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NRL Report 5594

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THE DESIGN AND TESTING OF AN EXPERIMENTAL FREQUENCY-SCANNING SONAR RECEIVER

[Unclassified Title]

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ABSTRACT

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Three experimental models of a frequency-scanning sonar receiver were built and tested between 1950 and 1955. The first model of the receiver used simple crystal filters and a radial-beam scanning tube (National Union Type RBE30A) for scanning the filter outputs. The second model used feedback type LC filters and mercury-wetted switches (Western Electric Type 218-A) for scanning, and the third model used conventional passive LC filters and a 30-contact motor-driven rotary switch (ASCOP Model H-00003) for scanning. In field tests comparing target detection using the visual display of the frequency-scanning sonar receiver with detection using conventional earphones and aural detection technique, operators using the frequency-scanning receiver consistently obtained detection at longer ranges than did operators listening with earphones. This difference is attributed in part to the narrow-band filters of the frequency-scanning receiver and in part to the "memory" characteristics of the long-persistence (P7) cathode-ray tube used in the display.

PROBLEM STATUS

This is a final report on this problem. The problem was cancelled on June 10, 1960.

AUTHORIZATION

NRL Problem S03-01
Project RF 001-03-42-4053

Manuscript submitted December 23, 1960.

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THE DESIGN AND TESTING OF AN EXPERIMENTAL FREQUENCY-SCANNING SONAR RECEIVER
[Unclassified Title]

INTRODUCTION

Many of the experimental active sonar equipments developed shortly after World War II used pulses longer than those provided in earlier equipments. The bandwidths of the resulting sonar echoes were far smaller than the doppler shift caused by target range rate, so conventional single-channel sonar receivers were poorly matched to the narrow-band signals of these newer equipments. The frequency-scanning receivers were developed to provide filters which were matched in bandwidth to the narrow-band signals of these long-pulse sonars (1,2).

The early work on the frequency-scanning technique for detecting sonar echoes has been reported (1-3), and the design and testing of various experimental models of the frequency-scanning receiver have been described (4-9). However, the earlier reports did not include an engineering description of some of the experimental models which were developed, and they did not include some details of the field testing that are given in the present report.

DESCRIPTION OF NRL FREQUENCY-SCANNING RECEIVERS

In the frequency-scanning receivers, the frequency shift caused by target motion is taken care of by using several narrow-band filters, each centered at a frequency a few cycles per second different from the center frequency of the next filter. Each filter is thus matched to echoes from targets having specific range rates, and the entire set of filters is designed to take care of all anticipated target range rates.

The output of each filter of the set is rectified, sampled periodically by means of a scanning switch, and used to brighten the trace on a cathode-ray tube. The horizontal sweep of the cathode-ray tube is synchronized with the scanning switch so that each horizontal position on the tube face corresponds to a specific range rate. The vertical sweep is synchronized with the transmitted pulse, so that each vertical position on the tube face corresponds to a specific range.

Model I

The first model of the frequency-scanning receiver (FSR) employed an assembly of 29 quartz-crystal filters. Available crystals were adjusted to center frequencies between 100.000 and 100.280 kc, in 10-cps increments. Each crystal filter had a total bandwidth of approximately 10 cps at the half-power points. Figure 1 shows the resultant response in idealized form.

Signals and noise present at the output of each filter are rectified by a crystal diode and passed through an RC integrator to the scanning system. Each channel contains an amplifier which also serves as an electronic gate. Thus, the envelope resulting from the filter-detector output may be sampled at any desired time by introducing a gating pulse at the appropriate grid in the circuit shown in Fig. 2.

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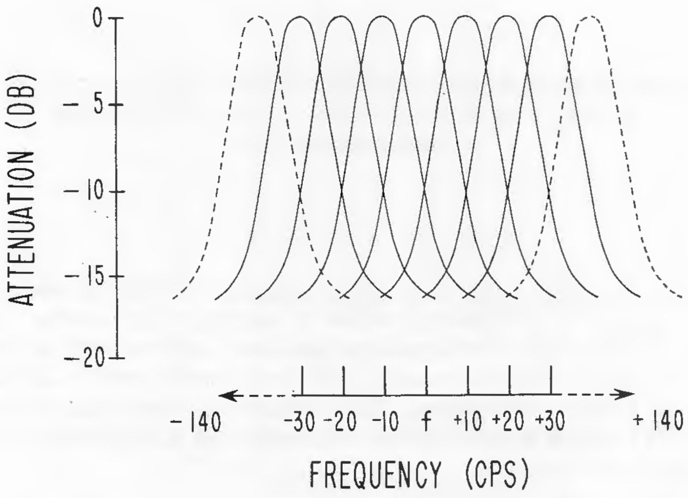

Fig. 1 - Bandpass characteristics of individual filters ([redacted]

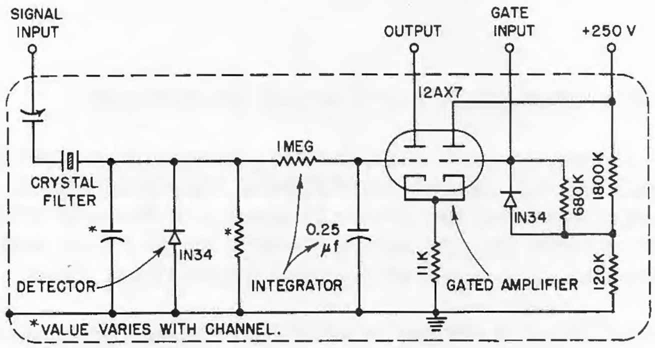

Fig. 2 - Circuit details of filter-detector-gated amplifier (Unclassified)

Twenty-nine units of the circuit in Fig. 2 were fabricated as plug-in assemblies for use in the first model. In order to scan the outputs of the 29 channels, it is necessary to generate a series of 29 sequential gating pulses. For this purpose an available radial-beam tube with 30 anodes (National Union Type RBE30A) was used, and 30 uniformly spaced pulses were generated, each 1/60th of a second. The 30th pulse was used for synchronizing the display sweep.

The scanned outputs of the 29 channels were displayed on a modified laboratory oscilloscope (Dumont Type 304) having a long-persistence screen (P7). A sawtooth waveform of adjustable period was used as the time base for measuring range information. A 60-cps sawtooth waveform, synchronized with the scanning rate, produced a horizontal deflection of the cathode ray. The scanned outputs of the filter-detector channels were combined to modulate the intensity of the display. This resulted in a display, in rectangular coordinates, in which range is the ordinate, frequency or range rate is the abscissa, and intensity is proportional to the amplitude of the signal envelope at the instant of sampling.

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The frequency of the outgoing ping was adjusted so that reverberations were centered on the display. Echoes received from targets moving toward the source appear to the right of the reverberation pattern. Conversely, targets moving away from the source, producing echoes of lower frequency, appear to the left (Fig. 3). An echo whose frequency occurs at the crossover point for two adjacent filters appears in two channels simultaneously.

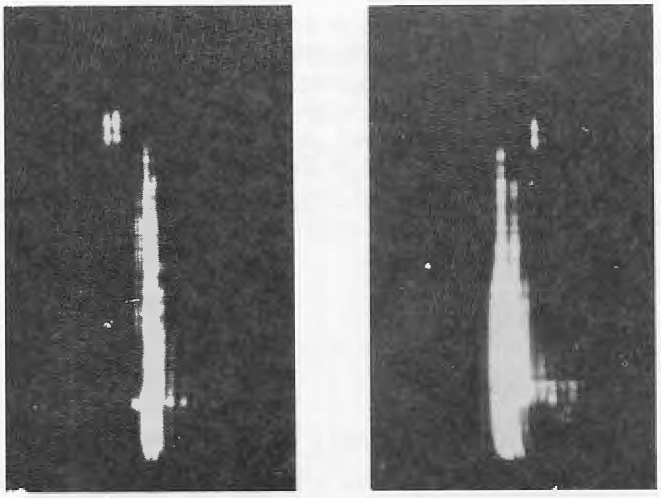

Fig. 3 - Display of reverberations plus echoes from opening and closing targets. The photo on the left shows an opening range, as indicated by the small pip to the left of the large reverberation pattern. The photo on the right shows a small pip to the right, indicating a closing range ([redacted]).

To insure that the reverberations are centered in a given channel of the display, it is necessary to compensate for own-doppler, which varies with the speed of own-ship and with transducer bearing. In the Model I equipment, a laboratory oscillator of adjustable frequency permitted manual compensation for own-doppler.

The channels of the spectrum analyzer were each 10 cps wide. At 20 kc, the frequency at which the equipment was evaluated, 10 cps corresponds to the doppler shift produced by a 0.7-knot change in range rate. The 29 filters cover a total band of 290 cps. Thus, range rates of ±13.5 knots are accommodated, with a resolution of 0.35 knot.

Model II

In the course of development and testing of the Model I equipment, a number of problems were encountered. The use of gated amplifiers for signal commutation (scanning) was neither efficient nor particularly satisfactory. Switching noise limited the useful dynamic range of the scanning circuits to a value less than 40 db. The crystal filters employed required extensive tailoring, and performance was not uniform throughout the array.

A program of component development was begun in 1951. Various types of filter elements were studied, with the aim of developing a simple, compact, reproducible array of very-narrow-bandwidth filters. One of the most promising approaches employed electromechanical filter elements–tuning forks, reeds, and/or vibrating bars and plates. Several experimental filters were constructed, and their performance was studied. Results were encouraging, although the models displayed very high values of insertion loss.

A parallel study of active filters, prompted by the work of Harris (10), yielded a convenient solution to the immediate problem of developing a comb-filter array for use with the 10-kc sonar, and the investigation of electromechanical filters was not carried further. The active filter, also known as a Q-multiplier, uses the negative resistance created by an amplifier with positive feedback to increase the effective Q of a tuned circuit. The circuit configuration shown in Fig. 4 proved to be quite stable for q-multiplying factors of 10 or less. A simple antiresonant circuit with a normal Q of approximately 100 was designed to operate in the vicinity of 3,500 cps. Multiplying the normal Q by 5 provides a resultant bandwidth $W = f_m/Q$ of 7 cps, where f_m is center frequency.

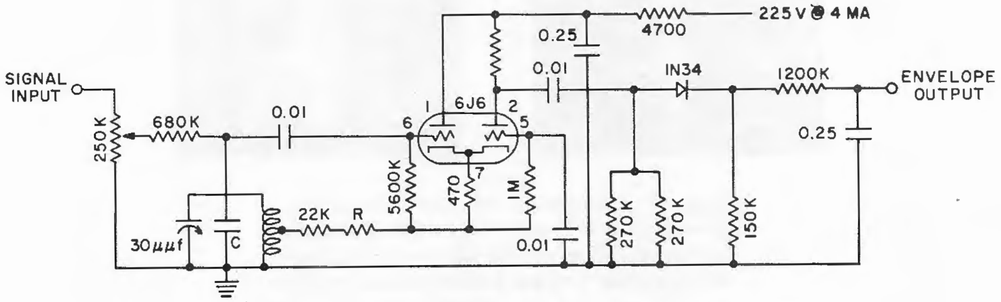

Fig. 4 - Active filter-detector, 3,500 cps (Unclassified)

A number of approaches to the scanning problem were explored. It seemed evident that a simple, high-speed mechanical switch, or commutator, should be an ideal device for the scanning operation. A few such devices were commercially available in 1950-1951. The majority of those investigated had an adequate number of contacts and low switching-noise levels, but they were not designed for long life at the switching rates required (about 1,000 channels per second). A mercury-jet switch developed by Nathan of NEL was promising. This switch containing fluid mercury, performs well in the laboratory, but it is less effective when subjected to the motions encountered on surface ships. Also, a requirement that the mercury be cleaned or replaced after several hundred hours of operation presents certain hazards.

An investigation of enclosed, mercury-wetted switch elements of the type found in high-speed mercury relays was begun. It was found that these elements had relatively predictable performance characteristics when actuated by a moving magnet. A 30-channel rotary switch was developed for use with the FSR, Model II. Using Western Electric Type 218A mercury switches and a rotating slug of Alnico V, the switch was operated at 1200 rpm to commutate at the rate of 600 channels per second. Switching noise and hum did not exceed two millivolts rms. A V-belt drive introduced speed fluctuations which appeared as jitter in the associated display. However, the device was rugged and had a long life expectancy, so it was used during the 10-kc evaluation of Model II.

The equipment shown in the block diagram of Fig. 5 was built in 1952. A crystal-controlled, 10-kc oscillator was used to stabilize the frequency of the ping. Pulse lengths of 100, 300, and 1,000 millisec could be selected manually. The available driver and power supply furnished up to 4 kw of electrical power to the transducer. At a pulse length of 1,000 millisec, used for most of the long-range studies, the pulse power was limited by the power supply to approximately 2 kw. Since the shipboard instrumentation required that all receivers be fed from a common preamplifier, receiver amplifier gain was controlled in stages following the preamplifier. Both manual control of gain and a modified form of time-variable gain, which can be adjusted to fit the decay rate of the reverberation envelope, were available.

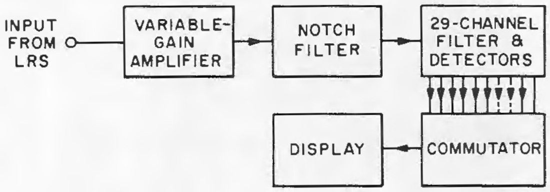

Fig. 5 - Block diagram of frequency-scanning receiver, Model II, installed in USS GUAVINA (SSO-362), March 1952 (Unclassified)

A sharply tuned band-stop filter (sometimes called a "notch" filter) centered on the reverberation-frequency band serves to attenuate reverberations before they reach the comb of 29 bandpass filters. The notch filter has a bandwidth of 11 cps and does not affect echoes from targets with range rates in excess of 0.8 knot, nor does it reduce the signal-to-reverberation ratio for zero-doppler echoes.

Conventional circuits were employed in the display. The adjustable range sweep, designed to display a maximum search range of 30,000 yards, proved inadequate for the normal display of echoes at the long ranges achieved in the field, and it became necessary to modify this sweep for gated operation, displaying only information from R to 2R, where R is the range at the normal setting of the sweep.

Model III

Model III was designed for test as an accessory to existing sonar equipment. Specifically, it was planned for use on board the Laboratory's experimental sonar ship (EPCER-851) equipped with a QCQ-2 sonar, although it is adaptable to any active sonar which provides ping lengths in excess of 100 millisec. The audio-frequency output of the sonar receiver (nominally 800 cps) provides the input for the FSR. The only other connections required between the FSR and the sonar are for transducer training control, own-doppler compensation, and synchronizing the keying interval and the range sweep of the FSR display.

As shown in Fig. 6, the FSR is housed in a console arranged to permit the operator to assume a seated position directly in front of the display. The most frequently used controls are arranged within easy reach on either side of the display. Audio output from the sonar receiver is available from a standard headset plugged into a receptacle located

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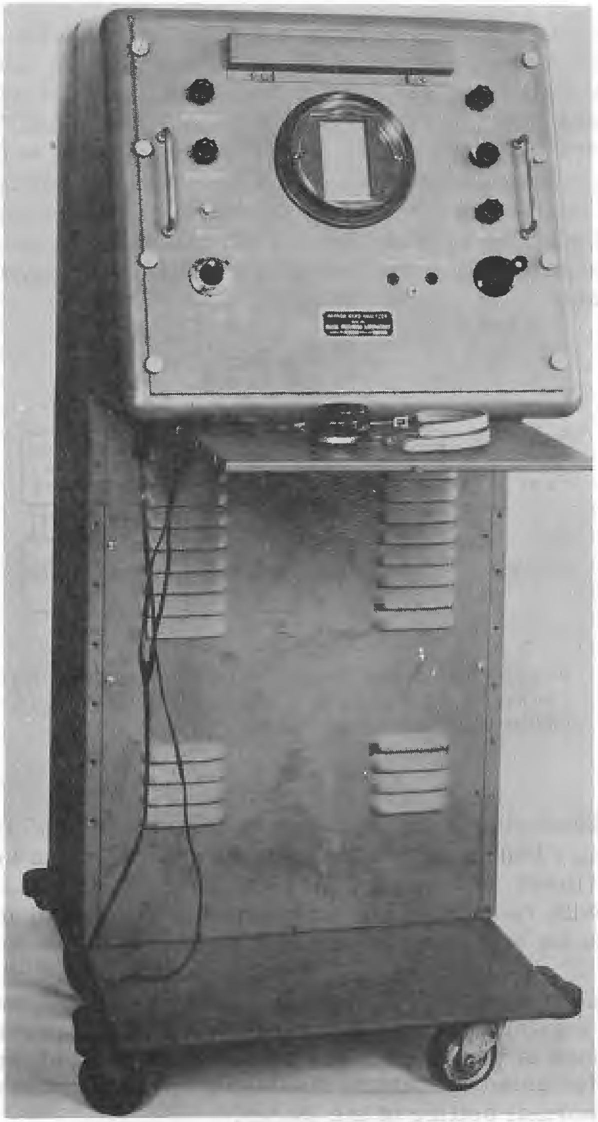

Fig. 6 - Frequency-scanning receiver, Model III (Unclassified)

on the console. The circuits are made accessible through the use of drawer slides or cover panels for ease of maintenance, as can be seen in Fig. 7.

The circuit design is straightforward. A block diagram, Fig. 8, shows the function of each major portion of the circuit. Circuit details are shown in Figs. 9 and 10.

Two interesting features incorporated into the FSR should be mentioned. It is obvious that the accuracy of range-rate measurement depends upon the stability of frequency-determining elements in the overall system. The long-term frequency stability of the transmitted pings is of little concern, since any drift is observable in the FSR display. Most present-day sonars employ oscillator circuits which provide adequate short-term

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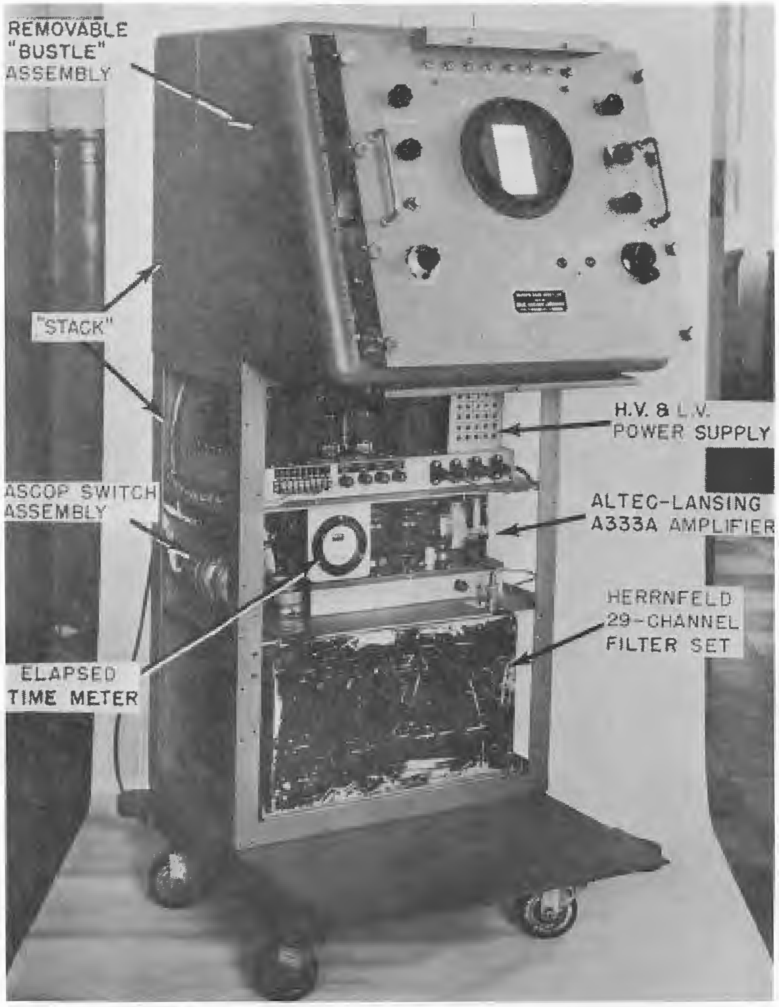

Fig. 7 - Bustle slide partly withdrawn, front and side cover removed (Unclassified)

stability. On the other hand, it is essential to the proper interpretation of the FSR display that the local oscillator of the sonar receiver be quite stable in frequency. A stable oscillator incorporated in the FSR serves two purposes; it replaces the receiver's local oscillator with one of adequate stability and, at the same time, provides the FSR operator with a control for own-doppler compensation. This permits him to keep the reverberation pattern centered on the FSR display so that range-rate measurements can be read directly from the calibrated scale on the display.

The filter set used in the FSR consists of 29 similar, constant-K, bandpass filters with nominal bandwidths of 16.4 cps at the -3 db points and 75 cps at the -20 db points. As shown in Fig. 11, each filter is followed by a full-wave linear detector employing germanium diodes. Each filter has a bandwidth equal to the doppler shift produced by a 1-knot change in range rate, for a 24-kc sonar frequency. Thus the coverage of the FSR is ±15 knots, with a resolution of 1/2 knot. When used with 48-kc sonars, these values are doubled.

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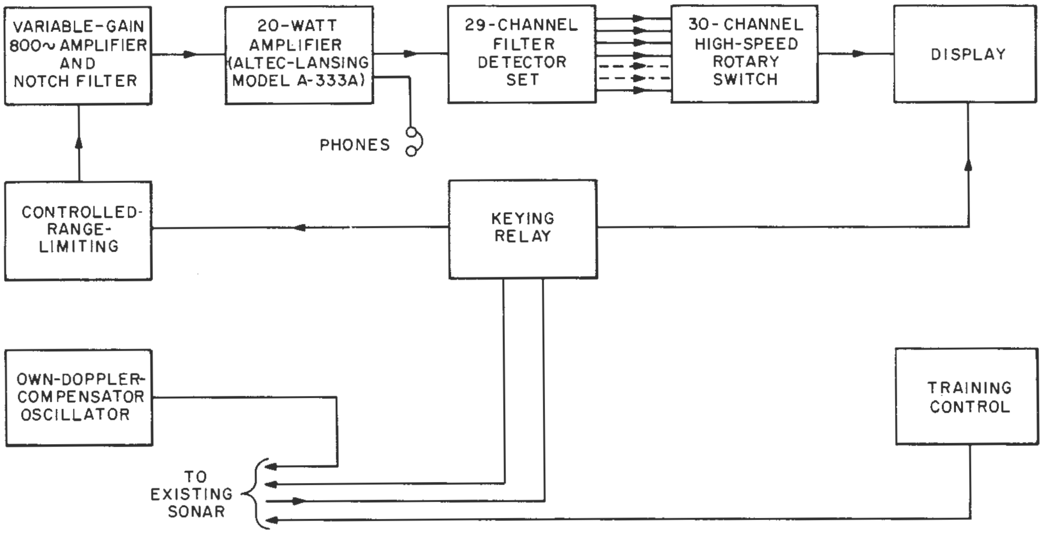

Fig. 8 - Block diagram of frequency-scanning receiver, Model III (Unclassified)

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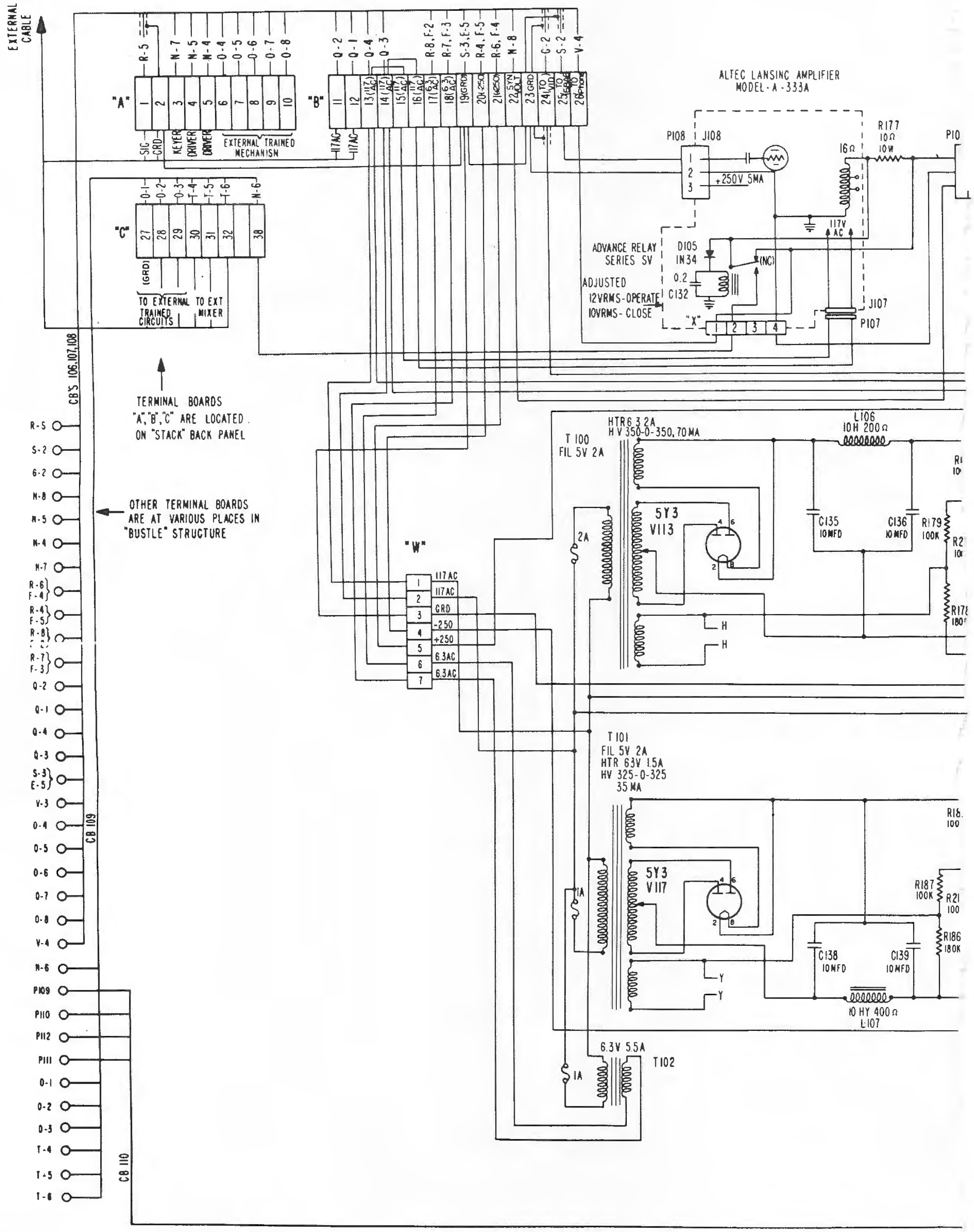

Fig. 9 - Stack schemat

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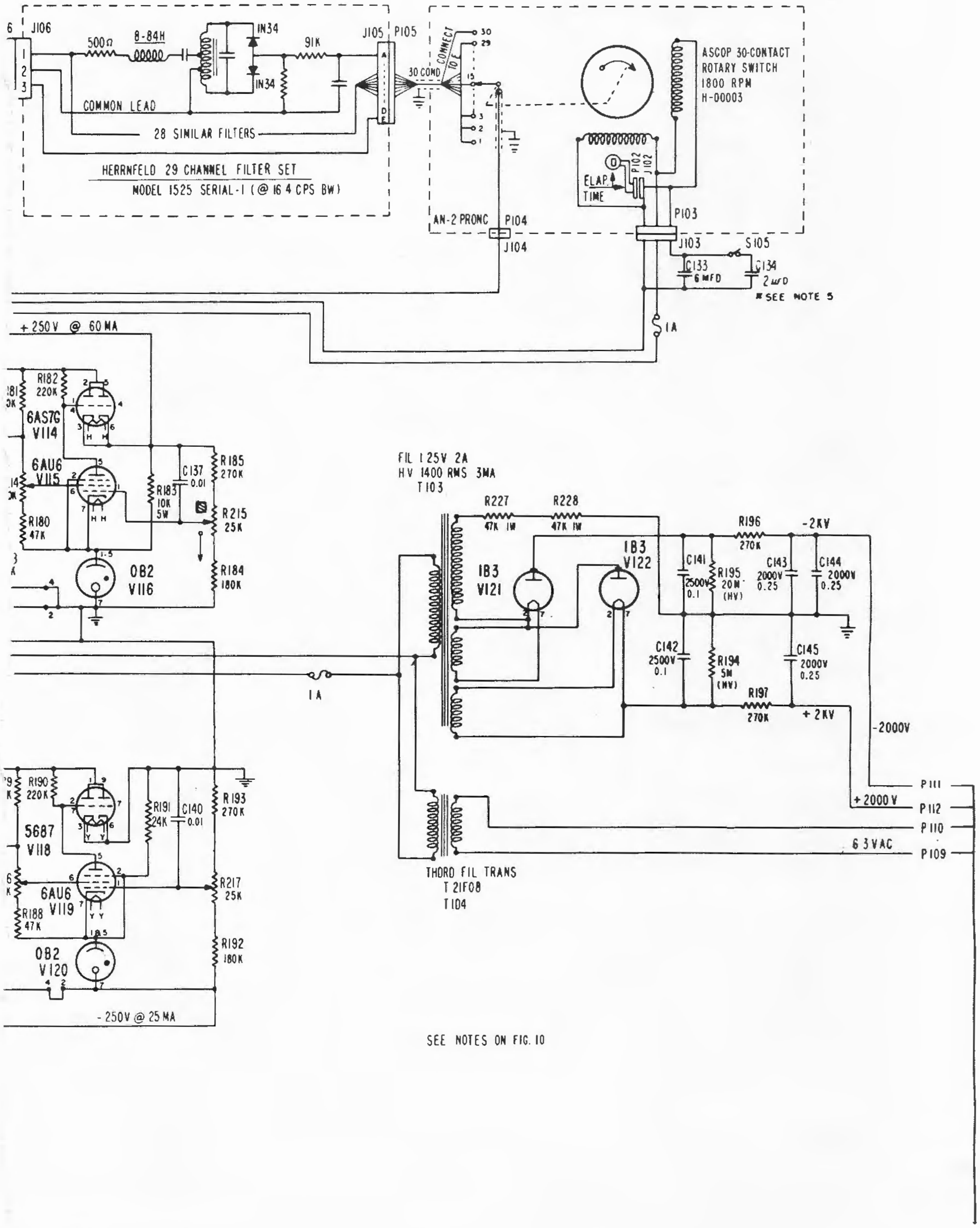

SEE NOTES ON FIG. 10

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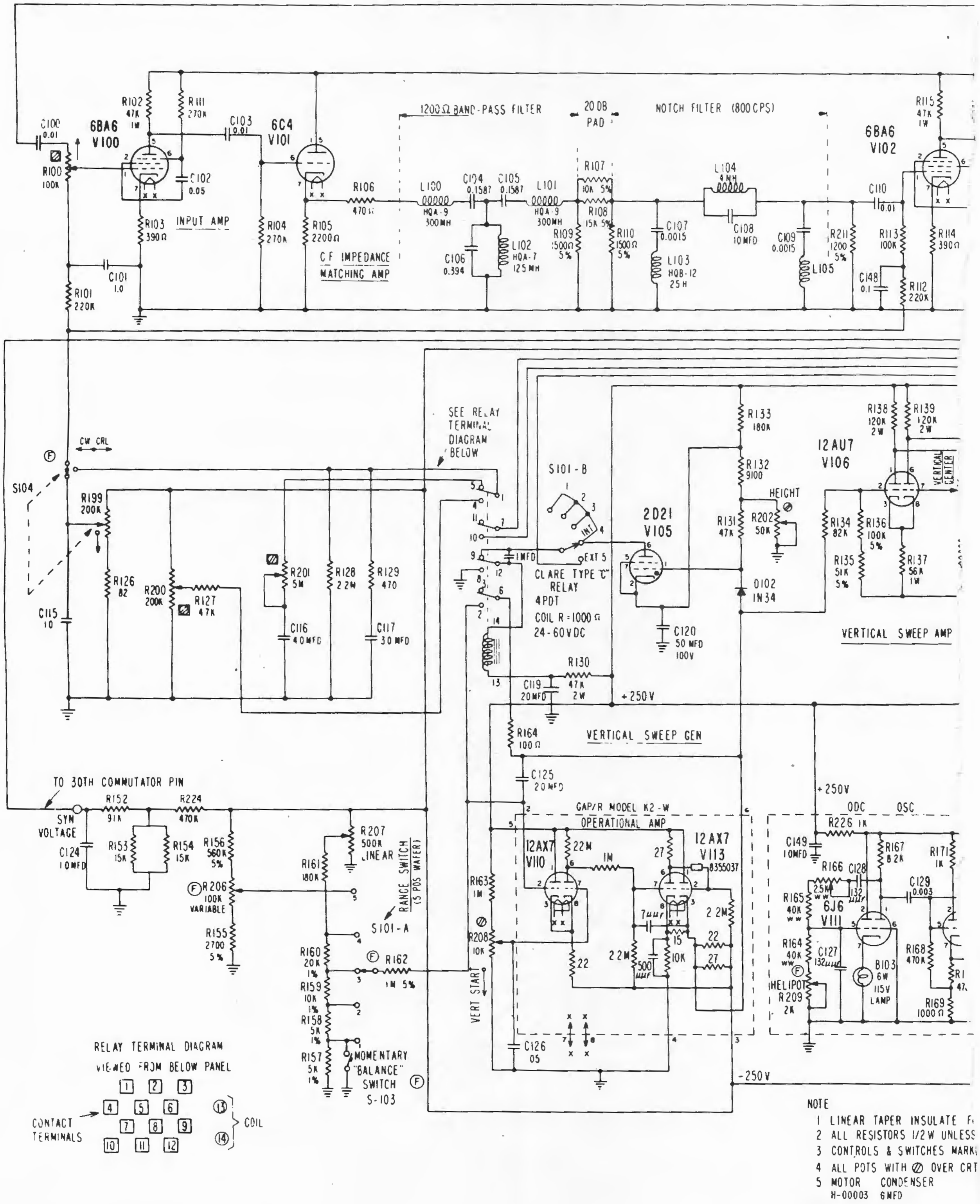

NOTE
1 LINEAR TAPER INSULATE F
2 ALL RESISTORS 1/2W UNLESS
3 CONTROLS & SWITCHES MARK
4 ALL POTS WITH ⊘ OVER CRT
5 MOTOR CONDENSER
H-00003 6MFD

Fig. 10 - Bustle schematic

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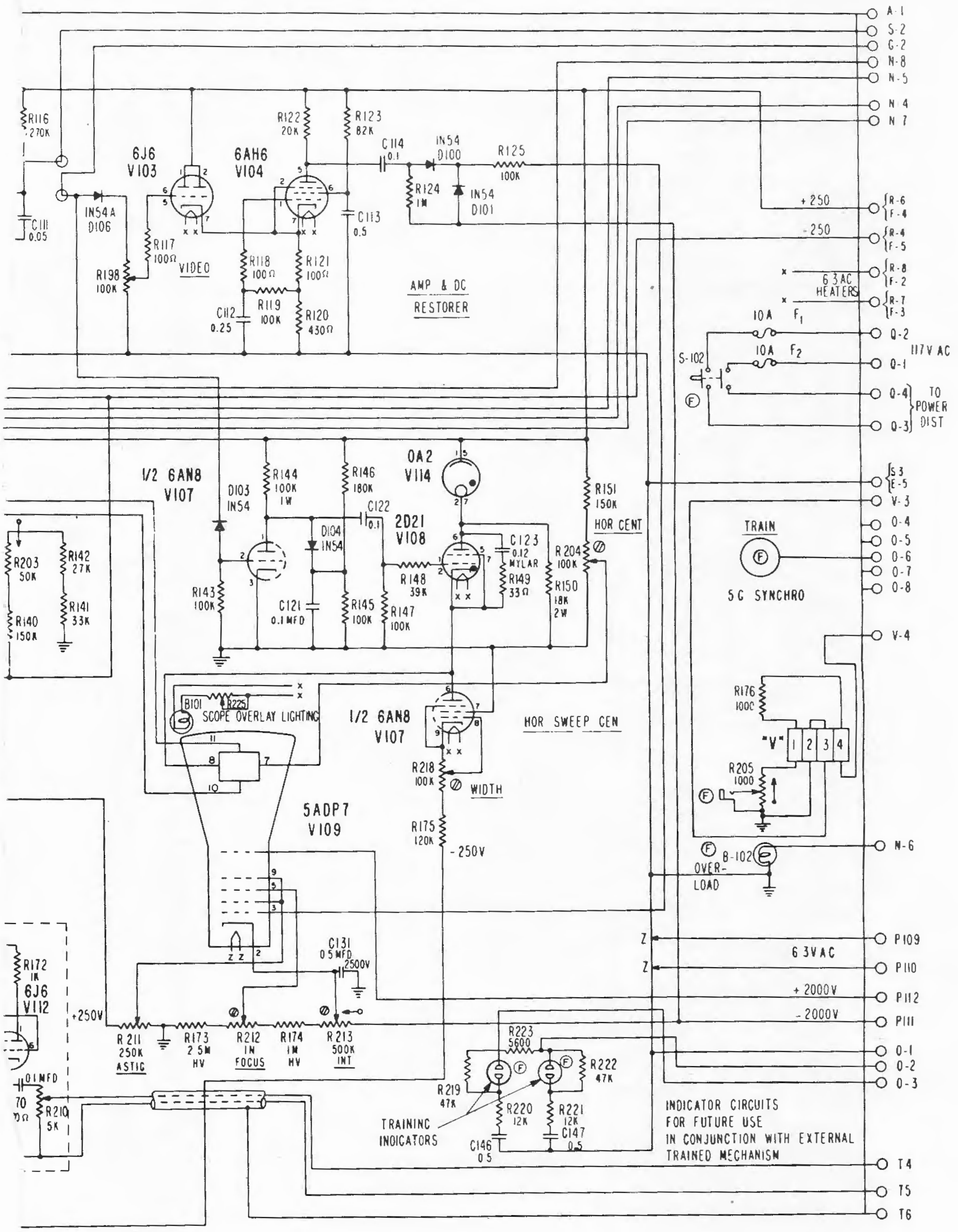

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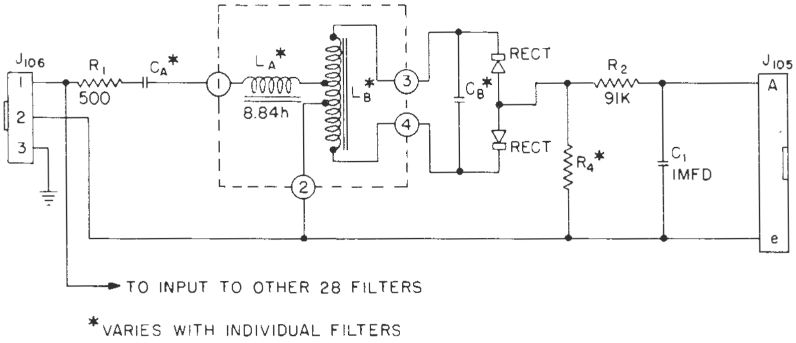

Fig. 11 - Typical filter from 29-channel filter set (Unclassified)

The outputs of each of the 29 detectors are terminated separately on 29 sequential contacts of a 30-contact rotary switch. The 30th contact is used for synchronizing the horizontal sweep of the FSR display. This switch (ASCOP Model H-00003) is operated at 30 rps to produce a scanning rate of 900 channels per second. Laboratory tests indicate that switches of this type have a life expectancy of a few hundred hours, when operated at this speed.

Both P7 and P25 phosphors have been used in the cathode-ray tubes of the FSR. The P7 is satisfactory for use in the present circuit, although its persistence is inadequate to permit pulse-to-pulse integration of successive long-range echoes.

EXPERIMENTAL RESULTS, NRL FREQUENCY-SCANNING RECEIVER

Model I

In the experimental model of the FSR tested in Oct. 1950, the filter outputs were displayed on the face of a 5-in. cathode-ray tube having a long-persistence screen (5CP7-A) in the form of a rectangular presentation showing frequency (doppler) and range information, as described earlier. During the tests nearly 100 photographs were made of the display for a wide range of target conditions. A set of three exposures taken at approximately one-minute intervals as the target turned on a 500-yard radius toward the sonar vessel is shown in Fig. 12. The first exposure shows a zero doppler echo, indicating a beam-aspect target. In the second, the range rate has increased to approximately 0.7 knot. The third example shows a target range rate of about 3.6 knots.

The field experiments were planned to permit direct comparisons between the FSR and aural detection of the same signals. During one 20-minute run, the USS MALOY steamed on a circular course of 500-yard radius about a point at 5,000 yards range. Simultaneous field comparisons of the performance of the FSR of conventional aural-detection techniques were made during the run. The results are presented in Table 1. A magnetic-tape recording of the same signals was later used in laboratory comparison studies where similar comparisons were made using six operators–two using frequency-scan displays, two using long-persistence A-scan indicators, and two using headsets. The tape recording contained 95 pings, with the ping length varying from 100 millisec to 1,000 millisec. Reverberations were nominally centered on a frequency of 800 cycles, and doppler shifted the echo frequencies as much as ±70 cycles. Table 2 summarizes the results of these tests.

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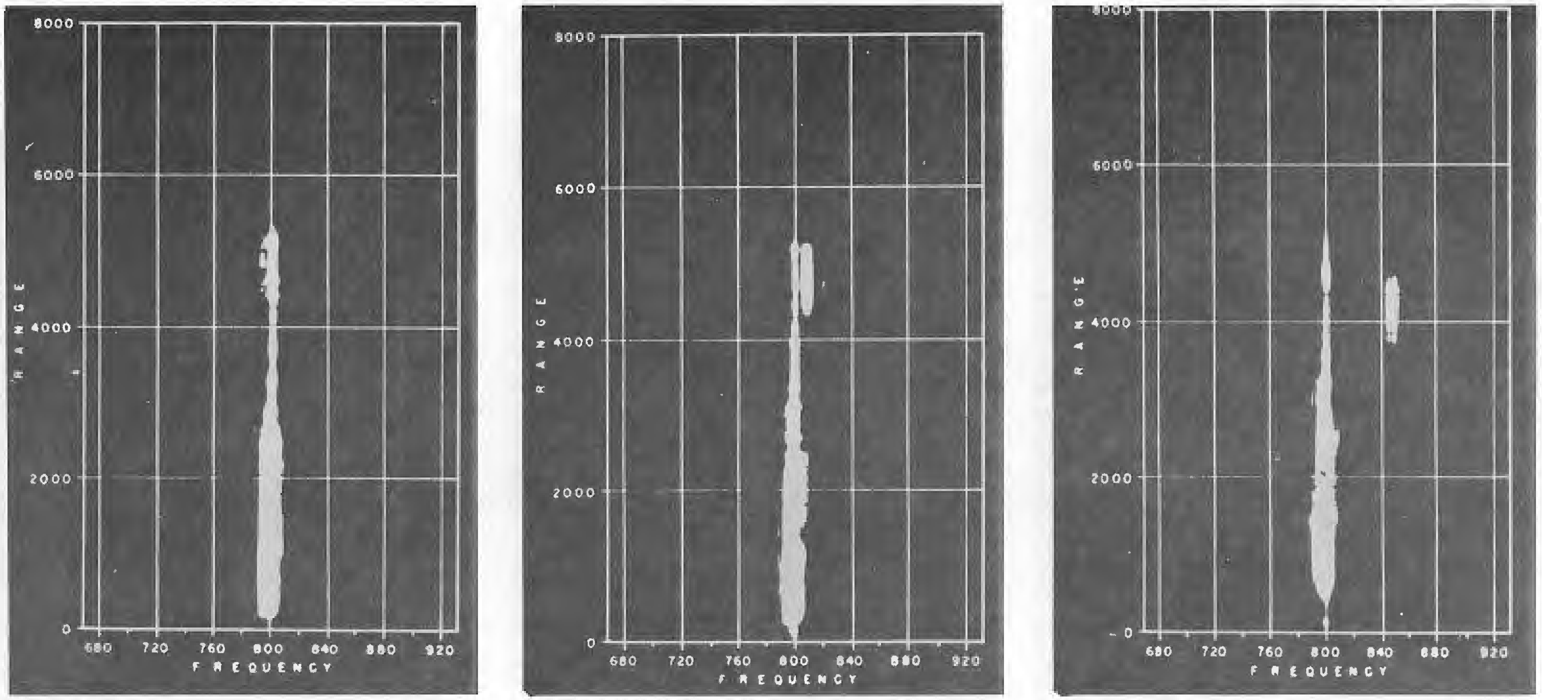

Fig. 12 - Examples of range-rate indication (C[redacted])

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Table 1
Comparison of Aural and Frequency-Scan
Detection of Echoes Following
16 Pings Occurring at Irregular Intervals
During a 20-Minute Field Test

Contact	Aural Detection 1,000 cps Bandwidth (percent)	Frequency-Scan Detection (percent)
Positive	31	69
Doubtful	19	19
None	50	12

Table 2
Comparison in the Laboratory of Frequency-Scan Detection
with Aural and A-Scan Detection Using Magnetic Tape Recording
of a 95-Ping Field Test Run*

Recognition (compared to total pings)	Aural Detection 300 cps Bandwidth (percent)	A-Scan Detection 300 cps Bandwidth (percent)	Frequency-Scan Detection (percent)
Echoes	67	37	78
False Echoes	2	2	1
Echoes not Recognized	31	61	21

*The scores are averaged results for six repeats of the test run. At the end of each run, operators shifted to different stations and employed a different detection method for the next run.

The shallow water of the operating area in which these tests were conducted (rarely more than 100 feet) produced sound channeling, and echoes were reverberation limited in nearly all cases. Echoes having up and down dopplers were observed at 8,000 to 9,000 yards. At these ranges the pulse length used was 1,000 millisec. One observation during tests of this device was that while aural observers were frequently dealing with reverberation-limited echoes, operators of the FSR consistently observed the presence of reverberation energy in at least one channel of the visual display at ranges extending beyond that of the target, but a target range rate of a knot or two placed the echo in a channel in which it was noise-limited. Although the quality of photographic reproduction of the visual display does not show the mottled character of the overall background due to the presence of noise, the continuation of the reverberations to ranges beyond the target can be seen in Fig. 12. For target echoes having small amounts of doppler, detection efficiency would have been enhanced by the use of a narrow-bandwidth rejection filter centered on the reverberation frequency and located ahead of the comb filter.

Model II

The Model II equipment, previously described, was tested on USS GUAVINA during the period March 3-14, 1952, using an experimental 10-kc sonar system (8). With

[redacted]

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USS CHIVO (SS-341) serving as a controlled submarine target, a variety of field experiments to measure detection probability and "lost-contact" ranges were carried out in the Florida straits and the Gulf of Mexico. Sonar conditions were generally poor during the first week of operations, and the maximum range at which operations were conducted was 11,000 yards. Figure 13 shows a bathythermogram card which indicates the negative thermal gradients observed in the submarine operating areas south and east of Key West. The operations during the first week permitted a thorough shakedown of the frequency-scanning receiver and a training period for the operators.

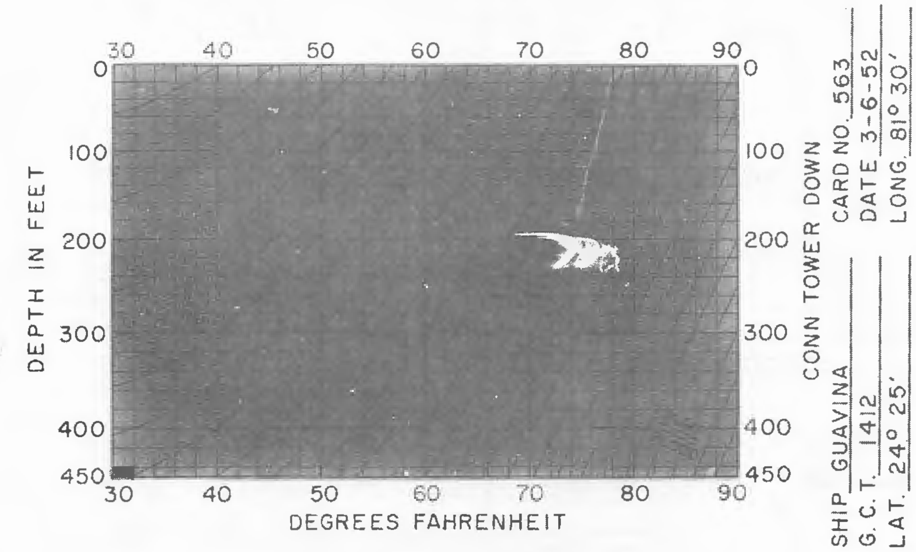

Fig. 13 - Bathythermogram, March 6, 1952
(Unclassified)

On March 10, 1952, GUAVINA and CHIVO began a week of experimentation in the deeper water of the Gulf of Mexico west of the Straits of Florida. Bathythermograms taken by both submarines at the first station revealed isothermal water to a depth of 240 feet. With two observers viewing the visual display of the FSR and two listening to the auditory receiver (with headsets), the data shown in Tables 3, 4, and 5 were obtained. Following these maneuvers, the range was gradually increased until contact was lost at 19,000 yards.

The following day, with very good water conditions, aural operators were able to track the target out to about 34,000 yards, and the FSR operator lost contact at about 42,000 yards. Figure 14 shows the FSR display with the target echo at 36,400 yards. Bathythermogram cards obtained by both submarines are shown in Fig. 15.

Model III

Sea trails of the FSR were conducted during the week of Oct. 24, 1955 in waters east of the Virginia Capes. Favorable water conditions existed with mixed layers extending

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Table 3
Run 1, March 10, 1952
Lat. 24°01′ N, Long. 82°40′ W
Sea State 2-1/2 to 3
Start 2005Z, End 2018Z
Min. Range 5000 yd, Max. Range 8500 yd

Echo Contact	Aural		Visual (FSR)	
	Op. A	Op. B	Op. C	Op. D
Positive	44	26	49	50
Doubtful	1	0	0	6
No Echo	17	36	13	6
Average (positive contacts)				
Numerical	35		50	
Percent	57		81	

During run 1, target and source diverged at 90 degrees, with target presenting port-quarter aspect.

Table 4
Run 2, March 10, 1952
Lat. 23°59′ N, Long. 82°42′ W
Sea State 2-1/2 to 3
Start 2044Z, End 2101Z
Min. Range 12,200 yd, Max. Range 13,300 yd

Echo Contact	Aural		Visual (FSR)	
	Op. D	Op. A	Op. B	Op. C
Positive	20	15	37	30
Doubtful	1	1	0	0
No Echo	27	32	11	18
Average (positive contacts)				
Numerical	18		33	
Percent	38		69	

During run 2, target SS executed constant rudder turn through an angle of 270 degrees.

[redacted]

[redacted]

Table 5
Run 3, March 10, 1952
Lat. 23°59′ N, Long. 82°48′ W
Start 2221Z, End 2243Z
Min. Range 13,700 yd, Max. Range 16,000 yd

Echo Contact	Aural		Visual (FSR)	
	Op. C	Op. D	Op. A	Op. B
Positive	7	5	15	21
Doubtful	0	2	1	0
No Echo	41	41	32	27
Average (positive contacts)				
Numerical	6		18	
Percent	13		38	

During run 3, target SS opened range at 90 degrees for 1 mile, then returned to base course. If only beam-aspect echoes are considered, averages become 9 percent for aural detection and 43 percent for frequency-scan detection.

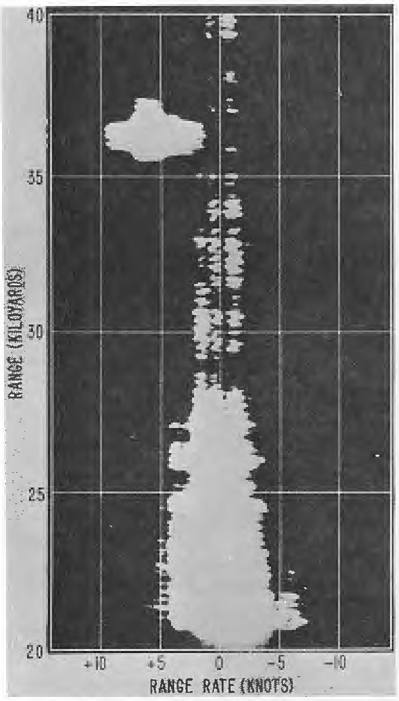

Fig. 14 - Echo from a submarine at 36,400 yd opening range at 6 knots [redacted]

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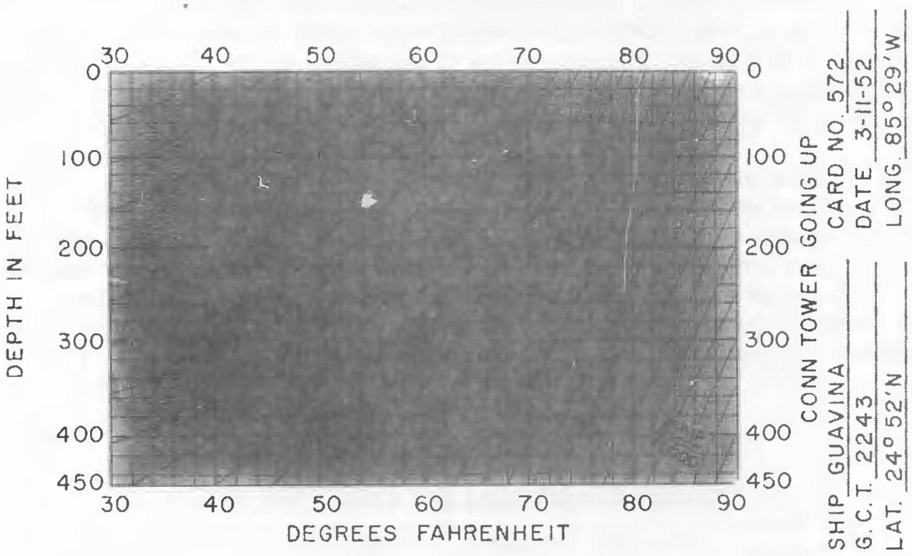

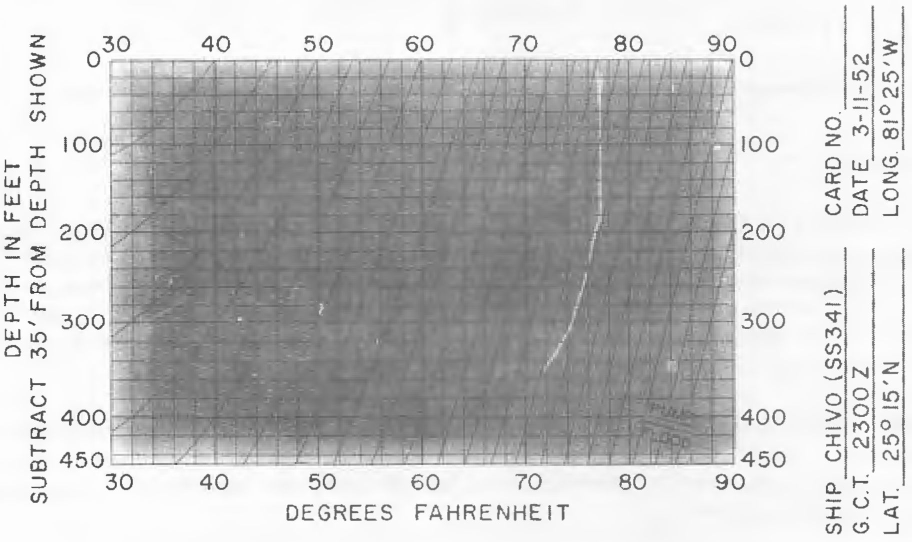

Fig. 15 - Bathythermogram cards obtained from source (GUAVINA, top) and target (CHIVO, bottom) (Unclassified)

[redacted]

downward to 270 feet. As outlined previously in this report, the FSR was adapted for operation in conjunction with a Type QCQ-2 sonar on board the USS E-PCE(R)-851. USS LSM-398 served as a controlled target during maneuvers in which simultaneous comparisons were made between aural presentation of the output of the conventional sonar receiver and the visual display of the same information processed by the FSR. Radar range and radar bearing of the target were continually available to the observer.

Four observers were used who alternated between the two displays. Data were collected over a period of two days for the same type of maneuver. An opening run was made with the target vessel on a relative bearing of 45 degrees until contact was lost. A closing run followed on a relative bearing of 135 degrees until sonar contact was assured. A total of 17 detection thresholds were obtained for each of the two displays. Comparisons were made between the displays from the pooled data for the four observers during two days of running. The summary is shown in Table 6.

Table 6
Field Test of NRL FSR Model III
Comparison of Aural and Visual Detection

Display	Average Detection Range (yd)	Standard Deviation (yd)	No. of Observations
QCQ-2 (aural)	2865	250	17
FSR (visual)	4147	486	17
	Difference 1282		

CONCLUSIONS

In the majority of the tests reported, two methods of displaying sonar signals and backgrounds were simultaneously employed—the visual display of the frequency-scanning receiver, and conventional aural display using headsets. Experiments were, in general, designed to present the information in short sessions, each lasting 15 to 20 minutes and permitting 30 to 60 detection observations. Between sessions, observers were usually shifted from one type of display to another.

The data which have been presented in this report support the conclusion that with long-pulse sonar, the frequency-scanning receiver provides more efficient detection of sonar echoes than is offered by conventional, aural detection techniques. The gains result principally from the following:

1. Bandwidths of the individual channels are significantly narrower than the effective bandwidth of the ear. In the Model II receiver, the filters have a bandwidth of 7 cps, or 1/7 of the ear's assumed bandwidth of 50 cps at normal listening frequencies. In the Model III system, the filters have a bandwidth of 16.4 cps, or about 1/3 of the bandwidth of the ear.

2. The visual display of the frequency-scanning receiver offers a convenient memory for time and frequency information and a degree of pulse-to-pulse integration. An observer using auditory presentation usually prefers to watch some form of time base while listening

for echoes from recurring pings. He must rely on memory to compare both the time of occurrence and the frequency of an echo with previous information. In the visual display, these factors are "remembered" on the face of the cathode-ray tube.

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