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MICROWAVE INTERCEPT SYSTEMS

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ABSTRACT

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Limitations of devices developed in World War II for monitoring enemy microwave transmissions led to a series of investigations at the Naval Research Laboratory on improved techniques for receiver control, signal display, and recording. These techniques are now being applied in the development of the AN/WLR-1 microwave intercept system. On continuous or repetitive microwave signals it is expected that the AN/WLR-1 will provide greater operational utility than has been available with previous equipment. Although the AN/WLR-1 employs a high-resolution superheterodyne receiver, it compares favorably in probability of intercept with receivers based on wide-open techniques. Use of unitized construction provides this system with a wide range of flexibility for future special installations. The speed of system operation is such that the rate of signal acquisition, of analysis, and of data storage will be limited by operator decision time instead of by equipment characteristics. Experience with the NRL system indicates the desirability and feasibility of supplemental improvements in the acquisition display, the manual signal store, the DF display, the recording camera, and the overall receiver noise figure. In addition, suitable attachments to provide monitoring facilities for shipboard jammers should be part of a future program. The AN/WLR-1 is the first prototype equipment that has techniques adaptable to the problems of coordinated operation of two or more intercept systems.

PROBLEM STATUS

This is an interim report; work is continuing on this problem.

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INTRODUCTION

The tremendous growth and expansion in electronic techniques during World War II, applicable to the tactical and strategic problems of military operations, coupled with the knowledge that these developments were roughly paralleled by electronic efforts within the military forces of the enemy spurred crash programs during the period 1941-45 to develop adequate receivers and direction finders to monitor enemy transmissions and, where possible, to provide "fixes" on enemy transmitting stations. Although most of these devices have long since become obsolete, they provided, nevertheless, the original tools through which our operating military forces acquired valuable experience, and demonstrated the importance of establishing the field of radio countermeasures as a permanent activity of the armed services. The period since World War II, including the "Cold War" and the Korean "police action," has served to further emphasize the phenomenal growth of enemy electronic applications to military problems. The armed services of the United States have recognized in this enemy activity both the opportunity for the collection of electronic intelligence and the need for increased effort to develop, and to have available for immediate operation, adequate systems for monitoring and fixing the source of these enemy radiations.

The first receivers developed during World War II for use in the microwave frequency range* employed manual tuning and provided little or no image or spurious signal suppression. In several cases they were calibrated in local oscillator frequency, requiring the determination of both image frequencies from which the signal frequency was calculated. Some receivers provided a wide range of possible operation in the frequency spectrum by means of manually installed, plug-in r-f tuning heads, and one receiver accomplished reception of signals in the range 3000 to 6000 Mc through second-harmonic mixing in the crystal mixer. The upper frequency limit of these early intercept receiver techniques was determined largely by the availability of satisfactory vacuum-tube oscillators. Although klystrons were available for spot frequencies as high as K-band for radar applications, those capable of wide-range tuning, with external cavities (such as the 707B, 2K28, etc.), were not successfully employed in experimental intercept-receiver prototypes until near the end of the war (X-MBT intercept-jam system), and no production receivers of this type were then available. Some of these klystrons were useful for frequencies up to about 4400 Mc but, generally speaking, the local oscillators most readily available for microwave intercept receivers were the "lighthouse tube" (later the 2C40), which was successful as a wide-range tuned local oscillator up to approximately 3100 Mc and the "acorn" tubes commonly used below about 500 Mc. With the exception of the experimental receiver in the X-MBT equipment, the receivers developed in World War II employed little or no preselection ahead of the first mixer, where conversion to the intermediate frequency was accomplished. Because of this last design deficiency, it was a characteristic of these receivers that local high-power radar signals produced so many spurious responses in the tuning range that practically all useful information from enemy signals was throughly obscured.

The development of the various World War II receivers was paralleled by the development of various devices intended to convert receiver outputs into forms directly detectable

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*For the purposes of this report the microwave radio frequency range is arbitrarily defined to include all frequencies from 50 Mc to at least 30,000 Mc.

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by auditory or visual means. The simplest of these devices were the audio transducers such as loudspeakers or headphones. Visual displays were developed such as the panoramascope for signal display, the video triggered servoscope for pulse-shape and time-width display, the cathode-ray-tube radial display employed with receivers and rotating directional antennas to provide signal bearing information, the comparison cathode-ray-tube display in which signal modulation frequencies were directly compared with locally generated, calibrated, variable frequencies for the purpose of measuring modulation frequency components, and the displays based on simple computing circuits which were intended to electronically measure pulse duration and pulse period for intercepted radar signals and to display the computer outputs on precalibrated milliammeter scales.

Looking back over the years since World War II and realizing that practically all of the electronic countermeasures devices developed prior to 1945 have now been superseded or discarded, one might be tempted to conclude that they proved to have little value and were poorly conceived and executed. When, however, the basic techniques developed in these early equipments are viewed in comparison with the "state of the art" of their times, it is clearly evident that they represented great technical strides forward and provided field operational ability which had never been available before. It seems certain now that it was through the operational experiences based on these first technical achievements that not only the tactical and strategic importance of radio countermeasures was well established but also the necessity for vast technical improvements in field operational equipments was made evident.

Well before the end of World War II the Radio Research Laboratory at Harvard University had successfully demonstrated the feasibility of developing a high quality superheterodyne receiver,* operating in the range 2300 to 4450 Mc (1). This receiver provided for the first time a reasonable order of signal sensitivity combined with very effective suppression of spurious signal responses. It was motor-tuned, with manual control of motor operation available as an alternate to continuous tuning within a chosen frequency sector. As compared to contemporary receivers the output indicating devices represented no radical departures. The operator, facing the controls and output indicators of this new intercept receiver, might have been tempted at first to feel that the designer had not made any material improvements but such a conclusion would have been seriously in error. The almost complete absence of spurious signal responses in this receiver represented a step forward in the man-machine relationship which must certainly be rated as of major importance.

POST WORLD WAR II DEVELOPMENTS

Intercept Receiver Techniques

The countermeasures groups in the Navy material bureaus were among the first to recognize the potential worth of the receiver techniques developed at the Radio Research Laboratory for the X-MBT system. The Bureau of Aeronautics and the Bureau of Ships countermeasures groups established development contracts to extend the frequency range to include, at first, the radio spectrum from 1000 to 10,750 Mc, and then at a later date, the additional range down to 50 Mc. That this total task was a matter of considerable magnitude can be recognized in that the first production contract for airborne receivers in the low-frequency range was finally established in fiscal year 1956. For a number of years the airborne receiver for the range 1000 to 10,750 Mc has been known as the AN/APR-9,

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*This receiver was made part of the X-MBT experimental intercept-jam system.

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and the receiver for the low range has been known as the AN/APR-13. These two receivers in the modern combined configuration comprise the AN/ALR-8. The shipborne receiver comparable to the AN/ALR-8 is known as the AN/BLR-1 (indication and control for one operator) or the AN/SLR-2 (indication and control for two operators). A comparable receiver employing the same basic techniques has been developed by the Army Signal Corps under the designation AN/TLR-1.

All of the above receivers are superheterodynes providing high orders of frequency resolution and spurious signal rejection. When designed to provide noise figures approaching the practical ultimate limits (2,3,4), the weak signal thresholds which can be obtained are better than those readily achievable by any other technique. Because of the high order of frequency resolution provided, compared to the frequency ranges of the individual tuning heads (approximately one octave), coupled with the low-speed tuning rate (one scan in 15 to 60 seconds) of the individual heads, these receivers have been generally reputed to provide only a very low order of "probability of signal intercept," and have been held to be not entirely satisfactory for their assigned tasks. In spite of this purported weakness, however, the airborne microwave superheterodyne receiver (AN/APR-9) has been procured in large numbers; it has consistently exceeded performance expectations, becoming, by reputation, the accepted "work horse" for strategic electronic search missions.

The countermeasures groups in all three branches of the Defense Department have continued to employ as basic instrumentation the several available forms of high-resolution superheterodyne receivers, while at the same time they have directed large efforts both in manpower and money to the problem of developing new receiver forms, which might possibly have all the desirable characteristics of the superheterodynes but which would at the same time provide an overall performance approaching unit magnitude for "probability of signal intercept." This effort has resulted in the exploration of a wide range of devices and physical phenomena which it was hoped might provide simultaneously wide-open spectrum response and high order of signal resolution. Some of the specific devices and phenomena studied by one or more groups have included (a) linear electron resonance for signal selection, (b) cyclotron electron resonance for signal selection, (c) signal modulation of a light beam by means of a Kerr cell, with subsequent resolution of sidebands by means of standard optical techniques, (d) conversion of signal frequencies to the supersonic range to provide frequency resolution by means of diffraction grating techniques, (e) a resonant quartz crystal wedge for signal selection, (f) ionization of low-pressure gas by means of resonant slots for signal selection, and (g) "instantaneous" frequency displays based on the output amplitude characteristics of conventional r-f discriminator circuits.

The above list cannot be considered to be more than a partial statement of the many techniques which have been investigated, but to the present time only (g) has been demonstrated as a real possibility for practical application. Both in the United Kingdom and in the United States experimental equipments based on the discriminator-display technique have been successfully developed and operationally tested.* The technique has two weaknesses limiting its range of utility, namely, (a) the maximum r-f spectrum that can be displayed is limited by the maximum bandwidth that can be designed into the discriminator circuits, and (b) the technique is prone to ambiguous response in the presence of more than one strong, modulated continuous-wave signal.

The technical difficulties which have so far prevented the satisfactory development of a true "r-f spectroscope," coupled with the requirement that logistic feasibility must

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*AN/ARD-6 is an example of this technique as applied in a Naval Research Laboratory development.

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be achieved, has brought about a reassessment of the operational objectives with a resultant simplification of the techniques now considered as satisfying the needs. Thus, the simple crystal-video receiver, small in volume, weight, and power consumption, is an entirely adequate device for indicating illumination by a pulse-type, fire-control radar, providing it is admitted that specification of frequency is adequate when it is known only to be somewhere within a particular octave. Four such receivers, arranged to form the popularly known "four-channel microwave DF," can provide bearing information for homing on a signal if that operation is required. Although receiving systems based on the crystal-video technique are often described as "high probability of intercept" receivers, it should be kept in mind that the overall useful signal sensitivity of such devices is some 40 to 50 decibels worse than for high-resolution superheterodynes. As a consequence, the crystal-video receiver is valuable principally as a detector for high-power pulse signals typical of most radars. Such a receiver has slight value for detection of low-power continuous-wave signals. Also, this receiver is usually incapable of detecting the minor and back lobes of high-power pulsed radars, even when the range to the radar is well inside the radar horizon (5,6). Hence, such a receiver provides a reasonably high order of "intercept probability" out to the radar horizon only when the radar cooperates by employing continuous rotation of its antenna and thereby illuminating the intercept site at regular intervals.

The overall simplicity of the crystal-video receiver has spurred a number of developmental efforts in recent years toward the general objectives of improved frequency resolution and sensitivity for this receiver without at the same time impairing its "high probability of intercept" characteristic. To achieve any major improvement in usable sensitivity some form of r-f amplification must be used ahead of the microwave diode. The broad-band microwave traveling-wave tube is an obvious choice for this application, providing the objectionable cross-modulation effects which are inherent in such a device (7) are overlooked. Since identification of separate cross-modulation products requires a reasonably high order of frequency resolution, such effects generated in a broad-band wide-open receiver usually are not noticed. Efforts directed toward a major improvement of the frequency resolution for such a receiver could, conceivably, result is resolution of the cross-modulation products if the broad-band amplifier is placed between the broad-band antenna and the narrow bandpass filter employed for frequency selection. More specifically, to minimize cross-modulation effects the broad-band amplifier should be placed between the bandpass filter and the detector diode.

A simple and effective technique for improvement of the frequency resolution of the crystal-video receiver has been successfully developed at the Naval Research Laboratory in an experimental laboratory instrument (8). In this device, the tunable r-f preselector normally used in the TN-129/ARR-9 was employed as a tunable bandpass filter ahead of the microwave diode detector in an otherwise simple crystal-video receiver. By means of a very simple mechanical arrangement the filter is caused to scan continuously and cyclically throughout its normal tuning range (2300 to 4450 Mc) at a rate of two full scans per second (one mechanical cycle per second). The frequency resolution provided by this device is in the region of two to four percent of the signal frequency. The scanning rate chosen was dictated not by mechanical limitations but rather by the direct comparison of "time on frequency" with the longest pulse period to be intercepted (9). For the purposes for which this experimental receiver was designed, the normal signal sensitivity for a crystal-video receiver was considered adequate. It is obvious that a suitable high-gain, broad-band, low-noise traveling-wave tube placed between the tuner and the microwave diode would provide a reasonably sensitive, relatively simple receiver having a fair degree of frequency resolution, and discrimination against cross-modulation effects, roughly comparable to the broad i-f bandwidth performance of the AN/APR-9 receiver.

The Electronics Research Laboratory at Stanford University has successfully demonstrated that it is electronically feasible to simultaneously improve both signal frequency resolution and signal sensitivity for a crystal-video receiver through the use of a suitable dispersive-type traveling-wave tube operating as an electronically tuned bandpass r-f amplifier preceding the microwave crystal-detector. As a bandpass amplifier this receiver is not as selective in frequency as desired for the large majority of the possible military applications. It provides a passband width approximately ten percent of the signal frequency with rather poor skirt selectivity. The major advantage offered by the use of a dispersive traveling-wave-tube amplifier is the resultant ability to tune the amplifier center frequency by varying an electric potential. This permits frequency scanning rates far beyond those possible by any known mechanical scheme. It is interesting to note, therefore, that the scanning rate selected at Stanford is again based on the direct comparison of "time on frequency" with the longest pulse period to be intercepted (9).

The dispersive traveling-wave tubes used as scanning filters are usually designed to tune through about one octave of the microwave spectrum. The passband is thus approximately ten percent of the available tuning range in the tube. If a "time on signal" no greater than four milliseconds is required (i.e., a minimum intercepted repetition rate of 250 pps), then the total scanning period is approximately forty milliseconds (a scanning rate of 25 frequency scans per second). Since this scan period is of the same order of magnitude as the "on target" time for the major lobe of many commonly used radars, there is a high probability that such a radar will be successfully received by this receiver at least each time the radar scans the bearing of the intercept receiver site. In addition, the improvement in sensitivity provided by the traveling-wave amplifier makes it possible in many instances for this receiver to intercept the minor front lobes of the radar antenna pattern at considerable range, thus improving the chance of receiving such a signal. For these reasons, such a receiver enjoys the reputation of providing a "high probability of intercept." Thus, through the use of a rapid scanning technique, the rather poor frequency resolution of the dispersive traveling-wave tube is exploited to provide an improvement in "probability of signal intercept."

It also has been demonstrated at Stanford University that by employing a broad-band, high-gain, low-noise traveling-wave tube as a preamplifier ahead of the dispersive traveling-wave tube it is possible to improve the overall sensitivity of this receiver to a point where it is capable of receiving the back-lobe radiation from high-power radars at ranges comparable to the radar horizon. This r-f amplifier does not improve the frequency resolution of the basic receiver; in fact it tends to make it more evident in the receiver panscope display that the skirt selectivity of the dispersive tube is rather poor.

Considerable effort has been expended under Defense Department development contracts to improve the frequency resolution of the crystal-video receiver without the employment of a frequency scanning system. The technique most often employed results in effectively quantizing the r-f spectrum into a relatively large number of adjacent narrow passbands, the individual outputs of which are then detected, amplified, and individually indicated. Thus twenty channels, each 50 Mc in bandwidth, or fifty channels, each 20 Mc in bandwidth, can provide spectrum coverage for 1000 Mc. It is evident that merely the individual detectors and high-gain video amplifiers for fifty channels require a relatively large number of tube envelopes and considerable power. After the techniques required for direction finding, signal analysis, data correlation, and storage are added to this frequency quantizing system, the number of total envelopes and the power required are likely to subject the entire system to severe criticism from the standpoint of military logistics. When it is recalled that the number of envelopes and the power required tends to rise in direct proportion to the frequency spectrum covered (this assumes constant bandwidth per channel), it would appear that this type of microwave receiver offers a very fertile field for immediate application of transistor techniques.

This type of multiple-channel crystal-video receiver is useful only for high-peak-power pulse-type signals. It is obviously possible, of course, to achieve a considerable improvement in sensitivity through the employment of suitable traveling-wave tubes as very broad-band r-f preamplifiers, wherein one such tube serves as the r-f amplifier for a relatively large number of individual, adjacent frequency channels. Such a broad-band amplifier provides no improvement in frequency resolving power and could conceivably promote spurious signal responses as the result of cross-modulation effects.

Display and Analysis Techniques

The signal display and analysis techniques developed during World War II may be divided into two main classifications: (1) those employing analog circuit techniques leading directly to cathode-ray-tube displays that plot the signal characteristics to be examined, and (2) those employing electronic computer techniques for the measurement and ultimate display of signal characteristics. The device used for signal display and analysis was usually developed as an attachment to be used with the basic receiver. Thus the RDO and AN/SPR-2 receivers for shipboard applications were commonly used with three separate, attached indicators: (1) the RDP panadapter, which provided panoramic spectrum display covering 10 Mc, (2) the RDJ pulse analyzer, which provided signal-initiated time bases for pulse-width measurement, a frequency-comparison Lissajous figure for pulse-frequency measurement, and a simple electronic computer which displayed pulse-repetition frequency on a milliammeter scale, and (3) the DBM rotating antenna system and associated radial display for direction finding.

The physical size of the receivers and the three attachments was so great that it was practically impossible to arrange the equipments so the operator could handle them with any reasonable degree of comfort. To acquire a signal, the operator tuned the receiver manually while observing the RDP indicator and listening with headphones. With the signal centered in the panoramascope, he turned his attention to the RDJ indicator where it was then necessary to choose (by manual switch) one of three available time bases for pulse-width measurement; as a second operation one of three possible prf scales had to be selected, or one of three possible frequency ranges for a Lissajous-figure measurement was used after switching the cathode-ray-tube display from pulse-width to prf mode of operation. Since all of the above operations were usually accomplished with the receiver attached to an “omnidirectional” antenna, display of bearing for the signal source was accomplished by switching the receiver to the DBM antenna while observing the associated display. Since no method other than manual logging was available for correlating signal data, it is evident that the operator of these early devices might find himself not only required to be something of a physical contortionist but also a very patient, persistent, and methodical individual if no errors were to creep into the record. The situation for the airborne electronic countermeasures operator was little better than for the surface ship operator. The major advantage offered in airborne installations was primarily the smaller size of the receivers and associated attachments, which permitted reasonably practical arrangements around the operator.

The X-MBT intercept-jam system employed a console arrangement in which the receiver and its controls were arranged in a fixed grouping that included the panoramascope and metered outputs from electronic computers for signal pulse width and for pulse-

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repetition frequency. The DBM direction-finding indicator was externally attached. The operator of this experimental equipment was still faced with the necessity for manual logging and for the proper manipulation of switching sequences as complicated as those previously described. The major improvements for the operator were the fact that this receiver was motor-tuned and was remarkably free from spurious signal responses. Although it was apparently not realized at the time, the complete lack of cathode-ray-tube displays other than the panoramascope for signal modulation analysis represented a technical handicap of no mean proportions.

In the period following World War II, the development of new and specialized signal display and analysis techniques has represented a major fraction of the effort expended in the general field of countermeasures intercept systems. Display and analysis are fundamental to the problem of signal intercept data acquisition, and it appears to be pretty generally agreed that the presently available, manually operated and observed intercept systems have data-handling rates far below the requirements of modern strategic and tactical operational requirements. This low data-handling rate has generally been considered to be a system weakness directly chargeable against the psychological shortcomings of the operator as compared to the potential ability of electronic machinery; hence it has become a matter of serious consideration, during the past ten years, as to whether or not the human being should be made an intimate part of the data-acquisition system. Proposed and existing solutions for the problems of data-acquisition range from the completely automatic device, which is intended to acquire, analyze, classify, and store data from field sites while being essentially "untouched by human hands," to the manually controlled, directly observed systems now generally in operation.

One of the best summaries of the research-development effort, which has been directed toward finding an optimum solution for the signal-data-acquisition problem, was presented at the Tri-service Symposium at New York University in May 1955 (10). Here were presented a wide variety of data-processing techniques ranging from direct analog displays suitable for human observation and photographic recording to completely unattended automatic systems which were described as devices having very high "probability of intercept" for all signals of certain types within a specified portion of the r-f spectrum, and purported to be capable of very high speed radio-frequency determination, modulation analysis, bearing determination, signal classification, and data recording and filing for future evaluation and utilization at some remote point.

Automatic systems designed to cover large portions of the r-f spectrum and to provide data-processing facilities as broad as have been described are systems employing literally thousands of vacuum-tube envelopes and requiring kilowatts of power. Since most of these vacuum tubes might conceivably be replaced by transistors at some future date, with a consequent reduction is space and power dissipation as well as improvement in overall reliability,the mere fact that fully automatic systems are very complex is probably not a valid objection in the long run. A far more important factor, governing ultimate success or failure of such a system, is the problem of reduction of data redundancy by the inclusion of circuit systems which will provide data samples only on desired signals and will automatically exclude information on undesired signals or signals on which analysis is essentially complete. Unless the acquired mass of data is rapidly reduced to optimum-sized signal samples, those human beings who are expected to exercise judgment in performance of the tasks of signal data evaluation and utilization find themselves faced with mountains of data, the detailed examination of which, on too many occasions, may prove finally to be largely a waste of time.

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Since it appears to be true that final evaluation and utilization of signal intercept data are functions performed exclusively through human judgment, and since unevaluated data has limited value, it seems evident that any practical intercept system that is proposed must operate at a data rate essentially matched to the rate of evaluation and utilization that is available. In short, it would appear that even the so-called fully automatic intercept systems are finally limited in data acquisition rate by the rate of flow of information through the brain. It is a recognition of this need to limit the acquisition rate in automatic systems which leads to the inclusion in these systems of analyzing devices which are designed to limit the response of the system to signals falling within relatively narrow ranges of characteristic specifications. Thus all radars except a particular type may be excluded through the choice of r-f spectrum bandwidth to be examined, or through the choice of pulse width or perhaps pulse period to be accepted for analysis and storage. Techniques of this nature have been recognized as feasible for many years (11,12) and represent a very small effort to include in automatic machinery a tiny spark of something remotely resembling an elementary form of human intelligence.

Since there does appear to be some reason to speculate on the desirability of including in an automatic data-acquisition system certain abilities to perform or limit performance in a manner faintly resembling elementary human intelligence, and since the development of synthetic intelligence of a high level is beyond even the far distant electronic horizon, it appears that assignment of human intelligence to be an intimate part of a data-acquisition system may not only be a wise step toward successful data reduction but also, logistically, appears to offer far more intelligence per pound-kilowatt than can be provided through known electronic devices.

It has been, of course, the lack of a successful automatic data-acquisition system rather than a positive belief in the value of human intelligence as a necessary part of the system which has caused all of the military services to continue active procurement and field utilization of the manually controlled receivers and directly observed data display devices. Following the design philosophy established during World War II, signal display and analyzing devices have been developed as attachments for use with the basic receivers such as the AN/APR-9, AN/APR-13, and the AN/ALR-8. Thus, there was developed a computor type pulse analyzer* for attachment to the AN/APR-9. The AN/APA-69 and its associated cathode-ray-tube display were designed originally as a DF attachment to the AN/APR-9 receiver. Later this technique was extended downward in frequency to cover part of the range of the AN/APR-13 receiver. As a step toward consolidation of indications, the Bureau of Aeronautics developed a single three-inch cathode-ray-tube display attachment which, by manual selection, provides either the conventional panoramascope display for the AN/APR-9 receiver or the radial display for the AN/APA-69 direction finder. Obviously this device is equally applicable to the AN/APR-13 and the AN/ALR-8 receivers. In the AN/SLR-2 and AN/BLR-1 receivers, consolidation of displays approached the practical limit in that a single three-inch cathode-ray tube, by various manual switching operations, is made to serve as (a) the conventional panoramascope, (b) the direction-finder display, (c) the pulse-width display, and (d) the pulse-period display. Since each of the above displays is available only by sequential switch and manual control adjustment, total analysis and manual logging time for a given signal can be rather long. Even though the AN/SLR-2 and AN/BLR-1 receiver-display system is relatively complete within itself, provision is made for easy attachment of additional display devices for use with the basic receiver.

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*AN/APA-64. This was an airborne development based on the meter-type displays used for pulse width and pulse frequency in the X-MBT intercept-jam system. Because of response ambiguities arising from multiple signal and receiver noise conditions this device was finally discontinued.

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At the Naval Research Laboratory, in the post World War II period, it was early recognized that signal analysis systems which required many sequential switch and control adjustments placed a heavy burden on the operator. Not only did he find himself serving as a detailed data recorder and logging clerk, but also his time was further wasted because of the complexity of the manipulations required to produce some of the desired displays. The necessity for many of these manipulations was removed through the development of a successful five-gun cathode-ray tube* which was applied in the initial development of a pulse-signal analyzer (13) based on five signal-initiated linear time bases on which were displayed the amplitude modulation characteristics of the intercepted signal. The two top traces in this display were calibrated in elapsed time (0 to 5 μsec, and 0 to 50 μsec) and were intended to display pulse shapes and widths in the range zero to fifty microseconds. The three remaining traces (0 to 1000 μsec, 0 to 5000 μsec, and 0 to 50,000 μsec) were directly calibrated in pulse-repetition frequency for the range 20 to 10,000 pulses per second. In this display-analysis technique the only manipulation required was the proper setting of the receiver gain control to insure that the display was not amplitude limited in either the receiver or the following amplifiers. Field tests of the multiple-trace display, using laboratory engineering models, demonstrated that it was a very desirable attachment for use with receivers such as the RDO, AN/SPR-2, and AN/APR-4 and that the general reaction of the operation personnel to this new display was very favorable. As a result of these initial tests and models, the Bureau of Ships developed the K1052P2 five-gun cathode-ray tube and the associated five-trace display known as the AN/SLA-1.

Subsequent to the development of the AN/SLA-1 and with the increased availability of the AN/APR-9 receiver it was demonstrated to be both feasible and desirable to extend the performance ability available in the five-trace modulation display. A new and improved five-gun cathode-ray tube,† employing sensitive deflection structures and a square envelope (to conserve mounting space) was developed and later standardized under the direction and control of the Bureau of Ships. A Naval Research Laboratory study (14) demonstrated that the performance of the multitrace analyzer display could be readily extended to provide and overall rise time of no more than 0.1 microsecond when used with standard AN/APR-9 receivers, trace synchronization was entirely independent of signal envelope waveform within the limits imposed by the passband characteristics of the associated video amplifier, and synchronization stability improved to an extent that pulse periods throughout the range from 0.5 to 50,000 microseconds could be displayed with negligible time jitter or staggering of the traces. These improved circuit techniques served as the technical background supporting the development of the AN/SLA-2 by the Bureau of Ships and the AN/APA-74 by the Bureau of Aeronautics. The AN/SLA-2 was designed to be used as an attachment for the RDO, AN/SPR-2, and AN/SLR-2 receivers. The AN/APA-74 was designed for use with the AN/APR-4, AN/APR-9, and AN/APR-13 receivers.

Because it was evident that neither the AN/SLA-2 nor the AN/APA-74 provided any material improvement in trace stability or linearity over that achieved in the original laboratory circuits, and because it appeared that such improvements were feasible, a Naval Research Laboratory study (15) was undertaken in which the establishment of optimum circuit designs was the major objective. This study was limited to the problems of proper choice and use of components and circuits in an effort to approach the ultimate quality in display with respect to tolerance in tube variations, freedom from crosstalk between the five independent displays, stability of trace positions and dimensions, and linearity of the individual time bases. This study did not include the problems arising from

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*7Z5P2; a five-gun cathode-ray tube, having a seven-inch-diameter display surface, developed by the Electronic Tube Corporation, Philadelphia, Pa., under NRL contract.

†7YP2; developed by DuMont Laboratories under NRL contract as the K1124P2.

the effects of wide temperature variations on circuit components. It was demonstrated that even the most critical circuits in the display system could be designed to operate reliably with any tube of the required type whose characteristics fell within the range of variation permitted by the JAN manufacturing specification. Trace stability and linearity were improved to such an extent that an alignment specification calling for an overall reading error no greater than one percent of full scale for each trace was demonstrated to be entirely feasible.

Although the AN/SLA-2 and AN/APA-74 analyzers considerably improved the operator's relationship to the physical machine required for signal modulation analysis, he was still faced by the fact that his attention had to be shifted to other cathode-ray-tube displays. Also, certain switching functions were required in order to observe the panoramascope or DF displays associated with receivers such as the AN/APR-9, AN/APR-13, or AN/SLR-2. In addition, the AN/APR-9 and AN/APR-13 receivers made no provision for direction finding on continuous-wave low-power signals, and this facility was made available in the AN/SLR-2 only by means of a switch manipulation. It was further realized that the linear time-base displays employed in the AN/SLA-1, AN/SLA-2, and AN/APA-74 had certain inherent disadvantages. The last two of the above analyzers employed five time-bases decimally related in time length (0 to 5, 0 to 50, 0 to 500, 0 to 5000, and 0 to 50,000 μsec) so that no reading on the four longest time bases was required to fall closer to the zero point than ten percent of full scale. The first ten percent of these four scales was thus wasted display area. In addition, the display on the five-microsecond trace was not favorable to the measurement of very short pulses, approaching one-tenth microsecond in duration.

Consideration of these factors resulted in the development at the Naval Research Laboratory of an entirely new display for attachment to the existing microwave receivers such as the AN/APR-9, AN/APR-13, and AN/SLR-2. In this new device, signal modulation analysis was accomplished by means of a three-trace display consisting of a signal-initiated exponential time base covering the range zero to five microseconds, which was then followed in time sequence by two two-decade, approximately logarithmic time bases covering the total range from 5 to 50,000 microseconds. This modulation display was shown to be theoretically possible (16) and then later proved to be feasible in practical design (17,18). Compression of signal modulation display to occupy only three time bases released two guns of a standard five-gun cathode-ray tube for other applications. Thus, it was a natural step to develop a method for display of signal direction in rectangular coordinates to use one of the released guns, while at the same time, the other available gun was used for the presentation of a panoramascope display commonly associated with receivers such as the AN/APR-9, AN/APR-13, and AN/SLR-2 receivers.

By combining the signal displays just described with the Veeder-Root counter used in the AN/APR-9 and AN/APR-13 receivers to display signal frequency, a unified display (19) was produced, feasible for attachment to these receivers, in which all pertinent data for a received signal, regardless of general type, was centrally displayed, with no requirement for manipulations other than those required for normal control and operation of the basic receiver and DF antennas. No contracts were initiated by the materiel bureaus to procure the unified display as an attachment for existing receivers however, because the results of a parallel investigation at the Naval Research Laboratory in the field of receiver control and signal frequency acquisition demonstrated the desirability and the feasibility of a complete redesign for both the basic receiver control system and the associated data displays.

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Receiver Control Systems

The receivers procured for field operations in World War II were generally designed for full manual operation. Receivers such as the RDO, AN/SPR-2, and AN/APR-4 were generally tuned manually while the operator listened for an audio output via headphones and looked for signal patterns in a narrow-band panoramascope such as the RDP. His knowledge of signal activity patterns within the tuning range of the receiver was developed only through the tedious process of longhand logging of all signals received while tuning across the band. Because of the length of time required for such a detailed inspection, signals radiated for intervals of only a few minutes could be missed completely through the chance that the receiver was never tuned to the signal frequency while the signal was present. In an active tactical operation, where the signal patterns might change on short notice, evidence of such a change could be delayed many minutes while the operator continued his search through the band.

The development of the receiver in the X-MBT equipment improved the operator's lot only to the extent that he was relieved of the manual labor of actually turning the tuning dial for long periods of time. This receiver was tuned by a motor which the operator could control by setting it to scan the receiver cyclically between chosen frequency limits or the motor could be manually controlled in direction and duration of motion by means of a directional jogging switch. In the usual monitoring operation the operator set the controls for automatic frequency sector scan, listening for audio outputs and observing a narrow-band panoramascope for signal patterns. When his attention was called to a signal output, he switched the motor control to manual operation, hoping that this switching operation could be completed before the signal was tuned beyond the passband of the receiver. If his reaction time was very fast (not more than 250 milliseconds) and the signal was continuously present, he might find the signal still within the panoramascope display so that it was a relatively simple matter to center the signal in the display by means of the jogging switch. If he was slow in action or the signal was intermittent such that there was no evidence of signal within the display after stopping the scan action, there was no way for the operator to know which way or how far to tune the receiver in order to center the signal in the receiver. Because this type of control provided no memory of receiver tuning position for a given signal, the successful intercept of an intermittently flashing signal, typical of that received from a slowly rotating surveillance radar at great range, was a slow, laborious process often beyond the patience of the human operator. In addition, lack of built-in receiver tuning memory made resetting to a previously logged signal a procedure demanding detailed operator attention. This type of machine operation was as badly matched to human abilities as were some of the very earliest radars, where the antenna was manually slewed and the only display was a simple "A" type time base where echoes appeared as amplitude modulations.

As has been previously pointed out, the AN/APR-9, AN/APR-13, AN/ALR-8, and AN/SLR-2 receivers, procured in the post World War II period, perpetuated the control system and signal acquisition indicator employed in the X-MBT system developed during World War II. Although these receivers have been rather widely condemned because of their purportedly "low probability of signal intercept," it appeared to the Naval Research Laboratory that the basic electronic design used in these receivers was almost ideally suited to many of the requirements of the signal intercept problem. It was recognized early that the major weakness of these devices was in the very poor match existing between the receiver and the operator's special abilities. Over a period of years, therefore, the Naval Research Laboratory has persistently searched for new techniques to alleviate this problem. This search has included efforts to develop new systems for signal-activity display which would include some form of useful memory as an aid to the operator in setting the receiver on signal, and to develop new methods for receiver control which would increase receiver operating speed and provide a manual control better adapted to an operator's abilities.

The first effort to produce a signal-activity display with useful memory culminated in the development of a special recording device (20) which could be used as an attachment to a standard AN/APR-9 receiver. This recorder, which essentially adapted an old idea to a new receiver, employed a sparking pen which moved across the width of a long strip of Teledeltos recording paper. The pen position was servo controlled by the tuning mechanism of the AN/APR-9 receiver. At the end of each tuning scan, the paper was advanced one line width. The received signals were registered as a density record with a position accuracy sufficient to permit manual tuning of the receiver to the signal frequency. A major weakness of the device was its inability to provide an adequate record of extremely short signal bursts, since in this case the overlay paper showed only one or two minute spark holes which were almost indistinguishable from the receiver noise. This experiment was later repeated using a dark-trace tube as the recording device (21). Again, a raster-type time-frequency diagram was developed for use with a standard AN/APR-9 receiver. Since the writing rate for a dark-trace tube is not favorable to the direct recording of single pulses of a small fraction of a microsecond, the dark-trace-tube recorder, like the Teledeltos recorder, was designed to respond to the envelope of the pulse groups in a received burst. Although this device was not practical for field application, it demonstrated the technical feasibility of successfully recording the tuning position for pulse bursts as short as one-thirtieth of a second, with an accuracy permitting the resetting of the receiver to the signal burst even when the signal was no longer present.

The major weakness of the time-frequency displays just described for the AN/APR-9 was the very slow rate at which the display was developed. One scan covering 2300 to 4450 Mc required approximately 45 seconds. In this time period a modern jet aircraft can fly ten miles. It was clearly evident that if the time-frequency diagram developed for a scanning receiver was to be of real value in a modern airborne signal-intercept installation, the rate of development of the time-frequency diagram and, consequently, the scan rate for the basic receiver would have to be materially increased. Since the AN/APR-9 was essentially an excellent microwave receiver, potentially approaching the ultimate limits of usable frequency resolution, signal threshold for all signal types, and suppression of spurious responses, and since there was every reason to retain its operating characteristics without appreciable deterioration, the immediate question was whether the scan rate of the basic tuning mechanism for this receiver could be increased by any large factor. It was realized, of course, that success in increasing the scan rate would make it imperative that an entirely new signal acquisition display be developed as a companion project.

In considering the question of increased scan rate for the AN/APR-9 tuning mechanism, it became evident that any one or any combination of five basic factors might actually limit or influence the scan rate that could be achieved or would be of operational value. A minimum scan rate limit was imposed by the rate at which the observed data pattern could be expected to vary. For a large majority of existing signals the high speeds of modern aircraft and guided missiles seemed to dictate a desired minimum scan rate at least ten times the rate in the existing receivers.

A second factor influencing the choice of minimum scan rate was the reaction time of the operator. In this case the concern was not the time required for a simple reflex action, which could be expected to be a small fraction of a second, but rather the total elapsed time from the moment when a data pattern change is first observed through the time interval required to judge the meaning of the pattern change and terminating at the moment when a

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no-action decision is made or action is taken. There is no conclusive data available as to the magnitude of this reaction time for an operator using a time-frequency diagram for signal acquisition on live signals, but discussion of this question with a few operators who have had a number of hours experience on live signals with such a display would indicate that a minimum reaction time of the order of one second might be a reasonable guess. It seems to be agreed that a scan period of forty-five seconds is a flagrant waste of the operator's available time. From the viewpoint of the operator, therefore, increasing the scan rate of the conventional receivers by a factor of at least ten is in order. The minimum scan rate permitting optimum use of the operator's ability to respond is a matter open to continued speculation but, in terms of scan period, may be somewhere in the range 0.5 to 5 seconds per scan.

A third factor to be recognized as limiting scan rate arises from laboratory operational experience indicating that audio monitoring by the use of headphones reduces the number of false alarms due to noise spikes on the time-frequency diagram display. Since the burst of audio output for a given signal has a time duration equal to the time the signal is within the receiver passband, and since this time is reduced as scan rate is increased, there is a real danger that the audio burst may be so short as to destroy much of the operator's ability to recognize distinct tones (22).

A fourth important factor, limiting the maximum permissible scan rate for high-resolution superheterodyne receivers, arises from the desirability of providing as high a rate as possible of accumulation of probability of intercept as a function of waiting time for the lowest pulse-repetition rates to be expected in field signal-intercept operations. Since the signal thresholds for modern high-resolution superheterodyne receivers permit reception of radar back-lobe structure for radars at or even somewhat beyond the radar horizon, the important condition to be satisfied in the scanning receiver is that, during scan, the "on-signal time" be equal to or greater than the longest pulse period to be received in order that the probability of signal intercept will rise to unity within a single scan (9, 23).

The fifth consideration is the practical fact that the higher the scan rate required, the greater is the power required to drive the scanning mechanism and the more rugged is the mechanical design required to provide satisfactory service life.

In the first successful laboratory experiments, the dual objectives of which were high-speed frequency scanning in an AN/APR-9 receiver and the development of a satisfactory time-frequency diagram display as a companion indicator, it was demonstrated that the TN-129/APR-9 tuning head, covering 2300 to 4450 Mc, could be driven at scan rates up to one full-frequency-range scan per second without serious difficulties (24).

Associated with this experimental receiver scanning system was an indicator employing the long-persistence characteristics of the P19 cathode-ray-tube phosphor. A time-frequency display was developed on this phosphor which permitted the operator to continuously inspect the signal activity within the tuning range, noting changes in the pattern during the preceding interval of time ranging to easily in excess of one minute. In this display, signals were presented as intensified spots in a raster where horizontal spot position accurately portrayed the instantaneous position of the tuning mechanism in the tuning range and the vertical position was controlled as a very slow uniform drift from top to bottom over a period of approximately two minutes. Signals of all types, continuously present, were successfully indicated in this display with precision adequate to permit rapid manual setting of the receiver on a chosen signal frequency by tuning the receiver to reset the cathode-ray-tube spot on the indicated afterglow.

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Manual tuning in this type of receiver was remotely controlled by a rotating dial connected to a precision potentiometer, with a suitable follow-up servo system driving the tuning head. By providing several such precision potentiometers and tuning dials, which could be selectively connected one at a time to control the servo system, it was shown to be feasible to effectively store several receiver tuning positions representing the tuned frequency of individually selected signals. Once an individual control was set on a signal and then left undisturbed, reselection of this control by connecting it to the servo system, automatically resulted in tuning the receiver to that signal frequency.

Thus the control and display system described in Ref. 24 provided two types of memory useful to the operator: (a) a short-term memory, within the signal activity display, permitting rapid setting of the receiver to an indicated signal frequency and (b) a long-term signal frequency storage, represented by a bank of individual tuning controls set to selected signal frequencies.

After a considerable period of experimental operation of the rapid-scan signal-acquisition system just described, during which various receiver scan rates in the range of one scan in one half second to one scan in four seconds were tried, it was decided that a scan rate of one scan in two seconds was probably the best choice for a developmental equipment because of the following reasons.

1. It appeared to be well within the mechanical design abilities already available in the existing receivers.

2. The data presentation rate was adequate to keep up with the speeds of modern aircraft and missiles.

3. The data rate appeared to be an adequate match to the operator's maximum speed of response.

4. The scan rate was slow enough so that even when scanning the frequency range from 7050 to 10,750 Mc, the on-signal time was long enough to provide audio signal bursts on most pulsed radar signals which were distinctly recognized as having tone qualities.

5. At this scan rate, the 20-Mc passband, when used as the scanning "frequency slot" for the raster display, provided an on-signal time such that one pulse within the passband was guaranteed for pulse repetition rates as low as 93 cps in the TN-131/APR-9, 76 cps in the TN-130/APR-9, 54 cps in the TN-129/APR-9, and 40 cps in the TN-128/APR-9. It appears unlikely that many radars or other signals with lower repetition rates will be encountered in these tuning ranges.

6. Only a modest amount of power was required to drive the tuning mechanisms at this rate of one scan in two seconds. Without major mechanical modifications within the tuning mechanisms, a 10-watt, two-phase servomotor was shown to be more than adequate (25). Later, it was demonstrated that a 5-1/2-watt motor would serve as well (26). And, in the most recent effort, it has been demonstrated at Collins Radio Company* that when the tuning mechanisms are redesigned to remove the relatively inefficient worm-gear mesh,† a 3-watt motor provides all the power required.

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*BuShips Development Contract NObsr 64683

†Experimental operation at NRL of the rapid-scan control system which employs the worm-gear meshes normal to AN/APR-9 tuning heads has conclusively demonstrated the existence of excessive wear in the worm-gear mesh. It is now obvious that mechanical redesign of the tuning-head drives to provide all spur-gear meshes is a requirement, if reasonable service life is to be assured.

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With the rapid-scan control system it is not possible to use the normal panoramascope indication for an AN/APR-9 receiver as a device for indication of signal activity during scan or as an aid to the acquisition of signal frequencies. The normal panoramascope indicator displays only those signals within the 20-Mc receiver passband. When the receiver is driven at a rate of one full scan in two seconds, signals are in this passband for a period ranging from approximately eleven milliseconds for the TN-131/APR-9 to approximately twenty-five milliseconds for the TN-128/APR-9. Furthermore, for the limiting value of low repetition rates for pulsed signals, specified in 5 above, only one pulse falls in the passband per receiver scan. This single pulse might be as narrow as one-tenth microsecond, and it is necessary that a display be used which will successfully indicate the presence of such a pulse and excite the phosphor sufficiently for adequate afterglow. In addition, such a proposed signal display should successfully indicate the presence of all other signal types, including those based on the use of low-power continuous-wave carriers. Although these requirements might appear difficult to accomplish, it has been demonstrated that such performance is rather readily achieved (24). In addition, to develop this display as a companion indicator for the unified display described in Ref. 19 requires very few additional components (26).

Signal Data Recording Devices

In spite of a considerable effort by several branches of the Defense Department from World War II to the present, there is still not available any single recording device or even system of devices wholly satisfactory for the storage of microwave signal data for subsequent detailed analysis. Unlike the great majority of signals encountered below 50 Mc where the use of signal modulation frequencies higher than 15 kc is relatively uncommon, those signals intercepted in the microwave frequency bands very often include signal modulation frequencies spread throughout the range from the subaudio frequencies to the video range, sometimes including components exceeding 10 Mc. No single recording system for field use is available today capable of handling this wide range of modulation components. In addition to signal modulation components, of course, there are other items of signal intercept data such as time and place of intercept, and signal type, frequency, and bearing which should be concurrently recorded. No recording system for field use exists which is capable of handling all such information as a coordinate data pattern. Largely because of the lack of such a versatile recording system, the maintenance of a detailed longhand log of signal intercept data is still one of the time-consuming duties of the intercept station operator. The developer of an automatic intercept system recognizes this situation in his efforts to develop electronic brains which will accept raw data from the receivers, analyze and classify this data, and finally, encode this information for automatic card punching, where each such card is equivalent to one entry in longhand log.

For operation with the widely used manually controlled intercept systems based on receivers such as the AN/ALR-8 and AN/ SLR-2, two relatively simple recording techniques have been demonstrated in field operations to be of considerable value for storing certain special forms of signal data as a supplement to the longhand log. In both cases the information recorded represents the analog output from the receiver detectors, and it is necessary, therefore, that the longhand log indicate whether the record is based on amplitude or frequency demodulation of the signal carrier. In both cases the technique is well understood, relatively simple to operate, and logistically sound.

The first of these devices is a magnetic recorder with an upper limit of frequency response at about 15 kc. In its earlier forms this recorder employed wire as the magnetic medium. In recent years the wire has been superseded by magnetic-plastic base tape which offers the added advantage of providing multiple-channel records for time-coordinate events.

This type of recorder is commonly used to record the receiver audio outputs normally delivered to the operator's headphones. Although the limited frequency response inherent in such a record makes it impossible on playback to determine the pulse width of an intercepted radar, it is possible to determine the pulse-repetition period with considerable accuracy and to determine, within useful limits, the general nature of pulse amplitude and period variations which may have occurred. Such a record provides a very convenient long time base from which may be determined both the rotation period and approximate radiation beam width for a rotating radar antenna. Where variation of either pulse amplitude or period is used to transmit low-frequency information for purposes of communication and/or control, the magnetic-tape record lends itself readily to detailed audio analysis techniques available through the use of commercially available sound spectrographs or instruments such as the Instantaneous Sound Spectrograph (27). When video demodulators (28, 29, 30) are available at the intercept site, the demodulation of pulse-carrier systems usually produces modulation frequency components within the range of the conventional tape recorders, permitting, thereby, the later detailed analysis of the information carried by such systems.

Unfortunately, many of the pulse-carrier communication systems employ pulse trains consisting of pulse groups in which one or more of the pulses in a group serve to establish a reference synchronizing time against which the following pulses in the group are modulated individually in time to produce a multiple-channel communication system. The overall average pulse repetition rate may easily exceed 100 kc for such a system, so that the audio-frequency range available in the average tape recorder is completely inadequate for purposes of storing this type signal for later detailed analysis. In addition, the only wide-range demodulator available for this type system (28, 29) is capable of demodulating only one channel at a time. In a ten-channel system, ninety percent of the available data is thus lost. One possible solution to this dilemma would be to use ten demodulators and a single ten-channel recorder. This is not, however, a practical solution, since a single demodulator, in its present form, is bulky and power-consuming to an extent that probably limits its use to land-based stations. It is here that the recently developed video-frequency tape recorders may eventually prove to be the best possible answer. Although such a precision recorder is a relatively fragile instrument of considerable bulk, its successful field use permits later analysis in detail of all the information available on all channels. It appears quite possible that the most efficient application for the demodulators mentioned above would be as a demodulator for the individual channels represented in the video-frequency record. Only one wide-band recorder and one demodulator would be required for this operation.

The second recording device, which has been rather widely used with microwave intercept systems, is the camera. The rather high order of redundancy inherent in the large majority of intercepted microwave signals permits the development of stable patterns for cathode-ray-tube displays, in which video frequency information up to as high as 5 to 10 Mc is directly observable as an analog amplitude-time pattern. Years of field operations have demonstrated that a small high-speed still-frame camera can quite successfully record samples of these cathode-ray-tube displays as seen by the human operator. The type KD-2 recording camera for 35-mm film, originally developed by the Bureau of Aeronautics, is representative of modern procurement in this field. This camera was designed as an attachment to the AN/APA-74 signal analyzer, and by use of an adapter is attachable to the AN/SLA-2 signal analyzer. By means of a dichroic mirror, the operator is able to view the five-gun cathode-ray-tube display against suitable scales in virtual projection. At the same time, the scales and display may be photographed by operating a pushbutton switch, which initiates shutter operation, limits the time of scale illumination, and advances the film in automatic sequence. A small watch, a data card, and a small Veeder-Root counter showing frame number are included in the photographed data to provide positive correlation with the longhand log.

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A still-frame camera used to photograph a display which is dynamically varying is able to produce a record representative of the signal pattern for only a very short interval of time and modes of pattern variation are often not properly displayed. It is quite evident that a more complete record would be made available through motion-picture sequences than through still-frame samples. Early experiments at the Naval Research Laboratory using a standard amateur 16-mm movie camera to photograph the first experimental five-trace signal display (13) demonstrated that the lack of synchronization between the display and the camera shutter resulted in rather serious chopping of the display in the individual frames of the record. These early experiments were performed with a P2 phosphor in the cathode-ray tube and XX film in the camera. The afterglow was not photographed by the film, so that events displayed during the shutter-closed period were excluded from the record. During the Korean War, the Air Force transmitted to the Naval Research Laboratory a 16-mm sound film which had been prepared by means of a special 16-mm sound-motion-picture camera attached to an AN/SLA-1 signal analyzer. Playback of this record in a standard 16-mm projector demonstrated that it was an excellent dynamic representation of the original display and its associated audible signal components, with the single exception that no appreciable phosphor afterglow was recorded, and so shutter breaks were clearly visible. In the spring of 1955, additional experiments at the Naval Research Laboratory with motion picture techniques demonstrated that it was entirely feasible to successfully photograph the dynamic presentations showing the actual operations of the Naval Research Laboratory signal-acquisition indicator for a rapidly scanned AN/APR-9 receiver (24) and the unified indicator for signal analysis (19). It was evident that successful recording of the phosphor afterglow visible in both of these indicators could be achieved (10). These motion picture records were produced, with the assistance of the Naval Research Laboratory photographic group, using Tri-X film, and it was obvious from the projected sequences that up to approximately fifteen seconds of the P19 afterglow in the signal acquisition indicator had been successfully recorded and that the P2 afterglow of the unified indicator and been recorded to an extent such that the shutter-closed intervals were almost completely obscured. In a later experiment (26) it was demonstrated that the unified indicator could be photographed with approximately equal success by a small amateur 16-mm movie camera which viewed the scales and the display through the camera port in the side of the KD-2.

It is important that it be understood that the successful recording of the P2 afterglow can be accomplished only if four operating conditions are firmly established. First, it is necessary that adequate excitation of the phosphor be provided. In the unified display the first half microsecond of the fastest time base is displayed at the rate of about two inches per microsecond. The experiments at the Naval Research Laboratory indicate that the 7YP2 cathode-ray tube should be operated with at least 5000 volts total accelerating potential if an adequate record of the first half microsecond of the display is to be achieved. Secondly, the camera lens aperature should be as large as possible, particularly if the exposures are to be made via a dichroic mirror such as is used in the KD-2 camera. The Naval Research Laboratory experience indicates that for this latter application an f/1.3 aperature is marginal and that an f/1 lens would seem to be quite desirable. The dichroic mirror in the KD-2 camera is only about 50 percent efficient with regards to light transmitted to the camera (31). The third condition requires the largest possible shutter angle available in the camera to be used. To conserve film it is desirable to operate the camera at a film speed no greater than 16 frames per second. This represents one frame exposed approximately every 63 milliseconds. If an hypothetical shutter angle of 120 degrees is assumed it follows that in the worst case, a pulse presented in the display just after the shutter closes must persist as afterglow for at least 42 milliseconds to be available when the shutter opens, and when the shutter opens, enough afterglow must still remain for successful photography in the shutter-open period of 21 milliseconds. A film for the New York University presentation (10) was prepared using a camera having a 170-degree

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shutter. The amateur 16-mm movie camera used in the later experiments has a shutter opening of 130 degrees. Inspection of individual frames of these films indicate the desirability of providing a shutter opening of at least 180 degrees. As the fourth and last requirement the development process for the exposed film must be carried to the extreme limits, assuring the fastest possible effective film speed. It is understood from the Naval Research Laboratory photographic group that the Tri-X film was developed in D-19 solution at 70°F for 20 minutes.

THE MICROWAVE SIGNAL INTERCEPT PROBLEM

The design of a microwave signal intercept system is, of course, largely controlled by the nature of the signals which must be successfully received, and by the tactical and strategic objectives which must be considered as governing factors for intercept system performance. Thus a submarine torpedo fire control system, which derives target range information from a single pulsed radar burst, consisting of perhaps five one-microsecond pulses spaced 500 microseconds apart, places two very special requirements on the intercept system designed to give warning of the presence of such a signal. A first requirement is that the electronic system which constitutes the basic receiver must be designed to intercept and display the bearing of such a signal with a very high probability of success on a single burst. A second and even more important characteristic required of such a system is that it be designed to perform its function so reliably and in such manner that the human observer readily identifies the proper tactical significance of the signal, and automatically discards the false alarms which may be produced by locally generated noise. The first requirement is only that the electronic machine must be designed to deliver a logical electrical, audio, or visual output when stimulated by the desired signal. The second requirement is the necessity for the observer to feel a high level of confidence as to the fidelity of the machine output as a measure of real tactical significance.

It is far easier to design a machine satisfying the first requirement than it is to develop the complete device, which will, by its performance, stimulate the level of confidence required. Exactly why this seems to be the case is undoubtedly a matter better understood by specialists in the field of psychology rather than specialists in the field of electronics. The electronics specialist needs to recognize, however, that the operator of an intercept system seems on many occasions to be a confirmed skeptic. Because a single short burst does not readily permit the operator to re-examine the signal in an effort to detect some form of redundance such as constant pulse width, regular pulse period, or systematic burst sequence, it is far too easy for him to confuse such a single burst with bursts of noise or other spurious responses and to reject it.

This situation suggests the need for some type of short-term storage of signal characteristics, which will permit the operator to readily re-examine the signal, even though it never occurs again. It is evident, of course, that in a noisy location or in the presence of many interfering signals, the operator's mental hazard is even more difficult to overcome, since he must then spend much of his time examining signals not related to the critical tactical objective. It is obvious, also, that where the dangerous signal is deliberately engineered to simulate random characteristics, thereby reducing redundancy to a minimum, the operator could well find himself completely unable to sort the signal from unrelated responses, even through he examined the stored record in detail. One possible solution to this dilemma is to guarantee, by complete radio and electrical silence, that such an intercept system would operate in an area where the only signal expected would be the single dangerous burst occurring with a signal-to-noise ratio sufficiently high that observer confidence could thus be stimulated to a degree that he would respond successfully, largely because false alarms would be practically eliminated.

It is not the purpose here to suggest the design of an intercept system for isolated signal bursts, but rather to point out the technical complexities which appear to be inherent in the design of such a device and which have not been successfully solved to this date. These problems do not occur to a serious degree in the case of signals either continuously present or recurring at regular short time intervals since even in the latter case the operator is able to reconfirm his knowledge of the signal on each succeeding burst. Flash type signals occur in great numbers under circumstances having considerable tactical and strategic significance, occur in many forms, ranging from low-power continuous waves to high-power pulses, and often occur in small portions of the radio spectrum already occupied by many other signals of similar nature. For these reasons, it appears to be desirable to design the intercept system for continuous or repetitive signals without imposing upon it the additional special, more complex techniques, not yet fully determined, which seem to be inherent in a flash-signal intercept system. The large variety and numbers of continuous or repetitive signals which must be intercepted and successfully resolved places upon the general signal intercept systems requirements calling for high orders of signal sensitivity and frequency resolution. Within the range of techniques now known, the achievement of a high order of frequency resolution is not conducive to the simultaneous achievement of high probability of intercept for a single signal flash occurring on a frequency unknown to the intercept operator. Conversely, the achievement of a high probability of intercept for a single signal flash on an unknown frequency is not conducive to the achievement of a high order of signal sensitivity or frequency resolution.

It appears logical, therefore, that two distinct types of microwave intercept systems should be developed, the designs for each being as near optimum as possible in terms of the tactical and strategic problems with which they are individually concerned. For the purposes of this discussion these systems are identified as the flash-signal and the general-signal intercept systems. The general intercept systems are here identified as the major concern in this report.

Intercept Probability Considerations

In the period following World War II it has become rather common practice for designers of signal intercept systems to characterize a specific receiver system as a device providing "high probability of intercept" or "low probability of intercept" without specifically stating the full meaning and implications of these phrases. Quite commonly, the crystal-video receiver, wide open over approximately an octave in frequency, has been presented as a receiver providing "high probability of intercept" and the high-resolution, frequency-scanning superheterodyne receiver has been described as a receiver providing only a very "low probability of intercept." Because these two descriptive phrases are so commonly used, and because serious misconceptions appear to arise from rather generally applied misinterpretations of these phrases, it seems desirable here to restate, briefly, the interpretation of "intercept probability" as it is understood at the Naval Research Laboratory.

Because a phrase such as "high probability of intercept" represents an incomplete mathematical concept, to this point in the discussion it has been presented always in quotes. A complete statement for a probability function must state and deal with the independent variable determining the function. Thus, in tossing a coin, it is usually understood that the probability of the occurrence of the first head is a function of the number of tosses. If the tosses are arbitrarily arranged to occur at a fixed number per unit of time, the probability of occurrence of the first head might, instead, be expressed as a function of time. In the field of signal intercept probability, a relatively large number of independent variables are available for selection. Thus, signal intercept probability might be stated as a function of such variables as radar antenna rotations, DF antenna rotations, the number of transmitted radar pulses, or the number of frequency scans in a scanning receiver. It is the opinion of the Naval Research Laboratory that elapsed time is the most generally suitable independent variable for all intercept probability statements (32, 23) and that such a probability statement provides a common reference within which valid, quantitative comparisons of intercept system performance may be made to determine optimum electronic designs and the limits of performance which may be expected under specified tactical and strategic situations (6). In the reference just specified, Bullock has shown the expected performance comparisons for three different intercept receivers applied to the problem of detection of a high-power pulsed radar and of a low-power continuous-wave doppler system. The receivers compared were (a) a crystal-video receiver (nonscanning in frequency), (b) a standard AN/APR-9 receiver (one frequency scan in 45 seconds), and (c) a rapidly scanned superheterodyne receiver AN/APR-9 performing one frequency scan in 2 seconds). Using the time-dependent intercept probability function as the criterion for comparison, the following four results were indicated.

1. Since the crystal-video type receiver is unsuited to the reception of low-power continuous-wave signals, the circuit techniques generally employed being such as to exclude such signals completely, it follows that the time-dependent intercept probability function for this combination of receiver and signal is everywhere zero.

2. When the crystal-video receiver is used to intercept a high-power pulsed radar at such range (not exceeding radar horizon range) that only the major and front minor lobes of the radar antenna pattern project a signal exceeding the receiver threshold, the slope of the intercept probability function is controlled entirely by the operating mode of the radar antenna system. Thus if the antenna continues to rotate at ten revolutions per minute, the intercept probability curve rises to unity in six seconds. On the other hand, if this radar is used for long intervals in a sector scan mode, covering a sector not including the azimuth position for the intercept receiver, the slope of the resulting probability function is certainly not favorable to this type receiver.

3. In contrast to a crystal-video receiver, the AN/APR-9 receiver is designed to intercept both low-power continuous-wave and high-power pulse signals, with an overall sensitivity such that even the back-lobe radiation from a high-power radar can be detected over a line-of-sight range extending many hundreds of miles. In the general practical case, a high-power radar at or even beyond radar horizon range is received by the AN/APR-9 receiver without regard to the mode of operation of the radar antenna. The slope of the intercept probability curve is in this case entirely dependent on the frequency scanning characteristic of the receiver. In the most unfavorable case, where the radar frequency is at one end of the receiver scan range, approximately ninety seconds elapsed time is required to assure the attainment of unit probability of intercept. If a continuous-wave signal is received under similar conditions, the same probability curve applies. It is evident that the major weakness in this receiver is the time required to complete one scan, a situation within the control of receiver engineering design.

4. A rapidly scanned AN/APR-9 receiver has the same general ability as that applying to an unmodified AN/APR-9 with the exception that any reduction in scan period that is achieved results in a proportionate improvement in the slope of the intercept probability curve. Thus, for a receiver performing one frequency scan in two seconds, operating against signals such as described in 3, the slope of the probability curve would be such as to insure unit probability of intercept after an elapsed time of four seconds.

The situation described in 4 contrasts with that outlined in 1 and 2 in that (a) the receiver is effective on all types of signals, and (b) the slope of the resulting probability of intercept function is not under the control of the enemy but is determined within the performance of the receiver itself. The rapidly scanned superheterodyne receiver is thus superior to the crystal-video receiver on at least two counts. A third factor, favoring the rapidly scanned superheterodyne receiver is its ability to provide a much higher order of frequency resolution than is readily feasible for a crystal-video device.

The Range of Utility Required

In the light of past experience at the Naval Research Laboratory, it appears to be reasonable to require that a general intercept system should be designed to provide the widest possible range of utility. With the sole exception of the flash type signal, the intercept system should provide facilities for the intercept of all general types of signals known to be feasible within practical engineering limits; and the output data from the system should be available in such forms as to be immediately useful for the tactical problem or permanently recorded for strategic applications.

Although in the past it seems too often to have been assumed that microwave intercept systems are satisfactory if they are capable of receiving and processing only high-power pulsed radar signals, this assumption is no longer valid. It has become necessary to consider the wide variety of pulse-carrier communication, control, and telemetering systems now in use, many of which have real tactical significance but do not radiate high-power signals, the increasing numbers of low-power continuous microwave carrier systems, employing various combinations of frequency and/or amplitude modulation for a variety of purposes ranging from special radar forms to data-communication links, the fact that many of these low-power microwave signals are propagated over narrow geographical channels by the use of fixed, narrow-beam antennas, and the conditions of spectrum occupancy which even today can place these weak signals dangerously close to the frequency of an adjacent powerful radar. All of these considerations place restrictions on the design of an intercept receiver, which can be met only by achievement of the near ultimate performance with respect to frequency resolution, signal thresholds, rise time, freedom from signal overload transients, and rejection of spurious responses. It is an unfortunate fact that ultimate receiver performance on different types of signals often requires radically different magnitudes for some of these general receiver characteristics.

As a typical example of a receiver design problem which must be solved, consider the extreme range of possible enemy signals that it seems reasonable to expect in electronic warfare, assuming only the extreme ranges of electronic design as limited by enemy logistic considerations. In the light of the widespread interest in crystal-video receivers in our own signal intercept operations, it is an obvious possibility for the enemy to employ cw microwave radar and communication systems. The latter devices, in particular, can be expected to employ very low powered transmitters combined with narrow-beam, high-gain antennas directed on a fixed bearing. Successful intercept of this type signal, especially if the intercept receiver is not located in the projected radiation beam, requires an exceptionally good signal threshold, which can be achieved only through a receiver design providing an extremely low noise figure and an extremely narrow bandwidth. Unfortunately, the narrowest feasible bandwidth in a microwave receiver is largely controlled by the stability of the microwave local oscillator employed. The enemy, however, is also limited by similar considerations in his designs, which in this case finally determine the minimum practical power levels for his transmitters. The intercept receiver design for the best possible threshold for continuous-wave carriers is thus the result of a continuous struggle to provide lower noise figures, more stable oscillators, and consequently narrower bandwidths.

In contrast to this situation we must face the fact that the enemy can be expected to employ pulsed radar and pulse-carrier communication and control systems. Desire for range resolution dictates enemy radar designs with regards to pulse width, the ultimate in resolution being largely limited by the maximum bandwidth that may be practical within feasible logistic limits. The narrowest pulse width expected in enemy designs largely dictates the maximum intercept receiver bandwidth. Obviously this maximum bandwidth requirement coupled with the best obtainable noise figure largely determines the receiver threshold that can be achieved for pulsed signals. The designer of a scanning type intercept receiver for pulsed signals is faced with an additional condition which states, in effect, that for a given receiver scanning rate (motion of the receiver passband in cycles per second) there is a minimum permissible scanning bandwidth for the receiver, which will optimize the rate of growth of probability of intercept for the maximum pulse-repetition period the enemy may be expected to use. The wider the bandwidth, the faster the receiver may scan for a given pulse repetition period. Thus, as the scanning rate is increased, a limitation is finally reached in the inability to develop adequate bandwidth in the limits imposed on electronic techniques by the logistic considerations of ease of adjustment and alignment and limits on primary power available at the field operating site. In receivers such as the AN/ALR-8, AN/SLR-2, and AN/TLR-1 this limit is largely imposed upon the equipment designer by the general effort to employ miniaturized components in well tried and tested circuitry that is relatively simple to align. The maximum i-f bandwidth of 20 to 25 Mc available in these receivers is approaching the limit for the 6AK5 vacuum tube in a staggered-triple amplifier. A more complex circuit configuration such as distributed amplifier for this tube does not seem to be desirable from the viewpoint of military logistics. Since enemy equipment is also bandwidth limited, it is not too surprising to note here that a receiver bandwidth of 20 to 25 Mc is quite adequate for the reception of the narrowest pulses that the enemy may be expected to employ in a great majority of his operating radar and communications systems.

From the two preceding paragraphs it is evident that a receiver for general-signal intercept must provide simultaneously both the narrowest and the widest bandwidths feasible. The outputs from both extremes of bandwidth should be simultaneously observable, with the best possible signal thresholds that can be attained. Merely to provide an extreme range of receiver bandwidths, however, is not enough. The fact must be faced that the enemy may employ these bandwidths in a variety of ways, which are largely predictable from a survey of the range of techniques possible within practical engineering limits. The designs for the great majority of intercept receivers now available were based on the assumption that the only important signals would be those employing amplitude modulation, hence only amplitude-modulation detectors were provided. Although it is still true that the great majority of intercepted signals employ amplitude modulation, there is now an increasing number of signal intercepts in which the carrier frequency is the modulated variable. A wide range of deviations is employed, from 25 kc, typical of sound channels for domestic television stations, up to at least 5 Mc, typical of microwave communication links. It is important, therefore, that the general intercept receiver in the future be provided with frequency discriminator type detectors to match both the wide and the narrow bandwidth ability of the basic receiver.

The modulation waveforms derived from the various receiver detector systems may range from rectangular pulses as short as one-tenth microsecond to sine waves in the low audio frequencies. Pulse repetition frequencies from twenty to two million pulses per second are easily within the range of possibility, where the limit of engineering feasibility for an enemy transmitter is used as the criterion. It is important, therefore, that the various signal displays associated with the basic intercept receiver should function with a high order of stability and readability for this full range of possible modulation frequencies. All displays used for initial acquisition of signals and for signal bearings should perform

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their intended functions regardless of the mode and waveform associated with the signal carrier modulation. Facilities for the permanent recording of this wide range of intercepted signal characteristics must also be made available.

The Logistic Problems to be Solved

Regardless of the nature of the electronic techniques which are employed in the development of a general intercept system, the conditions which must be met above all else are that the final assemblage must be logistically feasible and must provide a range of flexibility in installation which will permit it to be successfully employed in any of a wide variety of tactical and strategic operating configurations.

To be feasible for field operations, the equipment must fall within weight, space, and structural limitations which will permit successful packaging, shipment, delivery, installation, and maintenance in the field operating environment without serious deterioration of its electronic performance. As it is considered here, the operating environment includes not only the factors such as temperature, humidity, pressure, vibration, and shock but also the available power at the site and the nature and extent of the maintenance facilities. For fixed-point signal surveillance, these items of environment are either readily controlled or readily available at land-based centers, permitting the use of elaborate, sophisticated general intercept arrangements. The limitations imposed in an aircraft installation, by contrast, require that each of these factors be carefully considered in the design of the system, if it is to provide the maximum operational utility.

When it is realized that in many tactical operations the intercept system may be expected to operate in close harmony with data centers, jammers, and other intercept systems, it becomes a matter of considerable importance that the general intercept system be designed to readily permit a wide variety of special arrangements without, at the same time, requiring the development of a large number of special equipments. This flexibility appears to be best satisfied by the employment of unitized construction in which those component parts common to all installations (tuning head, amplifiers, indicators, power supplies, etc.) are developed as standardized units which can be readily assembled around specialized system control panels. Even the control-panel systems may often be reduced to unit sections, which are then available as component building blocks in large assemblies.

The Man-Machine Relationship

In the concept of a general-signal intercept system, man and his brain are considered to be an indispensable part of the overall system, serving the dual purposes of operator of the machine on the one hand and primary data evaluator and sampler on the other. In this modern period, in which there are an ever-increasing number and variety of signals in the microwave spectrum, it is no longer practical to consider that all available signal data are to be continuously collected and evaluated. The high signal density and high order of redundancy in the signals at typical signal intercept sites only permit the data pattern to be sampled, with the effort being to derive the optimum data sample which is one providing the maximum strategic or tactical value for the time and effort expended. The complexity of this sampling problem is far beyond the ability of any of the automatic intercept systems now conceivable within existing logistic limitations. It is the type of problem requiring the application of intelligence and judgment that is available only in a man, after an adequate training procedure.

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In the man-machine relationship the machine is the device required to detect the presence of electromagnetic radiation and convert this energy to forms detectable by one or more of the senses of man. The machine exists only to serve the needs of man; it is in effect his slave, and should be designed to do his bidding effectively and with dispatch. It is a prime obligation of the machine designer to consider the machine only as a device that, in response to man's motor-control system, provides logical stimuli which can be rapidly recognized and utilized by the human sensory-response mechanism. In the operation of an intercept system, the first problem facing the operator is the assessment of the signal activity pattern as it exists, described in both frequency in the assigned spectrum width and in elapsed time. To be satisfactory to the operator, such a pattern should be available immediately upon demand, covering any spectrum width or time duration which he might conceivably find useful. Signal resolution within the time-frequency display should be adequate to permit rapid selection of individual signals for detailed analysis.

Since in many signal intercept operations successive determinations of signal bearings are required, periodic reacquisition of the same signal should be a routine matter accomplished by automatic reset devices, removing all necessity for repeated manual-tuning operations for the given signal. The operator's attention should be directed on maintaining an adequate program of data sampling rather than wasted on the routines of manual resetting to signals previously acquired.

The pertinent characteristics for a particular selected signal should be simultaneously displayed without the requirement of any manual adjustment other than setting of a signal-level control. Recording of this display and associated data should be accomplished by the operation of a simple spring-return switch, all necessary adjustments in the recording system being preset and nonmanipulative. Such a recording system should replace the usual manually kept log and so serve to release the operator from a tedious task.

It is assumed that the general modes of operation, briefly outlined above, are to be provided through display arrangements and control assemblages so placed as to be logically related to the manipulative and sensory systems of the operator, permitting him to operate and function with a minimum of physical discomfort and nervous strain.

THE NRL MICROWAVE SIGNAL INTERCEPT SYSTEM

For a number of months there has been in existence at the Naval Research Laboratory the major components of an operating general intercept system for microwave signals. This system covers the frequency range from 1000 to 10,750 Mc in four tuning ranges and is based on the r-f and i-f techniques originally developed in the AN/APR-9 receiver. The technical details of this system have been completely covered elsewhere (26) and the results of considerable local operational experience, working against live signals, are now available (33). The prototype development for the AN/WLR-1 receiver system, under Bureau of Ships contract* and a similar development for airborne applications, under Bureau of Aeronautics contract† are based on the r-f and i-f techniques used in the AN/SLR-2 and the AN/ALR-8 receivers, respectively, combined with the control and display methods developed for the Naval Research Laboratory engineering model. These receivers under prototype development are intended to cover the total frequency range from 50 to 10,750 Mc in nine tuning ranges. It is the primary purpose here to review briefly the general nature of this type of system and then to point out in a somewhat speculative manner the possible extensions of this group of techniques to particular kinds of tactical and strategic applications.

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*BuShips Contract NObsr 64683 with Collins Radio Company, Cedar Rapids, Iowa

†BuAer Contract NOas 56682 with Loral Electronics Corporation, New York, N. Y.

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Description of the Operating System

The operator of the NRL microwave intercept system (Fig. 1) sits in front of two cathode-ray-tube displays at eye level, with all the major system controls within easy reach at desk level. Audio receiver outputs are monitored by headphones, and the major recording facility is a KD-2 camera. Any one of the four tuning ranges normal for an AN/APR-9 receiver is immediately selectable by manual rotation of the four-position switch common to all AN/APR-9 systems. The selection of a particular tuning range automatically attaches the proper antenna feed from the AN/SLA-3 DF antenna associated with the system. To date no omnidirectional antennas have been employed, and the quantitative effect on system performance of this deliberate omission is still to be determined.

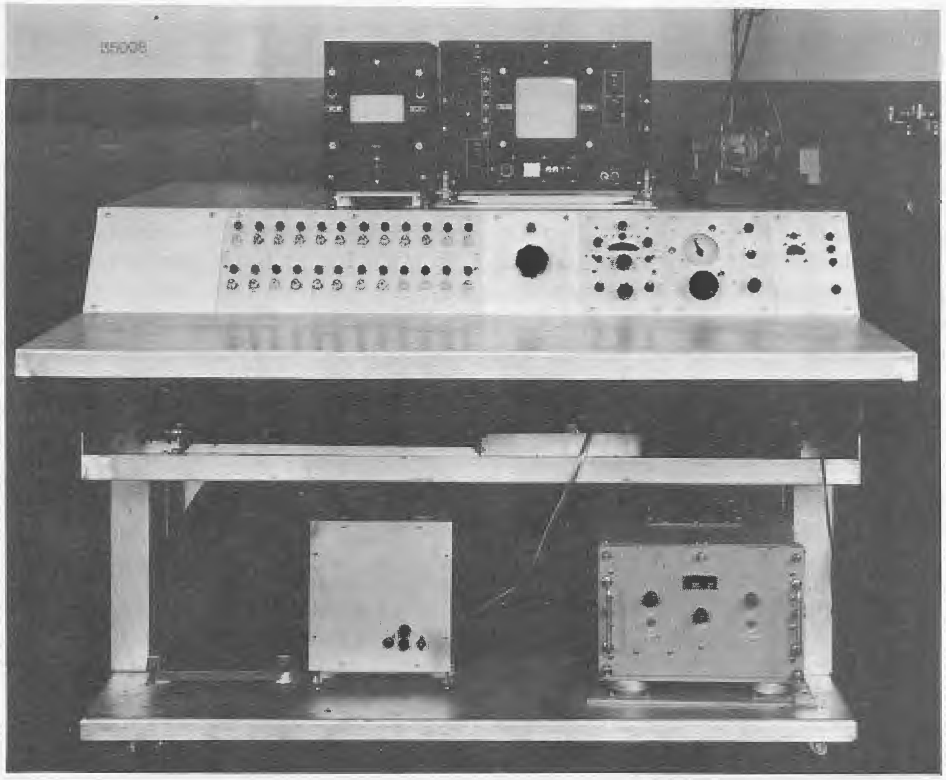

Fig. 1 - The NRL microwave intercept system

After selection of the desired tuning range the receiver is placed in its frequency scanning mode by pushing a single spring-return pushbutton switch. When in scanning mode, the receiver tunes cyclically through the selected tuning range at a speed of one full range excursion in slightly less than two seconds. The exact width of frequency scan is readily controlled within any limits down to about ten percent of full scan by manipulation of the sector limit controls common to an AN/APR-9. To maximize the slope of the cumulative probability of intercept function for low pulse frequencies, the bandwidth switch for the receiver is normally set for wide-band operation (a 20 Mc bandwidth). If maximum sensitivity is required and the major intercept interest is in high-pulse-frequency systems,

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the receiver is then set on the narrow-band position (a 0.7 Mc bandwidth). During the scanning mode operation for the receiver, the DF antenna is normally operated at its maximum azimuth scan rate in order that, at least on a scanning basis, the maximum gain for the antenna will be available on all azimuths. As Bullock has pointed out (33), the back lobes of the DF antenna system are quite effective for the detection of high-power radars well out to and even beyond the radar horizon.

During scan the receiver outputs are presented to the operator through the headphones on the one hand and by means of a time-frequency diagram on the other. The time-frequency diagram is developed on a 5FP25 cathode-ray tube, arranged so the spot moves horizontally in synchronism with the tuning-head motion, with receiver outputs being presented as intensity variations. In order that the signal activity intercepted on succeeding scans may be seen separately, for time-variation comparisons, the cathode-ray-tube spot is caused to slowly drift downward at a rate of about one inch per minute, developing a total vertical time dimension of two minutes before returning to the top to begin a new raster. In final development the operator observes a rectangular pattern four inches wide and two inches high in which signals on fixed frequencies appear either as vertical lines for signals present on every scan or as single dots spaced in a somewhat random manner on a vertical line for signals intermittently present such as those from radars at very long range. The very long persistence of the P25 phosphor permits the operator to continuously observe a pattern of signal activity extending backward in time for at least one minute. It is from the changes observed in this continuously developing pattern that decisions are often made as to which signals will be selected for detailed analysis. The operator is aided in making these decisions by the fact that enough information is presented through the headphones to permit him to roughly estimate the general nature of the signals seen in the developing time-frequency diagram. Pulse signals, typical of most radars, are heard as short bursts having tonal characteristics or as sharp pops in those cases where the repetition rates are very low. Signals employing superaudible repetition rates and signals employing low-power continuous carriers are commonly not heard in the headphones except as a possible momentary increase in the audible background noise.

When the operator decides to inspect in detail the characteristics of a particular signal indicated in the time-frequency display (now known as the signal-acquisition display), he can, by pushing any one of twenty-four spring-return pushbutton switches, take manual control of the receiver tuning system. By turning a conventional large control knob he can quickly position the cathode-ray-tube spot on the desired afterglow image in the signal-acquisition display. This operation places the desired signal within the display range of the AN/APR-9 panoramascope. If other signals are to be selected for analysis, this is accomplished by repeating the above operation using any of the remaining twenty-three pushbutton switches until all of the desired signals have been manually selected or all of the available switches have been used. After these operations are completed, any of the selected signals can be reacquired merely by pushing the switch originally associated with the manual selection of that signal. In order that the operator may easily identify the pushbuttons already in use, a small pilot light above each button remains lit once the button has been pushed. These lights can be extinguished only by a manual reset operation with each button. In addition, a second series of lights indicates the button last pushed, so that sequential sampling of the stored tuning positions can be accomplished with no loss of position reference.

The selection of the manual tuning control for the receiver automatically activates the signal-analysis display and the signal-frequency indicator. The signal frequency is indicated by means of the usual Veeder-Root counter used in the AN/APR-9. Unlike the AN/APR-9, in the system here described the counter automatically adjusts its display range to fit the tuning head selected. In manual control the counter always displays the frequency of the selected signal. In scanning mode the counter remains motionless at an indicated frequency near the center of the total tuning range. Directly above the Veeder-Root counter is the 7YP2 cathode-ray tube on which there is a combined display for signal modulation, bearing, and r-f spectrum. This is a five-gun display (19) in which the first three guns provide a signal initiated time base composed of three time-sequential displays, consisting of a 0- to 5-microsecond exponential time base followed by a two-decade approximately logarithmic time base running from 5 to 500 microseconds, which in turn is followed by a two-decade time base covering the range 500 to 50,000 microseconds. The fourth gun provides a DF display controlled by the AN/SLA-3. This is a rectangular display consisting of two traces, one above the other, in which the top trace indicates bearings from 270 degrees on the left through 360 degrees to 90 degrees on the right. The lower trace indicates bearings from 90 degrees on the right through 180 degrees to 270 degrees on the left. These traces are separated about three-fourths inch with video deflection downward from the upper trace and upward from the bottom trace. During antenna rotation the video pattern envelope indicates bearing in the usual manner. The fifth gun, at the bottom, displays the panoramascope display normal to the AN/APR-9. The signal amplitudes visible in these five displays are so proportioned that the only gain control adjustment required during signal analysis is that provided by the usual receiver i-f manual gain control circuits. For the great majority of signals a complete signal analysis is accomplished with the only manual adjustment required being the single gain control.

For newly acquired signals the initial detailed analysis often requires that the rotation of the DF antenna be stopped. In the AN/SLA-3 antenna it is not only possible to stop the antenna but it is also quite easy to manually set the antenna on the signal bearing to provide the maximum possible signal-to-noise ratio for modulation analysis as well as maximum azimuth resolution as an aid to signal separation. This operation is not usually required for subsequent analysis of the same signal since the only expected change is usually signal bearing.

The major recording facility for this intercept system is a modified KD-2 recording camera, which has been fitted with a new set of scales compatible with the displays developed on the signal analysis cathode-ray tube (7YP2). Since the camera structure includes an illuminated clock and a small data card for brief handwritten notations, all pertinent data on a selected signal other than signal frequency are recorded within the area of a single 35-mm-film frame. No provision has so far been made for including within the camera field of view the Veeder-Root counter which indicates the signal frequency.

The system, as briefly described, maintains the unitized construction philosophy common to the conventional AN/APR-9. The major difference between this system and those based on the conventional AN/APR-9 and its attachments is the improvement in speed and ease of operation that is provided. In the conventional receivers the speed of operation is limited almost entirely by the tuning speed of the r-f tuners. In addition, in the conventional receiver, a signal flashing at a very low rate is very difficult to tune into the passband even when its presence is definitely known. In the NRL system the speed of operation is largely controlled by operator response time regardless of the nature of the signal. Once a receiver setting for a given signal frequency has been stored in the manual control board, this setting can be re-established within an average time of one second after depressing the proper selector button. Proper setting of the receiver gain control is the major manual adjustment required of the operator for sequential analysis and recording of signals previously stored. The operator's time is largely concerned with decisions as to which signals will be next in analysis. The acquisition of new signal activity is almost an automatic reaction to the change in signal pattern as observed in the long-persistence phosphor of the acquisition indicator. Use of the long-persistence phosphor as a short-term storage device greatly relieves operator tension during acquisition of new signals. Fingertip operation of automatic control circuitry speeds up routine procedures of receiver tuning to an extent that it should be possible for the trained operator to concentrate on the larger problem of proper sampling of the signal data pattern. It appears self-evident that on a strategic search mission it should be possible to accumulate an adequate number of DF bearings on several times the number of signals now accommodated in the conventional systems.

Additional Techniques for Improved Intercept Performance

As the result of a number of months of operational experience with the NRL microwave intercept system it has become evident that the overall performance can be extended and improved by the addition of several devices and techniques. These techniques are directly applicable to the AN/WLR-1 and similar receivers, and they are concerned with possible variations of the signal-acquisition display, improvement of the manual signal-store board, provision for a DF tracking notch in the DF display, further modifications and improvements for the KD-2 camera recording system, and improvement of the basic receiver to provide the near-ultimate in overall signal sensitivity.

Acquisition Display Improvements — The signal-acquisition display, as it now exists, is developed as a rectangular pattern on the face of a five-inch round cathode-ray tube, and provides as an absolute maximum a four-inch horizontal dimension for signal frequency. If it is assumed that the maximum spot diameter for a saturation signal is 0.04 inch and that each such spot represents a separate signal (an assumption not valid in actual operation), then certainly no more than one hundred equally spaced signals could be optically resolved. When this display is the result of scanning the TN-131/APR-9 tuner, a total of 3700 Mc are displayed, representing approximately 185 i-f passbands when using the 20 Mc i-f bandwidth. If only relatively weak signals are intercepted, so that no signal occupies more than 20 Mc in the display, it is evident that the optical resolution provided by the cathode-ray tube is not adequate to insure visual separation of adjacent signals even though the signals are electronically resolved. Under the above conditions and where the logistic considerations of the military situation will permit it, there is then some reason to believe that the use of a ten-inch cathode-ray tube for the acquisition display would provide a useful improvement in its overall utility. It must not be overlooked, however, that very strong signals are often presented over as much as 40 Mc (due to skirt response on the i-f passband), and under this condition the optical resolution for a four-inch display is not quite so inadequate.

In contrast with the above situations, operation of the receiver with the narrow i-f passband (0.7 Mc) develops an acquisition display in which the optical resolution is completely inadequate. There is also the fact that using narrow bandwidth and scanning the receiver at the rate of one full scan in two seconds produce a display providing a steep slope for the cumulative probability of intercept function only for pulse signals having repetition rates of the order of twenty times the critical pulse rate for wide bandwidth operation. It is thus desirable not only to improve the optical resolution in the display but also to reduce the scan rate when operating the receiver in the narrow-band mode. Since it is of some operational importance to develop the vertical raster dimension at about the same rate in lines per minute regardless of i-f bandwidth used, it appears that a relatively simple and useful solution to the above problem can be achieved.

If only ten percent of a full tuning range is scanned with the narrow i-f bandwidth, using a scanning rate one-tenth the normal speed, and the resulting information is displayed on the full width available on a ten-inch cathode-ray tube with no change in the vertical drift

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rate, a display should be produced which could be of considerable potential value for those cases where a number of similar radars operating in a very narrow spectrum assignment must be intercepted and continuously monitored. Because the frequency spread of similar radars may often cover a spectrum width approaching ten percent of a tuning range, it does not seem desirable to provide for a sector narrower than this. At a scanning rate one-tenth normal the minimum critical pulse frequency for probability of intercept considerations using the narrow i-f bandwidth is only approximately twice the value for normal scan with wide bandwidth. This is, therefore, an entirely satisfactory operating condition for the great majority of tactical and strategic applications. Under the conditions described, switching from normal to ten-percent sector scan would produce no major change in the general appearance of the resulting display raster as seen by the operator; horizontal and vertical dimensions, spot velocity, and the number of horizontal lines per vertical inch would remain the same. Obviously the ten-percent sector-scan technique, as described, is directly applicable to acquisition displays developed on a five-inch cathode-ray tube, such as would be commonly used, with some loss in overall signal resolution. In Appendix A one possible circuit configuration is briefly described for development of the ten-percent sector scan as an attachment to receivers such as the AN/WLR-1.

Manual Signal-Store Improvements — On the basis of many months of operational experience with the NRL microwave intercept system, certain comments with regard to the performance of the manual signal-store system appear to be in order. The first of these comments is largely concerned with the desirability of storing, along with the signal frequency position in a tuning range, the specific tuning head in which the stored signal is to be found. In the NRL system this is accomplished by simply dividing the twenty-four manual store positions into four arbitrary groups of stores, with one group assigned to each of the four available tuning heads. In the AN/WLR-1, as designed at Collins Radio Company under a Bureau of Ships contract, selecting a particular manual signal-storage position automatically establishes a visible record of the tuning-head number in which the signal-storage operation is performed. It has, on occasion, been suggested that it could be arranged so that reselection of a storage position on which signal information has been stored would automatically select the tuning head in which the original storage action occurred. The operational experience at NRL indicates that, although such a composite storage system is feasible, it may not be entirely desirable. Especially in the TN-131/APR-9 tuning range, it has been observed that the klystron local-oscillator frequency is subject to a considerable thermal frequency drift during the first five or ten minutes after application of high voltage, even when the cathode heater is maintained in continuous standby operation. To a lesser degree this same condition exists in the lower frequency tuning ranges, indicating that rapid selection of stored signals distributed among several tuning ranges would, also, be accompanied by visible errors in observed signal frequencies as compared to calibrations based on the conditions existing after adequate warmup. A safer mode of operation appears to be one that maintains continued operation within a chosen tuning range for as long a time as possible before transferring to a different range. Under this type of operation, automatic selection of the tuning range is a matter of relatively minor importance, likely not to be desirable when considered against the additional circuitry which would be required.

Another group of comments relative to the manual signal-store system concerns the possibilities for improvement of precision in the store. In the NRL receiver it is known that thermal drifts in the servoamplifier thermionic type modulators can easily account for random storage errors of the order of one five-thousandth of a tuning rage. This is certainly not a large error, but it is an error which has been eliminated in the AN/WLR-1 receivers through the successful use of an electromechanical chopper type modulator. As has already been pointed out, thermal drifts in frequency of the local oscillators in the tuning heads are far from negligible. In the TN-131/APR-9, using the 2K48 klystron as

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oscillator with the cathode heater in continuous operation, application of high voltage to the tube has been observed to cause short-term drifts of the order of at least 5 Mc, which are observable in the panoramascope display as a displacement from center of at least one-fourth of the total display width. If the designers of klystron tubes could temperature-compensate the internal tube structure, the overall stability of the manual signal-store system could be greatly improved.

A third factor controlling the precision of the manual store is concerned entirely with the quality of (a) the precision potentiometers employed in the tuning heads to provide position reference for the tuning servo system, (b) the precision potentiometer used as the servo reference device in the Veeder-Root counter frequency indicator, and (c) the precision potentiometers providing tracking of the reflector potentials for the klystron local oscillators. It is particularly important that potentiometers (a) and (b) should provide the best possible resolution to permit the use of the maximum possible servoamplifier gain and the best possible linearity to minimize frequency alignment errors due to this source. Note here that a linearity factor in each of these two potentiometers amounting to 0.1 percent of full tuning range can result in a frequency error in initial alignment as great as 0.1 percent of the r-f head tuning range. In the TN-131/APR-9, in this worst case, the error due to each potentiometer could be as high as 3.7 Mc.

The linearity of the reflector-tracking potentiometer is also a factor to be considered in that the output frequency of a klystron is partially controlled by its reflector potential. If we again assume for this potentiometer a linearity factor of 0.1 percent and assume roughly 300 volts as the total potential difference required across the potentiometer to track the reflector across a tuning range, and if, in addition, we assume a reflector "frequency sensitivity" of 1 Mc per volt, then variations due to potentiometer nonlinearity would be of the order of 0.3 Mc. It is thus evident that the performance requirements for the reflector-tracking potentiometer are not nearly so great as those for the servo follow-up circuits. All three of the potentiometers discussed are associated in voltage dividers with trimming potentiometers and fixed resistors. Every effort should be made to assure that these networks are designed to minimize resistance drifts as a function of temperature. A fourth potentiometer to be considered, of course, is that used in the manual store to provide the stored reference potential representing a previously chosen signal. The two main requirements on this potentiometer are that it provide a high order of resolution (at least one part in ten thousand) and that it be associated with circuit elements which will assure a satisfactory order of temperature stability in the resultant reference network. It is not necessary that the manual storage potentiometers provide a high order of linearity.

In addition to all the factors just enumerated there is the question as to whether it would be feasible to improve the shapes of the drive cams or the capacitor plates (in the three lowest frequency heads of the AN/WLR-1) so as to provide a more linear frequency variation in the receiver local oscillators as a function of servomotor rotation. This question is undoubtedly answerable only in terms of the resultant problems concerned with maintenance of manufacturing tolerances during the fabrication of mechanical drive components and, in the case of microwave klystrons, how closely the shunt admittance (which acts as an end loading on the oscillator tuned cavities) can be maintained within narrow limits. A more practical solution to these problems might be the development of cavity drive cams and tuning capacitors with a greater number of mechanically adjustable points within the maximum range of motion. These are, of course, matters which can be determined only through exhaustive engineering studies.

Receivers such as the AN/SLR-2, AN/ALR-8, AN/WLR-1, and the NRL microwave intercept system are aligned against a series of crystal-controlled frequency marks extending throughout the range, up to 11,000 Mc. In the alignment procedure the effort culminates in the endeavor to provide an overall adjustment such that the counter frequency reading coincides within reasonable tolerance to the absolute frequency of the marker centered in the receiver. Since all of the sources of nonlinearity that have been listed tend to add in a somewhat random fashion, the alignment procedure has a general tendency to correct for the overall expected error. This is one more reason for believing that a greater number of points for tracking adjustments for the local oscillators might be a practical approach toward improvement of overall linearity of the receiver calibration.

There is considerable reason to desire that the overall calibrated frequency error for a given receiver should not exceed ±0.1 percent of a tuning range, so that, for example, in the TN-131/APR-9 this error would always be less than 3.7 Mc. Under this condition, if the reference potentiometers for the Veeder-Root counter drives have a range linearity no worse than 0.01 percent, the reference dc potentials in the manual control signal stores for two aligned receivers would represent the same frequency within a maximum deviation no greater than 8.14 Mc ($3.7 + 3.7 + 0.001 \times 2 \times 3700 = 8.14$). A signal could then be manually centered in the panoramascope of one receiver and another such receiver could be automatically set to the reference store of the first receiver with assurance that the chosen signal would appear somewhere within the range of the panoramascope display for the second receiver.

DF Display Tracking Notch — In the NRL intercept system and in the AN/WLR-1, controls for the DF antennas are completely separated from the main receiver control panel, and during full rotary scan there is no indication in the display to show the bearing to which the antenna will home when the mode of operation for the antenna is switched to full manual control. Thus, when a signal is observed on a particular bearing, to set the antenna on this bearing requires either reading the bearing and then setting this bearing on a dial outside the display before switching to manual slewing or reading the bearing and then switching the antenna to manual control and rotating it until the cathode-ray spot coincides with the bearing.

Either of these is relatively clumsy and requires that the operator remember the bearing long enough to set to it. A much more satisfactory control system would be provided if the manual slewing dial controlled the position of a marker pip or notch in the dynamic display, so that while the antenna is in full scan rotation the marker could be moved in the dynamic display to coincide with the signal bearing. Switching then to manual control would automatically cause the antenna to home on the desired signal bearing. In addition, the use of a manually slewed DF tracking marker would permit the operator to manually track the changing bearing of a moving signal. This would provide the possibility of transmitting the bearing data continuously or as time-spaced samples to remote displays concerned with area-situation problems.

The generation of a DF marker notch, having display deflection opposite to the displayed video, would probably require considerable redesign of the circuitry now available in the AN/WLR-1 signal-analysis display system. On the other hand, if a single, relatively large amplitude spike is used, and if this spike has the same deflection polarity as the displayed video, it appears feasible to add such a marker to the existing displays without any internal modifications of the indicators. The modifications required would be confined to the DF antenna control system and would probably employ a simple extension of the DF calibration marker system already developed for the AN/WLR-1. One possible solution would require the attachment of a 1 DG differential generator to the manual control dial shaft through which antenna position information would be passed to a 1 F synchro. The 1 F synchro would drive a low-inertia disk with a single narrow radial slot, through which a light beam would be passed to a phototransistor. The output from the phototransistor could then be passed through the transistor amplifier used to amplify and shape the DF calibration marks for the AN/WLR-1. The output from the transistor amplifier would be passed through a video mixer so that the DF marker pip would be presented with the input video to the signal analyzer display. It should be noted that the simple system described has the disadvantage that the DF marker will also appear in the 0 to 5 and 5 to 500 microsecond modulation analysis time bases, but since the marker would occur with a repetition rate not exceeding five pulses per second it should be only faintly visible when compared with most signal displays. When the tracking pip is not required, it would be a simple matter to switch it out of the display.

Recording Camera Improvements — One obvious change which should be made in the KD-2 camera for use with the AN/WLR-1 system is to provide within the data chamber a small four-digit Veeder-Root counter, servo-driven and controlled by the signal-frequency reference system, so that the frequency of the signal displayed in the analysis indicator would be included in all photographic records. This requires that the small servomotor drive and reference potentiometer be mounted on the top surface of the KD-2 frame in place of the carrying handle, with a mechanical drive shaft transmitting motion to the counter in the data chamber. This change would require removal of the three-digit counter now in the KD-2 data chamber for the purpose of providing a photo reference number, but since the data chamber would include both a signal frequency and a time record no photo reference number should be required. In the NRL system all circuit connections required for the existing signal-frequency counter drive are included in a single cable, and so are available for quick transfer to any future drive system installed on the KD-2 camera.

A second change in the KD-2 camera which appears desirable is the development of a small magazine-loading 16-mm movie camera to replace the still-frame 35-mm camera now in use. This camera should be designed with the widest possible shutter angle and lens opening that can be provided. An f/1 lens would be very desirable if film speed is limited to that now available in Tri-X film. To provide maximum utility such a camera should be capable of successfully recording the afterglow of the P2 phosphor for those events displayed on the signal-analysis indication during the dead time for the camera shutter. For certain special applications, where logistic considerations would permit it, a reel-loading sound-film 16-mm camera, having the above general optical performance, could be of considerable value as a means for providing a complete aural and visual record of the displayed signal.

Signal Sensitivity Improvements — Receivers such as the AN/SLR-2 and AN/ALR-8, the tuning heads of which employ tunable passive networks preceding the crystal mixers, provide excellent suppression of spurious signal responses but do not provide the ultimate in signal threshold that might be achieved. When these receivers are employed in areas adjacent to high-power transmitters, as is often the case in shipboard and airborne installations, the excellent selectivity characteristics of the passive preselectors often permit operation of the receivers over a large portion of the total tuning range without serious local interference. For the great majority of tactical and strategic applications, these receivers when fitted with low-noise i-f preamplifiers and operated with low-loss transmission lines to the antennas provide a level for signal threshold which permits successful intercept of radar back-lobe radiation from somewhat beyond the horizon. Such performance, when considered in terms of the logistics represented by the use of these relatively simple and rugged tuning mechanisms, can be argued as being entirely adequate for the large majority of tactical and strategic applications.

In the design of the AN/WLR-1 at Collins Radio Company, every effort is being made to optimize the performance of the tuning heads, even to the extent of considering the inclusion, where feasible, of active amplification in the signal preselector circuits to provide a better threshold through improvement of the overall noise figure. To date, the successful use of active amplification in the design of preselectors for the AN/WLR-1 has been limited to the tuning range 50 to 100 Mc. The lack of approval of the WE416B microwave triode for general service use as well as the increased maintenance problems which might accompany the general use of this tube in tuned preselectors above 100 Mc generally militates against the complete redesign of the AN/WLR-1 preselectors to provide active r-f amplifiers up to at least 1000 Mc or perhaps as high as 4450 Mc. Since the WE416B was designed to operate as an amplifier at frequencies of the order of 4450 Mc, it might be technically feasible to design a tunable amplifier around this tube for this high range. There is reason to pause, however, when it is remembered that experimental traveling-wave tubes centered around 3000 Mc have been developed with noise figures considerably better than can be achieved at these frequencies through use of the WE416B.

Although it may be successfully argued that provision for the ultimate in signal threshold is not a requirement for the great majority of operations, there are situations where the ultimate in threshold performance could, conceivably, be of considerable value. Such situations are generally associated with intercept installations well removed from powerful transmitters, so that it is not always necessary to consider the use of passive preselection for the rejection of such signals as a protection against cross-modulation in a following amplifier. Passive preselection following the amplifier can in this case provide adequate image rejection. In addition, to further promote signal sensitivity and so increase intercept range, receivers in such installations are usually operated with the narrowest i-f bandwidth available. Under conditions such as have just been outlined it appears feasible to consider the successful development of attachable tuned r-f amplifiers for use with those AN/WLR-1 receivers where the ultimate in signal threshold is a requirement.

For signal intercept operations involving the maximum possible reception range for rotating radars, it is to be expected that only occasional flashes of information from the transmitter will be displayed. It is evident then that the short-term memory inherent in the P25 phosphor of the acquisition indicator will be an important factor in achieving successful performance. Using the narrow i-f bandwidth in the AN/WLR-1 would indicate, from the probability-of-intercept viewpoint, the desirability of operating the receiver in the ten-percent-scan mode, which has already been proposed and described. Since in this mode the receiver is scanning at only ten percent of its normal scanning speed, it appears feasible to develop an attachable r-f preamplifier and preselector, which would be driven in a linear frequency scan by a servo system following the same control waveform as would be applied as reference to the basic receiver control servo.(See Appendix A). Such preamplifiers should be designed to provide 50-ohm input and output impedance matches for the r-f signal, so that the amplifier could be a simple insert between the antenna and r-f input jack for the basic receiver. At least one preamplifier would be required for each tuning range of the AN/WLR-1, and an additional servoamplifier and auxiliary power supply with associated switches for selection of tuning ranges would be required. Preamplifiers for the tuning ranges below 2300 Mc might be successfully designed to employ two r-f amplifiers designed around the WE416B. Above 2300 Mc it is entirely conceivable that low-noise traveling-wave tubes, now in experimental development, might provide a better solution than grounded-grid triodes. The broadband nature of such tubes could serve to completely eliminate the tracked tuning structure in those tuning ranges employing traveling-wave tubes unless, perhaps, it would appear desirable to employ some passive preselection preceding the tubes. To date, those traveling-wave tubes providing the lowest noise figures are, also, relatively narrow-band as compared to the AN/WLR-1 tuning ranges in which they might be used.

Since it is proposed here to scan only ten percent of a full tuning range, and since the available experimental tubes are adequate in bandwidth for this restricted scan, the full bandwidth for a given AN/WLR-1 receiver could be covered by use of several narrow-band, low-noise traveling-wave tubes designed to have overlapping passbands. It is evident from what has been written here that the development of the desired preamplifiers is a major task not simple to accomplish, and this is an additional reason for not attempting to include these techniques in the basic AN/WLR-1 at this time.

Additional Techniques for Jammer Monitoring

An important tactical function which may be required of the AN/WLR-1 in the future is that it perform satisfactorily as a monitor system for shipboard jammers. In such service, provision for monitoring should include continuous inspection of either wide or narrow spectrum ranges depending on whether the jammer to be monitored is of the barrage or spot jammer type. In addition, there is the requirement that some form of continuous look-through be available in order that the jammer operator may continuously observe the relative position in the r-f spectrum of the jammer signal as compared to that of the signal being jammed. The AN/WLR-1, as it is now being developed, does not provide adequate facilities for the functions just described, but there appears to be no reason why special indicators may not be developed in the future, which could then be used with the AN/WLR-1 as attachments for monitoring.

One of the most commonly used transmissions employed in microwave jamming systems involves the use of one form or another of random-amplitude video-frequency noise modulation. When a signal employing this type of modulation is displayed in the narrowband panoramascope of a receiver such as the AN/SLR-2 or AN/WLR-1, the displayed noise spectrum appears principally as an envelope rather than very fine grass because the pulse-stretching circuits needed to insure visibility of single narrow pulses now behave as pulse-peak detectors of the very high duty cycle pulses of which noise consists. To overcome this weakness on the jammer signal, the display circuits must be modified to remove the pulse stretchers so that pulse-peak detection will not occur. On the other hand, if this same display must also present, for example, the r-f pulses due to a radar signal being jammed, the display must then employ pulse stretching to make these pulses visible. Since the circuit requirements for these two desired displays are certainly not compatible, it is necessary to provide separately switched channels in order that circuit designs may be optimized for each of these two separately existing signals.

The two types of signals just described have been designated as separately existing since it is here considered that time-sharing look-through will be commonly used. In this type of look-through the transmitter is switched off for periods of the order of one to five microseconds at an average rate as high as 50 Kc, and during the transmitter off periods the receiver is free to receive the jammed signal without interference from the local jammer.

It would appear that a useful monitoring display utilizing the look-through periods for monitoring the victim signal would be one such that the usual panoramascope time base would be displayed horizontally, in normal fashion, with the unstretched jammer spectrum presented as a vertical deflection upward and the stretched video, presented downward, as a series of dots of one to five microseconds duration presented at spaced intervals along the stretched trailing edge of the victim signal. For a look-through frequency of 50 kc these dots would be 20 microseconds apart. If the slope of the stretched victim pulse requires 200 microseconds to return to the baseline, then the trailing edge would be represented by ten dots along the vertical display line representing the trailing edge of the pulse. It seems evident that a P2 phosphor with four to five thousand volts accelerating potential would provide adquate sensitivity and retentivity for such a display.

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The video deflection circuitry required for such a display would be identical with that used for the DF vertical deflection as used in the NRL microwave intercept receiver and the AN/WLR-1 with the exception that the signal input grids of the two amplifier tubes would be separated and unstretched video would be applied to one and stretched video to the other.

The bias on the signal grids would be adjusted to cause the switched baselines to coincide, and the look-through gates would be applied to the input grid of the Schmitt switching circuit as is shown in Fig. 2. For monitoring of a spot jammer the time base normally used for the receiver panoramascope would be employed. For monitoring a barrage jammer the time base used for the ten-percent-sector scan with narrow i-f bandwidth would seem to be more appropriate.

To prevent contamination of the stretched video display by the unstretched jammer video display it would be necessary to insure that the receiver video output was fed to the video stretching circuits only during the occurrence of a look-through gate. A block diagram of the required gating system is shown in Fig. 3.

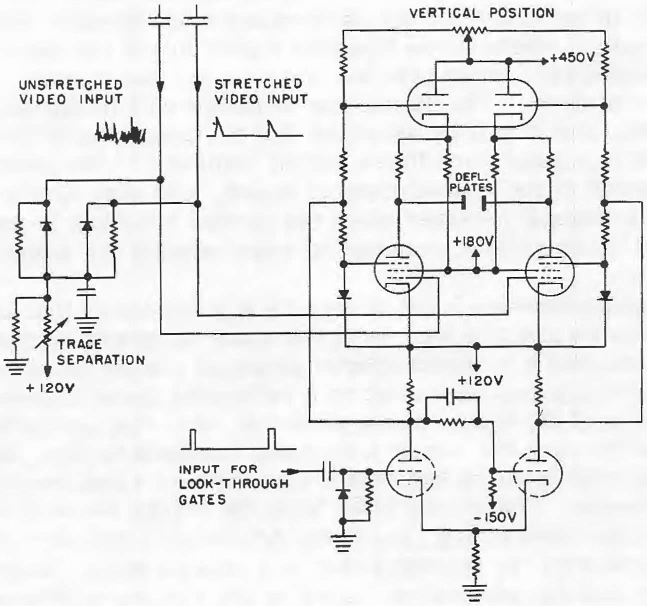

Fig. 2 - Vertical deflection amplifier for jamming-monitor display

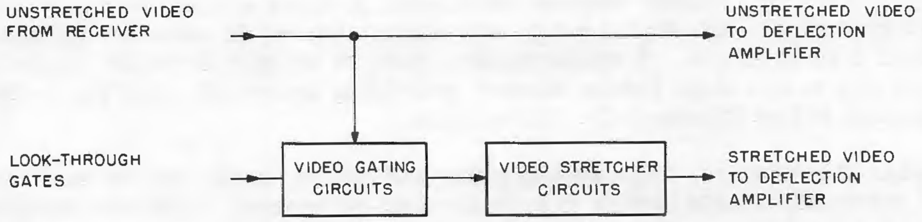

Fig. 3 - Video gating system for jamming-monitor display

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OPERATIONAL COORDINATION BETWEEN TWO OR MORE INTERCEPT SYSTEMS

There appear to be a number of tactical operations in which it could be important, at some future date, to provide for the continuous coordinated operation of two or more microwave intercept systems. Some of the simpler operational problems to be solved require the coordination of two or more systems in the same general locality while other, more complex problems, are concerned with coordinated operation of two widely separated systems. Typical problems in the first category are continuous-intercept search and analysis and/or track operations, or continuous search-and-jam operations. Typical problems of the remote-coordination category are the assignment of a specific jam-monitor effort to a jamming station remote from the point of initial intercept, or the determination and tracking of an airborne enemy radar through the cooperative efforts of two intercept stations on the ends of a known baseline.

Common to all these problems is the required technique which will permit precise impartation to a remote point of the radio frequency of the intercepted signal. In regions of low signal density, such as may be encountered by fleet units far from land, it could be that successful improvements in the precision of the manual signal store (previously discussed) would provide an accuracy for signal-frequency designation which would be entirely adequate. In those regions where more than one signal might normally appear within a single panoramascope display, more precise methods for designation, as yet undetermined, would undoubtedly be required. The discussion to follow will be entirely limited to the low-signal-density problem, and it will be assumed that the precision of the manual signal store can be improved to a point such that a signal centered in the panoramascope of one receiver, and thus stored in the manual control board, will also appear within the panoramascope display of a second receiver when the second receiver is permitted to home directly on the manual store reference potential representing the signal in the first receiver.

For such an operation between local receivers it is assumed that all reference potentiometers for all receivers are powered from the same dc power source. Where the receivers are so remote that a common source potential cannot be relied upon, it would be possible to consider the potential stored on a reference potentiometer in the manual store as being a fraction of the local source potential, this fraction to be determined automatically upon demand through the use of a digitally balanced bridge, the output of which would be a binary code representing the relative position of a particular signal frequency within a given tuning range. The binary code from the bridge balance plus a four-digit code representing the specified tuning range (the AN/WLR-1 includes 9 tuning ranges) would provide precision information for transmission to a remote point, where a normal conversion from digital to analog information based on the remote source potential should provide relatively precise frequency information for remote receiver set-on.

A ten-digit bridge balance would determine the signal tuning position in a given receiver to 0.1 percent of a tuning range. Because of accumulated errors in the chain of events required for the transfer between receivers, it would appear desirable to strive for even higher precision in the digital bridge techniques than would normally be available in the individual manual stores. It would appear, thus, to be very desirable to strive for the achievement of a twelve-digit bridge balance, providing an overall accuracy in the digital code of one part in five thousand of a tuning range.

By means of miniature, self-latching polarized relays, using one for each digit, it would be a relatively simple matter to provide semi-permanent, relatively simple reference stores for the binary-coded information representing specific signals. It is obvious, of course, that this information could be just as readily stored by any of a number of other devices, including the high-capacity devices represented by high-speed drum recorders for digital codes.

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Continuous Search-Track Operations

It seems evident that if the AN/WLR-1 is to represent a real tactical advantage against a potential attacker who openly employs active airborne search systems such as radar, then at least one receiver system in the tactical area must be maintained in essentially continuous signal-frequency search, with only those very short interruptions required for analysis and store of intercepted enemy signals. The very high speeds to be expected in future attacking aircraft indicate that diversion of the signal-frequency search operation to a signal-tracking effort, for even a short period of time, could be potentially disastrous. It appears, therefore, that a complete tactical operation at a given station would require that enemy signals intercepted by a receiver, used in continuous frequency search, should be designated and transferred to a separate receiver devoted entirely to the problem of tracking the assigned signals.

When combined with a DF tracking pip, proposed above, and when added to these facilities there could be analog-to-digital conversion devices for precise storage of DF bearings, the manual signal-store system in the AN/WLR-1 provides for the first time the opportunity for a manually controlled microwave intercept system which would be capable of providing DF tracking information on more than one enemy signal. In the AN/WLR-1 it will be possible to reacquire a stored frequency position in an average elapsed time of one second. If the operator then rapidly resets the DF tracking pip to the signal envelope in the dynamic DF display, this bearing could, by the push of a button, be inserted in the bearing store associated with the chosen signal. Completion of this relatively simple operation would permit him to select a second signal to be handled in a similar manner, followed by perhaps a third or even a fourth to complete a tracking cycle. At the end of the tracking cycle the operator would re-examine all tracked signals in sequence, and insert the corrected bearings into the store, the sequence of complete cycles to continue as long as needed. The periodically corrected information in the frequency-bearing stores would, of course, be continuously available for transfer to monitor-jamming systems or to other intercept systems either in the local area or at remote points.

It is interesting here to speculate that in a monitor-jamming system, continuous DF tracking of the victim signal might conceivably be possible through a modification of the receiver DF display to permit simultaneous display of the tracking pip and only that part of the receiver output available during look-through gates (Fig. 3). Such a special DF tracking display would be a logical part of the receiver attachments which might be developed for jammer monitoring operations, previously discussed. From such a tracking display, it should be feasible to derive directly the information necessary to successfully track a directional jammer antenna on a high-speed target that is carrying radar.

The Remote Coordination Problem

In considering the problems inherent in the coordinated operation of two intercept systems, separated in range, the major new problems which must be solved in addition to those already described are (a) the establishment of known baselines between two intercept stations, with adequate known lengths and directions, (b) the establishment of communication channels capable of handling the data exchange required between stations, and (c) the development of area type displays from which the range and bearing to an unknown transmitter can be continuously monitored and tracked in such fashion that the resulting target-tracking data can be readily inserted into the tactical data stores for the combat control centers. The problems to be solved under (a) and (b) would require very close cooperation between other shipboard electronic systems such as radar, IFF, communication, and the tactical-data-storage systems. Assuming that successful coordination with other electronic systems is achieved, the development of the desired tracking displays indicated under (c) would appear to be feasible.

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If it can be assumed that high-altitude, supersonic enemy aircraft and missiles carrying radiating radar systems are typical potential threats to the fleet which must be detected, identified, and located at the greatest possible range, it is then necessary to consider from the countermeasures signal-intercept viewpoint what facilities would probably be required to accomplish these objectives. In the discussion to follow it is assumed that the potential threat of existing nuclear and thermonuclear weapons is of such magnitude that future fleet groups will be dispersed over areas several hundred miles in diameter, with an average separation between individual ships comparable to at least horizon line-of-sight. It is assumed further that at least the extreme perimeter of the dispersed grouping will be guarded by high-altitude aircraft capable of service as electronic pickets.

To assure long-range intercept of high-flying enemy radar devices and to facilitate the establishment of the baseline lengths necessary for the determination of early rough-location data for such transmitters, it would seem to be required that picket aircraft carry airborne intercept equivalents of the AN/WLR-1 which could be used both for search and target-tracking operations. If both continuous-intercept search and tracking operation were required, then, as previously described, two complete receiver systems would be necessary in each aircraft. It is assumed that necessary data links between planes and between planes and their shipborne control centers would permit rapid exchange of signal identification and bearing data such that at the shipborne control center there is available (a) essentially continuous position-track data for each picket aircraft, (b) enemy signal bearing data from each aircraft on a continuous or periodic tracking basis, and (c) identification data permitting rough evaluation of the potential threat. If the above data are available at the control ship, it appears feasible to consider the development of an enemy position-tracking display in which (a) the relative position of the picket aircraft would be automatically displayed, (b) a radial bearing strobe would be automatically positioned from each picket aircraft to indicate relative direction of the enemy transmitter from the aircraft, (c) a radial bearing strobe with calibrated range notches would be manually controllable to permit manual tracking of the intersection of the bearing strobes from the individual aircraft, so that from this fix-tracking manual control system, range and bearing data on the enemy transmitter would be directly available to the data stores for the combat control systems. Obviously, a system such as has been very briefly outlined cannot be considered for practical development until all of the cooperating electronic subsystems have reached a point of excellence in performance which would provide reasonable reliability for the total ensemble operating as a tactical system.

SUMMARY

Through a logical, progressive series of modifications and improvements, based on the original devices developed in the World War II period, a gradual evolution in techniques applicable to general microwave signal-intercept systems is now culminating in the prototype development of the AN/WLR-1, employing display and control methods recently developed at the Naval Research Laboratory. It is now reasonable to expect that the AN/WLR-1 will provide a far greater range of general operational utility than has been available previously, particularly with respect to its ability to perform satisfactorily on all signal types, with the sole exception of the signal consisting of a single flash. In spite of the fact that the basic receiver technique is typical of all high-resolution superheterodynes, from the viewpoint of probability of signal intercept the AN/WLR-1 promises to outperform the typical "high-probability receivers" based on wide-open techniques. The employment of unitized construction, separating the control panel from the remaining units, will provide a wide range of flexibility for the purposes of future special installations. The relationships between the human sensory-motor system and the electronic-mechanical devices employed in the AN/WLR-1 have been improved to such an extent that

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the rate of signal acquisition, analysis, and data storage will be more nearly limited by operator decision time than in the conventional systems now in use.

Without materially disturbing the basic units now being developed for the AN/WLR-1, it appears desirable and feasible to consider the initiation of a series of supplementary developments designed to (a) improve the optical resolution of the acquisition display for narrow-band operation, (b) improve the accuracy of the manual signal-store system, (c) develop a tracking mark for use in the DF display, (d) modify the KD-2 recording camera to provide display of signal frequency in the data chamber and to allow installation of a suitable motion picture camera in place of the standard still-frame system now available, (e) develop suitable attachments to provide monitoring facilities for shipboard jammers, and (f) provide for the ultimate in signal sensitivity through the development of attachable preselectors, employing vacuum-tube amplification. Successful accomplishment of these supplemental developments would facilitate, at some future time, serious consideration of the more difficult problems concerned with coordinated operation of two or more intercept systems.

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APPENDIX A
Ten-Percent Sector-Scan Techniques

The narrow-band sector-scan display, which has been described in the body of this report, requires no major modification in either the NRL receiver or the AN/WLR-1. Since the servo control system driving the tuning heads is capable of a relatively rapid response, it is also feasible to apply to it a very low-frequency symmetrical-sawtooth control potential from an external source. This potential would thus serve as a reference voltage controlling the instantaneous position of the tuning mechanisms. The required sawtooth reference waveform can be readily produced by using a one-fourth-revolution-per-second synchronous motor to drive a 360-degree potentiometer provided with two taps separated by 180 degrees, the desired output being available on the arm of the potentiometer when the proper potentials are applied to the potentiometer taps. The sector potential position within the total tuning control range can be made adjustable by making the motor-driven potentiometer the central element of a voltage divider the top and bottom elements of which are potentiometers ganged on a common shaft. By proper choice of resistance values for the ganged potentiometers as compared to the motor-driven potentiometer it would be possible to insure a scanning control waveform which could be positioned anywhere in the tuning range with a peak-to-peak scanning excursion equal to one-tenth of the total tuning control range.

The circuitry described should serve to provide proper tuning-head motion for the sector display, but unless additional circuitry is used the resulting display in the acquisition indicator would always be approximately four-tenths inch wide, positioned in the total four inches available according to the location of the center frequency of the sector relative to the total tuning range. A suitable amplifier is required, therefore, which will always present the sector display as a full four-inch display centered on the cathode-ray-tube face regardless of the relative position of the sector within the total range. This amplifier must be direct-coupled throughout, have an overall voltage amplification of ten, have an output voltage range which will sweep between the same potential limits normally derived from the scanning reference potentiometers in the tuning heads, and it must be designed with a differential input stage which will accept a dc potential approximately equal to the center of the sector-scan range to balance out the common mode dc component variation resulting from variation of sector position within the tuning range. In addition, the output of the amplifier must be suitably limited in maximum excursion such that the cathode-ray spot will never move completely off the tube face. Without this last provision, selection of a manual positioning control on which was previously stored a position outside the displayed sector would leave the operator with no visual information as to which direction the manual tuning dial should be rotated in order to position the tuning head within the sector containing the chosen signal. Figure A1 presents one possible group of circuits which might serve to produce the required modes of operation and control for inclusion in the NRL intercept system, the AN/WLR-1, or similar systems.

In Fig. A1 are shown the blocks representing an r-f tuning head with its servo type tuning motor and dc reference potentiometer; the r-f tuning servoamplifier, and the acquisition indicator with its deflection amplifiers. No basic modifications to these units are required. Switch SW1 is the switching system by means of which the receiver is transferred from normal scan to manual control mode. The wiring of two decks of this switch must be modified by the addition of two circuits controlled by switch SW2, which is a function control to be added. Switch SW3 is the normal narrow to wide i-f bandwidth switch which must be changed from single-pole single-throw to single-pole double-throw and

[redacted]

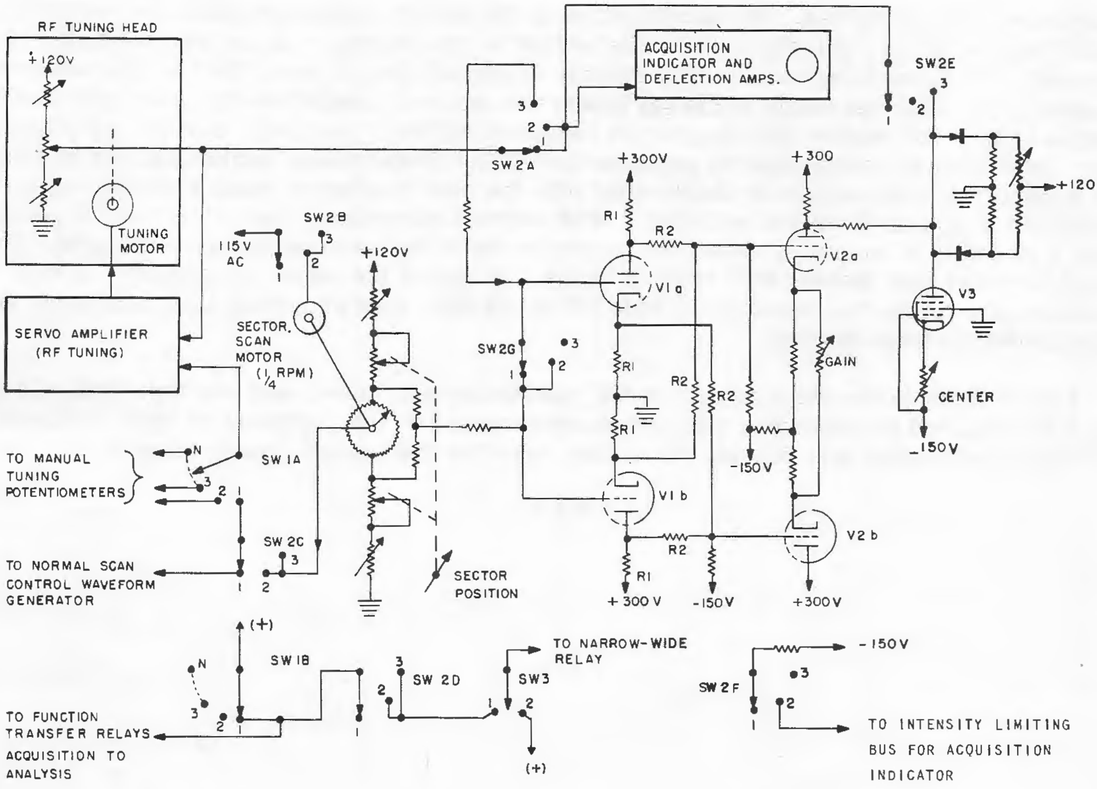

Fig. A1 - Sector-sweep amplifier circuit. Resistors R1 all have equal values, and resistors R2 all have equal values.

wired as shown. The amplifier, consisting of three envelopes and the associated sector-scan waveform generator, is the major addition required, and, as indicated in Fig. A1, this may be added to the basic receiver system essentially as a separately packaged attachment.

In normal operation all switches would probably be in position 1. This would place the receiver in normal full scan with the wide i-f bandwidth effective, the acquisition display activated, and the analysis display blanked. Switch SW3 would then have its normal function, controlling receiver bandwidth, since position 1 would be de-energized. Switch SW1 would have its normal function, controlling the receiver operating mode between full scan and selection of any one of n-1 manual storage control potentiometers. If, under these conditions, the operator observes a smear of signal activity in a narrow frequency sector and wishes to observe this activity in better detail, his next step would be to throw SW2 to the number 2 position. From Fig. A1 it can be observed that this operation would (a) retain normal gain in the acquisition horizontal deflection amplifier, (b) start the motor to generate the sector-scan waveform, (c) connect the control input lead of the r-f tuning servoamplifier to the output of the sector-scan waveform generator so that the r-f tuning-head motion would now be controlled by the sector-scan motor, (d) energize position 1 of SW3, thus switching the receiver into narrow i-f bandwidth, and (e) energize the intensity limiting bus to the acquisition indicator to prevent strong signals from damaging the phosphor. Under the conditions just outlined the operator would observe a scan in the acquisition indicator occupying about four-tenths inch, and positioned in the full scan range as dictated by the sector position control. The sector scan would be developed at a rate of a single direction excursion in two seconds, and it is for this reason that the phosphor

[redacted]

would have to be protected. By manipulation of the sector position control the operator should then be able to quickly position the sector on the afterglow of the signals to be observed. To expand the sector-scan display to the full four inches, SW2 would be moved to position 3. This operation would (a) insert the external amplifier with a voltage amplification of ten, (b) remove the acquisition indicator intensity limiting, and (c) maintain all other conditions as established by position 2 of SW2. Under these conditions, ten percent of a normal full scan should be observable with the best frequency resolution and signal sensitivity available from the receiver. With normal procedure, operation of SW1 should make it possible to manually select for analysis any of the several signals displayed. It should be noted that moving SW1 from position 1 to any of the other n-1 positions would automatically return the receiver to wide i-f bandwidth, thus providing a normal panoramascope in the analysis display.

The network in the plate circuit of V3, containing two diodes and two threshold adjustments is required in order that the extreme positions for the cathode-ray spot, in horizontal deflection, will never fall outside the visible area for the normal raster display.

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