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The Enigma of the AN/FPS–95 OTH Radar (U)

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(U) ~~(S)~~ Cobra Mist, the AN/FPS–95 over-the-horizon (OTH) radar built on the English North Sea Coast in the late 1960's to overlook air and missile activity in Eastern Europe and the western areas of the USSR, was the most powerful and sophisticated radar of its kind up to that time. The design, which emulated Naval Research Laboratory's Madre over-the-horizon radar, incorporated rather coarse spatial resolution and relied upon ultralinear, wide dynamic range components and complex signal processing in attempting to achieve the extreme subclutter visibility (SCV) of 80 to 90 dB needed to separate target returns from the strong ground clutter—a goal well beyond the 60-odd decibel subclutter visibility previously achieved. The detection performance of the radar was spoiled, however, because the actual subclutter visibility achieved was only 60 to 70 dB, the limitation being due to a noise with approximately flat amplitude-versus-Doppler frequency, which appeared in all range bins containing ground clutter and aircraft returns. Experiments performed at the site failed to uncover the source of the noise, either in the equipment or in the propagation medium. Other experimental results imply that the noise was associated with returns from land areas and not from sea surfaces; the possibility of electronic countermeasures was not ruled out. Because the source of the noise was not located and corrected, the radar program was terminated in June 1973 and the equipment removed from the site. The cause of the noise is unknown to this day.

INTRODUCTION

This is as strange a maze as e'er men trod;
And there is in this business more than nature
Was ever conduct of: some oracle
Must rectify our knowledge.

Shakespeare (The Tempest)

(U) ~~(S)~~ This paper recounts the story of Cobra Mist, the AN/FPS–95 over-the-horizon radar built in England on the North Sea Coast in the late 1960's and operated there until mid-1973, when the program was discontinued.

(U) ~~(S)~~ As many will remember, the AN/FPS–95 was the largest, most powerful, and most sophisticated OTH (over-the-horizon) radar of its time; and the OTH community as a whole had high hopes that in performance and capability Cobra Mist would set new standards for the OTH radar art. Quite the opposite happened, however. The radar was plagued from the beginning by difficulties, and although the problems within the equipment itself—which were never very serious—were tracked down and corrected, a residual problem, apparently in the external environment, seriously impaired the detection performance of the radar and led ultimately to the discontinuance of the program. The source of the difficulty that caused Cobra Mist's demise was never found. At the conclusion of the program a rather extensive set of reports on the program([1]) were prepared for the U.S. Air Force, but these were not widely distributed. Consequently, the community did not benefit fully from the AN/FPS–95 experience.

(U) ~~(S)~~ The authors of this paper were all in some way intimately associated with the AN/FPS–95, both in its initial operational phases and in the final phase when an all-out, though time-limited, attempt was made to locate and correct the critical difficulty. The point of this paper is to give an account of the final phase: to list the

*(U) ~~The markings NOFORN and NF used in this paper have been derived from the source material.~~

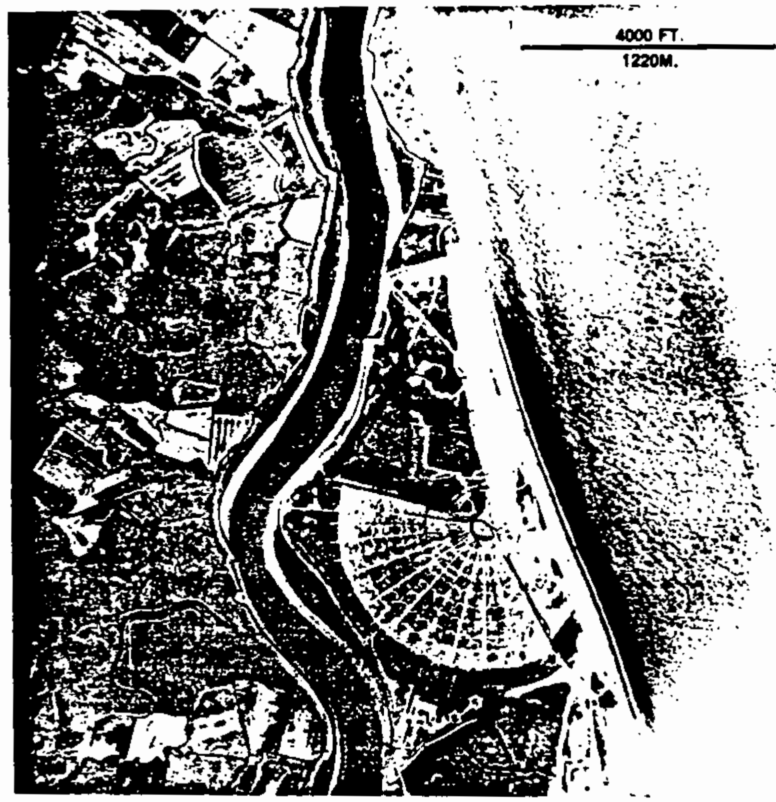

Figure 1. Aerial view of AN/FPS-95. (USAF photo.) (Figure unclassified.)

When detailed experimental plans were complete in mid-1971, groups from MITRE and the Naval Research Laboratory moved to the site, which by then had assumed the form shown in the aerial view of Fig. 1.

(U) ~~(S)~~ Technical difficulties with the system delayed both acceptance of the radar by the Air Force and the commencement of the DVST program until February 1972. From the beginning, the DVST program was hampered by problems, the most serious being the appearance of a mysterious noise which occurred in all Doppler filters corresponding to range intervals in which returns from the earth's surface (that is, "clutter" returns) were received. The range intervals containing the clutter return also contained the returns from the missile and aircraft targets the radar was to observe. The level of this "clutter-related noise" was high enough to impair seriously the capability of the radar to detect aircraft and missile targets, and as time went on, activities at the site shifted more and more from DVST to efforts to locate the source of the noise and to eliminate it.

(U) ~~(S-NF)~~ The DVST Technical Advisory Committee viewed the noise problem with increasing alarm and, in the report to the Air Force which followed its meeting in November 1972,[5] the Committee recommended that top priority be given to solving the noise problem, that control of operations at the site be shifted from the Air Force to a civilian scientific director, and that the latter mount a coordinated, systematic program to isolate and identify the source of the noise. The Air Force on Dec. 27, 1972 moved to put these recommendations into effect.

(U) ~~(S-NF)~~ DVST program was suspended, a scientific director was recruited from Stanford Research Institute, and a committee, called the Scientific Assessment Committee (SAC), was appointed with U.S. and U.K. members. The U.S. members previously had had no direct involvement with the Cobra Mist radar. This committee took a fresh look at the system, system performance, and noise data and structured a series of basic experiments[6] to determine the source of the noise. These experiments were conducted in the period from January to May in 1973, and in the ensuing appraisal it was found that the source of the noise

RADAR SYSTEM DESCRIPTION

(U) ~~(S-NF)~~ The AN/FPS–95 over-the-horizon backscatter radar([illegible]) was located at Orford Ness on the east coast of England. By beam steering, the radar was designed to make observations within a 91–deg azimuth sector extending from 19.5 to 110.5 deg clockwise from true north. The maximum range, assuming one-hop propagation via the ionosphere F-layer, was approximately 2,000 nmi, but the equipment would permit the observation of suitable, more distant targets using multihop propagation modes. A minimum range of approximately 500 nmi was set by the lower radar frequency limit and the upper elevation limit of the radar beams. Figure 2 shows the nominal coverage of the radar using single-hop propagation modes. The operating frequency range extended from 6 to 40 MHz.

(U) The radar employed the pulse-Doppler method to detect the radar signals from moving targets against the much larger return from the earth's surface. The waveforms used for search and tracking tasks took the form of radio frequency pulses, with durations selectable from 250 to 3,000 μsec and pulse repetition frequencies (PRF) from 40 to 160 pulses/sec. Received pulse-trains of selectable lengths were processed in a frequency analyzer, which in effect provided a contiguous set of bandpass filters that were approximately "matched" in the radar sense for targets with constant Doppler frequencies and also for targets with linear Doppler rates of change (constant accelerations). An oblique ionospheric sounder mode of operation was also available, wherein the earth surface backscatter returns could be displayed as functions of radar frequency and propagation time delay.

(U) To achieve sufficient signal-to-noise ratios against the predicted noise background, the radar was capable of very high transmitted power output. A peak power of 10 MW and an average power of 600 kw were originally specified, although these figures were not achieved in practice. Such high powers were incorporated in the design to compensate for the relatively low antenna gain of approximately 25 dB.

(U) ~~(S)~~ Both ionospheric propagation limitations and the scarcity of clear HF operating frequencies impose severe limitations on the design bandwidths of OTH radar signals and therefore on the attainable range resolution. This fact, coupled with the broad (7 deg) beamwidth of the AN/FPS–95, resulted in a very large radar resolution cell and, consequently, a large earth-surface radar backscatter power. To accommodate such large signals without causing unacceptably high intermodulation and cross-modulation effects, a radar receiver with the very large linear dynamic range of 140 dB was provided, together with signal processing equipment of commensurate capabilities. A simplified block diagram of the system is shown in Fig. 3, and the major parameters are summarized in Table 1.

(U) Following are brief descriptions of the major elements of the AN/FPS–95 radar.

ANTENNA

(U) ~~(S)~~ The antenna consisted of 18 log-periodic antenna strings, which radiated like spokes in a wheel from a central "hub." Figure 4 is a close-up photograph of one such string. Each string was 2,200 ft in length and carried both horizontal and vertical radiating dipoles. The strings were separated by 7 deg in angle, and they thus occupied a 119-deg sector of a circle. The complete antenna was located over a wire-mesh ground screen, which extended beyond the strings in the propagation direction.

(U) To form a beam, six adjacent strings were connected, by means of a beam-switching matrix situated underground at the hub of the antenna, to the transmit or receive beam-forming networks in the main building. The pointing direction of the beam was controlled solely by selecting the appropriate set of six adjacent strings from among the 18 available. According to the frequency of operation, a specific small section of each log-periodic string became resonant. Thus, at high frequencies the active portion would be close to the antenna hub, and it would move out toward the larger dipole elements as the frequency was lowered. While the linear extent of the active area extending across all six strings thus increased as the frequency was lowered, the net effect was to produce a beam whose angular dimensions and, hence, gain were almost independent of frequency. A simple way to view the action of the antenna is to regard it as a six-element broadside array, which moved around within the physical boundary of

TABLE 1. *AN/FPS-95 parameters.* (~~Table classified Secret.~~) (U)

Antenna	
Type	Log-Periodic Array
Frequency Range	6-40 MHz
Polarization	Vertical or Horizontal
Number of Beam Positions	13
Azimuth Coverage	91°
Azimuth Beamwidth (3 dB)	7°
Elevation Beamwidths (3 dB)	
Vertical Polarization	2° to 10°
Horizontal Polarization	9° to 30°
Gain (Vertical Polarization)	25 dB
Sidelobes	
First	-13 dB
Second	-18 dB
Other	-20 dB
Transmitter	
Type	Linear Distributed Amplifier
Frequency Range	6 to 40 MHz
Power Output	
Peak	3.5 MW
Average	300 kW
Pulse Shapes	Cosine-Squared, Flattened Cosine-Squared, Sin Mx/Sin x
Pulse Repetition Rates	10*, 40, 53.33, 80, 160 p/s
Pulse Widths	250 to 3,000 μs, 6,000 μs*
Receiver/Signal Processor	
Type	Analog and Digital
RF Bandwidth	5 kHz
Dynamic Range	140 dB
Noise Figure	7 to 14 dB (Frequency Dependent)
Analog/Digital Converter	18 Bit
Clutter Filtering	100 dB
Doppler Range	3 Hz to PRF/2
Acceleration Range	20 g
Integration Times	0.3125, 1.25, 2.5, 5, 10, 20 s

*(U) For special nonoperational use.

1. (U) Truncated $\cos^2$: This is a $\cos^2$ envelope modulation, which is truncated at the 10-percent voltage envelope points.

2. (U) Flattened $\cos^2$: This is a flat-topped pulse with truncated $\cos^2$ leading and trailing edges.

3. (U) Sin Mx/sin x: This pulse was used for the oblique ionospheric sounder mode of radar operation. The pulse was formed by the superposition of 10 carrier pulses, each of 200-μsec duration, with frequency separations of 100 kHz.

(U) The major transmitter parameters are shown in Table 3.

RECEIVER/SIGNAL PROCESSOR

(U) The receiver consisted of monopulse sum and difference channels to match the sum and difference outputs of the antenna beam-forming net-

TABLE 4. *Receiver/signal processor parameters. (Table unclassified.)*

Frequency Range	6 to 40 MHz
Bandwidth	5 kHz
Dynamic Range	140 dB
Noise Figure	
6 to 15 MHz	≤14 dB
15 to 23 MHz	≤ 9 dB
23 to 31 MHz	≤ 8 dB
31 to 40 MHz	≤ 7 dB
A/D Converter	18 bit
Cluttering Filtering	100 dB
Doppler Range	3 Hz to PRF/2
Acceleration Range	20 g

verter. These data were then available for analysis off line by the extensive programs that were specially developed as part of the DVST activity or for replay through the on-line system. Some of the main receiver and signal processor parameters are listed in Table 4.

DISPLAYS

(U) The signal processor outputs contained data on target range, azimuth, velocity, acceleration, and signal amplitude. These parameters, together with a time–history dimension, could be shown on a number of cathode ray tube (CRT) displays. Intensity modulation was not employed on these displays, with the result that only two of the foregoing six parameters were displayable in the chosen x-y format at any one time. Some of the remaining parameters could be thresholded by manual selection to restrict the number of displayed data. From among all the possible combinations of the six parameters taken two at a time, the AN/FPS–95 had the capability of displaying 14 such pairs.

(U) On those displays where the signal amplitude was not one of the exhibited parameters, an amplitude threshold had to be chosen. Thus, only those signals that exceeded this threshold would be "detected" and displayed, as in a classical radar signal detection process. Cursors were provided to allow readout of parameter values from the displays, and cameras were available for a permanent display record. In addition to the presentations on the cathode ray tubes, certain data could be recorded on magnetic tape or automatically typed. Figure 6 shows a view of the radar control console with its associated displays.

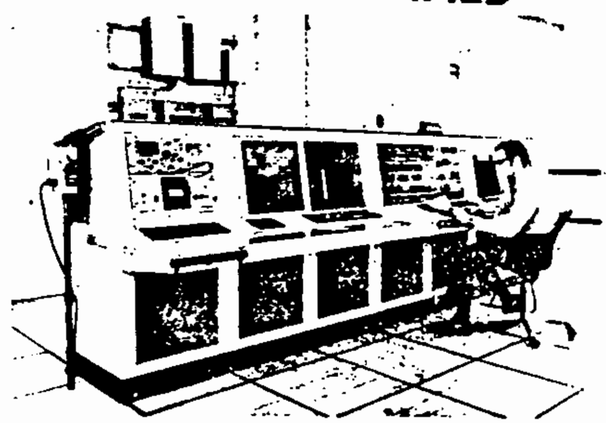

Figure 6. Radar control console. (Courtesy RCA Corp.) (Figure unclassified.)

ANCILLARY EQUIPMENT

(U) To support the AN/FPS–95 operation in the selection of radar operating frequencies, the site contained a vertical ionospheric sounder and a panoramic radio receiver.

RADAR CAPABILITIES AND LIMITATIONS

EXPECTED CAPABILITIES

(U) ~~(S)~~ The AN/FPS–95 was expected to detect and track (*a*) aircraft in flight over the western part of the Soviet Union and the Warsaw Pact countries and (*b*) missile launches from the Northern Fleet Missile Test Center at Plesetsk. Aircraft detection and tracking at ranges of 500 to 2,000 nmi, corresponding to one-hop ionospheric propagation, were considered feasible. Missile launches from Plesetsk were also within one-hop range from the radar. A searchlight mode was provided for high-priority targets whose approximate locations were known a priori. These targets could be single aircraft, compact formations of aircraft, or missile launches. In this mode, the radar continuously illuminated a small geographical area to obtain the maximum data rate on the selected targets. As an alternative, a scanning mode was provided, which allowed the radar to search in azimuth and range over any chosen sector of the radar coverage mode, the pulse Doppler radar signal processor was required to suppress the ground backscatter by 85 to 90 dB relative to aircraft returns—that is, to provide 85 to 90 dB of subclutter visibility (SCV). Somewhat lower probability of detection, and hence less subclutter visibility, would suffice for the searchlight mode, where the radar continuously illuminated a given target. In an attempt to achieve the required subclutter visibility, great care was taken in the design of the radar transmitter to minimize spectral noise and in the receiver and signal processor to minimize intermodulations and cross modulations and to provide a large linear dynamic range.

DESIGN VERIFICATION SYSTEM TESTING (DVST)

(U) (S) Following construction of the AN/FPS-95 and its acceptance by the government, a one-year research and development program was planned[4] to assess its capabilities. The 12 aircraft detection and tracking experiments assigned to MITRE during the DVST will be described briefly as a further indication of the expected capability of the radar. A number of other experiments, including all of the missile detection and tracking experiments, were assigned to Naval Research Laboratory and have been documented by that organization.[11] This paper will therefore discuss only aircraft detection and tracking, with which the authors have firsthand experience.

(U) (S) Experiment 202, Radar Aurora, was intended to determine experimentally the effects of HF radio aurora on OTH radar design and operation. Experiment 104, Signal Detectability, and Experiment 502, Target Detection and Calibration, were to determine probability of detection, probability of false alarm, and signal-to-noise ratios of detected targets, as well as develop procedures to estimate radar cross section of the detected targets. Three experiments dealt with real-time tracking of aircraft at the radar consoles and were designed to develop and evaluate this capability: Experiment 501, Evaluation of Target Window Printout; Experiment 505, Tracking Through Azimuth Beams; and Experiment 508, Track Capability and Track Sample Rate. One experiment dealt with automatic tracking of aircraft, conducted off line on a digital computer. This was Experiment 405, Track-While-Scan Feasibility. Experiment 506, Range and Azimuth Calibration, was intended to provide an absolute spatial calibration using ground transponders.

(U) (S) These eight experiments were intended to assess the general capabilities of the radar for aircraft detection. Four other experiments were directed toward specific intelligence objectives. Experiment 306, Vertical Velocity Estimation with Aircraft, was to exploit the fine Doppler resolution of the radar to measure vertical velocity. The Doppler difference between alternate ground-reflected propagation modes was to be utilized for this purpose. Experiment 312, Intelligence from Test Range Calibration Flights, surveyed aircraft activity near Plesetsk and other missile test centers. Experiment 314, Reconnaissance Aircraft Surveillance, tracked friendly aircraft over the Baltic Sea area, providing the only source of overwater aircraft tracking data. Experiment 315A, Aircraft R&D Test Intelligence, observed aircraft at the Ramenskoye and Vladimirovks Flight Test Centers.

(U) Of these 12 experiments, three were carried out and documented: Experiments 202,[12] 405,[13] and 506.[14] The rest were not completed for either of two reasons: (*a*) The experiment as conceived proved too ambitious for the actual capability of the radar or (*b*) the scientist assigned to the experiment was reassigned to efforts to improve the radar capability.

OBSERVED CAPABILITIES AND LIMITATIONS

(U) (S) Once DVST got under way at Orford Ness, it became apparent to the MITRE team (and others) on site that the actual radar capabilities were a good deal less than the expected capabilities. In the searchlight mode, aircraft detection and tracking were marginal, even when aircraft flight plans were known a priori. When the radar was carefully operated, with due regard for range and Doppler ambiguities and ionospheric propagation conditions, tracking trials on known aircraft in the searchlight mode produced tracks less than half the time. Furthermore, the tracks obtained were discontinuous, the aircraft return usually being above the noise level only near the peaks of the Faraday rotation and multipath fading cycles. Additionally, routine observations of areas of high air-traffic density, such as air routes near Moscow, in the searchlight mode often produced few or no target detections at times of day when the propaoften could be 20 dB, and in some cases even 30 dB, higher than the level of external noise received by the radar. Figure 7 is a photograph of the AN/FPS–95 Doppler–range display taken early in the DVST.[17] The range scale (horizontal) extends from 0 to 2,000 nmi, the nominal unambiguous range at a PRF of 40 HZ. The Doppler scale (vertical) extends from 3 to 20 HZ, with approaching and receding Doppler shifts folded together. A Doppler shift of 20 HZ corresponds to a radial velocity of 264 knots at the radio frequency of 22.1 MHZ employed to obtain these data. Ground backscatter in the 0- to 3-HZ region is suppressed by the digital clutter filter. In some range bins, corresponding to the skip zone for ionospheric propagation, the noise level is below the display threshold in all Doppler bins. In the succeeding range bins, generally corresponding to the ranges of first-hop ground backscatter, the noise level in all Doppler bins is much higher, hindering target detection.

(U) (S) That the excess noise seen on the radar displays was in fact clutter-related was demonstrated clearly by turning off the radar transmitters. This caused the display of Fig. 7 to go black. When the threshold was readjusted to observe the noise level, it was observed to be constant with range, as one would expect from external noise. After a number of such observations, it became apparent that even if a clear channel could be found, even if ionospheric propagation to the desired geographical area existed at the clear channel frequency, and even if the radar display limitations could be overcome, the excess noise would still provide a severe limitation on radar performance. Therefore, in parallel with DVST, an effort to characterize the excess noise was undertaken on site.

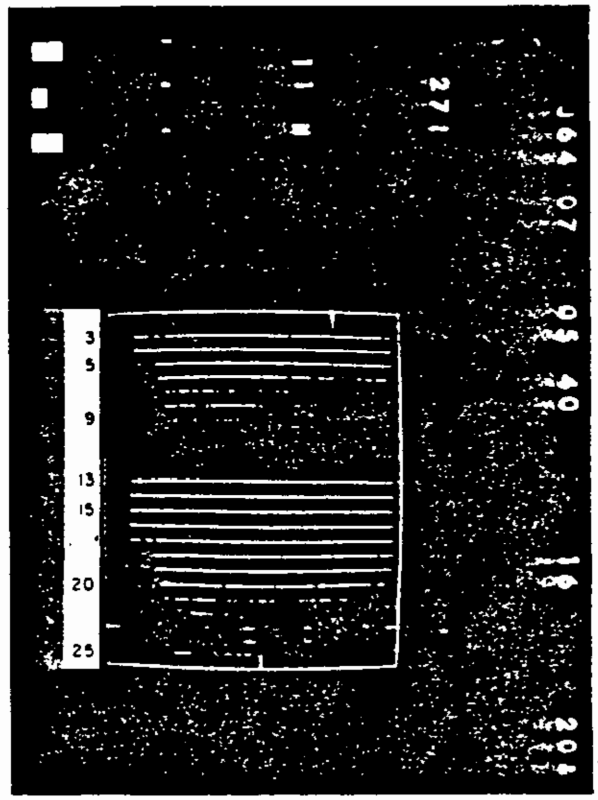

Figure 7. Doppler/range display illustrating excess noise (Figure unclassified.)

CHARACTERISTICS OF THE EXCESS NOISE

(U) (S) The radar displays presented the excess noise in a dramatic way, but a quantitative characterization of the phenomenon required the use of off-line digital signal processing programs.[18] The output of one of these programs is illustrated in Fig. 8 for data recorded near 7:00 Greenwich mean time on March 4, 1972 (Day 64) in beam 11 with vertical polarization at 22.1 MHZ—the same data as previously illustrated in Fig. 7. The variation of ground backscatter (clutter) and excess noise amplitude with slant range is plotted in Fig. 8. Note that the clutter curve is moved downward by 50 dB to facilitate comparison with the noise curve. Ground-clutter amplitude was computed by peak selection in a ± 1.5-HZ Doppler window. The amplitude of excess noise was computed by averaging the squared modulus of the digital signal processor output over all Doppler bins from 3 to 20 HZ on either side of the carrier, that is, over all those Doppler bins outside the radar clutter filter rejection band. The digital signal processor performed a fast Fourier transform (FFT) over 512 successive radar pulses in each 12.8-sec coherent integration interval. The plotted clutter and noise powers were then further noncoherently averaged over 15 successive coherent integration intervals.

(U) (S) One sees in Fig. 8 a marked variation of the excess noise amplitude with slant range. Strong excess noise exists at short range, in the skip zone just ahead of the ground clutter, and at the range of the ground clutter. The excess noise near the range of peak ground backscatter varies with range in direct proportion to the backscatter,

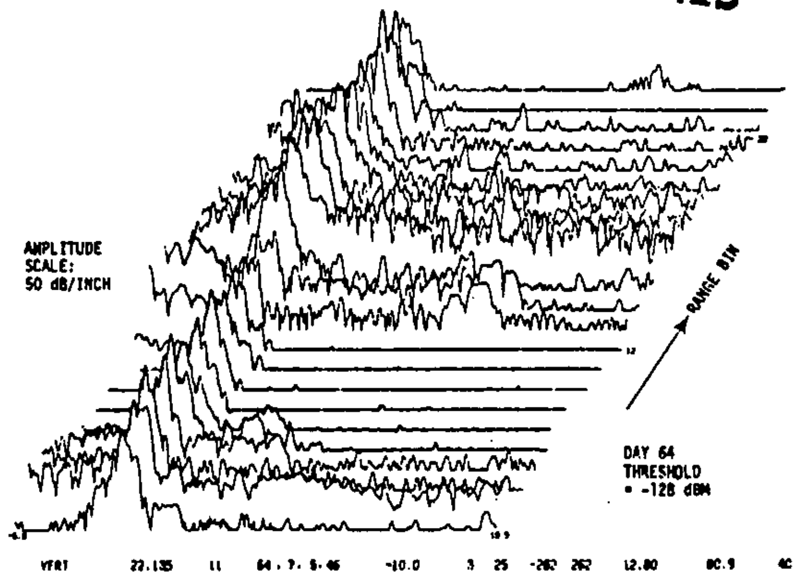

Figure 11. Range/Doppler display of excess noise.[17] (~~Figure classified Secret.~~) (U)

but the excess noise at short range and in the skip zone does not. To distinguish between the excess noise that occurs ahead of the ground clutter and the excess noise that occurs at the range of ground clutter, special terminology was used at the site. All sources of excess noise that varied with range were termed "range-related noise" (RRN). The portion of the excess noise that coincided in range with ground clutter was termed "clutter-related noise" (CRN). Although all of the range-related noise was of scientific interest, only the clutter-related noise interfered with detection of aircraft, which was the primary mission of the radar. To better characterize range-related noise, Figs. 9 and 10 were generated from the same data.[17] Here, the average power of range-related noise is computed separately for approaching and receding Doppler bins. In Fig. 9, noise power is averaged over Doppler bins 3 to 10 Hz from the carrier, while in Fig. 10 noise power is averaged over Doppler bins 10 to 20 Hz from the carrier. One sees that the clutter-related noise near the range of peak ground backscatter has a symmetrical spectrum close in (3 to 10 Hz) and a nearly

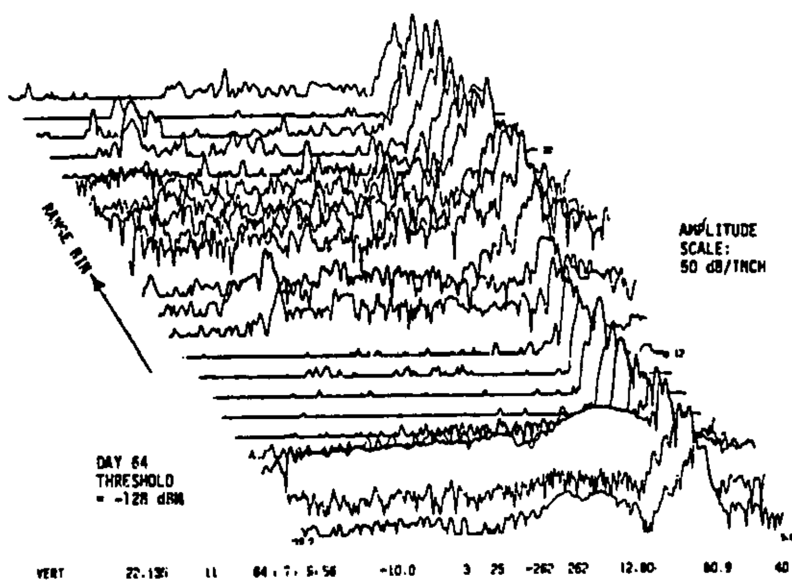

Figure 12. Range/Doppler display of excess noise.[17] (~~Figure classified Secret.~~) (U)

threshold for Fig. 13 is 20 dB higher than the thresholds of Figs. 11 and 12 to show the clutter-related noise peaks more clearly.

(U) (S) Figure 14 shows amplitude versus Doppler during successive coherent integration intervals for radar-range bin 23, which is 480 nmi behind the peak of the ground backscatter, but still illuminated by one-hop ionospheric refraction.[17] In particular, this range bin, at a slant range of 1,760 nmi, represents a ray path elevation of only a few degrees at ground level for one-hop propagation by means of the F2 layer of the ionosphere. The amplitude of range-related noise is much lower in range bin 23 than in range bin 17, which can be seen by noting that Fig. 14 has a threshold 20 dB lower than that of Fig. 13. One also notes in Fig. 14 a number of possible aircraft tracks (large amplitude returns isolated in Doppler and forming a Doppler–time trace) from the geographical area illuminated, which contained a number of Soviet military airfields. All of these apparent target returns in range bin 23 are well below the level of clutter-related noise seen in range bin 17. Thus, if the targets were in range bin 17, 480 nmi closer to the radar, they probably would not have been detected, even allowing for a 5.5-dB greater radar return due to the decreased range. Figure 14 illustrates the contention made earlier that aircraft detectability was not maximized at the range of peak ground backscatter, but rather at somewhat greater ranges, where grazing incidence for ground backscatter was approached.

(U) (S) The radar data illustrated, taken on a single day early in the DVST period, are reasonably representative of the range-related noise phenomenon. Characteristics of range-related noise observed throughout the period of AN/FPS–95 operation are summarized here:

(U) *1.* (S) Range-related noise was observed predominantly at three positions: at short range, in the skip zone ahead of the ground backscatter, and at the ranges of ground backscatter.

(U) *2.* (S) Both components of range-related noise at shorter ranges than ground backscatter had asymmetrical frequency spectra, with more power in receding Doppler than in approaching Doppler. The clutter-related noise at the ranges of ground backscatter generally had a more symmetrical frequency spectrum. Range-related noise decreased slowly with increasing Doppler shift in all three cases.

(U) *3.* (S) The amplitude ratio of ground backscatter to clutter-related noise near the range of peak ground backscatter (where the radar was intended to detect targets) was relatively constant, being in the range of 60 to 70 dB.

(U) *4.* (S) The amplitude ratio between range-related noise and external noise (noise received with the transmitter off) was more variable, depending on both the absolute level of ground backscatter and the level of external noise. Ratios varying from 10 to 30 dB were typical. The only times range-related noise exceeded external noise by less than 10 dB were the times when geographical areas of interest were weakly illuminated or the external noise level was very high. These were times, of course, when the radar would have had little detection and tracking capability, even in the absence of clutter-related noise.

(U) *5.* (S) Range-related noise was observed to occur at all times of the day, in all seasons, in all beams, at all radio frequencies, in both polarizations, and so on. It was not an isolated phenomenon.

THE SEARCH FOR SOURCES OF EXCESS NOISE IN THE RADAR

(U) (S) Once the effects of clutter-related noise on radar performance were understood, the AN/FPS–95 underwent extensive testing to see if the clutter-related noise might be originating in the equipment itself. There were two motives for first testing the radar itself before carrying the investigation to possible external causes of clutter-related noise:

(U) *1.* (S) Before using the radar as a test instrument to look for causes of clutter-related noise in the ionospheric propagation medium or in reflection phenomena in the target space, it was necessary to verify that the radar itself was not the principal cause of the observed clutter-related noise.

(U) *2.* (S) It was thought that, if sources of clutter-related noise could be located in the radar equipment, they could probably be alleviated

- (U) *Description:* Inject two test signals 10 HZ apart at 1 MHZ from the desired signal. Measure the cross modulation level on the desired signal.
- (U) *Results:* The cross modulation level was 82 to 85 dB down from the desired signal for a −10 dBm out-of-band input, in the worst case. Duplexer cross modulation effects were negligible.
- (U) *Frequencies:* 8 and 16 MHZ.
- (U) *Dates:* April 22 and April 28, 1972.

Test 7: Radio-Frequency Hardware Measurements(19)

- (U) *Description:* Measure spurious-free dynamic range of transmit/receive diodes and magnetic elements in the beam-forming network.
- (U) *Results:* No degradation in subclutter visibility by these components was found, unless electromagnetic interference (EMI) approaches 0 dBm, which is rare.
- (U) *Frequencies:* Not given.
- (U) *Dates:* January and February 1973.

Test 8: Electromagnetic Interference Measurements(24)

- (U) *Description:* Measure the power level of interfering HF signals at the receiver input, mostly in beam 7 with horizontal polarization.
- (U) *Results:* Out-of-band electromagnetic interference sometimes exceeded receiver ratings below 15 MHZ. Out-of-band electromagnetic interference seldom exceeded receiver ratings above 15 MHZ.
- (U) *Frequencies:* 5 to 10, 10 to 15, 15 to 20, and 20 to 25 MHZ.
- (U) *Dates:* Dec. 28 through 30, 1971.

Test 9: Simulated Clutter into Receiver(25)

- (U) *Description:* Inject a simulated clutter signal into the receiver at a range in the skip zone, ahead of actual ground clutter received in beams 1, 7, and 13 during full-power operation of the radar transmitter.
- (U) (S-NF) *Results:* Spectral noise level on simulated clutter was at least 80 dB down, while clutter-related noise on actual clutter was only 60 to 70 dB down.
- (U) *Frequencies:* 17.4, 18.4, and 22.1 MHZ.
- (U) *Dates:* June 2, 3, and 9, 1972.

Test 10: Receiver Attenuation(25)

- (U) *Description:* Attenuate received ground clutter from beam 7 at the receiver input in 6-dB steps to 30 dB.
- (U) (S-NF) *Results:* Clutter and clutter-related noise at the signal processor output were linear with receiver attenuation, indicating that receiver overload was not a source of clutter-related noise.
- (U) *Frequency:* 17.4 MHZ.
- (U) *Date:* June 3, 1972.

(U) (S-NF) Next, a number of tests of the radar antenna on reception are described. Spectrally clean test signals were radiated toward the radar antenna from various points in the local area, and the received signals were examined for spectral noise of a level comparable to the observed clutter-related noise. One might note that extensive rework of the antenna was undertaken by the contractor (RCA) from Aug. 4 to Sept. 17, 1972. Antenna tests before the repairs were made showed a higher level of spectral noise than subsequent tests, which tended to exonerate the reworked antenna as the principal cause of clutter-related noise.

Test 11: Loop Antenna at the Focal Point(25)

- (U) *Description:* Radiate a simulated clutter signal from a loop antenna located at the geometrical focal point of the radar antenna. Receive on beam 1 with vertical polarization.
- (U) *Results:* Spectral noise was observed 60 to 70 dB down from the simulated clutter. A similar level of clutter-related noise was simultaneously observed on actual ground clutter, with the radar transmitter operating at full power during the test.
- (U) *Frequency:* 22.2 MHZ.
- (U) *Date:* June 9, 1972.

Test 12: Monopole Antenna on Sea Wall(25)

- (U) *Description:* Radiate a test signal from the vertically polarized monopole. Receive on beam 13 with alternating horizontal and vertical polarization.
- (U) *Results:* Spectral noise was down 80 dB when receiving vertical polarization, but down only 45 dB (at 20.6 MHZ) to 70 dB (at 39 MHZ) when receiving horizontal polarization, that is, when cross polarized.
- (U) *Frequencies:* 20.6, 24.2, and 39 MHZ.
- (U) *Dates:* July 6 and 7, 1972.

Test 13: Vertical Dipole on Sea Wall(21)

- (U) *Description:* Radiate a test signal from a vertically polarized dipole. Receive on beam 13 with vertical polarization.

EQUIPMENT COMPONENTS AS POSSIBLE SOURCES OF CLUTTER-RELATED NOISE

(U) (S) All components of the radar, including its local environment, were considered as possible sources of clutter-related noise. For each component, one or more physical mechanisms capable of generating clutter-related noise were hypothesized. These mechanisms (see Table 5) were then considered in structuring the equipment tests for clutter-related noise. Table 6 summarizes the results of the 20 equipment tests as described earlier with respect to sources of clutter-related noise in each radar component. A minus sign (−) means that a given radar component was found not to be a significant source of clutter-related noise; a plus sign (+) means that a component was found to be significant. Many squares in the table are left blank, indicating no conclusive relationship between a given equipment test and a given radar component.

(U) (S) Spectral noise on the radar transmitter output could cause clutter-related noise to appear on ground clutter. The ratio of clutter to clutter-related noise expected would be approximately equal to the ratio of carrier to spectral noise on the transmitter output, if such spectral noise were the principal cause of clutter-related noise. The transmitter noise level measurement (Test 1) showed a very low level of spectral noise—much too low to account for the observed clutter-related noise. A test using a fan dipole on the sea wall (Test 3) also showed transmitted spectral noise to be much lower than the generally observed clutter-related noise. The two overall system tests using a repeater (Tests 17 and 18) also tended to clear the transmitter as a cause of clutter-related noise. Finally, the observed linearity of clutter-related noise with transmitter power (Test 19) was an indication that nonlinear effects in the transmitter were not a significant source of clutter-related noise.

(U) (S) Receiver testing was more extensive than transmitter testing, in part because numerous tests of the radar antenna also implicitly tested the radar receiver. Tests of receiver linear dynamic range, intermodulation distortion, and cross-modulation distortion (Tests 4, 5, and 6) showed that the spectral noise imposed upon received ground clutter by these receiver phenomena should be much lower than the levels of clutter-related

TABLE 5. *Physical mechanisms for clutter-related noise. (Table unclassified.)*

Radar Component	Physical Mechanisms
Transmitter	Spectral noise on carrier
Receiver	Intermodulation distortion; cross-modulation distortion
Signal Processor and Displays	A/D converter transient response Insufficient dynamic range Spectral aliasing
Antenna, ground screen, and RF Hardware	Wind vibration of radiating elements Wind vibration making and breaking contacts Arcing and corona Cross modulation in nonlinear joints
Local Environment	Cross modulation in ancillary electrical equipment Sea scattering from first Fresnel zone

noise actually observed, thus showing that the receiver was not the major cause of clutter-related noise. The electromagnetic interference measurements (Test 8) showed that out-of-band electromagnetic interference occasionally exceeded receiver ratings, which could allow cross modulation in the receiver to cause significant clutter-related noise. However, such large out-of-band electromagnetic interference was rare, whereas clutter-related noise was observed all the time when ground clutter was strong. Testing of the receiver with simulated clutter (Test 9) showed spectral noise on the simulated clutter to be smaller than observed clutter-related noise on actual clutter received at the same time. Actual clutter and clutter-related noise were also shown to be linear with received signal attenuation (Test 10), thus indicating that receiver overload was not a cause of clutter-related noise.

(U) (S) Antenna reception Tests 13 through 16 included the receiver in the test chain. Since low levels of spectral noise were observed, these tests also exonerated the receiver as the principal cause of clutter-related noise. For example, the test employing a vertical dipole on the sea wall as a signal source (Test 13) showed spectral noise down 91 to 95 dB from the carrier, which is far lower than the clutter-related noise-to-clutter ratios commonly observed. Transmit and receive system tests employing a signal repeater (Tests 17 and 18) also tended to exonerate the receiver, although the spectral noise in these cases was not quite so low, because of the limitations of the repeater.

(U) ~~(S)~~ The receiving chain and signal repeater tests also indicated that the radar signal processor and displays were not the cause of clutter-related noise. That is, spectrally clean test signals injected ahead of the signal processor were observed on the displays to be not corrupted with spectral noise to anything near the level of clutter-related noise observed on actual ground clutter. There was a further indication that all the radar signal processor circuits after the analog-to-digital converter had adequate linear dynamic range to properly spectrum-analyze ground clutter. An off-line digital signal processor was developed by MITRE[19] to supplement the on-line hybrid digital/analog radar signal processor. Careful comparison of clutter-related noise at the output of the off-line digital processor with clutter-related noise observed on the radar displays showed very close agreement in amplitude, spectrum, and time variation. While it is possible that both processors might have had an undetected flaw, it is extremely unlikely that both would have had exactly the same flaw.

(U) ~~(S)~~ A lingering doubt does exist about one component of the signal processor—the analog-to-digital converter. A colleague[20] has put forth the hypothesis that analog-to-digital converter transient response errors in following time-varying clutter might account for the spectrally spread clutter-related noise. Since all test signals, both cw and pulsed, had constant amplitude from one radar pulse repetition interval to the next, the transient response of the analog-to-digital converter may not have been adequately tested, according to this hypothesis. At this late date, there appears no way to resolve this question.

(U) ~~(S)~~ Four tests of the radar antenna, ground screen, and RF hardware were conducted in the spring and summer of 1972, before RCA reworked these components. The transmitter power reduction test 19 tended to rule out nonlinear effects in the transmitting antenna, such as arcing and corona, as the principal cause of clutter-related noise, but it was too limited in scope to be wholly conclusive. Cross-modulation distortion in the duplexers was measured in conjunction with similar receiver measurements (Test 6) and found to be negligible. Two early tests of the antenna on reception gave positive results, however. Spectrally clean test signals that were radiated from a loop antenna at the geometric focal point of the radar antenna (Test 11) showed spectral noise at the signal processor output comparable in amplitude to the clutter-related noise simultaneously observed on ground clutter. When a vertical monopole on the sea wall was used to radiate a spectrally clean test signal (Test 12) to the radar antenna, spectral noise was also observed at the signal processor output. With the radar antenna vertically polarized, spectral noise on the test signal was lower than the clutter-related noise usually observed on ground clutter. However, with the radar antenna horizontally polarized (cross polarized to the test signal), spectral noise on the test signal at some frequencies was higher than the clutter-related noise usually observed on ground clutter. The results of these two tests were taken as an indication that at least some of the clutter-related noise was originating in the radar antenna on reception—possibly in the ground screen, because it could produce cross-polarized spectral noise.

(U) As a result of these early antenna tests, a team of engineers from RCA Moorestown, the AN/FPS-95 contractor, came to the site in the fall of 1972. They inspected the antenna, ground screen, and RF hardware, had extensive repairs and rework done, and then participated in further tests of the reworked antenna. Rework of the antenna was conducted between Aug. 4 and Sept. 17, 1972. Expansion sections in the RF hardware and the ground screen clips were both found to generate spectral noise during two-tone intermodulation tests; corroded joints were also found by visual inspection. The expansion sections were replaced, steel towers in the antenna field were rewelded to reduce nonlinear RF effects at joints, grounding connections were improved, and the ground screen clips were welded. Coaxial lines to the baluns were modified and grounded, as were certain conduits and fan plates. All loose metal debris in the antenna field was removed.

(U) After the rework, extensive testing of the antenna on both transmission and reception was performed. Transmitting tests were directed toward both linear sources of spectral noise, such as wind vibration, and nonlinear sources, such as arcing and corona. Receiving tests took into account wind vibration also, as well as nonlinear effects, such as rectifying action at joints in the antenna and ground screen.

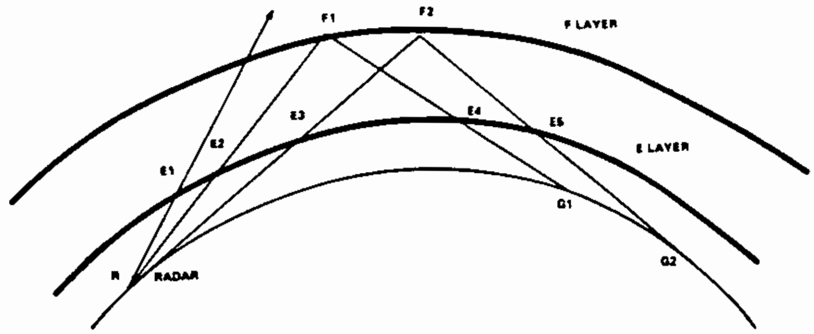

Figure 15. Ray path geometry. (Figure unclassified.)

related noise. One further piece of evidence—the absence of nonlinear effects during the transmitter power reduction Test 19—tended to negate the hypothesis of cross modulation in ancillary equipment.

CONCLUSIONS OF EQUIPMENT TESTING

(U) (S) Numerous tests of the AN/FPS–95 transmitter showed it to have exceptional spectral purity and to be a negligible contributor to the overall level of clutter-related noise. The radar receiver, always a prime suspect as the cause of clutter-related noise, was very thoroughly tested for spectral noise generation. It, too, was exonerated, except when very large out-of-band interferers were present at the receiver input. Since such interferers were rarely present, whereas clutter-related noise was always present when OTH propagation was good, it was concluded that the radar receiver was not the principal cause of clutter-related noise. The radar signal processor was shown through numerous tests to not be a significant source of clutter-related noise. A minority opinion[30] would have it that these tests did not adequately measure the analog-to-digital converter transient response to time-varying clutter.

(U) (S) Some spectral noise generation mechanisms were found in the AN/FPS–95 antenna, ground screen, and RF hardware. After extensive rework of these components by RCA, such noise generation mechanisms were considerably reduced, but still present. Extensive system testing on both transmission and reception showed that the antenna, ground screen, and RF hardware were not the principal cause of clutter-related noise. These components had particularly good spectral purity above 20 MHZ, whereas clutter-related noise on actual ground clutter was just as prevalent as it was at lower radio frequencies. Some tests of the radiating system also included its local environment, particularly the sea. The local environment seemed no significant source of such noise.

(U) (S) Having rather thoroughly exonerated the radar equipment as the limiting source of clutter-related noise, attention turned to factors external to the radar. Both the ionospheric propagation medium and radar reflectors in the target space were considered as sources of clutter-related noise, as discussed in the next section.

THE SEARCH FOR SOURCES OF EXCESS NOISE IN THE EXTERNAL ENVIRONMENT

(U) After an introductory discussion of propagation geometry, this section gives brief descriptions of all the relevant experiments and tests, followed by discussions of postulated causes of noise due to reflection effects and propagation phenomena.

PROPAGATION GEOMETRY

(U) (S) Figure 15 shows an idealized diagram of the propagation ray paths typical of radar operation using the ionosphere F-layer as the reflecting layer (the normal mode of operation). The rays emanating from the radar located at R are shown as being restricted to a range of elevation angles bounded by the lower ray path R–E3 and the upper ray path R–E1. In fact, of course, the actual elevation gain pattern did not have such sharp boundaries. It featured a direction of maximum gain that could be switched between an upper elevation angle of approximately 15 deg and a lower position of typically 5 to 7.5 deg by selecting, respectively, horizontal and vertical polarizations. The measured antenna patterns indicated considerable variations in elevation beam shape as a function of beam number and radar frequency.

each of beams 1, 7, and 12. During and beyond the duration of this test, local weather, solar flux, and the geomagnetic index were recorded to permit the investigation of possible correlation with clutter-related noise. The results of synoptic test data analysis clearly confirmed the persistent existence of the short-range, precursor, and clutter-related noises. They did not, however, reveal any clear correlation between the clutter-related noise and local weather, solar, or geomagnetic parameters.

(U) ~~(S)~~ An interesting effect noted in data recorded between September 1972 and May 1973 is that the ratio of ground clutter to clutter-related noise appeared to vary distinctly as a function of beam azimuth. The relative amount of noise was lowest in beam 1, rose gradually through beam 9, then dropped again until the most southerly beam 13 was reached.[32] The maximum variation (beam 1 to beam 9) was approximately 10 dB.

Land/Sea Test[33]

(U) ~~(S)~~ The object of this test was to investigate the hypothesis that the clutter-related noise was generated, through the modulation and backscattering of radar energy, by objects situated on or near the earth's surface, at ranges normally illuminated by the one-hop OTH radar propagation modes. Because of the importance of this experiment and its results, it is described in greater detail in the appendix at the end of this paper.

(U) ~~(S)~~ The test was arranged to measure the clutter-related noise powers from range–azimuth resolution cells within an area of AN/FPS–95 coverage encompassing both land and sea areas. The greatest variations in clutter-related noise levels were found to occur between adjacent land and sea areas. These results were not inconsistent with the assumption that no clutter-related noise was generated within the resolution cells located over the sea.

Short-Range Noise Test[34]

(U) The primary purpose of this test was to identify the sources of the component of range-related noise observed to occur at short radar ranges (less than approximately 600 nmi). The particular postulated mechanisms investigated were transmit/receive switch transients, transmitter-induced corona, antenna vibration, and meteor effects.

(U) Examination of off-line processed data showed that the switching transient effects were confined to extremely short radar ranges and that they could be ignored at the ranges of the observed short-range noise. Earlier in the AN/FPS–95 testing program, the presence of more serious switching transients had been observed using the on-line signal processor. These were subsequently reduced by an equipment modification. In this connection, it should be noted that the vast majority of data used in the investigations of range-related noise were analyzed by off-line techniques.

(U) Although antenna arcing had previously been observed at lower radar operating frequencies, measurements at 23 MHz, the frequency used for most short-range noise tests, failed to reveal any evidence of the phenomenon.

(U) A measurement made at a frequency of 23 MHz in beam 13 using vertical polarization contained a surface wave clutter signal at a range of 40 nmi. The amplitude of this signal was sufficiently higher than the noise background of the spectrally analyzed data to permit the conclusion that any spectral spreading of the signal (by antenna vibration) would be down by at least 66 dB. This conclusion does not, of course, necessarily exonerate the antenna at other frequencies, beam positions, and polarizations.

(U) ~~(S)~~ The main effort in this test was devoted to an examination of the meteor theory of short-range noise generation. The noise was recorded in beam 1 and beam 13 for each of the two available antenna polarizations (vertical and horizontal). Changing the polarization had the effect of raising the beam from a lower position to a higher position. The radar ranges of the recorded short-range noise were seen to shift in toward the radar when the beam was raised, in accordance with the hypothesis of backscattering occurring within the E-layer. The recorded data were used to calculate the antenna vertical beamshape for subsequent comparison with independent measured patterns. A good correspondence was thus obtained. The above measurements were performed both above and below the maximum usable frequency, at a frequency of 23 MHz, by choosing the appropriate diurnal time. Some of the measurements, when operation was below the maximum usable frequency, were made at a low pulse repetition rate

F-layer contained clutter-related noise and that via sporadic-E did not, then the F-layer as a possible unique cause of clutter-related noise could be inferred; if the signals that propagated via sporadic-E only had clutter-related noise and the F-layer-only signals did not, then the F-layer would be absolved and sporadic-E implicated, and so on. Because sporadic-E layers were not in evidence during the time interval within which the Scientific Assessment Committee's investigation was conducted (February and March 1973), use was made of data recorded in June 1972 in connection with Design Verification System Testing (DVST) Experiment 202, when sporadic-E was a frequent occurrence.

(U)(S) Analysis of the data showed clutter-related noise to be present in the spectra of signal sequences that propagated over two-way sporadic-E propagation paths and in the spectra of signals that propagated simultaneously over two-way F-layer paths. The characters of the noise and the clutter-to-noise ratios were roughly the same in the two cases.

Transmitter Power Reduction Test (25)

(U) (S-NF) Objective of the Transmitter Power Reduction Test which is relevant here was to determine whether the high power radiated by the transmitter was heating, and thus modifying, the ionosphere so as to cause the observed clutter-related noise.

(U) (S-NF) The test was done by members of the on-site staff on June 3, 1972 with the radar in its normal operating configuration, transmitting in beam 7 on horizontal polarization at a frequency of 17.4 MHZ. All six transmitters were used. The transmitter power was reduced in steps of 3, 6, 12, and 18 dB, each step being maintained for one minute, and all measurements were taken within about 5 min. In the data processing, range bins 80 nmi in range extent were formed, and the returns in each was coherently integrated for 6.4 sec. Further processing then yielded average noise power in all Doppler bins from PRF/8 to PRF/2 and the average clutter power in the first eight Doppler bins around the carrier frequency. These averages were computed for each range bin during each integration interval.

(U) (S-NF) The result relevant here is the behavior of average clutter power and average noise power in a range bin set near the peak of the ground backscatter. Here the clutter power and noise power decreased together as transmitter power was decreased, but clutter and noise were only 10 to 12 dB down for the transmitter power reduction of 18 dB. (The experimenter conjectured that poor calibration of the power reduction switch could have caused the discrepancy.) There was no *sharp* reduction in noise power at any point during transmitter power reduction. Both clutter power and noise power decreased smoothly and proportionately with transmitter power reduction.

REFLECTION EFFECTS

(U) (S-NF) Postulated causes of range-related noise which attribute the phenomenon to equipment, local environment, or propagation effects generally include the assumption of the earth-surface reflection as an element of the relevant two-way radar propagation paths. This reflection is regarded as that of a fixed reflector, however, which does not therefore alter the spectral composition of the reflected energy from that of the incident energy. The spectral broadening that accounts for the clutter-related noise is assumed to occur elsewhere. In contrast, this section discusses postulated causes of range-related noise in which the spectral broadening of radiation, which is reflected back to the radar receiver from distant locations, occurs at the actual point of reflection. This reflection point may be in the normal ground-clutter reflection area or at some totally different location.

(U) (S-NF) As described previously and as seen in Fig. 16, the range-related noise was observed mainly in three well-defined regions of radar range, that is, a "short-range" region extending out to approximately 600 nmi, a "precursor" region in front of the ground-clutter return, and a region coincident with the ground-clutter return. This latter noise is named "clutter-related noise," and it is the one of highest importance in its effect on the observation of most aircraft, since it is at the ranges of the ground clutter that the lower atmosphere is illuminated and, consequently, where the aircraft echoes are to be found. The other regions are also of some interest, however, since their noise may obscure the OTH observations of high-altitude targets such as ballistic missiles, as well as those of target echoes generated via multi-hop ambiguous-range propagation modes. Yet

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highly unlikely that the meteor effects would exhibit abrupt differences in their reflection capabilities as a function of their geographical positions within the AN/FPS–95 coverage.

(U) (S) To summarize, it appears that the clutter-related noise is a different phenomenon from the close-in and precursor range-related noise, both of which appear to be caused by reflections of radar energy from meteor-induced ionization within the E layer.

Auroral Effects

(U) The term "auroral" is a very loose description of the postulated causes of clutter-related noise considered under this heading. Such causes include all those which may be attributed to radar reflections from ionospheric irregularities, whether magnetic-field-aligned or otherwise. It happens that most of such well-known effects occur in the high latitudes and are somewhat loosely correlated in position with visible aurora.

(U) (S) The radio aurora effects are known to produce radar reflections over a wide radio-frequency range, including the HF band. Furthermore, these reflections exhibit Doppler frequency shifts and spreading on the order of the observed clutter-related noise spectral widths. Over-the-horizon measurements in the Arctic have shown this "diffuse spectrum clutter" as a severe limitation to the detection of aircraft.(11) Also, the ranges from the AN/FPS–95 to the zone of maximum auroral activity were such as to place the radar ranges of the auroral reflections within the AN/FPS–95 coverage.

(U) (S) Much information was gathered throughout the operational life of the AN/FPS–95 on the radar returns from radio aurora.(12) In addition, more of these data were specifically gathered as part of the synoptic data collection during the investigation of clutter-related noise. These data clearly distinguished auroral effects from those of clutter-related noise in a number of particulars. First, the auroral returns, while occasionally coinciding in range with those of ground clutter, were generally to be found at ranges and with statistical frequencies that varied considerably, depending upon the time of observation, season, magnetic activity, operating frequency, and azimuth. Second, the spectra of the auroral backscatter were generally highly asymmetrical. And third, the amplitudes of the returns were found to depend strongly upon the radar frequency, being 10 to 30 dB higher at 8 MHz than at 10 MHz.

(U) (S) These observed characteristics of radio aurora reflections contrast strongly with characteristics of clutter-related noise, which include gradual variations in level as a function of beam azimuth and radar frequency, symmetrical spectra, and a close correlation in range with that of the ground clutter.

Aircraft Returns

(U) (S) Among the less plausible suggested causes of clutter-related noise was the possibility that the reflections from a large number of aircraft, entering the radar receiver through the antenna sidelobes, could be the source. It would be ironic indeed if the AN/FPS–95 failed to see aircraft because it was seeing too many aircraft! Quantitative calculations to examine this postulated phenomenon have not been performed, largely because of a lack of data concerning the numbers, velocities, and dispositions of aircraft about the radar. It does, however, seem extremely unlikely that within a given range cell, even within a large azimuth sector, there would have been sufficient aircraft to occupy all the Doppler cells (typically several hundred) and, thus, have given the appearance of broadband noise. Even if this had been the case, then the relatively small number of aircraft within the antenna mainlobe should have been separately resolvable in Doppler frequency and would, on account of the large two-way gain differential relative to the sidelobes, have been easily discerned above the clutter-related noise background. One would also have expected to see marked diurnal changes in the noise due to the reduction in air activity at night.

Earth-Surface Effects

(U) (S) While there are virtually no objects on the earth or sea surface which have translatory velocities comparable with those of aircraft and which might therefore produce Doppler-shifted radar reflections to interfere with OTH aircraft detection, there are nevertheless many objects, particularly man-made, that move, vibrate, or rotate in such a manner as to modulate an incident radio wave, either in phase or amplitude, so as to generate sidebands in the reflected power. These sidebands could, if removed sufficiently in fre-

TABLE 8. *Propagation medium effects.* (*Table unclassified.*)

Postulated Cause \ Observation	One-Way OTH Path Tests	Sporadic E/F-Layer Comparison	Transmitter Power Reduction Test	Aurora Measurements	Land/Sea Comparison
F-Layer Vertical Motion and Waves	√				√
E-Layer and Sporadic-E Vertical Motion and Waves		√			√
Ionospheric Modification and Heating	√		√		√
Meteor-Induced Power Flow Modulation	√				√
Aurora-Induced Power Flow Modulation	√			√	√

was therefore suggested that the radar energy arriving back at the receiver, after many such reflections from multihop propagation modes, might be a cause of clutter-related noise.

(U) (S) One reason that this would seem to be unlikely is that such multihop returns would not generally coincide in range with that of the observed clutter-related noise, which is always approximately coincident with the ground clutter. Another reason concerns the fact that the observed single-hop Doppler shift due to rising or falling ionospheric layers is usually less than 1 Hz. Since the amplitudes of the returns from successively higher orders of hop would generally be attenuated, one would expect the corresponding spectrum to fall off sharply with frequency. It would also be rare to encounter the particular mix of rising and falling layers necessary to account for a symmetrical spectrum. From this reasoning, it appears unlikely that multihop effects could explain clutter-related noise: This conclusion is strengthened by the low PRF observations performed during the short-range noise experiment,[34] wherein clutter-related noise was observed during radar operation at a PRF of 10 Hz.

PROPAGATION MEDIUM EFFECTS

(U) The spectra of high-frequency radar signals could be corrupted by a number of mechanisms in passing from the radar antenna over the horizon to the earth's surface. It is the dual purpose of this section first to list the various phenomena that have been postulated as possible mechanisms for such spectral corruption and then to review the evidence for and against each case as the cause of observed clutter-related noise. Here we consider only *transmission* effects; *reflection* effects are dealt with in the preceding section.

(U) (S) The matrix of Table 8 lists at the left specific phenomena that have been put forward as possible causes in the transmission medium for clutter-related noise. Across the top are the names of various experiments that were performed to confirm or deny one or more of the causes. Check marks signify which experiments relate to the various postulated causes. The method here will be to consider each phenomenon in turn and to review for each the relevant experimental evidence that was generated in the attempts to find and eliminate the cause of the noise.

F-Layer Vertical Motion and Waves

(U) (S-NF) The experiments which bear on the F-layer of the ionosphere as the unique cause of clutter-related noise are the One-Way Path Tests,[35,36] the Sporadic E-Layer/F-Layer Experiment,[37] and reception of the AN/FPS–95 signal in the Eastern Mediterranean, we looked for meteor-belt-induced forward scatter by slewing the range gate ahead of and behind the main received radar pulse. Results were inconclusive, perhaps because of a lack of adequate isolation of the gate. But the spectrum of the received direct signal was not measurably corrupted in any way. As before, the Land/Sea Test results imply that the cause of clutter-related noise is not in the transmission medium.

Aurora Power Flow-Modulation

(U) ~~(S)~~ The question here is whether the cause of the observed clutter-related noise could be a modulation of the signal resulting from interaction with aurora as the signal passed through the propagation medium.

(U) ~~(S)~~ To cause spread-frequency noise (that is, noise resembling clutter-related noise) to be present in range intervals containing returns reflected from the earth's surface, either the main signal would have to be corrupted in passing through aurora-disturbed regions or the corruption would have to be impressed upon non-main-path signal components (that is, transmissions of the signal over paths containing aurora in the antenna sidelobe direction, and so on) that arrived back at the radar receiver at times corresponding to those of the arrival of the main-path clutter returns. For the former—corruption of the main signal by passage through auroral regions—transmission would have to be along certain beams, namely, the more northerly beams, and at times when aurora was present. One would then expect the clutter-related noise to occur in northerly beams only when aurora was present. But clutter-related noise was present with clutter returns from northerly beams whether aurora was present or not.[12] In fact, clutter-related noise was observed in returns via all beams, including southerly beams, whether aurora was present in the north or not. In regard to the conjecture that aurora-induced noise entered through the sidelobes of the antenna, studies[12] that analyzed the return in each beam as a function of time, range, and magnetic activity made it possible to distinguish and categorize auroral clutter. The studies also found, at times and for some beams, that auroral clutter could increase the noise level in the range bins containing ground clutter, but that *mostly* it would not.[12]

FEASIBILITY OF ELECTRONIC COUNTER MEASURES AS THE SOURCE OF EXCESS NOISE

(U) ~~(S)~~ In the absence of any convincing conventional explanation for the clutter-related noise, some speculated that the noise could have been generated deliberately. After all, the AN/FPS–95 was engaged in a surveillance of the Soviet Union and the Soviet-Bloc countries, a function that could have been deeply resented. Perhaps this resentment provoked countermeasures to reduce the radar's effectiveness and ultimately remove it from the scene. Admittedly, the notion seems "far fetched"; however, it is not easily disposed of and remains a possible explanation for the noise. In this section, we explore this possibility and describe how it could have been done.

(U) ~~(S)~~ If countermeasures were employed, they were not of the conventional jamming type, because jamming in the ordinary sense would have been observed by the site personnel. Furthermore, such jamming would have both violated international agreements and incurred severe criticism. But a jamming technique not easily recognized as jamming might be a distinct possibility. Granted that the notion of "covert jamming" seems even more ridiculous, it is, however, not without precedent. There is a technique referred to by some as "Villard's Disclosure" that provides a basis for covert jamming in OTH systems.* Over-the-horizon radars generally have large transmitting antennas and high-power transmitters, which combine to produce large power densities in the target coverage area. The actual return from the targets of interest is quite small compared with the incoming radiation and its scattered components from ground clutter. These target returns are detectable at the radar because OTH radar has a large receiving aperture; in the target coverage area, however, the target returns tend to be masked or covered by the large incoming and ground-scattered signals. In other locations, it is also difficult to discern the signals reflected from the target because of the large clutter return that covers the signal. These clutter returns are also present at the radar, but are removed by compli-

*(U) Probably because the technique was disclosed by O. G. Villard, Jr., many years ago, but the authors do not have a reference to support this conjecture.

$$\sigma = 100 \text{ m}^2,$$
$$L = 10 \text{ dB, and}$$
$$l = 10 \text{ dB},$$

then $\overline{p}=2.78\times10^{-4}$ watts/resolution cell.

(U) (S) Since the shortest pulse used on the AN/FPS–95 was 250 μsec long, corresponding to 20 nmi in range, each jammer must fill no more than five range cells. Since trailing cells require less power than the first cell, the power requirement due to range cells is less than five times the power requirement for the first cell. The highest PRF of the AN/FPS–95 was 160 HZ, and with 10 sec of integration, there are no more than 1,600 Doppler resolution cells. Consequently, there are less than 8,000 resolution cells in total, and the worst-case jammer at 500 nmi would require less than 2.22 watts. A site at 2,000 nmi would require 1/256 of this power. In either case, the jammer power requirements are quite small.

(U) (S) We are forced to conclude that the jamming technique is quite feasible, and it is not clear that the experiments conducted at the AN/FPS–95 would have discovered the jamming had it occurred. If experiments confirming or denying the possibility had been conducted, they would have perhaps resolved the issue. They were not conducted.

SUMMARY AND CONCLUSIONS

(U) (S) The AN/FPS–95 OTH radar built by the U.S. Air Force on the North Sea Coast of England in the late 1960's was plagued by noise that severely limited subclutter visibility and, thus, seriously impaired the detection performance of the radar. All-out attempts to locate and correct the source of the noise in the relatively brief time allotted in late 1972 and early 1973 were unsuccessful: The source was not found. Subsequently, the program was terminated abruptly on June 30, 1973, after which the radar was dismantled and its components removed from the site.

(U) (S) A host of tests were performed on the radar equipment to see if it contained the source of the noise. In the end, the equipment was exonerated; furnished by RCA Corp., Moorestown, N.J., it was generally of high quality and was judged as almost certainly *not* the source of the clutter-related noise.

(U) (S) Tests on the environment external to the radar seem to eliminate as causes of the noise all effects except what we have called earth-reflection effects. While the results of the Land/Sea Test, which explored the earth-reflection effects, are generally consistent with the hypothesis that clutter-related noise is present in returns from land surfaces and not present in returns from sea surfaces, the evidence is too limited, both in time and in regions examined, to be considered conclusive.

(U) (S) As this paper suggests, a few inexpensive, simple, repeater-type jammers with a few watts of power output each, distributed over the radar coverage zone, conceivably could have produced effects like those identified in the paper as clutter-related noise. No tests performed at the radar either confirm or deny the hypothesis that jamming caused the clutter-related noise.

(U) (S) The strange legacy of the AN/FPS–95 is the enigma surrounding the clutter-related noise. In all the time since the program terminated, the radar community—even including some OTH radar specialists—does not seem to have assimilated either the nature of the difficulty that beset the AN/FPS–95 or the details of the program that was mounted to try to find the cause. There seems to be a feeling that the Cobra Mist experience was anomalous and that the affliction will not recur. The authors would caution against such a view.

(U) (S-NF) The AN/FPS–95 experience may indicate that natural effects of some kind limit the subclutter visibility achievable in high-frequency OTH radars to about 60 to 70 dB. The AN/FPS–95 was the first OTH radar with enough power routinely to generate clutter returns 80 to 90 dB above external CCIR noise levels. Therefore, it is perhaps the first OTH radar to be afflicted routinely with clutter-related noise. But not the only one: During the Cobra Mist tests in 1973, members of the Scientific Assessment Committee visited another OTH radar site, bringing back data records that clearly showed noise resembling clutter-related noise in range bins containing ground-clutter returns.[7] So, at least in 1973, clutter-related noise was observed at another OTH radar.

(U) (S) If the cause of clutter-related noise is an area effect—and some believe that it is—it can be overcome in design by giving an OTH radar adequate spatial resolution, so that the returns from

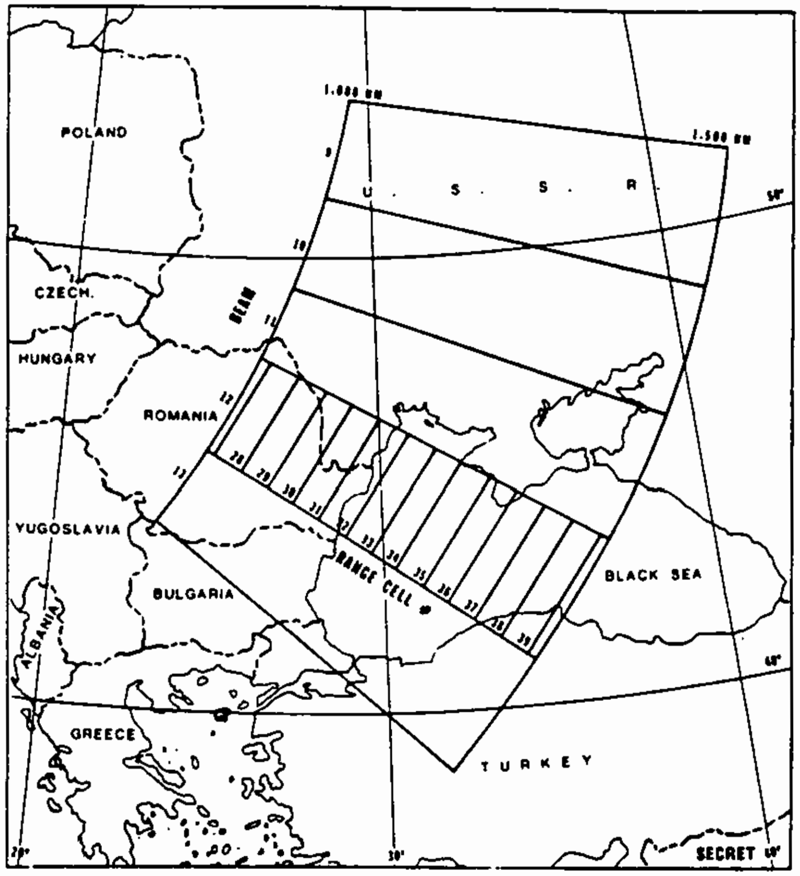

Figure 17. The geographical coverage chosen for the Land/Sea Test. (Figure classified Secret.) (U)

The beam positions on Fig. 17 correspond to the nominal azimuth directions of the AN/FPS–95 antenna structure. The radial lines indicate the nominal one-way half-power bearings of each beam. Measurements of the actual antenna patterns[45] revealed that the beam positions squinted inward, so that the high-number beams were actually pointing several degrees north of their nominal positions. This fact is important in the interpretation of the experimental data. The range-resolution cells drawn in beam 12 are each 40 nmi long. Reference to these cells is by the numbers indicated in the figure.

Operating Parameters and Procedures

(U) During data gathering, the AN/FPS–95 was operated using the following parameters:

Frequency: Variable
Pulse length: 500 μsec
Pulse shape: Cosine-squared
PRF: 40 pulses/sec
Antenna polarization: Horizontal
Beam numbers: 13, 12, 11, 10, and 9

(U) For each run, the data were recorded first in beam 13 for 2 min. Beam 12 was then similarly treated, and so on down to beam 9. The 10 min of data thus recorded on magnetic tape were all taken using a single radar frequency. Subsequent 10-min runs would not necessarily be at the same frequency. Over the course of the experiment, approximately 8 hr of data were recorded and analyzed.

Data Analysis

(U) (S) A full description of the signal and data analysis is beyond the scope of this paper, and the interested reader is referred to Ref. 33. Briefly, however, for each range cell the 2-min sequence of signal returns was divided into batches of 3.2-sec duration (128 samples) and submitted to an off-line spectral analysis. This permitted the ground- or sea-clutter returns, which are located in the vicinity of zero Doppler shift, to be separated from the clutter-related noise. Measurement of total clutter power was made in a Doppler band extending from +5 Hz to −5 Hz. Clutter-related thereby increasing the amount of clutter-related noise received in that beam. A numerical integration of the two-way antenna pattern for various assumed beam skews shows the following results for the expected ratios of clutter-related noise in beam 11 to that in beam 12 at the ranges of range cells 33 and 34.

Assumed Northerly Skew (deg)	*CRN Ratio*
0	28:1
3	7:1
5	2:1

(U) ~~(S)~~ These clutter-related noise ratios are seen to be not inconsistent with the ratios of 87:13 and 82:18 from Table 9, assuming existing beam skews of approximately 3 to 4 deg, which is within the range of the measured beam skews.

(U) ~~(S)~~ From the preceding arguments, it appears that the experimental measurements of clutter-related noise are fully consistent with the hypothesis that little, if any, clutter-related noise is returned from resolution cells corresponding to sea areas when compared with clutter-related noise returned from land cells. As Table 9 shows, the clutter-related noise variation between either adjacent pairs of land cells or an adjacent sea cell pair is generally much smaller than that observed at land/sea boundaries. The data in Table 10 for clutter returns are particularly interesting when compared with the clutter-related noise data in Table 9, for they show that at the land/sea boundaries, and unlike the clutter-related noise behavior, the clutter levels do not change appreciably. These facts do not support theories of clutter-related noise generation that propose that the radar energy is modulated during propagation to form clutter-related noise either before or after being scattered back from the land or sea surface. If such were the case, there would be little difference between the clutter-related noise returned from the land areas and that from adjacent sea areas.

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