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NRL MEMORANDUM REPORT No. 144

QUANTITATIVE MEASUREMENTS OF RADAR ECHOES FROM AIRCRAFT
X. THREE F-86 AIRCRAFT IN FORMATION

W. S. Ament
F. C. MacDonald
H. J. Passerini

RADIO DIVISION I

6 April 1953

NAVAL RESEARCH LABORATORY, WASHINGTON, D.C.

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QUANTITATIVE MEASUREMENTS OF RADAR ECHOES
FROM AIRCRAFT.
X. Three F-86 Aircraft in Formation,

9 memorandum rept.,

10

By

W. S. Ament,
F. C. MacDonald
H. J. Passerini

11 6 April 1953 12 44p.

Wave ~~Propagation Research~~ Branch
~~Radio Division I~~
Naval Research Laboratory
Washington 25, D. C. (251950)

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ABSTRACT

Echo amplitudes from a formation of three F-86 airplanes are nearly Rayleigh distributed for X, S, and L bands.

Averaged over all observed aspects, the median radar areas of the formation are 10, 48, and 9 square meters for 1250, 2810, and 9380 Mc/s respectively. The difference between the L- and S-band values is considered to be beyond the limits of experimental error, but no explanation has been found for this large difference. The X-band value is not considered reliable enough to be used in a frequency trend.

Comparison of the average radar area of the formation with that of a single F-86 (Report VI) shows that the formation average is larger by 2.5 db, 5.4 db, and 3.6 db, on L, S, and X bands, respectively. This comparison was made between the radar areas averaged over 5° azimuth intervals, using only those azimuth intervals for which data were available both for the formation and for a single F-86. Theoretically, the average radar area from three identical randomly moving targets should be three times (or 4.8 db) greater than the average radar area of a single one of the targets.

The aspect diagrams show a relatively wide peak at broadside, and echoes from the leading edge of the wing are prominent near 35° azimuth.

Spectrums of the formation echo were obtained near nose and broadside aspects and toward the tail. In general, the fluctuation frequencies are higher for the higher radar frequencies. The higher fluctuation

frequencies are believed due to the variations of the planes about their mean position in the formation.

PROBLEM STATUS

This is an interim report on the problem; work continues.

AUTHORIZATION

NRL Problem R11-17

Introduction

In nine previous reports[(1),(2)...(9)] some results were given of the measurements of radar echo characteristics of aircraft made by the Naval Research Laboratory for the Department of the Air Force. This, the tenth of the series, gives the results for a flight of three F-86's in Vee formation, the planes being separated by 50 to 100 feet.

Because the pulse length ($0.36\,\mu s = 175$ ft.) on X band (9380 Mc/s) is of the same order of magnitude as the size of the formation, the X-band radar measured a somewhat different phenomenon than did the L-and S-band radars with $5\,\mu$ sec. pulses.

A further difficulty arises in the analysis of the X-band data because the pulse length of the returning echo changes as the formation presents different aspects to the radar. Any changes in the spacing of the airplanes would also produce the same type of result. Normally this widening of the echo pulse would produce no error in the measurement of peak pulse amplitude, but, as described in Report V, the X-band video pass band was too narrow, and hence any widening of the pulse would increase the deflections presented on the oscilloscope. Further, the method for obtaining valid X-band results depends upon the assumption of a constant echo pulse length. That this assumption was not always true in the case of the F-86 formation was clearly evident from the film records.

The oscilloscope photography (Report I) did not permit an exact determination of the length or shape of the returning echo. One can, however, form a qualitative picture of the pulse shape and length by regarding the darkness of the photograph of the oscilloscope trace as an indication of how long the oscilloscope beam had a given deflection. The photographed X-band traces were dark usually at two or more distinct deflections, showing that the echoes from the three F-86's were partially resolved. The X-band target resolution was specially marked at broadside aspects, where the formation was viewed along its longest dimension. (Owing to the long S- and L-band radar pulses, the formation's echo appeared on the S- and L-band photographs as the echo from a point target of fluctuating radar area.)

Since the X-band echo entered the X-band video channel as a pulse of varying width and shape, the pass band of the video (a function of pulse amplitude in the pulse-to-pulse circuitry) caused an oscilloscope deflection for which no peak echo power could be assigned, becuase of the varying correction due to pulse length. The X-band radar areas quoted in this report have been obtained by applying the correction procedure of Report V to the <u>weaker</u> echoes, where pulse-to-pulse records were most reliable. Even so, the X-band average areas must be used with caution, owing to the generally extended video pulse, the partial resolution in the r.f., and the necessary emphasis on weak X-band echoes in the analysis.

In obtaining echo fluctuation rates, it is necessary to sample the echoes in regions where the general echo level is considerably above the noise level, and consequently, where the stronger echoes at X band are irregularly limited in the pulse-to-pulse circuits. Thus the X-band fluctuation information cannot be regarded as quantitative. Dominant fluctuation frequencies in the X-band voltage-vs.-time plots and spectrums provide fair qualititative information, owing to the fact that oscilloscope deflection has definite correlation with the peak amplitude of the complex echo that enters the video stages.

Amplitude Distributions

The amplitude distributions plotted in Figs. 2-8 are representative ten-second (1200-pulse) samples of the available airplane aspects (defined in Fig. 1). In these figures, cumulative distributions of echo pulse amplitudes are plotted, the ordinate being $10 \log_{10} \sigma$ (σ = radar area in square meters), the abscissa being the percent of time the amplitude of the observed echo exceeds the ordinate. For comparison, straight lines are drawn which correspond to the theoretical cumulative distribution (Rayleigh distribution) of noise powers.

Except near broadside aspect, the L- and S-band distributions follow the Rayleigh distribution with an accuracy sufficient for many purposes. The deviations of the X-band distributions from Rayleigh appear to be no different than those of L and S band, but this may be due to the fact that only the lower signal levels were used, as previously stated.

Aspect Dependence

Each of Figs. 9 - 14 covers one flight of the aircraft and consists of four graphs. The uppermost graph of each figure consists of a plot of the aircraft's aspect, as defined in Fig. 1, versus range, in thousands of yards. The remaining three graphs (one for each of the three frequencies employed) of each figure consist of plots of radar area, expressed in decibels above one square meter, versus range in thousands of yards. Each graph consists of three sets of points, each being connected by straight line segments. Each point represents one second of data, and data taken simultaneously are aligned vertically so that the uppermost point is the maximum, the middle point is the median, and the lowest point is the minimum radar area occurring during that second. The radar area as plotted contains variations due to interference lobes caused by ground reflections. At the center of each lobe or integral number of lobes is a circled X (⊗) indicating the median value (reduced to "free-space" value in accordance with the procedure described in the appendix to reference 2), of the median radar area values for that lobe or integral number of lobes, and these median values were used in determining the median value of σ for each five degrees of azimuth as described below.

The data were divided into intervals, each of which spanned five degrees of azimuth. For each such interval the median of the median set of points was determined for each frequency. These "median median" values are plotted in Fig. 15.

The listed azimuths are 10° less than those computed from the headings assigned to the planes for each run. The large echo from the leading edge of the wing occurred near an original azimuth of 45° instead of 38°, suggesting that the planes flew magnetic instead of true headings. The 10° correction also moves the large echo near broadside near to 90° azimuth instead of an original 100° azimuth.

The aspect dependence is similar in general to the aspect dependence observed for the single F-86 (Report VI) in that the "average" radar area is relatively constant except for a very broad region near broadside aspect. This 'broad region' is slightly broader for the formation than for the single F-86. The region over which echoes arise from the leading edge of the wing is similarly broadened, owing to the fact that the sharp leading edge echo occurs at slightly different times for different aircraft in the formation.

Frequency Dependence

To obtain representative measures of the radar area of the three F-86's in formation, the following procedure was carried out for each frequency employed. From Fig. 15 a single number for radar area was obtained for each five degree azimuth interval by averaging all numbers (in square meters) in that azimuth interval, without regard to the elevation angles involved. The results are plotted in Fig. 16.

One estimate was obtained by averaging the median radar area over the azimuth intervals (23 in number) common to all three frequencies. This estimate included the intervals from 65° to 110° in which some of the X-band values are only lower bounds but were treated just like the other entries.

	L	S	X
Square meters	10.3	49.7	>6.0
$10 \log_{10}$ (σ in sq. meters)	10.1	17.0	>7.8

When the azimuth intervals from 65° to 110° are excluded from the above, the following averages are obtained:

	L	S	X
Square meters	3.6	11.3	2.0
$10 \log_{10}$ (σ in sq. meters)	5.6	10.5	3.0

Another average is obtained by averaging the entries in Fig. 16, as computed without using the X-band "lower-bound entries" in Fig. 15. This gives the following averages.

	L	S	X
Square meters	10.3	49.7	9.2
10 $\log_{10}$ (σ in sq. meters)	10.1	17.0	9.7

This table and the preceding one give the best estimates of the dependence on radar frequency of the echo from the flight of three F-86's. The difference between L and S bands is considered significant while the X-band value is not reliable enough to be used to determine the trend with radar frequency.

The best estimate of the magnitude of the radar area should average all the entries in Fig. 16 and this gives values only slightly different from those in the first table above.

	L	S	X
Square meters	9.6	47.9	>6.0 (9.2)
10 $\log_{10}$ (σ in sq. meters)	9.8	16.8	>7.8 (9.7)

The X-band entry in parenthesis is the value obtained when the lower-bound entries in Fig. 15 are not used.

In the foregoing tables, the average area of the formation is about 7 db greater at S band than at L band. This difference seems too large to have arisen from systematic experimental error. The theoretical anticipation is that, for irregular objects large compared with the wavelength, the average radar area should be roughly independent of wavelength. This frequency-independence was found for the B-45 (Report VIII), where the averages were taken over about twice the amount of experimental data that was available for the present report. For the <u>single</u> F-86 (Report VI), the S-band average exceeded the L-band by about 2.5 db, an amount too small to call for explanation. Theoretically, the average radar area of three identical, somewhat randomly-moving targets should be three times (or 4.8 db) greater than the average radar area of a single one of the targets. Thus, the average radar areas of the present formation should be 4.8 db greater than the corresponding areas of a single F-86. Checking this prediction by comparison with the data of Report VI, one finds:

	L	S	X
Ratio of formation to single F-86	1.77 (2.5 db)	3.5 (5.4 db)	2.3 (3.6 db)

The S-band behavior of the average area lies closest to the theoretical expectation, a fact supporting the relative reliability of the present S-band data. The X-band averages are unreliable, as previously discussed. No explanation has been found for the large difference between S- and L-band areas.

<u>Fluctuations</u>

Spectrums of selected 5-second samples of the formation's echoes were prepared according to the procedure described in Report VII. The necessary plots of video voltage vs. time are shown in Figs. 20-22 respectively. The same spectrums are presented in Figs. 23-25 on an expanded frequency scale. For the latter Figures, the procedure described in Report IX was utilized in order to present more accurately the low-frequency echo fluctuation components.

As discussed in Report VIII, fluctuations from a single jet aircraft arise from the relative motions in the direction of the radar of echoing portions of the aircraft, in addition to the relatively slow change in radar area of individual portions of the aircraft, plus frequencies due to differing radial velocities among the aircraft in the formation. Radial velocity differences arise from two primary causes, the rate of change of azimuth of the formation as a whole, and relative motion of the individual aircraft in the formation. If the aircraft in the formation are considered to be connected by rigid, reflectionless bars, then relative radial velocities will be proportional to the rate of change of azimuth of the formation as a whole, the resulting radar fluctuation rates being calculable through the theory of Report VIII, pp 9 - 14. The second source of relative radial velocities lies in the jockeying of the individual aircraft about their mean positions in the formation.

In the spectrums presented here, the largest azimuthal rate is 4/5 degree per second, obtaining for the broadside spectrums. Assuming 100 feet as a representative dimension of the formation, one finds, according to the theory of Report VIII, that the highest resulting fluctuation frequency arising from a "rigid" formation should be about 30 cps at X band, the fluctuation frequencies at S and L bands being lower in proportion to radar frequency.

If the maximum relative motion of the aircraft, due to jockeying of each about its mean position in the formation, is F feet per second, the resulting maximum X-band fluctuation rate is about 20 F cps. Guessing that a reasonable value of F is about 5 feet per second, X-band fluctuation rates of 100 cps might arise. With the 120 cps radar pulse frequency, some of the X-band spectrums might possibly contain components arising from the beating between echo fluctuation rates and the p-r-f. (This phenomenon is especially marked with propeller planes, and is discussed in Report IX.)

From the foregoing discussion, one concludes that jockeying within the formation is the probable cause of the higher frequencies present in the spectrums, and that the influence of the p-r-f in the spectrums is negligible, except possibly at X band.

If the planes weave back and forth in the formation, the resulting radial rates vary, and the corresponding fluctuation rates vary correspondingly. This effect is well exemplified in the "tailward" voltage-vs.-time plots of Fig. 19., where a clear, dominant frequency is found first to decrease and then to increase with time on all three records. In any half-second interval the apparent fluctuation frequency is directly proportional to the radar frequency, in accord with the theory. On the corresponding spectrums of Fig. 22, there is strong scintillation, showing that the spectral component is strong in one part of the analyzed 5-second sample, and weak in the remainder. (This scintillation is discussed in Report VII).

The theory is also borne out in the "head-on" spectrums of Fig. 23, where the bulk of the spectrum is displaced to higher fluctuation frequencies in proportion to the radar frequency. There seems to be no clearly identifiable correlation of the fine structure on the various spectrums.

Conclusions

Echo amplitudes from a formation of three F-86 airplanes are nearly Rayleigh distributed for X, S, and L bands.

Averaged over all observed aspects, the median radar areas of the formation are 10, 48, and 9 square meters for 1250, 2810, and 9380 Mc/s respectively. The difference between L and S bands is considered to be beyond the limits of experimental error, but no explanation has been found for this large difference. The X-band value is not considered reliable enough to be used in a frequency trend.

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Spectrums of the formation echo were obtained near nose and broadside aspects and toward the tail. In general the fluctuation frequencies are higher for the higher radar frequencies. The higher fluctuation frequencies are believed due to the variations of the planes about their mean position in the formation.

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References

1) "Quantitative Measurements of Radar Echoes from Aircraft, I. B-36, B-45, F-51, and F-86," NRL Letter Report, Serial C-3460-73A/50 dated 24 October 1950.

2) "Quantitative Measurements of Radar Echoes from Aircraft, II. Formation of Three F-86's, B-29, F-80 with wing tanks, and F-80 without wing tanks", NRL Letter Report, Serial C-3460- 18A/51 dtd 12 February 1951.

3) "Quantitative Measurements of Radar Echoes from Aircraft, III. B-36 Amplitude Distributions and Aspect Dependence," NRL Letter Report, Serial C-3460-94A/51 dtd 19 June 1951.

4) "Quantitative Measurements of Radar Echoes from Aircraft, IV. F-86 Amplitude Distributions and Aspect Dependence," NRL Letter Report, Serial C-3460-138A/51 dtd 5 September 1951.

5) "Quantitative Measurements of Radar Echoes from Aircraft, V. Correction of X-band Values," NRL Letter Report, Serial C-3460-132A/52 dtd 24 October 1952.

6) "Quantitative Measurements of Radar Echoes from Aircraft, VI. Corrected F-86 Amplitude Distributions and Aspect Dependence," NRL Letter Report, Serial C-3460-143A/52 dtd 15 December 1952.

7) "Quantitative Measurements of Radar Echoes from Aircraft, VII, B-36 and F-86 Spectrums, "NRL Memorandum Report No. 107. dtd 15 January 1953.

8) "Quantitative Measurements of Radar Echoes from Aircraft, VIII. B-45" NRL Memorandum Report No. 116 dated 28 January 1953.

9) "Quantitative Measurements Radar Echoes from Aircraft, IX F-51" NRL Memorandum Report No. 127 dtd. 4 March 1953.

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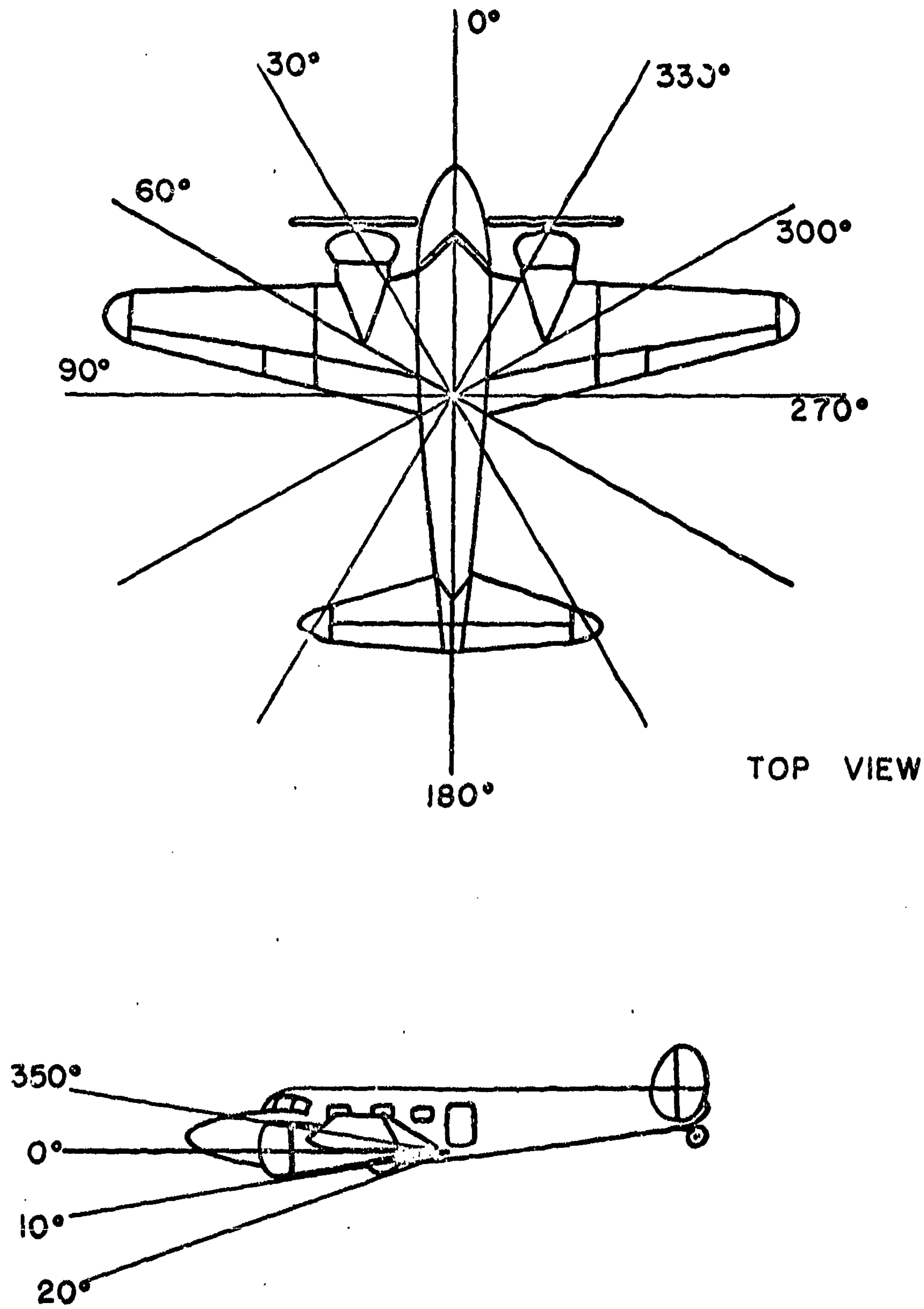

Definition of aspect angles

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Figure 1

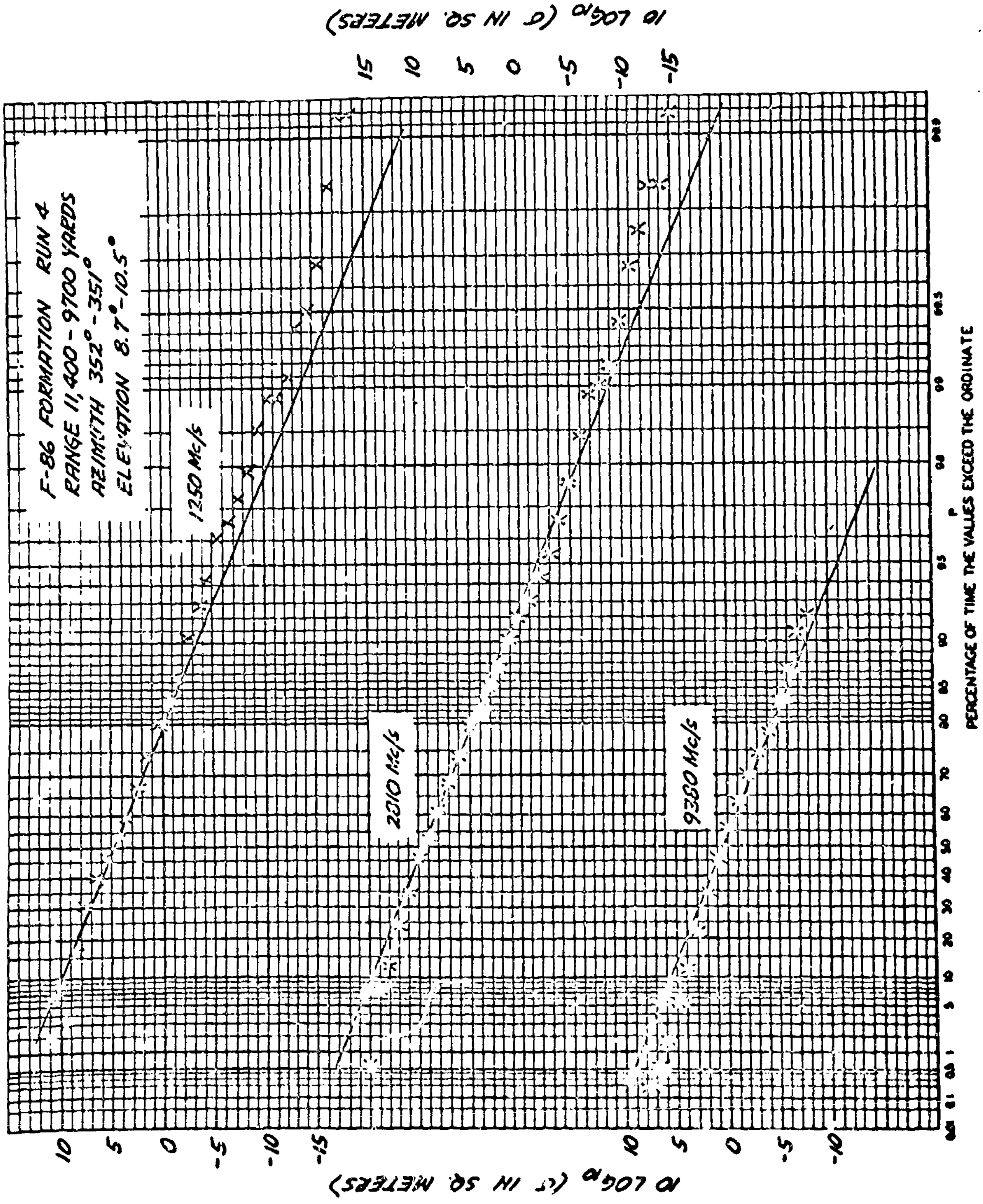

F-86 FORMATION RUN 4
RANGE 11,400 - 9700 YARDS
AZIMUTH 352° - 351°
ELEVATION 8.7° - 10.5°
1250 Mc/s
2310 Mc/s
9380 Mc/s
10 LOG10 (σ IN SQ. METERS)
PERCENTAGE OF TIME THE VALUES EXCEED THE ORDINATE

Figure 2

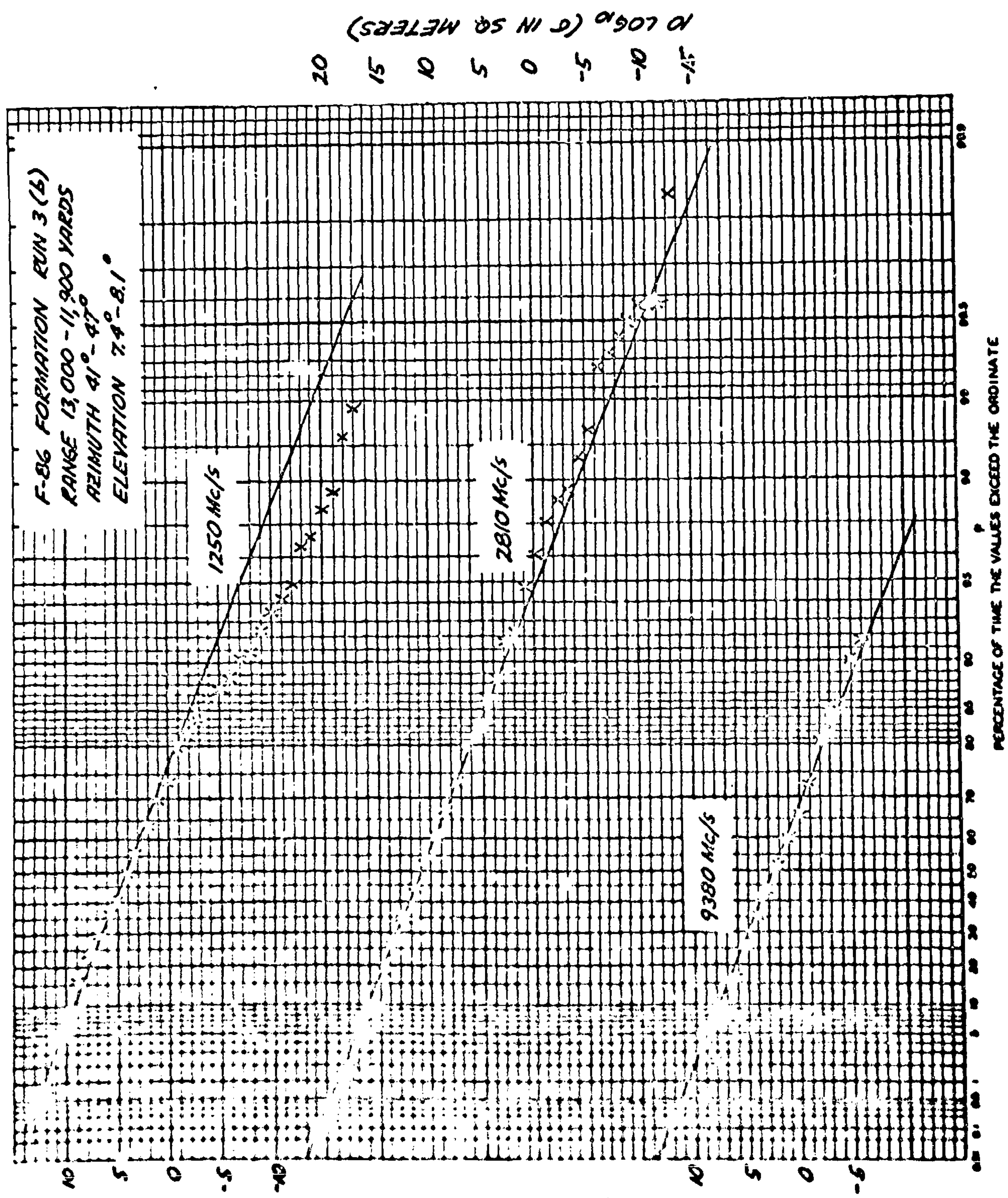

F-86 FORMATION RUN 3(b)
RANGE 13,000-11,900 YARDS
AZIMUTH 41°-47°
ELEVATION 7.4°-8.1°
1250 Mc/s
2810 Mc/s
9380 Mc/s
10 LOG10 (σ IN SQ METERS)
10 LOG10 (σ IN SQ METERS)
PERCENTAGE OF TIME THE VALUES EXCEED THE ORDINATE

Figure 4

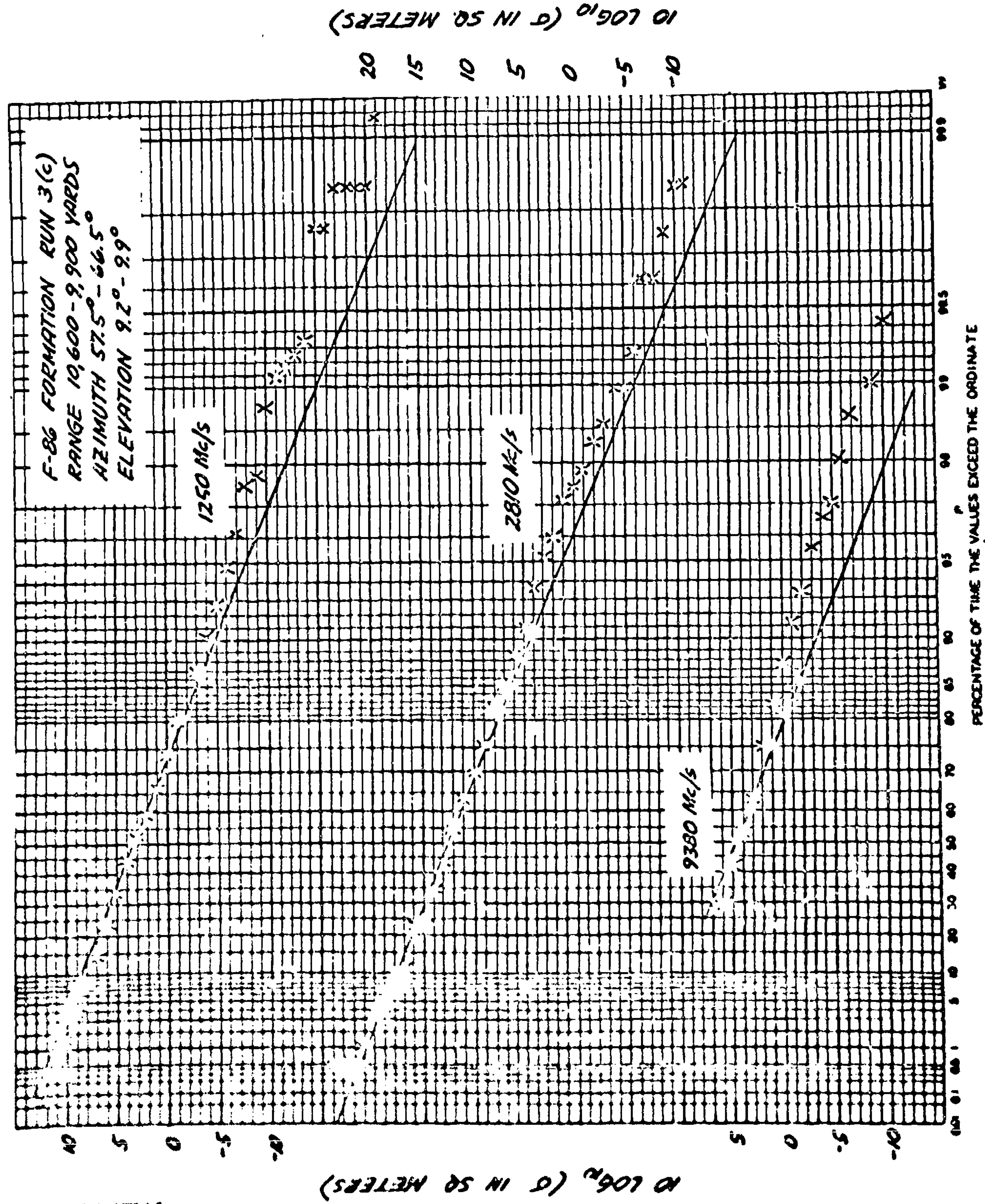
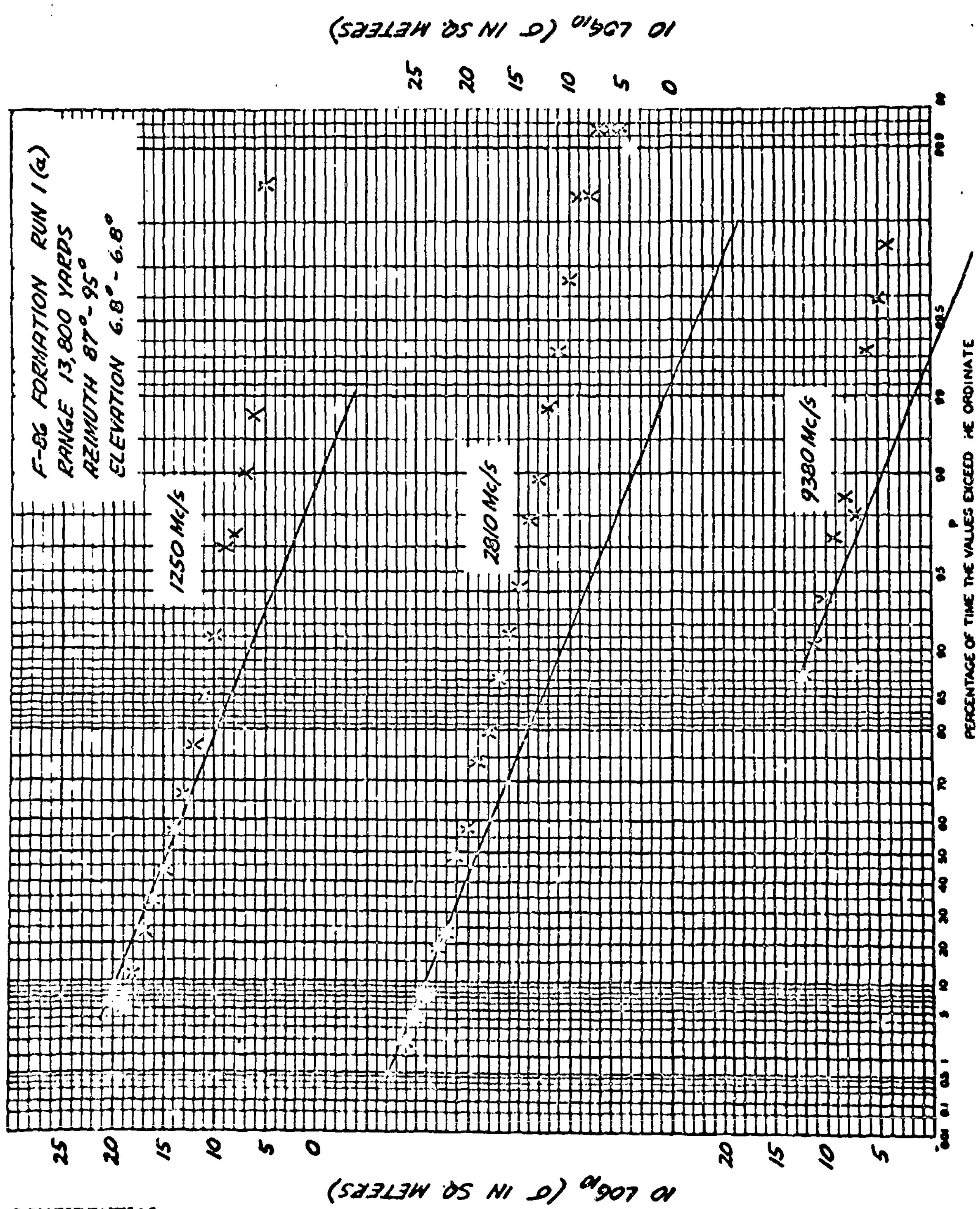

F-86 FORMATION RUN 3(c)
RANGE 10,600-9,900 YARDS
AZIMUTH 57.5°-66.5°
ELEVATION 9.2°-9.9°
1250 Mc/s
2810 Mc/s
9380 Mc/s
10 LOG10 (σ IN SQ. METERS)
PERCENTAGE OF TIME THE VALUES EXCEED THE ORDINATE

Figure 5



F-86 FORMATION RUN I (a)
RANGE 13,800 YARDS
AZIMUTH 87°-95°
ELEVATION 6.8°-6.8°
1250 Mc/s
2810 Mc/s
9380 Mc/s
10 LOG10 (σ IN SQ. METERS)
PERCENTAGE OF TIME THE VALUES EXCEED THE ORDINATE

Figure 6

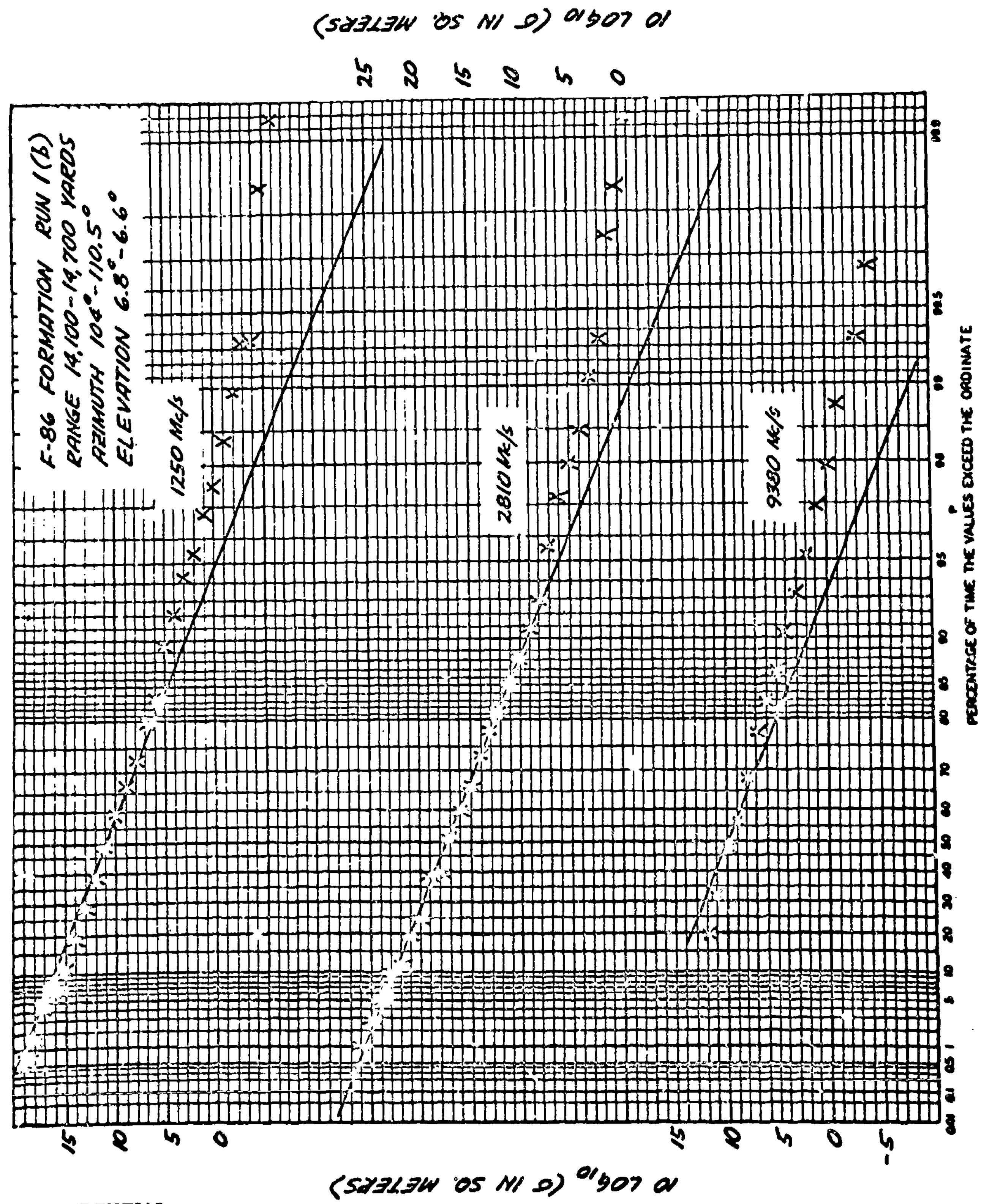

F-86 FORMATION RUN 1(b)
RANGE 14,100-14,700 YARDS
AZIMUTH 104°-110.5°
ELEVATION 6.8°-6.6°
1250 Mc/s
2810 Mc/s
9380 Mc/s
10 LOG10 (σ IN SQ. METERS)
PERCENTAGE OF TIME THE VALUES EXCEED THE ORDINATE

Figure 7

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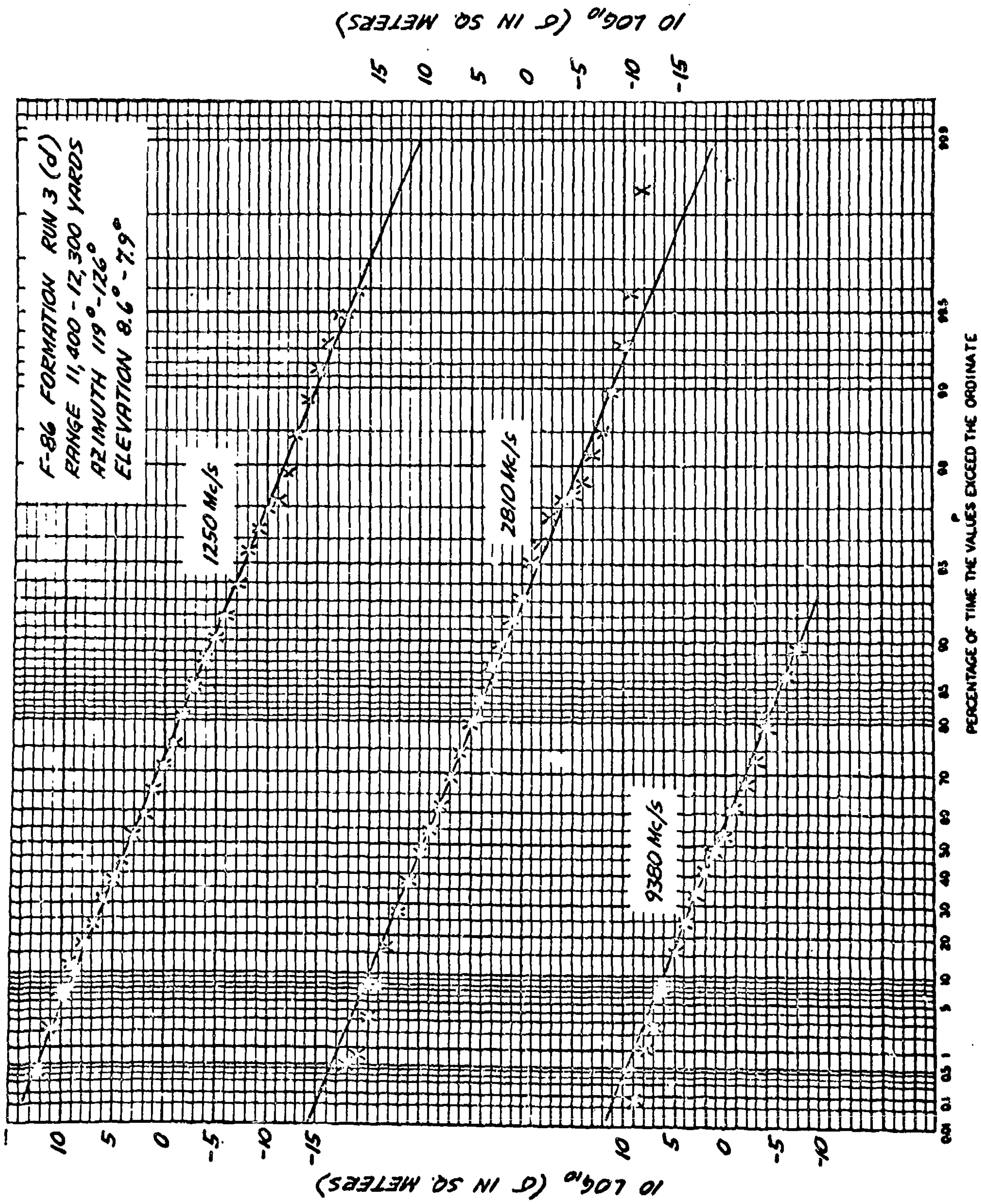

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Figure 8

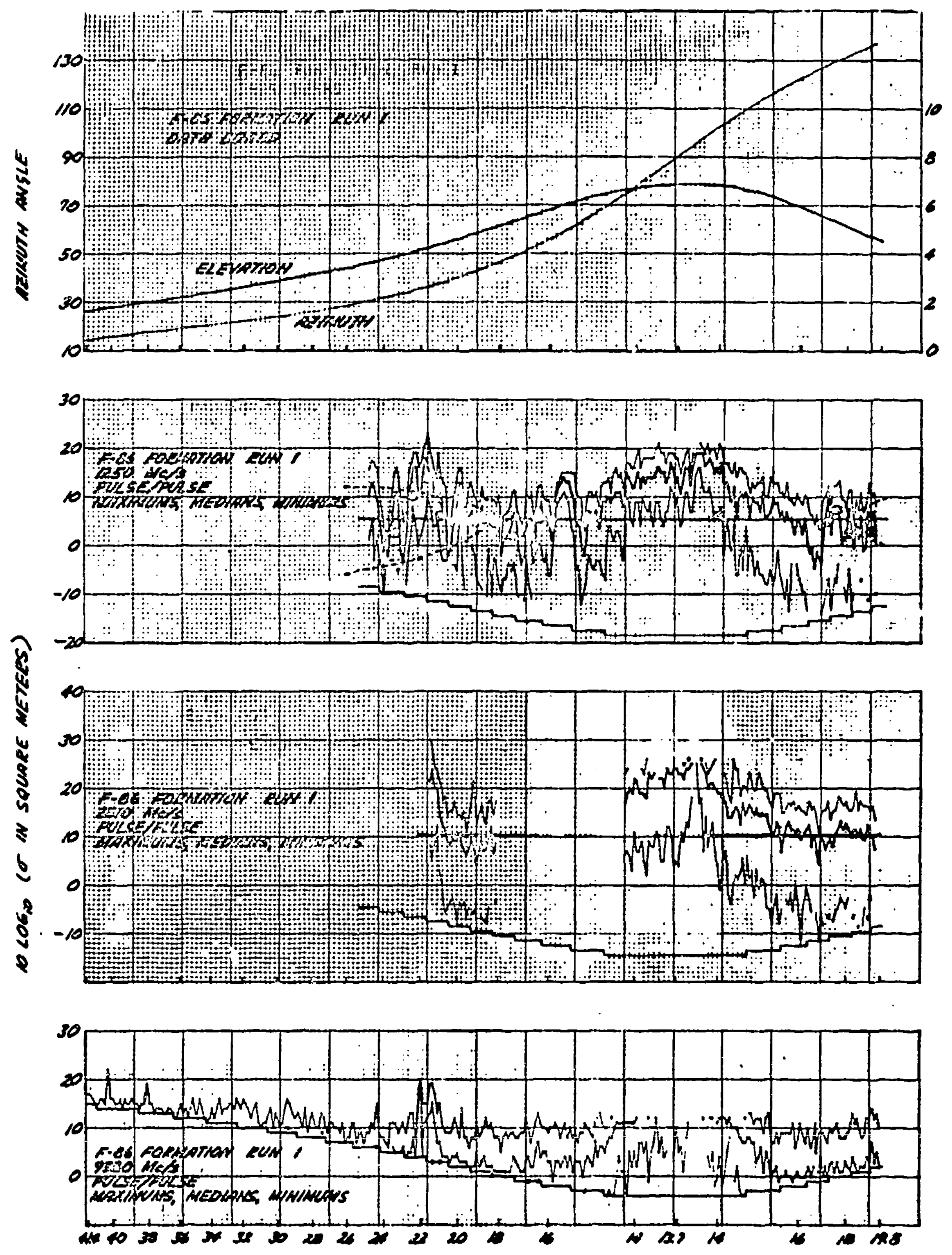
AZIMUTH ANGLE
ELEVATION ANGLE
ELEVATION
AZIMUTH
PULSE/PULSE
MAXIMUMS, MEDIANS, MINIMUMS
RANGE IN THOUSANDS OF YARDS

Figure 9

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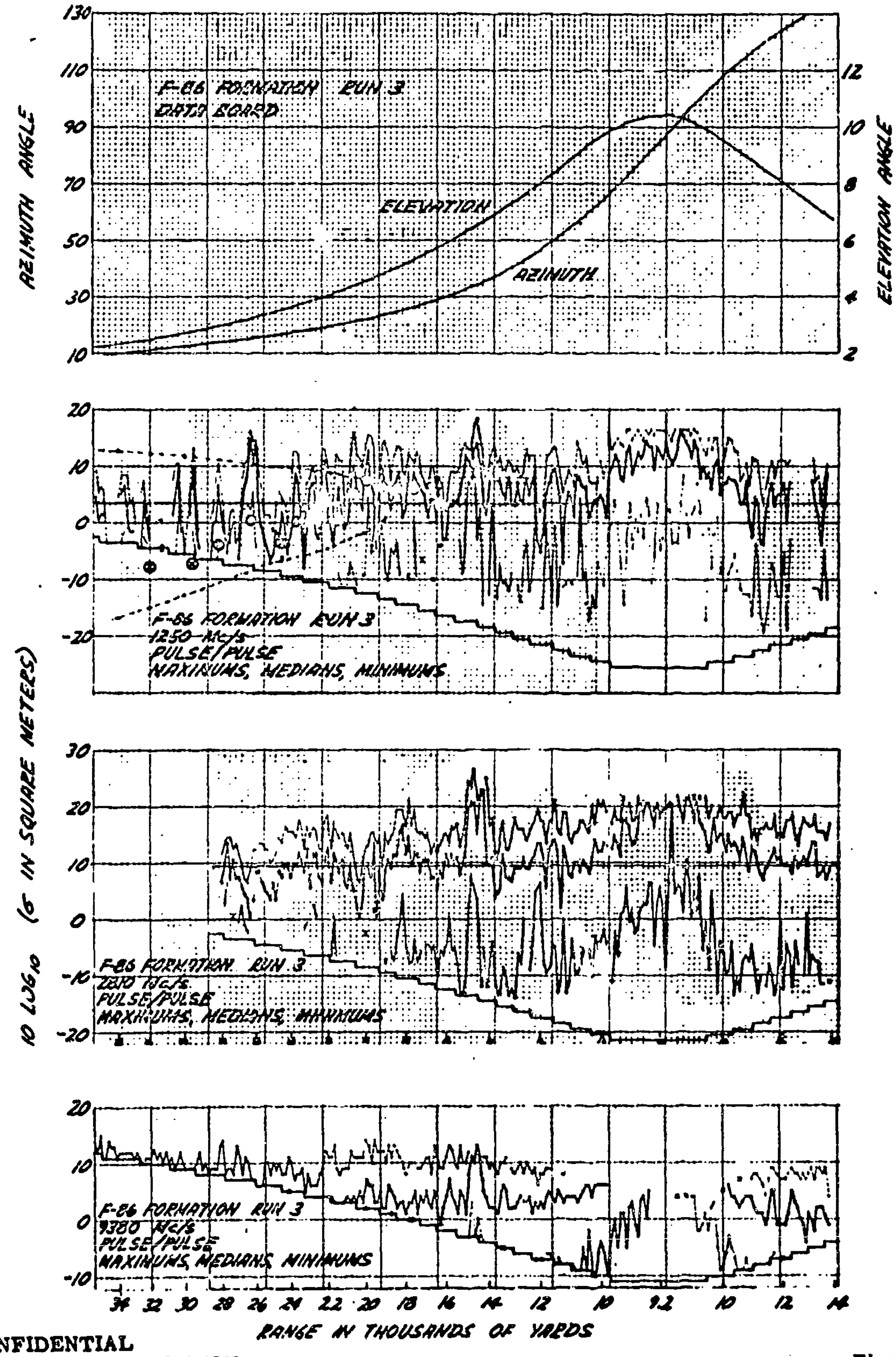

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Figure 10

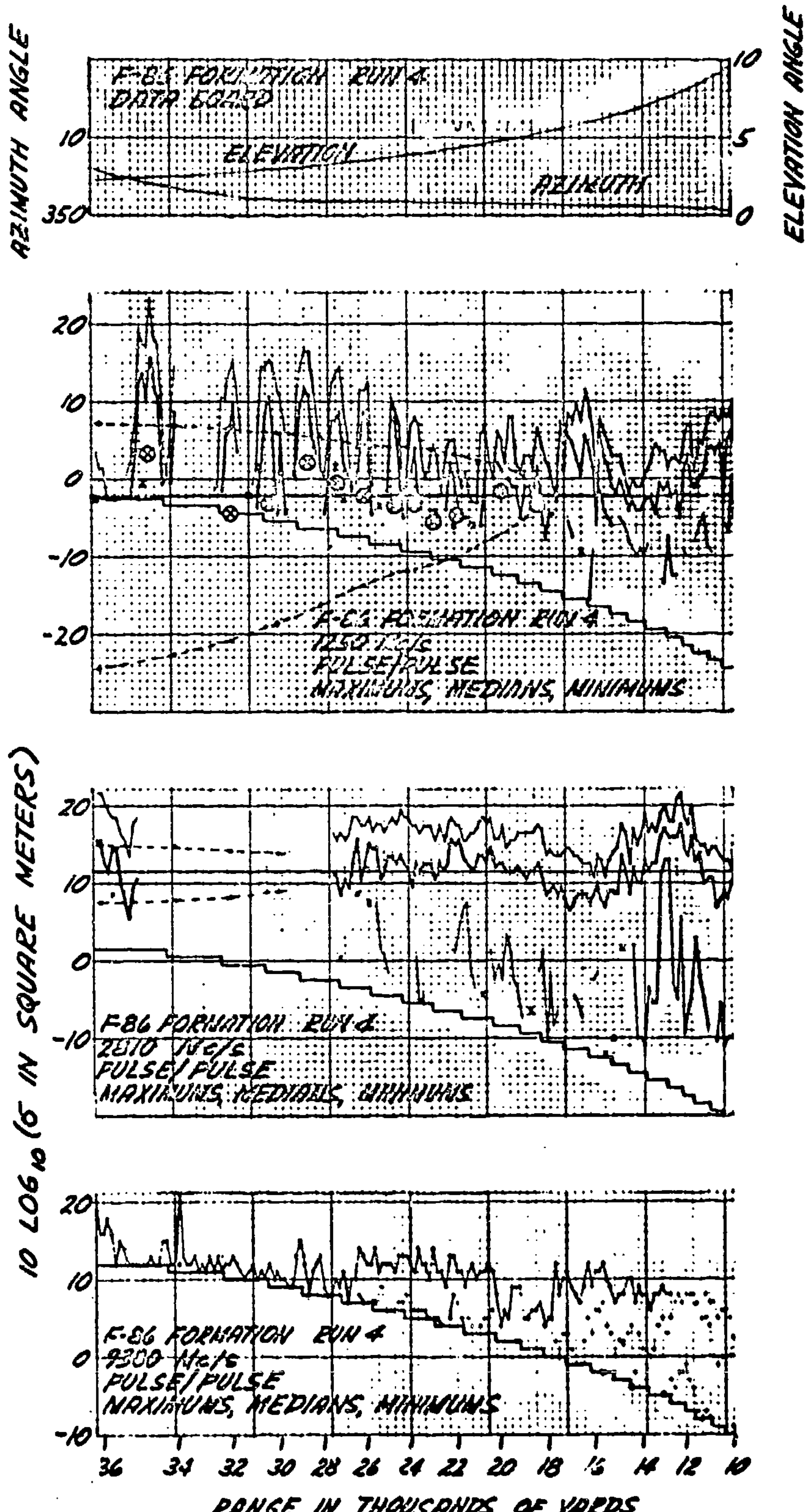
AZIMUTH ANGLE
ELEVATION ANGLE
ELEVATION
AZIMUTH
10 LOG10 (σ IN SQUARE METERS)
F-86 FORMATION RUN 4
PULSE/PULSE
MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 4
PULSE/PULSE
MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 4
9300 Mc/s
PULSE/PULSE
MAXIMUMS, MEDIANS, MINIMUMS
RANGE IN THOUSANDS OF YARDS

Figure 11

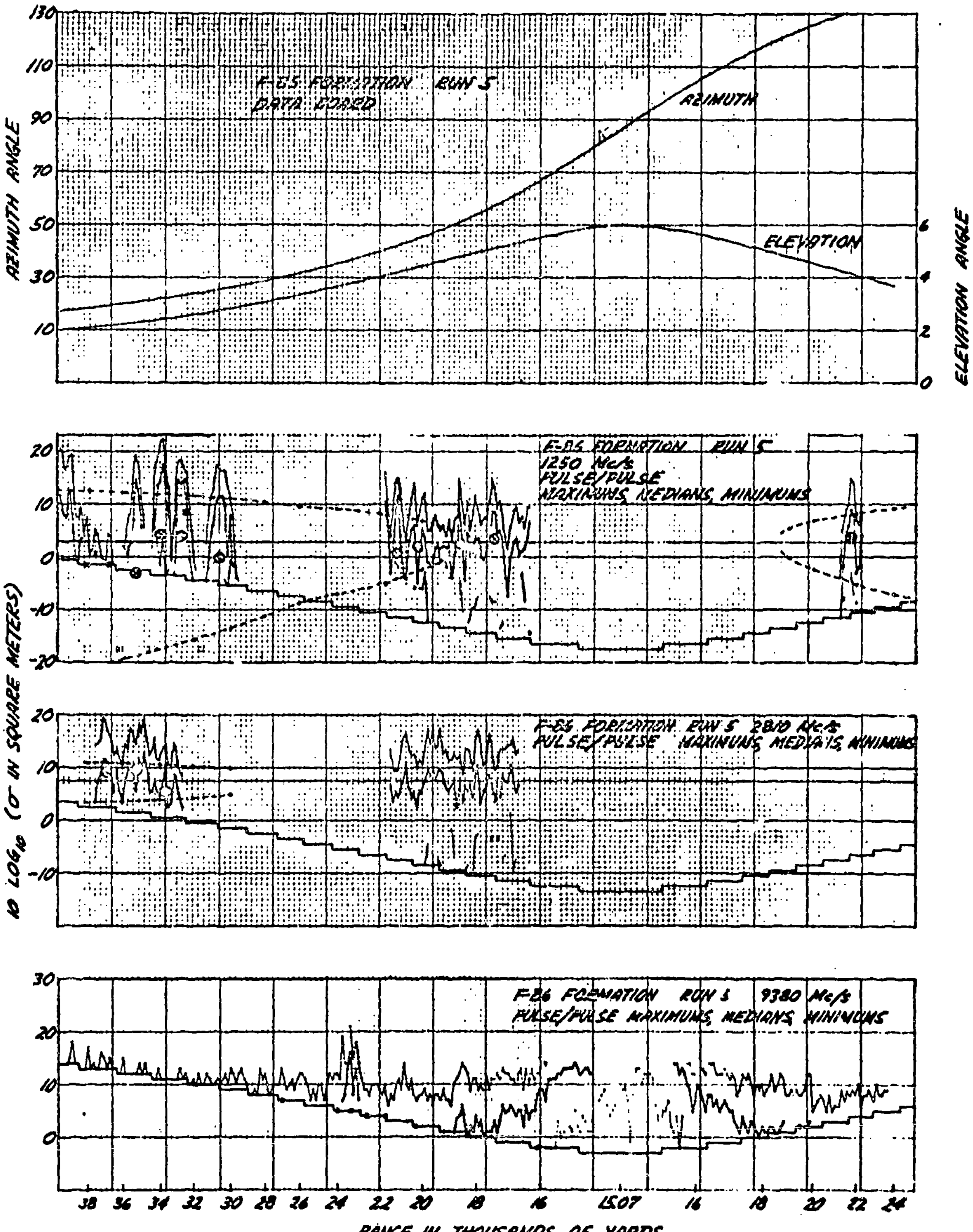
F-86 FORMATION RUN 5
DATA CORED
AZIMUTH
ELEVATION
AZIMUTH ANGLE
ELEVATION ANGLE
F-86 FORMATION RUN 5
1250 Mc/s
PULSE/PULSE
MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 5 2810 Mc/s
PULSE/PULSE MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 5 9380 Mc/s
PULSE/PULSE MAXIMUMS, MEDIANS, MINIMUMS
10 LOG10 (σ IN SQUARE METERS)
RANGE IN THOUSANDS OF YARDS

Figure 12

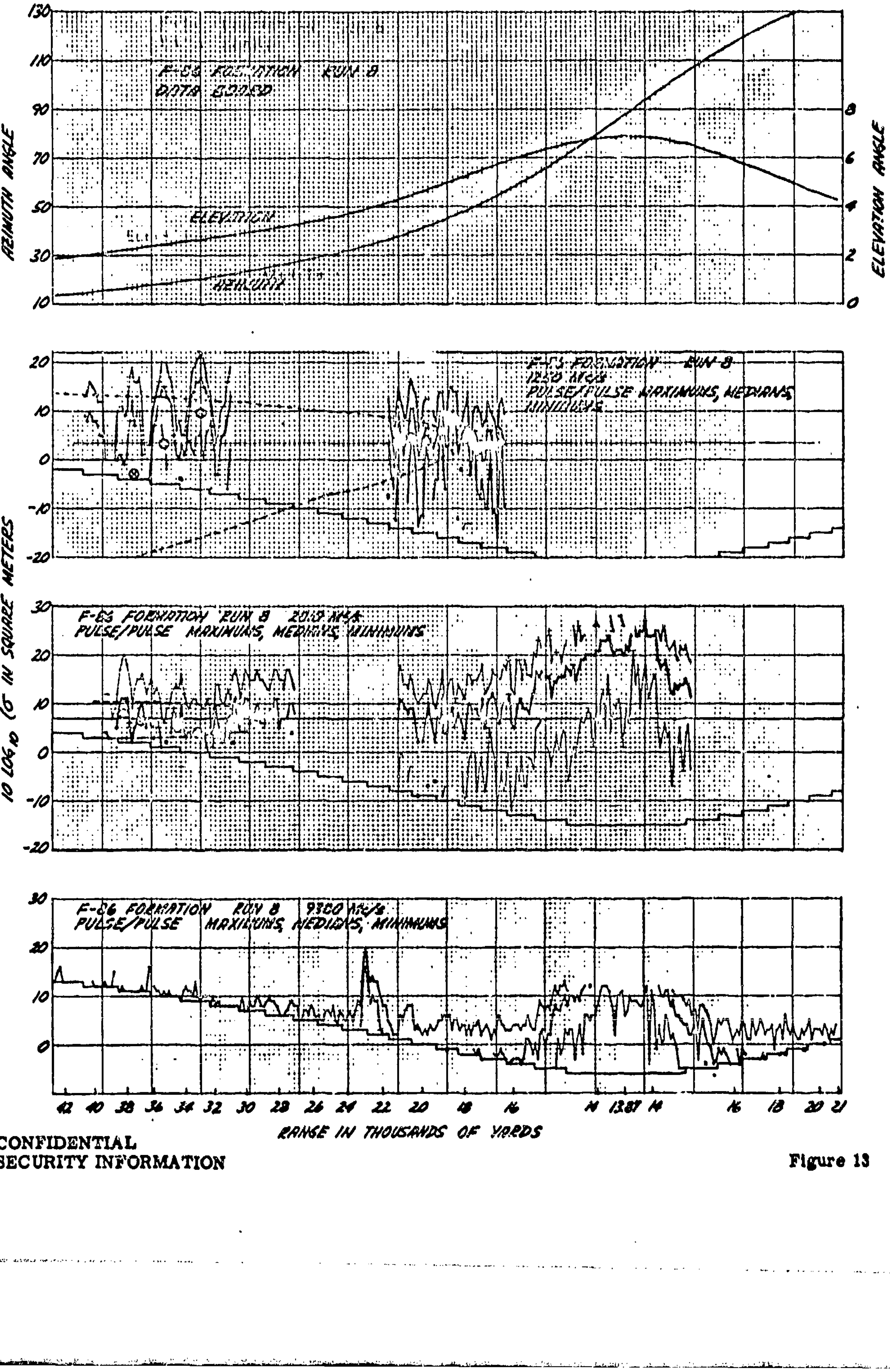
F-86 FORMATION RUN 8
DATA BOARD
ELEVATION
AZIMUTH
AZIMUTH ANGLE
ELEVATION ANGLE
F-86 FORMATION RUN 8
1250 MC/S
PULSE/PULSE MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 8 2019 MC/S
PULSE/PULSE MAXIMUMS, MEDIANS, MINIMUMS
F-86 FORMATION RUN 8 9300 MC/S
PULSE/PULSE MAXIMUMS, MEDIANS, MINIMUMS
10 LOG10 (σ IN SQUARE METERS
RANGE IN THOUSANDS OF YARDS

Figure 13

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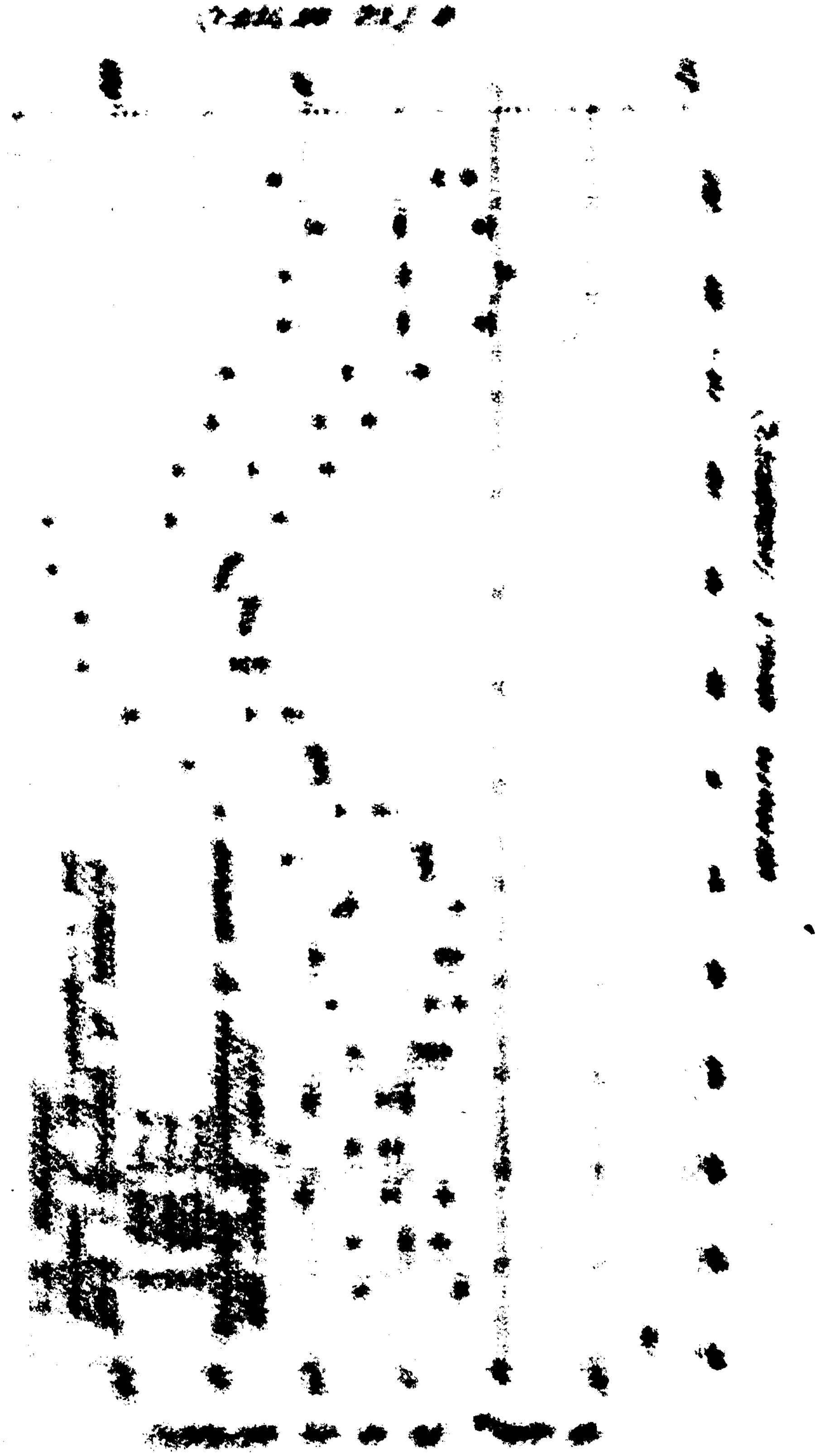

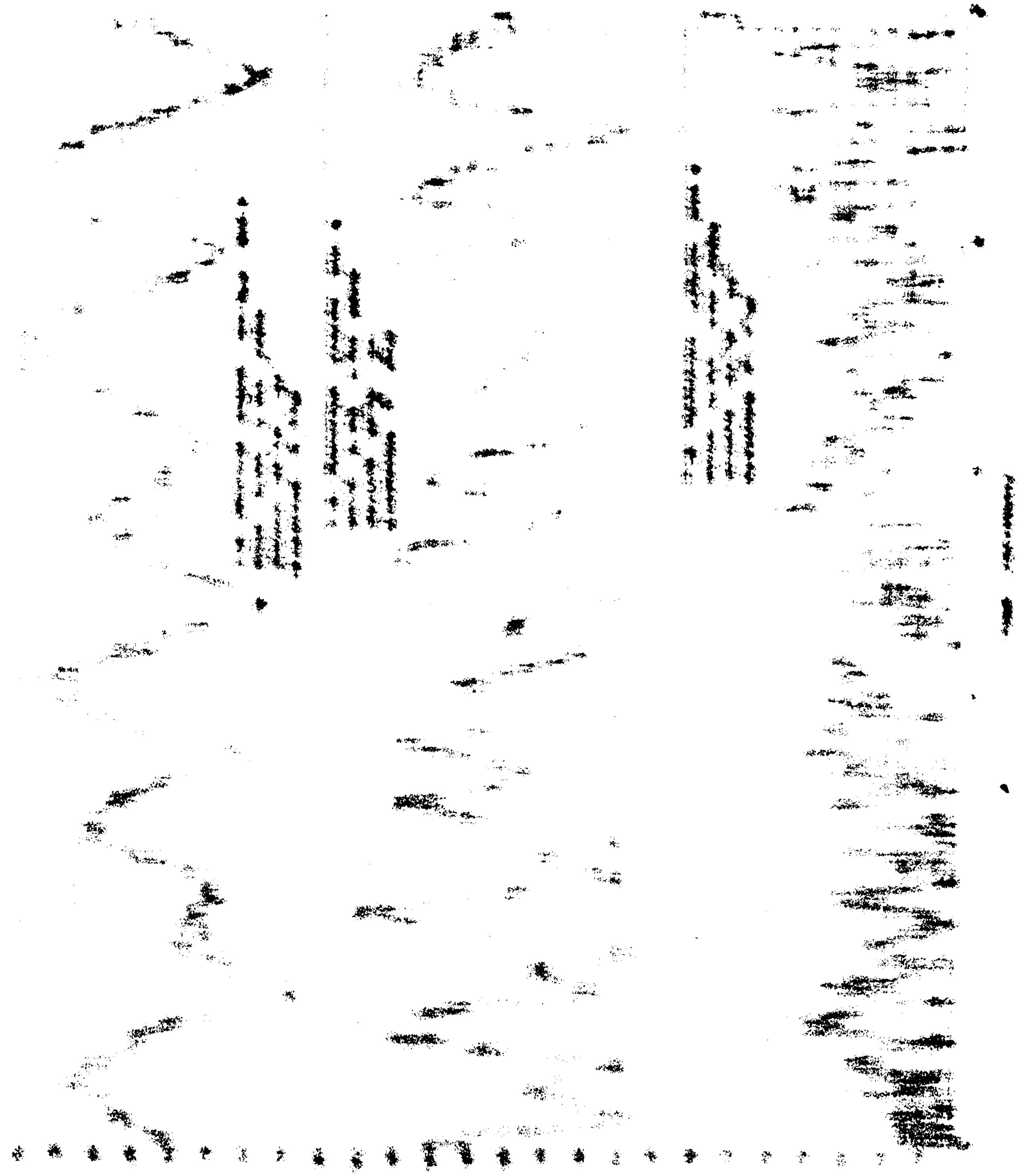

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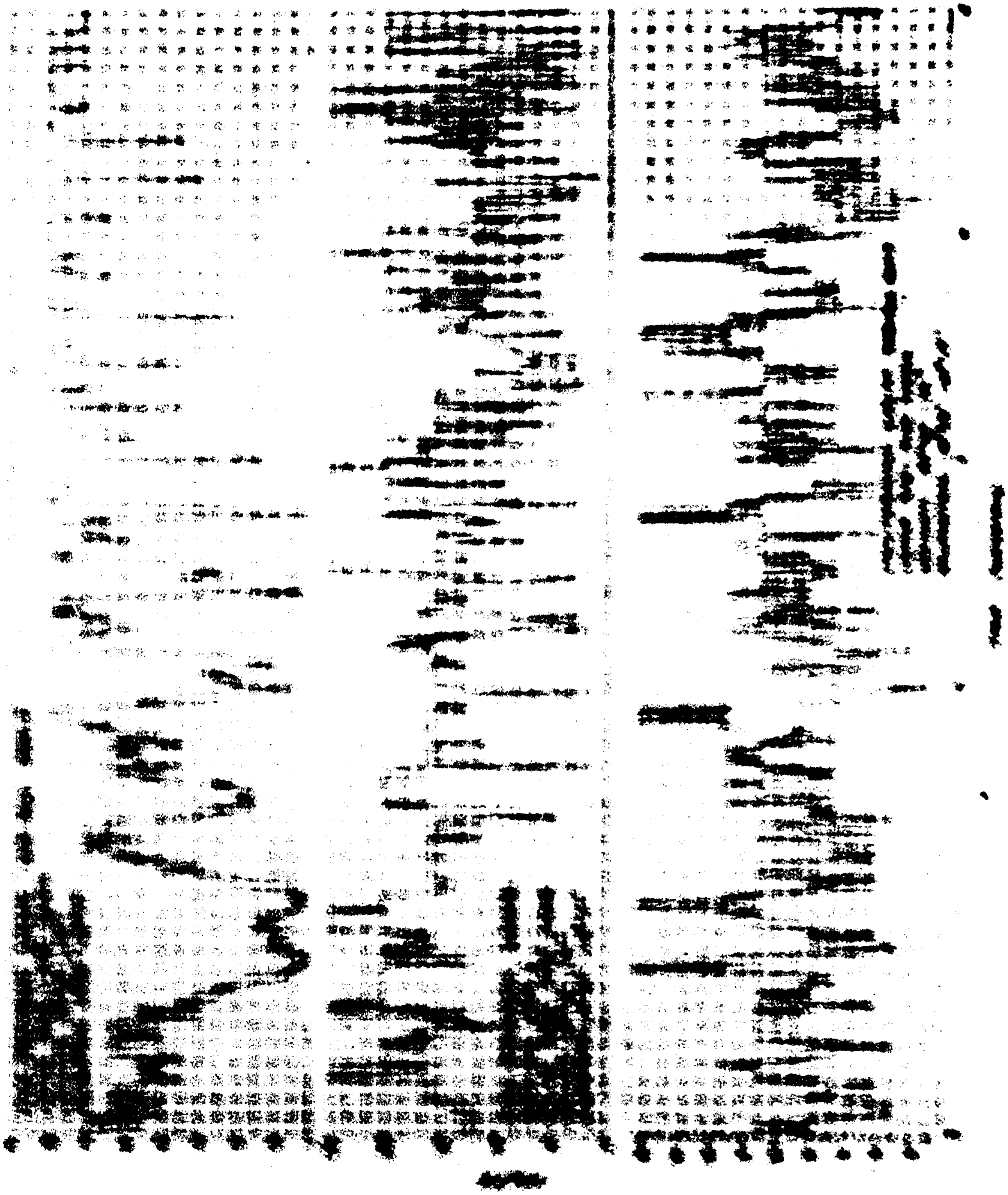

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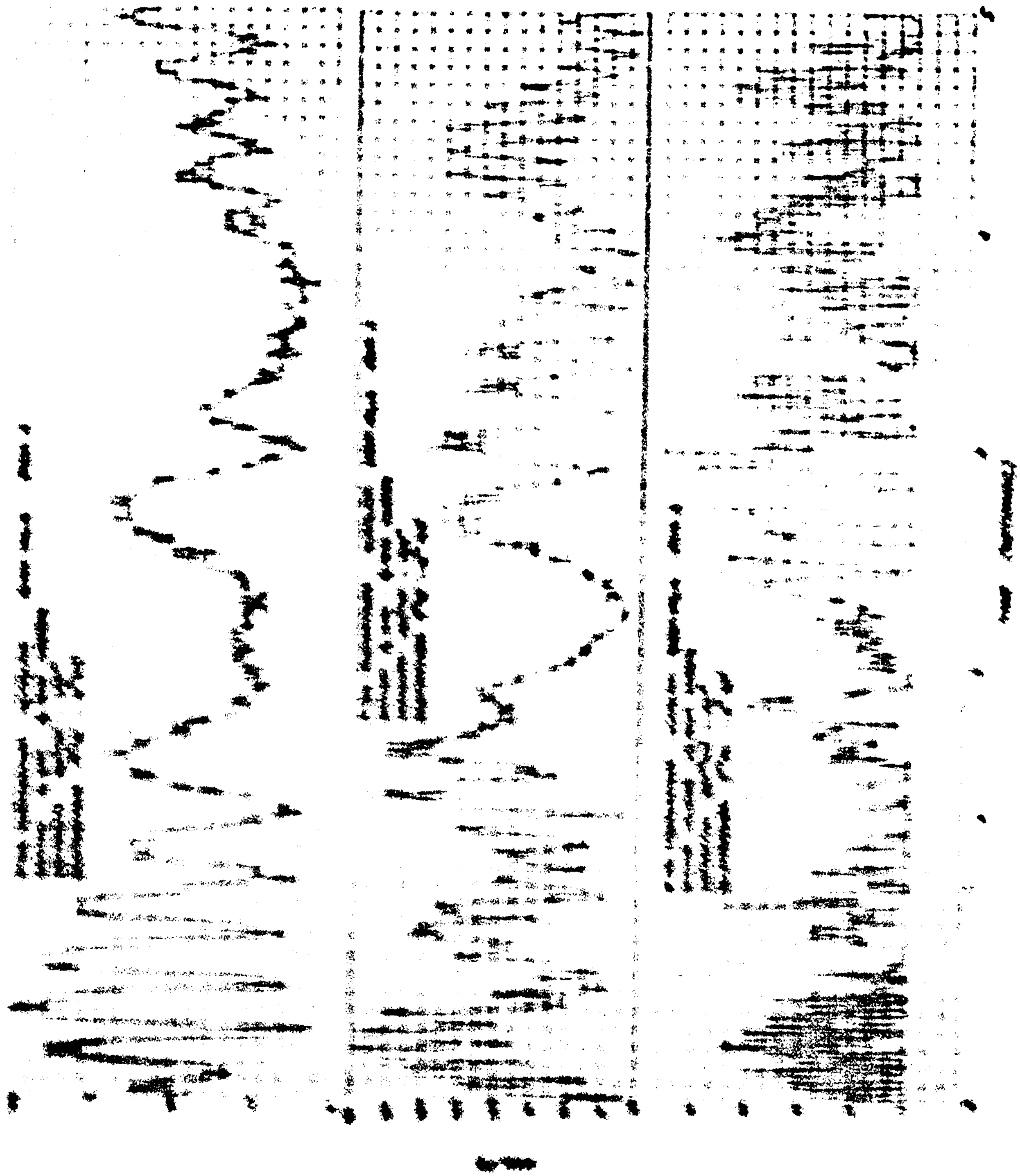

Figure [illegible]

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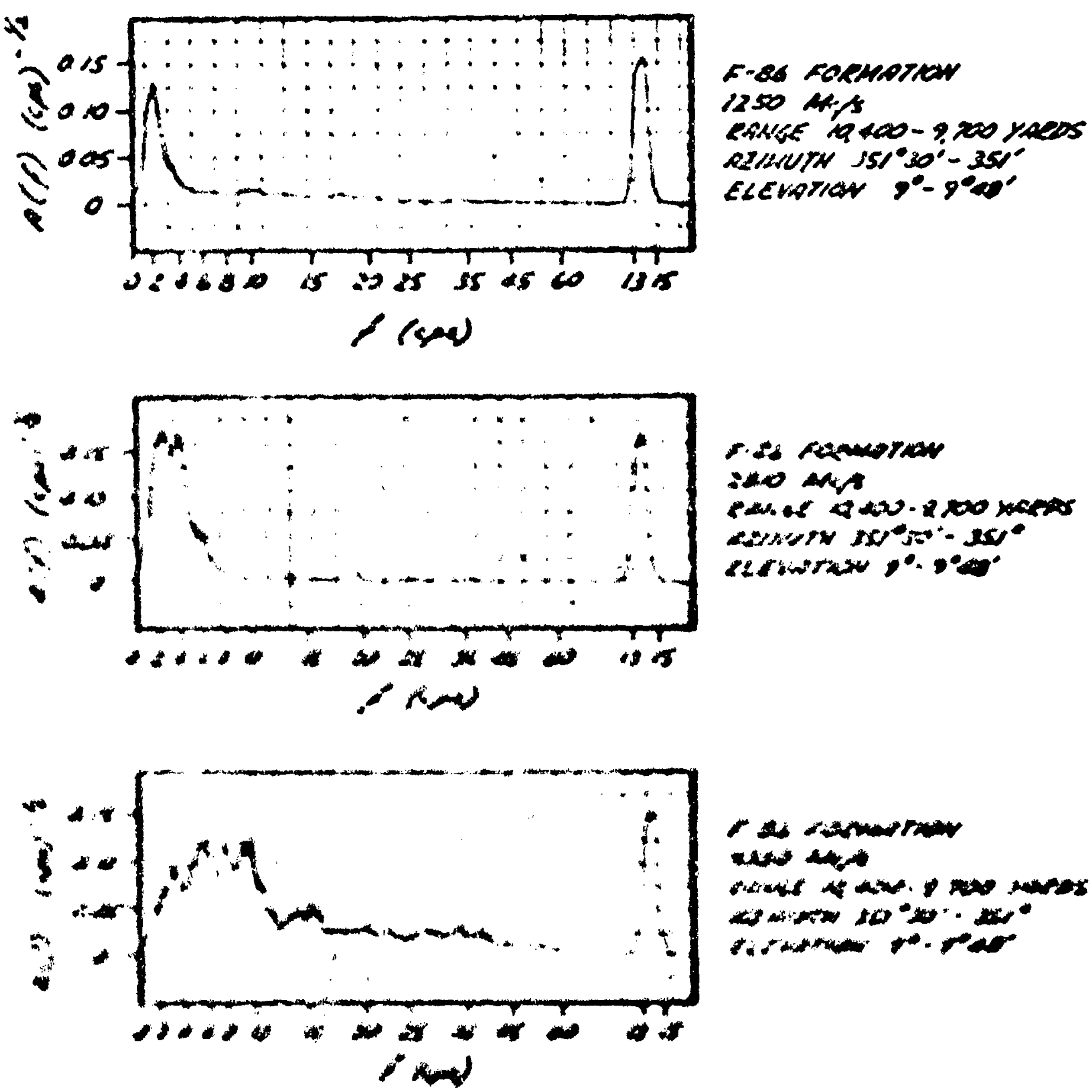

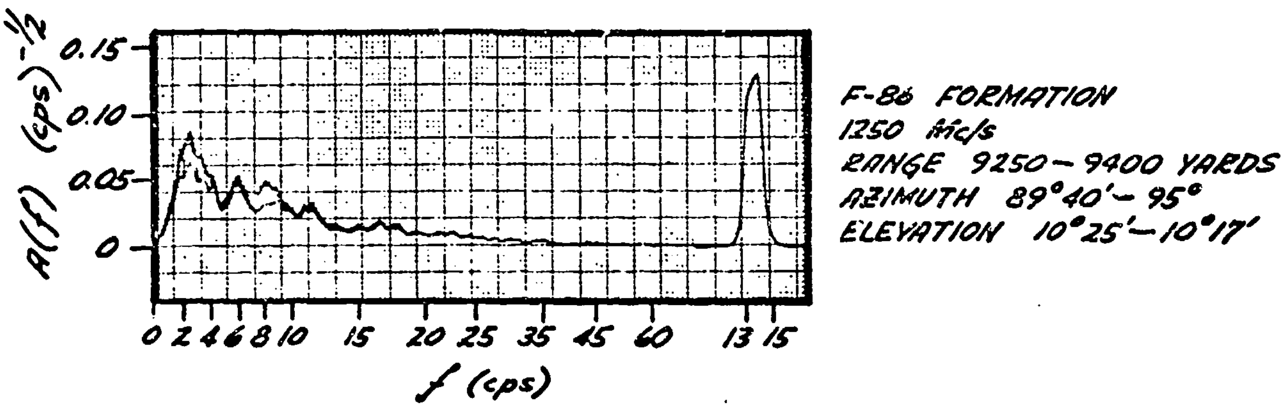
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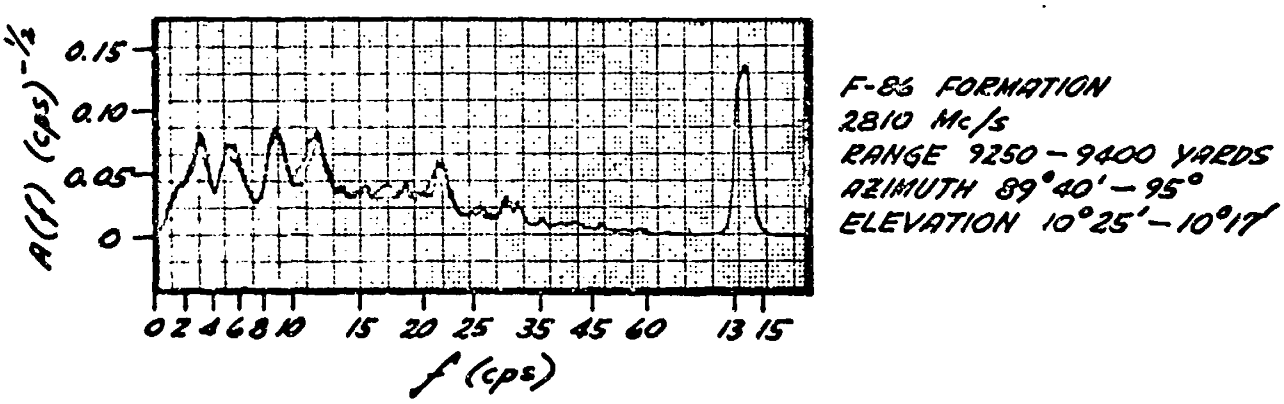
0.10
0.05
0
A(f) (cps)^-1/2
0 2 4 6 8 10 15 20 25 35 45 60 13 15
f (cps)
F-86 FORMATION
1250 Mc/s
RANGE 9250 — 9400 YARDS
AZIMUTH 89°40' — 95°
ELEVATION 10°25' — 10°17'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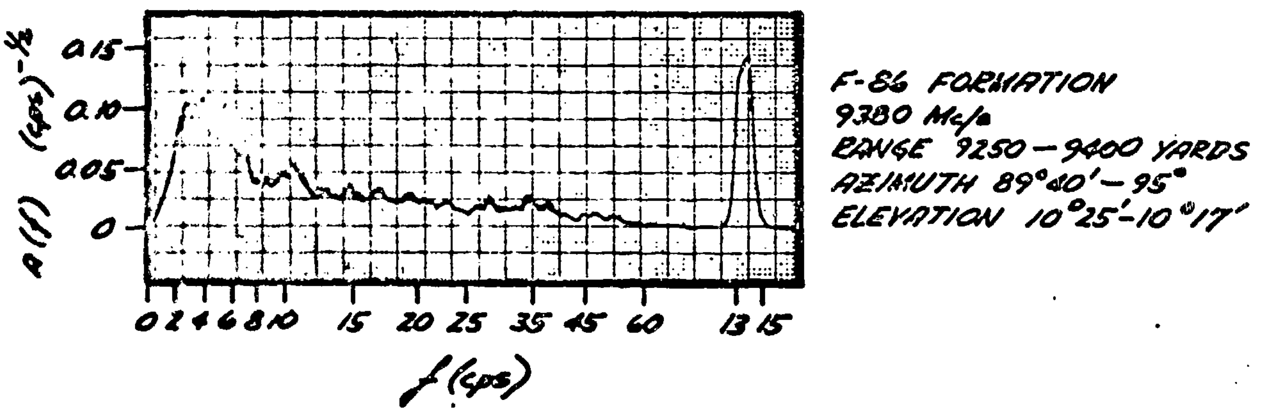
f (cps)
F-86 FORMATION
2810 Mc/s
RANGE 9250 — 9400 YARDS
AZIMUTH 89°40' — 95°
ELEVATION 10°25' — 10°17'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A(f) (cps)^-1/2
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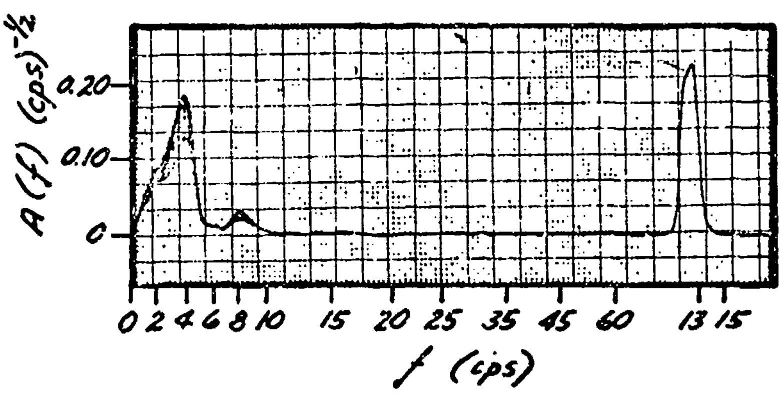
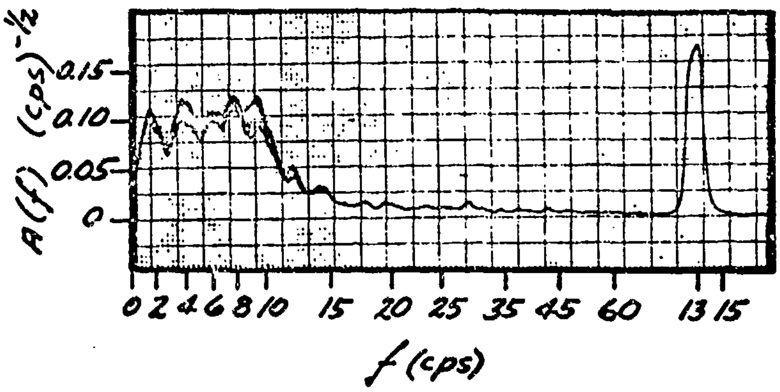
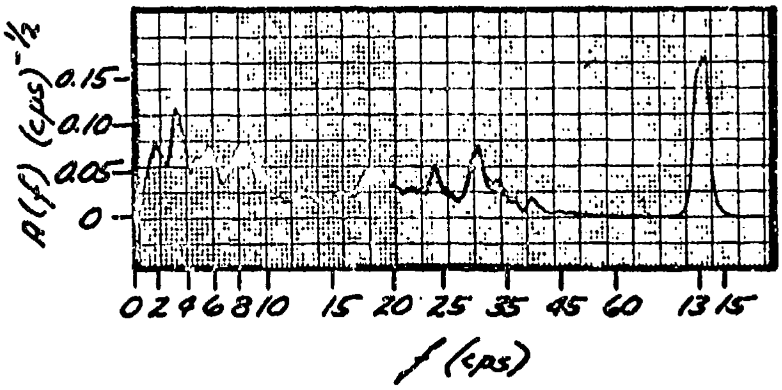
f (cps)
F-86 FORMATION
9380 Mc/s
RANGE 9250 — 9400 YARDS
AZIMUTH 89°40' — 95°
ELEVATION 10°25' — 10°17'



F-86 FORMATION
1250 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'



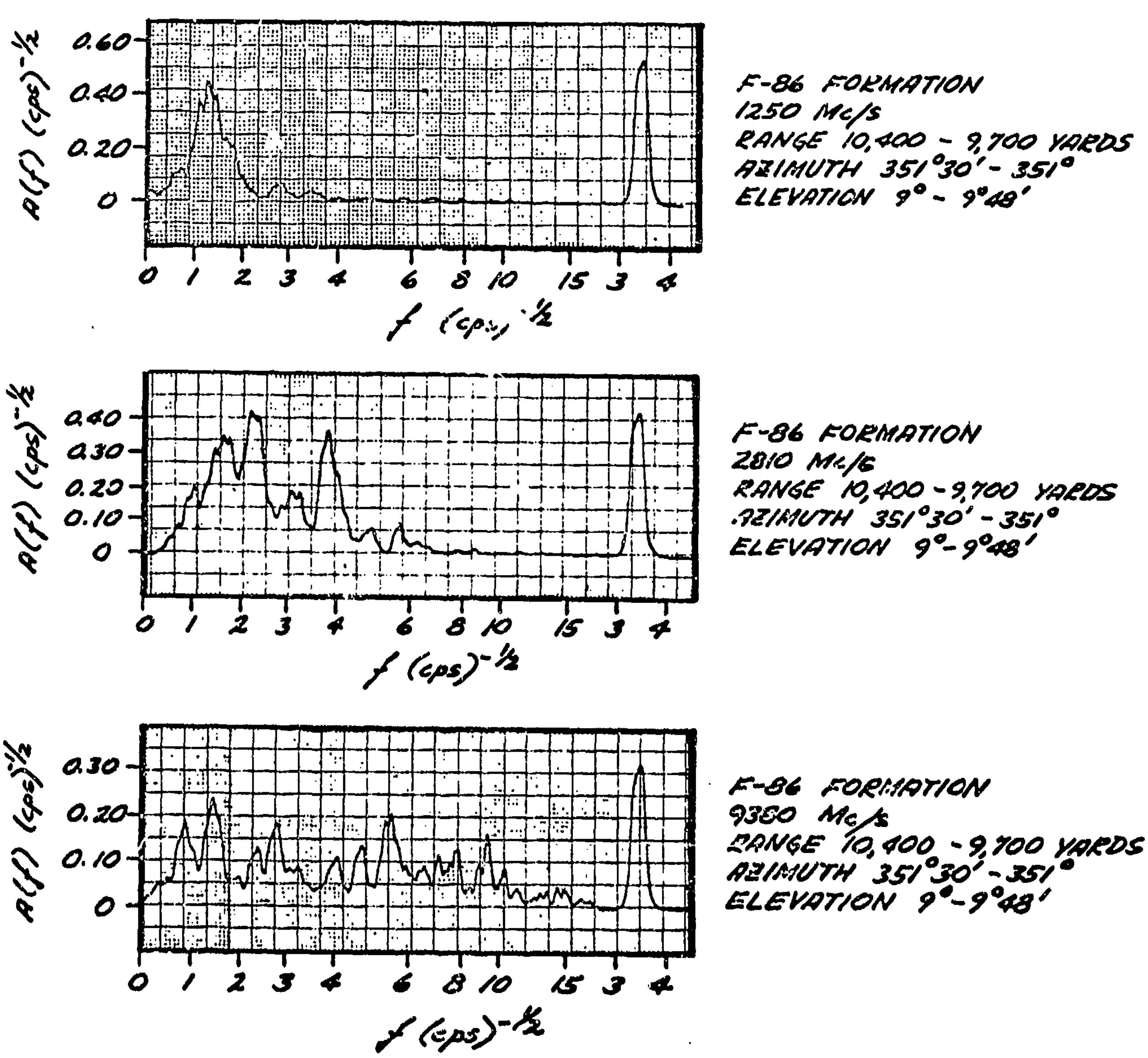
F-86 FORMATION
2810 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'



F-86 FORMATION
9380 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'

Figure 22

[redacted]



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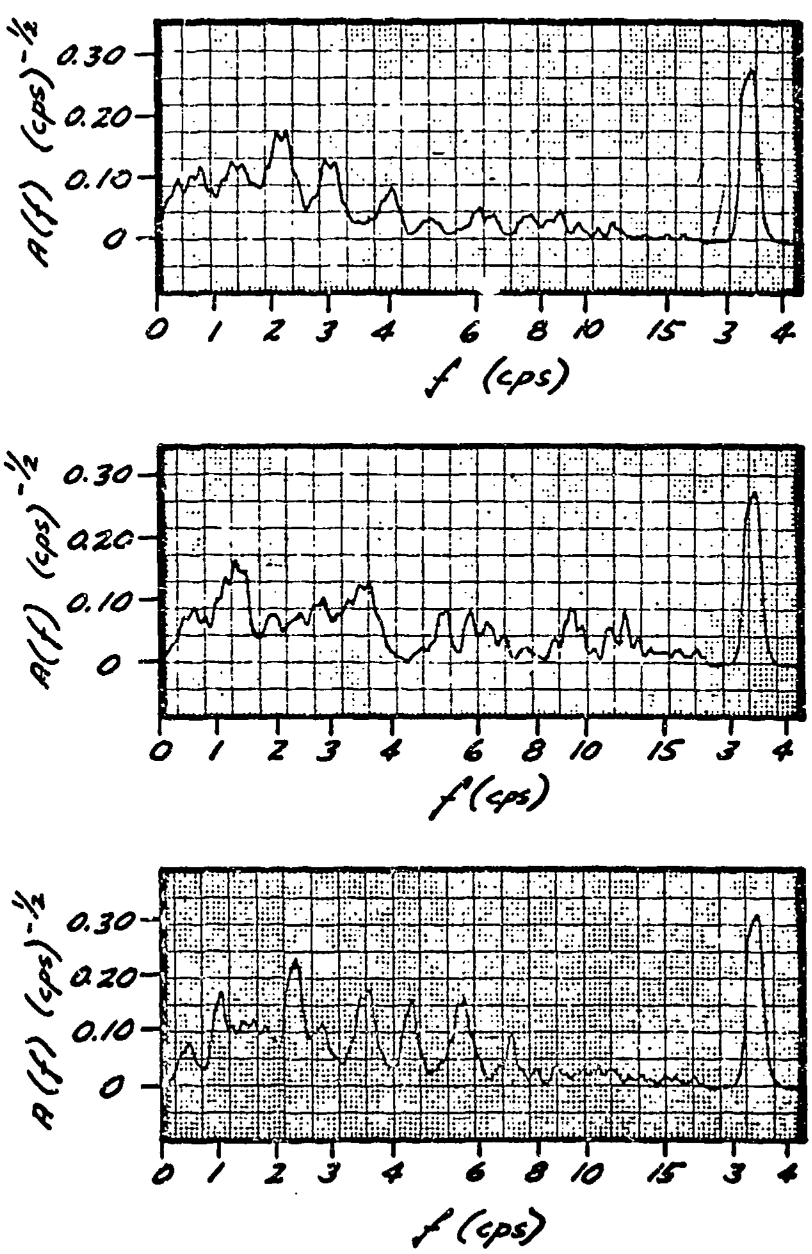
SECURITY INFORMATION

Figure 23



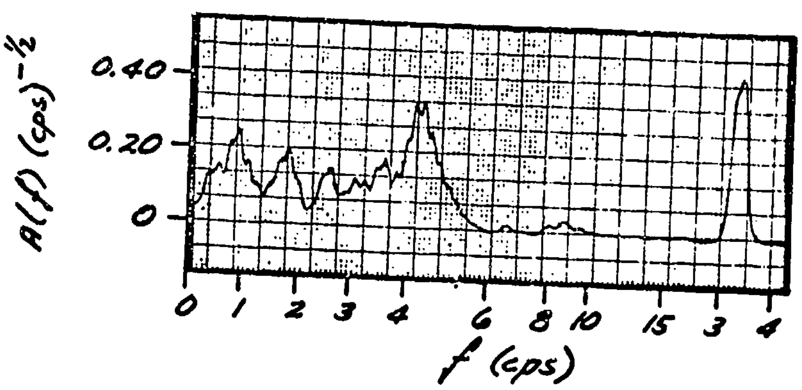
F-86 FORMATION
1250 Mc/s
RANGE 9250 - 9400 YARDS
AZIMUTH 89°40' - 95°
ELEVATION 10°25' - 10°17'

F-86 FORMATION
2810 Mc/s
RANGE 9250 - 9400 YARDS
AZIMUTH 89°40' - 95°
ELEVATION 10°25' - 10°17'

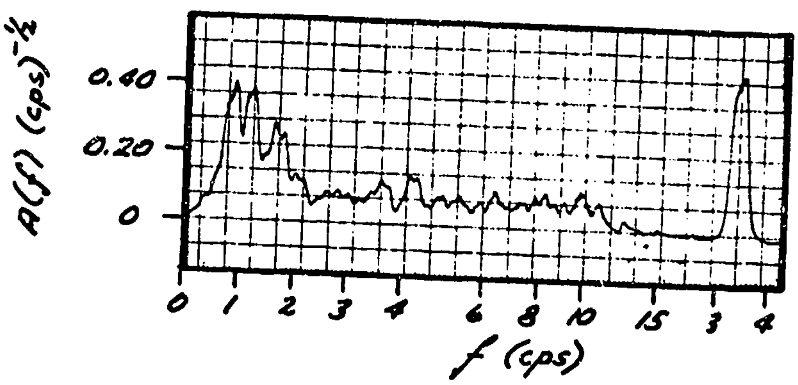
F-86 FORMATION
9380 Mc/s
RANGE 9250 - 9400 YARDS
AZIMUTH 89°40' - 95°
ELEVATION 10°25' - 10°17'

Figure 24

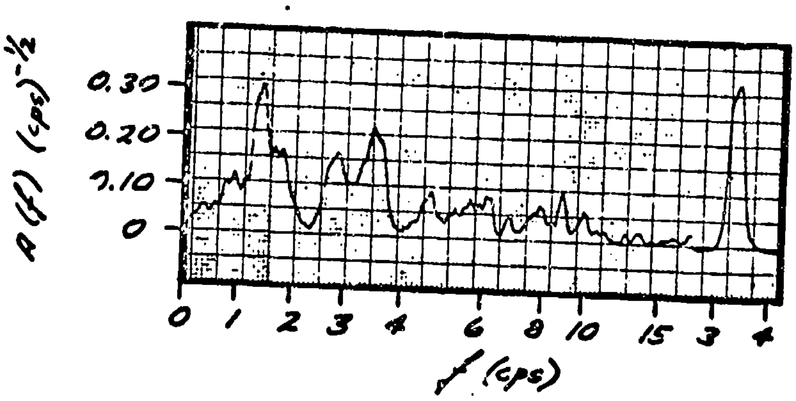
[redacted]



F-86 FORMATION
1250 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'



F-86 FORMATION
2810 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'



F-86 FORMATION
9380 Mc/s
RANGE 13,300 - 13,900 YARDS
AZIMUTH 130°40' - 133°
ELEVATION 7°16' - 6°53'

[redacted]
SECURITY INFORMATION

Figure 25