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NOISE IN TRACKING RADARS

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ABSTRACT

A radar, magnetic recorder, spectrum analyzer, and a plotting device have been assembled for measuring noise in radar echoes. Power spectra of the fluctuations in amplitude and angle of arrival have been determined and are quite consistent for any one plane aspect. Analysis of these results indicates the relative ranges at which sequentially lobed and monopulse systems are advantageous.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem R12-01D

DECLASSI

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NOISE IN TRACKING RADARS

INTRODUCTION

The problem of target echo noise— its effects on deterioration of the quality of radar tracking— has been known for many years. The characteristic echo fluctuation was observed in prewar radar systems, and it was realized that this fluctuation introduced "jitter" or "noise" in the tracking data by beating with the radar lobing frequency. Periodicities in echo fluctuations, such as those due to propeller modulation, were particularly troublesome if they occurred at or near the lobing frequency.

From purely physical reasoning, it appeared that the power spectrum of this fluctuation must diminish with increasing frequency, since the total noise power is finite. Thus noise reduction might be accomplished by increasing the lobing frequency. Mechanical limitations made thirty cycles per second a convenient lobing frequency for most large systems and about one hundred cycles per second a practical maximum for small ones.

The Naval Research Laboratory devised an electronically lobed system using a multiple feed antenna with RF lobe-switching capable of high lobing rates (one-quarter the pulse repetition frequency) in 1943 and proposed an amplitude-comparision simultaneous-lobing system in 1944. Both of these systems were constructed and evaluated in 1946-47, but unfortunately their performance, although excellent, was not significantly better than that of conventional conical scanning systems of good design. Either of two conclusions could be drawn from these facts: (a) The effects of echo amplitude fluctuation, which a high lobing rate should reduce and which simultaneous lobing or "monopulse" should eliminate, were insignificant relative to the total noise, or (b) the experimental technique was inadequate to resolve the differences. Accordingly, an analytical approach to the problem was begun.

NOISE AND ITS EFFECTS

The tracking radar output is contaminated by noise from several sources, all of which are uncorrelated.* These may be broadly classified into internal noise, that originating in the system, and external noise, that originating at the target. Internal noise may then be separated into receiver first-circuit noise and antenna-mount servo noise. Both of these are under partial control of the designer. Receiver noise can be reduced by increasing echo signal levels in obvious ways and servo noise by good mechanical and electrical design. External noise can be separated into amplitude fluctuation or "amplitude noise" and variation of the apparent angle of arrival or "angle noise," due to the finite dimensions of the target.

* NRL Report R-3424 (A. E. Hastings and J. E. Meade, "Improvement of Radar Tracking," Confidential, February 24, 1949) describes these sources and calculates their effects on tracking radars in detail.

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Only two of these noise factors are functions of target range. Servo noise is obviously independent of range. Receiver noise increases with the square of the range (due to the inverse fourth-power law for echo power received) up to the point where maximum receiver gain is reached. Amplitude noise, since it is interpreted by the radar as amplitude modulation of the mean signal level, is independent of range if a good automatic gain control (AGC) system is used. Angle noise is a function of the linear dimension of the target and therefore varies inversely with range, as long as the target subtended angle is small compared with the beamwidth of the antenna. Since these factors are uncorrelated, the total output noise (angular dispersion) in a given tracking system adds in mean square fashion (Figure 1). Curve A is the total output noise for a sequential lobing system. Curve B is the output noise for a monopulse system, assuming that amplitude noise is larger than servo noise. If the reverse is true, the improvement of monopulse over sequential will be negligible.

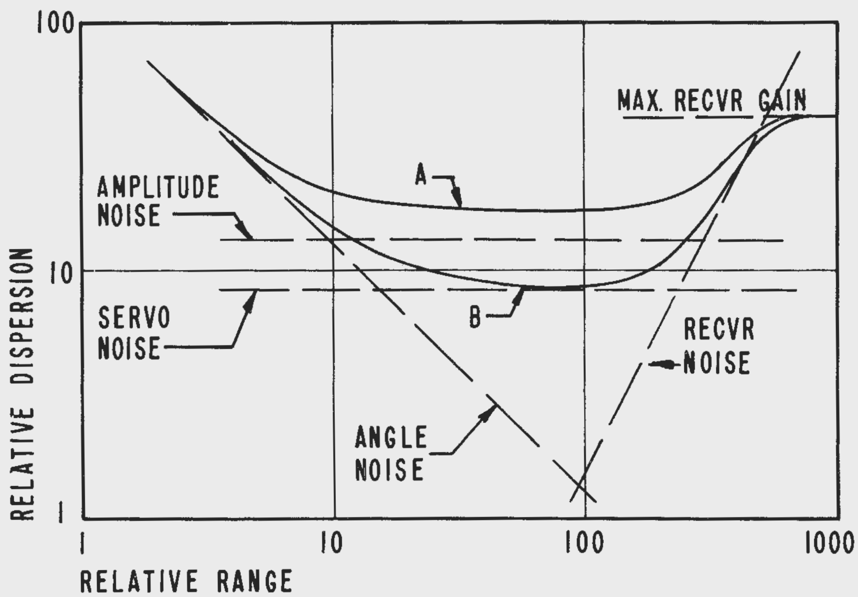

Figure 1 - Dispersion vs. range functions

Figure 1 shows only the general shapes of the dispersion-vs-range functions. In order to make use of such a function for prediction of system performance, it is necessary to determine the absolute magnitude of at least one point on each characteristic. In the case of external noise there is evidence that the absolute magnitude is also a function of target type, maneuverability, air turbulence, angle of view, etc. Thus a large quantity of experimental data must be obtained and analyzed to have quantitative data with reasonable reliability.

METHODS OF MEASUREMENT

The basic approach to the problem is to determine the magnitude of each noise component by establishing a condition of operation which reduces the effects of the other components to a negligible quantity. Having determined these magnitudes the performance of a system whose basic parameters have been established may be predicted, or, what is more important, the basic parameters may be selected to provide an optimum design.

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Servo noise is measured by turning off the radar and closing the servo loop through a potentiometer mechanically connected to the antenna mount. With normal gain settings the mount motion is a result of electrical and mechanical noise in the servo system, which may be determined. Maximum receiver noise is measured with the radar operating but with no target in the range gate. Receiver noise at another range can be measured by setting the gain manually to the value corresponding to a given target at that range.

The isolation of components of external noise presents a more difficult problem. In a sequential lobing system the components of amplitude noise in the servo band are removed by AGC, while the components around the lobing frequency determine the output noise. This requires determination of the power spectrum of amplitude noise along with the average amplitude of the echo. In a monopulse system the AGC removes the components of amplitude noise in the servo passband, and amplitude noise has no effect on the radar output. Amplitude noise is determined by pulse-to-pulse recording, using a simple searchlighting system with range gating but no lobing, at target ranges where receiver noise is swamped by strong echoes. Angle noise and servo noise are also absent, since without lobing the system is insensitive to variations in angle of arrival. The power spectrum is determined and evaluated at the lobing frequency, and the resulting output noise may be computed from this along with the average signal level, servo bandwidth, and antenna radiation pattern.

Angle noise measurement is the most difficult one and requires elaborate instrumentation. The angle of arrival of the echo relative to a reference point on the target must be determined, and is measured in train only. A complete tracking system is required and the effects of all other noise components must be minimized or eliminated. For this purpose a dual monopulse system was constructed having a common antenna system. One train channel operates as an echo-tracking system while the second train channel operates on the response of a beacon carried by the target. Either channel may be used to control the servo system or, if desired, manual optical tracking may be used. The beacon response is delayed slightly in time from the radar echo for channel separation. The angle sensitivities of the two channels are matched. After pulse lengthening, the outputs are subtracted. Since a monopulse system provides error information from every pulse, the subtractor output is proportional to the instantaneous angular difference between the apparent center of reflection and the beacon antenna. Conversion to linear measure at the target is accomplished by multiplication by target range in a potentiometer on the range unit. By incorporating rapid AGC response in the echo channel, amplitude noise is removed. Receiver noise is minimized by tracking at short ranges, which has the additional advantage of emphasizing the magnitude of angle noise. Servo noise does not affect the angular difference, since the error signals are nearly linear with respect to error angle out to about one-third of a beamwidth. It is important that the beacon antenna be arranged to avoid illuminating the target in order to insure the existence of a point source.

One of the major problems in this type of analysis has been the enormous effort required for data reduction. For practical purposes, it was decided that analogue computation from recorded data would be used and that the process would be mechanized to reduce manual operations. Magnetic tape was chosen as the most suitable recording medium as no processing is required and the output is available directly as a voltage. The complex instrumentation for angle noise measurement, using a beacon rather than photographic techniques, was chosen to permit direct recording of the desired function for easy analysis.

For power spectrum determination, a sample is cut from the tape, made into a closed loop, and played back. The output is scanned with a wave analyzer and the power spectrum is plotted by a recording voltmeter. For amplitude noise, the spectrum ordinates A_{amp} are in fractional modulation per $\sqrt{cps}$, obtained from the analyzer indication and bandwidth, and from the average echo level. Unity sinusoidal modulation is defined as the condition where the average echo level is equal to the peak of the sinusoidal modulating function. For angle noise, the ordinates A_{ang} are in yards at the target per $\sqrt{cps}$, obtained from the analyzer indication and bandwidth, and from the calibration of the radar in yards at the target per volt output.

The output angular dispersion due to the servo, σ_{ser}, has no easily calculable dependence on radar parameters. The output angular dispersion due to receiver noise is:

$$\sigma_{rec} = kBR^2\sqrt{\beta/AP_t}\ , \tag{1}$$

where k is a constant depending on the receiver noise factor, B the antenna beamwidth, R the range, β the servo bandwidth, A the equivalent target reflecting area, and P_t the transmitted power. The output angular dispersion due to amplitude noise, for a sequential radar, is:

$$\sigma_{amp} = 0.85\ B\ A_{amp}\ \sqrt{\beta}, \tag{2}$$

where A_{amp} is evaluated at the lobing frequency and is assumed constant over the range $\pm\beta$, and where the antenna pattern is assumed parabolic with crossover at 3 db (two-way pattern). The dispersion due to angle noise is:

$$\sigma_{ang} = A_{ang}\ \sqrt{\beta}/R, \tag{3}$$

where A_{ang} is assumed constant over the range β.

DATA

Figure 2 is the spectrum of receiver noise, entirely flat as would be expected. A spectrum of amplitude noise from a fixed target, shown in Figure 3, is quite noise-free; most of the magnitude at low frequencies is due to the tape splice. All spectra here have amplitude-frequency coordinates; power is the square of the ordinates. The values below 10 cps for amplitude noise and below 1/3 cps for angle noise are not significant since this is beyond the limit of analyzer operation.

Considerable data have been taken on one plane, an R4D. Angle and amplitude noise have been measured for three aspects: 0, 90, and 180 degrees. The aspect is defined as the angle between the radar line of sight and the longitudinal axis of the plane, a direct approach course being 0 degrees. The spectra taken at any one aspect are quite consistent.

Figures 4, 5, and 6 are representative spectra of amplitude noise at various aspects for the R4D, all plotted to the same scale. In Figure 4 (0°), propeller modulation at about 65 cps and its harmonics are superposed on a low-level continuous spectrum. This periodic modulation is absent in the other samples, but the continuous spectrum remains. In Figure 5 (90°), the continuous spectrum has much higher amplitude at low frequencies. These results are consistent with the clear view of the propellers at 0°, with the shielding of the propellers by plane parts at other aspects, and with the asymmetry of the plane at 90°,

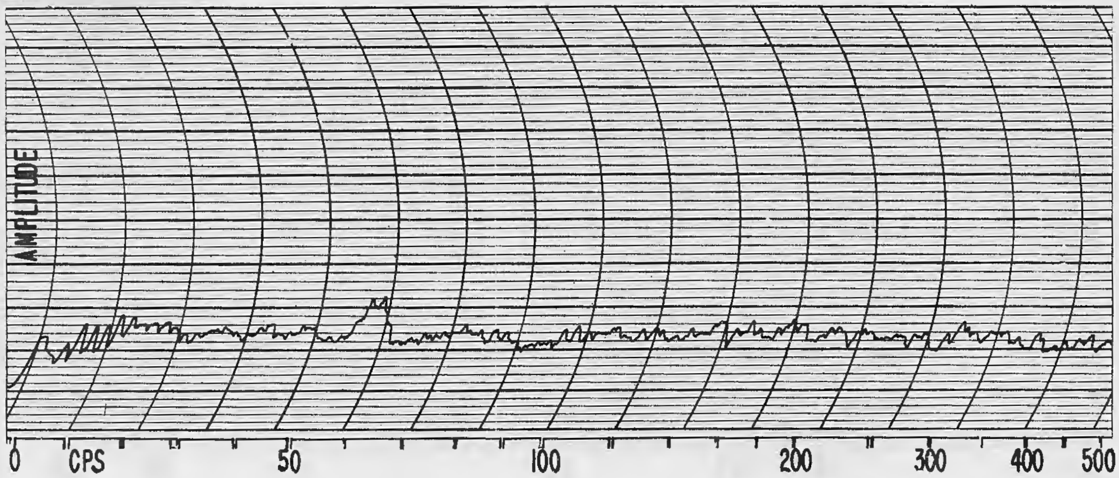

Figure 2 - Spectrum of receiver noise

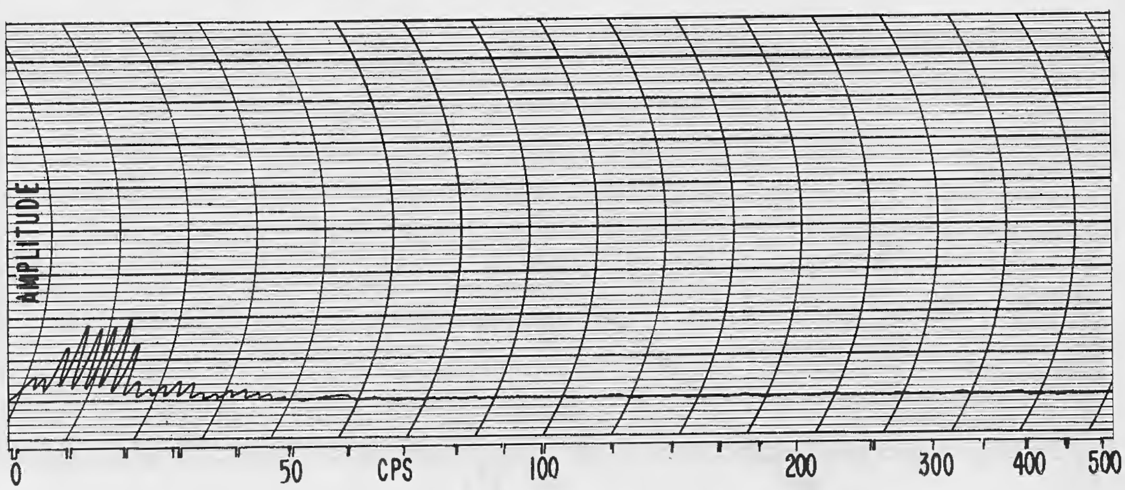

Figure 3 - Spectrum of noise from a fixed target

where small rotations of the plane bring reflections from large and dissimilar areas in and out of phase. The magnitudes measured at 30 cps, a common lobing frequency, and the output angular dispersion in mils resulting in a sequential radar with antenna beamwidth of 30 mils and servo bandwidth of 1/2 cps are shown in Table 1. For 0°, two calculations are made, one based on the continuous spectrum, the other on the periodic spectrum.

Figures 7, 8, and 9 are representative spectra of angle noise taken for the same three aspects. The spectra differ little, the ordinates decreasing with frequency about 15 db on the average over the range measured. The ordinates are somewhat larger in Figure 8 (90°), probably due to the asymmetry of the plane in this aspect. The ordinates measured at 1/2 cps and the output angular dispersion in a 1/2-cps bandwidth are shown in Table 1. A_{amp} is here extrapolated back to 0 as constant at the 1/2-cps value, in the absence of any data in this region.

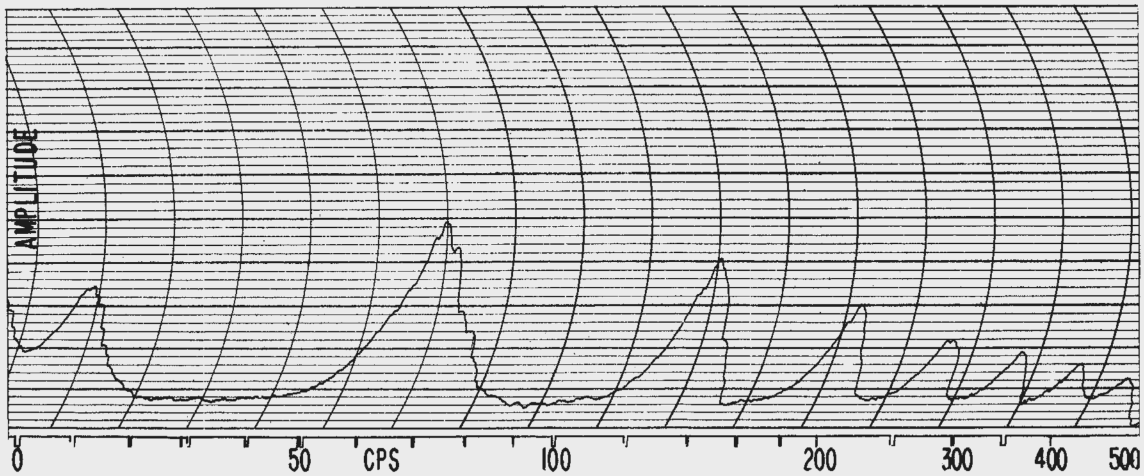

Figure 4 - Spectrum of amplitude noise from R4D at 0°

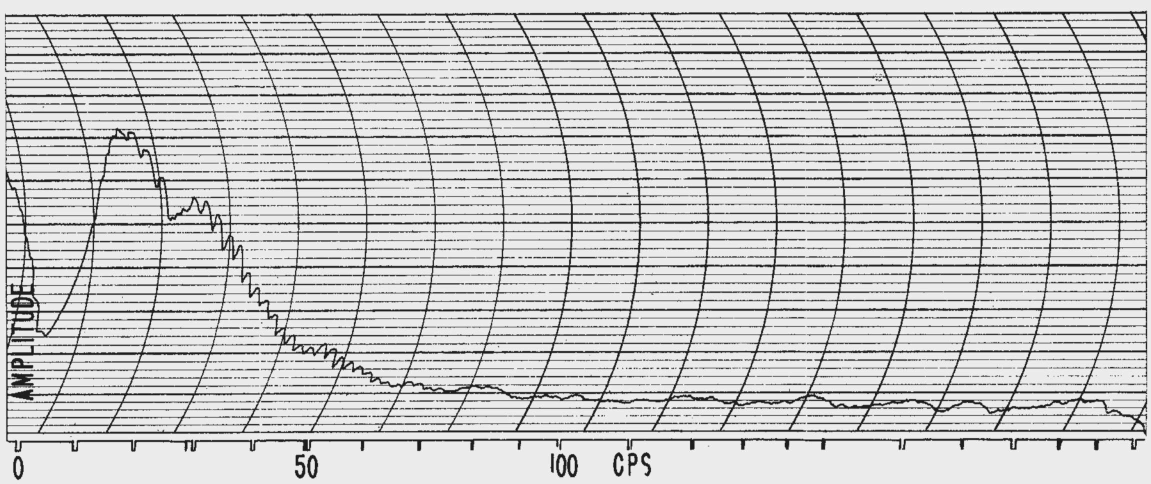

Figure 5 - Spectrum of amplitude noise from R4D at 90°

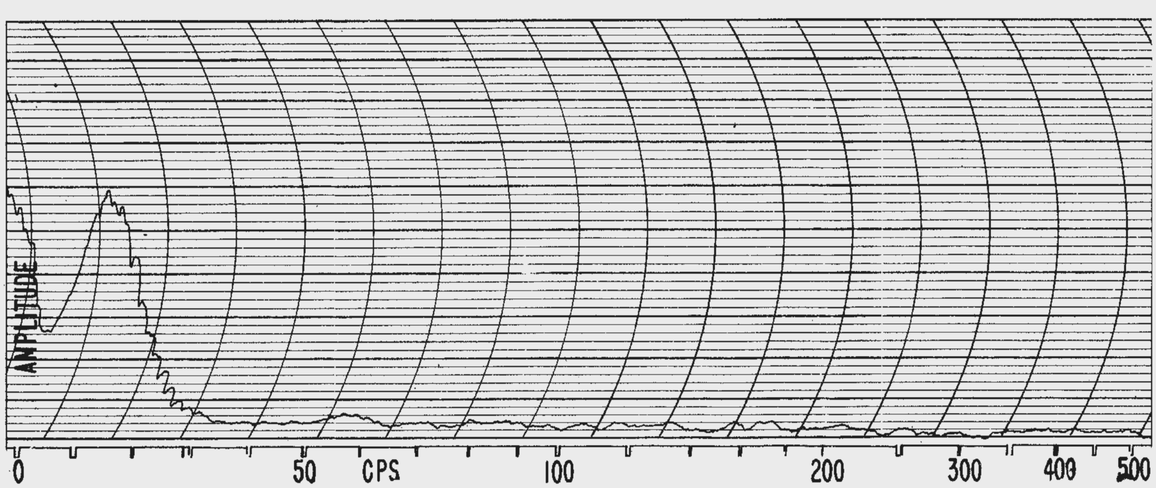

Figure 6 - Spectrum of amplitude noise from R4D at 180°

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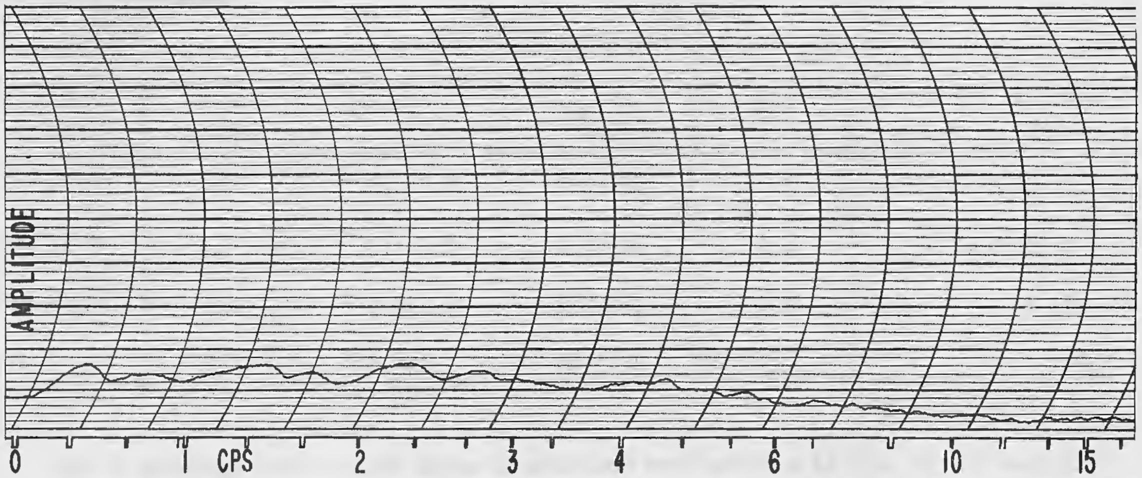

Figure 7 - Spectrum of angle noise from R4D at 0^0

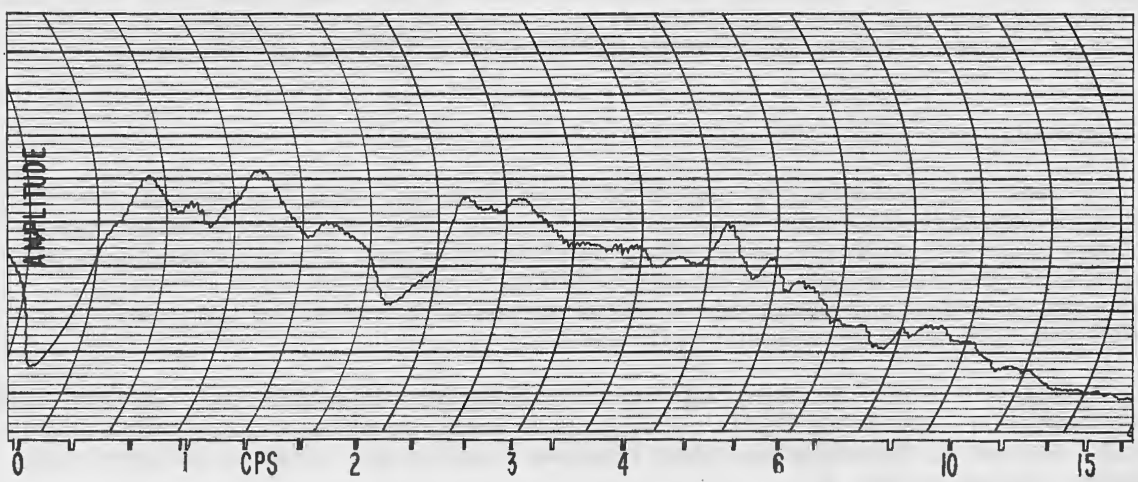

Figure 8 - Spectrum of angle noise from R4D at 90^0

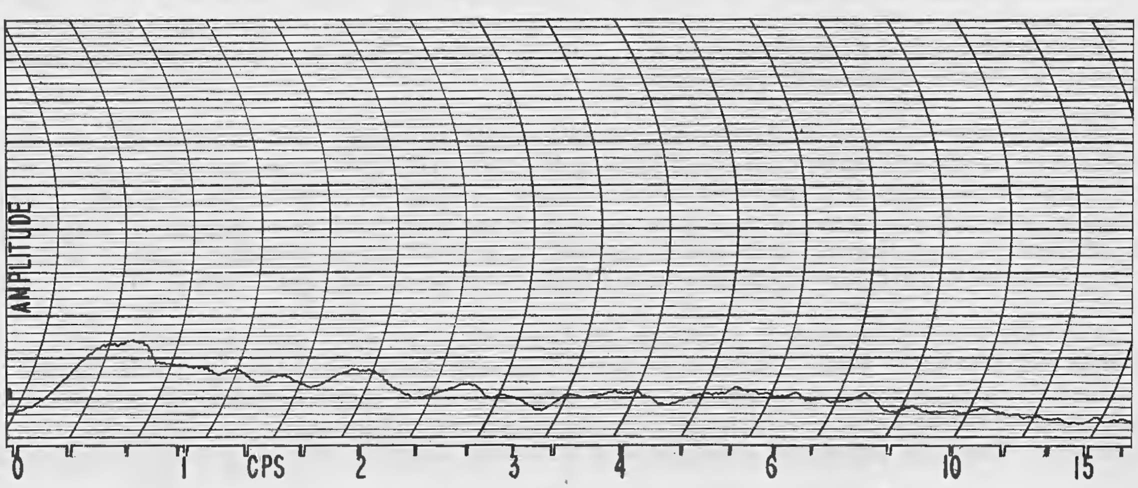

Figure 9 - Spectrum of angle noise from R4D at 180^0

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TABLE 1

Aspect (deg)	A_{ang}	σ_{ang} (mils)	A_{amp}	σ_{amp} (mils)	R_0 (yds)
0 (continuous)	3.7	2600/R	5.7×10^{-3}	0.1	26×10^3
0 (periodic)	3.7	2600/R	5.7×10^{-2}	1.0	2.6×10^3
90	7.7	5500/R	5.0×10^{-2}	0.9	6.1×10^3
180	4.5	3200/R	1.1×10^{-2}	0.2	16×10^3

Figures 10, 11, and 12 are the time functions of angle noise, corresponding to the spectra of Figures 7, 8, and 9. The ordinates are in yards at the target for an 8-cps bandwidth, one small division being approximately 3 yards, and the abscissae are 1/5 second approximately. At this bandwidth, the apparent center of reflection varies over more than the linear dimensions of the plane. There are occasional periods of as much as a second when the apparent center is nearly stationary as much as 10 yards off the average.

DISCUSSION

In Table 1 is calculated the range R_0 at which the output angular dispersions resulting from amplitude noise equal those from angle noise. The radar is assumed to have an antenna beamwidth of 30 mils and a lobing frequency of 30 cps. If it is assumed that the angle noise spectrum is flat over the range β and the amplitude noise flat over $30 \pm \beta$, this cross-over range is independent of the servo bandwidth and can be calculated for any other sequential radar from Equations (2) and (3).

At ranges less than R_0, input angle noise produces greater output noise than does input amplitude noise, and the monopulse radar gives no improvement in tracking over a sequential radar. Beyond R_0, the monopulse radar improves tracking until receiver and servo noise become limiting factors.

In a sequential radar, there is some gain by using a high lobing frequency, as is apparent in Figures 4 and 5, although a moderate increase in frequency would reduce the effects of the continuous spectra markedly, and a method of scrambling the lobing sequence would reduce the effects of the periodic spectra.

It should be emphasized that the data here is from one plane only, and that results obtained from tests with other planes might be quite different. Measurements now proceeding on several other types of planes will allow reliable conclusions to be made. Because of the complexity of the apparatus, accuracy of measurement is difficult to estimate. The spectrum amplitudes are reproducible within 20%, and absolute accuracy is probably within a factor of 2. Improved methods of calibration will eliminate some of this uncertainty.

A qualitative interpretation of the low-angle tracking problem may be made in terms of amplitude and angle noise. Surface reflection effectively places an image of the target at an equal distance below the surface. If the total subtended angle between the target and image is less than the radar beamwidth, the signal return is the vector sum of the signals from each. Since the reflection coefficient is a random variable, the magnitude of amplitude noise will increase somewhat. The magnitude of angle noise, however, is now determined by the angle between target and image instead of the subtended angle of the target alone and will therefore increase greatly. It has been shown experimentally that this is true. This low-angle effect is present until the target elevation angle is about one-half beamwidth, after which the target is resolved and the image ignored.

Multiple targets produce the same effect if they are not resolved in either angle or range. The tracking radar will hunt between the targets until either range or angle resolution is obtained. For very extended targets, greater than the beamwidth, the tracking performance is likely to be completely unpredictable.

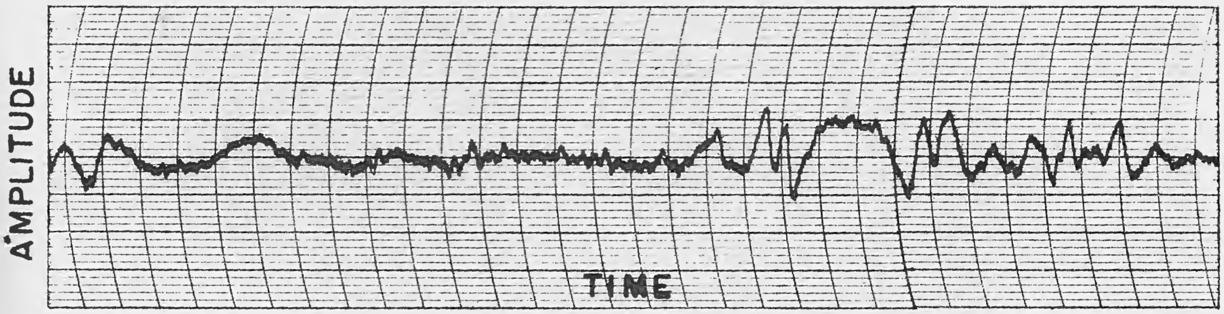

Figure 10 - Angle noise vs. time from R4D at 0^0

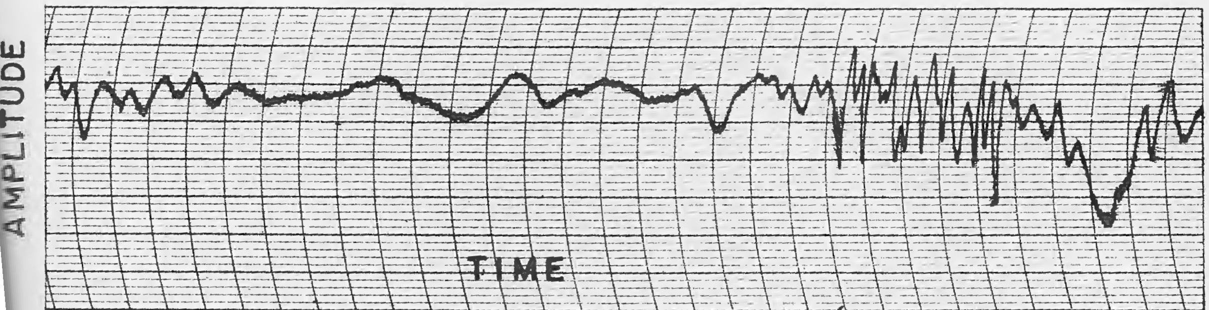

Figure 11 - Angle noise vs. time from R4D at 90^0

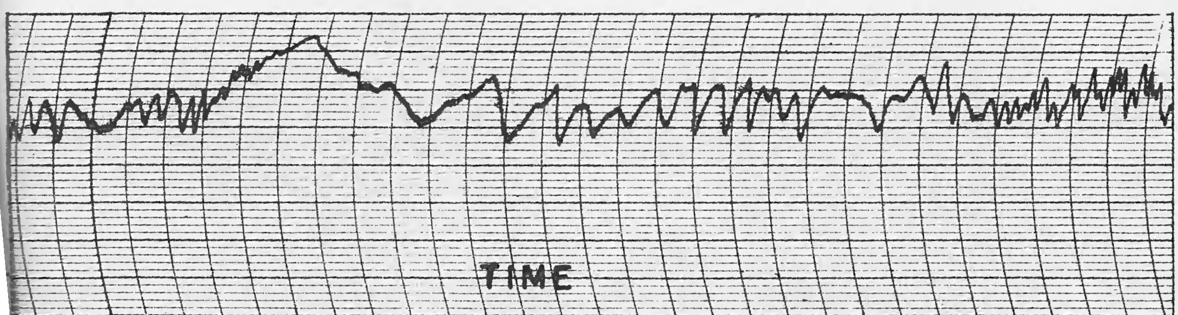

Figure 12 - Angle noise vs. time from R4D at 180^0

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