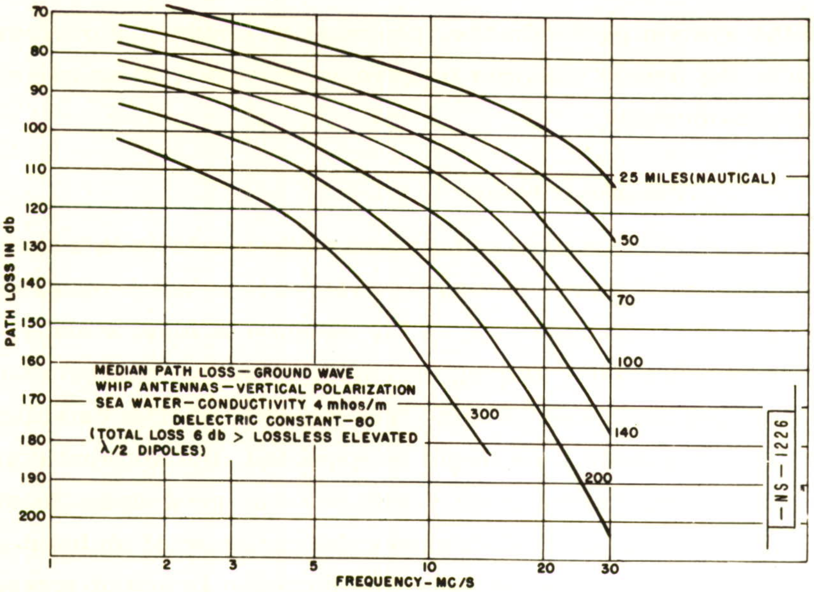

Fig.6D-1. Path loss.

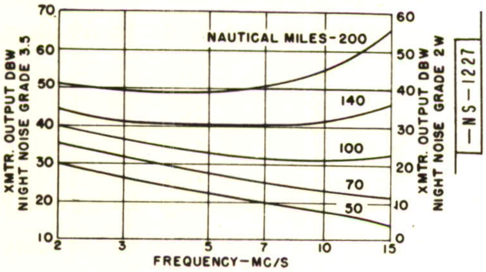

Fig.6D-2. Power required for DSB voice transmission at night.

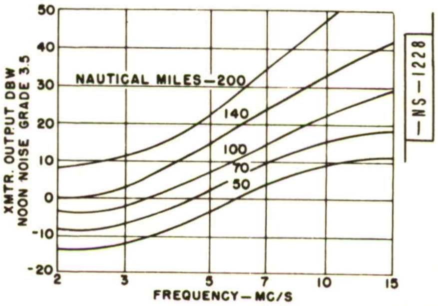

Fig.6D-3. Power required for DSB voice transmission at noon.

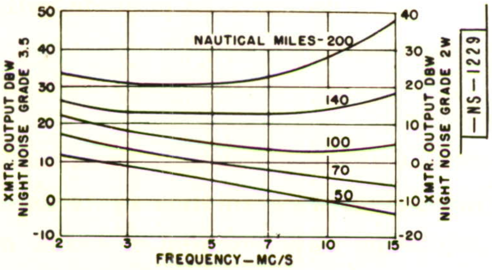

Fig.6D-4. Power required for 60-wpm RATT transmission at night.

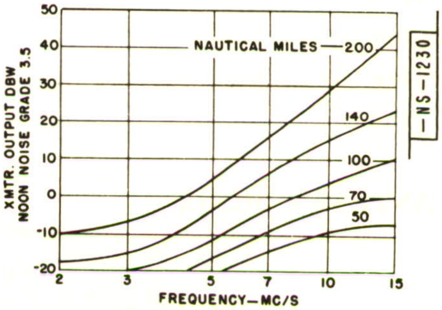

Fig.6D-5. Power required for 60-wpm RATT transmission at noon.

Project Cosmos Interim Report, Part II, Figs. B-8 through B-12, pages B 14 and B 15. Reprinted by permission.

When receiver noise limits the system performance, propagation conditions obviously make it desirable to operate at the lowest possible frequency; however, atmospheric noise may alter this picture considerably.

Atmospheric Noise

During the daytime, when the level of ionization is high and radio waves in this frequency region are highly absorbed by the ionosphere, natural interference is not propagated very far from its point of origin and, consequently, in the absence of local storms, receiver sensitivity is limited by set noise. During the night, however, the natural interference can be propagated long distances at some frequencies and thus establish high noise levels at remote receiving sites. As might be expected, the ambient noise level at different positions on the earth varies greatly with season, geographic location (particularly latitude) and local time. Figure 6C-5 shows the variation of ambient noise for the North American region at noon local time; note the decrease in signal strength in the 1- to 2-Mcps region where the absorption is highest. In the absence of absorption, the noise level at these frequencies would be of the order of 40 to 60 db higher than they normally are at night.

Optimum Frequency

Since the ground-wave attenuation and the ambient noise level vary differently as the operating frequency is varied, the optimum frequency for operation must take into account these two factors. Figures 6D-2,-3, -4, and -5, taken from the Cosmos report, show the power requirements for voice and teletype service, daytime and nighttime, for severe noise conditions. The systems are planned to provide 99 per cent reliable service. Noise grade 3.5 is so much worse than is normally found in the North Atlantic that the power requirements could be reduced 10 to 20 db and still provide reliable service for picket-ship and air-ground communications.

ANTENNA DESIGN

Aircraft Antennas

The experiments reported previously were conducted with existing horizontal wire antenna systems on the aircraft. A minimum improvement of 10 db, and possibly as much as 20 db, for both transmitting and receiving is estimated.

The aircraft antenna radiates only a small portion of the transmitter power as vertically polarized energy and, when receiving, greatly favors any horizontally polarized signal over the vertically polarized signal. Since the atmospheric noise is largely unpolarized, the horizontally polarized component of the noise will be greatly favored over the desired signal.

For optimum performance, a large vertical whip antenna should be used. At 3 Mcps, even a 1/8-wavelength antenna would probably be impractical, although a telescoping vertical antenna 30 feet long appears to be practical on both AEW aircraft and the large long-range fighters. For receiving when the ambient noise is very high, a short, inefficient vertical antenna provides better reception, since it will discriminate equally against desired signal and noise.

Shipboard Antenna Systems

An efficient vertical antenna can be employed, on shipboard, for which purpose (it is understood) the Bureau of Ships has had one designed. When so mounted as to provide an adequate spatial pattern, this antenna should provide a substantial improvement in the performance of ground-wave HF systems.

Where maximum reliability is required and space is available to permit it, the installation of a pair of vertical antennas with adjustable phasing equipment will often permit the noise level to be reduced considerably. Such a technique would also be of considerable use in countering enemy jamming.

NOISE LIMITING

Appendix 9-D of the Counter-Countermeasure report gives a description of a DF noise-limiting system that can greatly reduce the effect of impulsive noise in a receiver. Such a system appears to offer very great promise in counteracting the effects of atmospheric noise. In this scheme, a clipper tube is used following a relatively wideband DF amplifier to limit the impulsive noise peaks. The wideband amplifier is disabled for a time comparable to the reciprocal of its bandwidth by each impulse. The limiter is followed by a narrow-band IF whose bandwidth is established by the information being transmitted.

A receiver operating on this principle has been designed by Mr. Carl Wasmandorf, of the Hoffman Radio Company, who reports very great improvement in system performance. When high atmospheric noise is encountered, improvements as great as 30 db are estimated. The system also is effective, as would be expected, against wideband jamming signals.

J. B. Wiesner

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APPENDIX 6-E

IONOSPHERIC-SCATTER COMMUNICATION

INTRODUCTION

Scattering of VHF (30 to 60 Mcps) radio energy by the E-layer of the ionosphere has recently been employed to provide reliable radioteletype circuits over distances extending from 600 to 1200 miles.[1-5] Such circuits have proved to be independent of the usual propagation variations, and are thus much more reliable than conventional HF transmission, which depends upon reflection from the ionosphere. The existing circuits require large high-power transmitters (up to 50 kw) and large antennas. Recent work has indicated that it is possible to achieve satisfactory operation with more modest systems. The Central Radio Propagation Laboratory of the National Bureau of Standards has been operating a narrow-band low-power circuit over a path more than 1200 miles long. This system employs 5-element Yagi antennas for both transmitting and receiving. Satisfactory signal-to-noise ratio is achieved by employing very stable frequency sources at the transmitter and the receiver, and then using a narrow-band receiver.

Information now available indicates that satisfactory teletype operation will be possible with 1 kw of radiated power. The following sections summarize the pertinent facts regarding this form of propagation.

USEFUL FREQUENCY RANGE

This range, although not sharply defined, is now limited to the range of 30 to 60 Mcps. At frequencies somewhat below 30 Mcps, propagation by means of regular ionospheric reflection can occur frequently, usually with a very great increase in noise and interference. Above about 60 Mcps, the path attenuation becomes so great that very large radiated power is required. In this general frequency range, the path attenuation is roughly proportional to the inverse fifth power of frequency. The lower frequencies, therefore, are generally more desirable, although caution is necessary during the peak years of the sunspot cycle to avoid interference and noise caused by higher-than-normal MUF's.

For fleet operation in which the use of high power is undesirable and large antennas are impractical, 2-frequency operation may be desirable. In the daytime, a frequency in the 30- to 60-Mcps region would provide operation above MUF, while at night, a frequency in the 10- to 20-Mcps region would be practical.

USEFUL DISTANCE

Normally, the useful range is in the order of 600 to 1000 statute miles, which range roughly represents the "3-db" points of received power for frequencies in the vicinity of 50 Mcps. At distances less than 600 miles, the increasing angles of incidence of the transmitted and scattered rays with the ionosphere increase the path attenuation more than is compensated for by the reduction in path length. At distances greater than 1000 miles, the common scattering volume in the E-region of the ionosphere, visible from both transmitter and receiver, is reduced in size by the curvature of the earth.

INFORMATION RATE AND BANDWIDTH LIMITATIONS

While there is undoubtedly an upper limit to the bandwidth and information rate of this form of communication, this matter is only poorly understood at the present time. It appears, however, that there is a practical limitation imposed by power requirements rather than by dispersion in the medium.

SUSCEPTIBILITY TO JAMMING

A jammer at the azimuth of the transmitter must, in general, radiate a signal of strength comparable to that of the transmitter if both jammer and transmitter are in the 600- to 1000-mile range. If the jammer is outside the range, his power requirements will go up. It will generally be more difficult for the jammer to operate effectively if he is far from the transmitter azimuth, because the receiver antenna gain will operate to his disadvantage. If the jammer is closer than 150 miles to the receiver, he may make effective use of tropospheric propagation. Beyond 1100 miles, the jammer's problem becomes very difficult indeed. Of course, if MUF approaches the operating frequency, regular-layer transmission can occur, and jamming from great distances becomes possible.

ANTENNA SYSTEM

For power-conservation reasons, relatively elaborate antennas are usual; antenna gains of 20 db and greater can be effectively used. Both rhombic antennas and corner-reflector arrays are used, although there is some feeling that the latter may be somewhat better.

POWER REQUIREMENTS

In the 30- to 40-Mcps region, 10-kw/kcps bandwidth, in conjunction with 16- to 20-db antennas, seem about the minimum necessary for good reliability. The power required to maintain constant received signal strength varies roughly as the inverse fifth power of frequency. Experiments have shown that at nighttime, when the received signal strength is weakest, the large antenna systems do not realize their full gain; in fact, they often have little more gain than smaller Yagi arrays used for comparison purposes. Since systems must be designed to operate satisfactorily during the poorest propagation conditions, systems with small antennas should be practical.

J. B. Wiesner

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4. Quarterly Progress Report, Division 3, Lincoln Laboratory, M.I.T. (1 October 1952).
5. E.C.S. Megaw, "Waves and Fluctuations," Proc. IEE, 1 (January 1953).

APPENDIX 6-F

METEOR COMMUNICATIONS-JANET

Principle

BASIC CONCEPT

The principle of JANET is the transmission of information in intermittent high-speed bursts by coherent forward scatter from suitable oriented meteor trails in the ionosphere. Transmitters at both terminals radiate continuously. When the received level rises above a set threshold, an identifying signal passed around the loop triggers the high-speed transmission of information.

Operation

Transmitters at A and B are radiating continuously, and switches are set to transmit from A to B (Fig. 6F-I). The presence of a suitable meteor trail raises the power level at receivers A and B, actuating the intelligence gates. The high-speed storage units are triggered – the one at A feeds intelligence to the modulator, and the one at B takes it from the receiver. When the power level falls below another set level, the information flow is stopped. The low-speed storage units operate at the average speed of communication.

Present Development

A teleprinter application having the following characteristics has been developed and is now under test.

Frequency Range:– Usable between 30 and 60 Mcps with two transmitter frequencies spaced 1 Mcps apart.

Distance Range:– Usable up to 1000 miles. (This limit may be stretched with high antennas or in aircraft.)

Information Rate:– Information accepted from standard teletype at 60 words per minute (wpm) is transmitted at 1200 wpm, received, stored on magnetic tape, and printed at 60 wpm on standard teletype.

Bandwidth:– The bandwidth required depends on the modulation system used. One scheme uses 6-channel tone-shift modulation and requires ± 2500 cps. Another uses pulse-position modulation and requires ± 1300 cps.

Power:– Required power below 3 kva at 110 volts, 60 cps, single phase; output power, 50 watts.

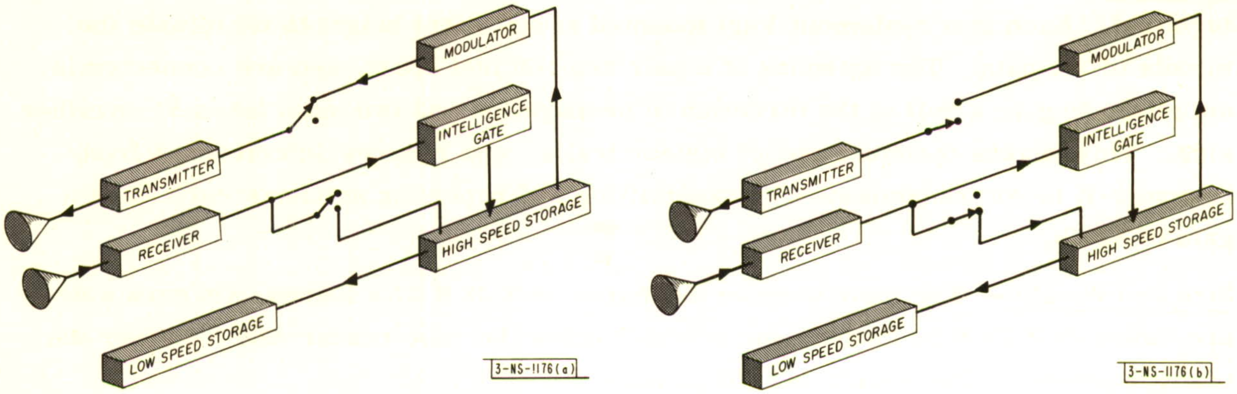

Fig.6F-1. Block diagram of JANET operation.

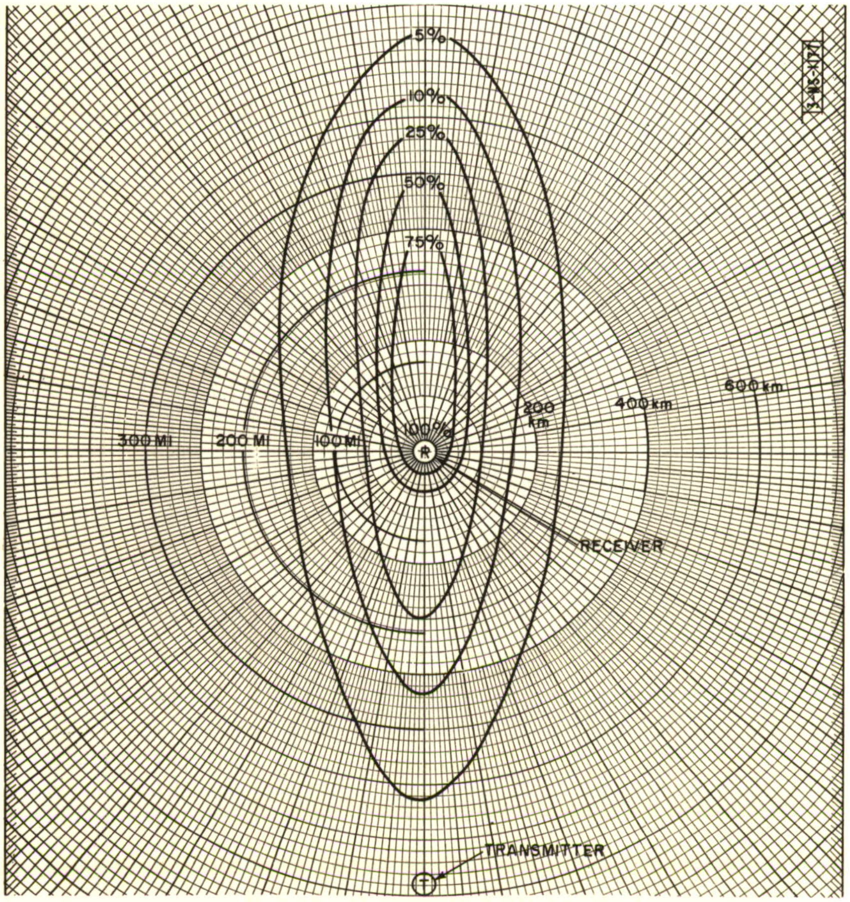

Fig.6F-2. Percentage of information intercepted by monitor.

Antennas:– Two antennas are used for reception and two for transmission at each terminal. Each is a 5-element Yagi mounted at sufficient height to illuminate the middle of the path. The antennas of a pair are 100 feet apart, and are connected in antiphase to give a null in the direction of propagation and two main lobes 5° on either side. This makes optimum use of meteor trails, and reduces interference from sporadic-E layer transmission. Transmitting and receiving antennas each have a gain of 12 db.

Size and Weight:– The main console measures 54 × 28 × 77.5 inches. On each side are tables 26 × 24 × 31 inches, one of which holds the tape reader and the other the teletype printer. The weight is 1200 pounds.

Time Delay:– A delay as long as several minutes can occur in transmission of a given message for an average rate of transmission of 60 wpm.

Propagation Reliability:– Not subject to ionospheric disturbances causing HF interruptions.

Security:– The signals are intermittent, high-speed, and unpredictable in time. Because of path and meteor geometry, information can be received with high reliability only near the receiver. The identifying signal that triggers the transmission of intelligence can so be coded as to depend on the history of transmission over the closed path. Figure 6F-2 shows the percentage of information that can be intercepted by a monitor in the vicinity of the receiver.

Jamming:– Could be jammed by a low-power transmitter near one terminal, or by a remote very-high-powered transmitter.

Theory of Operation

Power:– The power received from a meteor trail having optimum orientation is given by

$$P_r = KP_tG_tG_r\lambda^3q^2/R_1R_2(R_1 + R_2)\cos^2\phi$$

where

K = 5×10^{-32}, $q < 10^{14}$/meter,

R_1, R_2 = ranges to meteor trail from T and R,

q = electrons per meter, line density in meteor trail,

ϕ = interior half-angle between R_1 and R_2.

Thus, the received power varies with the cube of the wavelength, the square of the meteor-trail density, and is strongly dependent on the angle of scatter. When $q > 10^{14}$/meter, $P_r \alpha q^{1/2}$.

Duration:– The duration of meteor trails having line density less than the critical vale, $q_c = 10^{14}$/meter, is given by

$$r = k'\lambda^2/\cos^2 \phi$$

where $q = q_o \exp^{-t/r}$ and q_o is the initial line density on formation of the principal Fresnel zone of the meteor trail. Thus, the duration is proportional to the amplitude and the square of the wavelength. JANET depends for its operation on those trails having $q_o < 10^{14}$/meter and exponential decay.

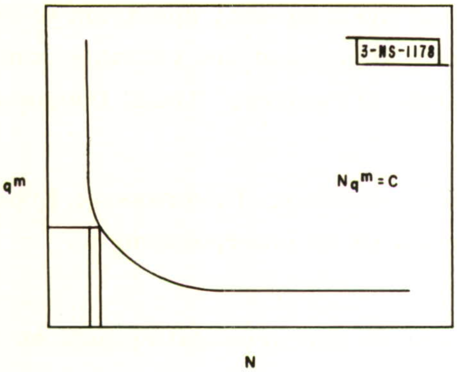

Fig.6F-3. Graph of meteor occurrence.

Meteor Occurrence:– The number of meteors N producing trails of density greater than q per unit area in unit time is given by $Nq^m = C$, where C is a constant (see Fig. 6F-3). According to one theory m = 1, according to another m = 1.46; experiment favors m = 1.

Only 2 to 6 per cent of meteors in the area of reflection having a given line density are actually detected by a particular circuit. The number of meteors per hour seen on a circuit is of the order of $N = 2.7 \times 10^4 A/q$, where A is the area in square meters of the ionosphere at 100 km height illuminated by the antennas.

The number of meteors seen increases approximately by a factor of 3.2 for each 10-db increase in transmitted power. As an example, given $P_t = 150$ watts, $G_t = G_R = 30$, A = 100 km × 300 km, $\lambda = 6$ meters, $R_1 = R_2 = 650$ km, $\phi = 79°$, $P_r = 10^{-14}$ watts (20 db above noise in 1.3-kcps band), q is found to be 10^{13} electrons/meter, and the number of meteors detected per hour is 80.

Total Percentage Time of Signal:– Experimentally, it is found that for the above example the required signal (20 db above noise) is present 5 per cent of the time. At a level of 10 db up, it is present 2 per cent of the time; at a level of 10 db down, 25 per cent of the time; at a level of 20 db down, 88 per cent of the time. Thus, with $P_t = 15$ kw, the required signal is present 88 per cent of the time.

Meteor-Signal Variations and Distribution

Variations:– The number of meteor signals varies by a factor of about 3 diurnally with maximum at 9 a.m. and minimum at 9 p.m. There is an undertermined seasonal factor of the order of 4.

The signal is the result of many random elements, with no steady component above the noise level in which individual meteors may raise the level 50 db in one second.

Enhancements:– Meteor showers produce smooth enhancements of background signal of 10 db lasting several hours. E-sporadic produces sudden strong enhancements of 20 to 30 db usually lasting less than one hour. When shower meteors are parallel to the circuit path, an increase in the number of strong meteor signals occurs.

Modulation:– Preliminary measurements indicate that the frequency spectrum of the received signal is of the order of 25 cps in width, with significant and variable components extending several hundred cycles on either side of carrier. Thus, frequency-shift modulation is not desirable.

Meteor bursts are preceded by whistles caused by the formation of successive Fresnel zones. These bursts are of low energy and are eliminated by incorporating a 0.1-second delay in the intelligence gates.

Dispersion is negligable for frequencies 1 Mcps apart, so that propagation puts no practical limit on the modulation frequency.

System Storage Capacity:– The average rate of transmission in words per minute is given by (60/25) FM, where M is the modulation frequency and F the fractional duty cycle.

The duty cycle is given by

$$F = \sum_{t=1}^{C} \frac{Nt}{T} + \frac{C}{T} \sum_{t=CH}^{\infty} N \quad ,$$

where N is the number of meteors per hour, t their duration in seconds, and T = 3600. In this expression, C is the time in seconds for which the storage unit can supply intelligence for transmission without being replenished. The last term is the contribution of signals lasting longer than C. Providing that the storage capacity is greater than

10 seconds, F is practically independent of C. It is important that the time of entry of the storage system be negligable.

Future Development

There are 4 main techniques of communication via meteors that must be considered in further development.

Technique I:– This technique makes use of similar transmitters at each end of the circuit, and information is passed simultaneously in both directions. The information is stored both before and after transmission. Consecutive units of information are transmitted in order, and each unit is transmitted once, and only once. This system, intended for the passage of information having little or no natural redundancy, is characterized by a significant degree of privacy. It is the technique used in the present JANET teleprinter.

Technique II:– This technique uses only one transmitter and is thus capable of passing information in only one direction. The basic information is broken up into units, each unit being repeated until the probability of reception at the receiver is high. The system has no significant privacy aside from that afforded by the limited range of the signal. The information-handling equipment is relatively simple at the transmitting end, but complicated at the receiving end. The technique is not efficient when accurate and complete passage of all the input information is required.

Technique III:– This technique is similar to II, with the exception that a simple return circuit is added in order to indicate when each unit of information is received. This system is somewhat more private than II and also is considerably more efficient for the passage of information in the form of the standard codes.

Technique IV:– This technique combines the information handling of Technique II with the principle of operation of Technique I. Just as in II, the input information is broken into units. However, instead of transmitting each unit a fixed number of times, it is kept circulating at high speed in an information store for a given length of time. When, and only when, a suitable meteor is present, the transmitter is connected to the information store so that the circulating unit of information is transmitted. A low-power transmitter at the receiving end of the circuit is monitored at the transmitting end in order to detect the presence of a suitable meteor. In its simplest form, this system would be applicable to information having a moderate degree of redundancy. It also provides nearly the same degree of privacy as that of Technique I. For the particular case in which the input information consists of a slowly changing array of information-carrying digits, the system transmits the complete array at irregular intervals determined by the occurrence of suitable meteors. It is then necessary to insure (by choice of the system parameters) that the frequency of these transmissions is sufficient to provide statistically adequate sampling of the input information. It seems probable that the information-handling equipment can be made reasonably simple, particularly at the transmitting end of the circuit.

APPLICATIONS TO CONTINENTAL DEFENSE

Introduction

The previous section outlined the principles and techniques on which meteor communication must be based. This section applies these principles and techniques to specific communication problems.

It must be emphasized at the outset that the parameters determining meteor communication have not yet been isolated and measured adequately; much research must be done before the basic phenomena are understood quantitatively. Although the relationships displayed in the curves of this section are based on the best available measurements and reasonable theoretical extrapolations, they must nevertheless be treated as only tentative. The conclusions are based on experimental and theoretical work (much of it as yet unpublished) carried on at the Radio Physics Laboratory of the Defence Research Board, Ottawa, under the direction of Dr. P. A. Forsyth.

Theoretical analyses of the 4 techniques outlined in the previous section have been undertaken, but only the main conclusions are presented below. Curves provide the quantitative relationships required for the design of specific communication circuits, and examples are given to illustrate the use of the curves.

General Parameters

The curves are calculated for the following standard conditions:

Range (transmitter to receiver)	1000 km (622 mi.)
Gain (10 db at each end)	20 db
Frequency	50 Mcps
Receiver sensitivity (cosmic noise)	10^{-16}w/kcps
Signal-to-noise ratio (minimum)	10 db

The curves cover the probable useful ranges. The limits are determined by the following consideration; (1) the number of signals per second must exceed a practical minimum, but must be less than the limit imposed by multipath reception; (2) low signal-to-noise ratios cannot be used, except with special techniques and low information rates; and (3) in closed-loop operation, the signal duration must be above a minimum set by terminal delays and transit times.

Range and Gain

New theoretical calculations indicate that meteor communication is feasible, from an upper limit at the meteor horizon of about 1600 km, right down to zero range. Communication below the previously assumed lower limit of 600 km is feasible with low-gain omnidirectional antennas. Either horizontal or vertical polarization may be used with little change in efficiency.

For short-range communication (up to 600 km), antenna gains of 3 to 6 db should be used. For long range (between 600 and 1600 km), gains of 6 to 10 db are optimum. At short range, one-half the signal is contributed by meteors within 15° of the horizon; consequently, the antenna pattern should provide good cover at low angle. At long range, the most efficient region for meteor scatter lies about 8° on either side of the Great Circle path. A split-beam pattern with a gain of about 10 db is then most efficient.

Using optimum antennas in each case, short-range communication will be about five times less efficient than the long-range conditions displayed in the curves.

Frequency and Sensitivity

In the useful frequency range for JANET (from 30 to 60 Mcps), cosmic noise determines the required signal level. Both the signal and noise power vary as λ^3, however, the signal duration varies as λ^2, consequently, the efficiency of a JANET system varies as λ^2. At higher frequencies, where cosmic noise becomes unimportant, the efficiency varies as $\lambda^{3.5}$.

Duration, Occurrence and Duty Cycle

Figure 6F-4 shows the number of useful signals per second, having durations within an increment of one second, as a function of the duration, plotted for useful values of power-to-receiver bandwidth. Example: Using 100 watts at the transmitter for every kilocycle at the receiver, there will be 15×10^{-4} signals per second, with duration greater than 6.5 seconds and less than 7.5 seconds.

Figure 6F-5 shows the number of useful signals per second, having durations above a given minimum, as a function of the ratio of transmitter power-to-receiver bandwidth.

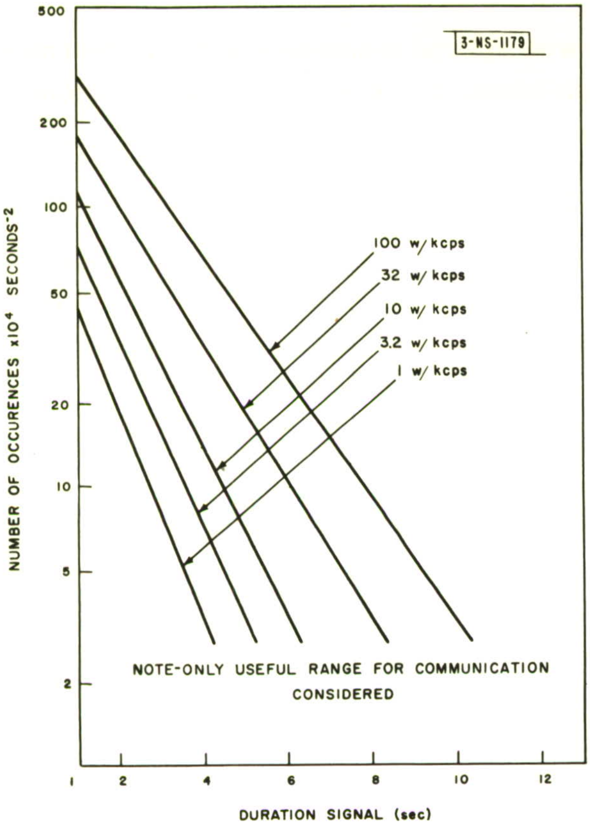

Fig.6F-4. Times per second that signal exceeds noise by 10 db (duration vs output powers).

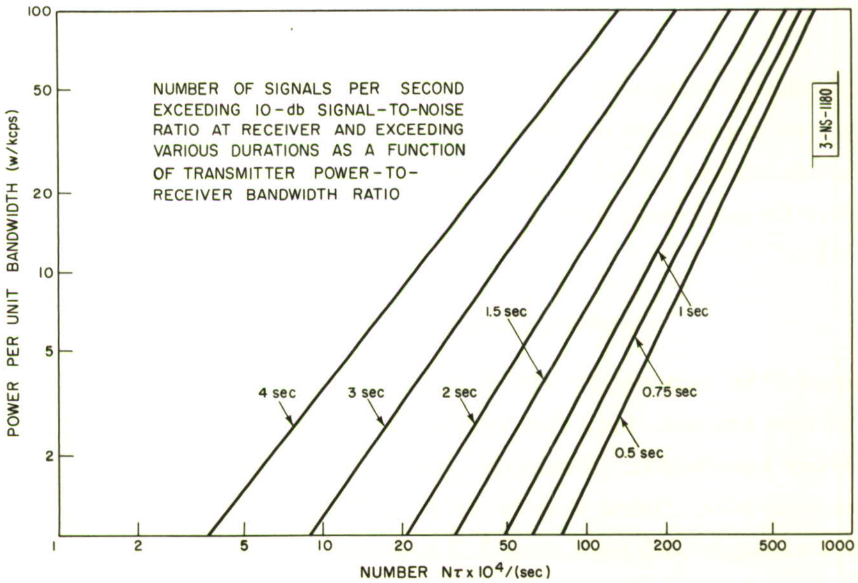

Fig.6F-5. Times per second that signal exceeds noise by 10 db.(Transmitter power-to-received bandwidth.)

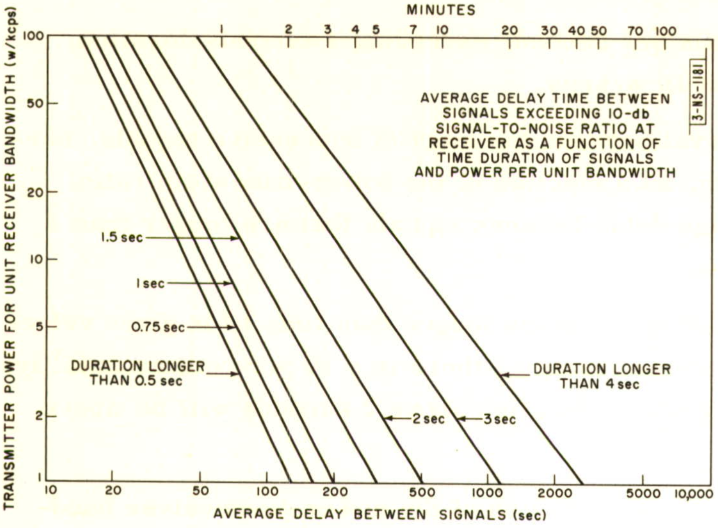

Fig.6F-6. Average delay time as a function of time duration and power.

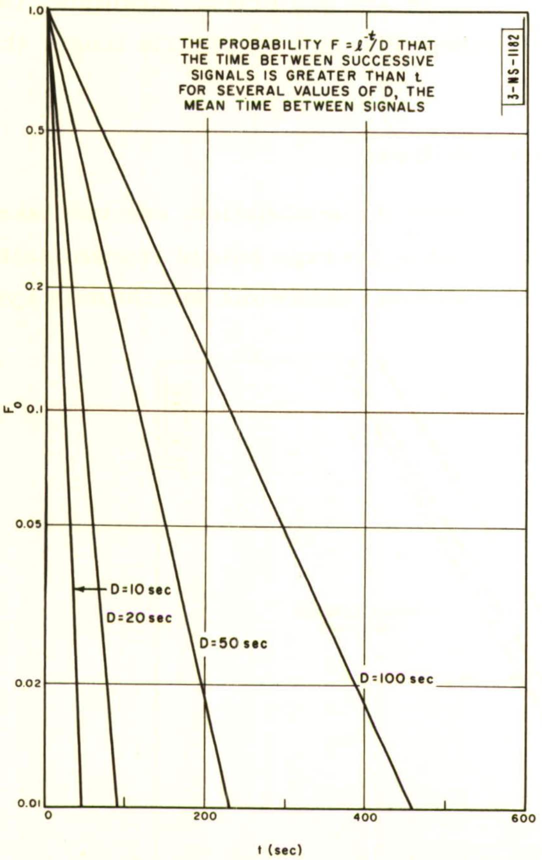

Fig.6F-7. Probability that time between successive signals is greater than t for values of D, mean time between signals.

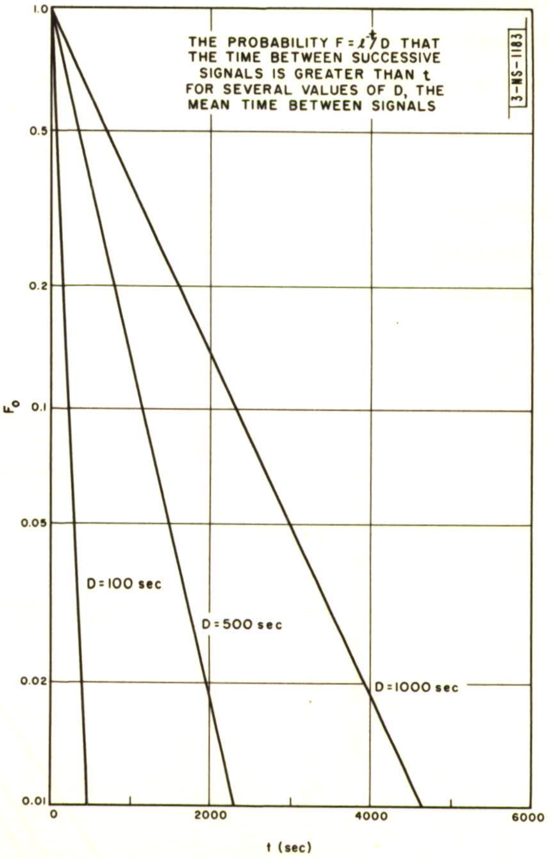

Fig.6F-8. Probability that time between successive signals is greater than t for values of D, mean time between signals.

Example: There are 20×10^{-4} signals per second, exceeding 4 seconds duration, when the power-to-bandwidth ratio is 10 w/kcps.

Figure 6F-6 shows the average interval between the start of successive signals, having durations above a given minimum, as a function of the power-bandwidth ratio. Example: For 10 w/kcps, the average delay between signals that are longer than 2 seconds is 120 seconds, or 2 minutes.

Figures 6F-7 and -8 show the probability of delays longer than time t for given values of average delay. Example: In the above example, there is a 10 per cent probability that the delay between successive signals of duration above 2 seconds will be above 280 seconds.

Figure 6F-9 shows the total duty cycle as a function of the power-to-receiver bandwidth ratio, using all signals above a minimum length for their whole duration. Effects of finite storage capacity and equipment delays are neglected. Example: Using 100 watts at the transmitter, 10-kcps receiver bandwidth, and all signals longer than 1 second, the duty cycle is 5 per cent.

Information Bandwidth and Power

Neglecting factors depending on noise and the nature of the modulation, one can take the information bandwidth in cycles per second, equal to the average rate of transmission in bits per second, and equal to the product of the receiver bandwidth and the duty cycle.

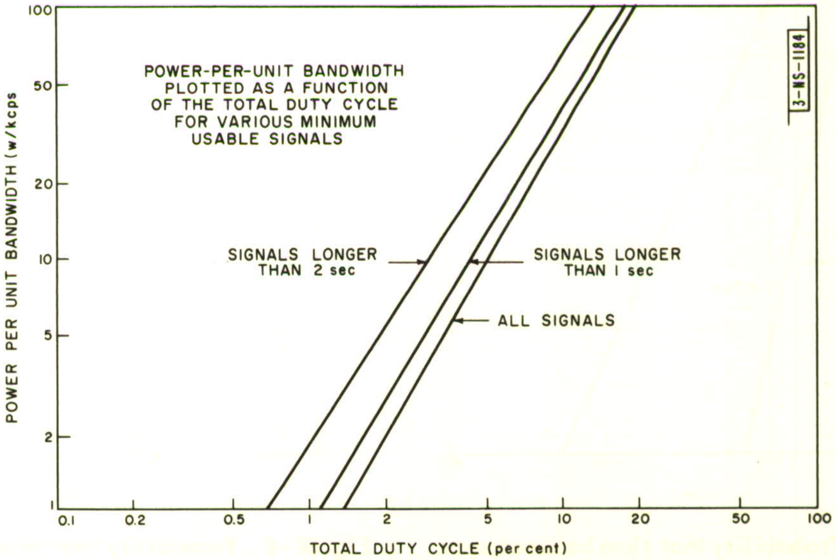

Fig.6F-9. Power-per-unit bandwidth as a function of duty cycle for various minimum signals.

If the transmitter could so be pulsed that the average power were equal to the product of the peak power and the duty cycle, then the previous curves would apply equally to the ratios of peak power-to-receiver bandwidth, or of average power-to-information bandwidth. However, the duration of useful meteor bursts is of the order of 0.5 to 4 seconds. It is questionable whether a transmitter can easily be designed to withstand peak voltages for periods long enough to take full advantage of the duty cycle.

In the techniques considered below, no attempt has been made to take advantage of the duty cycle at the transmitter. The average power and peak power are assumed equal. A large system gain would accrue if the transmitter could be pulsed efficiently.

Assuming peak power equal to average power, it follows that the power-to-receiver bandwidth ratio is equal to the power-to-information bandwidth ratio multiplied by the duty cycle. Example: In the previous example, for signals longer than one second, the power was 100 watts, the duty cycle 5 per cent, and the receiver bandwidth 10 kcps. The information bandwidth is, therefore, 500 cps and the average information rate 500 bits/sec.

Fixed Point-to-Point Teletype (Technique I)

Technique I (described in the section on Basic Concept) is the most efficient for fixed point-to-point communication when redundancy is low. In this technique, simultaneous transmission occurs in both directions, and nearly the complete duty cycle for all meteor signals is utilized. However, this technique has the disadvantage of transmitters at both ends radiating continuously on frequencies separated by about 1 Mcps, so that separate transmitting and receiving antennas must be provided and spaced sufficiently apart to provide isolation to the order of 200 db. A teletype application of this technique, now under test, has already been described.

Variable Bandwidth System (Technique I)

In the present teletype application, information is passed while the signal exceeds a fixed value at a constant rate. Because meteor signals may range in amplitude over 60 db, it would be a considerable advantage if better use could be made of the stronger signals. This could be accomplished if the information and receiver bandwidths could be varied directly with the input signal. The receiver signal-to-noise ratio would then be kept constant at, say, a value of 10 db.

Theoretical calculations show that about 15 times as much information could be transmitted in a variable-bandwidth meteor system in which the bandwidth varied up to 100 times the fixed bandwidth. Considerable development is required before such a variable-bandwidth system could be made practical.

Ship-to-Shore Communication (Technique IV)

Ship-to-shore communication up to ranges of 1000 miles appears feasible at moderate information rates using Technique IV.

Omnidirectional or steerable antennas with gains of 4 to 10 db should be used for common transmission and reception. This is possible in Technique IV, since transmitters and receivers are not on simultaneously. Technique IV can also be used for the transmission of written or typed material in a simple form of facsimile.

The power requirement is of the order of 1 kw/kcps of average bandwidth, and the average delay time of the order of one minute. Radar data can also be transmitted, provided that the average bandwidth can be kept to a few kilocycles and an average delay of 30 to 60 seconds is allowable. These limits could be greatly extended if transmitters of 2- or 3-kw average power rating, and 50- to 100-kw peak rating, could be used.

A useful feature of Technique IV is that the rate of occurrence of transmission can so be placed under the control of the operator at the receiver that he can, if he desires, increase the number of transmissions at the expense of the quality of individual transmissions.

Radar information is naturally divided into units suitable for transmission by Technique IV. The signal corresponding to one complete PPI frame is kept circulating in a store, at a speed much higher than the rate of sweep of the PPI trace. As the trace sweeps around and new information becomes available, it is used to replace the corresponding information circulating in the store. Whenever a suitable meteor trail occurs, the current information in the store is transmitted during the lifetime of the trail. The rate at which the information is circulated in the store (and transmitted during the suitable periods) is determined by the optimum length of the unit transmission. If the frequency of transmission is chosen to equal (statistically) the PPI-frame repetition frequency, then there frequently will be redundant transmissions in the sense that the information contained in a given transmission could be deduced from that contained in the preceding and following transmissions. Each transmission, however, contains the latest information available.

At the receiving end, the PPI picture may be reconstructed from the transmitted signals, the primary difference between the new PPI display and the original being that the new one is changed completely at intervals, whereas the original is changed one part at a time. Both are changed (statistically) at the same rate. At the instant of transmission, both PPI displays are similar in that one part of the picture contains new information, the age of the remainder varying according to position on the picture. Between transmissions, of course, the output PPI display remains static and is, therefore, inferior to the input display.

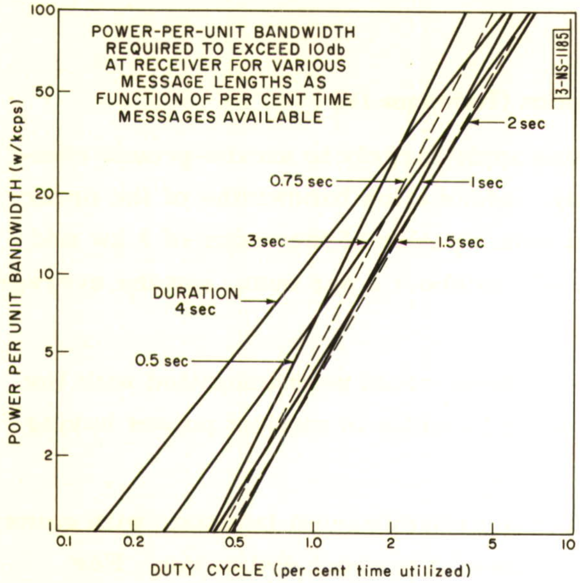

Fig.6F-10. Power-per-unit bandwidth required for various message lengths as a function of time messages available.

In Technique IV, the message length transmitted is constant, irrespective of the duration of the meteor trail. The duty cycle is, therefore, smaller than in Technique I in which the whole meteor signal is utilized.

Figure 6F-10 shows the dependence of the duty cycle on the power-to-receiver bandwidth ratio using messages of various fixed lengths. Example: Using a message length of 1.5 seconds, power of 1 kw, and bandwidth of 100 kcps, the duty cycle is about 2 per cent. Consequently, the information bandwidth that may be transmitted is of the order of 2 kcps. From Fig. 6F-4, it is found that the average delay between signals is 1.5 minutes.

It can be shown that it is desirable to choose the message duration T so that the product TN_T is a maximum, where N_T is the number of meteor signals per second of duration greater than T, and above a given signal-to-noise ratio. A maximum TN_T gives a minimum peak bandwidth.

TABLE 6F – I

OPTIMUM MESSAGE LENGTH AND MINIMUM PEAK BANDWIDTH

Power/Bandwidth (w/kcp)	Minimum Peak Bandwidth (kcps)	Peak Power (kw)	Message Length (sec.)
1	1870	1.87	1.13
10	600	6.0	1.43
100	140	14.0	2.05

Table 6F-I gives the optimum message length and minimum peak bandwidth for different power-to-bandwidth ratios.

Air-to-Ground Communication (Technique IV)

The conclusions reached in the last two sections apply largely to air-to-ground communication from large aircraft. That is to say, information bandwidths of the order of 2 kcps or 2000 bits/sec may be transmitted with a power of the order of 1 kw and a receiver bandwidth of 100 kcps. The duty cycle is about 2 per cent, and the average delay between signals about 1.5 minutes.

As already pointed out, much larger information rates could be transmitted with low average power if the transmitter could be pulsed efficiently in random pulses having lengths of the order of 0.5 to 4 seconds.

On the aircraft, omnidirectional low-gain antennas probably must be used, with gains of perhaps 3 to 6 db. These are optimum for ranges up to about 400 miles. For longer ranges (up to 1000 miles) antenna gains of 10 db would be optimum. Although experimental work has not yet been done with low-gain antennas, it is probable that the decrease in efficiency, using such antennas at 1000 miles, will not be greater than 10 db.

Conclusions

Much research on meteor propagation must be done before circuit parameters can be established quantitatively.

Communication at average information rates of 2000 bits/sec, with average power of the order of 1 kw and receiver bandwidth of the order of 2 kcps, is feasible over ranges up to 1000 miles using antenna gains of 10db. Message delays will be of the order of one minute.

Technique I should be developed further – it is more efficient, but is disadvantageous in that transmitters at both ends must be on continuously. Because of the requirement for separate transmitting and receiving antennas isolated to the extent of 200 db, it is not suitable for ship or aircraft operation. The variable-bandwidth proposal should be investigated for possible development.

Technique IV appears very promising for mobile communication from ships, submarines and aircraft, and should be developed with maximum speed. It has the advantage that transmitters are on only during the meteor bursts. If one could take advantage of the duty cycle at the transmitter by using high peak power, much higher information rates could be carried than stated in the second conclusion above.

Technique IV is ideally suited to transmission of redundant information, such as facsimile or radar data.

J.C.W. Scott

APPENDIX 6-G

TROPOSPHERIC-SCATTER COMMUNICATION

INTRODUCTION

Recent experimental work (Refs. 1 through 5) has shown that the strength of ultrashort-wave and microwave radio signals well beyond the horizon is much greater than was to be expected on a basis of normal electromagnetic diffraction theory. While the precise reason for this is not completely understood, it is generally believed to be due to scattering of the radio waves by inhomogeneities, caused by turbulence in the atmosphere.

Sufficient experimental data exist to permit proper system design for many purposes; however, the theoretical understanding of the propagation phenomena is not adequate to permit the design of systems widely different from present ones without experimental confirmation.

Scatter techniques have been employed extensively for point-to-point radio-telephone circuits up to distances of 350 miles, and there is some reason to believe that, with increasing power, voice and teletype communication could be accomplished to distances as great as 500 miles.

PROPAGATION CHARACTERISTICS

The signal strength measured well beyond the radio horizon can exceed by hundreds of decibels the field predicted by normal diffraction theory. Measurements have been made in many parts of the world and by many experimenters. As one would expect, considerable variation can be found between the results of the various investigators; however, when allowances are made for the differences in experimental conditions, the data are in substantial agreement.

Figure 6G-1 shows, as a function of range, the median signal loss in excess of that which would be encountered on a free-space circuit. This curve represents an averaging of available data, and displays yearly median signals about which there are wide fluctuations. During the winter, monthly values of median signal strength can be as much as 10 db less than the values given by the curve of Fig. 6G-1. In addition, a similar allowance must be made for daily variations in signal strength.

The slope of the line in Fig. 6G-1 is approximately 20 db per octave, so that doubling the range of a system requires 26 db of added system performance if comparable signal-to-noise performance is desired at the new range.

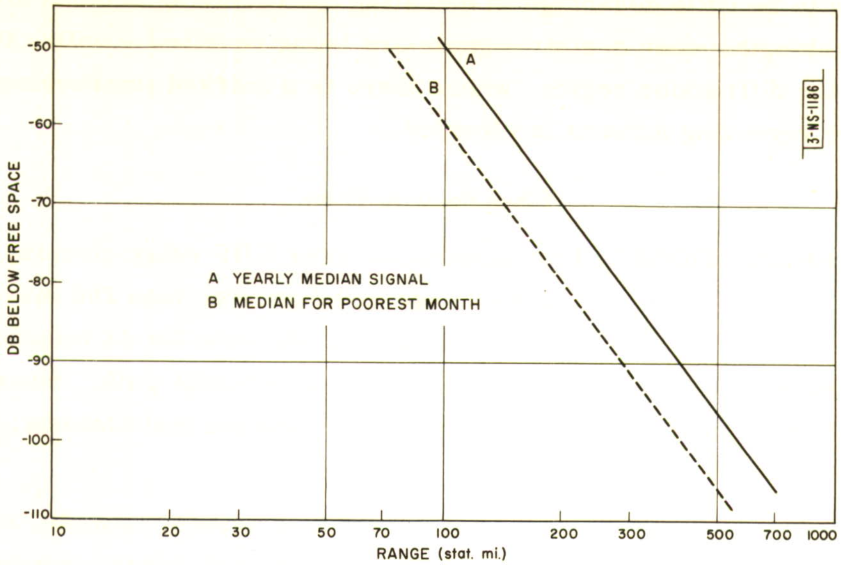

Fig.6G-1. Path loss for scatter signal in addition to normal free-space loss.

SIGNAL CHARACTERISTICS

A signal propagated by means of the scatter phenomena fluctuates rapidly in a random manner, the envelope of the signal being Rayleigh-distributed in most cases. Because of this, it is necessary to provide a considerable margin of safety in system performance if the signal is to be above the received noise level most of the time. It is customary to provide 20 to 30 db of system margin to allow for the fading and, in addition, diversity reception often is employed. The actual fading rates are determined by the operating frequency and the antenna size. For a frequency of 1000 Mcps, the fading period is of the order of a few seconds.

Phase coherence in a plane normal to the arrival path is observed for spacings up to 20 wavelengths and falls off rapidly at greater spacings, as a result of which the gain that can be realized with very large antennas may be limited. Spatial-diversity receiving systems can be employed to reduce the effect of fading.

Multipath effects are expected to limit the intelligence band that could be adequately transmitted over a tropospheric-scatter circuit; however, existing experimental circuits appear to be adequate to transmit video bandwidths of at least 5 Mcps. It is expected that the maximum bandwidth will be reduced somewhat if omnidirectional antennas are employed (as in the ship-to-ship relay suggested in a subsequent section); however, calculations indicate that even in this case the intelligence bandwidth should be greater than 1 Mcps.

There appears to be little advantage in elevating the receiving antenna above approximately 20 wavelengths when scatter signals are being received – unlike the situation that exists in the diffraction region, where there is a marked improvement in signal strength as the receiving antenna is elevated.

Fixed Point-to-Point

SYSTEM APPLICATIONS

Tropospheric-scatter UHF relay circuits have been operated over paths greater than 200 miles in length, and with bandwidth adequate for 24 telephone circuits. A single telephone circuit has been operated over a 350-mile path. Since this method of communication is now being used in several air defense installations, this report will not consider the details of broadband relays.

For many purposes in connection with the air defense system, simple, reliable, single-channel teletype or telephone circuits are needed. In such cases, tropospheric scatter can be used to advantage. The curves of Fig. 6G-2 show the power required, as a

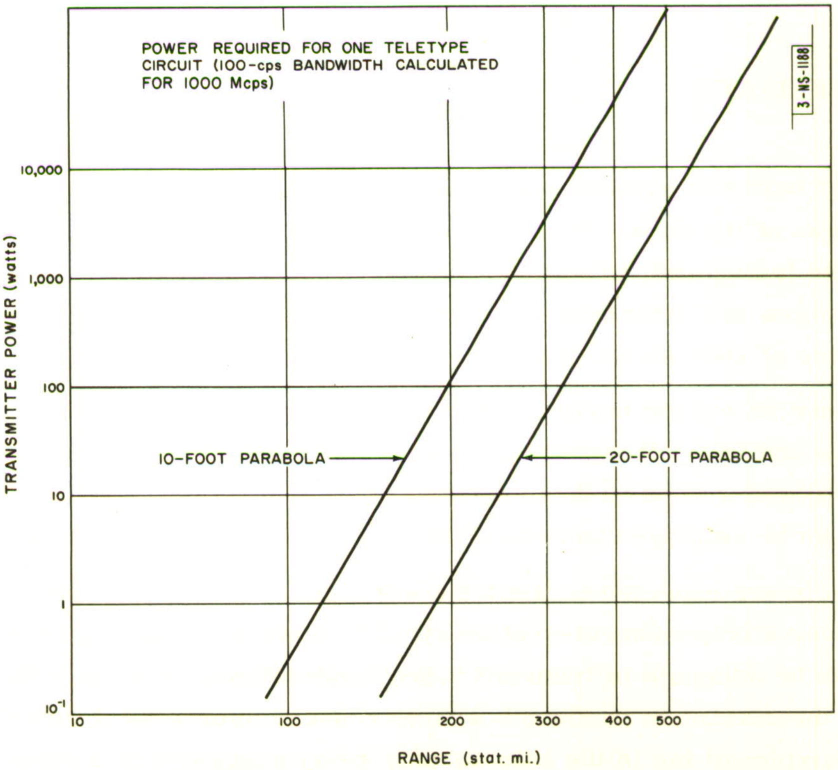

Fig.6G-2. Power required for one teletype circuit.

function of range, for a single teletype channel. The results are presented for two antenna sizes. The curves are predicted for a system having a 10-db noise figure in the receiver, diversity reception, and a 40-db margin to allow for seasonal and rapid fluctuations in signal level.

Figure 6G-3 shows the power required for a system providing a single telephone channel and using different antenna diameters. In deriving these curves, a 10-db noise-figure receiver was postulated, diversity reception was assumed, and a 30-db fading margin allowed. This margin is probably adequate for a single-hop telephone circuit. However, if the circuit is to be a link in a multiple-hop circuit, a 10- to 20-db addition margin should be allowed to noise-free reliable operation. These calculations assume that proper antenna locations are available; if it is not possible to get unobstructed antenna sites, considerably more power may be required.

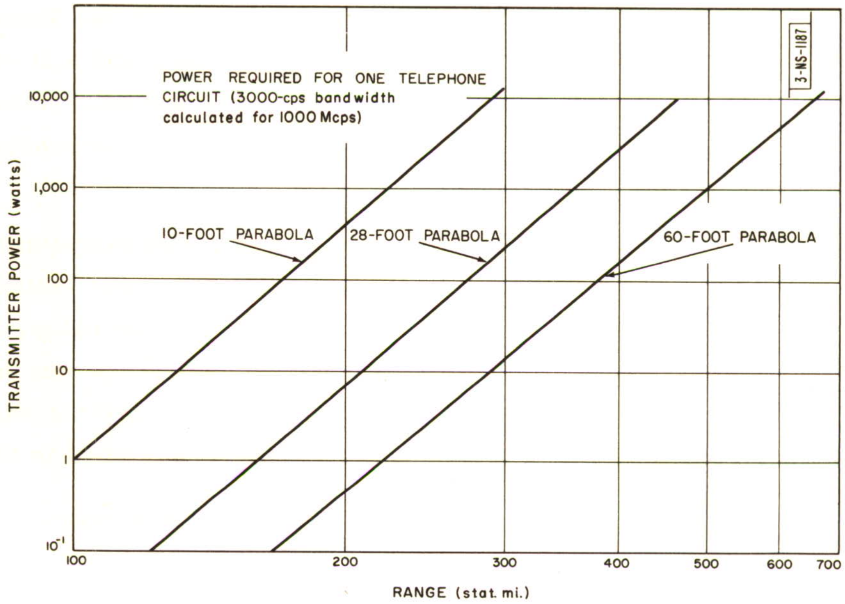

Fig.6G-3. Power required for one telephone circuit.

For the general surveillance system, radio-telephone or teletype communication is required from remote sites as much as 300 miles distant from communication centers. From Figs. 6G-2 and -3, it can be seen that tropospheric-scatter circuits using either teletype or voice communication can be used for this purpose.

Shipboard Operation

Navy data-processing systems, as presently envisaged by Project Lamp Light, require a continuous exchange of data between the various ships that must function as part of the system. Calculations indicate that it should be possible to achieve beyond-line-of-sight transmission to distances in excess of 100 miles using the scatter signals and employing omnidirectional antenna systems for both transmitting and receiving.

A calculation, employing the data of Fig. 6G-1, indicates that communication at a range of 100 miles would require approximately 0.1 w/cps of intelligence bandwidth. These calculations were made for a system operating on a frequency of 300 Mcps and having an omnidirectional antenna 5 wavelengths long, a 6-db receiver and a 30-db fading margin. If a 5-kw transmitter were used on each ship, operation for data transmission and voice could probably be obtained to a range 150 to 200 miles, depending upon the exact propagation and reception conditions.

It would not be difficult for an enemy to jam such a communication system if he were determined to do so. For this reason, it is recommended that the Centipede time-sharing system (described in App. 6-A), together with an airborne relay, be used for multiplexing the various circuits. Normally, this system would operate by means of scatter; but in the event of jamming, or if it is desired to increase the range over which communication can be maintained, the aircraft relay described in the Centipede section could be employed.

J.B. Wiesner

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CHAPTER 7

DATA PROCESSING

CHAPTER 7

DATA PROCESSING

Need for Modern Data-Processing Equipment

I. INTRODUCTION

In order to perform its mission in wartime, the Navy must be able to defend itself against attack by submarines and high-speed aircraft armed with atomic weapons. This calls for continued improvements in detection devices, such as radar and sonar, and for ever more effective weapons. It also calls for data-processing equipment that will make full use of all the information provided by the detection devices, and that will permit optimum use of all available weapons. The manual methods of handling data, which have not changed appreciably in 10 years, are presently the main bottleneck. Data-processing equipment and electronic computer techniques offer great promise for increasing the effectiveness of the Navy.[1,2,3*]

Definition of Data-Processing

Figure 7-1 is a simplified diagram of the flow of data within a ship. On the left are the sources of information: the detectors, such as radar, sonar, ECM, and paper inputs such as flight plans, status information, intelligence. All this input information is processed, analyzed and evaluated. Decisions are made and parts of the data, together with orders, are routed to the various users for navigation, vectoring intercept aircraft, directing weapons and so forth. "Data processing" will be used to refer to all handling and processing of data between the input and output devices, including the equipment and personnel involved in detection, tracking, display, analysis, evaluation and assignment. It also includes radio data-link equipment and weapons computers. Although emphasis will be placed on the electronic equipment involved in these operations, the interplay of man and machine must be considered at every step.

Present Data-Processing Methods

Today most of the data-processing is performed manually in the Combat Information Center (CIC). There the radar video is displayed on cathode-ray tubes. Trackers observe the tubes and report coordinates by telephone to plotters who record the tracks on a large, vertical "summary plot." Height, size and identity information are observed and relayed to the plotters in a similar manner. Information from the other inputs is also channeled through the CIC where it may be displayed on the summary

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[*] Please refer to numbered references at end of Chapter.

plot and coordinated with the radar data. Further information is displayed on status boards. Several officers observe the summary plot and the other displays, evaluate the situation, and transmit orders and coordinate data by telephone to the bridge and battle stations. Usually air intercept controllers and communications personnel are also crowded into the CIC. Each voice-telling operation introduces delay and loses accuracy. The summary plot is a confusing display and the whole CIC saturates on a small number of tracks. This centralization of data handling tends to bypass the bridge, so that the captain of the ship may have little knowledge or control of the situation.

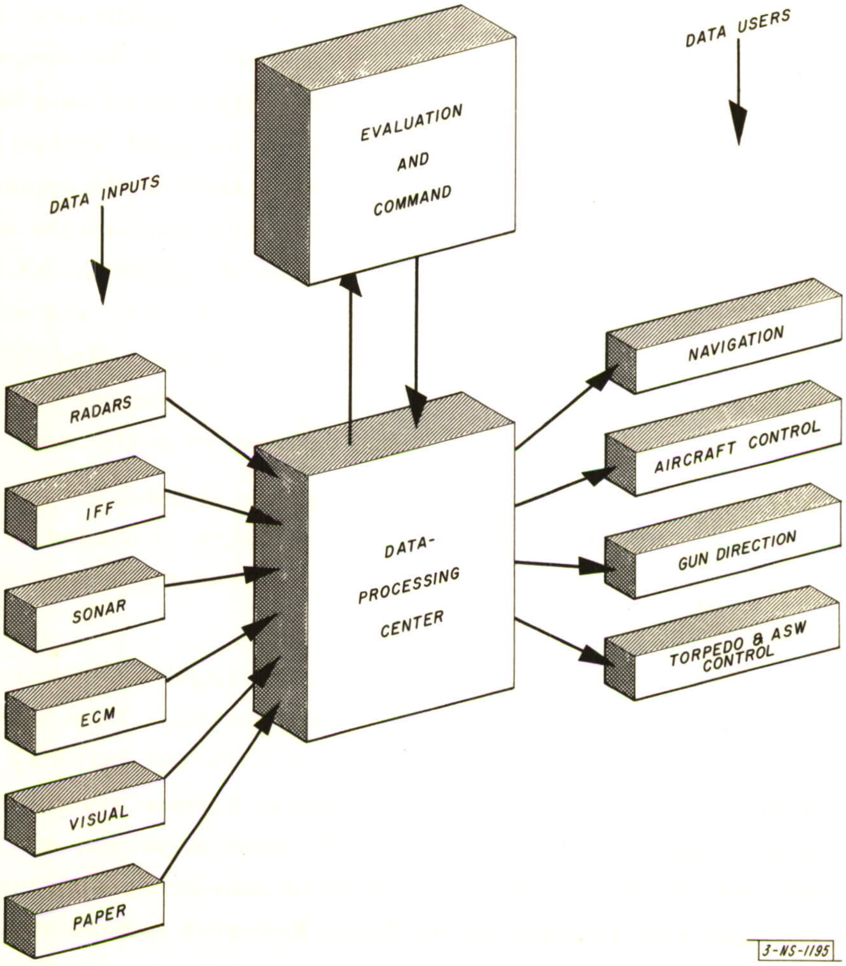

Fig.7-1. The flow of data within a ship.

Advantages of Modern Data-Processing Equipment

Great strides have been made in the field of data handling and data-processing for industrial, military and scientific applications since the war. These techniques can be applied to make each step of the naval data processing more efficient. For example, an electronic alarm can improve the detection capability of a radar observer. A rate-aided electronic store can increase the number of targets a tracker can follow. Automatic detection and tracking equipment is under development which may handle hundreds of tracks. All targets in a central store or any selected category from among them may be displayed accurately and without delay at any desired location. Electronic computers may be used to convert from polar to cartesian coordinates, to correct radar data for lack of stabilization, to assist in threat evaluation and weapon assignment, to control aircraft interceptors. It is possible to exchange target data between ships so that the total of all information may be available to command, and so that each ship may take into account targets observed by any of the vessels in the group. Data-processing equipment will provide higher sensitivity, will maintain the accuracy of the input data, will permit instant display and transfer of data from one station to another, will increase the track capacity by orders of magnitude, and will make possible the integration of all information available within a group. Any desired part of this information may be made available to all echelons of command. The different operations may be located where their functions can best be performed.

The desirability of installing data-processing equipment is taken for granted. This chapter is concerned with defining what kind of data system is needed, examining what knowledge and what hardware are available, and recommending a realistic program of research and production.

The next section develops the technical and operational requirements or basic philosophy which, we believe, should govern the choice of a system. Then certain relevant data-processing systems and projects are described, including the SAGE System for continental air defense with which the naval contiguous defense system must operate, the systems under development by the British and Canadian navies, and the projects currently supported by the U. S. Navy. Two types of data-processing installations are proposed: an analogue system based on the Naval Research Laboratory's "Electronic Data System"[4] for installation starting in 1957, and a high-capacity digital system for production by 1960. These systems are described. Some research projects are suggested to resolve a number of questions which cannot be answered satisfactorily on the basis of existing knowledge. There are a few remarks on other data-processing problems of interest to Lamp Light, and recommendations for improvements in radar.

The material in this chapter is restricted to what seemed to the Project to be essential for conveying our recommendations. Some of the topics are presented in more detail in Appendix 7-A.

II. REQUIREMENTS OF A NAVAL DATA SYSTEM

Choice of a System

The art of data-processing is sufficiently advanced that experts can predict future trends and make reasonable estimates of cost and practicability. A properly designed naval data system can provide capacity, speed and flexibility commensurate with the input detection devices and the weapons that are likely to be available. Some compromise must be made between the ultimate in sophistication and the cost of the equipment. The general requirements that follow were developed in the course of many discussions to serve as a basis for analysis of the many different programs.[5, 6]

Requirements

High Single-Ship Performance:– Every ship that carries radar should be provided with the basic elements of a data-processing system. These are the detection and tracking console, an electronic store, arithmetic elements for certain routine functions such as coordinate conversion and parallax correction, standard displays with choice of video or selected clear-picture presentation, and terminal equipment for exchanging target information with other ships over a data link. The amount of detection and tracking equipment, the number of displays, the computer capacity and the number of weapon-control consoles may vary depending on the size and mission of the ship. The system should be built up around a central unit that contains the store, the arithmetic elements and certain control elements common to all installations. A small ship would be provided with a few detection-tracking consoles, a few displays and a few weapon control consoles. On the basis of known rate-aided tracking techniques, 16 tracks seems to be a reasonable number for the smallest ship installation and perhaps 50 tracks for a large ship. A small ship might have facilities for vectoring four air intercepts simultaneously and the corresponding capacity for a large ship might be 20.

Rapid Exchange of Data within a Task Force:– To reduce vulnerability to atomic weapons, fleets will be dispersed. Rapid data exchange among the vessels of a task group is essential in view of the speed of modern aircraft and missiles. If all target data are transmitted on a data link, it will be possible to evaluate each situation and take prompt defensive measures in time to intercept even a concentrated air attack before it reaches its objective. Only in this manner can tracking be passed smoothly from one ship and radar to another. With data links, interceptors may be guided over long distances. The final phase of an interception can be guided from the radar that has the best view. (It might be noted that continual tracking of our own aircraft is the most reliable means of identification.) Such exchange of information is also useful for antisubmarine missions.

In common with others who have studied the problem, we feel that 1000 tracks is a reasonable size for the total target capacity of a fleet system. The speed with which this target information is transmitted must be adequate for keeping up with the air picture. The high-speed data link should have a range in excess of 100 miles. Slower digital data links for transmitting target information over longer distances are described in connection with the proposed data systems.

Flexibility:– The data-processing system must permit complete flexibility in mission or formation since the latter will depend on strategic or tactical considerations. The functions that may be performed by any fleet organization or by the units therein must not be constrained by the data-processing equipment. Although the air problem is most serious, it is important to design the equipment for surface and subsurface operations as well. Passive sonar and ECM devices give bearing information that must be transmitted and correlated with other bearing information to determine a position. If radars are jammed, the same sort of operation can be performed. A ship may operate alone or in a group or as a radar picket vessel. It may be engaged in air battles, hunting submarines, convoy duty or invasion. The equipment should be adaptable for all types of jobs.

Minimum Dependence on Communications:– Although every effort should be made to increase the reliability of radio communications and data links, the data system must retain high performance in spite of intermittent or complete interruption of communications.

> This calls for high single-ship performance, as described above.
>
> The narrower the bandwidth, the more reliable is the communication channel. There are a number of technical ways to reduce the bandwidth without compromising speed.
>
> Each ship should be provided with a local store large enough to contain all track information that it may receive from the data link. Such a store will carry over information during a fade or period of jamming. If the interruption continues, local tracking may be initiated on the basis of position and identity data retained in the store. A complete local store has a number of other advantages in that common track numbers may be used for all cooperating ships, the handover of tracks is simplified, non-flickering displays are possible, etc.

Steps should be taken to reduce susceptibility of the data links to jamming.

Encoding of the data should include error-checking symbols.

Displays:– Information in the store may be presented on conventional or projection cathode-ray tubes without delay. It is relatively simple to provide for selection of category such as "all surface targets" or "all friendly aircraft." Also, a limited number of symbols may be provided to identify different targets or different types of targets on the clear display. The best location and use of displays must evolve from experience with the equipment. There is no need to center operations around a large summary plot since displays with choice of video or selected clear-plot data may be placed at remote locations. (It is desirable to make video available in case of confusion or failure of some part of the data system.) Each display must include some device for presenting status information, and pushbuttons associated with an electronic hook for calling up all information in the store that pertains to a given target. There should also be electronic pointers and other means for passing control and information from one station to another.

Use with AEW Aircraft:– Airborne early warning (AEW) radar-equipped aircraft probably will play an important role in conventional naval operations and in the seaward extension of continental defense. Such aircraft can greatly extend the area of radar coverage. They can search at a distance from a surface formation that is maintaining electronic silence. They are not so vulnerable to attack as surface vessels. The data-processing equipment of the fleet should provide for receiving the AEW target data and for circulating it on the data link. The radar and the data-processing equipment of the AEW planes should be improved.

Compatibility:– Naturally, the data system of the U. S. Navy should be able to exchange information with the similar equipment of the Canadian and British Navies. A joint committee is presently working out a common data-link code for this purpose. There will be occasions when naval vessels will exchange data with a shore system; for example, the SAGE System. In such cases probably a translator box should be provided on the shore. The most important field is that of cooperation with the aircraft of the USAF and those of our allies. It is absolutely essential that communications and data links with AEW, bomber and fighter aircraft be identical. For example, it is proposed elsewhere in this report that U. S. Navy radar picket ships will receive data from USAF-AEW aircraft and provide intercept control of land-based fighters. (In answer to the question raised in the terms of reference for Project Lamp Light about compatibility with the SAGE System, one might say that data links or codes present no problem. The Navy is now incompatible with SAGE because it has, by comparison, no data-handling capability.)

Reliability, Servicing, etc.:– It should not be necessary to dwell on the need for reliability. In proposing additional electronic equipment to achieve higher performance, one must make sure that the manpower requirements are not increased. Improved data-processing equipment should permit operation by less highly trained personnel. The number of trackers and plotters may be reduced so that more effort may be available for maintenance. A basic principle should be to keep the number of different building blocks to a minimum so that training and spare parts are within reason. The system design should be such that failure or damage of a part of the system will not make the rest of the equipment useless. Thus, if automatic tracking circuits are employed, there should be means for reverting to manual tracking; if the store is damaged, video should still be available at all displays.

Further discussion of the requirements of naval data-processing equipment will be found in Appendix 7-A and Refs. 5 and 6.

III. STATE OF THE ART

List of Data-Handling Projects

In this section, the various projects and systems that might be considered for use by the U. S. Navy are reviewed. There are two American and one British analogue data systems that might be considered for early installation. There are one Canadian and three American projects for high-capacity digital systems. The SAGE System for continental air defense and the proposed Canadian air defense system are also described briefly. Those data projects of the U. S. Army and Navy that may be a source of useful information are mentioned.

These descriptions are based on available reports and discussion with representatives of the various projects.

Analogue Naval Systems

Mink:– The Mink optical-display system has been developed by the Control Systems Laboratory (University of Illinois) for the Tactical Air Force. Reflecting chips are made to track the radar echoes on a PPI. By means of lights and mirrors, the chips are projected, giving a large clear plot showing position, track number, heading, and identification. By means of Rafax data links and several Mink projectors, the composite picture from several dispersed radars may be presented on a single board. Rafax and Mink have been thoroughly tested by the Tactical Air Force and are in production for field use. Mink units are currently under investigation for ship use and for harbor defense installations. The Mink clear display is easy to use and understand, has a high tracking capability, is cheap, and has performed well in Air Force tests. It is not useful for remote displays, for target designation, or for data links.

Electronic Data System:– The Electronic Data System designed at the Naval Research Laboratory is a modern data-processing system specifically designed for early use by the Navy. It is an analogue system with electronic stores, rate-aided manual tracking and target designation. This will be described further in Sec. IV and Appendix 7-A.

Comprehensive Display System (British Navy):– The British Navy started work on a data system soon after the war. Experimental models were tested in 1951. Known as the Comprehensive Display System, it is a high-capacity analogue system with aided manual tracking, electronic store, air-intercept computer consoles, displays with category selection, and a data link. It is designed for installation with a high-power three-dimensional radar on major ships. Two carriers will be equipped in the next two years.[7]

Digital Naval Systems

Datar:– The Canadian datar program was initiated about five years ago. It is a high-capacity digital system. Three experimental sets were tested on ships in 1953. They were designed primarily to illustrate system use in antisubmarine operations, but the prototypes, recently ordered, are intended to satisfy all the requirements listed above.

Cornfield:– The Control Systems Laboratory has been carrying out experiments with the University of Illinois computer on a highly automatic, centralized data-processing system for the Navy, nicknamed "Cornfield." Electronic circuits on each ship in a group would digitalize the radar video for transmission to a central computer. Only major ships would be fitted with sorting and tracking computer facilities. The computer does automatic correlation and tracking on the data from the several radars, and the clear picture is broadcast back to the other ships. This system does not meet the requirements for high single-ship performance, and is more dependent on communications than other systems. It can be modified to give single-ship performance. The work on digitalizing of the video is of direct interest to the Canadian Datar project and is germane to the Phase 2 program described below. A model of the central sorting and tracking computer is to be delivered this fall. This solution to the problems of automatic tracking and automatic correlation of tracks from different radars is of considerable importance for the design of a digital data system, whether or not the Cornfield centralized philosophy is ultimately adopted.[8]

Cosmos:– The Cosmos study[2] by the Bell Telephone Laboratories covered communications and data-processing. The communications part of the Cosmos report is discussed in Chapter 6. The Cosmos report on data processing and the "Target Data Exchange" is full of useful information on the data a system must handle, on organization of a round-robin data link, on parallax correction, etc. The data system proposed would include manual detection, tracking, track-number assignment, height and identity consoles with electronic aids, and a store for local targets. Each ship would transmit in succession the data in its local store at a high rate so that either the total picture on the data link or any selected category could be displayed on cathode-ray tubes. Work is just starting on a laboratory model. This system would require a 35-kcps bandwidth for the data link and would fail the moment the data link fails. (Ref. 2, Parts 3, 4, 5, 6.)

SAAICS:– The Semi-Automatic Air Intercept Control System (SAAICS)[3] project was started to assemble an interim system and later became a study program by the Teleregister Corporation. A number of reports were written describing the operations that a data system should perform and proposing a high-capacity digital system similar to the Datar System. Some very useful work on intercept computers and displays was accomplished.

Digital Land Systems

SAGE System:– The SAGE System for continental air defense is of interest not only because it will be used in the United States but also because the techniques and the experience soon to be gained in its operation will be important for design of the naval digital system. It is a centralized system. Data from all radars in a subsector of about 200 miles on a side are transmitted to a computing and control center. For maximum flexibility, a general-purpose computer is used in the center for all tracking functions, for generating displays and for air-intercept control. The system is highly automatic with manual supervision at many points. Hundreds of people will be required to man such a SAGE center. Two hundred interceptions may be controlled at one time. The first model is now being installed at the Lincoln Laboratory. Six subsectors will be completed by 1958 and about 25 by 1960.[9]

Cadar:– Canada has under consideration an air surveillance and control system, called Cadar, for the area north of the industrial region. It is a decentralized system designed to keep communications to a minimum and may be quite similar to Datar.

Data-Processing Systems of Other Services

Time was too short for an adequate study of the data-processing projects supported by the other Services. They are certainly of interest since a considerable amount of experience and techniques, applicable to the Navy program, are available. A few are listed here.

The 414 A automatic track-while-scan data system for guided-missile batteries is directed by the Signal Corps Engineering Laboratories. It has been under development for more than six years and a few installations have been made in the United States. Improved analogue systems are being built by the Airborne Instruments Laboratory, and Hughes Aircraft is designing a digital system. The 414 B is a mobile version of this equipment.

The British "Orange Yeoman" system is similar to 414 A.

As mentioned before, the Tactical Air Force is using the Mink system; they also have a combination analogue-digital system which was developed at the Air Force Cambridge Research Center.[11] Prototype design has started at the ERA branch of Remington Rand. This system is similar to the NRL Electronic Data System with added automatic features. The Army also has a "Comprehensive Data Handling System" under development at the Bureau of Standards for weapons assignment and direction in the field.

The Air Force MX 1179 project at Hughes Aircraft has produced an airborne digital computer which will be used in all-weather fighters for autopilot, navigation, intercept control and direction of weapons.[10] It is worth noting that such a computer can be built in a size and price range that permits use in a large number of fighter aircraft.

In addition to the specific projects mentioned above, there has been a considerable amount of research on military data-processing problems at the Willow Run Research Center (University of Michigan), at Cornell Aeronautical Laboratory, and at many other private, industrial and Government laboratories. It should be evident that a great deal of information on the subject exists and that enough technical experience and know-how is at hand so that intelligent decisions can be made and developments pursued on sound technical grounds.

IV. RECOMMENDED SYSTEM – PHASE 1

Project Lamp Light believes that the U. S. Navy should have a modern data-processing system at the earliest possible date, and that it should have a high-performance system. If any of the high-capacity digital systems could be made available in 2 or 3 years, the problem would be simple. Unfortunately, this is not the case. Therefore we were forced to conclude that two systems must be programed: an analogue system, referred to hereafter as "Phase 1," for installation starting in 1957, and a digital system, called "Phase 2," for installation as soon as it can be developed and produced. Installation of Phase 1 equipment at an early date is vital to the security of our country. However, the systems available for Phase 1 have certain limitations. The Navy will not be so strong as it should be until the Phase 2 equipment is in wide use. This report recommends, in the strongest possible terms, initiation of a clear program for procuring Phase 1, Phase 2 and the corresponding data link equipments.

Special Requirements of a Phase 1 System

So far as possible, the Phase 1 system should meet the general requirements listed in Sec. II of this chapter. In particular, it should provide high single-ship capability and make use of a data-exchange radio link.

Since it is an interim system it should be relatively simple, inexpensive, and easy to install. It should make use of equipment that presently exists on shipboard.

It should perform, externally, in a manner similar to the Phase 2 equipment in order that: (1) ships equipped with Phase 1 and Phase 2 systems can work effectively together, (2) training and experience gained with the Phase 1 equipment will be applicable to Phase 2, and (3) operation of the Phase 1 equipment will contribute to choice of the most useful design for Phase 2.

Electronic Data System Proposed for Phase 1

The three systems that may be considered for Phase 1 are the British Comprehensive Display System, the CSL Mink optical display, and the NRL Electronic Data System (EDS). The first of these is a well-designed system that would give high performance. However it is intended for installation on large ships, is physically large and would make little use of existing equipment. The Mink is a device for increasing the tracking capacity and presenting a large, clear plot. It is not, in fact, a data-processing system in our sense. It may be useful as an adjunct to the Phase 1 system and is currently under investigation by the Naval Electronic Laboratory. The EDS has been designed specifically to meet the requirements listed above. It has been tested at the Chesapeake Bay Annex. Prototypes of part of the system will be produced this year. With the exception of two items that will be discussed below, well-designed laboratory models of all parts of the system are available. There is no question but that EDS should be the Phase 1 equipment.

Description of EDS

The EDS provides for electronic take-off of target data from PPI's by pointing a pencil to the target position on a conducting glass overlay, which replaces the reflection plotter on the conventional radar indicators. The target coordinates are stored in capacitors and may be read out to remote indicators and to automatic plotting boards. The target velocity is computed and likewise stored in capacitors. This velocity is used to correct the coordinate positions and to relieve the tracker of having to continually make corrections. Also, a store is provided for height, size and category. Those items are inserted manually by an operator but may be read out electronically wherever needed.

An "electronic plotter" samples the store and plots on a vertical plexiglass board the last predicted target position of each track in turn. Tracks may be selected by category so as to plot only those desired. A clear presentation of the stored data may be provided on PPI's at as many locations as needed. These positions may also be provided with switches for selecting categories. Target-designation equipment has also been designed that will automatically slew a gun director and provide it with height information.

Two other major pieces of equipment are needed to round out the equipment in the fleet. One of these is the intercept computer, and the other is terminal equipment for the data link. Cornell Aeronautical Laboratory will design such a computer in cooperation with EDS personnel. However, a contract should soon be placed with a commercial company for production design of the computer.

The data-link problem is more complicated. It will make use, at least to start with, of existing telegraph and voice transmitters and receivers. NRL has designed suitable analogue-to-digital converters for encoding the data in the EDS store. A parallax switch must be developed for adding the coordinate offset relative to a common origin for the task group, and for subtracting the offset from incoming signals. There are also problems to be solved in synchronization and timing. We propose a low-capacity data link using telegraph bandwidth on high frequency for the first installations. (This slow data link will be the main link for the sea-wing extension of continental defense to be described below.) This should be supplemented at a later time by a UHF voice-bandwidth data link for rapid (40-cps) exchange of targets within a task group.

The cost of a typical EDS ship installation should be less than the cost of a long-range radar. All parts of the system can be procured by mid-1957 if contracts are placed at once for production quantities. Further information on EDS will be found in Appendix 7-A.

Phase 1 Equipment for Continental Defense

The Lamp Light Data Group gave special attention to the data-processing requirements of the sea-wing extension of continental defense. Since a considerable part of the American population and industry is concentrated at the coastline, it is essential that the continental air defense system be extended seaward. On the east coast, for example, Project Lamp Light proposes installation of air-surveillance and intercept-control capability for about 1000 miles offshore and from Newfoundland to Bermuda. Reasons for and description of the sea-wing defense system are given in Chapters 12 and 14. In the 1957 period, 6-9 radar-equipped picket ships would be deployed at 200- to 400-mile spacing, and 15-21 AEW aircraft would fly in patterns over the area. The picket ships would give high-altitude radar cover; the AEW planes would serve as gap fillers, providing low cover; both would have intercept-control capability. All air-target information would be sent to a shore station and forwarded to the SAGE System without delay. Surface-target information would also be sent to the shore station at a slower rate for surface and subsurface surveillance purposes. This sea-wing system must give positive early warning in sufficient detail for rapid threat evaluation and early deployment of defensive weapons. Ideally, it should have the tracking and intercept-control capacity of the SAGE System. The Phase 1 data-processing equipment can provide warning but will not have adequate control facilities. Phase 1 data-processing equipment for the sea wing is summarized here. The Phase 2 equipment will be summarized in the next section. Both Phase 1 and Phase 2 equipments are described more completely in Appendix 7-A.

The data-processing system is shown schematically in Fig. 7-2. The AEW aircraft in 1957 will carry APS-20B and height-finding radars, manual tracking and AI control stations and radio transmission facilities for the video picture. We propose that tracking of targets be carried out on the sea pickets. Personnel in the aircraft would supply height and other information on request and be available for air-intercept control.

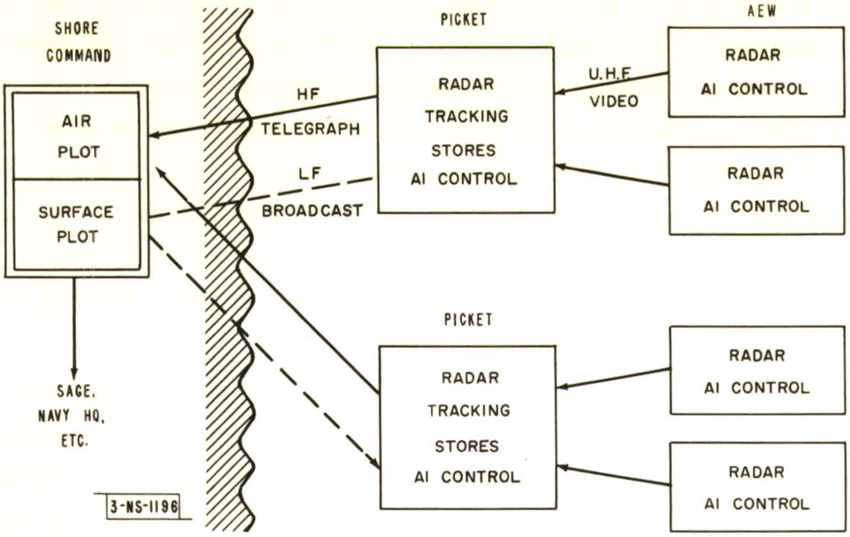

Fig.7-2. Schematic diagram of data flow for offshore continental defense.

Equipment in the AEW's should be improved as soon as possible in the following respects: (1) Range of radio picture link should be extended to give reliable transmission up to 200 nautical miles. Substitution of Rafax for the video link is an obvious first step. Automatic coordinate encoding of the video ("beam splitting" or "fine grain data") should be developed for this purpose. (2) Intercept control computers should be developed for use in AEW airplanes. (3) The search and height-finding radar should be improved (see Chapter 2).

The picket vessels carry SPS-6, SPS-8 and possibly SPS-17 radars. We propose that they be fitted with EDS tracking facilities for these radars and for PPI pictures received from two AEW aircraft. (The AEW tracking consoles must have circuits for stabilizing the display and adding parallax correction.) Track information on air targets would be fed to a common EDS store with a capacity of 72 tracks. Information in the store would be sampled, converted to digital form and transmitted to shore on high frequency. With a telegraph bandwidth, all air information can be repeated once a minute. Surface targets would be tracked on separate indicators and manually inserted on the data link at a comparatively slow rate. Air-intercept control computers, similar to those recommended above for the fleet, are needed for the pickets.

The shore station receives information from all the pickets (directly or relayed from shore receivers). The surface information will be passed to the sea surveillance center described in Chapter 14 and Appendix 14-D. The air surveillance data will be displayed at the shore station for over-all analysis and evaluation. At the same time, the data are forwarded to the SAGE System. After consideration of a variety of arrangements, we have decided to recommend building the Phase 1 shore station installation around a commercially available general-purpose computer such as the Remington Rand 1103 or the IBM 704, because: (1) the computer and all necessary input and output equipment exists, (2) it will perform all of the mathematical operations required, (3) it permits great flexibility in choice of displays, and (4) it will perform in a manner very similar to the equipment recommended for Phase 2 and to its SAGE System counterparts.

The responsibility for tracking must be passed from one picket vessel to another as targets pass through the area. The number of handovers will be large because the AEW planes move past the pickets. It is proposed that handover be routed through the shore station in the following manner. An operator on each picket watches the local tracks and notes those leaving the area. He adds an order to the data on such a target to indicate which picket should track the target next. Signals so labelled are tagged on the shore display and rebroadcast on one low-frequency area broadcast. All pickets receive the LF broadcast and take up the tracks labelled for them. Monitors in the shore station make sure that handovers are completed.

Summary of Recommendations for Phase I

The Lamp Light recommendations for Phase 1 data-processing equipment may be summarized as follows.

> EDS electronic stores for position and velocity; consoles for detection and tracking; and consoles (including stores) for height-size-identity (HSI); SPA-15 electronic plotting board; EDS target-designation console. These items are required for both ships of the fleet and sea picket vessels. All are based on NRL designs.
>
> Analogue air-intercept control computer for fleet and picket vessels. This may be designed by Cornell Aeronautical Laboratory, but there is no provision yet for production engineering.
>
> EDS lends itself to use with remote cathode-ray tube displays with category selection, which should be especially useful to the fleet for providing information to command and for dispersing the functions now concentrated in the CIC. These displays and devices for remoting tote board information need development.
>
> Development of terminal equipment for data links is urgently needed. A telegraph bandwidth system on high-frequency is

required for use in the fleet and the sea-wing system. A voice-bandwidth link should be developed later for use within task groups.

The sea pickets need EDS tracking facilities for use on the transmitted AEW picture. They will also need manual-plotting facilities for the surface picture.

Data-processing equipment needed for AEW aircraft are: (a) a 200-mile video link or Rafax link, (b) "beam splitting" or "fine grain data" equipment to replace the former, (c) air-intercept computer facilities similar to those listed above.

For the continental defense shore station, there should be data-link reception and terminal facilities, a large commercial digital computer, a variety of displays (which may be obtained through SAGE), facilities for transfer of tracking from picket to picket, and adequate communications to the several commands with which it must cooperate.

V. RECOMMENDED SYSTEM – PHASE 2

It was explained in Sec. IV that interim equipment must be procured to obtain the benefits of data processing in the 1957-60 period. A comparison of the proposed storage capacity, 72 at most for EDS and 1000 for a digital Phase 2 system, illustrates the added improvement to be expected from the latter. An air surveillance and control system, comparable with SAGE, is needed for seaward extension of continental defense at the earliest possible moment. Similar high-performance equipment is needed for the fleet.

Unless certain decisions are made now and unless a clear program of research and development is formulated, the high-capacity system will not be completed for a decade. We have shown in Sec. III that a great deal of information exists, not only on electronic circuits but on data-processing systems for land and shipborne use. In Sec. II and in Appendix 7-A, requirements have been developed that go a long way toward defining a system.

Choice of a System

Perhaps it is worth while to compare analogue and digital techniques. In an analogue system, an electrical quantity (for example, voltage) is proportional to each variable. Thus the x or y coordinate of a target may be stored in the form of voltage on a capacitor. A digital system makes use of numbers in much the same way as a desk calculator except that storage, addition, subtraction and other operations are performed electronically. Any degree of accuracy may be achieved in a digital system while 0.1% accuracy is very difficult to achieve in analogue circuits. Even in the most complicated

not necessarily "electric" – may be mechanical.

data-processing system, only a few different types of operation are required. Whereas a large number of different analogue circuits would be required, only a few digital building blocks may be needed. Analogue systems are more prone to error and harder to service. Analogue techniques are likely to be more suitable for small installations, while digital techniques are almost essential for high-capacity systems.

Analyzing the naval digital systems described in Sec. III (Cornfield, Cosmos, Datar, SAAICS) in terms of the requirements listed in Sec. II, we find that Datar and SAAICS come closest to filling the need. The Canadians, who have tested Datar and are designing prototypes to naval specifications, are several years ahead of the SAAICS program. Therefore we conclude that a Datar type of system should be adopted as the starting point for Phase 2 equipment, and that all available research and development potential should be directed toward improving and completing its design. The U. S. Navy should not depend on the Canadian government or on its contractors but should initiate promptly a full-scale research and development effort which takes advantage of the work done so far. Close cooperation with the Canadian project will be mutually beneficial.

Summary Description of Datar Equipment

Operationally, the Datar system is intended to meet the requirements of Sec. II. The technical description of the Datar prototype, given in Appendix 7-A, may be summarized as follows.

There is a central "memory" unit which is a magnetic drum. It has space to store all the information on 1000 targets – those tracked locally and those received on the data link. Associated with this store are several arithmetic units, to perform such operations as computing the velocity of targets, adding parallax correction to data transmitted over the data link, dead-reckoning computation, and so forth, which will employ transistor and magnetic-core techniques. There will be input consoles for radar, sonar, and ECM. Initially, the radar input will be from rate-aided manual tracking, but this probably will be replaced by semiautomatic tracking as soon as it can be developed. Cathode-ray-tube projection displays in two colors are planned, so that large and small displays will use the same basic components. Category selection, a limited number of category or informational symbols, electronic pointers and pushbuttons will be provided. Digital air-intercept computer consoles are contemplated, but have not been developed. The data link will handle information on 1000 targets on a voice-bandwidth channel and will employ an error-checking code. In the prototype system, duplication that arises because several ships may track the same target will be resolved by human monitors who assign common track numbers. The system handles bearing information and provides displays for getting fixes from passive sonar or ECM. It is a high-performance data-processing system using modern digital techniques for miniaturization and reliability.

Data Links for Phase 2

Two types of data link are recommended for Phase 2. One is a high-capacity link with a bandwidth of about 3 kcps, as mentioned in the description of Datar above. Because of the speed of jet aircraft and formations dictated by atomic warheads, the useful range of this link should be 150 or more nautical miles. The second is a long-range link with telegraph bandwidth. It would be used for passing information from one task group to another or from sea picket to shore. It would also serve as a backup link in case the high-speed net should fail.

Phase 2 Sea-Wing Equipment

In the 1960 period, we expect the configuration of the sea-wing extension of continental defense to be substantially the same as that described above under Phase 1. As before, the data will flow from the AEW aircraft to the picket ships to the shore station, and track handover will be accomplished through the shore station. The system should have the highest possible capacity for air surveillance and air-intercept control. The eastern and western sea wings may be thought of as SAGE sectors and each picket ship as a subsector (see Appendix 7-A, Sec. 3). Improvements in the data-processing equipment recommended for the Phase 2 sea-wing system are:*

> The AEW craft should be equipped with improved radar for search and intercept control including better height-finding radar.
>
> The "beam splitter" and air-intercept computer recommended under Phase 1 should have been completed.
>
> Automatic methods of conveying height information on all air targets to the picket vessel must be developed.
>
> The EDS equipment on the sea pickets should be replaced by Phase 2 equipment.
>
> The sea pickets should be given a tracking and intercept-control capacity at least as large as that installed on a major ship.

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*A minority recommendation for different Phase 2 equipment for the sea-wing system is given in Appendix 7-B.

> The ship-to-shore data link should be made as foolproof as possible. (JANET, with a bandwidth of about 3 kcps, appears to be most promising for this application (see Chapter 6 and Appendix 6-G).
>
> The shore station should be provided with SAGE computer and display equipment. This installation need not await production of other Phase 2 equipment, but rather should be made as soon as suitable SAGE-type equipment can be obtained.

Phase 2 Development Program

Equipment of the sea-wing extensions of continental defense with a high-performance system such as that described above, by 1960, is just as vital as are the SAGE installations on land. We believe that the fleet also needs such equipment, and that it can be produced in quantity by that time. As a first step, the U. S. Navy should order several Datar prototypes from the Royal Canadian Navy contractor (Ferranti, Ltd. of Canada). Also, the Navy should find a competent contractor to start development of similar prototypes in this country for delivery in 1958. Some latitude may be permitted in choice of design. Special attention should be paid to those parts of the system – for example, the intercept computer – that are receiving less attention in Canada. The goals of economy, size, weight, serviceability and reliability are obvious. A more difficult assignment is to arrange the components in such a way that new developments, discussed in the next section, may be incorporated in the production models if they prove to be advantageous. To realize this program by 1960 will require a very tight schedule, the best in engineering talent, and a high priority in the Navy Department.

Research Program

So long as data processing is performed in the Navy, some research will be required to keep it up-to-date. Research will be especially important in the next five years while the Phase 2 equipment is taking shape, in order to make sure that the production equipment is indeed the best that could be made. The following items appear to need further study at the present time. Other problems will almost certainly arise in the next few years.

> There should be an experimental program on data links, directed at finding the best frequencies and types of propagation to meet the requirements that have been listed above. A second part of this study should be concerned with vulnerability to jamming.

The recommended prototype program makes use of manual tracking and manual correlation of tracks from different radars. The work at Lincoln Laboratory on automatic detection and tracking is highly important to this program, and the work at the Control Systems Laboratory should be continued. The CSL experiment with tracking on data from a multiplicity of radars is of considerable interest, even though the Cornfield system is not recommended.

The system we have recommended makes use of special-purpose computers. Many experts believe that the added flexibility available in a general-purpose computer (such as that used in the SAGE System) is essential to meet the problems of the future. A serious study should be made to determine what advantage a general-purpose computer might offer to the Navy and how much it would cost in added size and complexity. An alternative solution, which CSL plans to investigate, is the use of special-purpose devices for detection and tracking, together with a general-purpose computer for intercept control and other mathematical operations.

We have found it difficult to compare the tracking capacity of different systems, and impossible to reach conclusions about vectoring of aircraft interception. Experiments must be designed to make realistic studies of the tracking and control equipment that presently exists and that will soon be developed.

The four items above seem to us to be the more significant problems at present. The Navy should also support research and development on components, such as transistors, magnetics and display devices. And it should support research on digital-computer techniques that might be useful in this program.

In addition to the existing test facilities at NRL and NEL, a research and development ship should be assigned to permit study of radar processing and of communications equipment under sea conditions.

Summary of Recommendations for Phase 2 Data Processing Equipment

In conclusion, the recommendations for Phase 2 are:

Initiation at once of a high-priority program to develop and produce high-performance digital data-processing equipment based on the Canadian Datar proposed system for delivery starting on or before 1 January 1960.

There should be a voice-bandwidth data link with 150-mile range, and a telegraph-bandwidth data link with a range of over 500 miles.

As was recommended under Phase 1, AEW aircraft should be fitted with beam-splitting or FGD equipment and analogue or digital air-intercept computers. Means must be developed to send height information to the surface vessel automatically.

High-capacity Phase 2 equipment should be installed in the sea pickets for continental defense at the earliest possible time. A highly reliable ship-to-shore data link should be developed for this service.

The shore stations should be fitted with modified SAGE equipment as soon as it can be made available.

The U. S. Navy should order, now, several Datar prototypes.

The U. S. Navy should contract for development of prototypes to meet the requirements listed in Sec. II, taking advantage of the Datar experience.

A vigorous research program should be initiated to stimulate and supplement the programs recommended above.

VI. RELATED ITEMS

Land-Based Data Systems

The SAGE System is to be installed in the strategic areas of the United States. There is a need for air surveillance and control facilities for the region north of this area in Canada. The requirements are similar in many respects to those relating to the sea wings which have been described above. The proposed Canadian air defense equipment, the Cadar system, will resemble the recommended Phase 2 data-processing equipment in economy, decentralization and minimum communications requirements. It will be developed in parallel with Datar. The Cadar equipment would seem to be of interest to the United States, not only because it will be installed in about 20 places in mid-Canada, but also because this type of equipment would seem to be suitable for installation in radar stations in locations such as the Pine Tree Line, Alaska, and the DEW Line, if it is desired to increase the data-processing capacity and add intercept-control capability.

Data Processing for Early Warning and the Remote Air Battle

In this study, data processing was not considered to be an urgent problem for use in early information and remote air battle zones. Because of the larger distances involved, rapid data exchange is not a necessity. The main problems in the remote zone are in the fields of radar and communications. We believe that the data-processing equipment recommended for the fleet, the sea wings and AEW aircraft, taken together with U. S. and Canadian plans for land-based equipment, will insure development of any data equipment that might be needed in the future for remote-zone applications.

Radar

Certain improvements in radar are required in order to obtain high or even acceptable performance with the data-processing equipment that has been described. First, search and control radars must be stabilized. Otherwise the position of targets is distorted by roll and pitch of the ship. Such distortion reduces the range of detection and will cause great confusion when tracks are exchanged between ships. Second, the present nodding-beam height-finder radars do not have adequate range, and the method of use – requesting height information on targets in turn – will limit system tracking capacity to a small number. Third, improved search and height-finding radars are needed for the AEW aircraft to reduce sea clutter and to provide information adequate for control of interceptors (see Chapters 2 and 4).

Stabilization may be achieved by stabilization of the ship (see Appendix 7-D), by mechanical stabilization of the radar antenna or (with certain radars) by electronic compensation of the data. We believe that three-dimensional scan radar is essential to give height information simultaneously with range and azimuth. This will provide very high tracking capacity with automatic circuits. It will make it possible to track in elevation as well as in x and y, in order to reduce confusion from crossing tracks. Three-dimensional radars, now under development, are the Royal Navy Type 984, the Sperry stacked-beam radar, and the Hughes frequency-scan radar. Mechanical stabilization is not required for the Hughes radar since the beam elevation may be electronically controlled and the data may be stabilized electronically. This, together with the relatively small size, make it peculiarly attractive for wide application if performance is satisfactory in other respects. AEW radar is discussed in Chapter 2.

Data Links

We have been concerned primarily with the ship-to-ship data links. We endorse the surface-to-air data link program and note that detailed planning of data equipment must take this link into account. Data links are more susceptible to jamming than are voice communications. We have noted this problem in connection with ship-to-ship links. The ship-to-air links, as presently envisaged, appear to be especially vulnerable. We have recommended increased control capability for the AEW aircraft and propose that an air-to-air data link be developed.

Navigation

We have been concerned about the speed and accuracy of navigation that is now possible, particularly in aircraft. Existing shortcomings in navigation systems have been reflected in many ways in the systems and data-processing fields. As an example, the difficulty of navigating aircraft accurately, particularly over water, is bound to increase the work of the sea-surveillance organization described in Chapter 14 and Appendix 14-D. Similarly, the inaccuracies of the gyro-compasses at present fitted in the fleet will greatly complicate either the equipment or the procedures that must be used to avoid confusion and multiplicity of targets when high-speed, high-capacity data-processing equipment is installed.

A more detailed discussion of the problem is given in Appendix 7-C. In general, we consider that the requirement is not for the development of any new form of electronic aid to navigation, but the treatment of existing aids from a systems viewpoint and the development of certain components that will allow the navigator to judiciously combine the results of internal and external aids as they may be available or preferable. Specifically, we have recommended the development of an airborne digital navigation computer which will dead-reckon continuously, receiving its data from compass, airspeed- or groundspeed-measuring devices and altimeter, which can accept manual input of such data as position, wind, magnetic variation and deviation, and which will automatically accept position data obtained from electronic aids to correct position and drift. We have recommended that a determined effort be made to incorporate the latest techniques in the Loran system, and that provision be made for coding the system to prevent its use by the enemy. We have recommended further development of the Doppler speed-measuring radar and accurate free gyros for aircraft. We recommend the production and fitting of a marine gyro-compass having a maximum error of ± 0.5°, even during high-speed maneuvers. Finally, we note the existence of the APQT visual and radar navigation trainer, which we feel has wide application.

VII. CONCLUSION

Project Lamp Light believes that development of modern data-processing equipment is essential for the Navy's role in continental defense and that such equipment is urgently needed for the fleet. We find it necessary to recommend installation of interim analogue equipment starting in 1957, and development of high-performance digital equipment for production by 1960. A set of requirements has been developed to define the type of equipment that should be procured. Special attention has been paid to the data-handling problem for sea-wing extension of continental defense, which has not been discussed in previous reports.

It is recommended that Phase 1 equipment make use of the Electronic Data System developed at NRL, with addition of an intercept computer and data links. Rafax, then beam-splitting equipment, should be developed for AEW craft. The sea-wing shore station should be built around a high-capacity, commercial digital computer, which should be replaced by SAGE equipment as soon as it becomes available.

We propose that the Phase 2 program be made as specific as possible, that effort be concentrated on a system of the Canadian Datar type. We recommend purchase of Datar prototypes and parallel design of prototypes in the United States. The questions that require further study are described, and a research program is outlined.

Two types of surface-to-surface data links are proposed: a long-range telegraph-bandwidth link for fleet and sea-wing applications, and a 150-mile high-speed net for data exchange within task groups. Data links are an essential part of the proposed data systems. An extensive research and development program will be required.

A strong plea is made for stabilized, three-dimensional search and control radar.

We recommend certain essential work be done on navigation equipment.

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CHAPTER 7 RECOMMENDATIONS

For Phase 1, we recommend the following:

1. *EDS electronic stores for position and velocity; detection, tracking and HSI consoles (including HSI stores), SPA-15 electronic plotting board, EDS target-designation console. These items are required both for ships of the fleet and for sea picket vessels. All are based on NRL designs.*

2. *Analogue air-intercept control computer and displays for fleet and pickets. Design work has been planned, but there is no provision yet for production engineering.*

3. *Development of displays and devices for remoting tote-board information. EDS lends itself to use with remote cathode-ray tube displays with category selection, which should be especially useful to the fleet for providing information to command and for dispersing functions now concentrated in the CIC.*

4. *Development of terminal equipment for data links. A telegraph-bandwidth system on high-frequency is required for use in the fleet and the sea-wing system. A voice-bandwidth link should be developed for use by task forces.*

5. *EDS tracking facilities needed by sea pickets for use on the transmitted AEW picture. Manual plotting facilities for the surface picture are also needed.*

6. *Data-processing equipment needed for AEW aircraft:*

   (a) a 200-mile video link or Rafax link,

   (b) beam-splitting or fine-grain-data equipment to replace the former,

   (c) air-intercept computer facilities similar to those listed under 2 above.

7. *For the continental defense shore station: data-link reception and terminal facilities, a large commercial digital computer, a variety of displays (which may be taken from SAGE), facilities for transfer of tracking from picket to picket, and adequate communications to the several commands with which it must cooperate.*

For Phase 2, we recommend the following:

1. *Initiation at once of a high-priority program to develop and produce high-performance digital data-processing equipment based on the Canadian Datar proposed system, for delivery starting on or before 1 January 1960.*

2. *A voice-bandwidth data link with 150-mile range, and a telegraph-bandwidth data link with a range of over 500 miles.*

3. *Data-processing equipment, as recommended under 6 (Phase 1), above. AEW aircraft should be fitted with beam-splitting or FGD equipment and analogue or digital air-intercept computers. Means must be developed to send height information to the surface vessel automatically.*

4. *High-capacity Phase 2 equipment installed in the sea pickets for continental defense at the earliest possible time. A highly reliable ship-to-shore data link should be developed for this service.*

5. *Shore stations fitted with (modified) SAGE equipment as soon as it can be made available.*

6. *Immediate procurement, by the U. S. Navy, of several Datar prototypes.*

7. *A contract by the U. S. Navy for development of prototypes to meet the requirements listed in Sec. II, taking advantage of the Datar experience .*

8. *A vigorous research program to stimulate and supplement the programs recommended above, including:*

   a. *Work on data links,*

      (i) *to find the best frequencies and types of propagation to meet listed requirement*

      (ii) *to reduce vulnerability to jamming*

   b. *Continuation of work at Lincoln Laboratory and Control Systems Laboratory on automatic detection and tracking*

   c. *A serious program to determine the relative merits of general-purpose and special-purpose computers, or combinations of the two*

   d. *Realistic studies of the requirements for tracking and intercept capacity, and of equipment for these purposes*

   e. *Research on components and digital-computer techniques*

   f. *A special ship to be assigned for research in data processing and communications*

   g. *In related fields, we recommend:*

      (1) *Investigation of the Canadian Cadar proposal for data processing in areas north of SAGE operation*

(2) Strong efforts to extend and improve stabilization of ships and equipment

(3) Improved search and height-finding radar for AEW aircraft

(4) The acquisition of three-dimensional scan radar

(5) Furtherance of the surface-to-air data-link program

(6) Development of air-to-air data link

(7) Improvements and developments in navigation equipment:

  - *(a) an airborne digital navigation computer for interceptors and AEW aircraft,*
  - *(b) modernization of the Loran system and introduction of a coding method,*
  - *(c) further development of Doppler speed-measuring radar,*
  - *(d) further development of free gyros for aircraft, and*
  - *(e) development of a marine gyro-compass with a maximum error of ±0.5° under any conditions.*

APPENDICES TO CHAPTER 7

APPENDIX 7-A

DETAILS OF DATA PROCESSING

INTRODUCTION AND RESUME

The material presented in Chapter 7 was limited to what seemed to be essential for presenting the Lamp Light recommendations in this field. Certain subjects, touched on in the chapter, are treated more extensively in this appendix.

Much of this material has been abstracted from the working papers of the Data Processing Group of Project Lamp Light. Although the group should not be held responsible for the accuracy of the descriptive material which follows, there was complete unanimity on all recommendations except for those discussed in Appendices 7-B and 7-D.

Although operational requirements of naval data systems have been discussed in many other papers and reports, it seems worth while to supplement the material in Sec. II of Chapter 7 in order to make the reasons for our choice of systems as clear as possible.

The SAGE System for continental defense is described for several reasons: (1) it illustrates the high importance attached to data processing by the Continental Air Defense Command; (2) the Phase 2 sea-wing equipment should have performance commensurate with that which will be afforded by the SAGE system; (3) it is the outstanding example of what a data-processing system ideally should be; (4) it is the only system studied that is based on a general-purpose computer; and (5) the experience soon to be gained with this system will provide much information useful for the Navy's data program.

More information is given on the Canadian Datar system, as it is now envisaged, since we have recommended this system as the starting point for the Navy's Phase 2 development program.

The Phase 1 systems, which were summarized in Chapter 7, are given fuller treatment below. The Phase 1 equipment for the sea-wing extension of continental defense is described in some detail, since the Lamp Light proposals for this installation are new and since this aspect of continental defense deserves special emphasis. There is also a comment on the intercept-control computer which needs development to round out the Phase 1 equipment.

The proposals for a Phase 2 research and development program are amplified in this appendix. A report discussing the possibility of employing high-performance data-processing equipment in AEW aircraft is included. The problem of administration and coordination of the Phase 2 program has received attention in the Lamp Light study. Our suggestions as to how this might be accomplished are presented in this appendix, since it seemed appropriate to restrict the chapter to technical considerations and recommendations.

Two minority papers are presented in Appendices 7-B and 7-D. The first of these is a proposal by N. Rochester for the use of the SAGE System installations in the sea-wing picket ships for Phase 2; the other members of the group believe that the sea-picket equipment should be similar to that employed in the rest of the fleet. The second is a proposal by D. L. Hanington for ship stabilization. The rest of the group did not feel qualified to take a position on this topic, which is outside the field of electronics. The group believes both these minority proposals to be worthy of further consideration.

REQUIREMENTS OF A NAVAL DATA-PROCESSING SYSTEM

General

It is realized that the usefulness of the information available to the major navies of the NATO nations is seriously impaired by the inaccuracies of existing data-handling systems. Except in the case of the Royal Navy's Comprehensive Display System, there is no efficient data-handling system in operational existence, although many proposals have been submitted in recent years. Most such proposals have concerned themselves solely with air defense of the fleet, because the air threat was considered to be the most dangerous and the most difficult to handle. This may well be so. However, as a result of this preoccupation with air defense, some of the proposals are so dependent upon maintaining certain tactical formations that they will not operate properly if others are used.

Such a sacrifice of flexibility cannot be tolerated if the fleet is to survive in the nuclear age. It must be possible for Command to adopt whatever tactical disposition he desires, varying from very small formations or single ships spaced far apart to large, close formations such as were employed in the Pacific.

Furthermore, it must be realized that, as formations vary, so the nature of the threat changes. The submarine, which is probably no great threat to a hunter-killer group, may spell disaster for a single attack carrier with a light escort bound on a vital mission. A convoy, which may or may not have air protection, may be menaced by both aircraft and submarines during its passage, depending upon its concentration and its whereabouts.

It is therefore obvious that control of the seas can be achieved only by making use of all the varied forms of information. The basic sources of information are: (a) radar,

(b) sonar, (c) ECM, (d) visual, (e) radio, (f) written orders and reports. In what proportion the usefulness of each of these stands is directly related to the tactical situation and, conversely, the tactical possibilities may well depend on which sources of information are available.

Since information from all these sources must be accepted, filtered and used, and since a great amount of it is in the various forms of position, course and speed, it is reasonable to handle it so far as possible in one computing system. Since the nature of the computing system must not lead to tactical inflexibility, each ship or aircraft must have sufficient equipment to process and use the information it requires for its own use, or to transmit information to some other unit as required by the force Commander.

In order that any unit capable of deep-sea operation may not be tactically limited, it must have access to all information concerning the tactical situation in its area of operations. This implies excellent communications between all units in a particular area, with instant access to all types of information. However, this is not practicable at present, because of (a) the imperfections of communication systems, and (b) the requirement for radio silence in many tactical situations. Such restrictions mean that periods when radio communications are operating must be fully used, and that the lack of communications should not imply a complete loss of the tactical picture.

Proper engineering of communications equipment and extension of sure ranges obtainable on ultra-high and high frequencies are of utmost importance. Such certainty will not only allow passage of much greater amounts of necessary information, but will also cut down time lags and unnecessary chatter.

Local storage of information is required, so that information will not be lost due to either the failure of radio links or the imposition of radio silence. The amount of local storage provided should be sufficient not only for the local control of weapons, but also for the unit to change its position, mission or destination, without the enforced passage of large quantities of data or a prolonged period of confusion. Since most fighting ships are capable of performing a wide variety of tasks, and since the manner in which a task is performed depends on the effect of the whole local tactical situation – not any one part of it – the individual ship must be able to examine the whole or any part of that situation at will. When taken in conjunction with the uncertainties of communications, this implies local storage of all target data held in the system. Such complete storage also assists in the organization of the system; for instance, since all units have the same target information, track-number allocation can be done automatically, computing equipment can be identical, and outputs can be added or subtracted without difficulty.

The system must be such that various types of ships can be given portions of the input and display equipment, according to size and function, without affecting the operation of the system as a whole. Such a system will require very careful design, since it must contain information essential for the conduct of each kind of operation without being cluttered up with nonessentials.

Specific

The remainder of this section describes the operations to be performed by a data-processing system. Such a system would be a first approximation to the required result, and obviously must be flexible enough to allow changes in equipment and procedures as experience shows them to be necessary, or as input devices or output requirements change. For instance, it must be possible to add a high-capacity intercept computer as one becomes available, or to take advantage of automatic-tracking devices when they are developed.

Information sources include:

Electronic Equipment

- Radars – Air search
  - Surface search
  - Height finding
  - Traffic control
  - Target indication
  - IFF
- ECM – receivers and analyzers
- Radio
- Direction finders
- Sonar – active and passive

Operational

- Orders
- Publications
- Intelligence
- Charts
- Weather

Visual

The first step in coordinating all this information is to provide an electronic storage facility whereby access may be readily obtained by target number or position coordinates. The various information sources may then change or add to the information in storage. This electronic storage facility should include:

- Target number
- Target position (x, y and/or R, θ)
- Identity
- Course
- Speed
- Altitude
- Size
- Type

Additional status information can be provided over a different facility and coordinated by track number. This may include such data as:

- Mission
- IFF code
- Radio channels
- Call signs
- Fuel, Ammunition, Time
- Weapon condition
- Weather
- Hydrophones
- ECM status
- Guards
- Formation

A method of operation to provide this internal coordination is as follows:

- Detection
- Tracking
- Identification
- Altitude
- Analysis
- Supervision

These operations are not required to be in sequence and may all proceed after detection. Raw radar displays are provided at each position, with manual operation assisted by electronic aids. Specifically, the individual functions would have responsibilities as follows:

Detection

Hooks the target appearing on the PPI, which automatically assigns it a track number and stores it with x, y coordinates. The target is now tabbed on the PPI as "detected."

The target is then manually or automatically assigned to a tracker.

Under certain conditions, the detection operator may be assigned IFF responsibility which is inserted into the store by keyset.

Tracking

The tracking operator will have markers appear by the targets he is responsible for tracking. He will continually correct the markers with target movement, and in this operation he will be provided with rate aiding. This operation provides the store with up-to-date position, course, and speed.

Identification

Identification challenge of each new detection may be the responsibility of a separate IFF operator, or it may be assigned the analyzer or detector.

Altitude

Altitude determination may be the responsibility of the analyzer, or it may be determined by a separate height-finding operator.

Analyzer

The analyzer operator investigates each detected target and assures that identification and altitude information is sent to store. He may be assisted by a separate IFF and RHI operator. IFF entry may be by number or coordinates, and RHI coordination appears most reliable by azimuth slaving and range gating.

Additional responsibilities of the analyzer may be detailed investigation of the target area by expanded PPI, B-scope, or storage A-scope to determine the size, type, composition, etc.

Supervision

The supervisor is responsible for monitoring the detection, tracking and analysis operations. He assures that all targets are under consideration.

He is responsible for track exchange, cancel, fades, splits and assist. He should be provided with category selection.

The operational use of the information provided must depend on the results of experience with the equipment. The displays and control provided should fit in with the present allocation of responsibilities to the various users. For instance, the air-control portion should assist the Air Direction Officers to appreciate the air situation and to allocate individual tasks to forces, ships or individuals concerned with air defense. In this respect, a cardinal principle is that each user should have an individual display, upon which he can produce such types of information as may be of interest at the moment, without disruption of any other user's information. Examples of users are:

Air Direction Officer (both Group and Ship)

Gunnery Liaison Officer and Fleet Antiaircraft Gunfire Coordination

Air Intercept Officers

Gunnery Target Designation Officers

Radio Warfare Controller

ASW Control Office

Surface Plot Officers

Flag Officers and Commanding Officers

Such displays should be as standardized in construction as possible. It is probable that only two types would suffice for all purposes: a PPI type for the display of air information, and a large, horizontal type for close-range surface and ASW information.

Each display must have associated with it some form of status display, upon which will be shown additional information that amplifies positional information but that is not so vital or so fast-changing as to justify its inclusion in the electronic data system. It must be possible to select such information either by position coordinates or by track number.

The second phase of information handling is the exchange of data between ships. Some of the factors to be considered in this mode of operation are:

- Radio Links
- Track-number assignment
- Reporting
- Multiple tracking
- Transfer and cancel
- Coordinate reference

It appears that multiple radio links would be the most reliable. These would be selected to handle long-range slow-speed information, short-range high-speed target information, messages, orders, and status. Track-number assignment should be common to the force and could be controlled by a master ship interrogating each ship in rotation. Track-number assignment on a force basis would take place only during the individual reporting cycle. Local tracking without reporting or multiple tracking may be desirable for backup in case of fades or track transfer. All positions should be reported with a common, fixed geographical reference point. The reporting ship identity should be contained in the reporting message.

This operational description is admittedly incomplete. It does not discuss facilities for weapon assignment or intercept computers. The functions are described as they might be arranged in a Phase 1 system or the Phase 2 prototype. As more automatic methods become available for detection, tracking, etc., the arrangement would be modified.

Further information on operational requirements and suggestions for the amounts and types of data to be handled at different places in the system will be found in a number of reports (see references at end of Chapter 7).

DATA PROCESSING IN THE SAGE SYSTEM

(The text and illustrations of this section have been taken from "Operational Plan, Semiautomatic Ground Environment System for Air Defense (Draft)," by permission of the Air Defense Command.)

Introduction

The Direction Center, equipped with the AN/FPS-7 Combat Information Central equipment, processes radar data and data from other system inputs, such as weapons status, weather, cross-telling, early warning, etc. The processed information is displayed to men at the direction center and transmitted to weapons and other centers.

Figure 7A-1 shows the information flow from data sources through the FSQ-7 input system and data processing to the displays and outputs.

Inputs to the Computer

The input system is divided into four general classes as shown in Fig. 7A-2.

The Computer

The computer is a parallel, binary, single-address general-purpose digital computer. Its three major units are the magnetic-core memory unit, the dual arithmetic unit and the control unit(composed of instruction control and input-output control). The interconnections between these units are indicated in Fig. 7A-3.

The magnetic-core memory stores 32-bit binary words which may represent either instructions or data. The instruction control extracts instructions from the memory and controls their execution, usually obtaining data from memory and controlling the arithmetic unit in its operation on such data. The arithmetic unit incorporates the circuits and registers necessary to perform the various arithmetic and logical operations, as specified by the instruction control. The input-output control consists of the control circuits and registers required for the transfer of information between the high-speed magnetic-core memory and the lower-speed drums (and other input-output devices).

Displays

Information generated by the computer is displayed to human operators on various scopes via the display systems. Figure 7A-4 is an outline of the display system.

Output System

The AN/FSQ-7 output system feeds the automatic data lines that carry information from the Direction Center. The output system, illustrated in Fig. 7A-5 consists of an output buffer drum and the necessary storage and shifting circuits to hold information while it is being transmitted.

For additional details of the SAGE System, the reference cited above should be consulted.

TECHNICAL CHARACTERISTICS OF A NAVAL DATA SYSTEM

General

The Canadian Datar system has been recommended as a starting point for development of the Phase 2 digital system. This section describes the prototype

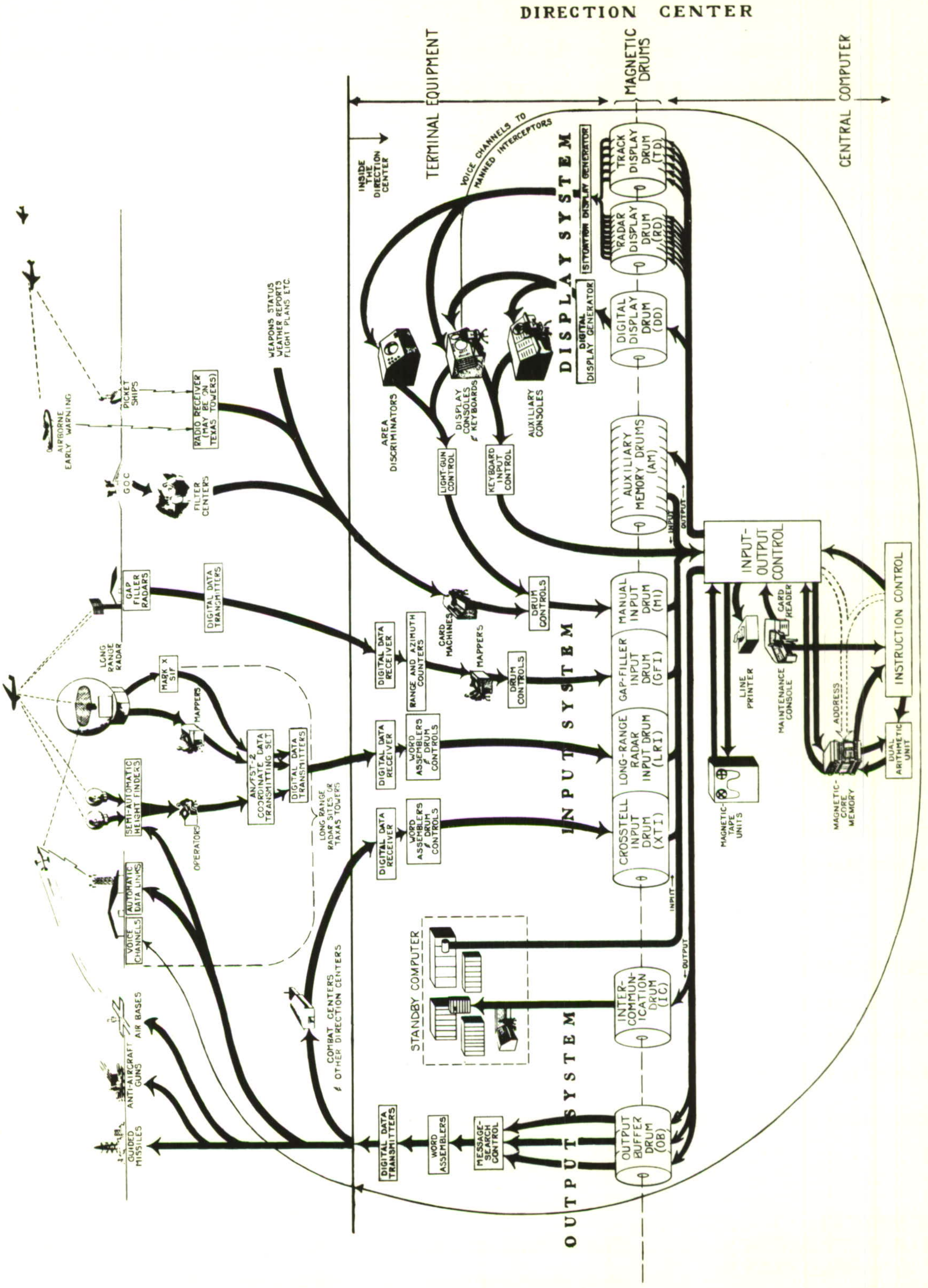

Fig.7A-1. Information flow in the Direction Center.

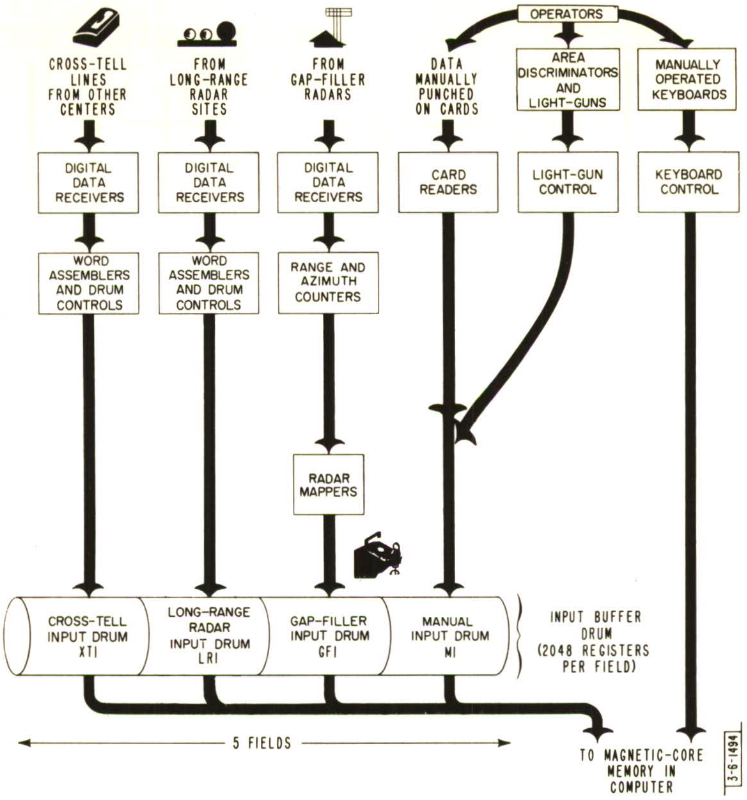

Fig.7A-2. Outline of Input System and Input Buffer Drum. Provisions are made to connect the following inputs:

(1) Gap-Filler Radar Inputs (inputs from as many as 16 gap-filler radars).

(2) Long-Range Radar Inputs (inputs from as many as 18 long-range radar sites. Each site includes a long-range radar, a Mark X beacon, and 2 height finders).

(3) Cross-Tell Inputs (automatic inputs from as many as 12 sources, including other centers and weapons bases).

(4) Manual Inputs: (a) Inputs (from 3 card readers, 64 light guns, and one area discriminator); (b) Keyboard Inputs (from about 115 keyboards at the display consoles).

Most of the input data are accumulated on 5 fields of the Input Buffer Drum which acts as a reservoir from which the computer can draw data whenever necessary.

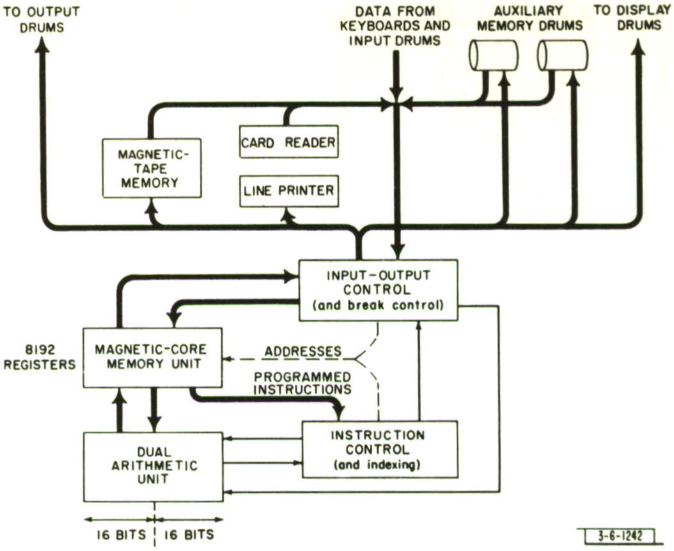

Fig.7A-3. Outline of Computer.

The computer is the main information-processing device. It takes the raw data from the input drums or keyboards at rates up to 100,000 pieces per second, and performs operations on the data at an average rate of 60,000 operations per second.

There are 48 different arithmetic and logical operations possible. Most of these operations (termed "instructions") are performed in a dual arithmetic unit which can deal with two 16-bit "half-words" simultaneously. The portion of the program of instructions currently being performed, and the required data, are stored in the magnetic-core memory unit.

The magnetic-core memory unit consists of 8192 storage locations (registers), each of which can store a 32-bit word plus a single parity check digit. The complete sequence of events required to refer to a given register of memory is called a "memory cycle" and requires about 6 μsec.

In addition to this high-speed core memory, the computer has two supplementary memories: auxiliary drums (medium-speed memory) and magnetic tapes (slow-speed memory). The 8 auxiliary magnetic drums provide storage for a total of 98,304 words, and are used principally for storing the complete computer program. There are 4 magnetic-tape units, each of which contains a reel capable of holding 1,150,000 words. The computer can write or read 3125 words per second on any one of the 4 units. The principal function of the tape units is the recording of a tactical battle situation for later analysis.

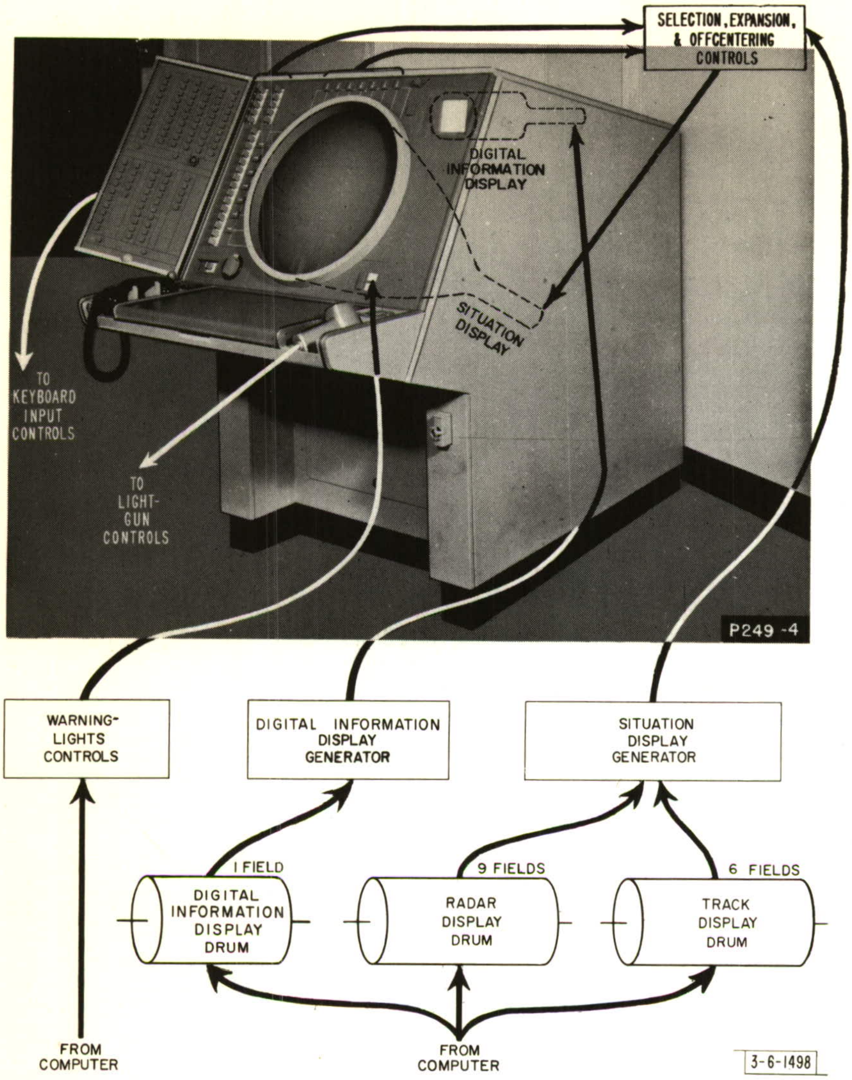

Fig.7A-4. Outline of Display System.

The display drums relieve the computer of the task of repeatedly generating displays at a rate that matches the phosphor characteristics of the situation display scope, and limit the necessity for computation to that required to revise the existing track displays. The display-drum system consists of one 2048-register field for digital information display, 6 fields for track and vector data, and 9 fields for past and present radar data. The output of the display drums is distributed, independent of computer control, to the display system.

The function of the display system is to provide a visual presentation of data about the air situation to human observers for the purposes of interpretation, identification, evaluation of alternative tactics, and control of men and weapons. The displays fall into two principal categories: situation display and digital information data display. The situation display is a map of the current air situation showing aircraft tracks with identifying information, air bases and other geography, and suggested battle tactics. This display is presented on a 19-inch Charactron mounted on the situation-display console, and can show up to 1536 pieces of track or vector data, and 16,384 radar returns covering the past 8 radar scans. These data are displayed on the scope face in a repeated sequence. To display all the drum data requires 2.5 seconds. Switches at each console enable operators to restrict their displays to classes of data of immediate interest to them. Other switches enable the display to be contracted or expanded. The digital-information display appears in tabular form on 5-inch Typotron tubes. Each digital message contains up to 32 lines of 5 characters each.

In each direction center there are approximately 135 consoles, of which about 90 contain the situation display, about 115 contain digital information displays and about 100 contain manual input keyboards. A system of 256 warning lights (some actuating buzzers) controlled by the computer are distributed on the display consoles in order to call attention to various unusual conditions.

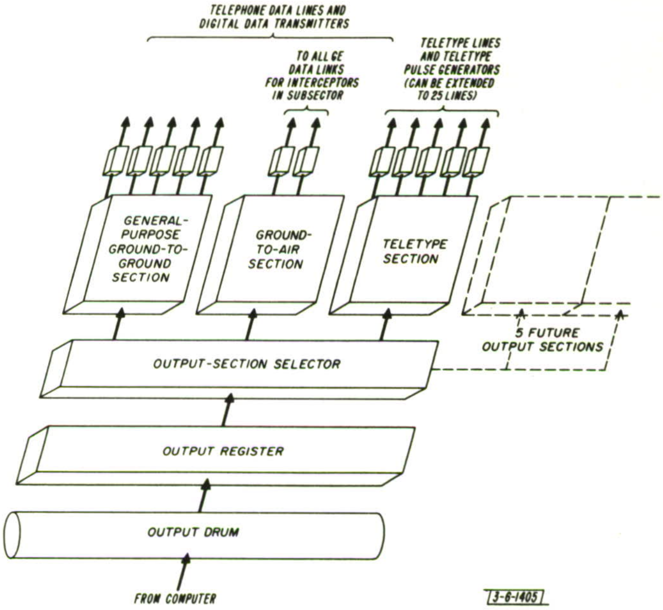

Fig.7A-5. Output System.

The 6144 registers of the drum are scanned in sequence. Data are transferred to the proper output section at the proper time as determined by an address and a "burst number" stored with the data on the drum. The output-section selector has capacity for 8 output sections.

as it is currently planned. An experimental system incorporating much of the equipment discussed in this section was tested successfully in 1953. The experimental system was a laboratory model using conventional circuit techniques and vacuum tubes. The prototypes, which will make use of transistors and miniaturization techniques, are to be delivered in late 1957 or early 1958, and will embody the principles described here, although some physical details may be modified during the design study. This data system may be regarded as typical of a class that embodies the following basic characteristics:

> The system is essentially digital, although certain operations (such as the display of target position) are analogue.
>
> The communications requirements for the system are minimized without sacrificing flexibility and accuracy.
>
> The system is decentralized, and each ship can operate indi-vidiaully or as a unit in a group.
>
> Adequate capacity is available in each ship to store all tracks of interest and other relevant data from all sources within a prescribed operational area. Further, the store has adequate capacity for the handling, in conjunction with arithmetic units and controls, of certain logical and arithmetical operations.
>
> The central store and control equipment is common in all ships, although the local inputs and outputs are dependent upon the class and size of ship.
>
> Certain additional computations, which cannot readily be handled by the central store and associated equipment, will be performed by special-purpose computers that operate in conjunction with the central store.

Description of a Ship Installation

The flow of information in the naval data system under consideration is given in Fig. 7A-6. It is assumed that all position information is stored in the central store in (x, y) coordinates with own ship's position as origin. On the radio link, information is transmitted in (x, y) coordinates relative to a common fixed geographic origin, which is determined by the "command" or "master" ship and which may be changed from time to time depending upon the situation. All raw radar and sonar displays are north-stabilized.

It is convenient to consider the insertion of data into the system in terms of personnel engaged in these operations:

<u>The Detector-Tracker</u> (D/T) is responsible for the detection and insertion into the system of new radar plots. He is provided with automatic alerting. The D/T console consists of a PPI display on which are superposed synthetic markers, indicating all

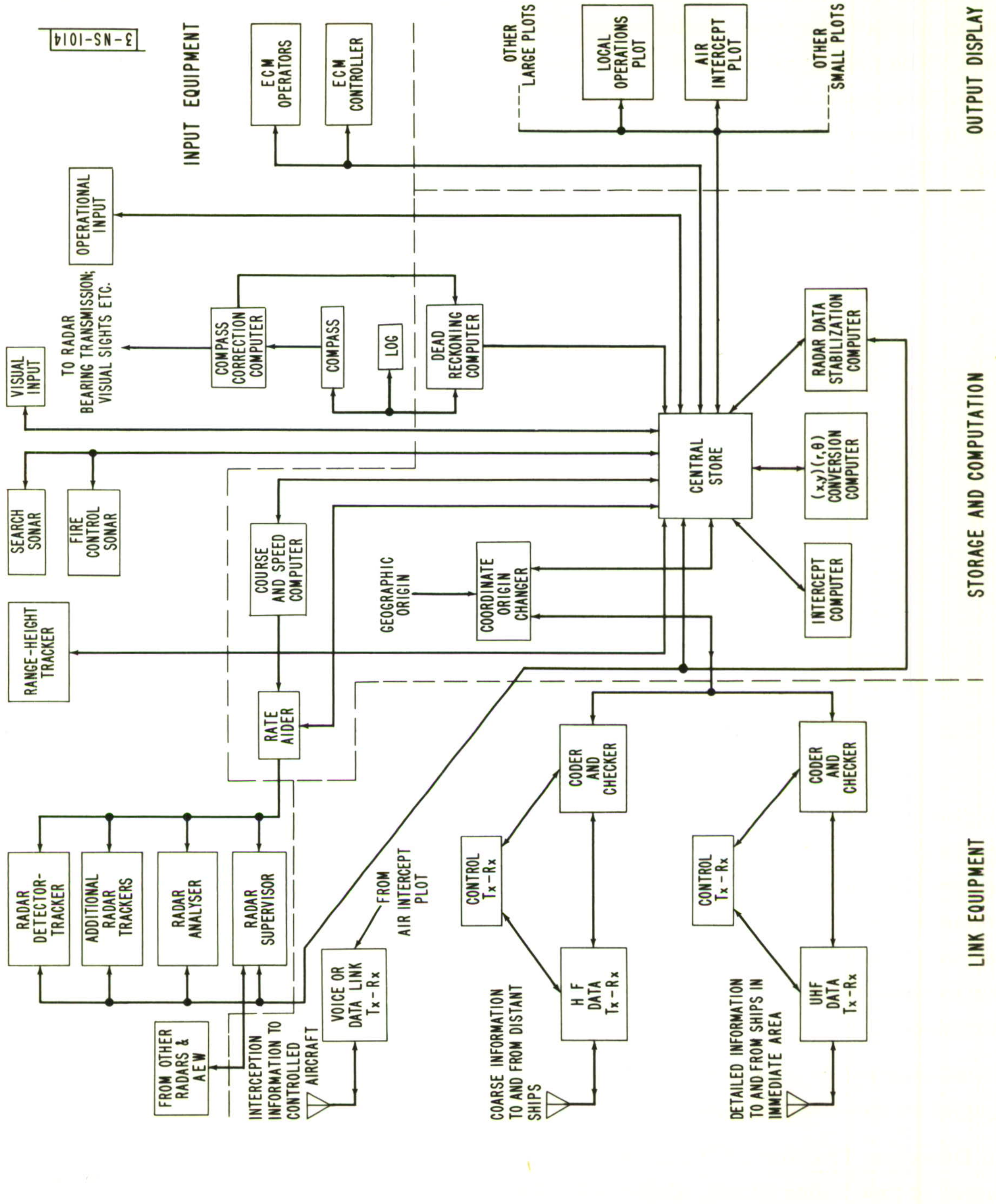

Fig. 7A-6. Information-flow diagram of a naval data-processing system.

targets under surveillance of own ship that have been inserted into the system. Controls are provided for inserting coordinates of single targets into the store. In cases where it is impossible to resolve a raid into individual targets, the procedure is to split the raid into groups, defined perhaps by three or four special markers that enclose the raid area, and to store and display the key points. This latter facility is considered to be of high importance in the engagement of massive raids having high target density. The D/T can also insert ECM position information into the store – again, either as a point or as an area.

Trackers keep tracks up-to-date in the ship's own zone of coverage. Individual trackers are allocated tracks sequentially by the central control system or as directed by the supervisor. The trackers are assisted by synthetic markers indicating track currently up for attention, which markers are rate-aided in steps corresponding to target motion between successive scans of the radar antenna. A tracker should be capable of handling 6 to 10 tracks. In the case of repetitive fades, crossing tracks and ECM conditions, a tracker can hand over tracks for the supervisor's attention

It is probable that manual detection and tracking will eventually be replaced by fully automatic detection and tracking (e.g., track correlation) in three dimensions. The data processing and associates sorting and tracking computer developed by Control Systems Laboratory (CSL), University of Illinois, may be suitable for these operations. An experimental version of the computer will be available in late 1955 for test. The CSL proposals are compatible with the system under consideration.

Height Operators determine height of tracks allocated automatically or by the supervisor. The height operator's console contains the height-finding display and a PPI. Height is inserted into the system through a keyboard and switches.

The Analyzer obtains information relating to target identification. His equipment includes PPI, A-scope, expanded B-scope, controlled markers and perhaps a distress indicator. The clear picture plot, raw radar, or a combination may be selected on the PPI. He can call up status and revise status information through a keyboard. With these aids he can determine IFF and raid size, and may also be able to obtain some information on size and type of target.

The Radar Supervisor monitors and directs the operations above. He has complete displays and controls to modify information in the store or take over an operation. Hand-over of tracks from one ship to another is assigned to another operator who is also responsible for assigning the same track number to a target viewed by two or more radars.

Sonar Operators obtain information relating to the position, identity, depth and behaviour of submarines in the vicinity of own ship, using search and fire-control sonars. Data are converted into digital form by analogue shaft position/digital converters, and, in the case of status data, by keyboards; the data are then handled by the central store and storage. In a passive role, the hydrophones can give bearings on submarines, which information, stored in terms of time, point of origin and orientation of bearing, can be stored and displayed.

ECM Analyzer and Operators handle radio warfare aspects of the naval data problem. The group obtains information by means of radar and radio receivers with directive antennas. Perhaps 20 different items may be required to describe a situation, and the rapid dissemination of such information is of considerable importance.

Visual Inputs may be fed into the system through mechanical encoders associated with optical direction finders.

Miscellaneous Inputs:– Ship's log and compass inputs are coded into binary digits and used in the dead-reckoning computer to provide up-to-date own ship's position. The compass input is also fed into a compass correction computer in order to obtain north-stabilized radar plots.

Pointer facilities, whereby the Air Defense Controller and other supervisory personnel can indicate special points or areas of interest on clear-picture plots, can also be regarded as system inputs. The pointer can be addressed to any or all ships in the group, or to operational personnel on own ship as desired.

Radio Data Link:– Input information from other ships in the group is received, checked for errors, converted to ship-centered coordinates (in the case of position plots), and stored.

Storage and Control:– The central store on each ship consists of a magnetic drum capable of storing approximately 200,000 binary digits. It appears that a drum rotating at 3600 rpm and having 100 tracks with 2048 bits/track is adequate. Some 60 tracks are used to store data on up to 1000 targets and/or other items, and the remaining storage capacity is used for control, computation operations, and for the generation of special timing waveforms.

The basic logical and numerical operations for which "wired programs" are provided and which are handled by the central store and control are:

Track-number allocation
Category selection
Data rate changing (e.g., basic digit rate on link differs from

basic frequency of terminal equipment)
Routing of data to displays, special-purpose computers, etc.
Coordinate origin shift and scale changing
Target speed and course determination
Parallax correction

The experimental data system mentioned previously incorporated all the above facilities. The circuits associated with the central store, arithmetic units and control unit will be based on transistors and to some extent on magnetic cores.

Special-Purpose Computers

In addition to the logical and computational operations listed previously, other computations may be required that may most effectively be carried out by using small special-purpose computers. These are:

Compass correction
Dead reckoning
Radar data stabilization
Cartesian/polar conversion
Intercept control
Weapon assignment

Some of these special-purpose machines may be analogue rather than digital in character, and some may embody analogue/digital techniques.

System Outputs

The system is so designed that data can be extracted from the central store rapidly and, through the category selection and other data-routing gate matrices, considerable flexibility is available. All target position and bearing information, unless subject to category selection, is displayed continuously on summary plots, such as the Local Operations Plot, while special-purpose displays show detailed pictures of selected categories. Status information associated with each target (friend or hostile) can be extracted from the store by either manually dialing track number, or by obtaining position coincidence between a controlled marker and the appropriate target. Data required for fire-control directors or radars can likewise be extracted from the store, fed through the coordinate converter, and used to operate servo systems which control the director.

It is proposed to dispense with large summary plots and tote boards, and to replace them by individual displays of position and status information patterned to suit the particular task of a tactical control officer (e.g., Air Defense Controller, Intercept Officer, Gun Target Designation Officer, etc.). The position-display consoles for operational use are divided into two main types:

Geographic Plots, approximately 3 feet square in display area, will have a fixed origin of coordinates, as determined by the command ship, and scales corresponding to perhaps 1/4, 2 and 10 miles to the inch. One and two color projection-type displays are proposed for all consoles in order to simplify installation and maintenance. On all clear picture plots, approximate course and speed vectors are associated with each target, while status information is indicated by color and by some 8 or 9 "Lissajous figure" shapes. Similarly, bearing lines, shown solid, dotted and in 2 colors, can be used. Each console incorporates a manual control for positioning a marker or pointer, and a keyboard for inserting information or extracting information from the store by "call-up" on a status display.

Relative Plots (own-ship centered), with adjustable scales, will be approximately 18 inches square. An important requirement for these relative plots is the availability of own ship's raw radar information. Accordingly, the plot may be clear picture, video or composite, as desired. As in the case of the geographic plots, vectors, shapes and bearings may be displayed.

Status information, available at all supervisory, operational and analytical positions on a call-up or demand basis, includes target height (or depth), track number, accurate course and speed, raid strength, detailed identity, damage condition, staleness of last plot, etc. Status relating to ECM and radio warfare is different from target status, and the ECM controller is provided with special target indicators and displays.

Radio-link information constitutes another basic output of the system. Information for transmission is selected from the store by the transmit-receive control units, which also control the transmit and receive sequences, and the coding and error-checking equipment. The coder and checker unit transforms information from the store into link "language and timing" during transmit periods, and effects the revere transformations during receive periods; the unit also introduces synchronization and error-checking codes into the transmitted information, and checks the accuracy of information received over the link according to criteria dependent on the form of message.

Communications

The three basic types of radio links required by the system are:

A UHF data link for exchange of detailed information between ships in a localized area defined by UHF line-of-sight transmissions.

A high-frequency data link between ships separated by greater distances for exchange of general situation information and target information of special interest to a distant ship.

A voice link, which will eventually be replaced or supplemented by a data link, between an Intercept Officer and a fighter under his control.

In order to minimize channel capacity, it is recommended that (1) Both the position and velocity coordinates of the target be transmitted over the link. Ships receiving the information will extrapolate target positions, and (2) The message content corresponding to a single track or item be transmitted on the link in 2 or 3 separate sections, a message section to be transmitted when a change occurs.

The UHF data link will be of a time-sharing type, in which each ship of a group transmits in sequence. An approximation to the link-channel requirements can be obtained by considering the total information generating capabilities of all ships in a group. (Surface and subsurface data may be neglected because the amount of such data will be small.) The largest unit in a group might transmit position data on 40 aircraft tracks per minute. Changes in identity, strength and height occur less often, and may be transmitted at 10 per minute. The total number of data groups is about 50, which, at 75 bits per group, requires a rate of 75 bits per second. Smaller ships may generate 40 bits per second. A naval task force consisting of 4 major ships and 16 lesser ships would require 940 bits per second. Allowing for interrogation, synchronization, and surface and subsurface tracks, the required bandwidth is less than 2000 bits per second.

Communications over the high-frequency link will presumably be between designated ships in each force. These ships will transmit information in geographic coordinates with data rates of perhaps 100-400 bits per second, depending on the range. The following types of information will be transmitted:

Coordinates of designated ship of group,
Course and speed of group,
Number of targets (friend and hostile) within a prescribed area,
Fighter status within combat zone.

PHASE 1 EQUIPMENT FOR THE FLEET

Introduction

This section describes an interim electronic system for handling target data on ships which utilizes existing techniques and equipment as far as possible. This system could be operational in limited quantities and with limited facilities in 1957. The program is aimed first at improving the fighting capability of the individual ship by (1) electronic aids to tracking of targets, electronic storing of data and automatic plotting, which together increase the tracking capacity, decrease errors, and reduce time delays; (2) providing a coordinated system for designation of targets to gun and missile directors; and (3) providing an electronic intercept-control computer, which improves the accuracy of intercept and increases the number of interceptions that can be controlled by a single individual.

In parallel, communication facilities are outlined for exchange of data between ships to give to Command information for coordination, modification of doctrine, and regulation of force disposition. Also, track data are exchanged between ships to facilitate hand-over of tracking from one ship's sector of responsibility to another.

The basic equipment both for ships operating as a part of a task unit, and for ships operating on picket duty as a part of the continental offshore contiguous coverage system, is basically the same. There will be differences in the communications organization, however, because of the differences in distances between ships and the amount of data to be passed. A fleet ship can take up offshore picket duty, can receive data from offshore pickets, and can operate within the picket area in a coordinated manner.

A special shore-based installation is required for the offshore coastal area to serve as a communication center and command post for coordinating the seaward surveillance system, evaluating the situation, and making interceptor assignments. Through this center the track data are routed to the proper SAGE sectors and higher command is advised as necessary.

In all instances stress is placed upon early filtering of data in order to utilize on-the-spot evaluation, distribute the work load, and minimize the data which must be passed over the communications net. Also, decentralization is stressed for flexibility and protection against enemy action.

Own Ship Improvement

The ships are fitted with the Electronic Data System (EDS) similar to that developed and demonstrated by the Naval Research Laboratory and more completely described in NRL Report 4473. This system provides for electronic take-off of target data from PPI's by pointing a pencil to the target position on a conducting glass overlay which replaces the reflection plotter on the conventional radar indicators. The target coordinates are stored in capacitors and may be read out to remote indicators and to automatic plotting boards. The target velocity is computed and likewise stored in capacitors. This velocity is used to correct the coordinate positions and to relieve the tracker of having to continually make corrections. Also, a store is provided for height, size and category. These items are inserted manually by an operator but may be read out electronically wherever needed. An operator is provided with a height indicator having connection to the height store such that a storage potentiometer is substituted for the height potentiometer for each track as it is gated out for height measurement. Size and category are set in on switches by the operator from information furnished by sweep examination of the target, IFF, and other intelligence.

The target-designation equipment provides for automatically slewing a gun director and setting the range gate from stored data on tracks simply by setting switches to connect the director to the proper store position. Repeat-back of the director position is displayed by a characteristic symbol, matching the target position, on a PPI to provide monitoring of the director following. Elevation is computed and transmitted to the director with a meter display. The PPI monitor is provided with conducting glass overlay so that designation may be made by pencil pointing. This indicator is provided with raw radar input for further monitoring the situation and for damage protection.

The intercept computer, as a first improvement, displays to the controller the course the interceptor should fly for interception. This carries through from the approach phase to the final turn at which time either AI or visual control takes over. While voice may be used to pass information to the pilot, time delays would be reduced by using the discrete address system being developed by the Services. A further improvement can be expected by completing the development of a pilot display which in effect allows the pilot to become his own controller, thus giving him more flexibility in programming the final phase. Not only does the pilot display provide information on course and relative altitude but permits the AI radar to be trained in the direction of the target so that the scanning angle may be reduced resulting in greater detection and lock-on range.

Organization of the equipment is flexible depending upon the size of the ship and the CIC arrangement. In general, however, it would be expected that facilities such as the following would be supplied:

Detector Console. This position sees raw radar and markers representing stored target positions. A standard PPI, such as the AN/SPA-8 is fitted with conducting glass overlay and electronic pencil for inserting position information in the store. This operator assigns targets to a tracker by voice intercom or by using a telewriting feature of the electronic pencil which allows him to write messages to appear on the tracker's indicator. The detector can cause the store to be rapidly scanned, presenting all markers representing tracks, in order to locate new targets and monitor the trackers performance. During standby conditions, one operator could detect and track from this position.

Tracker Console. This is similar to the detector console. As many positions as necessary to cope with the load may be used. A small ship may have two, while a capital ship might have six or more. The tracker is presented a marker indicating the next target track to be corrected. The marker is "fixed" to the radar blip, moving in steps as the blip is painted. The marker sequences through the trackers targets either automatically stepping as soon as the correction is made or stepping under control of a foot switch.

Supervisor Position. In small ships, the detector may supervise operation, while in large ships another position may be set up for this function.

Analyzer Position. Height, size, and category must be inserted in the store. An operator performing this function should be provided a range-height indicator, a size scope and IFF interrogation facilities. On a large ship, these functions may be divided between as many operators as required. On a small ship, the supervisor may assume the analysis function.

Summary Plot. The AN/SPA-15 samples the store and plots on a vertical plexiglass board the last predicted target position of each track in turn. As many boards as desired in different locations may be used. Tracks may be selected by category so as to plot only those desired. Store number (track) is displayed on an associated panel as the track is being plotted. These numbers may be transferred to the board with grease pencil along with other status information as desired.

Tactical Display. A clear presentation of the stored data should be provided at as many locations as needed on PPI's. These positions should be provided with switches which will allow category selection of such things as air, surface and subsurface targets; and friendly, enemy, or unidentified. At the operator's option these various categories may be marked with distinguishing symbols such as a circle, square, elipse, etc. Symbols should be symmetrical. These tactical displays are expected to eventually replace the large summary plot as techniques for their use are developed.

Electronic Store. The stores may be built up around units of about 24 tracks. One unit would be enough for the smallest ship and perhaps two units would be average for a capital ship. The sea pickets may be provided with three units, one for own ships radar, and one each for two AEW receiving terminal stations. In addition, ships designated for force command may have one or two units in which consolidated data is stored for command use.

The target designation system and the intercept control equipment is coordinated with CIC electronic data system but at the same time may operate as independent units.

This provides for a maximum of flexibility and damage protection. In each case the facilities provided would be determined by the weapons which the ship might be expected to have under control.

Data Exchange

Command must be provided target data to aid in making decisions on assignment and exercising control. The transmission distances are such that it will be necessary to use high frequency sky wave for the near future in many cases. To insure reliability, the data rates must be confined to about that of a standard telegraph channel. The data should be filtered by each reporting ship and consolidated before transmitting. In the fleet case this data should be exchanged on a single net when a common frequency is satisfactory and high frequency ground wave utilized when ships are not too far apart.

More detailed data must be exchanged between ships of a fleet group in carrying out the hand-over of tracks from one ship's sector of tracking responsibility to another. Also, in monitoring the over-all performance of the various ships, the detailed data is useful. Therefore, a higher-data-rate net operating on UHF within line-of-sight is desirable. The terminal equipment should be similar for the two functions, differing only in data rate. This equipment is more fully described under the section on data links.

The data exchange for the seaward extension using pickets is organized somewhat differently but uses the same type equipment. Each picket ship collects data from its own search radars and from one or two AEW planes. Evaluated tracks are maintained in the ship's EDS store. Data on these tracks are transmitted on a high-frequency telegraph channel to the shore station. Each ship is assigned its own individual channel for passing data to the shore station. Some communication between pickets, such as handing over of tracks, is necessary. To avoid a multiplicity of circuits between ships, all reports are addressed so that automatic telegraph switching equipment at the shore station can repeat any such reports over a low-frequency telegraph broadcast to all pickets. This arrangement minimizes the shipboard equipment and increases reliability by having one terminal on the shore where antennas may be optimized.

Target Reports

Position reports are made in rectangular coordinates having an origin common to the operating group. Reports have their positions corrected to this origin by the originating ship before being put on the data exchange net. The receiving ship subtracts its position from the incoming data to obtain own ship's centered data. The information to be reported, with the approximate numbers of bits, is as follows for the various circuits:

Picket Ship-to-Shore

Information	Bits
Address	4
Track number	12
x-Position	16
y-Position	16
Height	8
Size	2
Category	2
Speed	4

This will take about one second to transmit on the low-rate channel; thus each ship could transmit data on each track about once a minute under heavy-load conditions. When so addressed, the report is retransmitted by the shore to the pickets but, since only a small fraction of the total reports will be retransmitted, appreciable delays should not occur. This outgoing link will also carry command messages regarding track-number assignment, interceptor-control plans, and AEW redeployment orders.

Short-Range Fleet Circuit

Information	Bits
Track Number	12
x-Position	12
y-Position	12
Height	8

This circuit can operate at higher rates and could be expected to handle about 40 reports per second. Each ship would transmit upon request under control of a central ship. Each ship would be identified from the request and would transmit all tracks that command had designated for reporting after which an end-of-message character would initiate the next request. The store keeps the position of all tracks up-to-date, hence velocity is not transmitted. These data are used primarily to facilitate hand-over, and the receiving ship will start tracking and storing the target as soon as possible and will then become the reporting ship. Track numbers are maintained throughout the system and are associated with store number on each ship through a switch (plug board). The reporting rate varies with the traffic, but the cycle may reach several seconds before becoming objectionable. With proper doctrine on tracking and reporting, this net has the capacity for raids of several hundred targets. Status information is transmitted on a command net when arrangements are made for hand-over. Otherwise, this information is not transmitted since it is always available in the stores of the ship having responsibility for the sector, and is available to command in consolidated form on the net described below.

Long-Range Fleet Circuit

Information	Bits
Reporting ship	8
Raid designation	8
Category	4
Size	2
x-Position	12
y-Position	12
x-Component of velocity	8
y-Component of velocity	8
Height	8

This net is designed primarily for assisting command in getting an over-all picture in order to make force assignment and to coordinate the battle. The data are consolidated so as to report such items as strikes, raids, etc. It is transmitted from ships in turn on request, as with the short-range net. However, since the data rate may be rather slow and variable, velocity information is contained in the report.

Aids to Command Display

Large ships which may perform command functions need a composite display of the data from the long-range net. When received, the data are stored in punched tape from which status information may be taken off and posted. At the same time, position and velocity are inserted in an electronic store and the stored positions are kept current by the velocity information. Tracks are generated by an AN/SPA-15 plotting board as a summary for command.

Equipment

The equipment required for the system is tabulated in Table 7A-I.

TABLE 7A-I. Equipment Required for Phase 1

Equipment Items		Number Per Ship					
		Light Ship*			Capital Ship*		
		A	B	C	A	B	C
24 target x,y (analogue) store	(a)	1		1	2	2	
24 target $\dot{x},\dot{y}$ (velocity) store	(b)	1			1		
24 target height, size, category store	(c)	1			2		
48 target $\dot{x},\dot{y}$ manual store	(d)					1	
Automatic plotting board	(e)	1			1	1	
Electronic-pencil data take-off console	(f)	3			6	1	
AEW terminal equipment	(g)	1			2		
Target designation (4 directors)	(h)	1			2		
Intercept computer (3 intercepts)	(i)	2			4		
Analogue-to-digital converter	(j)			1			1
Digital-to-analogue converter	(k)			1			1
Parallax computer	(l)			1			1
Standard Items							
Remote PPI displays				– as needed –			
Teletype			X			X	
Radio links			X	X		X	X

*Equipment items are tabulated as number of basic units required. Column A is for own ship improvement which is the basic requirement, B shows items added when the coarse grain net is employed and C the additional items when the fine-grain net is added.

Items (a), (b), (e) and (f) exist in laboratory prototype form with commercial prototypes under procurement for delivery in the fall of 1955 except item (e) which was to be delivered about January 1955. Also an item similar to (c) will be delivered in the fall of 1955.

The laboratory model of the target-designation system (h) has been demonstrated and is ready for commercial prototype development.

Contract negotiations for the intercept computer (i) are now in process.

Laboratory models have been designed for items (j) and (k). The 48-target x, y manual store (d) does not exist as such, but it would be a simplified version of item (b). The AEW terminal equipment is the existing equipment modified for electronic pencil take-off with the same equipment used for item (f) which is the standard AN/SPA-8 indicator with conducting glass overlay and pencil coordinator equipment. The parallax computer has not been designed, but appears straightforward, since it is a simple slow-speed digital adder.

The complexity of the equipment is represented by the number of vacuum tubes. The light-ship CIC EDS requires about 210, the target-designation unit about 90, and the intercept computer about 80 for the 3 intercept units. These numbers apply to added equipment only and do not count the tubes in existing PPI's that must be used in the system.

INTERCEPT-CONTROL COMPUTER

This section describes the need for electronic aids to intercept tracking and control, and makes specific proposals for production of a prototype intercept computer for Phase 1 application.

The critical nature of the need for better intercept control at sea can be realized by noting that under optimum laboratory conditions a controller is 60 per cent effective in bringing about talley-ho (not kill). Under fleet conditions, this percentage is much worse. The reason for the poor performance of controllers is partly that they have inadequate height information, and partly that interceptor speed margins are narrowing and speeds are increasing. Critical decisions such as "calling the turn" are made incorrectly, and therefore serious misses or long tail chases result. The controller does not need guidance in collision-course navigation, which is elementary, but he does need help in executing the precise maneuvers required to orient the interceptor into the proper place with the proper altitude, so that the interceptor pilot can see the target on his AI radar and can execute a successful attack once he has seen the target.

Effective intercept control is important to extension of defenses seaward as well as to naval air defense. Existing facilities and procedures for intercept control have been made relatively ineffective by narrowing speed ratios, reduced radar cross sections of targets, and a multitude of other technical problems.

Increasing speeds of aircraft and decreasing interceptor speed advantages have made timing of critical air-control maneuvers exceedingly important. At the same time, AI and search-radar performance limitations, together with new and more severe requirements on the final phase of intercept control, have imposed stringent requirements on the accuracy required of air controllers in positioning their interceptors for target acquisition.

An improved intercept-control capability for extension of defenses seaward should be provided immediately by taking advantage of studies and computer development programs already carried out under Navy Bureau of Ships, Bureau of Aeronautics and Air Force auspices. Intercept tracking and control computer aids that would greatly improve present capabilities can be provided by:

> Insisting upon a computer capable of functioning independently of data-processing equipment designed to collect and disseminate CIC information,
>
> Basing the computer aids on existing PPI and RHI indicators and upon tested designs of experimental intercept-control computers and experimental aided track-while-scan computers,
>
> Resisting any impulse to broaden the basic function of the aid or to achieve a degree of improvement out of consonance with the basic aim of immediate improvement.

The intercept computer specified for immediate improvement of the intercept control picture should:

> Operate as an aid to the air controller, facilitating his tracking of target and interceptor, and making it possible for him to attain the precision required in calling the final turns leading to talley-ho (computation of offset points is imperative),
>
> Be based on use of a continuous raw radar presentation to the air controller,
>
> Fully treat the air intercept-control problem in three dimensions by incorporating height finding into the computer console.
>
> Be operationally flexible to provide for a number of air-control needs, such as
>
>> Interceptor vectoring on to a final approach heading favorable to employment of interceptor armament,
>>
>> Provision for adjustment of final approach heading in order to favor various weapons in being or development,

Control of aircraft en route to, on or returning from, Combat Air Patrol missions,

Assisting the rendezvous of aircraft to be joined for a specific mission.

Allow the air controller to continue to exercise judgment in areas such as

Monitoring of aircraft movement and air hazards affecting his control assignments (required to maintain strong pilot confidence under all visibility conditions and to maximize air safety in general),

Adaptability to variations in tactics and mission requirements.

The technical information to satisfy these requirements for an intercept-control computer is available today and many basic designs can be drawn upon directly.

BuShips should initiate a contract with a selected company to design a production prototype. The design should be guided by developments under the BuShips contract for an experimental prototype of the AN/SPA-22 for a ship-based computer and the NRL "Triangle" development which includes airborne display of intercept information.

PHASE I EQUIPMENT FOR THE SEAWARD EXTENSION OF CONTIGUOUS COVERAGE

General

The material in this section presents the results of many group discussions on the subject. While stated in terms of a certain size of installation located off the eastern coast of the United States, it is believed that the instrumentation and communications are sufficiently flexible so that the equipment proposed would be suitable for a larger or smaller installation and for a similar installation off the west coast.

It has been proposed that the YAGR radar picket ships, which are currently being commissioned to serve as gap fillers for the continental defense, be used for the sea pickets in this application. It has seemed to Project Lamp Light that EDS equipment might be installed in these ships as fast as the individual items become available, and that facilities and equipment for the shore station might be ordered at once.

Equipment for this area is of vital concern to both the Navy and CONAD. The total number of sets required is comparatively small, so that it seems to be an obvious place to start the Phase 1 installations. It is also a place where data-processing equipment is especially needed. Although YAGR's may be used at the start, they do not appear to be suitable for this mission and will presumably be replaced.

Objective

Approximately 10 picket ships are stationed off the east coast of the continent, as shown in Fig. 7A-7. Intership spacing is typically 300 to 400 miles, and the ships are deployed from 300 to 1000 miles from shore. AEW aircraft (WV-2) patrol above the picketed region. The picket ships serve as communication and data-processing relays for the AEW aircraft. A data-processing and command center on the shore provides coordination for the entire system.

Blimp-borne radar may also be used in the system. Perhaps 20 AEW's and blimps might be in simultaneous operation.

The primary objective of the system is to provide warning, surveillance, and interceptor control against air attack. Secondary objectives are to provide surveillance on surface and subsurface craft and to provide defense against these, and (for the pickets) to provide some self-defense against air attack.

This section is concerned with the electronic instrumentation of the Phase 1 system for the time period beginning in 1957. The instrumentation for the airborne threat is given in considerable detail. Instrumentation for the surface and subsurface threat is largely omitted.

Functional Description of System

Radar Cover:– Air surveillance is provided by both the AEW radars and the picket radars. The latter are quite effective against high-altitude targets but do not provide complete coverage. In regions where the AEW's operate, the coverage is complete and includes low-altitude targets. Height radar and Mk X IFF are provided on both the pickets and the AEW craft.

The mobility of the AEW aircraft makes it possible to employ raid-trailing doctrines. Thus continuous coverage of hostile raids may often be obtained, even though 100 per cent coverage might not be normally available.

Surveillance Tracking:– Surveillance tracking is done primarily on the pickets. Manual rate-aided equipment (EDS equipment developed by NRL) is employed. This equipment provides electronic storage of track data (position and velocity) and auxilliary information (height, size, identity). Both the video generated on the ship and video remoted from the AEW are tracked by the EDS equipment and operators. Automatic read-out and transmission of stored data is provided.

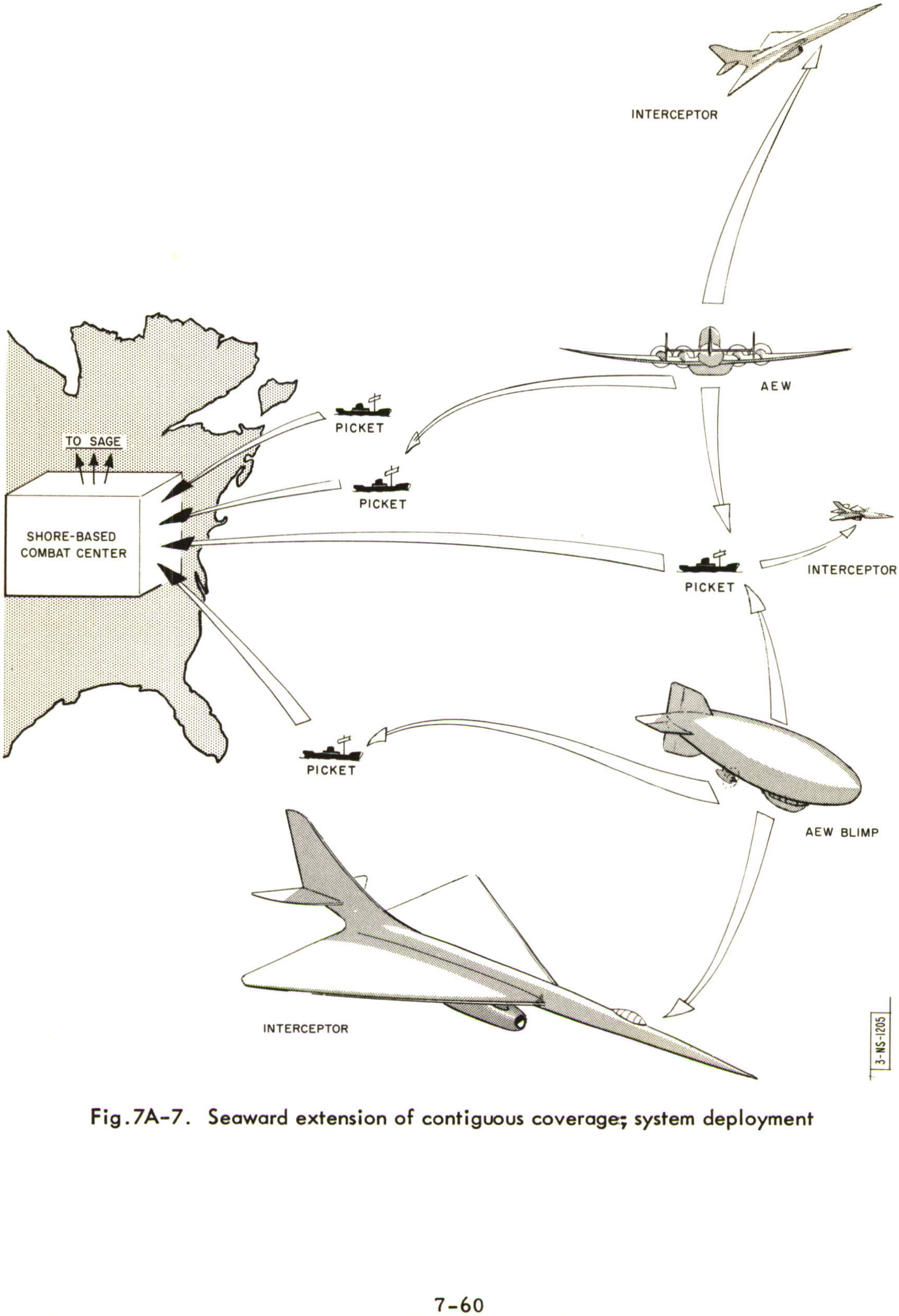

Fig.7A-7. Seaward extension of contiguous coverage~~;~~ system deployment

Surveillance tracking can also be performed on the AEW aircraft (with voice-telling of data to the picket). However, this is regarded as a standby function, and the AEW radar operators are normally reserved for intercept-control operations.

Considerable attention has been given to the problem of passing tracks from one picket to another so that consistent track numbers are maintained as a target passes through the system.

The tracking capacity of a picket ship is 72 surveillance tracks which may be distributed among two sources of AEW data and the ship's own radars. Additional tracking capacity is provided in intercept-control equipments for interceptors and targets engaged in combat.

Identification:– When the system is fully operational, the Air Defense Identification Zone (ADIZ) can be moved to the perimeter of the system. Identification is then performed at the picket locations. Identification will make use of electronic IFF, voice code words, coded manuever and flight-plan matching. Because commercial coastal aircraft do not penetrate the ADIZ, normal identification operations apply only to overseas traffic, and the load is consequently light.

Intercept Control:– The system can operate with medium-long-range, shore-based interceptors available in the period beginning in 1957. These include the F-101 with 760-mile combat radius, and the F-102 with 400-mile combat radius.

Intercept control is performed at the point closest to the origin of video data. This may be either the picket or the AEW. Both craft will have control capability and will have voice communication to the interceptors, or to carrier-based interceptors if available.

Shore-Based Combat Center:– All surveillance data are sent to a shore-based combat center. Here the summary surveillance situation is developed. Here information exists for assignment of interceptors and for rough guidance of interceptors to the combat areas. The specific role of the shore center in the conduct of air defensive warfare must be determined by the different Services involved in this theater.

Connection to SAGE System:– All air-situation data are in digital form (teletype) at the combat center. It is relayed by land wire to nearby SAGE direction centers where it is entered into the SAGE system. At the Sage direction and combat centers, the entire offshore air situation, or appropriate portions of it, can be presented on electronic displays.

Time Delays:– Surveillance information in the offshore system is handled in digital teletype form. This type of data transmission eliminates most of the delays that would be encountered in voice telling. However, it is not so satisfactory as a higher-speed digital data link (which is believed to be available beyond the 1957 time period). With the teletype system delays in surveillance-data transmission can be held to less than 2 minutes.

Communications

Inward Data Flow:– Because of the large overwater distances involved, communication is a critical part of the system. The following discussion is concerned only with tactical communications, and no attempt is made to describe administrative communication requirements.

Figure 7A-7 shows the flow of surveillance information from the radars inward.

Two means exist for relaying search-radar video from the AEW to the picket vessel: Rafax and the wide-band video link. It is doubtful that the range of the latter will be sufficient for this application, so that evaluation and implementation of the Rafax data link is presumed to be essential.

Mk X IFF data, height data, and visual-recognition information are transmitted from AEW to picket on UHF voice.

Two high-frequency RATT (radio-teletype) channels are provided from each picket to shore. One is for automatic transmission of digital surveillance data. The other is ordinary teletype for transmission of command acknowledgements and miscellaneous tactical information.

It is believed that single-channel high-frequency RATT data rates are sufficiently low that multipath-propagation difficulties can be avoided. By proper selection of frequencies, continuous reliable communications should be attainable.

Outward Data Flow:– A single low-frequency RATT channel is provided for transmission from the combat center to all pickets. The normal function of the channel is to broadcast automatically to the pickets data on targets in regions of overlapping radar cover. These data assist the track-acquisition operation as tracked targets enter the cover of a picket. Automatic overlap data transmission is interrupted, when required, to transmit brief standard-format teletype messages pertaining to track number assignment, interceptor-control plans, and AEW redeployment orders.

For interceptor vectoring, the pickets and AEW craft have UHF voice communication to interceptors.

AEW Equipment Configuration

The equipment configuration is that currently in use on the WV-2 aircraft with one exception: the addition of a Rafax scanner-encoder and a UHF voice transmitter to handle its output.

In the period immediately following 1957, improvements can be made in the WV-2 equipment. These include: airborne intercept control computer, clutter-locked MTI or UHF radar for the APS-20.

Of these, the first represents the more difficult and more urgent requirement. The proposed system relies heavily on the AEW as a source of interceptor control. At present the control capabilities are quite limited and attrition rates may be expected to be low.

Picket

The equipment configuration is based on the EDS aided-manual tracking equipment developed at NRL; high-frequency RATT data links; standard RATT communication terminal equipment; and the SPA-22 intercept control computer, which we believe can be available in 1957.

Surveillance Equipment:– Figure 7A-8 shows the YAGR equipment used for the detection and tracking of aircraft. The system consists of several operator stations and associated displays, coupled to a common electronic store. These include:

> Three detector stations normally assigned on each to ship's radar, AEW-1 and AEW-2.
>
> Six tracker stations that are manned in proportion to the traffic and may be allocated as needed among the various sources of video.
>
> One height-size-identity (HSI) station manned by two people and containing both PPI and RHI displays. This station operates only from ship's radar.
>
> Two HSI stations (one for each AEW) for setting into store the HSI data which is voice-told from the AEW.
>
> A track number tote board station for maintenance of the (grease pencil) board.
>
> A summary plot station for handling overlap data and for plotting miscellaneous data (e.g., weather). The air situation is automatically plotted.
>
> PPI stations for a CICO and an assistant.

Intercept Control:– The intercept control portion makes use of the SPA-22 (under development by Cornell Aeronautical Laboratory) and its associated controller-tracking

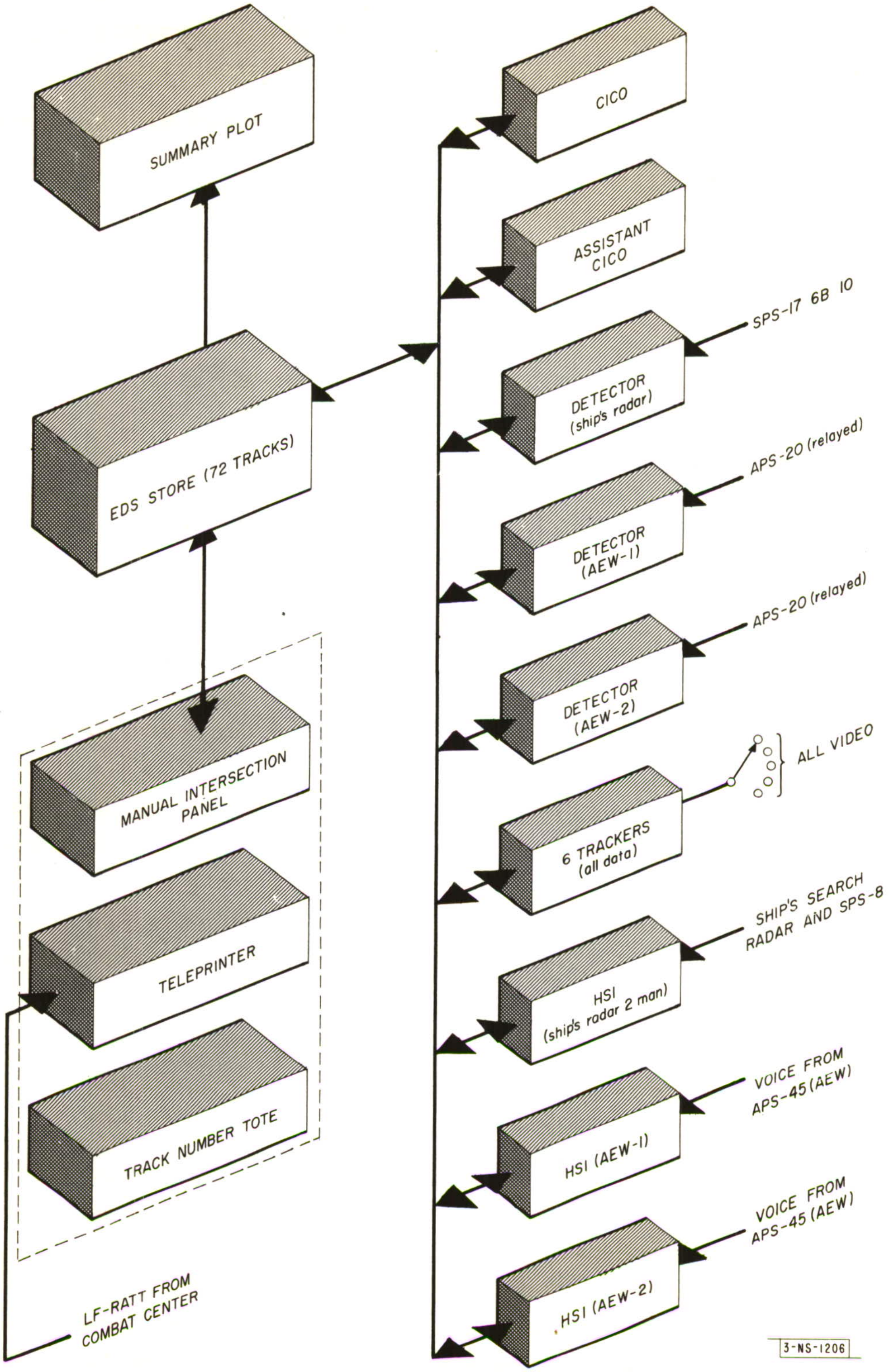

Fig.7A-8. Picket-ship surveillance equipment configuration.

stations. Each station is capable of handling 3 intercepts. Electronic target designation from the EDS store is employed to assist in track acquisition.

Data Flow Between Picket and Shore:– Figure 7A-9 illustrates the data flow between picket and shore.

Outgoing data are automatically taken from the EDS store, converted to digital form, and transmitted on the high-frequency RATT link. EDS stores are sampled in sequence, and the store numbers are implicit because of the sequential sampling. The following data are sent for each track:

Quantity	Teletype Code Groups
x	3
y	3
H	2
S	1
I	1
Address	1
Miscellaneous	1
	12

The time required to sample all stores is about 100 seconds, if all information is transmitted in each frame. Several schemes can be used (at the expense of added equipment) to increase the effective data rate by transmitting slowly changing quantities less frequently.

The address and miscellaneous digits listed above require explanation. The address digit is used to address track data to an adjacent picket when the track is approaching a region of overlapping radar coverage. Changing the address digit from zero will cause the track to be rebroadcast automatically from the shore station to the indicated picket. The miscellaneous digit is used to indicate a variety of useful things, such as target kill, return to base and track fade.

Incoming data are handled as shown in Fig. 7A-9. All information appearing on the low-frequency RATT broadcast is addressed, and each picket pays attention only to pertinent data.

Two teleprinters on the picket route incoming data to appropriate personnel. A teleprinter at the CICO station reproduces interceptor control plans. (see next section). A teleprinter or equivalent indicator at the summary plot station receives track number assignments. These are plotted on a grease pencil tote board which shows the track number – store number equivalence for targets of interest. Overlap data also appear on this teleprinter and are manually inserted into EDS store (whence they appear on a summary plot.

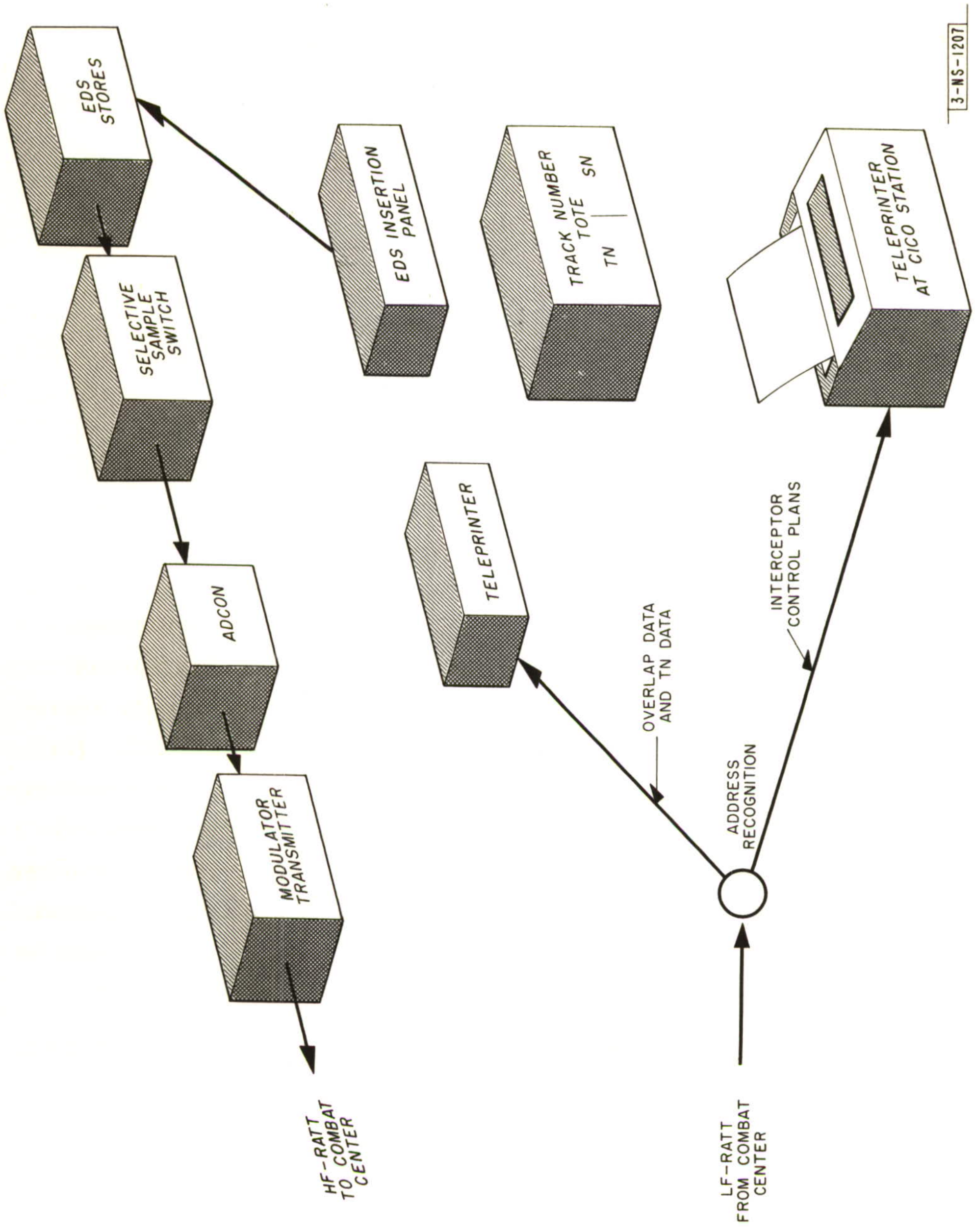

Fig. 7A-9. Digital data flow in picket ship.

Shore-Based Combat Center

Tasks :– The shore station performs the following tasks:

Receives up to 72 tracks from each of 10 pickets together with auxiliary information and ship's estimate of own position.

Retransmits all incoming data to the appropriate SAGE subsectors.

Translates from ship-centered coordinates to latitude and longitude; displays all or any chosen part of the targets for command and coordination of the area.

Automatically adds parallax correction and rebroadcasts tracks marked for handover from one picket to another.

Compares tracks with known flight plans and sends such additional information to pickets.

Sends summary or alarm information to various commands such as CONAD, CNO, CINCLANT and SAC.

Periodically receives coordinates of surface shipping and passes them on to the surface control center.

Possibly participates in assignment and direction of land-based interceptors to combat areas.

Computer:– The shore station equipment is built around a large general-purpose digital computer. A SAGE FSQ-7 or FSQ-8 is especially designed for this sort of operation. Until SAGE equipment can be obtained, either of two commercially available computers may be used: The IBM 704 or the ERA (Remington Rand) 1103. (In order to insure continuous operation, a spare computer would be required.) Commercial computers are designed to perform mathematical calculations at high speed, so that they can perform the required operations with ease. On the other hand, the large volume of input and output data will tax the machine. Equipment exists for input and output of data on teletype tape and for displays. A computer and accessories could be obtained within a year.

Inputs:– Figure 7A-10 shows the equipment for the shore station and the flow of data. Target data, received from the pickets, are punched on teletype tape. At intervals information, accumulated at slow speed on the tape, is transferred to the computer by the high-speed tape reader. It is estimated that this operation will occupy 12 per cent of the computer time. Flight plans and other information available at the shore station may be fed in on punched cards.

Displays:– A wide variety of displays is possible. For example, slides may be prepared by photographing a 7-inch Charactron, using a technique under development for

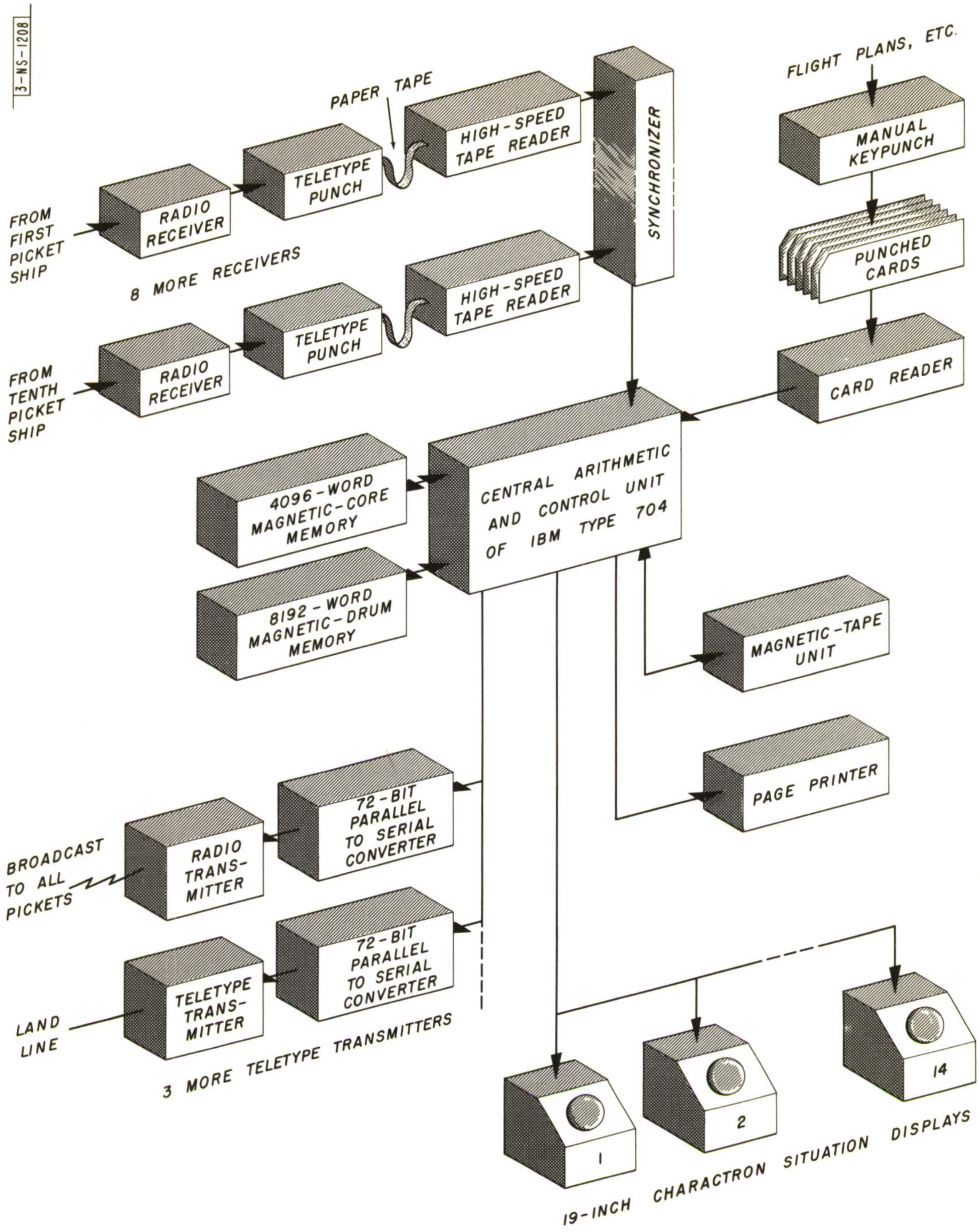

Fig.7A-10. Flow of data in shore-based combat center.

SAGE. Separate slides may be prepared for each picket in one minute and simultaneously projected on a map of the sea area. Alternatively, a number of 19-inch Charactrons may be used to display sectors. Convair makes such a display for use with this type of computer. Fourteen such displays can be painted with 72 targets each every 2 seconds in 5 per cent of the computer time. Possibly the SAGE display equipment could be used.

Calculations and Outputs:– Data from the pickets may be immediately relayed to the SAGE system or processed first in the shore computer. In the latter case, local store numbers could be changed to a set of track numbers, position data converted to latitude and longitude, and the code converted to the SAGE format and speed.

Tracks marked on the pickets for handover are given the offset of the receiving picket's position and fed out through a register. A storage unit accepts the messages at high speed and feeds them to the transmitter at low speed and interlaced in time with the other LF broadcast messages. Operators monitor the transfer of tracks and make sure that original track numbers are retained.

Surface data, which are received at a low rate, would be corrected to latitude and longitude and passed to the surface surveillance center. (It is possible that the same computer might be used for coordination of the surface data.) There would be other teletype outputs to CONAD, Naval commands, etc.

Periodic reports may be desired. Information for such reports may be stored on magnetic tape. Reports can be prepared by the machine and punched on cards or printed on forms.

Other Alternatives:– The concept of the Contiguous-Cover system went through many changes as it developed in Lamp Light discussions. One of the working papers on which this section is based describes a shore station equipped with Mink projectors, and another, written by R. Hulsizer, describes both ship and shore installations using Mink equipment.

PHASE 2 – RESEARCH AND DEVELOPMENT

It is unfortunate that both a short-term analogue program and a long-term digital program are required, since there will be a tendency to favor one or the other or to let them interfere. If there were any conceivable way to obtain the high-performance equipment at an early date, certainly the Phase 1 proposals would have been abandoned. However, this appears impossible and the urgent need for data processing equipment demands that both Phase 1 and Phase 2 programs be executed without hesitation.

The Phase 2 program can be carried out in a reasonable time only if it is given a high priority and if basic decisions are made as speedily as possible. A number of decisions can be made now on the basis of available information. Others require further work. We have proposed that the Datar system be chosen as the starting point. We have tried to define the problems which remain to be solved and to determine how and when the answers should be obtained. This may be visualized as proceeding in two parallel columns. In one is the prototype development program which is primarily concerned with engineering a Datar type of system. In the other column is the research program, which has a well-defined schedule. In some cases the research program may prove that features of the prototype development are sound. In other cases the research program may find that a different approach will give much higher performance. Such developments of the research program are peeled off and incorporated in the production design. Perhaps the most difficult factor in the prototype design is the requirement that it be able to incorporate modifications suggested by the research.

As an illustration, rate-aided manual tracking is to be employed in the Canadian Datar prototype. Automatic tracking is under development at both the Lincoln and Control Systems Laboratory. The original design must be such that these automatic developments may be incorporated by changing certain arithmetic units and subassemblies, but without requiring major modification of the central store-computer racks or the tracking consoles (which are required in the automatic case for "video mapping" and supervision). We have tried to list the major problems of this type in Section V of Chapter 7.

Another device, which is necessary to speed the development, is to program tests of the different components so that designs may be accepted for production piece by piece, as rapidly as possible. It is entirely possible to test digital storage equipment with the EDS input and output equipment which should be available in the Fleet in 1957 or 1958.

Most important for the success of the whole program is the administrative structure. The lines of responsibility should be simple and clearly defined. Expert advice must be available to evaluate progress at regular intervals, with authority to make decisions as soon as adequate information is at hand.

The Cosmos, SAAICS and Cornfield projects have been administered through different offices and bureaus. There has been little coordination of effort or exchange of information. A similar situation has obtained with respect to the EDS, Mink and Rafax intership data link (last item not described in this report), projects of interest for Phase 1. A single code in BuShips must have clear responsibility for all aspects of the Navy data-processing program – Phase 1, Phase 2 and data links. This does not imply that all contracts should be issued from the same office, but that one office should know exactly what is happening and have a voice in how everything is to be done. Nor would such centralization of authority relieve the Office of Naval Research of its responsibility for coordinating activities in this field.

We would suggest two types of committee activities: one concerned with exchange of information and coordination of activities at the level of the working engineer, and the other concerned with evaluation of the program and the making of decisions at a high level.

The Project Lamp Light Data Processing group held a three-day meeting with technical representatives from CSL, Lincoln Laboratory, Ferranti and BTL and with contracting engineers from the Canadian and U. S. Navy agencies. This meeting was very useful for the exchange of information and made a start toward achieving a common approach. Such information meetings should be held at regular intervals.

There should also be a steering committee to guide the responsible naval officers. Some members of this committee would be drawn from Navy bureau personnel, from NRL and NEL. Some of the members should be outside experts. This committee should meet at frequent intervals to receive reports on the program and to make recommendations on the decisions discussed above, on change in emphasis or on priority.

Finally, we believe that the responsibility must also be clearly defined at the contractor level. Here the Phase 1, Phase 2 and data-link fields may be considered separately, but in each case the Navy should deal directly with one prime contractor, or at least with a small and definite group of individuals who will insure that no piece of equipment is forgotten, and that the different boxes conform to a common design.

PHASE 2
AEW EQUIPMENT

In the recommendations for data-processing equipment for AEW aircraft, it has been assumed that a moderately high level of performance could be obtained by making use of compact digital and analogue techniques;

that the video could be converted to "fine-grain data" (FGD) for transmission to the surface on a narrow-bandwidth data link by a comparatively small unit with quartz delay lines, and that relatively simple analogue or digital computer facilities would provide capacity for directing 8 to 10 simultaneous air intercepts. It is worth noting than a more sophisticated approach, not recommended at this time, has been proposed by N. Rochester.

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APPENDIX 7-B
ALTERNATIVE PROPOSAL FOR PHASE 2
SEAWARD EXTENSION OF CONTIGUOUS COVER

This appendix describes a direct extension seaward of the type of apparatus and organization used in the SAGE System. This system would yield a more effective data-gathering and control capability but, after considerable review in Lamp Light, it was rejected because of its greater expense and because it is less compatible with the data system recommended by Lamp Light for fleet air defense. It is reported here because it represents quite closely a view held by some of the people concerned with SAGE and will no doubt be the subject of some subsequent discussion.

INTRODUCTION

To counter the threat of large masses of bombers attacking the northeastern United States from over the Atlantic, it will be necessary to extend the area of efficient control of interception well out over the ocean. This appendix describes such an extension of the SAGE System. The key elements of this extension are picket ships which would perform the function of SAGE direction centers and act as radar platforms. AEW aircraft would provide low-altitude radar cover and transmit radar data to the picket ships. A shore station would receive filtered data from the picket ships, provide over-all control, over-all threat evaluation, and weapons assignment.

PHASE 1

The Phase 1 data-processing system is proposed to follow interim measures for the 1957-58 period (see Chapter 7). These interim measures are briefly:

Provision of an area of contiguous radar cover reaching 1000 miles or so seaward.

The quality and quantity of data relayed to shore would be adequate for warning and weapons assignment but not for intercept control.

Provision of some degree of intercept control by means of analogue intercept computers in the picket ships, and purely manual intercept-control facilities in the AEW.

PHASE 2

The 1960-61 system would provide:

Picket ships to act as combined direction centers and radar platforms. They would have general-purpose stored-program computers like the AN/FSQ-7 but transistorized and ruggedized for shipboard installation. These would include an extensive array of display consoles but not quite so many as an FSQ-7.

AEW aircraft for low-altitude cover. These would be provided with efficient data compressors like the Fine Grain Data system of Lincoln Laboratory, or the "Data Processor" of Control Systems Laboratory, but with certain improvements needed for airborne operation with less manual aid. The 10-cm radar of the 1957-58 period would be replaced with UHF (or possibly L-band) radar to reduce the effect of sea clutter. Thus they would provide a larger rate of flow of more precise data, and would make it possible for the picket ships to control interceptions on the basis of AEW radar data.

Communication to shore made more reliable by the use of JANET (meteor) links.

Shore stations which would be installations like an AN/FSQ-8, and would perform a function analogous to that of a combat center of the SAGE System. The chief difference would be that the shore station would not allocate the long- and medium-range fighters to the pickets on a day-by-day basis but only on the basis of single missions.

AEW

For airborne early warning, the CL-257, which is the large-wing Super Constellation, would be used because of its ability to carry a heavier load a longer distance at higher altitude.

It would contain a UHF search radar to replace the APS-20B 10-cm radar, in order to reduce the sea return. (Because of sea return, the APS-20B must be flown at about 2500 feet, and thus cannot provide much low-altitude cover.) The UHF radar should be able to fly at 20,000 feet without serious sea-return difficulties and thus see low-altitude targets out to a range of 170 miles and targets at 3400 feet to ranges of 240 miles.

The larger (35-foot) antenna which the CL-257 aircraft can carry would provide a 4.5° azimuthal beamwidth.

If an L-band search radar is developed, and if its performance with respect to sea return is satisfactory, it could be used instead of the UHF radar. The beamwidth of this could be about 1.2°, hence it would be better for controlling interceptions if the sea return were not a problem.

One of the most important functions of the AEW aircraft is to make possible low-altitude surveillance and intercept control. The larger radars on the picket ships would probably be used for most high-altitude work because the communication problems are not so severe. Therefore, the worsening of beamwidth that results from the change from 10-cm radar to UHF radar is more than compensated for, even in running interceptions, by the improved low-altitude cover.

One of the major shortcomings of the present AEW aircraft is that the APS-45 height finder is neither sufficiently accurate nor does it have sufficient range. There appears to be a possibility of using the vertical lobes of the UHF radar to determine the height of aircraft. If this promise is fulfilled, there will not only be a saving of one radar set but also improved height-finding performance.

In this improved system, the normal function of the AEW aircraft is to collect radar data and transmit it to the picket ships which would do the tracking and control the interceptions. Therefore, very high-quality radar data must be transmitted from the aircraft. Unless some special measures are taken, high-quality data means wide bandwidths. Unfortunately, wide communication bandwidths are unlikely to be available, so that it will be necessary to partially process the data to compress its bandwidth before transmitting it.

A method of compressing the bandwidth without destroying the resolution of the radar data has been developed for the SAGE System and other applications. The principle is to transmit the range and bearing of each target instead of transmitting whether or not there is signal at each possible place where there might be a signal. (The reason that this results in bandwidth compression is that there are few signals compared to the total area of radar cover. Another way of saying this is that there is much more black than white in a radar picture from which most clutter has been removed and each significant target has been compressed to a single spot.) In the SAGE System, the method used is the Fine Grain Data (FGD) system which is attached to each long-range radar.

There are certain problems that remain to be solved before such a bandwidth-compressing device would be practical in an aircraft. At present, it is necessary to have a video-mapping operator to filter the radar data before it goes to the bandwidth-compressing unit. The job of this man would become difficult if not impossible in an airborne radar. Furthermore, in an aircraft it is too costly in weight and space to furnish such a man. However, it appears that certain improvements can be made in the equipment which would eliminate enough of the clutter from AEW radar over the ocean. This would prevent saturation of the bandwidth-compressing unit with irrelevant signals. It would still be necessary to retain an operator for the bandwidth-compressing unit, but his task would be mainly monitoring the performance of the equipment and he would also assist it to distinguish between signals and clutter.

Another problem is the size of the equipment. While it could be put in an aircraft (after merely being redesigned to withstand vibration), it would occupy as much space as three radar operators and their indicators. By changing from vacuum tubes to transistors, the equipment would be reduced to a size equal to that occupied by only one radar operator and his indicator. This would be practical because it would give the aircraft a very greatly increased capability to report radar data to the surface without seriously impairing its ability to control interceptions.

An AEW aircraft so equipped would be able to transmit the coordinates of 1000 targets to the picket ship in one 10-second scan. It would be possible for the AEW to transmit the coordinates of every plane in a 500-plane raid if the aircraft were deployed so that the radar could resolve them.

This performance can be compared with what can be achieved by manual or rate-aided manual tracking. The number of targets that a man can track is surely not more than 6, and even this has not yet been achieved except under special simplified conditions. If one of four operators does detection, then three are left to do tracking. Not more than 18 targets at the very most could be tracked, and it is doubtful if this could be achieved.

Another alternative is to transmit the radar data to the ship by means of Rayfax or SDV. These equipments are not so complex as FGD, but the radar data are rather seriously degraded. Probably the degradation is too great and would significantly reduce the probability of successful intercepts.

AIR-TO-SURFACE LINK

The basic high-data-rate link is a 2000-bit-per-second channel for transmitting the search-radar data to the picket ship. The UHF radar will have a range performance of 250 to 300 miles on high-altitude aircraft. Therefore the air-to-ground link should also have this range. High-frequency polarized ground wave will be satisfactory here.

Since the AEW aircraft can be used at 20,000 feet, UHF line-of-sight communication will work out to 170 miles and would be usable for certain deployments. One of the several possibilities that this opens up is the use of Centipede (see Chapter 6). Another is the transmission of raw video to the picket.

An additional communication need is for the height finder. The picket would have to interrogate the AEW height finder. This could be done by transmitting a digital specification for a range and azimuth gate to the AEW aircraft. The height finder would then determine the height of the target within the gate and transmit this back to the ship. This would be a very low data-rate requirement and hence would not be a serious problem.

The high-frequency equipment used for the medium-range data link (just beyond line-of-sight) on the ground wave could also be used for aircraft-to-shore communication via the sky wave. This would be a CW (or possibly teletype) link and would be essential if the picket ship were sunk by the enemy.

PICKET SHIP

The picket ship would contain a general-purpose digital computer and displays like those in the FSQ-7 in the SAGE subsector (i. e., in a direction center). Since there would be much less complex air traffic, and since there would be fewer radar inputs, not so many people would be required to operate it. Furthermore, the equipment would be reduced in volume and power dissipation by the use of transistors. In this way, the equipment would become suitable for shipboard installation.

The primary reason for using a general-purpose digital computer with a stored program, rather than a special-purpose computer, is to achieve flexibility. Jamming provides an example of the necessity of flexibility. It now looks as if it is really going to be necessary for a tracking computer to be able to track with radar data as long as radar data are available and then, when the enemy begins jamming, to change to a new program to do the best possible job of sorting out cross-bearings on jammers. A stored-program machine is sufficiently adaptable to make this or even greater transitions, while a special-purpose machine is not. We can expect surprises from time to time either as a result of technological developments or from intelligence leaks, and stored-program computers will minimize the equipment changes needed to adapt to the new problem.

A secondary reason for using stored-program computers is that they are the least complex possible equipment for very complex jobs. The reason for this is that the stored program can be exceedingly complex, much more complex than the machine itself, and it never gets out of order. There is a threshold complexity, and below this threshold, for simple jobs, the special purpose machine is simpler. On the other hand, jobs that are more complex than the threshold can be more simply mechanized with a stored-program machine.

A third great advantage of a stored-program computer lies in maintenance. Modern computers of this sort are maintained by the combination of marginal checking and diagnostic programs. These techniques allow the great power of the computer itself to be brought to bear on the problem of trouble location. Special-purpose computers must either have elaborate built-in test equipment or be really archaic and require that all troubles be located by maintenance personnel. It is particularly important at sea to reduce the demands that the system makes upon the maintenance force.

Because the computer would have to deal with data from moving radars, it would have to deal at times in relative coordinates in order to achieve the precision needed for intercept control. This would complicate the computing problem. At other times, it would have to engage in additional calculations to reconcile data from radars whose location or orientation was poorly known. These difficulties would compensate for the fact that otherwise the computing problem would be easier. A computer with about the same arithmetic capacity as an FSQ-7 would be needed.

The size of the installation can be estimated by scaling from the present FSQ-7 which requires 150 × 150 feet area for the computer and the same space for the indicators and a staff of about 150 people. Such an installation can manage 400 tracks, 200 interceptions, and a vast coordination job with other shore-based facilities.

If the capacity of an ocean direction center were cut to 300 tracks and 150 interceptions, and if the miscellaneous coordination facilities were cut to 40 per cent, the personnel would be halved. This would mean battle stations for about 75 men which would occupy about 5000 ft^2. This can be reconciled with the 22,500 ft^2 used in the SAGE direction center by considering that the number of men has been halved, and the rest of the compression achieved by moving the indicators closer together and reducing the aisle area.

The computer of the ocean direction center would need to have the full capability of the FSQ-7, although the speed would be employed differently. Therefore the compression could be achieved only by transistorizing and moving the equipments closer together. The equipment would fit in about 5000 ft^2. It should be remembered that this allows two of the full computers of the duplex system. A single computer could fit into about 2500 ft^2.

SURFACE-TO-SURFACE COMMUNICATIONS

If the JANET System fulfills its promise and is available by 1960-61 for shipboard installation, it would probably be more reliable and surely more secure than high frequency. It would probably be used for relaying data from the picket ships to shore.

Cross-telling of track data from picket ship to picket ship would be done by addressing a message to another ship and sending it to shore whence it would be retransmitted to the other ship. JANET can easily be arranged to provide simultaneous two-directional communication and could be used for the shore-to-ship messages. However, shore-to-ship communication by means of a low-frequency broadcast with messages addressed to individual ships requires simpler terminal equipment and is probably better.

Probably some extra JANET equipment should be provided on the ships in order to make possible some direct communication between ships. This would provide for an emergency net in case the shore station were destroyed.

High-frequency ionospheric scatter also promises to yield a satisfactory link. The importance of communication is such that it might be desirable to provide both ionospheric scatter and JANET links so that jamming would be more difficult.

The regular mode of communication should be teletype. Unless there is a sufficient improvement in reliability and jamming resistance of teletype, there should also be radio operators with the capability of using CW. At present, CW can frequently get through when teletype cannot.

SHORE STATION AND CONNECTION TO SAGE

The shore station would have an installation like the FSQ-8 of a regular SAGE sector headquarters. Just how it would operate and what responsibilities it would have would depend upon whether the contiguous area of the Atlantic Ocean were incorporated into the Eastern Air Defense Force or set up as a separate command under CONAD. The function of this installation would be to furnish weapons to the picket ships and to provide over-all control.

SUMMARY

The data-handling system described in this Appendix provides a continuation of SAGE surveillance and weapons direction 1000 miles or so out to sea. The basic elements of the system are picket ships. Each of these acts as a direction center like the direction centers on land, and also serves as a radar platform. AEW aircraft provide a function equivalent to the gap-filler radars on shore and transmit low-altitude radar data to the picket ships. A shore station coordinates the picket ships, and carries out a function similar to that of the combat centers of the SAGE System on land.

N. Rochester

APPENDIX 7-C
NAVIGATION

INTRODUCTION

The investigation of the available navigation equipments and methods, in relation to the requirements for systems considered by Project Lamp Light, has shown certain deficiencies, which have come to light primarily because we have looked at the problem from a systems viewpoint. This approach has been recognized as the proper one by the Services and present procurement is on this basis. Extending this idea further, we have tried to develop some diversity to give reliability in the face of enemy countermeasures. Equipment of existing aircraft is not on this basis.

The problem of navigation is the determination of position, course and speed, and, in the case of aircraft, altitude. Determination of these for enemy aircraft is covered in the radar chapters.

General

AIR NAVIGATION

The problems associated with the navigation of commercial, AEW, and interceptor aircraft have much in common, so these general points of similarity will be covered, followed by details related to the specialized aircraft use.

For successful determination of position, it is necessary to have available and to use several different systems, one system or a certain combination of methods being best under a given set of circumstances. Visual correlation between ground and map is obvious but not necessarily easy, especially in unfamiliar areas; it is often extremely difficult in areas such as central and northern Canada. Associated with this method is the correlation of radar displays with maps. There is available the APQT type trainer which could be used very effectively for training aircrew for both visual and radar navigation. These units were designed for SAC but have much wider possibilities.

Under blind-flying conditions, the only way to obtain a fix is by electronic means. A variety of these has developed, but the one with the greatest coverage at present is Loran. Another hyperbolic system, DECCA, covers western Europe and can be considered equal to Loran but not compatible. Within the United States, coverage is fairly good with Omnirange DME. The U.S. Navy is now installing TACAN, a system similar to but not compatible with Omni-DME, on its ships and at a chain of shore stations around the country.

These aids are very fine in the areas of coverage and during good reception, but unfortunately they are most needed when reception is very bad and when the aircraft has wandered over the edge of the coverage. Furthermore, these aids are very susceptible to a variety of enemy jamming techniques and can be jammed inadvertently by our own emanations. These remarks are equally true for radio compasses and aid from ground radars. For limited lengths of time, electronic methods may not work.

When electronic aids are inoperative, accurate navigation depends on excellent dead reckoning. A full-time navigator can do this, but it is very unlikely that, under operational conditions, a navigator's other duties will allow him to spend the whole time on dead reckoning. Since the order of accuracy required for carrying out identification procedures, data processing and aircraft control is high, and time lags must be avoided, all these aircraft need automatic navigation computers which will perform continuous dead reckoning and accept electronic position data for correction of position and drift. With such computers, it will be possible to maintain good position information even though a fix with an electronic navigational system can be obtained only occasionally, such as once every half-hour. It is hard to believe the enemy could keep Loran, Decca, Tacan or VOR jammed solid for this long if the navigator is free to monitor his equipment or it is on continuous automatic search.

Astro-navigation is a necessary check system on long flights and a faithful crutch in the event of system failure or aircraft damage that disables the electronic systems and navigation computer. While much has been done to simplify astro computations for a fix, a fighter pilot could well use a special one-sheet table good for close return to his home base with an accuracy of ±20 miles. The sextant should be operable one-handed, since the autopilot might not be working under these circumstances.

AEW and Commercial Aircraft

Using Loran and feeding the information from the receiver directly into an auto-correcting navigation computer, it should be possible to know position under very adverse circumstances, whether jammed or maneuvering, to a maximum error of ±5 miles when 1000 miles off the North American coast. At 400 miles, this error would be less than ±2.5 miles. This would always be checked by radar fixes and astro sights where possible.

Interceptors

The navigation computer can smooth the Tacan data and give better information to the pilot than a direct-reading system. Operating on broadcast control, it should be possible to work right down to sea level with confidence that the maximum error would be ±2 miles even out to 200 miles. Further, over land the gaps in coverage would not give the trouble they now do.

Close control of interception takes the navigation duty away from the pilot. The only restriction put on the ground intercept controller is that the final intercept should be directed from the same radar that is tracking the enemy. This precludes errors entering the intercepting problem as a result of slant height, parallax, and lack of register.

Electronic Aids to Navigation

Loran is the system with the best world coverage. For this reason, it is of prime importance and an earnest effort should be made to incorporate the latest in techniques, procedures, and maintenance to increase its present accuracy. Furthermore, provision must be made to code the system by changing delays on a scheduled basis so that this system cannot be used by the enemy. (We cannot turn it off, because we are dependent on it.) This coding needs to be developed, and the distribution of the key must be planned for maximum use commensurate with real security. Such a security system is a basic requirement for all long-range electronic navigation aids and desirable on short-range systems.

Navigation Computer

There are under development and in production a variety of navigation computers. Some operate with rectangular coordinates, some with polar coordinates, and others with latitude and longitude. The best coordinate system is a function of the problem and is outside the scope of this review. Any computer should be provided with electronic information insertion for correction of speed and drift from last position and memory for computation of future position. All the current computers except one employ analogue techniques which were satisfactory for the quality of input data formerly available; but, with the new speed-measuring devices, the input data are more accurate than the computer. Further development of digital computers for this duty should be encouraged. Furthermore, the cost of analogue computers is very high and cannot be reduced in quantity production as easily as can digital computers.

Speed Measurement

Speed-measuring devices using ram pressure are inaccurate and cannot be greatly improved with the wide ranges of air density and speeds over which they are required to operate. Even in short-time navigation, their use gives only fair results. Doppler speed-measuring schemes are now available with accuracies of better than 0.2 per cent (APN-81). The present weight of this unit is 300 pounds, but a miniature version has been proposed, as have several other types with accuracies better than this for a weight of less than 150 pounds. Doppler speed measurement makes dead reckoning very reliable due to its high accuracy and ability to resolve the drift component. Certainly for AEW aircraft the miniature version is a very practical device. In the areas not covered by electronic navigational systems, this sort of equipment is necessary for interceptors. Fighters operating in northern Canada and out over the ice need such equipment until beacons are installed.

Inertial speed-measuring devices have not achieved the accuracy of the Doppler systems, nor does it appear that they will do so in the near future if restricted to equal weight. It is possible to build an inertial system within these weights with an accumulated error of one mile in 15 minutes or on a percentage basis of 0.5 per cent. The care required in constructing and maintaining inertial equipment of this accuracy is considerably greater than in the case of the Doppler radar equipment. For these reasons, it appears that the Doppler systems have the most promise for service in AEW and interceptor aircraft in the near future.

Altitude Measurement

For determination of altitude, present aneroid instruments are quite good and, for more accurate information, existing radio altimeters have given reliable service. This is an area where present performance and the developments of the immediate future meet projected requirements.

Course Determination

There are available several good J-4 type magnetically slaved gyro compasses. These are very reliable and, below 70° north latitude, are reasonably accurate. As navigation computers improve, better compass inputs will be necessary. There is under development (for the APN-79) an airborne, north-seeking gyro which should fill this need if it meets its design accuracy of 0.4°. Low-drift free gyros hold good promise for the near future, especially when used with a navigation computer with accurate speed inputs, for then a position fix allows correction of directional errors.

Above 70° north latitude, continuous direction information can be secured only from free gyros. The J-4 type gyros operating free have given good results and can be corrected from sun or star bearings. Beacons at some of the radar stations will be necessary if continuous patrols are to be maintained or if the northern radar chain is to be air-supplied throughout the year.

Meteorology

Before any flight is undertaken, the crew always makes a detailed study of the weather, because the success of the whole operation may depend on how the flight can take advantage of or overcome the weather. Detailed knowledge of winds can confirm the satisfactory operation of computers and speed-measuring equipments.

Knowledge of pressure patterns and winds will help with the identification of commercial and long-range flights. Taking advantage of the available winds gives average range improvement of 15 per cent, and this can often be as high as 35 per cent. Obviously, commercial traffic will be found in the areas of advantageous winds. Similarly, there will be preferred paths for attacking aircraft so that the direction of threat can be predicted. This also means that a direct great circle route to a given spot is not generally the quickest and most economical route. What looks like a transpolar attack on Kansas City may be an attack on Chicago by the quickest route and this possibility would be quite apparent to a meteorologist.

Position

SHIP NAVIGATION

For offshore picket ships, position can be determined with an accuracy of ±1 n. mi. This order of accuracy is undoubtedly quite satisfactory. Present equipment and methods can do this with the exercise of diligence and care.

Bearing Reference

For correlation of radar data, a good continuous bearing reference is required. There are grave doubts that existing gyro compasses are accurate enough for this duty. The gyro and computer art has advanced so far in the last 10 years that there are now no known technical reasons why gyro compasses cannot be built good to 0.5° even during maneuvers. This minimum accuracy is required if ship data are to be absorbed into data-handling links accurately and quickly.

W.T. Buhl

APPENDIX 7-D

SHIP STABILIZATION

There are three ways to stabilize radar information, i.e., stabilize the antennae physically, stabilize the information electronically, or stabilize the ship. To note first the disadvantages of each: antenna stabilization increases weight aloft by several times and leads to mechanical troubles due to lateral accelerations, etc.; electronic stabilization of the information does not overcome the problems due to losing information completely when the antenna does not see the target; ship stabilization cannot be made complete without causing unacceptable structural stress and discomfort to personnel.

It has been general practice in the past to provide physical stabilization of each separate piece of equipment that required it. Thus we find, in one ship, separate stabilization systems (with their accompanying heavy machinery and motors) for fire-control directors and radars, guns, height-finding radars, sonar transducers and A/S weapons systems. With all this complexity, nothing has been done to increase personnel efficiency and comfort or to take the strain off other kinds of equipment.

This deficiency has long been recognized and trials have been carried out with various types of ship stabilization systems. Three main types have been investigated:

> Gyro stabilization, in which a large flywheel is so coupled to the ship's structure as to resist the rolling moment. Tried by the Italians in SS Conte di Savoia, it made the ship so stiff that structural damage resulted (not to mention loss of crockery) and she was extremely uncomfortable.
>
> Stabilization by transfer of water ballast in synchronism with roll. This requires very heavy machinery and large ballast tanks. It is, literally, sloppy, and is not at all popular with seamen.
>
> Fin stabilization employs the same principle as ailerons in aircraft. This has proven very successful in cargo and passenger vessels, and in "Bird" class sloops of the Royal Navy, which are ships some 300 feet in length and 2000 tons displacement. According to literature on the subject, the decrease in angle of roll for speeds between 14 and 19 knots is approximately 20°, even under very unfavorable weather conditions. The gear is available, being built by Denny-Brown in the United Kingdom, and has recently been fitted in HMCS Labrador, the new RCN icebreaker.

It would appear that a combination of ship stabilization and electronic stabilization would produce very satisfactory results, since not only would information be correct but a far steadier platform for purposes such as gunnery would be provided, and personnel comfort and efficiency would be greatly increased.

Further action should be taken to try various combinations of stabilization methods, with a particular view to stabilizing the ship to the greatest practical extent.

D.L. Hanington

CHAPTER 8

IDENTIFICATION

CHAPTER 8

IDENTIFICATION

GENERAL IDENTIFICATION PROBLEMS

Efficient defense against air attack is dependent upon highly reliable identification. A satisfactory level of effectiveness can be reached in the identification of friend or foe by utilizing a variety of methods appropriate to the circumstances, provided an adequate detection system exists.

While the defense of the North American continent is the subject of this discussion, the techniques apply in general to any contiguously defended area. The defended area is considered to be the land mass plus the overwater extension so far as contiguous detection and tracking is possible. During an armed peace or cold-war situation, detection and identification or warning serves just one purpose: to indicate the possibility of an enemy raid. A typical indication is unusual activity of possible enemy planes. Since such planes may consist essentially of unknowns, it is important to keep to a minimum the number of unknowns in order to detect the least absolute variation from the normal.

When activity indicates a possible raid, decisions must be made. Closely, related to identification is determination of intent. It is not necessary to know that the intent is hostile before constructive decisions and actions can be taken. Various degrees of alertness may be initiated – interceptors may be dispatched to be on hand to accompany questionable planes, and to take action as later required.

After war starts, and this may be as soon as determination is made that an enemy raid is on its way, the identification problem expands immediately to all defensive and offensive units – the interceptors, the strategic and tactical planes, the antiaircraft weapons. To simplify the whole problem, all commercial and private air traffic should be grounded before the raid is expected to appear in the combat area. Normal traffic can be maintained in unaffected areas and resumed under control in the combat area as soon as it is cleared.

Identification Techniques

Electronic IFF systems have been used since the early days of World War II. These systems have been of the transponder beacon type with some limited amount of coding. They are subject to use by an enemy wishing to appear as a friend. Their major usefulness has been in providing improved detection and tracking of friendlies and in determining the specific friendly through use of the codes provided. While an aid to identification, they are not compatible with the short times available for identification with modern high-speed military targets. A system must be provided that will be positive in indicating a friend when the proper signal is received even though the enemy possesses our equipment. Security against deception of such a system must be placed in a key which is used for a period of time and is kept secure from the enemy. Transmission of the key must be by cryptographic channels and its security should be as good as these channels. Use of such a system is therefore confined to the military services. The equipment should be designed to permit the key to be set in at least two parts by different individuals.

Nonmilitary planes, unable to use the electronic system for security reasons, must be identified by other means. The best possible identification method is to keep track of all friends from takeoff to landing. Such a system has limited traffic capacity and is likely to become confused with the uncontrolled high-speed flights of military operation. It is applicable, however, to commercial aircraft and, to a lesser extent, to private planes flying in areas where surveillance can be maintained. This system is in operation within the continental boundaries and appears to be satisfactory. The country is divided into identification zones. Unauthorized crossings of the boundaries between these zones are investigated by fighter scramble. This system is particularly applicable during peacetime. If war is initiated, such traffic must be first grounded and then rigidly controlled.

Another type of situation arises with commercial planes entering our surveillance area from overseas. Since continuous tracking is impossible, a system for identifying such planes at our surveillance boundaries is necessary. A proposed system is described in the following section. Experiments have been conducted by the Air Defense Command, using procedures similar to those described. If the proposed electronic aids are provided and an adequate administration is set up for carrying out the plan, it should be highly efficient. Because it requires extensive cooperation there must be a realization of its importance and a determined will to make it work. Its importance can not be overstressed for the cold-war period since it is this system that makes early warning useful by giving a sensitive indication of a possible hostile raid even of small dimensions. This could be the means of preventing a serious crippling blow. Use of the CAA safety beacon on all commercial planes will not only improve safety but will materially extend the detection range on incoming planes.

These identification techniques cover the various air defense situations: electronic systems for military aircraft, code-word identification system for overseas scheduled aircraft, and continuous surveillance within our continental and coastal boundaries. There are, however, some special problems that will be discussed.

Antiaircraft Weapons

Antiaircraft guns and surface-to-air missile control stations are located to protect specific targets. If they are to be used, rapid decision to fire must be made. At the discretion of the Air Defense Commander, these weapons must be free to fire on any plane during wartime unless it shows electronic IFF (secure system assumed). No hesitancy must exist because of a possibility of a friendly plane's appearing with inoperative IFF.

Air-to-Air Identification

A technical problem exists in providing adequate IFF for interceptor-to-interceptor identification. Provision of directivity to give azimuth correlation between the IFF and radar is under active investigation by the military services. Utilization of pulse-train codes encounters multipath problems because of ground reflection. Positive correlation between the IFF and radar signals may be provided by a simple beacon system, but such a system is subject to deception by the enemy using similar beacons. It appears that, for the interceptor under close control, responsibility for security could be placed on the surface-to-air system at the surface site. The interceptor would thus be advised if the target were using a beacon. Though extra equipment would be needed at the surface site, airborne equipment would be simplified. A long-term research program toward a secure system for air-to-air identification is needed. Air-to-air IFF is particularly important for broadcast control of interceptors, which may become necessary in the event of a large concentrated raid.

Unauthorized Interrogation

The existing electronic systems may be interrogated by an enemy. Such interrogation provides an enemy with positive identification of our planes, provides extended detection through the beacon facility, and furnishes a signal that could be used by a homing missile. All these may be countered by turning off the transponder. In fact, this may be a satisfactory doctrine over certain enemy areas where the first two uses may be most useful to the enemy. The use by a homing missile might occur in any place. It is true that other electronic radiations on which the enemy missile may home will also be available. However, for the near term simple provisions can be made to lessen the possibility of homing on the IFF. If the transponder transmitter is turned off, the missile is countered. Provision should be made on beacon systems that will allow the pilot to switch to interrupted operation in which the transmitter is on for times too short for the missile to acquire and complete its run, but is on long enough to provide identification service. An on-and-off time of about 20 seconds would appear reasonable for the surface-to-air system. This would insure identification during an entire antenna scan for most search radars. The air-to-air beacon system should be interrupted at a higher rate because of the short times permitted for identification.

A system that cannot be interrogated by an enemy is desirable, and research in this direction is recommended on a long-term basis. Appendix 8-A describes one possible approach to this problem.

Determination of Hostile Intent

The determination of possible hostile intent is not a part of identification but is closely related. This determination and the permissible action is set forth in the Rules of Engagement. These apply to the sovereign boundaries of the United States, the coastal air defense identification zones, and to self-defense of forces outside these areas.

The present coastal air defense identification zones extend in places for a few hundred miles from shore. It would appear that, as we extend the area of contiguous detection and tracking, these zones must be extended to encompass all areas in which we are capable of surveying and engaging targets.

In view of the increasing speeds of aircraft and greater use of missiles, careful consideration must be given to reduction of delays in decision to engage.

At sea during wartime, the Navy must take action against any aircraft acting in a hostile manner. In the past, this has resulted in destruction of some friendly aircraft when their identity was questionable. Adoption of the CAA safety beacon by all commercial planes will give friendly aircraft more protection by providing additional intelligence on which to arrive at a decision.

IDENTIFICATION OF SCHEDULED AIRCRAFT ARRIVING FROM OVERSEAS

Introduction

Aircraft approaching our shores from overseas customarily follow flight plans and operate on established schedules. This class of aircraft includes commerical planes of numerous countries and our military transports – totaling about 600 flights per day. These aircraft must cross a line formed by our early detection system; this line would also be crossed by a hostile raid. During the cold-war situation, warning of a hostile raid is a major concern. A very sensitive indication is a significant increase in unidentified air traffic approaching our boundaries. The fewer unknowns under normal conditions, the more sensitive this raid indication becomes. A small number of unknowns is permissible because we can afford to scramble fighters to take control of this situation. A large raid designed for high destruction could not be hidden in a limited number of unknowns. The level of permissible unknowns as a result of initial identification must be determined by balancing the effort in cost of equipment and administration between the identification system and the fighter scramble. A code-word system along the lines discussed by the Air Defense Command, with adequate electronic aids to simplify the operations, is proposed. The effectiveness of this system is dependent upon realization of its importance and upon the will to make it work.

Proposed Identification Method

The heart of the system lies in use of code words characteristic of each flight, with provisions to prevent an enemy from entering the system. Prior to takeoff from his last port before entering the defended area, each pilot is given a sealed envelope containing his code words. The envelope is numbered, and this number is transmitted as a part of his flight plan together with a beacon-code assignment. The detection sites that may intercept this flight receive the flight-plan information and have been furnished the code words associated with envelope numbers. When an aircraft is detected, interrogation of the beacon and reading of its reply code indicates the flight. Communication is established with this flight and it is interrogated with an interrogation code word; also, the pilot may be informed of his distance from the radar site. If the interrogation code word agrees with the one supplied in the envelope and the interrogation is made at predetermined distance, the pilot gives the reply code word. During this conversation, the radar operator obtains positive correlation between the plane and the radar position coordinates by observing that the beacon reply code changes to a predetermined code (I/P, identification of position) when the plane's transmitter is energized. Back-up procedures may be established by doctrine which requires check turns, further conversation with the pilot, and even diversion to an alternate airport if there is equipment or pilot failure.

Code Word Distribution

The code words must be made up in a central agency. A large number of words forming a master list are chosen which are easily understood and unlikely to be confused with each other. Multiple words are permissible. Sufficient sets are made up for each location where envelopes are to be distributed to take care of the expected traffic. The words are chosen at random, with care taken that no choices are repeated among those used over a 24-hour period. An interrogation and a reply code word are sealed in each envelope and the envelope numbered on the outside. The envelopes are marked for use on a specific date and only enough are supplied for the expected maximum number of flights. A reserve of envelopes may be provided for use only after all the regular envelopes have been assigned.

The local distribution of the envelopes to the pilots may be made by airlines individuals selected to be as trustworthy as possible. Special military officers need not be used except possibly at a few sites where high traffic exists. The dispersion of the envelopes provides against a material compromose. The organization should make it improbable for any one individual to come in possession of an appreciable number of envelopes. Even though the enemy obtains possession or knowledge of the envelope contents, he must adhere to expected flight schedules and correlate with filed flight plans.

Transponder Beacon

At the present time commercial aircraft do not carry a transponder beacon; however, a satisfactory design exists in the CAA safety beacon now undergoing evaluation. This set weighs 25 pounds and could be produced at the rate of 500 per month within a year. This beacon is interrogated by a double pulse on L-band and in fact responds to the IFF Mk X mode 3 interrogation. Its reply is a pulse train having the characteristics of the SIF modification to IFF Mk X. The design permits a maximum of 64 reply codes if selection switches are provided (at present only 10 codes are wired into the selector switch). The full number of codes is desired in order that flights arriving at any one entry point may be identified with a different code for up to a 24-hour period. One of these codes (all pulses present) is emitted whenever the communication transmitter is energized, regardless of the normal code setting. A circuit at the radar recognizes this code and produces a distinctive display on the radar indicator to identify the position of the communicating aircraft. In addition to aiding in the identification process, this beacon provides for extended detection range independent of the radar and assists in traffic control.

Navigation Requirements

The pilot should know his position to within about 10 miles when interrogated. This is necessary to prevent an enemy from substituting himself for the friendly plane by appearing ahead of the friendly plane with electronic equipment that will give the correct beacon reply, thereby inducing the code word interrogation which may be relayed to the friendly aircraft to induce the code word reply. All this can be done by radio relay. However, if the friendly pilot knows that he is not at the proper distance for interrogation, he does not give the code word reply. If he is within 10 miles of the interrogation position – and this position is always chosen to be 10 miles within radar detection range – the enemy can not succeed in this tactic. There remains the possibility of an enemy "attaching" himself to a friendly aircraft so that the two aircraft cannot be resolved by the radar. Friendly pilots should be instructed to be alert for such tactics.

Reliability

A high degree of reliability is to be expected when the administration of the system becomes routine. The only critical electronic equipment in the system is the radio communication, and this is given careful attention because of safety requirements. The beacon is only an aid that simplifies and speeds the process. If it fails, procedural turns may be requested to identify the plane's position. Another factor is pilot cooperation. The system should be made regulatory as far as possible and procedures should be designed to encourage cooperation.

CHAPTER 8 RECOMMENDATIONS

1. The present IFF system cannot be trusted to distinguish friend from foe. However, with new digital techniques, it is possible to develop cryptographic coding which would be practical for a secure system. We therefore recommend a program to provide military planes with such a system.

2. The identification of incoming commercial scheduled overseas flights, of particular importance during the cold war, can be satisfactorily accomplished with codeword techniques. To prevent an enemy from inducing the code reply from a plane and then substituting himself for it, the pilot should reply only when within about 10 miles of a predetermined position. We recommend study of the requirements that this procedure places on the navigation system.

3. Identification of overseas flights would be facilitated by use of the CAA safety beacon with the full 64 codes. This beacon would also be useful for extended radar tracking and safety of planes. We therefore recommend the use of this beacon with not less than 64 codes.

4. It is difficult to prevent an enemy from "attaching" himself to a friendly plane in such a manner that they cannot be resolved by search radars. Examination of the radar echo with an A-scope will assist. Also, improved all-around visual viewing would assist a pilot in preventing such a tactic as well as giving additional safety. We recommend development work toward these improvements.

5. We recommend increased effort on obtaining a satisfactory solution to the identification of interceptor by interceptor. Pending a solution of this problem, greater responsibility for identification will have to be placed on the surface organization that controls the interceptors.

6. To prevent unauthorized interrogation, we need the establishment of suitable doctrine for the use of the IFF on-off switch. For the near term, provisions are recommended by which, at the pilot's option, the IFF response can be interrupted in a manner to prevent a homing run by an enemy missile. For the long term, we recommend research toward new IFF systems that are not vulnerable to unauthorized interrogation.

APPENDIX TO CHAPTER 8

APPENDIX 8-A TIME-SYNCHRONIZED IFF

APPENDIX 8-A

TIME-SYNCHRONIZED IFF*

DESIRED PERFORMANCE

It has appeared that an electronic IFF should meet the following requirements if it is to be used on military aircraft during peacetime and if it is to be capable of being used in wartime, either to permit loose control of fighter aircraft against bomber targets or if it is to be used in close support of troops.

> The IFF reply, as simulated, mimicked or otherwise attempted by an enemy, should never appear friendly, even though the enemy were to have captured our equipment and were to have full knowledge of its use, and even though he were to throw interrogations at our IFF in large numbers. The security of the IFF should rest with one or more keys. Enemy aircraft equipped with listening gear and with methods of mimicking our replies should not be called friendly by the IFF so long as these planes are located at a distance greater than some minimum resolvable amount from friendly aircraft.
>
> The IFF should not aid a guided missile or interceptor toward homing on a friendly aircraft by enemy-elicited IFF responses.
>
> The IFF should be spatially as selective as possible so as to treat individual targets rather than groups of targets, in order to accommodate proper identification in high traffic density.
>
> The key that permits a friendly reply should be capable of being split into more than one part, and the several parts of the key should be capable of being handled by two or more individuals, so that defection of one individual could never cause compromise of the entire system.
>
> The IFF should be simple, light-weight, reliable, and integratable with radar and communications systems.

OPERATING PRINCIPLE

The IFF to be described achieves its desirable performance in part because a received question will be called friendly only if two conditions are fulfilled simultaneously. One condition is that the received question must arrive at any one of a number of discrete time intervals. The other condition is

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*The system described herein should not be confused with previous synchronized IFF systems considered in the past. One such system, known as the Short Interval Identification System, employed a mechanical clock and paper tape. This system has sometimes been referred to as Phase II of the SIF system. It had a rate of change of code of once per minute at most. This system also had the usual difficulty of most IFF in that an enemy could monitor the code and relay our replies in an extremely short time interval after the code had been changed. Hence this system had negligible security. It also had some difficulty with regard to the administrative problem of producing and distributing the necessary tapes. The system described in this appendix has neither of these shortcomings.

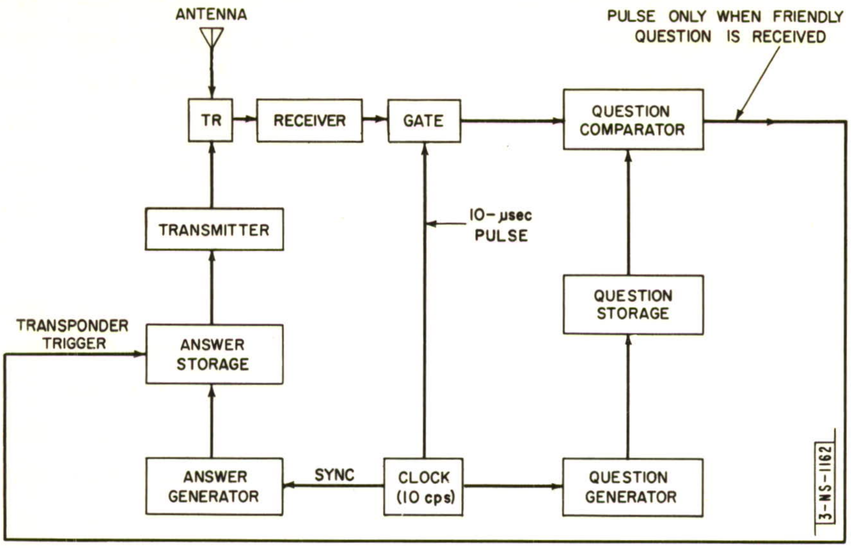

Fig.8A-1. Transponder of time-synchronized IFF.

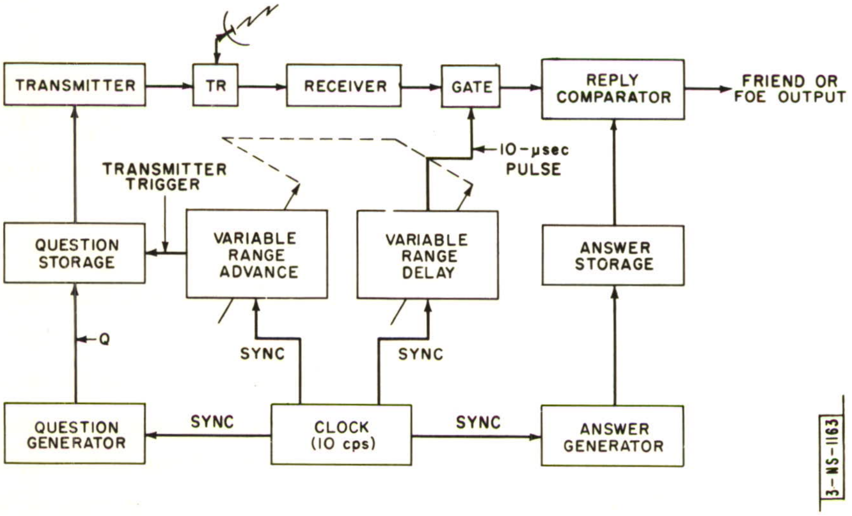

Fig.8A-2. Interrogation site of synchronized IFF.

that the question that arrives must be coded to correspond to what at that particular time is known to be a friendly question.

For example, the IFF receiver (Fig. 8A-1) will be permitted to listen to signals only when they arrive exactly within a narrow gate (perhaps 10 μsec wide) centered around the time zero, the time 0.1 second, the time 0.2 second,* and so on. Any questions arriving outside this narrow gate will be ignored. Any questions that do arrive within this 10-μsec time gate will be inspected for their friendly composition. In general, the question will be made up of a series of pulses lasting for a total duration of perhaps 3 μsec.

In order that the question be identifiable as to whether it is friendly, both the interrogation site and the interrogated site will have to have a copy of an identical code which changes with time, so that a new code appears each 0.1 second. The question might be about 10 bits long, permitting a choice of one in a thousand different questions each time a question is asked. This number makes the chance that an enemy will guess the right question at any time only one in a thousand.

If a friendly question is received within the 10-μsec time gate of the receiver of Fig. 8A-1, this question is answered with a reply that is also chosen in accordance with a preselected random code. This answer again might be of a duration of about 3 μsec, and might contain about 10 bits of information.

At the interrogation site (Fig. 8A-2), the received signals are gated to permit passage only at the expected time when a friendly reply should come through. If the reply comes through at this time, it is compared with the known reply which should come through at that instant of time.

OPERATIONAL PROCEDURE

The procedure by which one then interrogates a target is as follows. First, one must establish the range to the target. In general, this will be known, since one is interested in interrogating a particular target. One then causes emission of a transmission prior to one of the 0.1-second time markers. The time advancement is so made that the question will arrive at the target exactly at the time T = 0, corresponding to some multiple of a 0.1-second time

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*These numbers chosen for the timing of the system must be considered extremely tentative. Further analysis of the system will probably show that the tentatively selected numbers might be off by a factor of two or more. However, it is believed that the numbers will adequately illustrate the principle of operation.

interval. The necessary advancement in time of the transmitted question can be done readily through circuitry means according to the block diagram of Fig. 8A-2, and aided by a photoelectric pencil, for example, pointing to a part of the PPI where the target appears on the radar scope.

The transmission from the interrogation site is by means of a directional antenna, which may be scanned synchronously with the radar antenna or which may be an integral part of the radar antenna.* It would be reasonable to assume that the wavelength used for interrogation would be at L-band or higher frequency. A wavelength on the order of 10,000 Mcps or higher would seem desirable if the IFF system is to permit air-to-air identification with good directional characteristics.

Since the receiver (Fig. 8A-1) at the friendly aircraft is gated on for a 10-μsec period which will encompass the 3-μsec question arriving, the friendly aircraft will be able to compare each received 3-μsec question with a corresponding locally generated question which is expected to be received at the particular instant of time. In transistorized form, circuits that would permit this comparison could be made very small. If the comparison proves sufficiently accurate to insure that the interrogation was friendly, then a fresh locally generated reply is instituted at a known and fixed time delay after receipt of the question.

Meanwhile, at the interrogation site the receiver of Fig. 8A-2 is so arranged that it is gated on for a short interval (10 μsec) after transmission of the interrogation question, delayed by a time delay equal to the round-trip time of transmission, plus the time delay at the target responder. The received reply passing through the gate is likewise compared with the known signals which should come at that particular 0.1-second time interval. If the comparison is proper, the target is friendly.

GENERATING IDENTICAL CODES AT SITES

There are two attractive methods whereby the codes necessary for providing a list of proper questions and answers may be made available at both the interrogation and interrogated sites. One of these methods involves magnetic recording. The magnetic recording would have two channels – one channel capable of asking one question per 0.1 second, and the other channel capable of answering one question per 0.1 second. This would call for a channel capacity in each channel of about 200 cps. Such a tape could run at a speed of about 70 feet per hour. New questions and answers as read off a tape at low bandwidth rate would be

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*Alternatively, it may be more desirable operationally to use a separate steerable antenna for interrogation, in order to provide greater flexibility.

stored in two 10-bit flip-flop storage machines once every 0.1 second. Thus a new question and new answer is set up in the storage box so that questions may be compared with the storage signal as they are received. Needless to say, the questions and replies would be arranged on the tape in random order with no correlation existing between the question channel and the reply channel.

The magnetic-tape method poses some problems of distribution of code words: in general, physical transport of the tape from a central generating tape area to the operating areas would be necessary. Also, it has the disadvantage of not being broken down easily into subparts to prevent compromise by one individual defector.

The second method by which the series of synchronized questions and replies may be made available at the interrogation and interrogated sites simultaneously is the use of an accurate clock at each site, the output of which clock is counted by a digital counter. The counter is arranged to advance one digit every 0.1 second. The total count that the digital counter must be capable of registering shall be sufficiently high that the count may go on for a duration of days or months, or whatever time is necessary between changes of code. (A counter of this capacity is still a relatively compact box when transistors are used.) The output of the counter is then fed into two separate scrambling boxes: into one is set a key suitable for questions; into the other is set the key designated for the answers. Each key is so arranged that, when any particular number appears at the input to the scrambling box, another number (a 10-bit code) appears at the output. The interrelation between the input and the output is determined by the key set into the scrambling box. Thus one scrambling box has as its output fresh questions that should be asked at the moment, and the other scrambling box has as its output information as to what answers are considered friendly at the moment.

Alternatively, a single scrambling box could be used, and the counting rate could be increased at the input to the scrambling box to cause two counts every 0.1 second. The scrambling box would then emit two outputs every 0.1 second: one output would be stored and used as a question, and the other would be stored and used as a reply. This method would save some hardware, namely, that involved in one scrambling box. It would also lose no security, since a single key used for both questions and answers would not compromise the system.

The scrambling box should be so designed that any given number about to come out its output can not be predicted on the basis of listening to its prior output. Moreover, this scrambling box should be designed mechanically so that the proper key that sets up the scrambling box at both the interrogation and interrogated sites can be handled by more than one man, if operational doctrine makes such operation desirable. That is, the box should be so designed that the entire key can be set into the box only when more than one person carries his separate and distinct part of the key to the scrambling box; electrical or mechanical tampering with the box should cause it to lose its stored key information. Thus defection of any one individual could not permit an enemy to have the entire key available.

TARGET CLASSIFICATION

It has been suggested above that all codes used by friendly aircraft be identical; however, this is not necessary. Operation can also be provided wherein each overseas flight, for example, has its own private code issued at the time of departure. The code key used could be stored in an envelope, a copy of which envelope containing the same code information is available at the interrogation station. The envelope number would be a part of the flight plan. By this means, the ground interrogation site can identify the received reply to be that of the particular aircraft rather than simply that of any friendly aircraft. This result is achieved by having at the ground site a comparison device that compares the received reply with a list of possible received replies from expected friendly aircraft at the moment.

Likewise, the IFF could be expanded so that the reply would include not only the friendly reply described above, but additional data designating task group, altitude, flight number, name, gasoline in tanks, etc. This additional information can be given in uncoded form, or could be put through a coding operation similar to the friendly reply code. By this means the reply could be made to contain as much information as desired.

In this connection, it is noted that the total reply may be permitted to be of a duration substantially longer than the 3-μsec question without causing an ambiguous reply. For example, consider the case when there is a large number of aircraft along the same radius from the interrogation site. The ground interrogator may direct his questions at any one of several of these, provided they are not so close together that the interrogations overlap. Since the interrogations are 3 μsec long, the site could, in principle, send out a new interrogation every 3 μsec. In practice, however, if the replies from the aircraft are made perhaps 20 μsec long in order to contain more data than the fact that the aircraft is friendly, the interrogation site can choose to interrogate simultaneously only aircraft that are separated by more than 20 μsec along one radius. It may then interrogate the other aircraft within this 20-μsec interval at a later time.

The 20-μsec reply would permit something on the order of a 40- to 100-bit reply from the aircraft. This could identify a large amount of data from the aircraft.

PROBLEMS

The IFF system suggested above has certain problems that should be considered and tested before the system could become operational. One of the problems concerns the accuracy with which time may be kept at the interrogation and interrogated sites. Means for accomplishing this when the target is within range of the Centipede communications system are described elsewhere in the Lamp Light report. Such timing systems would provide for an accuracy of better than one μsec as long as the friendly aircraft is within communication distance of three Centipede transmitters. Actually, if navigation is known to within an accuracy of about one-half mile by some other navigation scheme, when the friendly aircraft is within range of only one Centipede or other transmitter time check he may still set his clock to an accuracy of about 5 μsec, which would be close enough to achieve the expected IFF performance.

The severity of this timing problem is substantially reduced in view of the recent development of high-precision clocks that are accurate to one part in 10^9. Such a clock would have to be reset only once every hour to provide 3-μsec accuracy. More frequent time checks ought to be available operationally.

In addition, there is the problem of obtaining freedom from multipath transmission for air-to-air propagation. These transmission difficulties could cause misquantization of the questions or answers, particularly over water. Vertical antenna directivity at the interrogation site is helpful in this regard; hence one is again led to favor microwave interrogation, particularly from an airborne platform. In this connection, it would appear that FM transmission would have some advantage over AM, since it is well adapted to permitting a strong signal to suppress weaker ones.

METHOD OF INITIALLY SETTING CLOCKS

When clocks that run at the proper speed have been achieved, there is still the problem of initially setting the clocks to an absolute accuracy of better than 0.05 second in order to effect proper selection of questions and answers; and even worse, the clock error must be kept less than about 3 μsec in order to cause proper gating action of questions and answers.

It is believed that this problem of initially setting clocks is best solved by having the clock (crystal oscillator or atomic beam) with its flip-flop count-down circuits packaged in a small plug-in unit (battery operated). The unit is set on the bench to agree with a submaster clock, turned on and carried to the aircraft, where it is plugged into a multi-prong socket in a recess available from the exterior of the aircraft. It may be left in this state without resynchronization for any time less than the time it takes for the clock to drift 0.05 second. A greater drift would cause wrong question selections. If the clock is a crystal accurate to one part in 10^7, this would permit 5-day* storage between initial bench setting and first resynchronization from air-synchronizing signals. These air signals would set the clock to better than 3-μsec accuracy at the start of flight, and periodic resynchronizing to this accuracy would take place throughout flight.

JAMMING AND SPOOFING

One of the intended purposes of the suggested IFF system was to provide an IFF that would not reply to unfriendly questions. It is apparent that, since such a question may be asked only every 0.1 second, an enemy asking questions at random could therefore, on the average, get a response from the system only once every 100 seconds. Hence he could not provide very good navigation toward a friendly aircraft if he asks his questions at random. The enemy could presumably do better than ask questions at random. In fact, he could listen to our questions, and then mimic these repeatedly, with successively longer time delays. This procedure would permit him to elicit answers from friendly aircraft within a certain distance, this distance being the difference in range between the enemy and the friend to whom the question was originally expected to be delivered from the interrogation site. When the enemy is at a greater range than the friend being interrogated by the interrogator, any mimicking of the interrogated question by the enemy can elicit no responses from anyone. Likewise, when the enemy is outside the beamwidth of the interrogating transmitter, his receiver presumably will not be sufficiently sensitive to pick up the interrogation and hence, under these circumstances, he can not utilize any received information to advantage. Therefore, the enemy can elicit responses only when he is in a straight line between the interrogation site and the interrogated responder; under these circumstances he may elicit responses only over a limited range. Furthermore, he may elicit responses only when the interrogator asks a question of the target. In the interests of security, the interrogator should ask the question only when the classification of a target is in doubt, rather than leaving the interrogator on each target for all times. This will further reduce the enemy's capability of eliciting responses from friendly aircraft.

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*Transistors make battery operation for this time feasible with crystal clocks.

A similar problem arises with regard to an enemy that tries to make a reply that is friendly. Again, such an enemy can achieve his objective only if he can elicit a friendly reply from one of our aircraft and repeat it soon enough to be accepted as a friendly reply at the interrogation site. In order for the enemy to elicit such a friendly reply, as it was pointed out above, he has a difficult problem, and even if he could elicit such a friendly response, if he should relay this it would come in at the interrogation site too late to be acceptable. Moreover, it has been pointed out that he cannot elicit such a friendly response when he himself is being interrogated. The above comments apply, provided the enemy is farther than some critical distance from the friend. This distance is dictated by the 10-μsec tolerance that has been allowed for clock drift. Hence the enemy must be within a mile of the friend in order to be confused as being friendly. If the enemy is this close to the friend, in many instances visual observation from the friend will permit identification of the enemy.

The other tactic available to the enemy is to jam the questions and answers so that they are not received properly. This is always a problem with any communication system, and if the enemy has enough power to do this he may be successful. However, it will be noted that the peak powers that can be used in this system for friendly questions and replies can be very very high. The questions are radiated directionally, and replies received directionally. Hence an enemy has difficulty in jamming the system from an omnidirectional antenna. Moreover, the enemy would have difficulty in jamming the system from the standpoint that the receiver gates are open only for a short instant of time, and he would have to put energy into the system for this instant of time. Since he will not know the instant of time when he should put energy in (particularly if we jitter the repetition rate, previously assumed 0.1 second) he would have to adopt the tactic of putting the energy in at nearly all times. This requires him to use a duty cycle of about 100 times that of a friend. Hence the average power required of the enemy to jam the system is enormous as compared to the average power utilized by the friend for this IFF function.*

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*The enemy must use about 20 db more power simply because he does not know when to transmit, and he must use about 30 db more power if he utilizes omnidirectional transmission against our friendly aircraft as compared to our directional transmission. Thus his power requirements will be on the order of 50 db greater than ours for the same range. If we utilize an average power on the order of 100 watts, his problem is made substantially impossible for broadcast jamming of the IFF system, since he must then radiate some 10 kw to 10 Mw average power.

RESUMÉ

The proposed IFF system would appear to have all the advantages necessary for an operationally practical IFF. Its complexity has yet to be evaluated, but this is a matter that will be helped greatly with the advent of transistorized circuitry. The IFF has the advantage of providing substantially complete security, as well as nearly complete denial of use by the enemy for aiding his interceptors or missiles against our aircraft. Likewise, the IFF system is extremely difficult to jam. The security of the IFF (the feature that prevents an enemy from appearing as a friend) rests with a key that is inserted into the IFF – either in the form of a coding into a scrambling box or in the form of a magnetic tape. It is only this part of the system that must be kept away from the enemy. The apparatus itself need have no security classification.

An IFF with the security of the system proposed would appear to be a necessary part of the air defense picture. All present-day IFF's do not appear to have this security, and alternative IFF proposals appear to be subject to aiding an enemy in homing on our responses to his queries.

D.E. Sunstein

CHAPTER 9

DEFENSE AGAINST ELECTRONIC COUNTERMEASURES

CHAPTER 9

DEFENSE AGAINST ELECTRONIC COUNTERMEASURES

INTRODUCTION

Project Lamp Light has not considered the use of ECM by our own forces against an attacking bomber force. Rather, we have concentrated our efforts on how we might keep our own electronic measures working in the threat of potential enemy countermeasures.

The fact that Project Lamp Light did not consider our own use of ECM against an attacking force is in no way intended to imply that this would be unimportant.

The following discussion is divided into the separate fields of radar, communications, navigation and weapons.

Threat

RADAR

Presently known countermeasures could heavily cripple our present defense system. Our radars can be blinded so that range information is denied over substantially all ranges at which a target bomber carrying a jammer would ordinarily be seen. The effective distance at which a bomber with a jammer can be ranged upon will be on the order of ten to one less than the range obtainable against the bomber without the jammer. (This is shown in Appendix 9-C and summarized in Appendix 9-B.) Our radars can also be misled as to the size of the raid. They can be caused to report a large number of spurious targets* so that the data links and the inputs to the computers will be saturated with false targets.

To meet this potential threat, Project Lamp Light has evolved three types of recommendations. The first type of recommendation is that which will permit the defenses to operate in the near term against such a possible threat. The second type of recommendation is concerned with longer-term studies that are expected to provide improved performance in the presence of ECM by taking advantage of the ECM when possible. The third type of recommendation is concerned with measures to improve the performance of radars in the presence of jamming by still permitting them to determine range through echo-timing techniques.

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*For each 2 pounds of chaff dropped against radars of diverse frequency, one false data box print can be made and sustained for the life of the chaff.

Immediate Radar ECCM Recommendations

The following measures are urged for incorporation in ground radars and interceptors of the near future to permit partial operation in the presence of the expected ECM. A verification of these recommendations is applicable to the radars now in operation.

Exercises:– Realistic appraisal of the effects of ECM on present defense systems can be obtained only through continuous exercises of radar and intercept systems in the presence of realistic ECM. Such exercises are therefore urged on a routine basis to develop the proper psychological approach to ECM on the part of the operators, the military services and the designers of the electronic equipment. The exercises will keep operators trained to the point where they can recognize ECM and where they can intelligently utilize the best ECCM measures available to them. Such exercises will also highlight the various shortcomings of the present electronic components in systems. The results of these exercises should be classified no higher than the security classification pertaining to other radar performance data (CONFIDENTIAL or SECRET at most), so that the results may be made known to those who are in a position to provide corrective ECCM.

Intelligent Report Limiting:– Means should be provided for intelligently limiting the number of reports issued per radar site. These means should permit the maximum amount of useful information to be transmitted from the radar site. That is, the present practice of blanking all jammed sectors on the PPI should be abandoned, or at least supplemented. The angular position* of the jamming transmitter should be transmitted over the data link as well as the location of various target discrete echoes. Initially such report limiting will probably have to be done manually, but as one establishes the means of accomplishing this objective, it is anticipated that automatic methods of limiting the number of reports in an intelligent fashion could be provided.

DF Overlay:– In order to provide some measure of target location when each target carries a jammer, apparatus should be provided in the radar sites, the data links and the computer sites so that a DF overlay computation may be obtained. The actual DF overlay computation could be made either by an analogue computer or by an appropriate programing of the centralized digital computer. Geographical location of radar sites should be chosen so that at least three radar sites can view each jammer. A DF overlay based solely on bearings from two sites has severe ambiguity troubles when multiple jammers are encountered. Three sites considerably reduce this ambiguity trouble by causing most of the "ghost" intersections to be of a transitory nature, which can therefore be ignored by the computer.

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*See p.12 for footnote.

Spurious targets are created in the DF overlay by antenna sidelobes at each radar site. This problem is much worse in the passive operation than in normal radar because the antenna is used only one way. To reduce the trouble this causes, it is suggested by Project Lamp Light that consideration be given to relaying from the radar site the amplitude of the jammer signal at each azimuth. It is believed that the DF overlay computer may take these amplitude data into account, along with known sidelobe responses to materially reduce the false bearings due to sidelobes.

A simple analogue DF overlay can be based, for example, on a rapid development photographic process in which a positive is produced from each reporting PPI. Three or more positives are then superposed. Only the intersections of the radial strobes then permit passage of light, and these intersections correspond to jammer locations. Project Lamp Light has not had time to weigh the relative merits of such analogue techniques against the possibility of a digital operation for the DF overlay.

AI Radars Equipped for Passive Use:– Such modifications as are necessary to the AI radars to permit them to maintain angular tracking on jammers should be made. This may require an increase in dynamic range of the radar receiver and certain changes in the locking circuits so that a range or velocity lock is not required. Also, the circuits should be so contrived, if possible, that programed jammers do not cause break of lock, i.e., either jammer or radar echo should maintain lock smoothly as the jammer is cycled on and off. Project Lamp Light has not had time to explore the various AI radars to ascertain the extent of modifications required in this regard, but it is believed that any modifications needed would be trivial.

The angular data from the AI radar should be fed to the autopilot to put the plane on a collision course. At some smaller range encountered thereafter, the radar may again be able to measure range or, alternatively, missiles such as Sidewinder may be launched visually.

Long-Term Radar ECCM Recommendations

It is recommended that the following steps be started now in order to improve the performance of object-location devices in the presence of jamming, to a degree far greater than can be provided by the initial measures outlined in Sec. B above. The ECCM measures listed below also include devices that would tend to make the carrying of the jammer by the opposing force unattractive.

Call the Tune on Jammed Frequency:– Our ground sites should force jamming on a short wavelength such as 3 to 5 centimeters. This can be done simply by including

3 to 5 centimeter radars in the ground operation. By requiring that if the enemy jams, he shall jam at these wavelengths, we help ourselves with regard to resolution and sidelobes for passive operation.

Passive Correlation Radar:– The feasibility of the 2-site correlation radar (as described in Appendix 9-E) should be further explored. This is believed to have already been undertaken at Rome Air Development Center. This target-location method will require considerable transmission bandwidth between the various ground-station sites. It is deemed necessary in the long run to provide accurate target location from totally passive information. This method would appear to largely overcome the ambiguity trouble of a DF overlay.

Multiple Sensing:– The feasibility of multiple-sensing airborne instrumentation in the interceptor should be studied. The senses which might be included would be the normal AI active radar, a passive microwave receiver at the same wavelength or at the wavelength of the ground stations, infrared passive sensing, sensing of the IFF along with an interrogator of the enemy's IFF, sensing of the altimeter, and sensing of any rendezvous beacons or communication emanations expected. The angular data obtained from the passive listening through two or more of these multiple senses should be used to feed through the autopilot to keep the plane on a collision course with the source of the radiation. Obviously foolish data coming over one of these senses, through programed jammers or chaff, for example, can be discarded automatically by a method such as that described in Appendix 9-N.

Range by Maneuver:– The feasibility of determining target range through a maneuver of an airborne platform should be studied. Such a maneuver could either be from a tail-chase course to a collision course, or could be in the form of a maneuver off a collision course. Alternatively, the range may be computed from a measurement of the gain around the closed loop formed when the angular information from the passive or active tracking sensing apparatus is fed through the autopilot to control the aircraft. These possibilities are discussed in Appendix 9-F.

Improvements to Reduce Susceptibility to Jamming

Supplementing the discussion in Chap. 4, the following class of recommendation is offered to point toward methods of keeping radars operating to determine range by echo timing. These methods tend to become brute force rather than clever. It is believed that, in the long run, the jammer will always come out on top of these methods as the art progresses, and that therefore the recommendations of Secs. B and C above, which stress taking advantage of the enemy's radiation, must be pushed. However, what follows will provide a useful measure of active radar improvement which cannot rightly be ignored.

Frequency Spread

General:– Because a jammer, to be effective, must jam all radars of a given class or function, increased frequency spread of our ground radars will necessitate the jammer's spreading his power over a wider spectrum, and hence reduce his ease of jamming each radar.* If we double the spectrum utilized by our operating radars, we can increase the range at which we are able to measure range to target by 40 per cent. The following steps are therefore recommended.

Short Term:- Transmitter tube specifications, procurement and supply, should be so modified that the maximum possible spread in frequency in the present bands is obtained at an early date. In addition, where possible, those particular components of the plumbing or antennas which limit the bandwidth of the present system should be redesigned. This increase in frequency spread should be enforced through appropriate procurement methods, which stress that it is not a virtue to have all magnetrons test out as close as possible to band center.

Long Term:– New radar bands should be opened up as appropriate. Specific bands recommended will be found in the radar portion of the Lamp Light report (Chap. 4).

Antennas:– Strong measures should be taken to utilize the narrowest possible beams, together with low sidelobes. Sidelobes of 30 db or better are desirable for passive operation, and they are also desirable for reducing the vulnerability of the radar to jamming when echo ranging is desired against targets not carrying a jammer.

Likewise stacked beams, which permit greater antenna gain on reception, are desirable either for passive operation or active operation, since they permit discrimination against jammers at other than a particular altitude. They are also important for passive operation from another standpoint, since they will reduce the spurious azimuthal reflections of the jammer caused by close-by ground objects. Although frequency shift for elevation scan does not have this advantage, it does provide more gain

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*This assumes the jammer will use wideband noise jamming covering our entire assigned radar band or bands instead of spot-frequency jamming which would cover only the specific portion of the assigned band occupied by an individual radar site. Spot-frequency jamming of the several specific radars encountered on a bombing mission requires complicated equipment and probably considerable operator attention, and hence would probably not be used. The present program (Ajax) of pulse-to-pulse frequency jumping would also insure that wideband noise jamming be used instead of spot jamming.

TABLE 9-I

SUMMARY OF ANTENNA COMPARISON

			Receiver Antenna $\frac{G_{sig}}{G_{jammer}}$		Relative Integrated Signal-to-Jammer Response*	
Antenna	Relative Gain on Transmit	Time on Target	Jammer in Target	Jammer above or below Target	Jammer in Target	Jammer Above or below Target
$\csc^2$	1	1	1	1	1	1
Frequency-Shift	N	$\frac{1}{N}$	1	1	$\sqrt{N}$	$\sqrt{N}$
Stacked-Beam	1	1	1	N	1	N

*Noncoherent integration of hits assumed.

on transmit than either a $\csc^2$ or a stacked beam, and hence provides improved range against a target carrying a jammer. This comparison is summarized in Table 9-I, in which N is the number of resolvable elevation beamwidths.

It is therefore recommended that:

> Where purely passive surface operation is intended, stacked beams be used, with sidelobes down at least 30 db,
>
> For active surface radar operation, a $\csc^2$ beam be abandoned, where possible, in favor of either stacked-beam or frequency-scanning antennas.*

High Power:– Obviously, power should be pushed to the limit to obtain adequate ranging in the presence of active jamming. In this connection, it is strongly urged that the feasibility of radars having good range resolution but with a long pulselength be explored. These radars utilize a wide transmitted spectrum, which may be obtained, for example, by utilizing a saw-tooth of FM during the transmitted pulse. The transmitted pulse might typically be as long as 100 microseconds, thereby permitting a 10 to 20 db increase in average power (when the radar is not peak-power limited but average-power limited, which has been the case in many instances at the relatively longer wavelengths). The companion receiver for such a transmitter would provide a

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*The choice between these two types requires further evaluation.

range resolution as though the transmitted pulselength had been short, but with the signal-to-noise performance and a signal-to-jammer performance substantially improved. The receiver could, for example, use a matched filter having the proper phase distortion which causes all the received frequency components to add up at one particular instant of time instead of being spread out over the entire duration of the long transmitted pulse. This type of technique should be explored, particularly for UHF radars (see Chap. 2).

Specific Antijamming Measures:– The feasibility of specific fixes against certain types of jammers should be studied. For example, the Carcinotron as currently modulated is not white noise, and advantage may be taken of this fact. Measures for doing this are discussed in Appendix 9-D.

Velocity Sorting:– Study of the effectiveness against jamming of various types of reduction in radar effective bandwidth should be considered. On a pulsed radar these measures all amount to some form of velocity sorting. Such measures are Argus, as developed at Lincoln Laboratory, Sinufly, as developed at the University of Illinois, and Redap, as being considered by Philco Corporation. The maximum improvement which such systems could theoretically provide is given in Appendix 9-O. For various reasons, any practical velocity sorter will fall short of this limit.

Threat

COMMUNICATIONS ECCM

Communications systems are subject both to jamming, which renders the communication unintelligible or (in case of data systems) randomly erroneous, and to deception techniques, which cause the received messages to be erroneous in some particular misleading way. To reduce this vulnerability, the following five feasibility studies are recommended. These are over and above the usual good engineering practices from an ECCM standpoint, such as preventing overload or spurious responses in the early stages of a receiver.

Noise-Correlation Communication

The feasibility should be explored of communications systems such as currently being built at Lincoln Laboratory which use wideband transmission of relatively narrowband data, in which the intelligence is heterodyned with or modulated by noise, so as to increase the effective transmitted spectrum, and in which the received signal is subsequently heterodyned with an identical noise signal. This technique increases the required jamming power directly as the transmitted bandwidth is increased over the intelligence bandwidth. In order to obtain a clean noise reference, very precise timing is required at the transmitter and receiver so that each may have identical noise signals to work with. This technique is discussed in Appendix 9-L.

Two possible variations of this method are described in Appendix 9-Q. In one of these methods, the jammer signal itself serves as the noise reference. In the other, the correlation noise signal is generated at the message-receiving end, and transmitted to the message-origination end. These possibilities warrant further study.

Authentication

Methods can be provided in principle for insuring that the received signal is indeed an authentic message generated at the moment rather than a re-recording of some previous authentic message and rather than some totally erroneous message generated by the enemy. Authentication can be based on precision timing together with appropriate encoding. Such techniques are discussed in Appendix 9-J. This appendix does not discuss how one would compensate for the time of transmission between the transmitting site and the receiving site, and this may be a serious problem in certain wideband cases. The measures necessary to adjust for this finite time of travel are straightforward, however, since in general the time delay over the path is known.

Another authentication method, not requiring precision timing, is described in Appendix 9-K.

By the methods proposed in Appendix 9-J or 9-K it is expected that the vulnerability to jamming is increased, but that any message that comes out of a receiver and that passes the authentication test can be guaranteed as being one which was freshly generated by a friendly source at the moment. This will prevent misguidance of weapons or interceptors.

These authentication procedures are in no way to be confused with secrecy precautions sometimes used in message transmission, although the equipment that provides for authentication is in some ways related to equipment that provides for security against message reception by an enemy. That is, secrecy systems are intended to prevent the enemy from understanding the message. Authentication may or may not prevent the enemy from understanding the message, depending upon what authentication procedure is used.

It is recommended that the feasibility of operational use of authentication systems be explored.

High-Power Modulation Methods

Those modulation methods which permit high average powers for transmitting information should be employed. In this respect, frequency-division subcarriers currently being considered for certain data links for ground-to-air are believed extremely vulnerable, since useful amplifiers to provide high power from the ground are impractical to build because of intermodulation difficulties. Time-division systems are less vulnerable in this regard, since linearity in the final stages of the transmitter is not of prime importance. In this respect the Centipede communication system discussed elsewhere in this report is believed attractive, since it permits, with FM transmission, extremely high power with a simple class C transmitter.

Airborne Relays

Where UHF propagation is used, it is apparent that a considerable freedom from jamming may be obtained when only line-of-sight propagation is used. In order for this to obtain over substantial areas, it is necessary to employ airborne relays. The Centipede makes airborne relaying appear practical in that one airborne receiver and transmitter could simultaneously handle 50 or more nets. Likewise, the airborne relay can have high transmitted power (100 kilowatts or more). Such a relay will prevent one from having to rely on tropospheric scatter to get beyond the horizon at UHF, and hence will provide a signal perhaps 50 to 80 db stronger than would be provided without the airborne relay.

Exploitation of Propagation Path

The usual measures of exploiting certain peculiarities of the propagation path between the receiver and transmitter should continue to be explored. Paramount among these is the use of antenna gain where possible and the use of steerable nulls in the antenna so that a null may be put on one or more jammers.

Likewise, for high-frequency communications, the peculiar properties of the propagation path should be exploited by using what is best at the moment by way of choice of carrier frequency. The Cozi equipment may make this possible. By this means, it might be expected that about 10 db better signal response would be obtained under average conditions, and under some propagation conditions the improvement might be substantially greater than this.

In addition, certain methods of communication exploiting favorable propagation paths are desirable as an ECCM measure. JANET is one such method, which utilizes ionospheric meteor trails. By utilizing the meteor-trail propagation path, a certain degree of immunity to jamming from transmitters located remote from the transmitter to which one is listening is obtained. However, in order to obtain this, it is necessary that the JANET system be contrived so that an enemy cannot evoke information out of the JANET transmitter by utilizing meteor trails occurring at other instants of time which happen to link the JANET jamming site with the friendly transmitting site. This insurance can be provided by having the signal which evokes intelligence from the JANET transmitter so coded that only a particular type of evocation message coming in at each particular instant of time will be useful for evoking a message response. That is, the signal which evokes a response should have applied to it authentication methods comparable to those described in Appendix 9-J or 9-K.

ECCM FOR WEAPONS (FEASIBILITY RECOMMENDATIONS)

Although Project Lamp Light has not thoroughly explored the ECCM for weapons, the following recommendations are made to initiate feasibility studies in an attempt to insure that electronic countermeasures used against our missiles will be made relatively unattractive for the enemy to carry.

Spoof-Proof Guidance Links:– The command links which are utilized to guide weapons, where such guidance is called for, should be made spoof-proof (see Appendices 9-J and 9-K).

High-Power Commands:– The highest possible power, together with directional antennas, should be utilized to provide communications to the missiles from the launching site where such guidance is utilized.

Fuzing Diversity:– Any fuzing method that requires secrecy is vulnerable to ECM, which could cause premature explosion or which might prevent explosion. The feasibility of utilizing fuzing diversity in each individual weapon should be explored, so that the consensus of opinion of many fuzing sense organs may be measured in the weapon automatically. Ship mines have had to use such multiple sensing for some time, and it appears that a much more costly item to deliver and to build such as a guided missile should certainly have diversity of fuzing. Simultaneous sensing of two or more of: contact, microwave, infrared, capacitive or inductive influence effects, shock waves, acoustic noise, or temperature, might be appropriate. If it should prove that diversity of fuzing is not appropriate in any one missile, then at least our arsenal of weapons should have fuzing diversity so that countermeasures against one type of guided missile will not be effective against another type of guided missile.

Multiple-Sense Target Trackers:– The feasibility of target trackers having multiple sensing should likewise be explored. For example, each single missile might carry active or semiactive radar, which is capable of operating passively should the target turn on a jammer. Additionally, infrared might supplement the guidance provided by the microwave signal. A method of making the missile ignore foolish instructions in one channel is shown in Appendix 9-N.

If it does not prove feasible to utilize multiple sensing in a single missile, at least our arsenal of weapons should include weapons with different types of senses in their seekers.

Simultaneous Lobing:– Where angular information is required at microwave or infrared, it is recommended that simultaneous-lobing techniques be utilized rather than conical-scanning systems. This is simply to remove from the enemy the possibility of providing jamming which is amplitude-modulated at almost the conical-scan frequency. Such jamming is very effective for throwing off course the conical-scanning systems, but it is totally ineffective against simultaneously lobing systems having appropriate AGC characteristics.

Jammer-Seeking Missiles:– One or more missiles capable of homing on jamming should be developed. (This is discussed more fully in Chap. 10.) If these can be achieved economically by minor modification of already existing missiles, such action is recommended. Project Lamp Light has not had time to explore this possibility thoroughly but preliminary thinking of Appendix 9-I would indicate that such possibility is very real. It is believed that the tracking circuits utilized in the missiles could be made so that when jamming takes place, the missile will lock on the jamming, yet when the jamming ceases, the missile will go back to its former method of tracking. The circuits should be so designed that program jamming among several possible jammers cannot confuse the missile. For this purpose, the missile should have some memory as to the location of the target, and should not try to obey obviously foolish instructions such as would be received when one jamming transmitter is turned off and another one turned on at a distinctly different location. Methods of achieving this capability are discussed in Appendix 9-M.

OVER-ALL ECCM PHILOSOPHY

We need electronics as a major part of our defensive effort for guidance, identification, communications, object location, and fuzing. At present, our entire defense can be badly crippled by known potential countermeasures. We must therefore very rapidly develop counter-countermeasures to the point where it is unprofitable for the enemy to employ countermeasures against our electronic devices.

Where possible, our counter-countermeasures should be of such form that they may take some advantage of any countermeasure the enemy may choose to use.

In the field of electronic object-location devices, we can indeed choose such a course of action by providing passive back-up facilities to augment active echo-ranging radar. In the fields of guidance, communication and fuzing, no such direct substitute appears wholly satisfactory.

However, in all these fields, active ECM by the enemy still betrays his location, and hence homing interceptors and missiles of appropriate variety will tend to discourage his use of active ECM. In addition, specialized improvements in each specific electronic field are suggested which, when combined, would further reduce the incentive of an enemy to try ECM to such an extent that it would not pay him to expend the development effort or to reduce his payload for ECM.

NOTE ADDED IN PROOF:

To preserve angular accuracy on jammers, without excessive side-lobe responses, the radar receiver generally must have much less gain than when used for echo location. In order that target echoes (interceptors or non-screened bombers) can still be seen, however, in sectors that are not jammed, the gain must be high. This conflict is perhaps best handled by the use of two receivers and two indicators, one of which normally shows target reflections, and the other of which normally has perhaps 40 to 60 db less gain, for showing jammer bearings.

CHAPTER 9 RECOMMENDATIONS

Radar

1. *To develop the proper psychological approach to ECM on the part of the operators, the Military Services and the designers of the electronic equipment, we recommend continuous exercises of air defense system operation in the presence of realistic ECM. We urge that the results be made known to those who are in a position to provide corrective counter-countermeasures.*

2. *We recommend the development of means for intelligently limiting the number of reports issued from each radar site, and to include jammer bearing data among the reports.*

3. *In order to provide some measure of target location when each target carries a jammer, we recommend provisions for DF-overlay computations.*

4. *We recommend that AI radar be modified to permit angular tracking on jammers.*

5. *To induce enemy jamming on frequencies favorable to passive locating techniques, we recommend that the ground radar system include operation at 3 or 5 cm.*

6. *We recommend that the feasibility of two-site correlation radar be explored for passive location of jammers.*

7. *We recommend study of multiple-sensing installations in interceptor aircraft, including AI radar, passive microwave receiver, infrared passive sensing and other special devices.*

8. *We recommend the study of passive range determination from an interceptor by means of special maneuvers.*

9. *To obtain the maximum possible spread in radar frequencies at an early date, we recommend modification of transmitter-tube specifications and procurement, and broadband design of RF and antenna components. As a longer-term development, new bands should be opened up for radar.*

10. *For optimum antenna performance against jammers, we recommend the use of narrow beams with low sidelobes, and of stacked beams.*

11. *To obtain adequate ranging in the presence of active jamming, we recommend extremely high output power obtained by the use of long pulses with frequency modulation or matched-filter techniques.*

12. *We recommend study of specific fixes against particular types of jammers, such as the Carcinotron.*

13. *We recommend study of radar bandwidth reduction by velocity-sorting techniques.*

Communications

14. *Feasibility studies are recommended on the following methods of reducing the vulnerability of communications systems:*

(a) *Noise-correlation techniques,*

(b) *Authentication procedures,*

(c) *High-power modulation,*

(d) *Airborne relays,*

(e) *Exploitation of optimum propagation path.*

Weapons

15. *To reduce the vulnerability of our missiles to enemy countermeasures, we recommend studies of:*

(a) *Spoof-proof guidance links,*

(b) *High-power commands,*

(c) *Diversity in fuzing methods,*

(d) *Multiple-sense target trackers,*

(e) *Simultaneous lobing,*

(f) *Missiles capable of homing on jammers (See Chapter 10).*

APPENDICES TO CHAPTER 9

APPENDIX 9-A

CHECK LIST OF ECM TECHNIQUES

The following list gives a partial accounting of ECM techniques that might be used by the United States or the Soviet Union.

Chaff Techniques

- Area or corridor sowing of screen
- Area or corridor of false targets
- Deception (raid size), delayed action
- Break lock on fire control
- Break lock on AI
- Break lock on seekers
- Diffusing IR smokes

Jamming Techniques

- Preset spot
- Manual-spot
- Automatic spot
- Low-speed sweep
- Carcinotron sweep
- Barrage
- Time-sharing jamming
- Pre-detonating methods
- Towed transmitters
- Expendable transmitters

Homing Missiles (HE or nuclear)

- Radio seekers
- IR seekers
- Combination

Decoy Techniques

- Long-range area decoys
- Short-range local defense decoys
- Wind-blown decoys
- Power-driven decoys
- Passive and active methods of increasing apparent target cross section
- IR decoys

Receiver Techniques

- Navigation (U.S. radiation such as Texas Towers, or clandestine beacons)
- Warning for evasive action
- Control of ECM devices
- Interception of messages

Electronic Deception Techniques

- Raid-size deception repeater
- Range deception repeater
- Azimuth deception repeater
- Automatic track error repeater
- Insertion of false message in communication circuits

A. Bark

APPENDIX 9-B

SUMMARY OF EFFECT OF ACTIVE JAMMING ON DEFENSE RADARS

SUMMARY OF EFFECTIVE ACTIVE JAMMING ON DEFENSE RADARS

Radar		Nominal Range (n.mi.)	Range Against a Screened Bomber (n.mi.)
SAGE	FPS-3	150-200	8
	CPS-18	30	4-1/2
AI	(E Series)	10-15	1-1/2
Ship	SPS-6	80	2
	SPS-17	150-200	8
AEW	UHF	175	8
	APS-20B	80	5
	Sentinel		11
	FPS-7		31

W.P.G.Pretty
J.Keilson
D.S.Watson

APPENDIX 9-C

NOTES ON THE EFFECTS OF ACTIVE ELECTRONIC JAMMING ON RADARS

ASSUMED RUSSIAN POTENTIAL

In determining the effects of electronic countermeasures against U. S. radars, a number of important assumptions have been made.

Russia is credited with knowing the frequency bands used by all U. S. radars.

Russian knowledge of ECM methods is comparable with that of the U. S. In particular, it is assumed that Russia possesses the Carcinotron,* technical details of which have been published in unclassified documents in Europe.

Russia is prepared to sacrifice some 2500 pounds of normal bomber payload to enable each bomber aircraft to carry ECM equipment for self-protection, and will endeavor to jam all radar frequency bands. A suggested ECM package weighing less than 2500 pounds is shown in Table 9C-I.

TABLE 9C-I

POSSIBLE PACKAGE FOR NOISE JAMMING*

Frequency Band (Mcps)	Power Output (w)	Weight (lb)
9345 ± 30	500	200
2850 ± 150	1000	300
1300 ± 50	1000	400
600 ± 30	1000	1000
425 ± 25	250	250
220 ± 5	50	50

*Over-all weight of ECM package = 2500 pounds

The weights shown in the above table are a little less in pounds per watt output than currently available in U. S. production, but are believed achievable in the near future.

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*A wide-band oscillator of high power output, easily tunable over great ranges by simple variation of voltage, which will usually be noise for jamming purposes.

BASIS OF CALCULATIONS

In order to express the effects of ECM on the various radars that have been examined, reference is made to the "self-screening range" (R_{ss}) of the radar against the above package; this is the maximum range at which the radar response is visible through the jamming noise emanating from the package. Three self-screening ranges have been calculated: 100-m^2 target, 10-m^2 target and 2-m^2 target.

By associating the azimuthal discrimination or beamwidth θ with the self-screening range, it is possible to derive a mental picture of the extent of the jamming in the various cases.

The requirement that the target be just seen above the jamming noise is that the ratio of radar energy to jamming energy is sufficient for detection, and is expressed as follows:

$$\frac{\dfrac{P_{peak}\, G_R^2\, \lambda^2 \sigma}{(4\pi)^3\, R^4}}{\dfrac{PG_J}{4\pi R^2} \cdot \dfrac{G_R \lambda^2}{4\pi} \cdot \dfrac{1}{T}} = \left(\frac{S}{N}\right)_{min}$$

This can be rewritten as

$$R_{ss} = \sqrt{\frac{P_{peak}\, T}{P} \cdot \frac{G_R}{G_J} \cdot \frac{\sigma}{4\left(\frac{S}{N}\right)_{min}}}\ ,$$

where

R_{ss} = self-screening range (meters)

P_{peak} = peak power of radar transmitter (watts)

T = pulsewidth of radar transmitter (μsec)

G_R = gain of radar antenna

G_J = gain of jammer antenna

σ = echoing area of target (m^2)

TABLE 9C-II

CALCULATION OF SELF-SCREENING RANGES

Equipment	Use	Frequency Band (Mcps)	P_{peak} (Mw)	τ (μsec)	P_J (kw)	P (w/Mcps)	G_R (db)	G_J (db)	N_H	S/N (db)	R_{ss} (n.mi.) 100 m^2	10 m^2	2 m^2	θ (deg)
TPS-1D	Ground-based warning	(L-band) 1250 – 1350	0.6	2	1	10	27.5	5	48	0	7	2	1	3.6
TPS-1D Mod C	DEW 1955	(L-band) 1250 – 1350	0.16	6	1	10	30	5	96	−2	10	3	1	2.8
TPS-1D Mod X	DEW 1956	(L-band) 1250 – 1350	0.16	6	1	10	34	5	68	−0.5	14	4	2	1.25
FPS-3	Ground-based warning	(L-band) 1250 – 1350	2	3	1	10	33	5	26 (3.3 rpm)	1	26	8	4	1.3
FPS-7	Ground-based control	(L-band) 1250 – 1350	10	7	1	10	36.5	5	10 (6 rpm)	3	105	31	15	1.5
APS-20	AEW	2980 ± 20	2	2	1	20	35	5	12	3	15	5	2	1.5
Sentinel	DEW 1957 ?	600 ± 30	0.15	40	1	20	30	0	110	−2	34	11	5	2.7
AEW/UHF	AEW	425 ± 25	2	6	0.25	5	18.5	0	84	−1.5	23	8	3	10
AI (E series)	AI	9345 ± 30	0.25	0.5	0.5	10	36	10	10	3	2.5	1	0.4	3
AI (E series)	AI	9345 ± 30	0.25	2	0.5	10	36	10	10	3	5	1.5	0.7	3
SPS-6C	Ship-borne warning	1250 – 1350	0.5	4	1	10	27.5	5	15	2.5	7	2	1	3.5
SPS-17	Ship-borne warning	215 – 225	0.75	10	0.05	5	18	0	225	−3.5	22	8	3	27
CPS-18	Gap filler	2700 – 2900	0.6	0.5	1	5	35	5	96	−2	14	4.5	2	1.6

S/N = minimum signal-noise-ratio required for PPI detection and a function of the number of radar hits (N_H) on the target.

P = jammer power (watts/Mcps)

N. B. In calculating the effect of jamming against various radars, a number of assumptions have been made:

Regarding jammer antenna gain:

On the longer wavelengths, no gain has been assumed.

Against L- and S-band radars a vertical gain of 5 db and no azimuthal gain has been assumed.

Against AI's (X-band) a vertical gain of 10 db has been assumed on the basis that the fighter aircraft will not differ greatly in height from the target at ranges where AI jamming is important to the target.

The minimum detectable signal-to-noise ratios assumed have been chosen in conformity with the customary square root law for incoherent PPI integration.

CONCLUSIONS

Results of the calculation of self-screening ranges are given in Table 9C-II. A scrutiny of Table 9C-II reveals a situation of extreme gravity. The following examples may serve to illustrate this point:

In the DEW line, where Sentinel may in due course be deployed on the basis of a reliable range of, say, 150 to 200 nautical miles on a 10-m^2 target at 30,000 feet, the self-screening range on such a target in the presence of the jamming described will be 11 nautical miles.

In the case of picket ships equipped with SPS-17, the self-screening range on a 10-m^2 target is 8 nautical miles.

The self-screening range of AI's is as little as 1 to 1-1/2 nautical miles.

Such figures demonstrate that current plans for the deployment of ground-based, ship-borne, and airborne radars as at present conceived, must be reviewed radically. Any effort to regain contiguous cover by conventional means will involve a very substantial increase in the number of radar units, and hence in cost and system complexity. Moreover, it seems probable that system efficiency would be jeopardized as a result of this added complexity.

W.P.G. Pretty
J. Keilson
D.S. Watson

APPENDIX 9-D

THE DICKE FIX TO THE CARCINOTRON

A Carcinotron is a very-wide-band, rapidly tunable oscillator whose frequency is controlled by voltage. If this voltage is noise of 2-Mcps bandwidth, the frequency sweeps across the available bandwidth at a corresponding rate.

In the Dicke (Dr. Robert H. Dicke) fix, a wide-band input amplifier is followed by a limiter and then by an amplifier with the optimum radar bandwidth. The wide-band input-limiter combination confines the Carcinotron energy to a moderate amplitude and brief duration. The jamming noise-level increase is then smal and the radar signal legibility almost unimpaired.

The input band should be of optimum width. The presence of the Carcinotron signal suppresses the radar signal in the limiter. If the input band is too wide, the radar signal will be suppressed too long. If the input band is too narrow, it will ring too long and pass too much energy into the radar band. The optimum bandwidth ΔF is that whose natural decay time is equal to the average passage time of the Carcinotron frequency through it, i.e.,

$$\frac{1}{\Delta F} = \frac{\Delta F}{df/dt} \quad ,$$

where (df/dt) is the average frequency traversal speed of the Carcinotron.

If W is the jammer bandwidth, and f_N the bandwidth of the modulating noise voltage,

$$\frac{df}{dt} = \frac{\pi W f_N}{4} \quad ,$$

to a good order of magnitude, and

$$\Delta F \simeq \sqrt{W f_N} \quad .$$

When the Carcinotron jamming is present in the wide band, i.e., for time $1/\Delta F$, the signal is gone. The interfering duty cycle of the Carcinotron is then

$$1/\Delta F / 1/f_N = \sqrt{\frac{f_N}{W}} \quad .$$

Note that when f_N starts becoming comparable to W, the fix breaks down. For $f_N = 2$ Mcps, and $W = 100$ Mcps, the interfering duty cycle is only 15 per cent.

The ratio of clipping-voltage level C to thermal noise N_T determines the additional noise introduced (and the subclutter visibility). The ratio of jamming noise power to thermal noise power is given by

$$\frac{P_J}{P_{NT}} = \left(\frac{C}{N_T}\right)^2 \frac{\Delta f}{W} \quad ,$$

where Δf is the radar bandwidth. If $(C/N_T)^2$ is 20 db, $\Delta f = 1/2$ Mcps and $W = 100$ Mcps, the jamming noise is 3 db below thermal noise. We see that the system has ample latitude.

It must be emphasized that the fix will work only to the extent that $f_N < W$. As the noise becomes more "white," the fix breaks down. The thought immediately comes to mind that the simple expedient of using an untuned multimode echo box in the jammer antenna feed would make the noise more "white" and negate the Dicke fix.

D.J. Keilson
D.S. Watson

APPENDIX 9-E

TWO-STATION CORRELATION JAMMER LOCATOR

The paper superiority of the jammer in the jammer-radar paper battle calls for some attempt to make the radars work passably well even when they are jammed. It is obviously possible to use the jamming signals to pinpoint the jammers; that scheme will be exemplified here. This technique spots a jammer by correlating the jamming signal received by two radars. It is believed that work is proceeding at Rome Air Development Center along these lines, but we have not had time to examine that work. The two signals are relayed to some common point, variably delayed, multiplied and integrated. Each intersection of jamming strobes is tested separately. If the radars are rotating at 6 rpm, approximately 15 minutes will be needed if the intersections are not deliberately examined, that is, for continuous scan. With the present radars, rotation rates very much larger than 6 rpm are impractical. This implies that our radar has to stare along one jamming strobe at a time until the other radar has scanned along it. This is a fairly easy job of coordination, but it is a drastically different mode of operation from its ordinary one (which it probably should maintain, at least intermittently).

Differences in relative speed can be as high as 2×10^{-6}. At 1000 Mcps this gives a 2-kcps Doppler difference frequency. Antenna discrimination and the position and activity of the other jammers affect the discrimination required from correlation.

The chief question is how much interference from other jammers is likely to mar the estimate. It seems that between 20 and 30 db correlation improvement will be needed in a real-life environment. Suppose the upper figure is taken. 30 db means that the integrating bandwidth must be at most 1/1000 of the total bandwidth. If we use the entire video (1 Mcps), we must therefore use a band of integrating filters, say 500 cps wide, to allow for Doppler. A 2-msec integration time means that the jammer will remain well inside the intersection of the two antenna beams.

The system suggested by these considerations is shown in Fig. 9E-1, which should be fairly self-explanatory. The correlation computers (in the dotted area) are at some of the radar sites, or, perhaps, a number of them can be located at the central computer. In this latter way, different pairs of radars may be correlated by adjusting the variable delay, the video (microwave) links and perhaps, the integrating filters.

Necessary elaboration would include the coordination of the radars for alarm in the presence of jamming, coordinating the program of the antennas for inspection of jamming strobes and modifying the computer to analyze and handle the data.

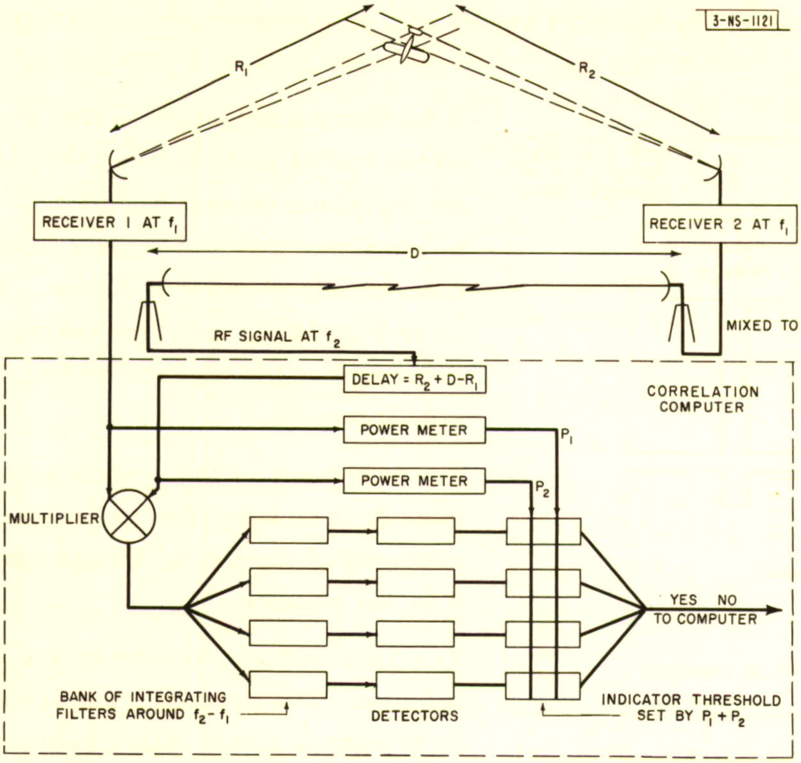

Fig.9E-1. Correlation detection by pair of adjacent radars.

Note that we have not considered height information. In the study we recommend, height information should be considered ab initio. Height information must be transmitted along the data link, and serves to differentiate between intersections.

Since this scheme envisions one radar's interrupting its ordinary antenna rotation, it was suggested that separate receivers do the job by rotating rather faster than usual. In its whole field of view, there are roughly 4×10^4 possible intersection boxes. For 2 msec per intersection, total scanning time would take 80 seconds for a single scanning beam, however the scanning be programed. This is comparable to what the altered radar operation would take, but it has the advantage of not affecting the large radars. This technique would not alter any of the previous conclusions or suggestions.

A possibility to reduce the scanning time is to provide the receivers with broader beams so that they could rotate faster. This would certainly work, but it would raise the level of the gain needed by correlation because of the likelihood of receiving more signals from other jammers. Another possibility is to use multiple receiver beams, each fed to separate correlators.

There is no doubt that such a system would be seriously expensive. That is, it represents expense in substantial extra equipment, more than mere modifications of the present system.

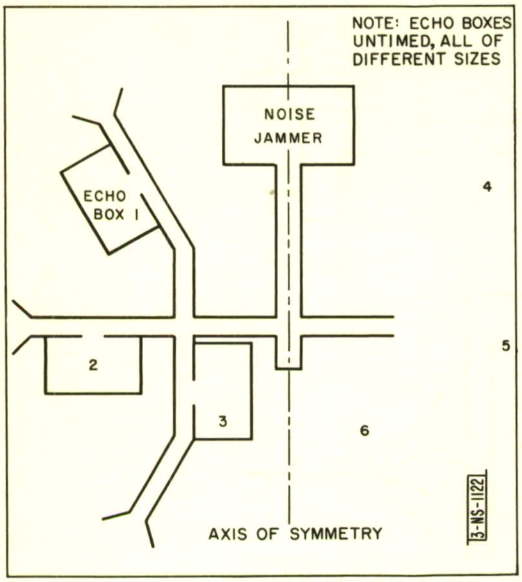

Fig.9E-2. Direction of signal sent from jammer.

A further disadvantage is that its action depends on the radial uniformity of the jamming signal. An ingenious enemy might find it advantageous to send uncorrelated signals in different directions by any of several means. For example, as in Fig. 9E-2, different untimed echo boxes could smear the signals feeding the jams in six directions.

The efficiency of the system cannot be easily judged; it is very likely to work with small numbers of jammers, though against a multitude it is not so sure.

The data-link requirements are large and expensive. The present links are 3 kcps wide on telephone lines. Our system would need 1-Mcps links joining adjacent pairs of radars or every radar with the central computer. Additions and modifications to the computer, while feasible, would not be simple.

O. G. Selfridge

APPENDIX 9-F

PASSIVE RANGE DETERMINATION TO A TARGET

It has been pointed out elsewhere in the Lamp Light report that air-borne intercept radars have certain deficiencies, even in the absence of countermeasures. In the presence of countermeasures, the difficulties are multiplied many times – particularly, it appears that the normal radar may be totally denied its range-determination capability. In the text that follows, there are pointed out measures whereby an AI radar may actually, under certain conditions, be improved by the presence of normal jamming; that is, its range may be increased and its ability to determine range may still be utilized to an effective degree when armament is in the form of guided missiles.

Let us imagine that the normal active radar is displayed on an indicator tube, but that a portion of this indicator tube is reserved for displaying passive information. For example, the top portion of the tube might be a conventional AI radar B-scan. The bottom portion of the tube could be used for an elevation-vs-azimuth display, and would then show elevation vs azimuth of targets carrying transmitters of some sort. Let us further imagine that the AI radar antenna is utilized for reception of both passive and active information, and that the antenna and receiving systems have so been instrumented that the antenna can lock on to a source of radiation and continue to track-in-angle that source of radiation. We could imagine such tracking to be instituted either by the echo from the target in normal radar fashion, or by reception from the target of signals emanating at the target. Once the antenna has locked on to the target, the angle of the antenna, with respect to an inertial reference as established by a gyroscope, may be utilized to fly the interceptor on a collision course with the target. This is achieved by flying in the direction at which the radar indicates a line-of-sight angular rate of zero.

Thus, if the pilot sees a target at a bearing which he feels corresponds to a target of interest, or, more particularly, if the signal emanating from the target is diagnosed (by suitable signal-interpreting means aboard the interceptor) as a signal emanating from an enemy target, then the interceptor is put on a collision course with the target by the means above described.

The question then arises as to how the interceptor may determine the range to the target with this simple, passive, listening scheme. The interceptor needs to know this range for two purposes – first, to ascertain if, indeed, the target is the one that he should chase; and second, to tell when the interceptor is close enough to the target to fire a missile. Of course if the interceptor, while on the collision course, happens to

Another method is to employ the angle D that the antenna makes relative to the space-stabilized reference. Equation (2), relating range R to antenna angle D, is also derived in Appendix R.

$$R = \frac{V_I \tau [\dot{\Gamma} \sin(\dot{\Gamma} t + \Gamma_o) + \frac{1}{\tau} \cos(\dot{\Gamma} t + \Gamma_o)]}{\dot{\Gamma} D \quad (1 + \tau^2 \dot{\Gamma}^2)}$$

$$+ [\frac{V_I}{D} (t - \tau) \sin \Gamma_o - \frac{V_I}{D \dot{\Gamma}} \cos \Gamma_o] \quad . \tag{2}$$

The latter method may provide additional smoothing because of the integrating characteristic of the antenna servo.

In these equations, λ is the angle between the radar antenna and an inertial line in space; Γ is the angle between the radar antenna axis and the interceptor ground track; and Γ_o is the value of Γ at the beginning of the turn, that is, just when the interceptor is changed from a collision course to the laterally accelerating course. τ in these expressions is the time constant of the radar antenna in reducing an error between its angle with respect to the true line of sight to the target. V_I in the above equation is the interceptor velocity, and $\dot{\Gamma}$ is the interceptor turning rate.

When typical values are substituted in the above equations, it appears that the turning of the interceptor at about 6° per second would be sufficient to measure target range to about 10 per cent accuracy when at a range of 30 miles. This assumes either infrared tracking or simultaneous lobing tracking. At greater ranges, the required time to determine range to the same percentage accuracy simply increases linearly with range.

It would seem that a computer could be built which would solve either of the above equations in relatively simple fashion. The computer would be fed data concerning the antenna angle, and the angle between the aircraft ground track and an inertial line in space. It would also have to be fed with aircraft ground velocity.

It is noted that the maneuver in the above fashion will not only determine the range to the target, but it will also give sufficient data to compute the target speed and target heading. It can also compute the range rate and, hence, the time to go. This information would appear very useful, but is not always provided with present interceptor instrumentation.

In order for this system to operate with accuracy, it is necessary that the rate of change of line-of-sight angle be measured accurately. With a conical-scan system or to get close enough to see the target visually, then range may be estimated by the usual measurement of subtended angle.

However, if this is to be an all-weather interception, it would be worth while to utilize some property of the arriving signal itself to determine range. Continuous observation of the angle of arrival of the signal has proved, in principle, to be sufficient to determine range if the interceptor makes an appropriate maneuver. The maneuver, which may be brought about by any of several means, will in any event, always cause the interceptor to go from one course to another or to oscillate continuously about some central course. It is the lateral excursions of the interceptor relative to a collision course which essentially provide a method of measuring range by measuring bearing to the target at more than one time interval. More particularly, at least the following three methods of manuevering would appear attractive:

> Method 1. A measurement of the gain around the closed guidance loop formed when the target angular tracker is used to keep the plane on a collision course. The gain measurement requires that a pilot carrier signal be injected somewhere into the loop. This pilot carrier will cause aircraft maneuvering a little to either side of the collision course;
>
> Method 2. Measurement of the error signal fed to the antenna to keep it pointing at the target, while the interceptor maneuvers from a collision course toward the line-of-sight course (described in Appendix 9-R, which will be summarized shortly);
>
> Method 3. Likewise, the rate of change of line-of-sight angle will determine target range when the interceptor maneuvers from any given course onto a collision course (described in Appendix T).

Lamp Light has not yet fully explored any of the above methods but, briefly, the indications are that at least methods 2 and 3 could be potentially useful. For example, a maneuvering off the collision course, as described in Appendix 9-R, can be used in either of two ways.

One method is to employ the error angle E, i.e., the angle between the antenna boresight and the line of sight from interceptor to target. The error angle E is proportional to the line-of-sight rate $\dot{\lambda}$, and lags behind it because of the antenna-tracking time constant τ. Equation (1), relating range R to error E, is derived in Appendix R (note that the error angle E is also the signal that actuates the tracking servo).

$$R = \frac{V_I \tau}{E(1 + \tau^2 \dot{\Gamma}^2)} \left[(1 + \dot{\Gamma}^2 \tau^2) \sin \Gamma_o - \sin(\dot{\Gamma} t + \Gamma_o) + \tau \dot{\Gamma} \cos(\dot{\Gamma} t + \Gamma_o)\right] . \quad (1)$$

with a monopulse system, this rate of change of line-of-sight measurement is, in general, proportional to the strength of the signal fed to the gyro to cause precession. This signal will, in turn, depend upon the signal strength received in the antenna, unless certain precautions are taken. It suffices to say that these precautions involve the use of suitable AGC or limiting techniques, or some other mechanism that compares the ratio of the right and left signals and the up and down signals, rather than their absolute magnitudes, in order to provide a gyro precession signal. By making the comparison in this way between left and right, the gain around the seeker loop is relatively independent of signal strength; consequently, the rate of change of line-of-sight angle is easily measured by measuring the signals fed to the gyro, which is precessed to coincide with the antenna angle.

For this sort of operation to be successful, the interceptor should fly at an altitude not much above 35,000 feet, so that the interceptor has available enough air density to pull high g's. When he gets to within the range at which his missile will operate, he will launch the missile even though this might involve a snap-up of the missile to some higher altitude where the target might lie.

The above technique is particularly applicable when there is only a single jammer or other source of radiation within the field of view of the antenna. If more than one jammer is within the field of view, the system can be confused fairly readily because the ability of the interceptor microwave receiver to employ beam splitting disappears when there is more than one target in the field of view, particularly if the targets utilize noise or programed jamming.

In order to handle this possibility, it would be desirable that the interceptor antenna have coupled to it an infrared telescope slaved to the same angle as the antenna. The infrared seeker could be used in those cases at high altitude where the target is visible at infrared, which provides a further measure against microwave countermeasures suitable programed. Both the radar antenna and the infrared seeker antenna would be slaved by the same intelligence, whether it be radar intelligence, passive microwave-received intelligence, or infrared-received intelligence. Appendix M describes methods that could cause such servo operation.to be controlled solely by that signal which, at the moment, appears to make the most sense; i.e., the signal most likely to be that of the target rather than of some extraneous jammer off the side of the target.

While the system described above is rather elegant and automatic for passive range determination, it would seem desirable in the near future – and even in the long run – to instrument the interceptors with an ability simply to home on radiation of a wide variety of wavelengths. For example, it would appear desirable to include the ability to home on radiation from a bomber altimeter or communications transmitter,[*] as well as radars, should they be needed for navigation. Another source of radiation that is useful to home on is enemy IFF. In order to insure that such IFF will be emitted, the interceptor should carry an IFF interrogator. This technique was used successfully against German fighters in the last war by Mosquito interceptors.

If we succeed only to the extent of making passive guidance of our interceptors and missiles as good as active guidance, we would still increase our chances of target destruction by not alerting the target. Natures many experiments have resulted in silence on the part of all beasts of prey.

D.E. Sunstein

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[*] Such homing devices may not give accurate angle information (particularly for long wavelength reception) and, hence, may not permit accurate determination of range in the manner described above. However, these homers can be relatively simple devices that would permit the interceptor to head directly at the target, rather than on a collision course, by simple DF techniques.

APPENDIX 9-G

INTERFEROMETER CANCELLATION OF JAMMING SIGNAL

It would appear possible to construct a radar range finder for use against targets which emit an appreciable amount of radiation on short wavelengths.

Suppose that three highly directional antennae A, B and C are mounted on a gantry, the directions of maximum gain of the aerials being at right angles to the gantry, and such that the distance AB = BC (Fig. 9G-1). Suppose, also, that the radiating target is at point X, then the distance to the three aerials taken in order is XA, XB and XC. It can be established that if d is the distance AB = BC and θ is the angle XBA, then

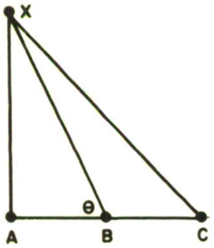

Fig. 9G-1.

$$R = \frac{d^2(1 - \cos^2\theta)}{(XC - XB) - (XB - XA)}$$

If the gantry is pointed at the target, θ is approximately 90°, and the expression becomes

$$R = \frac{d^2}{(XC - XB) - (XB - XA)}$$

The distance (XC – XB) – (XB – XA) can be measured as follows. Suppose that the signals on the link XC are delayed by some delay device not sensitive to frequency; then some setting of the delay will allow the signals received from antennas C and B to be balanced in a bridge network. If a similar device is fitted for antennas B and A, the difference of settings in the two devices will measure the distance (XC – XB) – (XB – XA).

There is probably a strong cycle-to-cycle correlation in the signals of certain types of jammer; thus, in order to avoid ambiguities, it is necessary to arrange that over the working region of the system the difference is limited to one wavelength.

If the antennas can be aligned reasonably accurately at right angles to the target, the differences in length between XC, XB and XA will be small, and a delay system of the order of only one wavelength may be sufficient, the correlation between sucessive RF cycles being satisfactory to absorb a certain number of unit wavelength differences between XC and XB, and between XB and XA. If delay systems were available which allowed considerable delays to be introduced, it might be possible to allow the antennas to be separately mounted, provided they are rotated so that they all point in the same direction. The cos θ term is then of importance. It will be noted that the delay system used must be insensitive to variations in the frequency over the band to which the detector on the bridge responds.

Suppose that the system is on 10 cm and that the minimum range that is to be measured is 5 miles, corresponding to approximately 9000 meters, then d must be 30 meters. When the path difference (XC – XB) – (XB – XA) is 5 cm, the range is 10 miles; at 1 cm, 50 miles.

It is not known to what accuracy the path difference can be measured. If it can be achieved to an accuracy of 0.1 cm (one part in 100 of the wavelength) an accuracy of measurement of around ± 10 per cent could be achieved at 50 miles.

The total width of the system would be around 70 to 80 meters, which sets a difficult engineering problem if the antennas have to be mounted on a gantry, since the mechanical variations of position must be held to a small fraction of a millimeter. Trouble may be caused by ground reflections.

The accuracies mentioned above may be more than adequate to determine whether a target is within range of a homing missile. It will be noted that only one source must be present in the antenna beams at the same time. Thus high directivity is required of the system.

D.S. Watson

APPENDIX 9-H

INTERFEROMETER TO MEASURE RANGE ON JAMMER

The fact that the source of jamming does not coincide physically with the source of the echo enables an interferometric solution to the jamming problem. This is technically difficult and would be considered only if the technique of limiting (see Appendix 9-D) were inapplicable. It should be emphasized that a basic difficulty with attempting to preserve active radar in the presence of jamming is that any solution is apt to be easily cirumvented by a relatively simple change in the jamming technique. The interferometric solution to be described is so complicated that it would be unwise to count on it.

As a simple example, consider a single aircraft carrying a single jammer. Assuming that the jammer radiation pattern from the aircraft differs from the reflected radiation pattern, it is possible to distinguish between the two types of signal and to eliminate the jamming signal by employing two widely separated on-the-site antennas in an interferometer arrangement. By receiving at two different antennas, the interference can be eliminating by adding the two signals together after delaying or advancing and attenuating one of the signals. A balance achieved in this way should be sufficiently good over the whole band provided very long radar pulses are employed. The jamming signal has been canceled but, because of the differences in radiation pattern, the return echo is, on the average, unweakened.

For purposes of a concrete example, it will be assumed that the range is 100 miles, that the wavelength is 5 cm and that the radar is to be used against an aircraft with a 100-foot wingspread. In order to be able to discriminate between the reflected and jamming radiation patterns, an antenna spacing of at least 300 feet would be required. For a 100 foot wingspread, and assuming the most frequency-sensitive jamming radiation pattern (i.e., radiators at the two wingtips), the bandwidth must be sufficiently narrow to allow sufficient cancellation over the entire band. This imposes a condition that the pulselength be greater than 10 μsec.

It should be indicated that this limitation on pulselength is not a fundamental one. If the bandwidth condition is not met, the cancellation can still be made complete, but the simple delay and attenuation are not sufficient to bring about cancellation. A complicated correlation-computing technique would be required.

Should there be a group of aircraft, each with its own jammer and separated by at least one-half mile in azimuth, the other aircraft cannot be neglected because of antenna sidelobes. However, if each antenna has multiple feeds, each with its own receivers, then by combining the data from two antennas placed 300 feet apart (each carrying 9 antenna feeds), 17 separate jamming signals can be canceled out by feeding the output from the 18 receivers into a computer designed to combine these signals to eliminate the jamming.

Representing jamming and target signals as complex numbers that are varying functions of the time,

$$A_j(t) = \text{complex number} = \text{signal in } j^{th} \text{ IF channel} \quad ,$$

$$J_{jk}(t) = k^{th} \text{ jamming signal in } j^{th} \text{ antenna} \quad ,$$

$$S_j(t) = \text{signal in } j^{th} \text{ antenna channel} \quad ,$$

$$A_j = \sum_k J_{jk} + S_j \quad ,$$

$$\text{Output signal} = \Sigma C_j A_j = \sum_{jk} C_j J_{jk} + \sum_j C_j S_j \quad .$$

As the equations

$$0 = \Sigma C_j J_{jk}$$

are 17 in number and the complex numbers C_j are 18 in number, the above equation always has a solution with the C_j's not all zero. This solution is such that

$$C_j S_j \neq 0 \quad .$$

Should there be more than one plane in the antenna beam, it is necessary to use more than two on-the-site antennas. Three jammers in the antenna beam will require four widely spaced antennas.

It should be emphasized that this scheme is very complicated and would be a poor solution in view of the ease with which it can be circumvented.

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Princeton University

APPENDIX 9-I

NOTES ON FEASIBILITY OF MISSILES TO HOME ON JAMMERS

It is felt that the greatest threat is from wide-band noise jammers. Such jammers simply and effectively block frequency shifting of radars from being effective. If missiles can be made to home on such jamming sources, the likelihood of jammer use is reduced. If those missiles already in the arsenal can have this ability added at small cost, their effectiveness will be increased.

Simple experiments and elementary considerations indicate that most, or all, radar target seekers will automatically give directional information on jamming energy. In most cases, fairly elementary alterations in circuitry are necessary to permit the seeker to recognize the jamming and to cause it to steer according to this directional information.

For the simple case of a single target carrying a jammer, the requirements on the missile seeker itself are that it recognize that the jamming interference is in fact a signal containing directional information and not system noise, and that it act on this information. In case the jammer fades, is turned off, or the radar signal-to-jamming ratio improves due to the approach to the target, the seeker must be able to switch back to the normal homing mode.

In the case of the conical-scan missiles at present planned for production, there will be an increase in tracking noise while passive homing on a noise source. This will result in a greater probability of miss, an increase in aerodynamic drag with consequent range reduction, and an increase in total control power consumption. In addition, radar influence fuses on or near the jamming frequency may also be jammed.

For all these reasons we should try to insure normal missile homing, especially at the latter stages of the flight. It would be desirable to use the following:

> Multiple senses for both homing and fusing; In particular, infrared auxiliary trackers and fuses. It would appear that a very small simple IR seeker of perhaps one-inch diameter would have sufficient range to be of considerable use in the terminal phase of flight (see Appendix 9-N).
>
> Active radar seekers, if practical. The signal-to-jamming ratio with active seekers improves inversely as the distance squared.
>
> Simultaneous-lobing (monopulse) antenna systems, if no great penalty is otherwise incurred. Where sufficient dynamic range and proper angular-detector design are employed, simultaneous- lobing antennas should not show a target noise increase when homing on noise.

Multiple jammers on close-spaced targets present a similar angular-resolution problem to that facing semiactive radar seekers. Resolution in a properly designed system then becomes similar to the radar case for semiactive systems. If the missile system is designed for an active radar, the antenna resolution may be insufficient for resolving multiple targets in the passive homing mode. In any case, the antenna should be designed to have the maximum directivity and minimum sidelobes.

Programed multiple jammers can be a more serious threat. However, all variations in jamming signal must be downward, increasing the likelihood that normal radar homing might be resumed. This is analyzed in Appendix 9-M, which shows that, with intelligent circuitry which knows what to ignore, the multiple programed jammer can also be handled.

Launching requirements of missiles, while not so critical as those for guns and rockets, are nevertheless sufficiently stringent, particularly in the matter of proper range at launch, that jamming of the AI radar may seriously impair system operation. Many missiles require accurate range information for any radar lock-on, as well as carefully controlled launching course. A missile system requiring only rough range and course gives much more latitude in the presence of jamming. Ground vectoring information, or some approximate range measuring scheme, such as described in Appendix 9-F, may then be used, if necessary, for missile launching.

All missile systems should be designed to have as much capability as possible against jammers – particularly noise jammers. In selecting missile systems for tactical use, effectiveness in the presence of jamming should be a major consideration. This should apply to the entire system and not alone to the missile. It is believed that considerable effectiveness, particularly in some systems, can be obtained cheaply and rapidly.

As a final caution, it should be remarked that since missiles capable of homing on enemy radiations can also home on friendly radars, IFF and communications, care should be exercised in their use.

W.R.Hutchins

APPENDIX 9-J

AUTHENTICATION IN ONE-WAY COMMUNICATION

The systems described above have in common the feature of effecting authentication in a one-way communication, with consequent relief from chatter in the return link. It was possible to accomplish this because it was assumed that sufficiently accurate clocks and methods for aligning them were available.

In the text that follows we shall briefly define a coding procedure which makes possible authentication in a one-way link without the use of clocks. The system in mind would consist of a central control station (e.g., a transmitter on the ground), which can address several receiving stations (e.g., interceptors in the air).

Transmissions are in terms of "frames" n-digits long. Each frame F is subdivided into smaller digit blocks as follows. First of all, a certain number of digits are needed to specify the address A of the plane to be contacted. To convey commands or messages, a block M is reserved; there are no restrictions on the nature of M. Next, a block of digits C, representing the order number of the frame is required. C is generated by the ground station by numbering each frame consecutively, independent of which plane happens to be addressed. A certain number of digits are further required to provide redundancy E. The block F would thus be of the form:

$$(A \;;\; M \;;\; C \;;\; E).$$

Redundancy can, of course, be introduced in many ways. Perhaps the simplest and also most useful way is repetition of any one of the blocks in the frame F. Either one of the following arrangements would do:

$$(A \;;\; A \;;\; M \;;\; C) \text{ or}$$

$$(A \;;\; M \;;\; M \;;\; C) \text{ or}$$

$$(A \;;\; M \;;\; C \;;\; C).$$

Actual length of the different blocks will depend on operational requirements, such as number of planes to be controlled, number of distinct commands available, amount of traffic expected, degree of authenticity desired, etc.

Again, depending on the application, redundancy can be increased by such arrangements as

$$(A \;;\; M \;;\; M \;;\; M \;;\; C),$$

and the like. If one prefers to leave open the type of redundancy coding to be used, frame F is simply represented by

$$(A \; ; \; M \; ; \; C) \, \epsilon$$

where ϵ now represents any transformation, on part of or on the complete frame F, which introduces redundancy.

Let us remain with a specific example, and choose as our basic frame

$$(A \; ; \; M \; ; \; M \; ; \; C).$$

Before transmission to the plane, this frame will be enciphered as a complete block by secrecy system S with the specific key K, represented by S_K. The enciphering transforms F into F'; i.e.,

$$(A \; ; \; M \; ; \; M \; ; \; C) \, S_K = F'.$$

The secrecy system S needs the following properties:

> The n-digits of frame F will be transformed by S into a new block of digits F', also n-digits long. Since, in general, each one of the digits in F' will depend in a very complex manner on all the digits of F, we shall not be able to claim any digit-position in F' as specifically belonging to A or M or C in F.
>
> The transformation must be reversible; i.e., it must always be possible to transform F' back into F without any ambiguity.

The frame F' is transmitted, and all planes receiving it decipher it, thereby obtaining the original frame F. Each plane checks the address conveyed by F. Only the particular plane that finds its address in F need pay any further attention to the communication. We shall, however, assume that all planes continue processing F. In the next test, it is checked if the digits of M are repeated as required. If this condition is fulfilled, the order number C will be inspected, for which purpose each plane carries a register in which it can memorize digits C. At the beginning of each mission, all planes clear their registers to contain zeros only.

Let us assume that the frame just being processed by our planes is the first one it received since take-off. Whatever the actual order number may turn out to be, it certainly must be larger than the number zero now stored in their registers. Only if C received is larger than C in the register can the communication be authentic. Whenever this is the case, the planes will clear the register and replace the old order number with the new order number C, for future reference. If any one of the planes, for one reason or another, does not change the contents of its register, no particular harm will be done as to future readiness of the system to be operable. The important thing is that the planes should not, under any circumstances, increase the order number in their registers unless they have established authenticity of frame F received.

After readjusting the registers, only the plane singled out by the address will pay any further attention to the communication.

Fulfillment of the three requirements on address, repetition and order number is considered sufficient to establish interest and authenticity, and effects acceptance of the command M conveyed by frame F. This method of authentication does not require uninterrupted transmissions and will allow addressing the planes in any order. The ground station is not burdened with complicated bookkeeping; all it must do is number consecutively the commands it transmits.

Any one of the planes, even if not contacted for some time, can easily recognize authenticity of a frame addressed to it. During intervals in which a plane is not contacted, it will not change the contents of its register. When finally an authentic communication arrives, F will have an order number larger than the C stored in the register, and being "larger" is the only condition on C. The effects of missing a frame are self-adjusted in later communications.

The system becomes saturated when the ground station has used up its reservoir of possible numbers C. When this threatens to happen, provision can be made to reset all registers to zero and start the system all over again with a new key K.

It is desirable to include among the set of possible addresses two special types, namely, "calling all planes" and "calling no planes." The first type would be useful, for instance, in resetting the registers. Frames tagged "calling no planes" would play the role of a null or dud, and would be completely ignored by all planes. This, of course, would not be obvious to an enemy. Frames of this type would be useful if an enemy attempted to effect response to his efforts by intercepting a legitimate frame F, while simultaneously jamming reception in all friendly planes. Having obtained a legitimate frame and having prevented proper advancing of any of the registers, the enemy could now interrupt jamming to retransmit the recorded frame. F' would now have the required "larger" order number, although the command it conveys may no longer be valid. A sufficient number of null-frames could lower enemy hopes for success in this sort of an approach as much as desired. A disadvantage of the larger order-number system is that all the digits within a frame F' have to be received correctly, because the particular enciphering process used here will introduce strong intersymbol dependences. A single digit received incorrectly may turn the decipherment into complete garble, which the plane will recognize and, hence, reject; but the intelligence will have been lost.

A remark may be in order as to the need for special redundancy since, in a sense, digits C already provide redundancy. Redundancy amounts to a required formalism. The constraint imposed on the code structure by requiring only a larger order number is, of course, not a very strong one. Certainly in the beginning of the operation of the system, it would be possible to select a frame F' at random and expect, with almost certainty, that upon decipherment it will yield a C which is larger than the C in any of the registers at that time. But if it is also required that digits M be repeated, the probability of accidental fulfillment of these conditions can, with blocks M of adequate size, be decreased as much as desired.

We conclude by observing that frames F of types such as the following are also suitable for authentication:

$$(A\ ;\ M\ ;\ C)\, S_K\ ;\ M\, S_K \quad , \text{ or}$$

$$(A\ ;\ M)\, S_K\ ;\ (M\ ;\ C)\, S_{K'}\ , \text{ or}$$

$$(A\ ;\ M\ ;\ C)\, S_K\ ;\ M .$$

In all three examples we have split F into two separate frames without destroying the authentication feature. Such splitting would be helpful if the number of digits in a frame F became too large for convenient enciphering in terms of a complete block. Enciphering would then be applied to the smaller "split" blocks. In the third example, the intelligence conveyed by M appears in the clear and is hence available to the enemy. Authentication, however is still effective.

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APPENDIX 9-K

AUTHENTICATED COMMUNICATION AND RECOGNITION IN SYNCHRONOUS SYSTEMS

With the consideration of high-speed automatic communication and control systems, methods that establish with adequate reliability the authenticity of a received communication become increasingly more important. It can be of great help for an enemy to record intercepted communications of the friend and consider their re-transmission later on, at his discretion and to his advantage. Transmissions of this type, in which an enemy attempts to appear as a friend, are often referred to as "deception" or "spoofing". Military activities provide ample examples as to what an enemy can accomplish by judicious use of spoofing techniques. Thus, in Korea, enemy transmission of false navigation signals has proved effective by guiding friendly planes into mountains or the sea. Reception and obeyance of faked commands, such as "retreat immediately" or "delay attack", has resulted in major disasters in many wars. It appears that authentication should be of central importance in control links where an automatic device, rather than a human brain, has to filter messages and decide on their acceptance or rejection. In many applications, any command but the correct one can be very harmful. Rendezvous techniques, communications in SAC, naval communications and missile control all depend on authenticity. Compliance of a friend to an illegitimate command to "reveal position and strength", or response of a beacon providing guidance to a foe, can seriously endanger any mission.

One might consider conventional IFF techniques as a possible countermeasure to spoofing. Use of this approach usually amounts to an inverse IFF, i.e., a method in which the receiver by some challenge-reply procedure, attempts to establish the command transmitter as a friend. Simultaneous use of IFF and inverse IFF is often referred to as "complete loop IFF". It is possible to arrange, by some such procedures, for the authentication of commands. However, since the approach involves dependence on correct reception of return communications, reliability is decreased. The most serious drawback is the fact that a return communication is for many applications not tolerable. "Return chatter" reveals the location of its source. Any kind of response that can be solicited at will by a foe can be fatal to those in need of concealment. This is true even if such a response, when initiated by a friend, can help to authenticate intelligence transmitted.

Let us consider a different approach to the authentication problem. The suggestions outlined below vitally depend on the realizability of clocks of sufficient accuracy. In what follows, we shall abandon the use of the conventional challenge-reply techniques of IFF. We shall regard "Authenticated Control" as the core to military communications, with IFF resulting as a by-product.

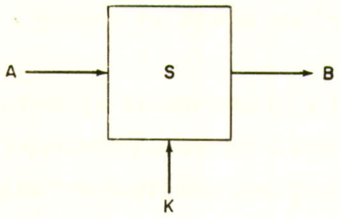

Fig.9K-1. Secrecy system in ordinary IFF.

Let us review, briefly, the use and resulting shortcomings of a secrecy system in ordinary IFF. In Fig. 9K-1, let S be any secrecy system (i.e., cryptobox) which one has selected for use. We shall here ignore the internal structure of S and merely say that its resistance against analysis by an enemy is assumed to be adequate for the application. S comprises an astronomically large number of possible transformations. Let K be the specific key, i.e., the specific combination in use. The box S has inputs A and outputs B. A and B are blocks of binary digits, or vectors. If we regard digits A as a plain-text, digits B would form their encipherment, or the cryptogram. In this particular way of enciphering A, it is required that digits A can be recovered from B, i.e., the transformations induced by the system must be reversible. Hence B must comprise at least as many digits as A. Other methods of communicating enciphered messages are described later.

In IFF, digits A would form the challenge; digits B, the reply. Clearly, the reply B could be shorter than the challenge A. Box S would be part of the transponder.

Let us inspect the sort of patterns of information that must be considered available to an enemy analyst in various applications. Digits B, whether we are dealing with communication or IFF, can always be intercepted and must therefore be assumed to be freely available to an enemy. In communication, digits A are, in general, not freely available to an enemy although he might attempt to guess them correctly. In IFF, however, even a passive enemy can listen to the challenges and replies of the friend and can collect them. In fact, at least in principle, an enemy can always challenge the transponder with any sequence A he desires and collect the corresponding reply B.

Let us refer to these three approaches to obtain material for analysis purposes as: (1) the probable-word method, (2) the certain-word method, and (3) the selected-word method.

It is possibility of using the selected-word method that introduces a serious burden to the designer of cryptosystems for conventional IFF.

In summary, the shortcomings typical of conventional IFF are:

> Due to the existence of (3) above, a complex system for crypto-encipherment is needed. This implies:

Strong intersymbol dependence and hence necessitates correct reception of every single challenge digit. The challenge is thus highly sensitive to interference and jamming.

Challenge-reply IFF provides a "cheap radar" on which an enemy may home.

Let us see what one might expect in advantages if one used a synchronous system. (A clock device now becomes the nucleus of the system. We shall introduce the type of systems we have in mind step-by-step, starting with the simplest possible arrangement, describing the central idea.) In Fig. 9K-2, we consider a transmitting station X and a receiving station Y. The problem is to arrange a procedure in such a way that station Y receiving a communication can recognize whether it was generated by a friendly source, here Station X. In both the transmitting and receiving stations, we have a clock device (plus generator) which feeds its synchronizing pulses into a counting device, say, an n-digit binary counter BC. The binary counter simply registers in terms of an n-digit binary number, or vector, the number of pulses emitted by the clock since it started, i.e., it tells the "time". An n-digit binary counter can count up to to 2^n pulses. Initially, the binary counter would register the vector consisting of n-zeros, i.e., time "zero". For each new pulse emitted by the clock, the binary counter BC will advance to the next higher number. At the end of the counting cycle the counter will register the vector consisting of all "ones".

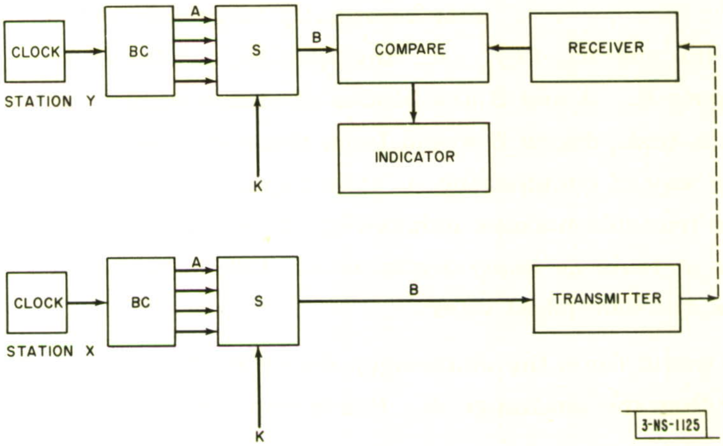

Fig. 9K-2. Synchronous system.

We shall use the time count registered by BC as the input vector A to the crypto-coder box S, i.e., we let box S encipher the "time". We thus use the "time" indicated by BC in the same way as a challenge is used in IFF. As in IFF, for each input vector A, the box S will manufacture a corresponding block of digits B. But here vectors A will be used in the specified numerical order – they form an ordered set or "s equence". For the sake of simplicity, let us use box S in such a way that for each input vector A it generates an output vector consisting of a single binary digit B.

For each new input A to box S, a new output digit B will be generated. As "time marches on", the sequence of input vectors A will cause S to generate a "stream" of corresponding output digits B. Let us denote the complete sequence of the 2^n distinct vectors A by A^*. Sequence A^* will hence generate a stream of 2^n binary digits B. Let us refer to the complete stream as B^*. When desirable, any individual digit B in the stream B^* will be specified by the subscript t which denotes its order number in the stream, i.e., the time at which it was generated. For an n-digit binary counter, stream B^* can be arranged not to be periodic for 2^n digits. It is evident that, even if the digits in the stream B^* are generated at microsecond rates, values of n are realizable for which the point of repetition will not occur for months.

Instead of using a sequence A^* which has numerical order, we could well use some generator other than a binary counter. Let us call the combination of sequence generator and secrecy system a "stream generator".

In any case, we assume that the respective clocks in X and Y are in synchronism, and that X and Y are "sufficiently" close together. At any given time-instant, X and Y will then generate exactly the same digits B_t of the stream B^*.

To identify itself as a friendly source, station X transmits digits B_t currently generated by its own stream generator. Station Y can compare each digit B_t received with digits B_t it locally generated at the properly corresponding time-instant (box labeled "Compare"). Increase in the number of matches identifies with increased reliability the received communication as generated by a friend.

We have here a scheme in which a friendly source identifies itself continually by saying over and over in the "required" form: "I am a friend."

Let us now take the next step and consider a little more refined system, based again on utilization of synchronized streams. In Fig. 9K-3 some Station X is again communicating with a Station Y, but this time we would like to be able to effect a response or action from station Y, whenever and only whenever station X so desires. We also require that no other station, say, one copying transmissions of X for re-transmission later on, or those trying their luck by transmission of random sequences to Y during periods of silence of X, should have much hope for success.

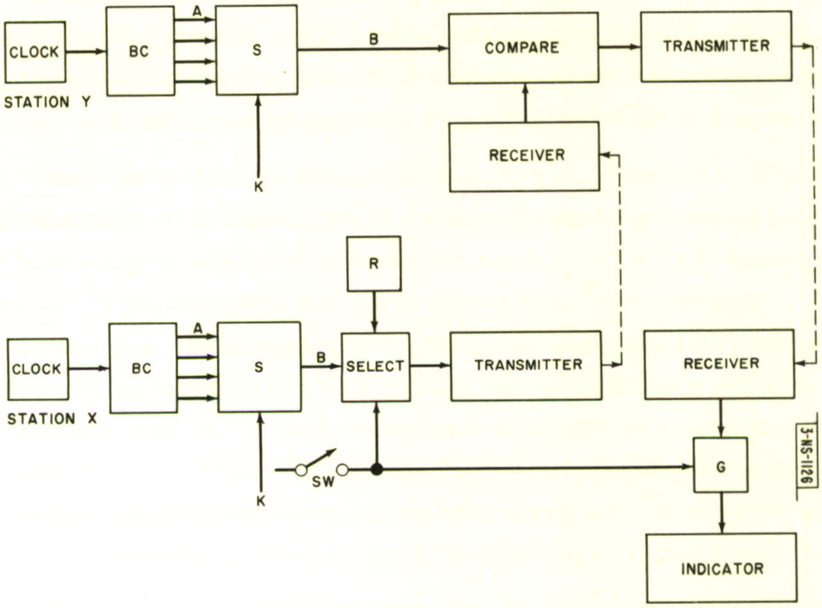

Fig.9K-3. Refinement of synchronized-stream system.

In the system now to be considered, station X is normally silent. As before, both stations X and Y generate in synchronism sequences B^*. Station X, however, with switch SW (controlling a selector-box) can now decide at will, whether it wants to transmit the digits B_t currently generated or simply some digits generated at random by generator R. If digits B_t are transmitted, station Y will recognize this when matching the received digits B_t with the corresponding digits B_t generated locally. If they match sufficiently often, station Y has, as before, established the source of the transmission as a friendly one. Once this information is established, it can be used to initiate in Y any action desired and agreed upon – for instance, a reply of some required type (e.g., a reply always consisting of a fixed number of special pulses).

Had we, instead of transmitting the correct stream digits B_t, transmitted random digits R, station Y would ignore the communication. An enemy could not effect a response from Y by re-transmission of earlier parts of B^* or some randomly chosen digits of his own. In either approach his chances for attaining the required degree of matching in station Y can be made as small as X and Y desire and establish by initial agreement.

We note that switch SW in station X is also used to open a gate to utilize the response received from Y to operate an indicator. Since station X knows when such replies should be received and when they should not be received, station X can also establish station Y as a friendly source. We have thus established mutual identification of sources.

Station Y, regarded as a beacon, would fire only when requested to do so by a friend. The system cannot be used by an enemy at will, as a cheap radar for homing, nor can an enemy analyst collect from the transponder replies to those inputs A to S which he might desire for attack on the crypto-system S. We refer to this type of a beacon as a "crypto-beacon".

Let us now summarize what advantages we have gained so far by the use of a synchronous system.

> An enemy can no longer freely challenge the transponder S. Since we grant him complete knowledge of the system in use (except for the key K) he will still know at each time instant the input to S, but he has to be satisfied with whatever this input may be. The position of the enemy is thus less favorable than in the case of challenge-reply IFF. His possibilities for collecting analysis material have now been reduced to the certain-word method. We thus expect that the task of the crypto-designer to arrive at systems with sufficient strength has been considerably eased. If this is so, we would expect a simpler black box for S.
>
> We are utilizing a crypto-system without introducing increase in susceptibility to interference or jamming. Interference with anyone of the digits B during transmission will not affect correct reception of any of the future digits B. The identification information here is thus no more sensitive to interference than a communication in clear-text, say, English, would be.
>
> Station Y responds to a friend only.
>
> We obtain mutual identification information.
>
> We have attained means for controlling any off-on function in Y, while this is denied to an enemy. Having accomplished this much we can, in principle, control any function.

So far we have outlined the authenticated reception of a yes-no command (here "reply" or "do not reply"). A simple modification of the scheme leads to a system allowing authenticated communication of any message.

In Fig. 9K-4, X desires to send a command to Y. X generates in synchronism with Y, as before, a stream B^*. We shall now utilize digits B_t to convey information M. Box M is the message generator. The digits generated by M (synchronized with C1) are added (mod 2) to the respective digits in sequence B^*, forming digits C and are then transmitted. Station Y, upon reception of digits C, adds the locally generated digits B_t to C, resulting again in digits M. If we assume that M in station Y generated binary digits representing English text, the human interpreter at station X will have no trouble in recognizing it as making sense and, hence, will accept it as "authentic". We note that M was assumed to be a source of information with statistical structure.

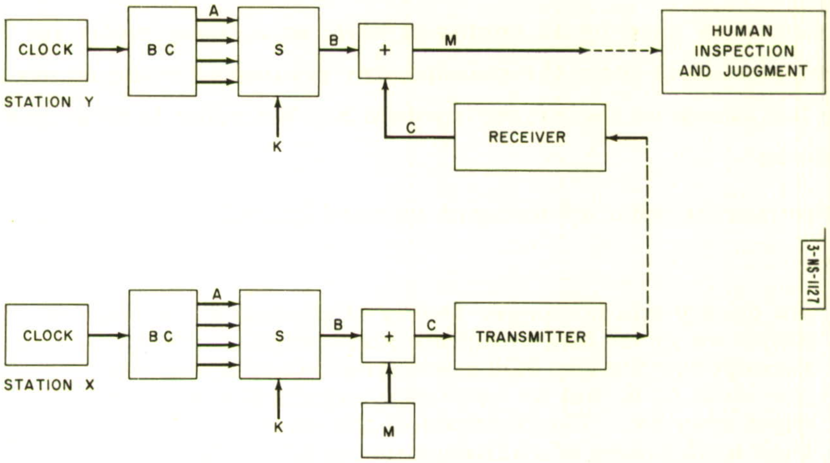

Fig. 9K-4. System for authenticated communication of any message.

Let us now consider the case of communication of an arbitrary digit sequence, lacking any redundancy or obvious specific meaning, such as might be encountered in an automatic communications link.

In Fig. 9K-5, we have now a source N which generates messages without any specific statistical structure – for instance, any one of 32 possible and roughly equiprobable commands in a 5-digit control code. For our purposes here, we may regard N as a source of digits zero and one selected at random, each block of 5 digits being assigned a meaning in form of a specific command, say, "turn right", etc., by agreement.

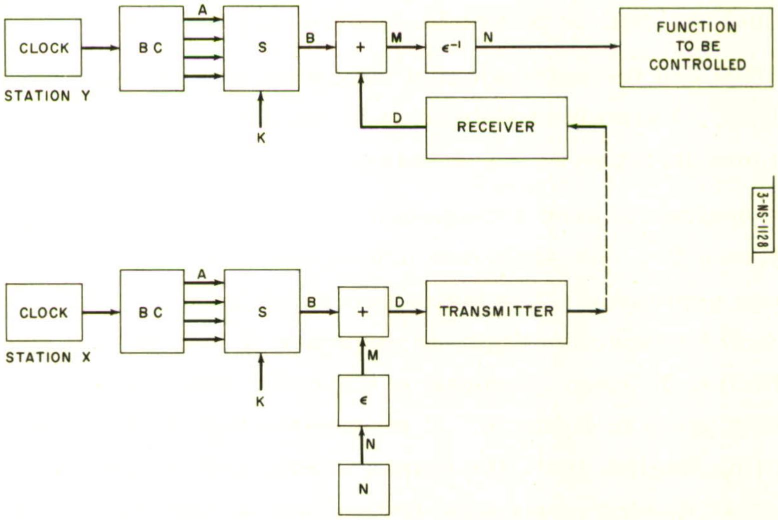

Fig. 9K-5. Modification of system of Fig. 9K-4.

We are now in a situation different from that of Fig. 9K-4, where the message source generated information with statistical structure, i.e., messages with redundancy. If we now transmitted the messages generated by a source of type N in the system represented by Fig. 9K-4, the addition box in station Y would supply messages that have simply random character. Neither a human being, as indicated in Fig. 9K-4, nor a machine could decide on this kind of evidence, whether the digits here received originated from a friendly source. This is true in spite of the fact that we assumed our clocks to be in synchronism and hence streams B^* to be of required structure. Had the clocks not been in synchronism, and had we therefore used in station Y a different part of the stream B^* than station X used, the digits M now resulting would, of course, again have no familiar structure – one block of digits being as probable and looking as legitimate as any other block. We can go one step further, noting that station Y would be no better or no worse off had it used for decipherment a stream $B^{*\prime}$ generated by flipping a coin or had it used some random stream supplied by an enemy, or had Y deciphered a random communication from the enemy with a correct stream B^*. Through lack of redundancy in the information source we have lost the ability of the system in Fig. 9K-4. to recognize "information which makes sense", i.e., the ability to authenticate.

In Fig. 9K-5, we have modified the system of Fig. 9K-4 to function even if sources of type N are used to generate commands.

We now introduce into the system a box ϵ which provides an appropriate type of redundancy to the digits generated by source N. The type of redundancy introduced should be something that a simple machine can recognize, such as mere repetition. A Hamming Code could also be used, but it would introduce intersymbol dependence, resulting in sensitivity to interference. To effect authentication, it is sufficient for ϵ to be an error-detecting code. Error correction, especially on a statistical basis, could provide an anti-jamming feature.

In Fig. 9K-5, let box ϵ convert nonredundant digits N into redundant digits M. The process will, of course, involve a "message expansion". As before, we now encipher digits M by addition to digits B, resulting in digits D, which we transmit. In station Y, we add digits D to digits B, obtaining again the digits M of required redundancy structure. Box ϵ^{-1} checks digits M for this redundancy. If they pass the test, box ϵ^{-1} removes the redundancy, with digits N resulting as desired. Since the redundancy test was passed, digits N can now be regarded as having been generated by a friendly source, and are hence accepted as "authentic".

We also note that decipherments with wrong parts of sequence B^* or random sequences B^*, or decipherment of digits D generated at random by an enemy, will not in general produce in box ϵ^{-1} the required redundancy, and hence "communications" of this type will be rejected as unauthenticated.

The systems outlined so far do not include provision for a return communication, except for the system of Fig. 9K-3, in which the return link carries a specified response.

In Fig. 9K-6, we present a system in which station Y can either upon authenticated request from station X, or upon its own initiative, freely communicate with station X. Typical applications might be acknowledgement of receipt of instructions from station X, or a reply to specific inquiries from station X, etc.

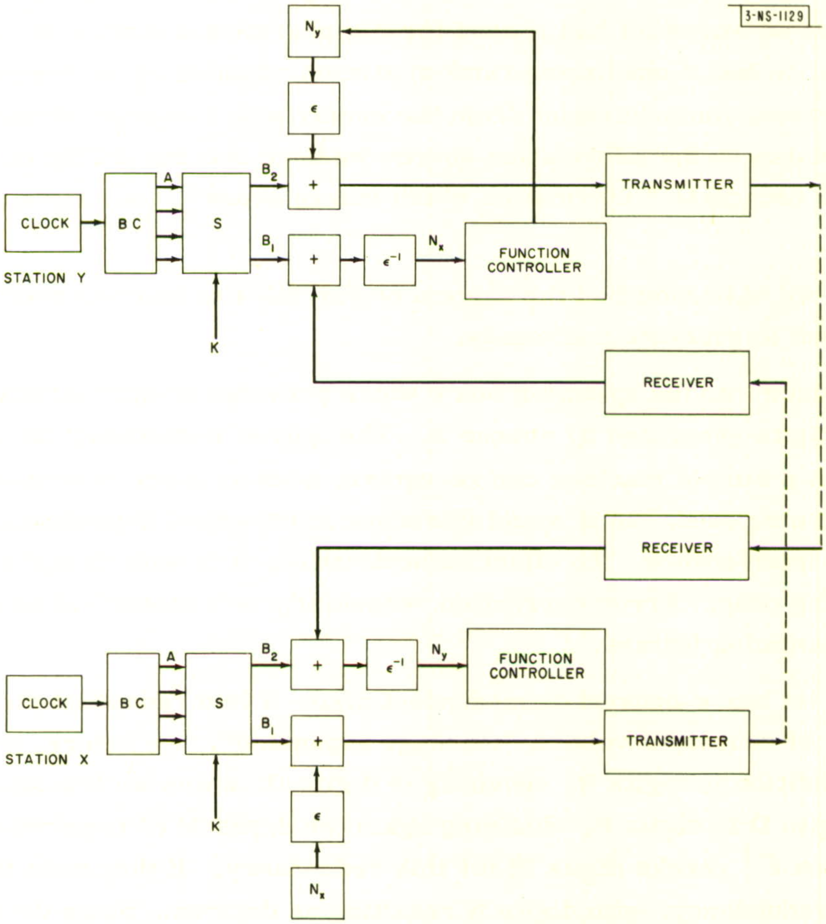

Fig.9K-6. System for free communication for station Y to station X.

Such an arrangement is possible without much change if we simply utilize box S or our stream generator in a different way. Instead of using S with only one output B as before, we now let S generate two streams for us, B^*_1 and B^*_2. If S is the right type of a secrecy system and used correctly, B^*_1 and B^*_2 will be distinct. In principle, it would be possible to let a box S with n inputs generate n output streams without requiring any significant changes in the design of box S.

Except for the return link, the system in Fig. 9K-6 is very much like the system in Fig. 9K-5. In station X, a message source generates messages N_x; box ϵ performs the redundancy coding. The output digits are again added (mod 2) to the digits of stream B^*_1 then valid and transmitted. In station Y, the local stream B^*_1 is used for decipherment, box ϵ^{-1} performs the redundancy check, digits N_x are recovered, and the function controller effects the instructions conveyed by digits N_x. In this example we assume that the function controller is instructed to request a return message from message source N_y. The digits N_y are, as before, coded for proper redundancy structure, enciphered with digits of stream B^*_2 and then transmitted to station X. In station X, decipherment with the locally generated digits of B^*_2 and checking by box ϵ^{-1} will recover and authenticate the message digits N_y.

The stream B^*_2 could also be used to form an IFF response, which in contrast to the fixed reply of Fig. 9K-5, would vary all the time.

Synchronized stream generators might also be useful in controlling repetition of narrowband transmissions at different times or on different channels to provide redundancy to effect anti-jamming. This type of time-frequency dodging may be regarded as a digital analogue-to-noise communication scheme.

Instead of using the type of stream generation outlined above, we could of course have used any supply of randomly selected binary digits – for instance, digits stored on tapes. The advantage of the type of stream generator envisaged here would primarily be that we need no longer worry about the digit storage problem which would otherwise be sizable for most communications applications.

One would expect authentication to be of interest in almost any military communication. Authentication is certainly necessary in any control function from which one wants to exclude an enemy. Guidance, navigation and recognition are typical examples.

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APPENDIX 9-L

REVIEW OF RANDOM-CARRIER AND CONJUGATE-FILTER TECHNIQUES FOR ANTI-JAMMING

THE NATURE OF JAMMING

The term "jamming" is used here to indicate the transmission of a radio signal by an enemy to disrupt radio communication between friendly stations. In order for jamming to be successful, the enemy signal must contain a component that, roughly speaking, appears to the receiver as a bona-fide friendly signal. For instance, since a conventional AM receiver is unable to discriminate between signals falling within its passband, it may be jammed by any enemy signal having, within its passband, a component of strength greater than that of the friendly signal being received.

The manner in which a jamming signal ultimately affects the output of a friendly receiver depends, to a considerable extent, on the mode of operation of the particular receiver. The friendly signal may be "masked" by the jamming signal, or it may be "distorted" beyond recognition, or it may be transformed into a different signal that could well have been sent out by the friendly transmitter. This last situation, which would result in the reception of erroneous data, can be made very improbable by properly designing the receiver.

Regardless of the detailed character of the ultimate effect of jamming, the vulnerability to jamming of any given communication system depends primarily on the ability of the enemy to generate a signal against which the receiver is unable to discriminate. Maximum jamming effectiveness is achieved by an enemy when his jamming signal is indeed identical to a possible friendly signal. Such a jamming signal may be produced, for instance, by picking up and retransmitting a delayed (or otherwise distorted) copy of the signal transmitted by a friendly station. Minimum jamming effectiveness results when the enemy transmits a random signal in the hope that some component of it will appear to the receiver as a friendly signal.

The first objective in designing a communication system that must operate in the presence of enemy jamming is to deprive the enemy of the ability to generate a signal similar to that generated by the friendly transmitter. If this objective is achieved, the enemy is forced to employ random jamming. Thus, the second objective is to reduce as far as possible the effectiveness of random jamming.

The following introductory example of how a communication system might be made less vulnerable to jamming will illustrate the above considerations. Let us consider an AM system in which the carrier frequency is changed discontinuously and randomly every

τ seconds. Let us assume that complete knowledge of the future changes of carrier frequency is available to the receiver beforehand, so that the local oscillator can be made to track the carrier at all times. The friendly receiver will then be in a position to detect the friendly signal just as in a conventional AM system. The enemy, on the other hand, not knowing the future changes of the carrier frequency, will be limited to injecting into the receiver a copy of the friendly signal delayed by some time τ_j. This delay cannot be smaller than the difference between the propagation time over the path transmitter-jammer-receiver and the propagation time over the direct path from the transmitter to the receiver. If $\tau_j > \tau$, the enemy will be unable to jam the receiver effectively.

If the enemy resorts to random jamming by transmitting white noise over the entire frequency band in which the transmission may take place, most of his power will be wasted. In fact, if the carrier frequency is equally likely to be at any point of a frequency bandwidth Δf, and if Δf_m is the IF bandwidth of the receiver, only a fraction $\Delta f_m / \Delta f$ of the jamming power will enter the receiver. We can say, then, that the use of a variable-frequency carrier reduces the vulnerability to jamming by the factor $\Delta f / \Delta f_m$.

The main disadvantage of the variable carrier system (apart from equipment complexity) is that it must occupy a frequency spectrum much larger than the bandwidth required by the data to be transmitted (the modulation bandwidth Δf_m). This disadvantage, however, is not so serious as it might appear at first, because other systems can operate in the same frequency band Δf without serious mutual interference. If the carrier frequencies are so perfectly synchronized that no two signals will ever occupy the same part of the spectrum at the same time, as many as $\Delta f / \Delta f_m$ channels can operate simultaneously. If, on the other hand, the channels are not synchronized, some interference will result. If S is the power of the desired signal and S_i is the total power of all interfering signals, the effective signal-to-interference power ratio will be

$$\frac{S}{S_i} \frac{\Delta f}{\Delta f_m} ,$$

just as in the case of random jamming. The maximum number of unsynchronized channels that can be operated simultaneously depends, of course, on the relative locations of transmitters and receivers.

STORED-REFERENCE SYSTEMS

The essential feature of the illustrative example discussed above is the random character of the carrier. Other types of random carriers (unpredictable by the enemy) can be used just as effectively. As a matter of fact, it can be shown that the performance of all such systems is essentially the same for the same bandwidth Δf occupied by the carrier and for the same modulation bandwidth Δf_m. We refer to this class of systems as "stored-reference systems" to stress the fact that complete knowledge of the time function used as a carrier (reference) must be stored at both the receiver and the transmitter to permit the generation of identical, synchronized time functions at the two ends of the communication link.

The basic mode of operation of systems employing random carriers is illustrated in Fig. 9L-1. The two boxes marked C – one at the transmitter and one at the receiver – are sources of identical random carriers. The carrier may be assumed to be random noise with a uniform spectrum over a frequency band Δf centered on some arbitrary frequency. Each of the boxes marked X is a conventional mixer followed by a bandpass filter of width Δf, and centered on a frequency equal to the sum (or difference) of the mean frequencies of the two input signals. Then, if $f_1(t) \cos w_1 t$ and $f_2(t) \cos w_2 t$ are the two inputs to one of these mixers, the output from the mixer will be

$$f_1(t)\, f_2(t) \cos (w_2 \pm w_1)t \quad .$$

The box marked LO is a local oscillator that may be modulated (amplitude, frequency, pulse, etc.) by the input signal. The box marked N is a source of disturbances (noise, jamming, etc.) that are added to the signal during transmission. Finally, the box marked Δf_m is a bandpass filter centered on the frequency f_o of the local oscillator; its bandwidth Δf_2 must be sufficiently wide to pass the modulated output of the local oscillator. We shall refer to Δf as the carrier bandwidth, and to Δf_m as the modulation bandwidth.

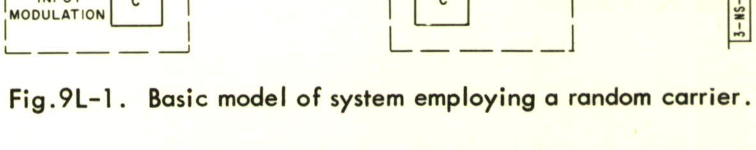

Fig. 9L-1. Basic model of system employing a random carrier.

When the local oscillator at the transmitter is unmodulated, the output from the filter Δf_m at the receiver is a sinusoid of frequency f_o (that of the local oscillator) plus some residual noise. It can be shown that, if $(S/N)_{in}$ is the ratio of signal power to noise power at the input to the receiver in the bandwidth Δf, the power ratio at the output from the filter is given approximately by

$$\left(\frac{S}{N}\right)_{out} = \left(\frac{S}{N}\right)_{in} \frac{\Delta f}{\Delta f_m}$$

provided that the ratio $\Delta f/\Delta f_2$ is much larger than unity. The same relation applies when the local oscillator at the transmitter is modulated. Thus, the over-all performance of the system can be determined in a conventional manner on the basis of the type of modulation impressed upon the local oscillator, using $(S/N)_{out}$ as the signal-to-noise ratio at the input to the detector. It can be shown further that random jamming is equivalent to additional noise, so that its effectiveness is also reduced by the factor $\Delta f/\Delta f_m$. A high-frequency communication system employing a random carrier has been constructed and tested by the Communications Techniques group in Lincoln Laboratory headed by W. B. Davenport, Jr. Identical random carriers are obtained simultaneously at the transmitter and at the receiver from quasi-random sequences of positive and negative impulses. Sufficient stability of synchronization is obtained by special techniques whose discussion is beyond the scope of this brief review. The random carrier occupied a band $\Delta f = 10{,}000$ cps, and the information band (for teletype transmission) was $\Delta f_m = 45$ cps. The theoretical improvement against random jamming of

$$10 \log_{10} \frac{\Delta f}{\Delta f_m} = 24\,\text{db}$$

was substantiated by test in the laboratory. Transcontinental tests indicated a comparable performance when a single propagation path was present. However, the performance deteriorated appreciably in the presence of multipath propagation. Attempts are presently being made to circumvent this difficulty. The reader is referred to the Division 3 Quarterly Progress Reports of Lincoln Laboratory for further information on this project.

THE USE OF CONJUGATE FILTERS

A different method of communicating by means of random signals, which may have some important advantages over the method illustrated in Fig. 9L-1, is based on the use of pairs of conjugate (matched) filters.[4, 8, 9] Two linear networks are said to be conjugate if they have the same amplitude response and

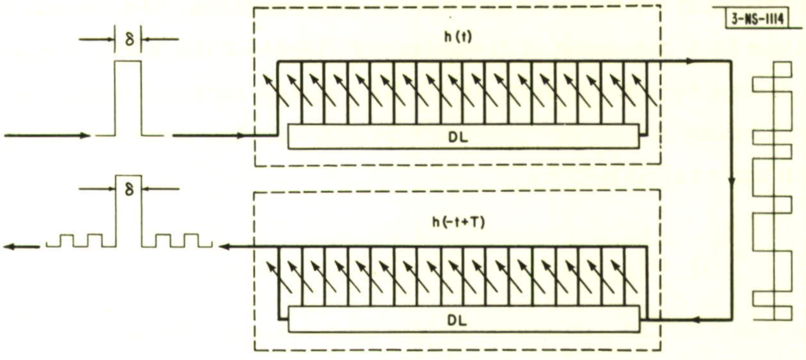

Fig. 9L-2. Operation of a pair of conjugate filters.

phase responses equal in magnitude but opposite in sign (apart from a constant difference in slope – that is, a constant delay). This is the same as saying that if h (t) is the impulse response of the other network is

$$h'(t) = h(-t + \tau_0) \quad ,$$

where τ_0 is a constant.

The manner in which pairs of conjugate filters may be used for communication purposes is illustrated in Fig. 9L-2.

The two devices indicated with DL are identical tapped delay lines with a maximum delay T. The delays of the successive taps should be approximately equally spaced for best operation but, in any case, should be identical for the two lines. The arrows on the outputs from the taps indicate the possibility of changing the polarities of the signals at will. Attenuation in the two lines is neglected since the magnitudes of the signals output from the taps can be equalized if necessary. It can be shown that the two filters formed by linearly superimposing the outputs from the taps are conjugate if the corresponding taps are connected with the same polarity.

Suppose now that a video (or RF) pulsewidth δ is fed into the upper filter. A chain of pulses lasting for a time T will appear at the output of the first filter. The polarities of the successive pulses depend, of course, on the polarities on which the outputs from the taps are superimposed. Suppose further that the output from the first filter is fed into the second filter, as indicated. The output from the second filter can be shown to consist of a large pulse occurring T seconds after the pulse was fed into the first, preceded and followed by a chain of relatively small pulses lasting for a total of 2T seconds. The ratio of the amplitude of the large pulse to the amplitudes of the small pulses can be made equal to at least $\sqrt{T/\delta}$ by proper design; thus the small pulses can be neglected for large values of the ratio T/δ.

It can be seen that the operation of the pair of conjugate filters amounts roughly to spreading over a time T the energy concentrated in the pulsewidth δ and then reconcentrating it into a similar pulsewidth δ. It can be shown further that, if a noise of power N within the band occupied by the filter is injected into the second filter, the signal-to-noise power ratio for the output pulse is approximately equal to T/δ.

While conjugate filters may be used with advantage in conjunction with various communication systems, their full potentialities are realized when used in the same manner illustrated in Fig. 9L-3. The boxes marked F_1 and F_1', F_2 and F_2' represent two pairs of conjugate filters. The box marked S represents a switch that may feed each input pulse to either F_1 or F_2. If the pulse if is fed to F_1, a corresponding pulse will appear some time later at the output of F_1', while no pulse of comparable amplitude will appear at the output of F_2'. The detector D can thereby determine the position of the switch S and, therefore, the binary instructions fed to it.

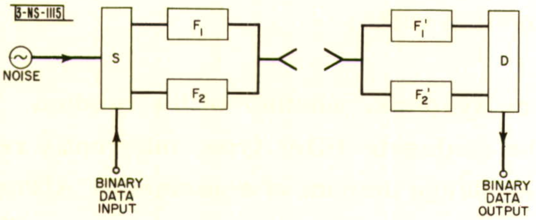

Fig. 9L-3. Binary system employing conjugate filters.

An important property of this method of communication is that it is asynchronous, at least in the sense that it does not depend on the timing of the pulses input to S or on the channel delay. Furthermore, if several propagation paths exist between the transmitter and the receiver, no fading or confusion will arise at the receiver so long as the difference between any two path delays is larger than δ and smaller than the time interval between input pulses. In fact, while the multiplicity of paths will result in several pulses being input to the detector, the function of the detector is merely that of determining the identity of the filter from which the pulses come, regardless of their number or time of arrival.

The performance of the system illustrated in Fig. 9L-2 in the presence of enemy jamming is essentially the same as that of the systems discussed in the preceding section, provided that the impulse responses of the filters are changed frequently enough to prevent the enemy from determining them. It should be noted also that a larger number of pairs of conjugate filters can be used, instead of just two, thereby increasing the rate of data transmission. Although a discussion of the maximum number of filters that can be used is beyond the scope of this brief review, it should nevertheless be stressed that the number of different filters can be increased exponentially with the keying period T, thereby making the rate of data transmission independent of T. Furthermore, all pairs of filters can be constructed from just one pair of delay lines by superimposing the outputs from the taps on different sets of polarities.

The scheme of communication outlined in Fig. 9L-3 has not yet been investigated experimentally to a sufficient extent to evaluate its feasibility. The key question is, of course, whether pairs of delay lines with a large number of taps (at least 100) can be built with delays that are stable within the required tolerances. Various methods have been suggested of constructing such delay lines (or equivalent devices), but none of them has yet been conclusively evaluated. It is the opinion of the writer that a determined effort should be made to construct suitable tapped delay lines, because of the important advantage that communication systems employing conjugate filters seem to offer in the presence of a multiplicity of propagation paths.

TRANSMITTED-REFERENCE SYSTEMS

Stored-reference systems, whether of the random carrier or of the conjugate-filter type, inherently require a relatively large amount of equipment. Although such equipment may eventually be packaged in a sufficiently small volume for airborne use, it would be well at this time to investigate the wide range of compromises that exists between equipment complexity and performance in the presence of jamming. Such compromises involve the transmission through a separate channel of the entire random carrier or of data that would permit the receiver to reconstruct it without the need of complex equipment.[2, 3, 6] The major problem, of course, is that such a transmission of the random carrier must be accomplished without enabling the enemy to obtain from it sufficient dats for effectively jamming the communication system. Since such a problem depends largely on the amount of time and of analyzing equipment and of jamming equipment that the enemy can afford to use in any particular tactical situation, it cannot be solved in general terms. The writer believes that a useful compromise should exist for line-of-sight communication in a region where the enemy jammer must be airborne. In such a case, the use of relatively simple secrecy features in the transmission of the random carrier should be sufficient to prevent the enemy from extracting useful information from such a signal. If a powerful ground-based transmitter could be used to fill the region with a sufficiently strong signal, different random carriers could be constructed in synchronism by a large number of transmitter-receiver pairs. The power advantage of this reference transmitter over the enemy jammer would probably be sufficient to keep the signal-to-jamming ratio above unity at all points of interest, thereby preventing random jamming from reducing the performance too much below that of stored reference systems.

The theoretical considerations involved in the evaluation of transmitted-reference systems are too involved to be presented here,[1, 2, 3, 6] and the various possible schemes that one may envision cannot be discussed further without reference to such theoretical considerations. Therefore, the writer can only express his personal belief that it would be highly worthwhile to investigate in detail the wide area of compromises outlined above in relation to the various tactical situations of interest.

CONCLUSIONS

Various possible methods have been briefly sketched by which the vulnerability of radio communication to enemy jamming can be reduced in principle by at least one order of magnitude. One of these methods has been tried with a considerable amount of success; the others are still at the paper stage, or very close to it. It is the opinion of the writer that great potentialities exist in the various schemes discussed and, therefore, that a determined effort should be made in the direction of their physical implementation and testing.

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APPENDIX 9-M

HOMING PASSIVELY ON PROGRAMED JAMMERS

The following is a rough approximation of the possible homing behavior of a radar homing missile, operating against two jammers spaced 2 nautical miles apart, in a head-on situation.

It is assumed that the targets will alternate their jammers in the manner most unfavorable to the missile.

Missiles are presently available which can resolve one of the targets when the line-of-sight angle is at least 3.5°, even when the two jammers are operating simultaneously.

The consensus of opinion of radar people at Lamp Light is that the addition of a small amount of circuitry can provide the missile with intelligence to disregard a large, abrupt change of signal after lock-on has been achieved, and to cause the missile to remember and to continue its turning rate as established after lock-on. The following calculations bear out the feasibility of such a plan, since they indicate that 10 seconds of memory is adequate to place the missile in a position where the signal strength received from the resolved target exceeds that from the target whose jammer is actively engaged in an effort to pull the missile off of its intended target. Ten seconds of flight after the minimum lock-on range has been reached results in a range-to-go of 11.5 nautical miles for the case of a 2-nautical mile target separation. This is considerably more range than is required for satisfactory interception. Indications are that successful homing can be reasonably expected against jammers separated by a distance of somewhat less than 2 nautical miles.

ANALYSIS

Assumptions

Antenna diameter (in.)	10
Resolution beamwidth (total deg)	7
Jammer noise (w/Mcps)	2
Active CW system	
System bandwidth (cps)	500
Target speed (m/sec)	270 (about 900 ft/sec)
Missile speed (m/sec)	630 (about 2000 ft/sec)
Target separation (n. mi.)	2 (3650 meters)
Effective navigation ratio of the homing system	4
Jammers cycled in an effort to confuse missile	

Referring to Fig. 9M-1, let

λ_T = line-of-sight from missile to the target resolved,

$$\lambda_T = \frac{1825}{R} \quad , \tag{1}$$

$$\dot{\lambda}_T = \frac{-1825\,\dot{R}}{R^2} \quad , \tag{2}$$

$$\dot{R} = -(270 + 630) = -900 \text{ m/sec},$$

$$R_o = \frac{1825}{\tan 3.5°} = 29800 \text{ m} = \text{initial range},$$

$$\dot{\lambda}_{T_o} = \frac{1825 \times 900}{29800^2} = 0.00185 \text{ rad/sec}.$$

$$\text{Turning rate} = \dot{\chi} = 4 \times 0.00185 = 0.0074 \text{ rad/sec}.$$

Thus,

$$\dot{\chi} = 0.424 \text{ deg/sec}.$$

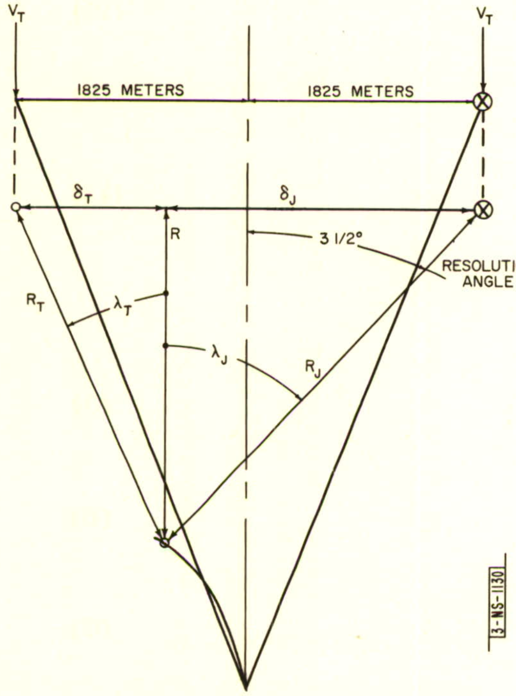

Fig. 9M-1. Homing passively on programed jammers.

The missile resolves the target. It turns at a rate of 0.42 deg/sec. After the target turns off its jammer, the other target turns on its jammer. The missile ignores this discontinuous command, and continues to turn at a rate of 0.42 deg/sec for a long enough time period to assure that the received signal strength from the target already resolved is greater than that from the now active jammer located in the other target.

$$R = 29800 - (V_M + V_T)\,t \quad , \tag{3}$$

where

V_M = missile speed,

V_T = target speed,

t = time (sec).

$$\delta_T = 1825 - V_M \int_0^t \chi_M \, dt \tag{4}$$

$$\delta_T = 1825 - V_M \int_0^t \dot{\chi} \cdot t \, dt \tag{5}$$

$$\delta_T = 1825 - V_M \frac{\dot{\chi} \cdot t^2}{2} \tag{6}$$

$$\delta_T = 1825 - \frac{630 \times 0.0074 \, t^2}{2} = 1825 - 2.33 \, t^2 \tag{7}$$

Similarly,

$$\delta_j = 1825 + 2.33 \, t^2 \quad . \tag{8}$$

Thus,

$$\tan \lambda_T = \frac{\delta_T}{R} = \frac{1825 - 2.33 \, t^2}{29800 - 900 \, t} \quad , \tag{9}$$

$$\tan \lambda_j = \frac{1825 + 2.33 \, t^2}{29800 - 900 \, t} \quad , \tag{10}$$

$$R_T = \frac{1825}{\sin \lambda_T} \quad , \tag{11}$$

$$R_j = \frac{1825}{\sin \lambda_j} \quad . \tag{12}$$

SUMMARY OF WORKING EQUATIONS

$$R_j^2 = \frac{1825^2}{\sin \lambda_j} \quad , \tag{A}$$

$$R_T^4 = \frac{1825^4}{\sin \lambda_T} \quad , \tag{B}$$

$$\lambda_j = \tan^{-1} \frac{1825 + 2.33 \, t^2}{29800 - 900 \, t} \quad , \tag{C}$$

$$\lambda_T = \tan^{-1} \frac{1825 - 2.33 \, t^2}{29800 - 900 \, t} \quad , \tag{D}$$

$$P_{Rj} = \frac{P_j \, G_{\lambda_j} \, \lambda^2}{(4\pi)^2 \, R_j^2} \quad , \tag{E}$$

where

P_{Rj} = power received from the jammer,

G_{λ_j} = antenna gain at angle λ_j,

λ = wavelength P_j = power transmitted by jammer.

$$P_{RT} = \frac{P_T \, G_o^2 \, \lambda^2 \, \sigma}{(4\pi)^3 \, R_T^4} \quad , \tag{F}$$

where

P_{RT} = power received from the resolved target,

G_o = antenna gain at center of beam,

σ = effective target cross section (m),

λ = wavelength P_T = power transmitted by missile.

$$\frac{P_{RT}}{P_{Rj}} = \frac{P_T \, \sigma \, G_o^2 \, R_j^2}{4\pi \, P_j \, G_{\lambda_j} \, R_T^4} \tag{G}$$

= ratio of target signal strength to jammer signal strength at the point where the missile may resume homing without further reliance on memory.

NUMERICAL DATA

P_T = 100 w,

P_j = 10^{-3} w,

σ = 10 m^2,

G_o = 23 db.

Antenna beamwidth is 7° at 3 db down; minimum antenna gain is 18 db down. This occurs at G_{λ_j} above 6°. Thus the missile is required to turn sufficiently to cause $\lambda_T + \lambda_j$ to exceed 6°.

Using Eqs. (9) and (10),

t (sec)	λ_j	λ_T
0	3.5°	3.5°
5	4°15'	4°
10	5°40'	4°23'
15	8°10'	4°35'

Using Eqs. (A) and (B),

t (sec)	R_j^2	R_T^4
5	6.03×10^8	469×10^{15}
10	3.42×10^8	325×10^{15}
15	1.62×10^8	270×10^{15}

At t = 10 sec,

$$\frac{P_{RT}}{P_{Rj}} = \frac{100 \times 10 \times 1000 \times (200)^2 \times 3.42 \times 10^8}{4\pi \times 3.16 \times 325 \times 10^{15}}$$

$$= \frac{4 \times 10^{18} \times 3.42}{12.64\ \pi \times 325 \times 10^{15}} = \frac{4000 \times 3.42}{12.64 \times 325\ \pi} = 1.05 \quad .$$

Therefore, if the missile is asked to remember its turning rate, as determined and commanded by the radar before the large jamming discontinuity occurs, it will have reached a position where it can completely ignore all jammer tactics, being able to home on the resolved target regardless of whether its jammer is on or off.

J.J. Jerger

APPENDIX 9-N

METHOD OF INTELLIGENTLY COMBINING THE OUTPUT SIGNALS

It has been suggested elsewhere in the Lamp Light report that multiple sensing will indeed be an attribute toward providing a counter-countermeasure for AI target trackers and for missiles, in case one sense is jammed.

This appendix is concerned with the methods whereby these multiple senses may have their outputs combined in such a fashion that jamming becomes extremely difficult.

The principal thing that should be attempted in designing an automatic weapon system to remove the threat of programed multiple jammers is to cause the weapon system to ignore what would be to a human pilot obviously foolish instructions. Such an arrangement may be easily achieved by utilizing a proper control characteristic in the output of each of the senses before combining these various outputs. For example, suppose that we have in the interceptor or missile two directional receivers – one for infrared, and the other for microwaves. Let us imagine that the infrared antenna is arranged through conical-scanning or other techniques so that an output signal is available from the infrared seeker circuit indicative of how far the infrared sourceis off the axis of the infrared antenna. Let us imagine, also, that we have provided out of the microwave antenna the usual sort of circuitry so that a signal may be produced which is proportional to how far the target is off the axis of the microwave antenna. In fact, we can produce two signals – one signal representing that of radar target reflection, and another representing that of jammer signals. The target signal would be gated in range or velocity, depending upon the type of radar system employed, and the jammer signal would be one responsive to a band of frequencies at least as wide as the radar bandwidth. These three sources are illustrated in Fig. 9N-1.

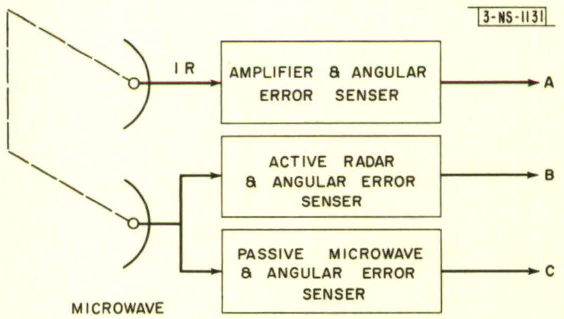

Fig. 9N-1. Sources of signals.

It is now desired to combine the three signals A, B and C so as to control the direction in which the two antennas are pointed (it will be assumed that both antennas are arranged to point always in the same direction).

Let us put in cascade with the output of each one of these channels a nonlinear device which has an output proportional to input over a limited range of input but, for inputs in excess of some predetermined value, the output of this nonlinear device will be zero. Such a device will then have a transfer characteristic as shown in Fig. 9N-2.

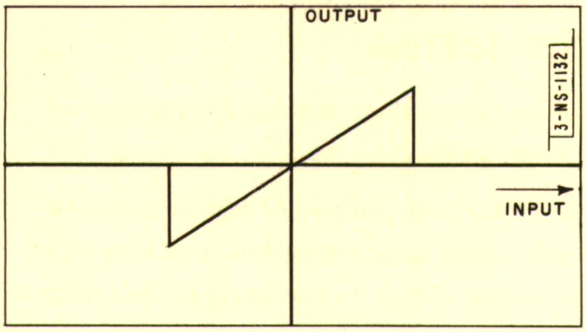

Fig. 9N-2. Nonlinear filter.

The output of such a device then will be zero when an instruction which is obviously foolish is fed to the input of the device. Thus after the antenna mechanical assembly tracking the target jammer properly, when that jammer goes off and a new jammer comes on the air which momentarily captures one of the senses, it will tend to cause out of that sensing circuit itself a very large output, but when fed through this nonlinear operation, the effective signal available to control the angle to which the antenna points will be zero.

Thus the over-all closed loop for the target tracker might include three nonlinear boxes each as shown in Fig. 9N-2, and each fed with a signal A, B or C of Fig. 9N-1 with the output of the sum signal utilized to control the antenna in one coordinate (for example, horizontally). A similar arrangement would be provided with three separate nonlinear boxes for controlling the vertical displacement of the antenna. Thus as long as any one of the three senses is working, smooth tracking is obtained. In order for the enemy to deceive such a multiple-sensing system, he must deceive each of the several senses and these all in a similar manner. This would indeed be difficult for those target ranges where all three senses are operative.

D.E.Sunstein

APPENDIX 9-O

ULTIMATE LIMIT OF RADAR BANDWIDTH REDUCTION THROUGH VELOCITY SORTING

The purpose of this appendix is to point out the eventual quantitative limitations of radar bandwidth reduction as a counter-countermeasure.

Let us assume that we utilize a coherent pulse radar, the output of which is range-gated into several range bins, the output of each range gate being fed into a bank of separate Doppler filters. Such a radar can be made either in the manner described (Argus at Lincoln Laboratory) or by utilizing Redap (as developed at Philco) to achieve the equivalent of range-gating without the complexity thereof, or by Sinufly (as developed by University of Illinois), which again does a comparable filtering job using storage tubes as frequency multipliers.

It can be shown* that the effective RF bandwidth Δf of the radar receiver is limited in principle only by the number of range bins N that are desired, and by the time on target (Tk $\Delta f = N/T$). Thus, if one is trying to determine range to 1 per cent accuracy, then about 100 range bins are needed; and if one is willing to let the antenna stay on the target for a second, then one could in principle reduce the bandwidth of the receiver down to 100 cps. This is an effective bandwidth ahead of detection. If range is desired to only one part in ten, then the effective bandwidth could be reduced to 10 cps. Present radars are not usually designed with this type filtering, but if and when they are, and if the jammer is of the Carcinotron type radiating one watt per megacycle, then only on the order of 10^{-5} watts appear in the 10-cps effective bandwidth. Assuming that the radar transmits a kilowatt average power and has an antenna

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*This expression is based on the following argument: If the antenna spends a time T on target, we must make the bandwidth of each velocity bin equal to or greater than $1/T$. If the radar is a pulse radar, then the maximum number of velocity bins M we can use is given by half the repetition rate of the radar divided by the bandwidth of each velocity-bin filter, i.e., $M = (\mathrm{prf} \times T/2)$. This limitation is caused by the fact that the transmitted signal is a line spectrum with grating spacing of the prf, and upon the fact that one cannot readily distinguish whether a received signal is from a Doppler-shifted adjacent transmitted spectral line, or from any other transmitted line. Likewise, if we utilize the maximum possible repetition rate to achieve N range bins in an unambiguous fashion, then the number of range bins that can be accommodated is equal to the reciprocal of the repetition rate times the pulselength. If we have N range bins, and if we choose a pulselength of the longest possible duration to accommodate these range bins, the minimum IF bandwidth is approximately $\mathrm{prf} \times N$. Since each velocity-bin filter of bandwidth $1/T$ is preceded by a range gate, the effective noise bandwidth to which the output of the filter will respond is not $1/T$, but $1/T$ multiplied by the IF bandwidth preceding the range gate, and divided by the rate at which the range gate is closed (prf). Thus, the effective noise bandwidth Δf that can cause a response in the output of each velocity channel is given by (IF bandwidth/$T \times$prf). Making a few simple substitutions from the above definitions, it is found that this equivalent noise bandwidth Δf is equal to the number of range bins divided by the time on target. This derivation is off perhaps by a factor of 2 or π, but should properly show orders of magnitude.

with a gain of 30 db, a target of 10 square meters will cause an echo equal to the jammer at 50 miles range. This assumes that the jammer is located in the target and that the jammer antenna gain is one. Hence, one could expect that ranges of less than 50 miles could be ascertained by the radar if the jammer were to continue to be broadbanded. (A standard radar, without both velocity and range sorting, would be good only out to 5 miles if it has a 100-kcps RF bandwidth.) The radar must be so contrived that the jammer is induced to spread his energy over this wide a bandwidth (1000-Mcps or more). In order to achieve this, it is necessary that the radar program its frequency in some unpredictable fashion over this entire range or, alternatively, it is necessary that a large number of radars be used, scattered over the 1000-Mcps bandwidth coverable by a single Carcinotron.

The above, therefore, bounds the degree to which the radars can be made immune to jamming of the noise type (i.e., standard radar is jammed for all targets beyond 5 miles, whereas coherent velocity sorting could increase the useful range to 50 miles, both figures assuming omnidirectional jammer transmitters). It is believed that some of this immunity can be bought at relatively little complexity of the radar, but it is also clear that other ECCM methods, set forth elsewhere in the Lamp Light report, for finding target locations in the presence of jamming must be explored actively for target ranges greater than 5 to 50 miles.

D.E. Sunstein

APPENDIX 9-P

PASSIVE DETERMINATION OF TARGET RANGE BY MANEUVER OFF COLLISION COURSE

The following calculations show that there is a possibility that range can be determined via interceptor maneuvers, by causing the interceptor to veer off a collision course with the target.

ASSUMPTIONS

The target flies a straight-line course at a fixed speed.

The problem occurs in a single plane.

The range does not change significantly during the time consumed in making the range determination,

Interceptor speed is constant and known.

The radar is able to "see" the target, and is able to resolve angular errors.

The tracking error, i. e., the difference between the boresight angle and the line-of-sight angle relative to a fixed reference is reasonably approximated by the equation

$$E = \frac{\tau\dot{\lambda}}{1 + \tau p} \quad , \tag{1}$$

where λ is the angle between the line-of-sight and a reference line fixed in inertial space, τ is the tracking time constant, and $p = d/dt$.

The interceptor attains maximum turning rate in zero time.

RESULTS

For a tracking time constant of 1 second, an interceptor speed of 1200 ft/sec, and a target flight path normal to the line-of-sight, it takes 10 seconds for the radar to register a tracking error of +0.08° and 20 seconds to register +0.19° at a range of 100 n. mi. if the interceptor turns toward the line-of-sight at a rate of 0.10 rad/sec. Turning away from the line-of-sight is much less effective. If we assume that a tracking error of 0.19° is sufficient to show through noise, the range error would be 1200 × 20 = 24,000 feet, or 4 n. mi. out of 100. Actually, this decrease of range would tend to make the tracking error slightly greater.

At a range of 30 n. mi., the tracking error is +0.14° in 6 seconds. This corresponds to a range error of 6 × 1200 = 7200 feet, or 1.2 n. mi., amounting to 4 per cent.

OPERATING TECHNIQUE

It was assumed that the interceptor would establish a collision course. Since the interceptor's radar tells him his flight path angle Γ, relative to the line-of-sight, and since interceptor speed is known, this operation in effect establishes the target's rate normal to the line-of-sight. The interceptor then executes a turn at maximum maneuverability. This causes a line-of-sight rate which is picked up by the fact that the radar continues to track the target, resulting in enough information to compute the range.

ANALYTICAL APPROACH

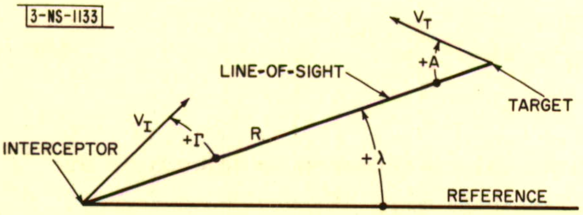


Fig. 9P-1. Determination of target range.

Referring to Fig. 9P-1, the line-of-sight rate is

$$\dot{\lambda} = \frac{V_T \sin A - V_I \sin \Gamma}{R} \quad . \qquad (2)$$

This approaches zero as the interceptor approaches a collision course. The interceptor turning rate is $\dot{\Gamma}$. After the interceptor has established a steady turning rate, the line-of-sight rate is

$\dot{\Gamma}$?

$$\dot{\lambda} = \frac{V_T \sin A - V_I \sin(\Gamma_o + \dot{\Gamma} t)}{R} \qquad (3)$$

Add to Eq. (3) the terms $(V_I \sin \Gamma_o / R) - (V_I \sin \Gamma_o / R)$. Then,

$$\dot{\lambda} = \frac{V_T \sin A - V_I \sin \Gamma_o - V_I [\sin(\Gamma_o + \dot{\Gamma} t) - \sin \Gamma_o]}{R} \quad .$$

But $V_T \sin A - V_I \sin \Gamma_o$ is zero, and essentially remains zero, since the line-of-sight angle changes only a negligible amount during the range-determination period, in so far as the target rate normal to the line-of-sight is concerned.

Thus

$$\dot{\lambda} = \frac{-V_I}{R} [\sin(\dot{\Gamma} t + \Gamma_o) - \sin \Gamma_o] \quad . \qquad (4)$$

From Eqs. (1) and (4),

$$E = \frac{-\tau V_I}{R} \frac{[\sin(\dot{\Gamma} t + \Gamma_o) - \sin \Gamma_o]}{1 + \tau p} \quad . \qquad (5)$$

Therefore,

$$\frac{dE}{dt} + \frac{E}{\tau} = \frac{-V_I}{R} \left[\sin(\dot{\Gamma} t + \Gamma_o) - \sin\Gamma_o\right] \quad , \tag{6}$$

$$E = e^{-t/\tau}\left\{\frac{-V_I}{R} \int e^{t/\tau} \left[\sin(\dot{\Gamma} t + \Gamma_o) - \sin\Gamma_o\right] dt + C\right\} \quad . \tag{7}$$

Therefore,

$$E = \frac{-V_I}{R} \; \frac{\left[\frac{1}{\tau} \sin(\dot{\Gamma} t + \Gamma_o) - \dot{\Gamma} \cos(\dot{\Gamma} t + \Gamma)\right]}{\dot{\Gamma}^2 + \frac{1}{\tau^2}} + \frac{V_I \tau}{R} \sin\Gamma_o$$

$$+ \left\{\frac{V_I}{R} \; \frac{\left[\frac{1}{\tau} \sin\Gamma_o - \dot{\Gamma} \cos\Gamma_o\right]}{\dot{\Gamma}^2 + \frac{1}{\tau^2}} - \frac{V_I \tau}{R} \sin\Gamma_o\right\} e^{-t/\tau} \quad . \tag{8}$$

The third term of the right-hand side is nil at time values required to determine the range. Thus,

$$E = \frac{-V_I}{R} \; \frac{\left[\frac{1}{\tau} \sin(\dot{\Gamma} t + \Gamma_o) - \dot{\Gamma} \cos(\dot{\Gamma} t + \Gamma_o)\right]}{\dot{\Gamma}^2 + \frac{1}{\tau^2}} + \frac{V_I \tau}{R} \sin\Gamma_o \tag{9}$$

E is the tracking error, output of the radar, and R is the unknown range. All other quantities are known. Therefore Eq. (9) uniquely determines the range, for the assumptions made. Thus,

$$R = \frac{V_I \tau}{E(1 + \tau^2 \dot{\Gamma}^2} \left\{(1 + \tau^2 \dot{\Gamma}^2) \sin\Gamma_o - \sin(\dot{\Gamma} t + \Gamma_o) + \tau \Gamma \cos(\dot{\Gamma} t + \Gamma_o)\right\} . \tag{10}$$

NUMERICAL CALCULATIONS

The following calculations were made to develop a "feel" for the magnitudes involved.

Assume $V_I/V_T = 1.2$. This assumption is not equivalent to assuming the target speed. It is employed only to determine the maximum interceptor heading relative to the line-of-sight during a collision course. The higher the interceptor speed advantage, the smaller this angle. Hence the choice of a small speed advantage.

Let

V_I = 1200 ft/sec.

$\dot{\Gamma}$ = ±0.10 rad/sec. ≈ 6°/sec

Since, for a collision course, $V_I \sin \Gamma = V_T \sin A$, $\Gamma_{max} = 56°$ (the case where target flies normal to line-of-sight).

Let

R = 100 n. mi. = 600,000 ft.

τ = 1 sec.

<u>Case I</u>: Using Eq. (9) and an interceptor turning rate of $\dot{\Gamma} = -0.10$ rad/sec, determine E at t = 10 sec.

$$E = \frac{-1200}{600{,}000}\left[\frac{\sin(-1 + 0.98) + 0.10 \cos(-1 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{600{,}000}$$

$$= -0.0002 + 0.00166 = +0.00142 \text{ radians} = +0.081° \quad .$$

<u>Case II</u>: Find E for $\dot{\Gamma} = +0.10$ rad/sec, t = 6 sec (long enough to make interceptor path perpendicular to line-of-sight).

$$E = \frac{-1200}{600{,}000}\left[\frac{\sin(+0.6 + 0.98) - 0.10 \cos(+0.6 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{600{,}000}$$

$$= -0.00197 + 0.00166 = -0.00031 \text{ radians} = -0.018° \quad .$$

<u>Case III</u>: Find E when $\dot{\Gamma} = -0.10$ rad/sec, t = 20 sec.

$$E = \frac{-1200}{600{,}000}\left[\frac{\sin(-2 + 0.98) + 0.10 \cos(-2 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{600{,}000}$$

$$= +0.001585 + 0.00166 = +0.00325 \text{ radians} = +0.186° \quad .$$

<u>Case IV</u>: Find E for $\dot{\Gamma} = +0.10$ rad/sec, t = 10 sec.

$$E = \frac{-1200}{600{,}000}\left[\frac{\sin(1 + 0.98) - 0.10 \cos(1 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{600{,}000}$$

$$= -0.00191 + 0.00166 = -0.00025 \text{ radians} = +0.0143° \quad .$$

<u>Case V</u>: Find E when $\Gamma_o = 0$ and $\dot{\Gamma} = -0.10$ rad/sec, t = 10 sec.

$$E = \frac{-1200}{600{,}000}\left[\frac{\sin -1.0 + 0.10 \cos -1.0}{1.01}\right]$$

$$= +0.001575 \text{ radians} = +0.09° \quad .$$

Case VI: Find E when R = 30 n. mi., $\dot{\Gamma} = -0.10$ rad/sec, t = 3 sec, for $\Gamma_o = 56°$.

$$E = \frac{-1200}{180{,}000}\left[\frac{\sin(-0.3 + 0.98) + 0.10\cos(-0.3 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{180{,}000}$$

$$= -0.00467 + 0.0055 = 0.00083 \text{ radians} = +0.0475° \quad .$$

Case VII: Find E when R = 30 n. mi., $\dot{\Gamma} = -0.10$ rad/sec, $\Gamma_o = 56°$, t = 6 sec.

$$E = \frac{-1200}{180{,}000}\left[\frac{\sin(-0.6 + 0.98) + 0.10\cos(-0.6 + 0.98)}{1.01}\right] \frac{+1200 \sin 56°}{180{,}000}$$

$$= -0.00305 + 0.0055 = +0.00245 \text{ radians} = +0.14° \quad .$$

Case VIII: Find E when R = 30 n. mi., $\dot{\Gamma} = +0.10$ rad/sec, t = 3 sec, and $\Gamma_o = 56°$.

$$E = \frac{-1200}{180{,}000}\left[\frac{\sin(+0.3 + 0.98) - 0.10\cos(+0.3 + 0.98)}{1.01}\right] + 0.0055$$

$$= -0.037° \quad .$$

Case IX: Find E when R = 30 n. mi., $\dot{\Gamma} = +0.10$ rad/sec, t = 6 sec, and $\Gamma_o = 56°$.

$$E = \frac{-1200}{180{,}000}\left[\frac{\sin(+0.6 + 0.98) - 0.10\cos(+0.6 + 0.98)}{1.01}\right] + 0.0055$$

$$= -0.0066 + 0.0055 = -0.0011 \text{ radians} = -0.063° \quad .$$

A check of the change in the line-of-sight angle λ for Case I shows that this is 0.44°.

RANGE RELATED TO ANTENNA ANGLE

The following is a derivation of the relationship between range and antenna angle.

$$D = \frac{\lambda}{1 + \tau p} \quad , \tag{11}$$

$$\dot{\lambda} = \frac{-V_I}{R}\left[\sin(\dot{\Gamma} t + \Gamma_o) - \sin\Gamma_o\right] \quad , \tag{12}$$

$$\lambda = \int_o^t \dot{\lambda}\, dt \quad ,$$

$$\lambda = \frac{-V_I}{R}\left[-\frac{1}{\dot{\Gamma}}\cos(\dot{\Gamma} t + \Gamma_o) - t \times \sin\Gamma_o\right]_o^t \quad ,$$

$$\lambda = \frac{-V_I}{R}\left[-\frac{1}{\dot{\Gamma}}\cos(\dot{\Gamma} t + \Gamma_o) - t\sin\Gamma_o + \frac{1}{\dot{\Gamma}}\cos\Gamma_o\right] \quad , \tag{13}$$

$$\frac{dD}{dt} + \frac{D}{\tau} = \frac{-V_I}{\tau R}\left[-\frac{1}{\dot{\Gamma}}\cos(\dot{\Gamma} t + \Gamma_o) - t\sin\Gamma_o + \frac{1}{\dot{\Gamma}}\cos\Gamma_o\right] \quad , \tag{14}$$

$$D = e^{-t/\tau}\left\{\frac{-V_I}{R}\int e^{t/\tau}\left[-\frac{1}{\Gamma}\cos(\dot{\Gamma}t + \Gamma_o) - t\sin\Gamma_o + \frac{1}{\dot{\Gamma}}\cos\Gamma_o\right]dt + C\right\} ,$$

$$D = e^{-t/\tau}\left\{\frac{-V_I}{R}\left[\frac{-e^{t/\tau}}{\Gamma(\frac{1}{\tau^2} + \dot{\Gamma}^2)}\dot{\Gamma}\sin(\dot{\Gamma}t + \Gamma_o) + \frac{1}{\tau}\cos(\Gamma t + \Gamma_o)\right.\right.$$

$$\left.\left. - \tau^2\sin\Gamma_o e^{t/\tau}(\frac{t}{\tau} - 1) + \frac{\tau}{\Gamma}e^{t/\tau}\cos\Gamma_o\right] + C\right\}$$

$$\therefore\ D = \frac{+V_I\tau}{R\dot{\Gamma}(1 + \tau^2\Gamma^2)}\left[\dot{\Gamma}\sin(\Gamma t + \Gamma_o) + \frac{1}{\tau}\cos(\Gamma t + \Gamma_o)\right]$$

$$+ \frac{V_I\sin\Gamma_o \times (t - \tau)}{R} - \frac{V_I}{R\dot{\Gamma}}\cos\Gamma_o + C\,e^{-t/\tau} \quad . \qquad (15)$$

when $t = 0$, $D = D_o$.

$$\therefore\ D_o = \frac{+V_I\tau}{R\dot{\Gamma}(1 + \tau^2\Gamma^2)}(\dot{\Gamma}\sin\Gamma_o + \frac{1}{\tau}\cos\Gamma_o) - \frac{V_I\tau}{R}\sin\Gamma_o - \frac{V_I}{R\dot{\Gamma}}\cos\Gamma_o + C ,$$

$$C = D_o + \frac{V_I\tau}{R}\sin\Gamma_o + \frac{V_I}{R\dot{\Gamma}}\cos\Gamma_o - \frac{V_I\tau}{R\Gamma(1 + \tau^2\Gamma^2)}$$

$$\times(\dot{\Gamma}\sin\Gamma_o + \frac{1}{\tau}\cos\Gamma_o) ,$$

$C\,e^{-t/\tau}$ is nil at the time values required to determine R.

$$\therefore\ D = \frac{V_I\tau}{R\dot{\Gamma}(1 + \tau^2\dot{\Gamma}^2)}\left[\dot{\Gamma}\sin(\dot{\Gamma}t + \Gamma_o) + \frac{1}{\tau}\cos(\dot{\Gamma}t + \Gamma_o)\right]$$

$$+ \frac{V_I}{R}(t - \tau)\sin\Gamma_o - \frac{V_I}{R\Gamma}\cos\Gamma_o \quad . \qquad (16)$$

$$\therefore\ R = \frac{V_I\tau}{D\dot{\Gamma}(1 + \tau^2\Gamma^2)}\left[\dot{\Gamma}\sin(\dot{\Gamma}t + \Gamma_o) + \frac{1}{\tau}\cos(\dot{\Gamma}t + \Gamma_o)\right]$$

$$+ \frac{V_I}{D}(t - \tau)\sin\Gamma_o - \frac{V_I}{D\Gamma}\cos\Gamma_o \quad . \qquad (17)$$

Thus, the dish angle D (measured with respect to space-stabilized reference) may be used instead of the error angle E used in Eq. (10), to compute target range.

J. J. Jerger

APPENDIX 9-Q

PREVENTION OF COMMUNICATION JAMMING

INTRODUCTION

In some communication systems jamming can be avoided, under favorable conditions, by suitable choice of frequency and by use of antennas having a null in the direction of the jammer. For example, in high-frequency communication, providing the circuit is distinctly different from the path to the jammer, in location or length, a frequency can be chosen which cannot be propagated from the jammer, due to conditions of absorption and ionization. However, jamming may occur when such measures are ineffective.

The following ideas are intended as spurs to more detailed analysis of the problem; they include proposals, applicable to all frequency bands, that will provide security against jamming in certain situations.

THE JAMMER AS A CORRELATOR

Under conditions in which the jamming signal originates from one location and is received at both terminals of the communication circuit, the jamming signal itself may be used as a correlator (see Fig. 9Q-1). The jamming signal, which may have an arbitary waveform but which will be assumed to be random noise, is received at both the transmitter and receiver on frequency f_1. At the transmitter this signal from the jammer is heterodyned in the mixer with the keyed-oscillator output at either frequency δf or $\delta f'$. The noise from the jammer is thus shifted in frequency by δf or $\delta f'$ for mark and space, respectively. The noise within the bandpass W at frequency f_2 is amplified and transmitted.

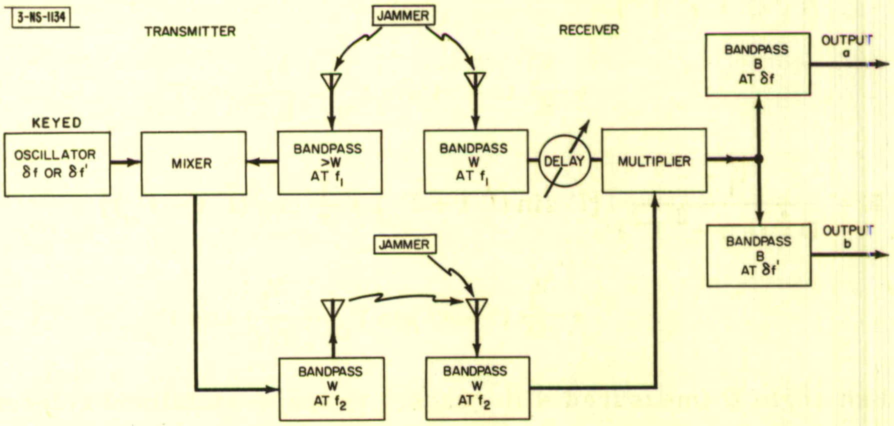


Fig. 9Q-1. Jamming signal used as a correlator.

At the receiver the same signal is received directly from the jammer at frequency f_1 and, indirectly, via the transmitter at frequency f_2. A variable delay is introduced at f_1 to compensate for the difference in propagation path. In addition, noise from the jammer is also received on frequency f_2. The signals are then multiplied together and the heterodyning frequency, δf or $\delta f'$, is recovered in the narrow-band filters at a or b for mark and space. If the jammer or the circuit terminals are moving, a means of varying the delay to adjust for the varying path lengths will be required. Also, the filters at the outputs a and b must be sufficiently wide to accept the Doppler shift.

This communication system will operate at a minimum signal-to-noise ratio of the order of $P/N >> 1/(2WT)$, where P is the signal power and N the noise power received on the communication channel f_2. The receiver bandwidth is W, and T is the transmission time for one bit of information. The signal-to-noise ratio required is thus given by one-half of the ratio of the information bandwidth to the receiver bandwidth.

It will be realized that this system has the same protection against jamming as obtained in single-channel noise-correlation systems using complicated means of reference-signal synchronization. The proposed system uses the jamming signal instead as a noise-free reference.

THE RETURN-PATH CORRELATOR

The jammer will not necessarily be operated continuously. Moreover, the use of the jamming signal to obtain correlation will not be feasible if the jamming signal is not received at both terminals of the communication circuit. Again, if several jammers are used simultaneously in separate locations, no single delay can be introduced to compensate for propagation-path differences.

The return-path correlator described in this section should provide protection when only one terminal is jammed. Figure 9Q-2 illustrates the principle.

A single noise source at the receiving terminal B provides noise in a band greater than W to an amplifier at frequency f_2. This noise is transmitted to the transmitting terminal A. Here it is heterodyned to frequency f_1 with the signal from the keyed oscillator at frequency δf or $\delta f'$ corresponding to mark and space, respectively. The noise passed in bandwidth W at frequency f_1 is amplified and transmitted to terminal B.

Noise from the same source is also passed at frequency f_2 through the bandpass W to a variable delay that compensates for the propagation-path delay from terminal B to terminal A and return. This noise on frequency f_2 is multiplied with that received from terminal A on frequency f_1. The oscillator frequency δf $\delta f'$ is recovered in the narrow-band filters B at a or b for mark and space.

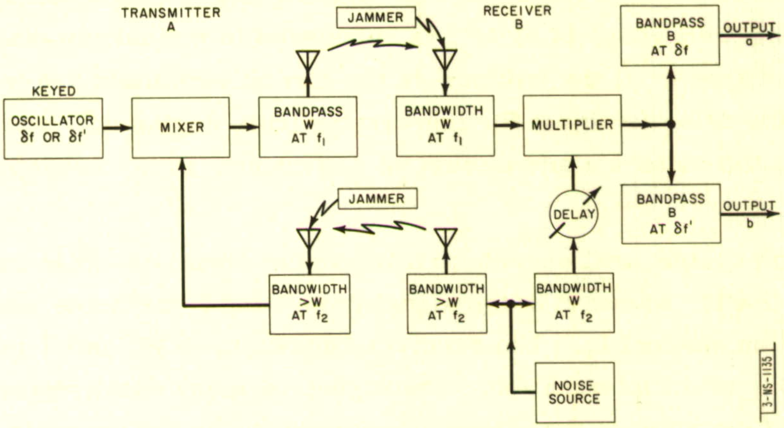


Fig.9Q-2. Return-path correlator.

This system will have nearly as great protection as a single-channel system when only one terminal is jammed. The minimum signal-to-noise ratio on which operation will be feasible will be given approximately by one-half the ratio of the information bandwidth to the receiver bandwidth, just as in the jammer-correlated system and in single-channel systems using complicated means of synchronization. Its important feature is that the reference noise, obtained directly from the noise source, is uncontaminated by external noise.

SECURITY

These systems have been proposed for protection against jamming. They are not claimed to be secure since, in both, the reference signal is transmitted and may be monitored with suitable equipment. However, in the return-path correlator, in the absence of jamming, the signal strength required may be many decibels below the ambient noise level. The transmission may therefore be concealed. Experiments made with a two-channel noise-communication system, in which transmission was in the same direction on both frequencies, proved that an ordinary receiver could detect no addition to the ordinary noise level while reliable communication was in progress.

J. C. W. Scott

APPENDIX 9-R

PASSIVE DETERMINATION OF TARGET RANGE BY MANEUVERING ONTO COLLISION COURSE

The following is a feasible procedure for determining target range, employing AI radar or infrared angular information. It appears to be superior to the procedure presented in Appendix 9-P in that measurements are made in straight-line flight rather than during a violent maneuver. A further advantage lies in the relatively simple computer.

Referring to Fig. 9R-1,

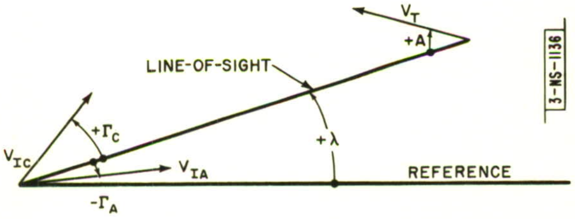


Fig. 9R-1. Determination of target range, using only radar information and a two-course procedure.

V_{IA} = interceptor velocity along an arbitrary straight-line course,

$-\Gamma_A$ = arbitrary interceptor course relative to the line-of-sight,

V_{IC} = interceptor velocity along collision course,

$+\Gamma_C$ = interceptor collision course relative to line-of-sight,

λ = line-of-sight angle relative to a line fixed in space.

Procedure

Step 1

Fly along the arbitrary course for a time period of at least three radar-tracking-system time constants.

Read the radar antenna angular rate pD, where D is the dish angle.

Read interceptor speed V_{IA} and course angle $-\Gamma_A$.

Compute $V_{IA} \sin \Gamma_A$.

Step 2

Turn to heading $+\Gamma_C$ along a collision course as determined by a dish rate of pD = 0.

Read interceptor speed V_{IC} and course angle Γ_C.

Compute $V_{IC} \sin \Gamma_C$.

Step 3

Compute range as follows:

$$R = \frac{V_{IC} \sin \Gamma_C + V_{IA} \sin \Gamma_A}{pD} \qquad \text{(A)}$$

Note that in cases where $V_{IC} \sin \Gamma_C$ is large enough to read through noise (crossing courses), Γ_A may be taken as zero, i.e., it is permissible to measure pD while flying along a heading parallel to the initial line of sight.

Proof

While flying the arbitrary course,

$$R = \frac{V_T \sin A + V_{IA} \sin \Gamma_A}{\dot{\lambda}} \tag{1}$$

V_{IA} and Γ_A are measurable aboard the interceptor While flying the collision course,

$$V_{IC} \sin \Gamma_C = V_T \sin A \quad . \tag{2}$$

Since V_{IC} and Γ_C are measurable aboard the interceptor, Eq. (2) measures $V_T \sin A$.

$$\therefore \; R = \frac{V_{IC} \sin \Gamma_C + V_{IA} \sin \Gamma_A}{\dot{\lambda}} \quad . \tag{3}$$

Since the dish is tracking the target,

$$pD = \frac{p\lambda}{1 + \tau_p} = \frac{\dot{\lambda}}{1 + \tau_p} \quad ,$$

where τ_p = radar tracking time constant.

If pD is measured after the passage of at least three time constants (3τ), it is essentially a measure of $\dot{\lambda}$.

$$\therefore \; R = \frac{V_{IC} \sin \Gamma_C + V_{IA} \sin \Gamma_A}{pD} \quad . \tag{A}$$

General Remarks

It seems that, no matter how we attack the problem, a certain amount of heavy maneuvering is required of the interceptor, for the simple reason that the development of a line-of-sight rate requires velocity components normal to the line-of-sight. Thus, if the target is on a crossing course, and the interceptor on an initial line-of-sight course, the line-of-sight rate will be adequate at once. Nevertheless, the interceptor must then maneuver rapidly through a relatively large angle (say, about 60°) in order to attain a collision course. On the other hand, should the interceptor find itself initially on a course that results in a very low dish rate, approaching zero, he finds it necessary to turn through a fairly large angle (again probably about 60°) in order to cause a sufficiently large line-of-sight rate for a decent measurement. He must then turn back through the same angle to a collision course.

Note that the dish angle is measured in two situations to provide interceptor course information, and that dish rate is measured in one situation to determine line-of-sight rate.

Range Rate

Having given a reasonable approximation of the target speed, it is possible to employ the above information for a rough determination of range rates. This can be done as follows: Since we know $V_T \sin A$, we can calculate A, the target aspect angle, using the approximate target speed. Thus, we can also compute $V_T \cos A$. Also available is $V_{IC} \cos \Gamma_C$. Thus,

$$\dot{R} = V_{IC} \cos \Gamma_C + V_T \cos A \quad . \tag{B}$$

J.J.Jerger

CHAPTER 10

AIRCRAFT AND WEAPONS

CHAPTER 10

AIRCRAFT AND WEAPONS

AIRCRAFT

The aircraft used in air defense are part of an overall weapons system. Their characteristics must therefore be coordinated intelligently with the ground environment, the communications, and the airborne electronics and weapons if we are to attain a well-balanced and effective defense.

The "state of the art" in aircraft design is such that the United States and Canada can provide the aircraft required by the several air defense systems studied in Project Lamp Light, on a time scale comparable with other developments, either by modifying existing aircraft or by designing new aircraft.

Presently Planned Supersonic Interceptors

These aircraft, when operating under fairly close ground or sea control, can achieve a high degree of effectiveness. System improvements, however, can be made in these aircraft to provide increased effectiveness against the estimated bomber threat, by the following means:

> Improved AI radar (see Chapter 3) to increase acquisition range, especially needed at low altitude. Such improved radars will probably require either larger antennas or multiple antennas.
>
> Aircraft and/or fire-control modifications, where necessary, to permit the use of nuclear air-defense weapons.
>
> Higher effective combat ceilings, obtainable either by the use of thrust augmentation (super fuel, rocket boost, etc.), or by exploiting the "altitude jump" capabilities available from air-to-air weapons.

Aircraft for the Remote Air Battle

These aircraft (see Chapter 13, Part II) are conceived as working in areas beyond the regions of close control, for the purpose of increasing the duration of the air battle in both space and time. These aircraft are characterized by:

> AI radar of significantly greater range, and probably antennas of larger size, than is required for interceptors working under close control.
>
> Long range and high speed, to provide the capability for early engagement and for multiple attacks during the subsequent "air battle in depth." Against fast-flying jet bombers, where the long-range interceptor described has no speed advantage,

multiple attacks are against different targets as the interceptor flies through an attacking formation. Against propeller-driven bombers, multiple attacks against a single target are possible.

Because of the larger number of attacks that are possible against a mass raid during such an air battle in depth, the number of air-to-air weapons that should be carried is greater than the number of such weapons carried by the close control interceptor.

More complete usage of the "altitude jump," speed maneuverability, and extended range capabilities of improved air-to-air weapons to attain improved effectiveness from the radar-weapon-aircraft combination.

Aircraft that are available and that appear adaptable to such an air-defense function in the 1957-1961 time period are of the medium jet-bomber class, e. g., the B-47, the B-66, the B-58 and the P6M. A supersonic version of such an aircraft concept is feasible, and could be operational in 1960-1961 if immediate action were taken to obtain it. The nature of the air-to-air weapons suitable for this type of aircraft is discussed in Chapter 13.

AEW&C Aircraft

The primary functions of AEW&C aircraft are to provide: early information; height finding; interceptor control.

Secondary functions that should be accomplished only if they can be done without significantly affecting the primary function capabilities are: trailing; self-protection.

The AEW&C aircraft must be designed, first and foremost, around the characteristics of the radar, the equipment and the operating personnel that are to be carried, the speed and altitude requirements of the radar itself, and for the mission ranges required by the over-all air defense system.

It appears that further study is required to determine if the presently programed AEW&C aircraft compromise the AEW&C functions when the required larger antennas (i.e., 30 by 8 feet instead of 17 by 4 feet) are carried. If the presently programed aircraft compromise the AEW&C functions, then prompt action must be taken to cure the functional shortcomings, either by modification of the present aircraft configuration or by promoting the design and procurement of suitable new aircraft as soon as possible.

ECM

While the effects of massive use of ECM (see Chapter 9) by the enemy against an air defense system are not yet fully understood, and the means by which such a tactic could be turned to our advantage have not been thoroughly explored, there is reason to believe that equipment and tactics are more heavily involved than is aircraft design.

Other

Essential to the development of any air defense system are targets against which the system and its components can be tested. SAC nicely provides opportunities for radars, both ground-based and airborne, to demonstrate their performance.

There is a deficiency, however, in expendable targets representing the radar cross sections and ECM characteristics, as well as the speed, altitude and maneuver capabilities, of present and anticipated enemy aircraft.

It is recommended, therefore, that target drones having these characteristics be developed and procured at the earliest possible date to assist all the elements in the air defense system, on a continuing basis, in developing and maintaining a high degree of proficiency and effectiveness.

WEAPONS

While weapons are an essential part of continental defense, Project Lamp Light has devoted principal attention to other areas, well aware of the various weapons studies sponsored individually and jointly by the Services, and has commented on weapons as they relate to the other areas of study on continental defense.

General Considerations

For weapons in continental defense, these factors are essential: effectiveness, reliability and availability. Present weapons are deficient in one or more of these. ECM prospects appear as a serious threat to the effectiveness of almost all the weapons systems considered, but the prospect is by no means one-sided. There is usually some way either to avoid or to utilize each countermeasure to the advantage of the weapon system. For example, wideband noise jammers can undoubtedly block several present weapons systems, but some weapons systems can, with slight modification, operate in spite of the jamming. Others can utilize the noise transmission for homing on it, for triangulation, or (at the least) to increase greatly the detection radius. More attention to adaptation of weapons systems for coping with countermeasure appears very much in order.

Air-to-Air Weapons

The primary immediate need is to demonstrate and build the generation of air-to-air missiles (AAM) to which we, as a nation, are already committed – such as Sparrow, Falcon and Sidewinder – improving especially the low-altitude performance, as much and as soon as possible.

Beyond this primary task, there appear to be real gains in providing small-yield nuclear weapons in ample supply, and with jump-up capability of 10,000 to 20,000 feet above interceptor altitude.

The use of guns and especially of rockets from aircraft is still important, particularly with warheads of improved lethality.

For any new guided missile to be undertaken in the next few years, particularly for long-range interceptors capable of multiple attacks, designs should provide internal stowage with space utilized more efficiently than present air-to-air missiles generally permit. The use of a low aspect-ratio, mono-wing design, to operate at high Mach numbers with substantial contribution from body lift, appears to have some advantages. Also, an entirely distinct system, utilizing warheads of at least several hundred and perhaps a few thousand feet lethal radius, appears to have notable advantage in several respects. Because miss distances can be substantial, the slow response of tail-controlled missiles, depending on body lift, appears reasonably satisfactory. Such missiles can be stowed internally without large space allowance for wings or fins, and can permit desirable loads to be carried without the drag penalties from external stowage.

The ideal guidance for such a missile system may be a two-radar command system, with one antenna tracking the target (the AI radar probably would perform this function), since this guidance system will permit the minimum energy (up-and-over) trajectory to be used for long ranges (i.e., approximately 25 nautical miles). However, other forms of guidance such as semiactive homing can be used, generally with limitations in range. It should be noted that the missile-tracking radar antenna of a command system such as this need not have large capture cross section, because the missile will carry a beacon. Several configurations can be considered: two separate antennas; coaxial mount with the small antenna either looking through the large one or mounted in front and blocking a small portion of the large one; or a lens system, with separate polarizations and separate treatment of the two radiations.

The missile itself will be essentially a pointed cylinder with small tail fins, which can efficiently be carried within the aircraft and later propelled through the air. Drag, weight and bomb-bay-space characteristics of such a missile appear favorable.

Surface-to-Air Weapons

The primary needs again are to demonstrate and build in significant quantity guided-missile systems to which the United States is already committed, such as Nike, Talos, Bomarc and Hawk. Low-altitude capability needs especial attention, with effort to obtain it on Nike, Talos, and Bomarc. (Hawk is being designed primarily for low-altitude use.) There appears to be substantial prospect of success in obtaining low-altitude capability, with different techniques for Nike, Talos, and Bomarc.

Surface-to-air missiles in general are capable of immense fire power with a high state of readiness after short notice. Their potential is seriously diminished if unduly restrictive rules of engagement are in effect, or if confusion of targets with friendly aircraft in large numbers is permitted. In spite of excellent electronic developments, it must be expected that mass attacks and certain low-altitude attacks will preclude accurate knowledge of the situation at any remote headquarters. Short-range weapons systems (such as Nike and Talos) must be authorized and instructed to fire at targets in certain categories without detailed instruction from the central headquarters.

Surface-to-air missile systems must be examined as to their effectiveness against air-to-surface supersonic missiles and, if possible, they must be made to cope with this type of threat. This is of especial importance with respect to the interception and destruction of the small high-speed (about Mach 2.0) high-altitude air-to-surface missiles, which appear to be within enemy capability by 1960 or shortly thereafter.

The susceptibility of long-range surface-to-air weapons systems, as represented by Bomarc, to serious target-tracking errors resulting from the enemy's use of massive broadband ECM techniques to deny to the data-gathering system the use of direct range and altitude measurements is of critical importance during both mid-course and the transition from mid-course guidance to active terminal homing.

The ability of the ground radars and the SAGE System to provide Fine Grain Data in the absence of ECM is not nearly so important as their ability to provide the necessary target-tracking accuracy to permit target-seeker acquisition when active ECM's are in use by the enemy.

Antisubmarine Weapons

While it is not necessary or desirable to review here the various weapons for use against submarines, it does appear worth while to point out the advantage and the technical feasibility of providing an antisubmarine weapon that requires very little time delay after positive sonar identification before destruction of any submarine target. This could be and should be achieved readily by a rocket-propelled antisubmarine weapon, provided the lethal radius of its warhead for underwater explosion is some 1 to 10 per cent of the range, with fairly simple and certain fire control. The availability and water-entry characteristics of such warheads are beyond the scope of this discussion, but the value to continental defense, if such antisubmarine weapons can be provided in the next few years, is noteworthy. A time saving of ten to fifteen minutes in destruction of an enemy submarine, once it has been located, can appreciably decrease its chance of inflicting casualties on our forces, or of escaping. The propulsion and fire-control techniques appear available.

AIR-TO-AIR MISSILES THAT HOME ON JAMMERS

The Need

Noise-jamming techniques can be used to reduce greatly the effectiveness of radar fire-control systems, radar-guided missiles and radar influence fuses, unless measures are taken to mete out severe damage to the user of jamming.

Effective use of enemy jamming signals can be made if weapons systems are developed which fully exploit the potentialities (see Chapter 9). The following facts serve as the basis for the development of a noise-jammer homing-missile weapon system. Discussion is limited to the case of an air-to-air missile whose objective is the destruction of attacking enemy bombers.

> The enemy must operate his jammer over the frequency band of the interceptor radar. Hence, a jamming-signal receiver with a reasonably narrow bandwidth can be used.
>
> The power of the jammer must be such that it renders reflected signals unusable by the interceptor's radar. Therefore, the interceptor jamming-signal receiver will do an effective passive search job at long ranges. A range of 100 miles or more is achievable.
>
> With a passive homing missile, the enemy bomber does not know when a missile is coming; hence, bomber defensive measures based on knowledge of approximate arrival time of missile are not operable.
>
> Enemy knowledge that we have an effective jammer-homing missile will tend to make him use jamming to a lesser extent and, therefore, make our equipment that is dependent on radar more effective.
>
> The enemy must consider and develop complicated tactics to use his jammers.

Technical Feasibility

Intercept receivers exist, or can readily be made, which will give directional information at long range. Intercept search for bombers can therefore be accomplished passively at adequate range. (See Appendix 9-I.)

Range information can be obtained from the jamming signal by a relatively simple interceptor maneuver. Several methods are available. In one of these the interceptor, upon acquiring the target, goes through a two-course procedure; one a straight course making a substantial angle (approximately 60°) with the line of sight to the target, followed by a collision course. A simple computer is required to automatically calculate range (see Appendix 9-F for further discussion of other possible tactics).

Because of the range-determination problem, missile systems that do not require accurate range information for launch are best suited for this application. The larger the operating envelope of a missile, the more versatile it will be when it is to be launched with range data obtained from noise jamming. It should be noted here that operation on noise jamming will increase the range and launching angle of those missiles that are now radar(seeker)-limited.

Target Angular Resolution

While the noise-jamming missile is passive in character, its target angular-resolution problem is essentially that of a semiactive seeker with a strong target signal. Target resolution at greater range is therefore obtainable. To get the highest possible angular resolution, the use of antennas with maximum directivity and minimum sidelobes is essential.

Appendix 9-M discusses in some detail possible jammer-homing behavior in the presence of two jamming aircraft 2 miles apart, alternating their jammers in a manner unfavorable to the missile.

The consensus at Project Lamp Light is that addition of a small amount of circuitry can provide the missile with the intelligence to disregard large abrupt changes in signal after lock-on has been achieved, and thus cause the missile to continue its turning rate as established after lock-on.

Calculations bear out the feasibility of such a plan. A 10-second memory is adequate to place the missile in a position where the signal strength it receives from the resolved target exceeds that from the enemy jamming aircraft actively engaged in an effort to pull the missile off its intended target. Ten seconds of flight after minimum lock-on range has been reached results in a range to go of 11-1/2 nautical miles for the case of a two-mile target separation. This is considerably more range than is required for interception. Indications are that successful homing can reasonably be expected against jammers separated by a distance somewhat less than 2 nautical miles. The presence of special warhead rockets and missiles will make grouping of planes at closer than 2-mile separations a questionable tactic.

Additional Operational Requirements

A jammer-homing-missile weapon system should be one with multiple sensing capability, since it must be effective whether noise jamming is present or not. The ability to home on noise jamming can be added to most existing homing missiles by relatively minor additions and changes. Switching must also be added to ensure that the missile can automatically (or by preset at launching time) select the stronger signal to operate on. Thus, the missile can operate in the absence of noise jamming; it can operate using a noise signal; it can switch from noise signal to radar signal if the jamming source is turned off or when the range becomes such that the normal signal overpowers the noise (if automatic).

While the ability to switch automatically from one mode of seeker operation to another appears attractive, emphasis upon this feature may be unnecessary. It would appear satisfactory to have systems in which the mode of operation was preset at launching time. The time of missile flight is short (10 to 30 seconds). The bomber must know accurately the interceptor's missile launch time to change between a noise-jamming and a "quiet" situation. With his noise jammer on, he cannot get this information. If the bomber is attempting to sneak in without emitting microwave radiation, he again will be unable to determine time of missile launch.

The system should also include in the missile an infrared sensing element to be used in terminal homing. Such an element, with a working range of one to two miles, can be packaged in a 2-inch diameter (possibly less). Such a sensing element would be effective against fast-flying bombers in both head-on and tail attacks.

A range calculator that automatically accepts the necessary inputs and then automatically puts out range information must be added. This computer is a relatively simple one that could feed its information directly to an autopilot, or visually to the pilot. The design of this computer should be considered in conjunction with the automatic navigation computer discussed in Chapter 7.

The tactical use of existing missile weapons systems, modified as indicated in this section, would be unchanged except for range determination for launch when noise jamming is used by the enemy.

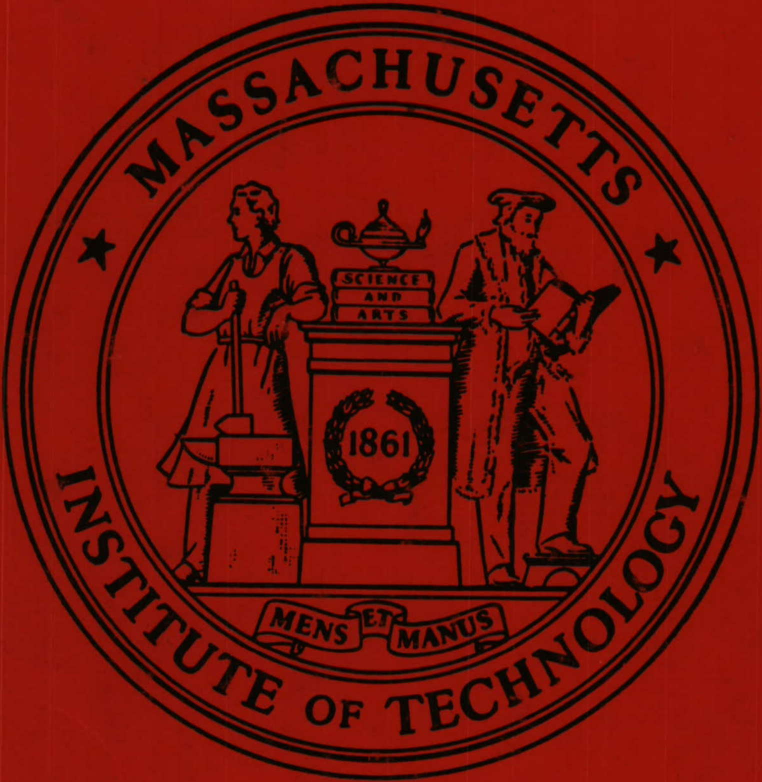
CHAPTER 10 RECOMMENDATIONS

1. Mount a noise source in a target airplane, modify an AI radar as necessary to insure tracking of that source, and determine angular accuracy obtainable. Such flight tests should be combined with limited kinematical studies. A number of companies appear to be in a position to do this almost immediately.

2. Develop and build an experimental computer based on results of (1).

3. Conduct studies of modifications to existing air-to-air missile systems toward the following objectives:

- *(a) To use noise-jamming signals for determination of range and direction.*
- *(b) To install infrared receivers in systems not now having them.*
- *(c) To install fuzes satisfactory in presence of countermeasures.*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DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA

DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC

3 September 2008

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Department of the Navy
Naval Research Laboratory
ATTN: Vicki L. Cicala
4555 Overlook Avenue SW
Washington, DC 20375-5320

Dear Ms. Cicala

Your letter dated 9 January 2008, requesting a Mandatory Declassification Review of the following documents:

S30921 Final Report of Project Lamp Light, Vol I DTIC AD0311318
S30922 Final report of Project Lamp Light, Vol II DTIC AD0311319
S30923 Final Report of Project Lamp light, Vol III DTIC AD0311320
S30924 Final Report of Project Lamp Light, Vol IV DTIC AD0311321

The appropriate Air Force agency has reviewed the documents IAW the Executive Order 12958, as amended, and finds we have no objection to the declassification and release of the Air Force information.

Address any questions concerning this review to the undersigned at DSN 223-2560 or COMM (703) 693-2560 and refer to case number 08-MDR-040.

Sincerely

Joanne McLean

JOANNE MCLEAN
Mandatory Declassification Review Manager

1 Atch
Documents for Review (S)

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