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FINAL REPORT
Theoretical Study of V Antenna Characteristics
for the ATS-E Radio Astronomy Experiment

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REPORT
by
THE OHIO STATE UNIVERSITY ELECTROSCIENCE LABORATORY
(Formerly Antenna Laboratory)
Columbus, Ohio 43212

Sponsor National Aeronautics and Space Administration
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Investigation of Theoretical Study of V Antenna
 Characteristics for the ATS-E
 Radio Astronomy Experiment

Subject of Report Final Report .

Submitted by J. H. Richmond
 ElectroScience Laboratory
 Department of Electrical Engineering

Date 13 February 1969

ABSTRACT

A theoretical analysis has been carried out for the V antenna system on the ATS-E Satellite for radio astronomy experiments. This report summarizes the techniques and presents numerical results for impedance, current distributions, patterns and radiation efficiency.

ACKNOWLEDGMENT

The author is sincerely appreciative to Dr. D.V. Otto for his very significant assistance in the theory of thin-wire radiators and electromagnetic fields in general.

Contributions from N. Hugh Geary in the realm of mathematics were crucial in developing the techniques into a practical and efficient form.

Accurate experimental data were obtained through the careful and dedicated measurements by Danai Lekhyananda.

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I. OBJECTIVES

The characteristics of the V antenna system on the ATS-E Satellite were to be determined by means of a theoretical analysis. Digital computations were required for V angles from 124 to 154 degrees and frequencies from 60 to 4102 KHz, taking into account the imperfect conductivity of the metallic surfaces and the mutual coupling among the various elements of the system.

II. INTRODUCTION

In the history of antenna theory, isolated antennas have yielded to theoretical analysis more readily than coupled antennas. The cylindrical-wire antenna has an extensive bibliography, and the publication rate is still high on this subject. By comparison, the V antenna has received scant attention except by Schelkunoff.¹

Apparently no solution has been published for coupled V antennas. On the other hand, the theory of coupled linear antennas has developed on two distinct levels. On the most elementary level, the "two-segment solution", the current distribution is assumed sinusoidal on each dipole. In 1932 Carter² used this induced emf formulation to derive expressions for the mutual impedance between half-wave wires. In 1957 H.E. King³ determined the mutual impedance between parallel antennas in echelon with arbitrary wire lengths. Baker and LaGrone⁴ employed numerical integration techniques for skew antennas.

The two-segment sinusoidal solution has proven useful for coupled dipoles with lengths up to about 0.5λ . In this range, the current distribution on each thin-wire antenna is not greatly disturbed by the other, even when they are quite close together. More sophisticated techniques are required, however, for longer antennas. One approach is to reduce the integral equation to a system of simultaneous linear equations. The unknown constants in these equations are usually sample points on the current function $I(z)$ or coefficients in a modal expansion for the current.

For example, Harrington⁵ divided the cylindrical antenna into N segments or subranges along its axis and wrote a power-series expansion for $I(z)$ on each segment. Using a digital computer to solve the resulting system of simultaneous equations, he obtained accurate results with a piecewise-linear expansion on 32 segments.

Chang and King⁶ used a piecewise-quadratic expansion on 12 segments to treat parallel antennas. They obtained consistent results with a five-mode two-segment formulation.

This report treats a symmetric pair of coplanar V antennas. The antennas are closely coupled and the total length of each ranges from 0.01 to 1.1 wavelengths. Although this geometry is more complex than that of the parallel linear antennas, we have developed an accurate and efficient N-segment solution based on the reaction concept of Rumsey⁷ and a piecewise-sinusoidal expansion for the current distribution.

The starting point is the rigorous theory for the free-space field of a sinusoidal line source. This forms the subject of the following section.

III. RIGOROUS FIELD EXPRESSIONS FOR PIECEWISE-SINUSOIDAL LINE SOURCES*

Schelkunoff and Friis¹ have presented in most convenient form the exact fields of a time-harmonic electric line source with sinusoidal current distribution:

$$(1) \quad I(z) = A \cos kz + B \sin kz$$

$$(2) \quad E_z(\rho, z) = \frac{j}{4\pi\omega\epsilon} \left[I'(z') \frac{e^{-jkr}}{r} + I(z') \frac{\partial}{\partial z} \frac{e^{-jkr}}{r} \right]_{z'=z_1}^{z'=z_2}$$

$$(3) \quad r = \sqrt{\rho^2 + (z - z')^2}$$

As indicated in Fig. 1, the line source extends from z_1 to z_2 on the z axis. $I'(z)$ denotes the first derivative of $I(z)$ and $k = \omega\sqrt{\mu\epsilon}$.

By superposition, the field of a line source with piecewise-sinusoidal current distribution (Fig. 2) is

$$(4) \quad E_z(\rho, z) = \frac{j}{4\pi\omega\epsilon} \sum_{i=1}^{n-1} \left[I'(z') \frac{e^{-jkr}}{r} + I(z') \frac{\partial}{\partial z} \frac{e^{-jkr}}{r} \right]_{z'=z_i}^{z'=z_{i+1}}$$

*D.V. Otto and J.H. Richmond, "Rigorous Field Expressions for Piecewise-Sinusoidal Line Sources", IEEE Transactions, Vol. AP-17, January 1969.

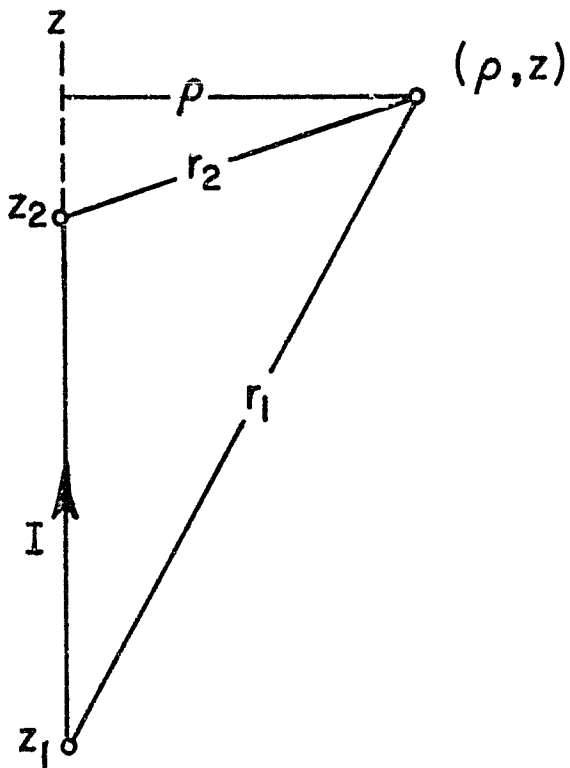


Fig. 1. An electric line source is located on the z axis and its field is observed at (ρ, z) .

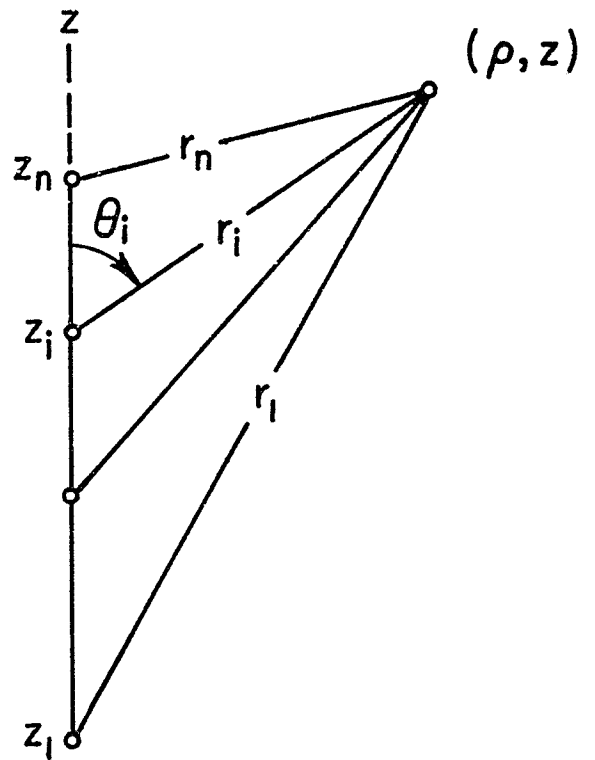


Fig. 2. A line source with piecewise-sinusoidal distribution.

The current $I(z)$ is assumed to have the form of Eq. (1) between each neighboring pair of points z_i and z_{i+1} .

If the current $I(z)$ is continuous across the junctions z_i and vanishes at the endpoints z_1 and z_n , Eq. (4) readily reduces to

$$(5) \quad E_z(\rho, z) = \frac{j}{4\pi\omega\epsilon} \sum_{i=1}^n \Delta I'_i \frac{e^{-jkr_i}}{r_i}$$

where

$$(6) \quad \Delta I'_i = \lim_{\epsilon \rightarrow 0} [I'(z_i - \epsilon) - I'(z_i + \epsilon)]$$

The constants $\Delta I'_1$ represent the slope discontinuities in the current function at the points z_1 . Of course, $I'(z_1 - \epsilon) = I'(z_1 + \epsilon) = 0$.

In a similar manner, it is found that the radial field is

$$(7) \quad E_\rho(\rho, z) = \frac{-1}{4\pi\omega\epsilon\rho} \sum_{i=1}^n \Delta I'_1 e^{-jk r_1} \cos \theta_1$$

Despite their extreme simplicity, the new field expressions (5) and (7) are rigorous even in the near-zone.

IV. THE N-SEGMENT INDUCED EMF TECHNIQUE

To introduce the N-segment induced emf technique, consider first the two-segment solution.

For a linear or V antenna, we replace the original source with equivalent surface currents

$$(8) \quad \underline{J} = \hat{n} \times \underline{H}$$

$$(9) \quad \underline{M} = \underline{E} \times \hat{n}$$

on the closed surface S of the antenna. The outward unit normal vector on S is denoted $\hat{n}$, and the electric and magnetic current densities $\underline{J}$ and $\underline{M}$ are called the "true sources". From the equivalence principle of Schelkunoff,⁸ $\underline{J}$ and $\underline{M}$ generate the true field outside S and a null field in the interior region. For perfectly conducting antennas, $\underline{M}$ vanishes except in the gap region.

Now we place a filamentary electric line source on the axis of the antenna and "react" this "test source" with the true source. (React means apply the reciprocity theorem.) In this step the tube of electric surface-current density $\underline{J}$ can usually be replaced with an equivalent filamentary source parallel with the test source. These two line sources have a sideways displacement equal to the wire radius.

The current distribution on the test dipole is given by

$$(10) \quad I_t(z) = \frac{\sin k(h - |z|)}{\sin kh}$$

where h is the arm length, z is measured from the center, and $k = 2\pi/\lambda$.

In a two-segment solution, the current on the true source is expressed by

$$(11) \quad I(z) = I_1 \frac{\sin k(l_1 - |z|)}{\sin kh}$$

and the objective is to determine the terminal current I_1 excited by a given voltage generator V_1 . From the reciprocity theorem, the solution is found from

$$(12) \quad I_1 Z = V_1$$

where Z is the reaction between the test source and the true source:

$$(13) \quad Z = -\frac{1}{I_1} \oint_S \underline{J} \cdot \underline{E}_t \, ds$$

The field of the test source is denoted by $(\underline{E}_t, \underline{H}_t)$. It may be noted that our two-segment solution for the linear antenna coincides with the induced emf theory presented in many textbooks.

Figure 3 illustrates the two-segment solution for the mutual impedance between coplanar linear dipoles as a function of the angle ψ between their axes. Figures 4, 5, and 6 show the two-segment solution for the mutual impedance between coplanar V dipoles. Figure 7 compares the two-segment solution with Schelkunoff's result for the self impedance of a single V antenna.

Schelkunoff⁹ demonstrated the variational property of the induced emf formulation. He states that the similar expression obtained from the energy theorem lacks this property and the distinction between them vanishes when the antenna current is approximated in the two-segment sinusoidal manner.

The two-segment solution is, of course, useful only for a limited range of antenna lengths and radii. Therefore, let us consider next the four-segment solution for a single linear antenna. (The extension to the N-segment solution for single and coupled antennas will then be obvious.) If the terminals are located at the center, the antenna is divided into four equal segments as shown in Fig. 8.

The unknown current distribution on the antenna is expanded in the piecewise-sinusoidal fashion described in Section III. The complex constants I_1 and I_2 represent samples of the current function $I(z)$;

$$(14) \quad I_1 = I(0)$$

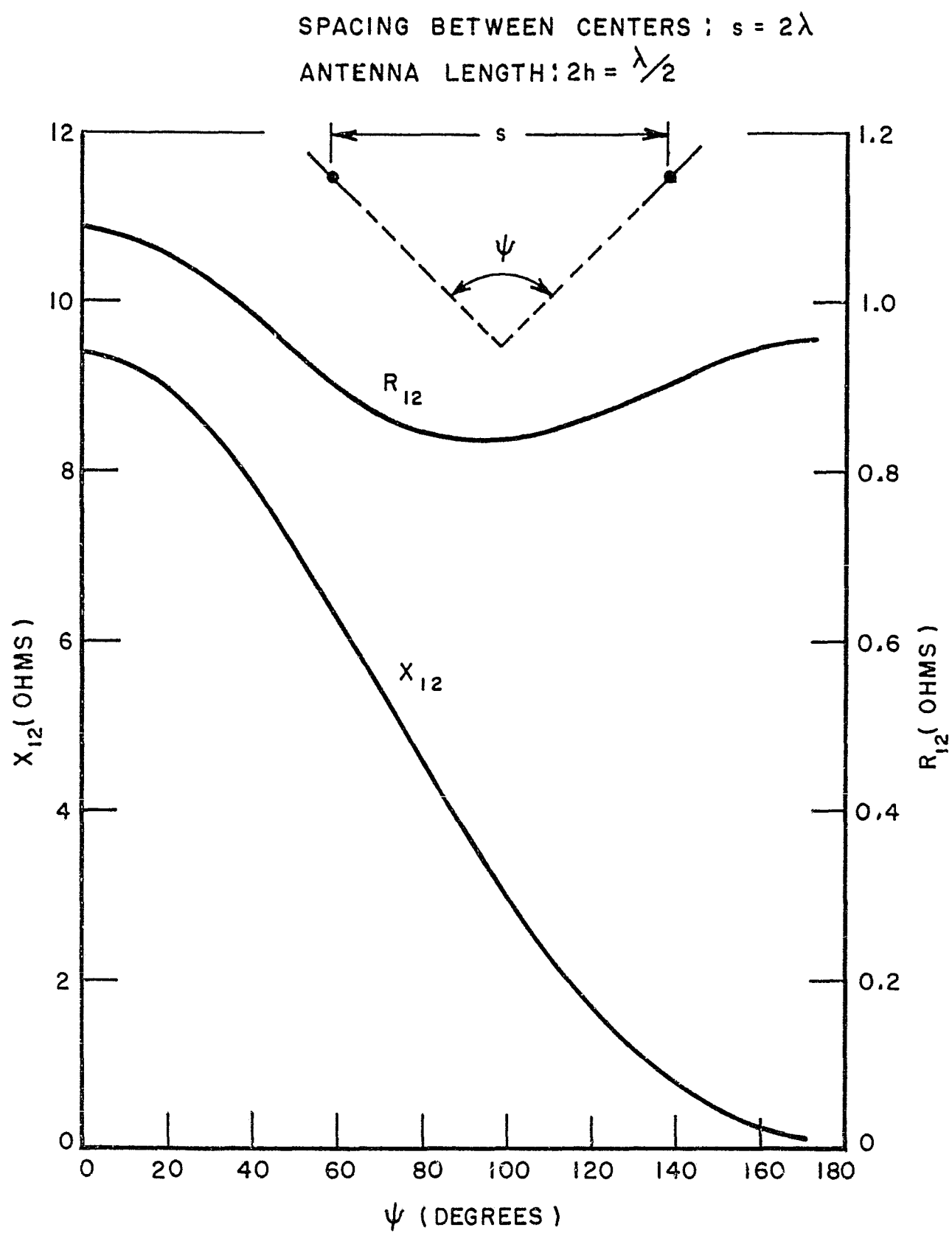


Fig. 3. Mutual impedance between coplanar skew antennas.

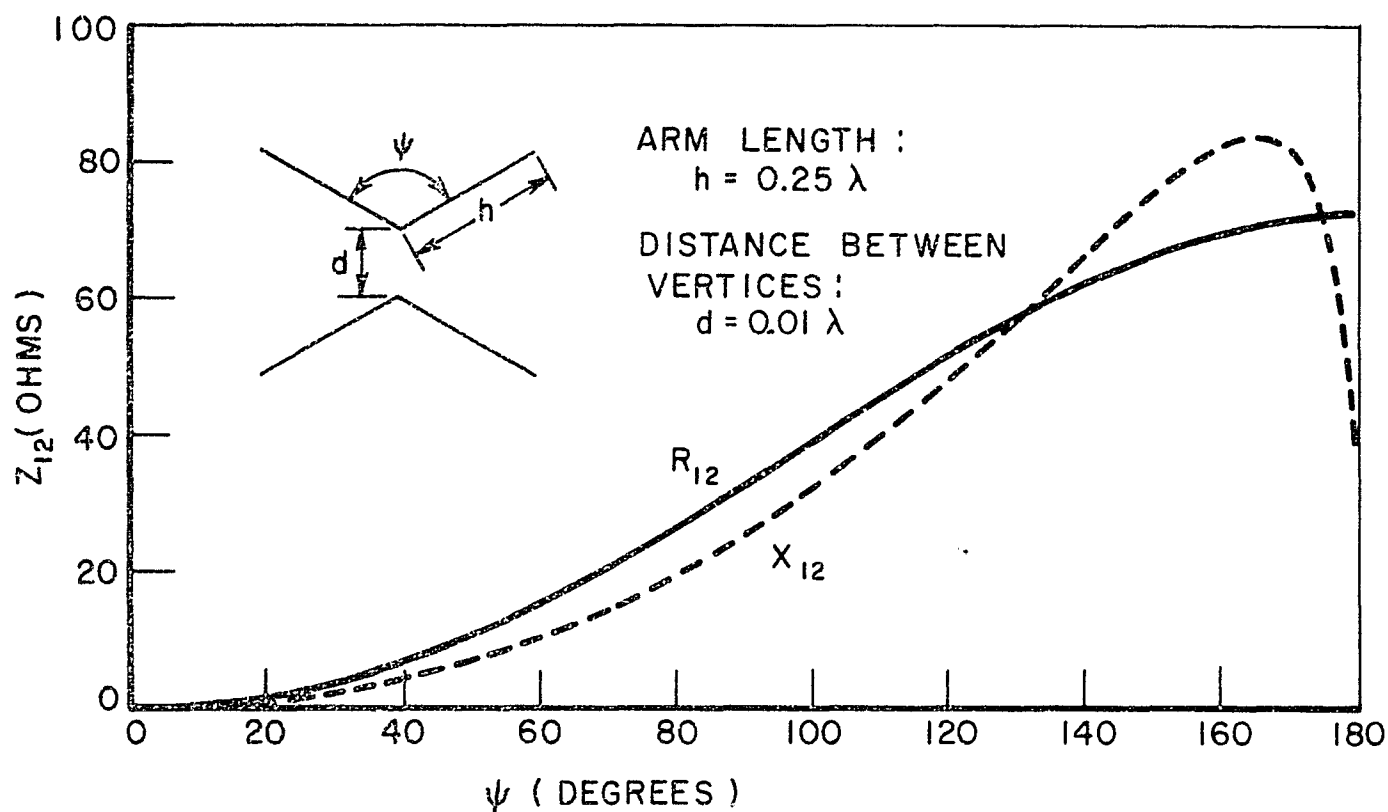


Fig. 4. Mutual impedance between coplanar V antennas.

$$(15) \quad I_2 = I(h/2)$$

and the current is assumed to vanish at the ends of the antenna.
 Thus,

$$(16) \quad I(z) = I_1 \frac{\sin k(h/2-z)}{\sin kh/2} + I_2 \frac{\sin kz}{\sin kh/2} \quad \text{for } 0 \leq z \leq h/2$$

$$(17) \quad I(z) = I_2 \frac{\sin k(h-z)}{\sin kh/2} \quad \text{for } h/2 \leq z \leq h$$

The objective is to determine I_1 and I_2 . This is accomplished by applying two reaction tests on the true current $I(z)$. One equation is obtained by reacting $I(z)$ with a test dipole centered on the antenna axis as in Fig. 8. This test dipole has arm length $h/2$. The dipole is then moved to the right a distance $h/2$ and reacted with $I(z)$. This yields a pair of simultaneous linear equations:

$$(18) \quad I_1 Z_{11} + I_2 Z_{12} = V_1$$

$$(19) \quad I_1 Z_{21} + I_2 Z_{22} = 0$$

Z_{11} and Z_{22} represent the mutual impedance between parallel filamentary dipoles with sideways displacement a and no stagger. In Z_{12} and Z_{21} the dipoles are in echelon with displacement a and stagger $h/2$. The impedance matrix is made symmetric by doubling Z_{21} and Z_{22} in Eq. (19).

Figures 9 and 10 illustrate the results obtained with the N-segment solution for a single linear antenna. As N is increased, the impedance converges rapidly and monotonically to the 32-segment data of Harrington.¹⁰

V. EXPERIMENTAL VERIFICATION

Figures 11 and 12 compare our four-segment solution, Schelkunoff's mode theory and experimental measurements for the admittance of a single V antenna. These curves cover the resonance region. In the experimental measurements, a single monopole was located on a large ground plane and fed with a coaxial line. The monopole axis was inclined at a 30 degree angle from the normal. Image theory was employed to relate the measurements to the admittance of a complete V antenna in free space. Some deviation is to be expected between the experimental data for the brass antennas and the calculations for perfectly conducting antennas. The measurements were carried out at 375 MHz. Figures 11 and 12 clearly verify the accuracy of our new solution, and there is substantial evidence for expecting even better results from a six-segment calculation.

Similar measurements were conducted with the V monopole mounted on a hemisphere over a ground plane. The coaxial feed extended through the ground plane to the surface of the hemisphere.

The results for hemispheres with 5 cm and 10 cm diameters (when compared with Fig. 11 where there is no hemisphere) suggest that the spacecraft influence on the impedance may be negligible for the ATS-E satellite in the frequency range of interest. Additional information on the spacecraft effect is presented in Appendix I.

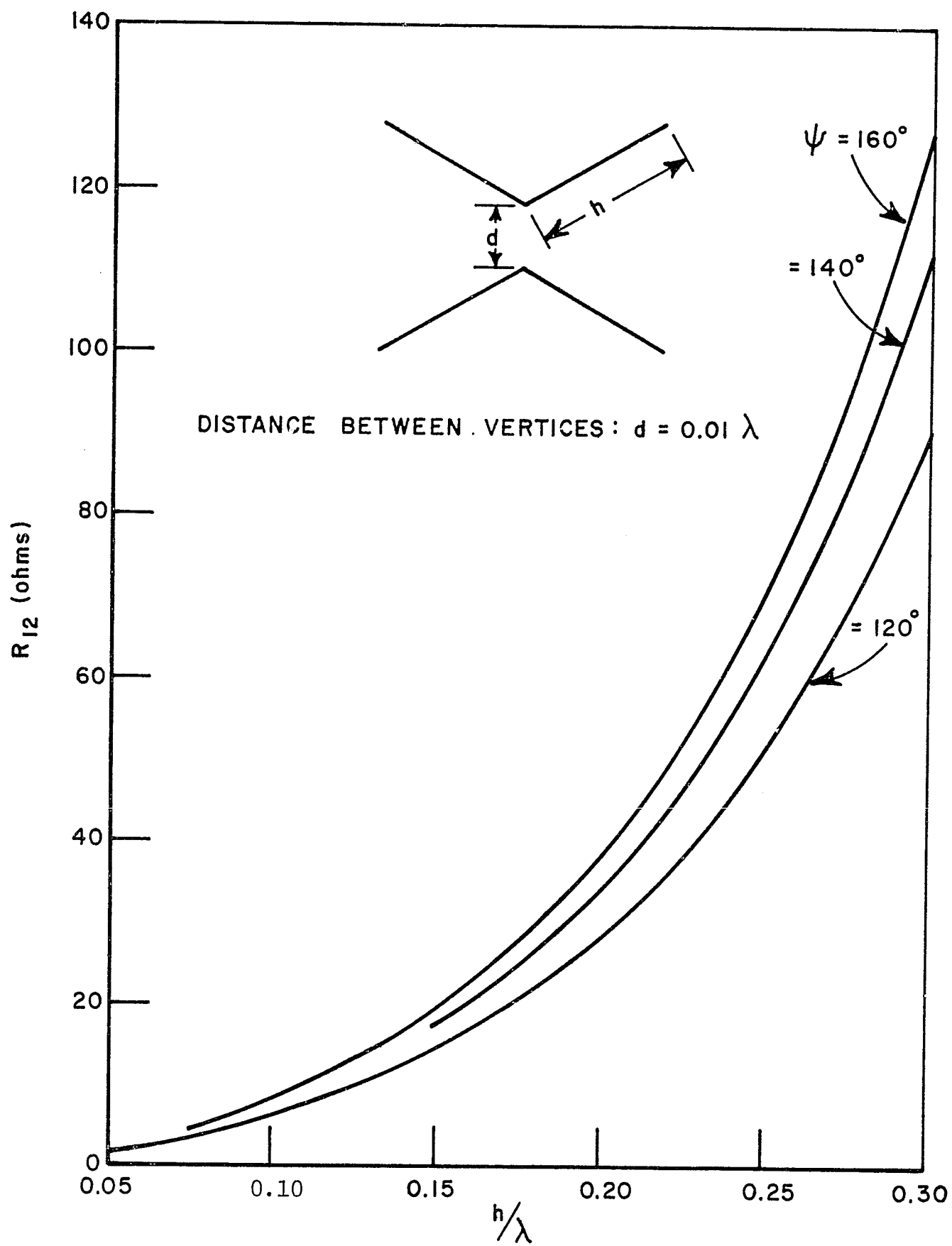


Fig. 5. Mutual resistance between coplanar V antennas.

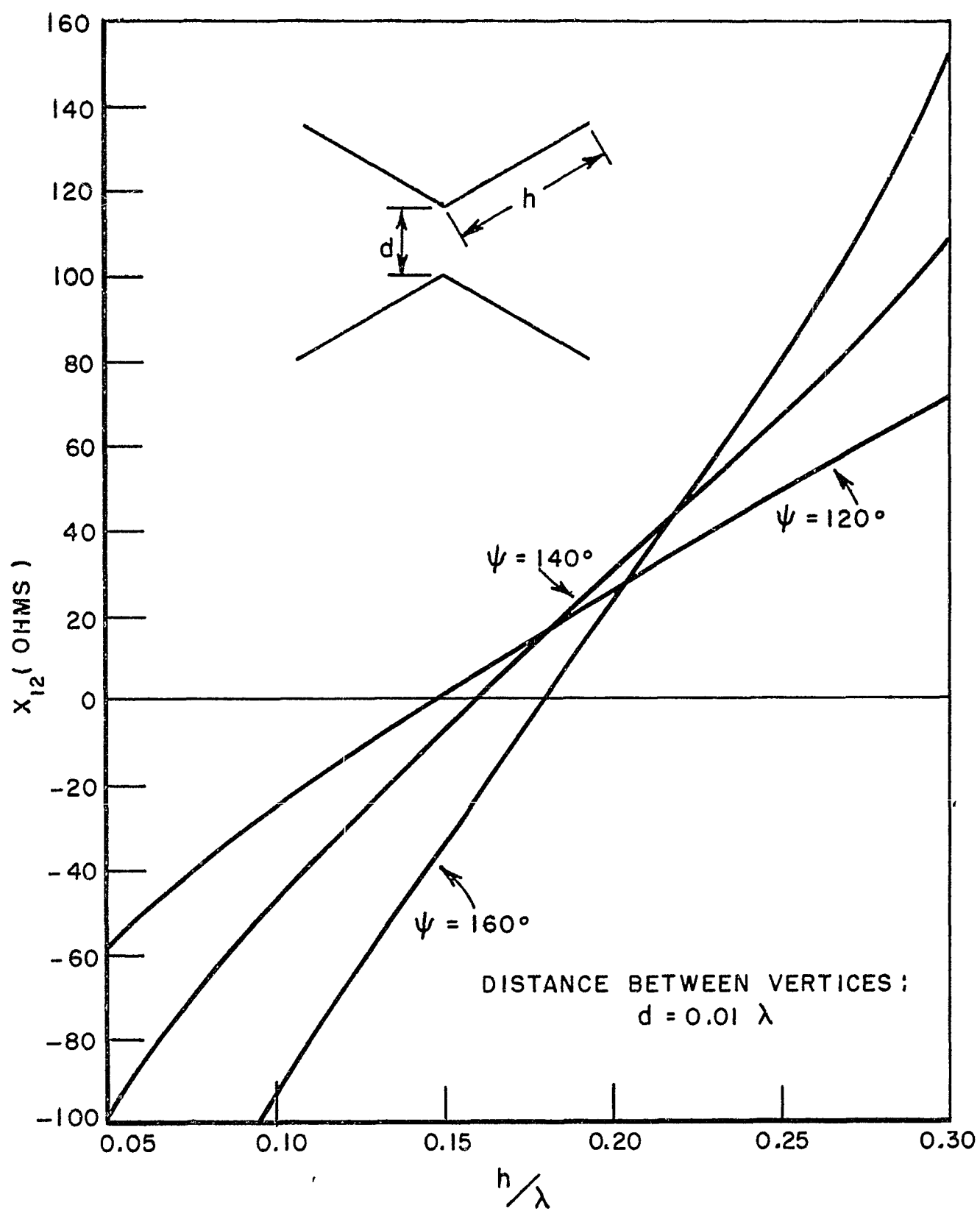


Fig. 6. Mutual reactance between coplanar V antennas.

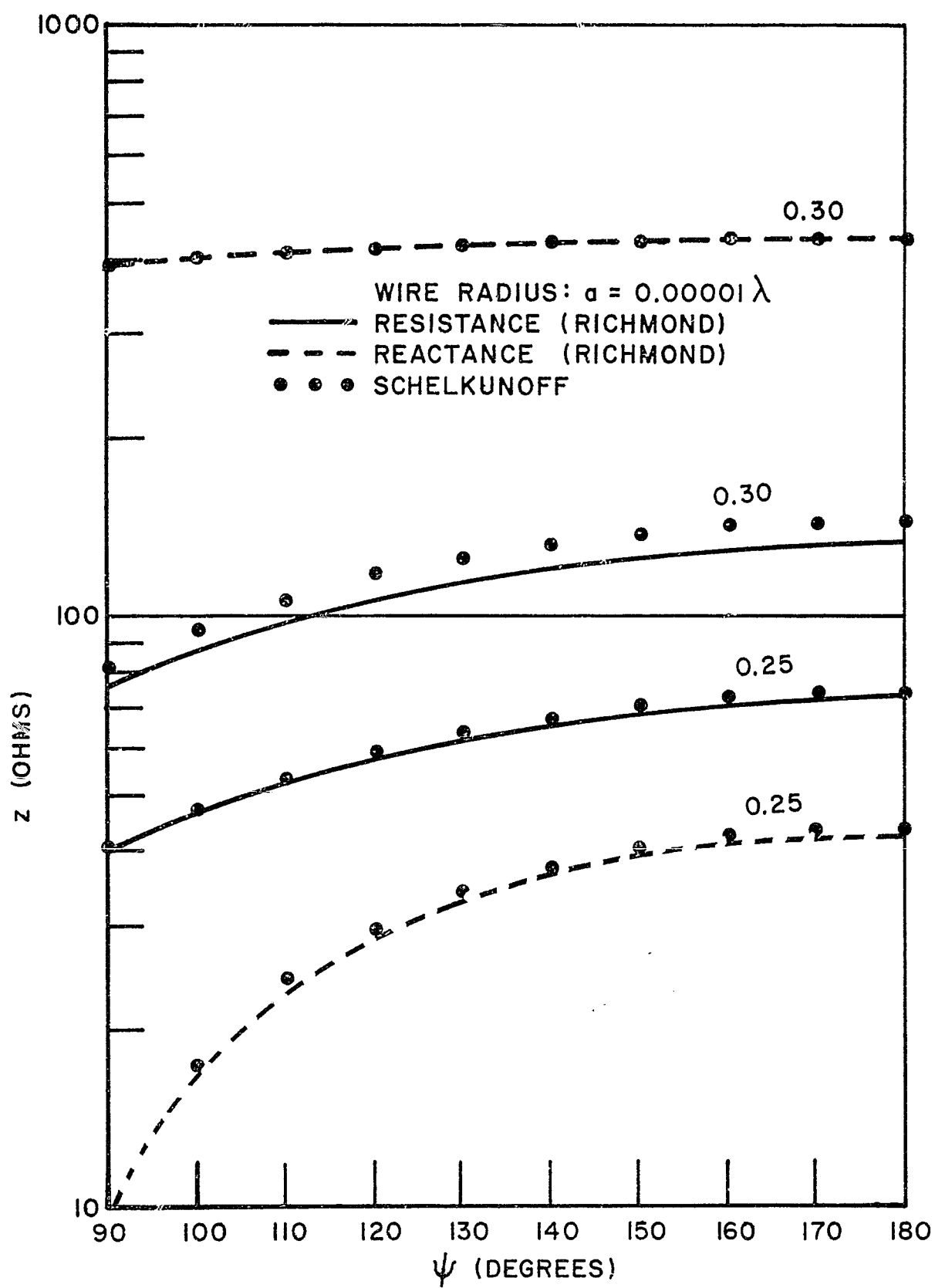


Fig. 7. Self impedance of single V antenna versus the V angle ψ .
 The parameter is the arm length h/λ .

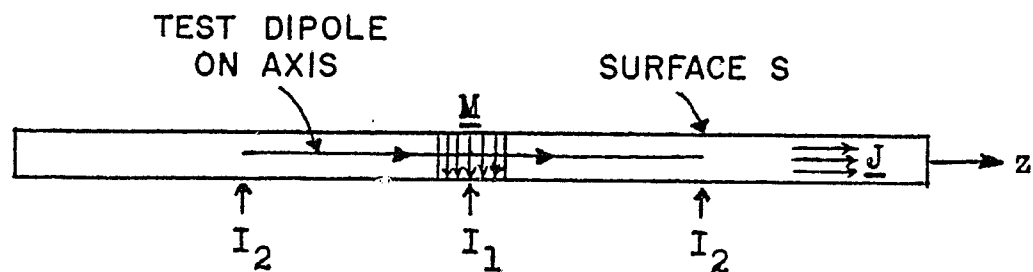


Fig. 8. In the four-segment solution, the antenna is divided into four segments for a piecewise-sinusoidal current expansion.

VI. THE GEOMETRY OF THE ANTENNA SYSTEM

The antenna system for radio astronomy experiments is illustrated in Fig. 13. One V antenna serves as a receiver and the other is "floating" with eight-pound tip masses for gravity stabilization. The insulated tip masses increase slightly the effective length of each antenna.

The floating V is open-circuited at its terminals. However, the mounting system introduces a shunt capacitance of approximately 50 pf treated as an effective lumped load.

The arm length h of each V antenna is 123 ft., the vertices are approximately 3 feet apart, and the cylindrical satellite has a diameter of 5 ft. The V antennas are symmetric and coplanar. The libration damper, prominent in Fig. 13, has an overall length of 90 ft. The numerical data presented in this report apply when the libration damper is in its "nominal position". In this position the libration boom has no mutual coupling with the V antennas, and the impedance and pattern perturbations are minimized.

The antenna and libration booms are thin-wall cylindrical tubes with a diameter of 0.5 inch. The beryllium-copper alloy has a conductivity of 20 megamhos/m and a thickness of 2 mils.

The surface impedance of these hollow tubes is defined by the ratio of the tangential electric and magnetic field intensities at the outer surface. Figure 14 shows the surface impedance versus frequency, using an analysis similar to that of Ramo and Whinnery.¹¹

In the calculations, Z_s is increased by the factor 1.35 to account for a periodic array of holes in the beryllium-copper shell. These holes reduce the conducting surface area by 15 per cent.

The following sections present numerical results for this antenna system, using a four-segment piecewise-sinusoidal current expansion.

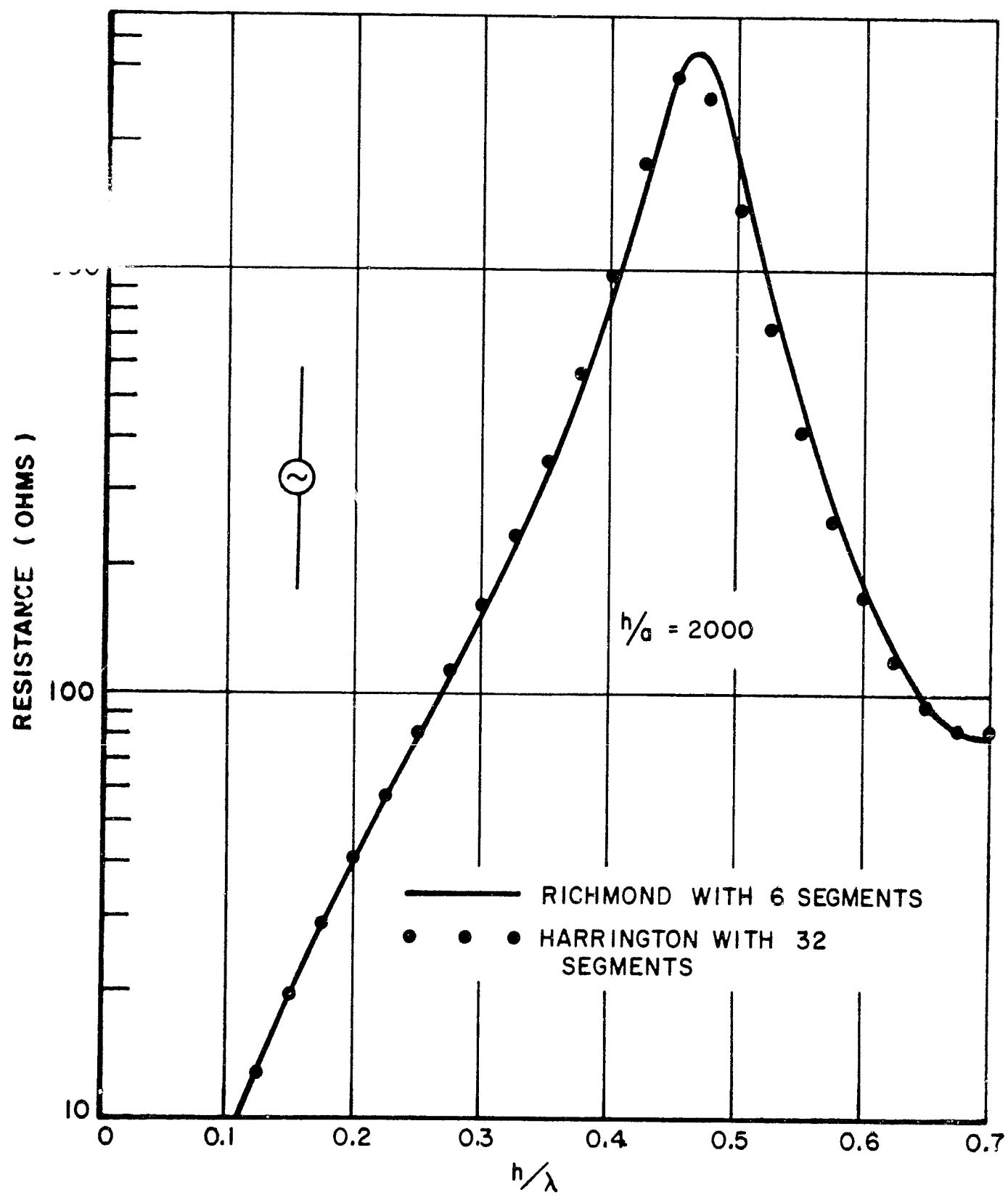


Fig. 9. Input resistance versus h/λ for cylindrical-wire antenna with radius a and total length $L = 2h$.

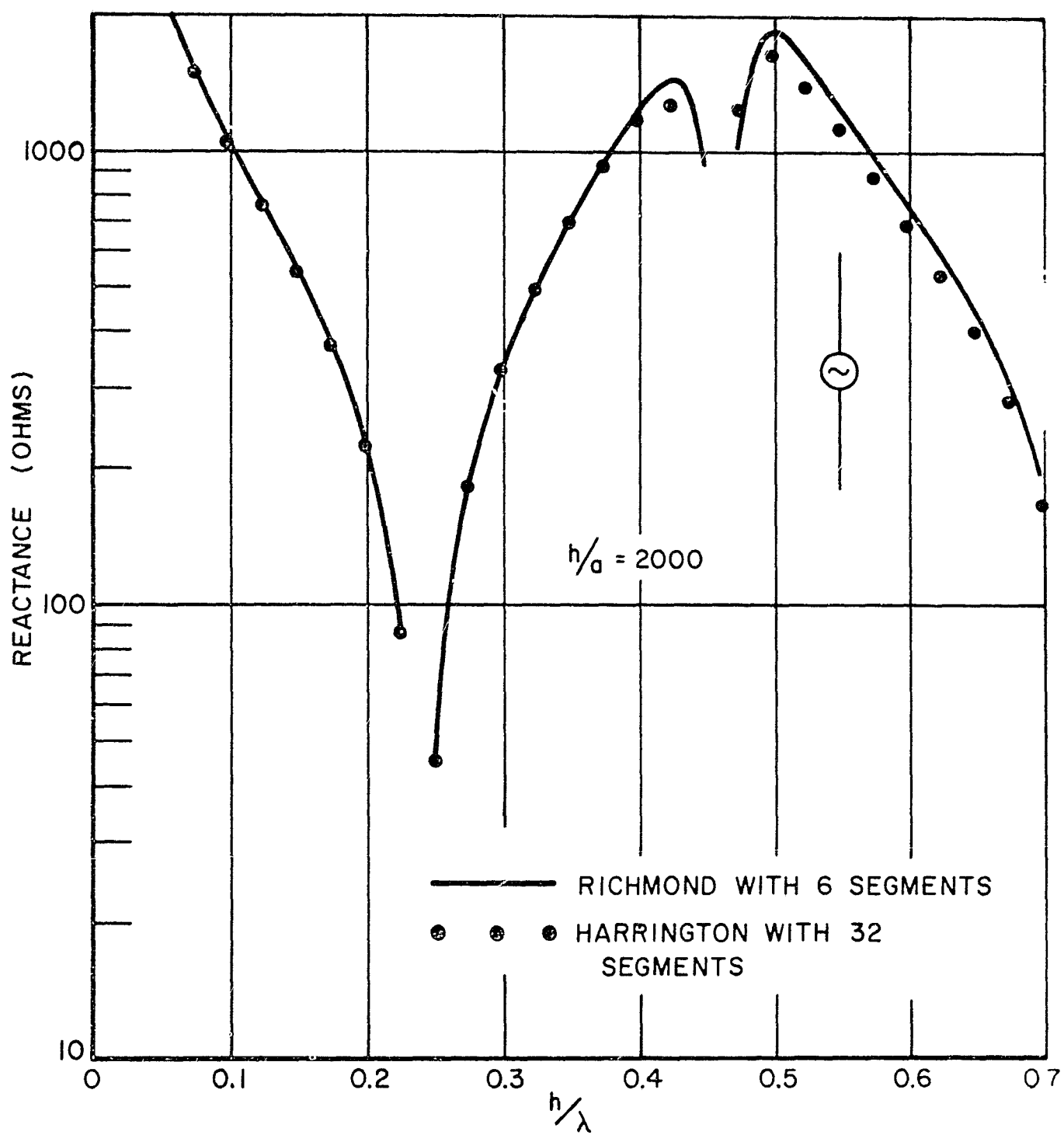


Fig. 10. Input reactance versus h/λ for cylindrical-wire antenna with radius a and total length $L = 2h$.

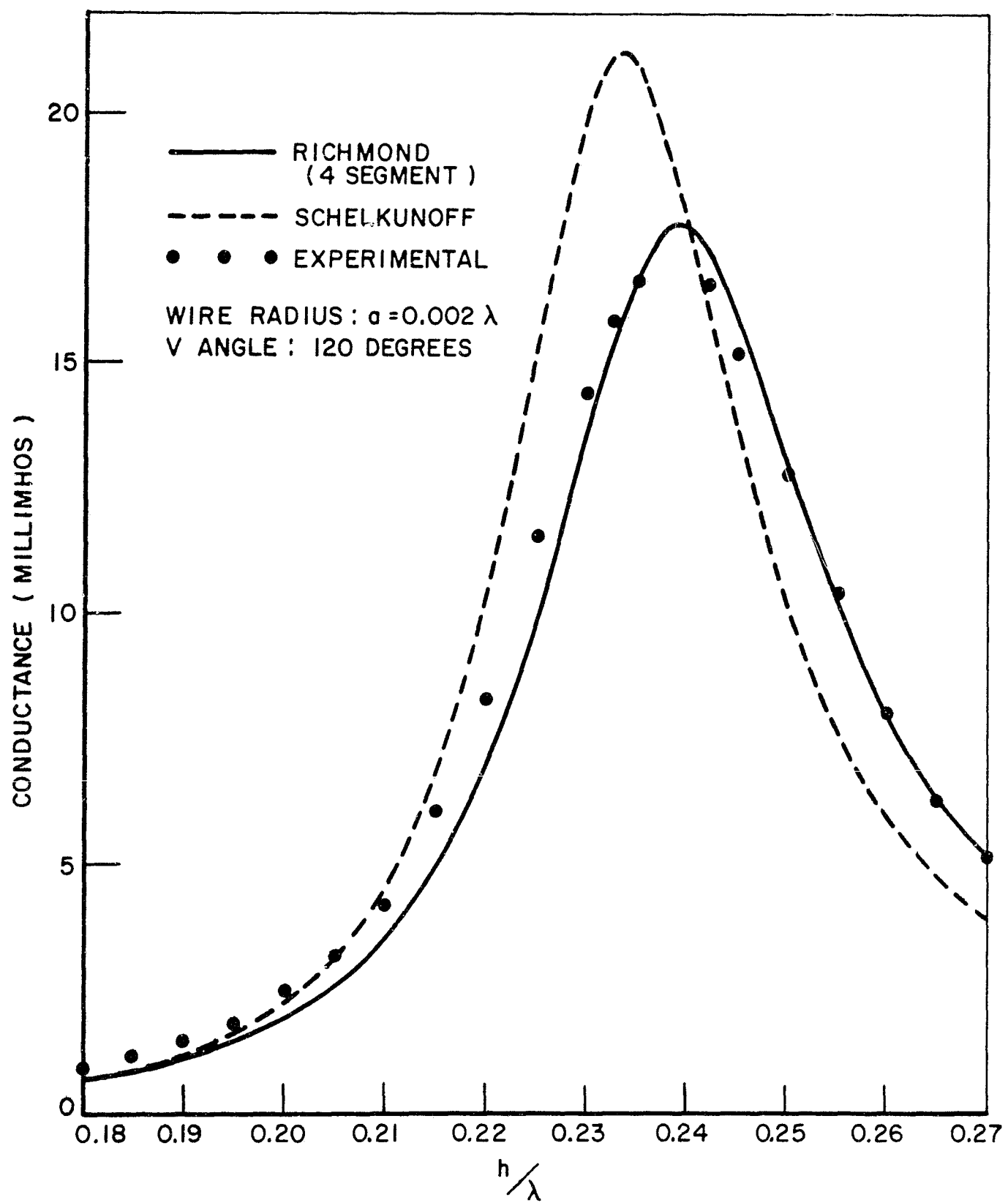


Fig. 11. Experimental and theoretical conductance of single V antenna.

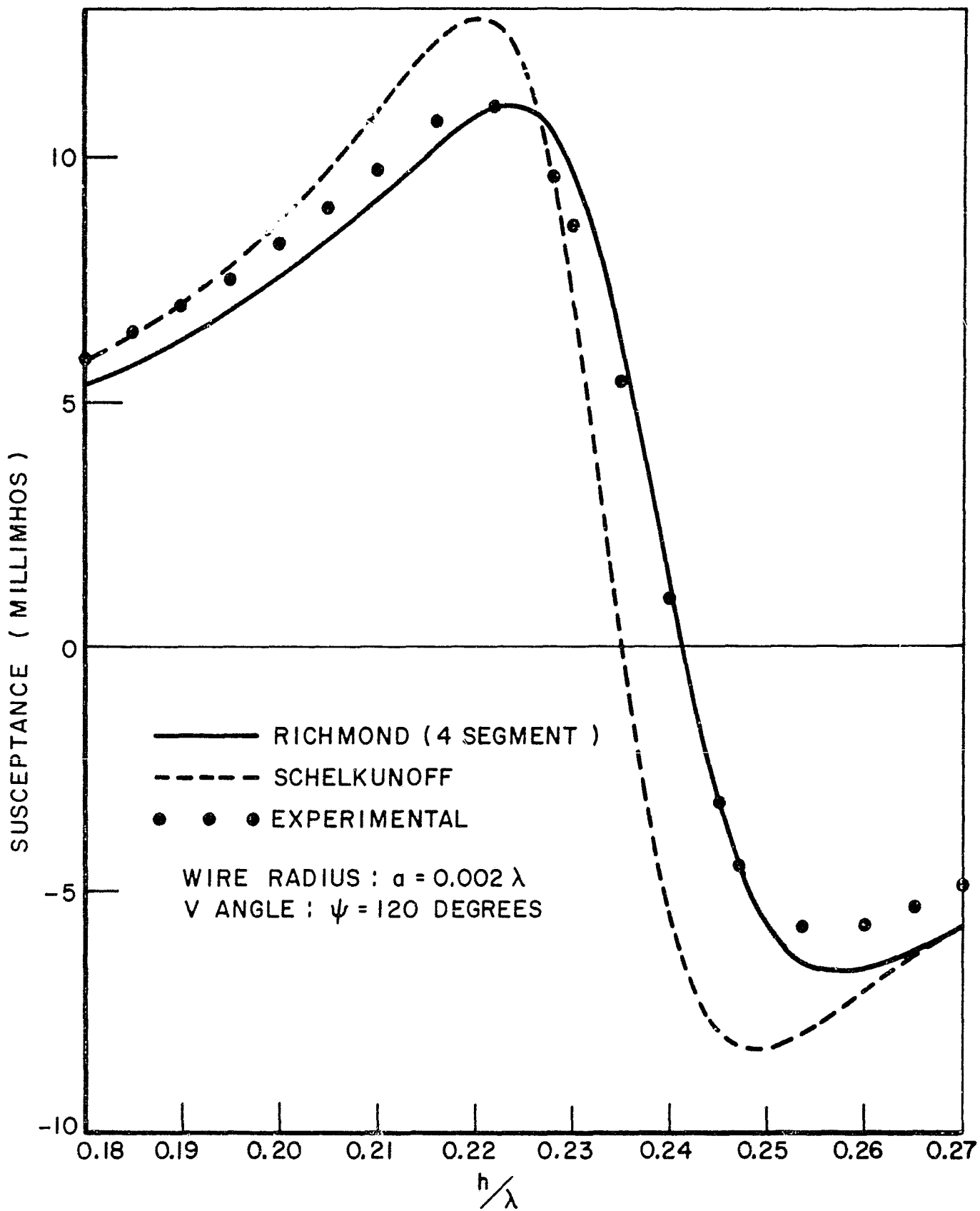
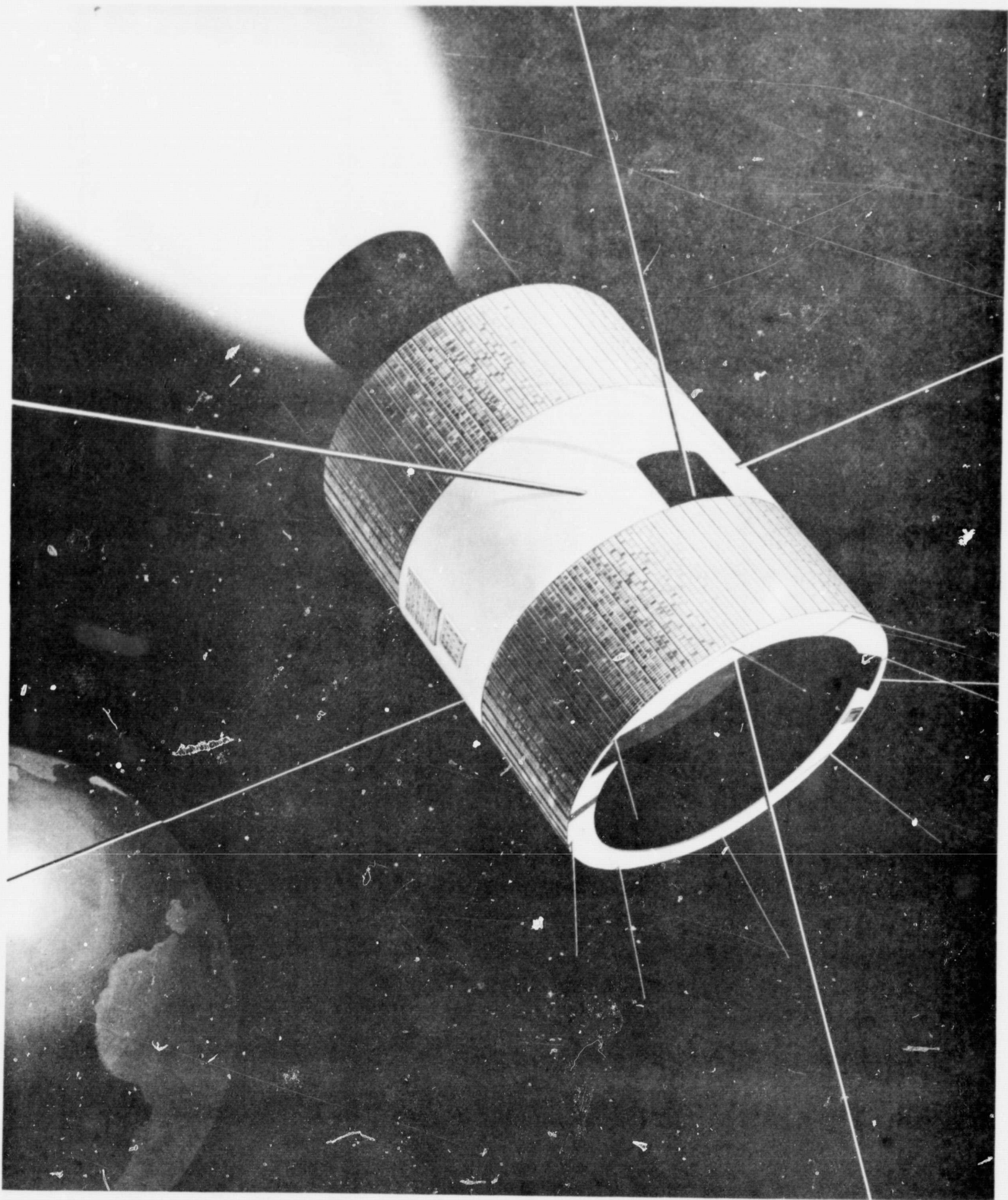


Fig. 12. Experimental and theoretical susceptance of single V antenna.



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Fig. 13. A satellite similar to the one considered in this investigation.

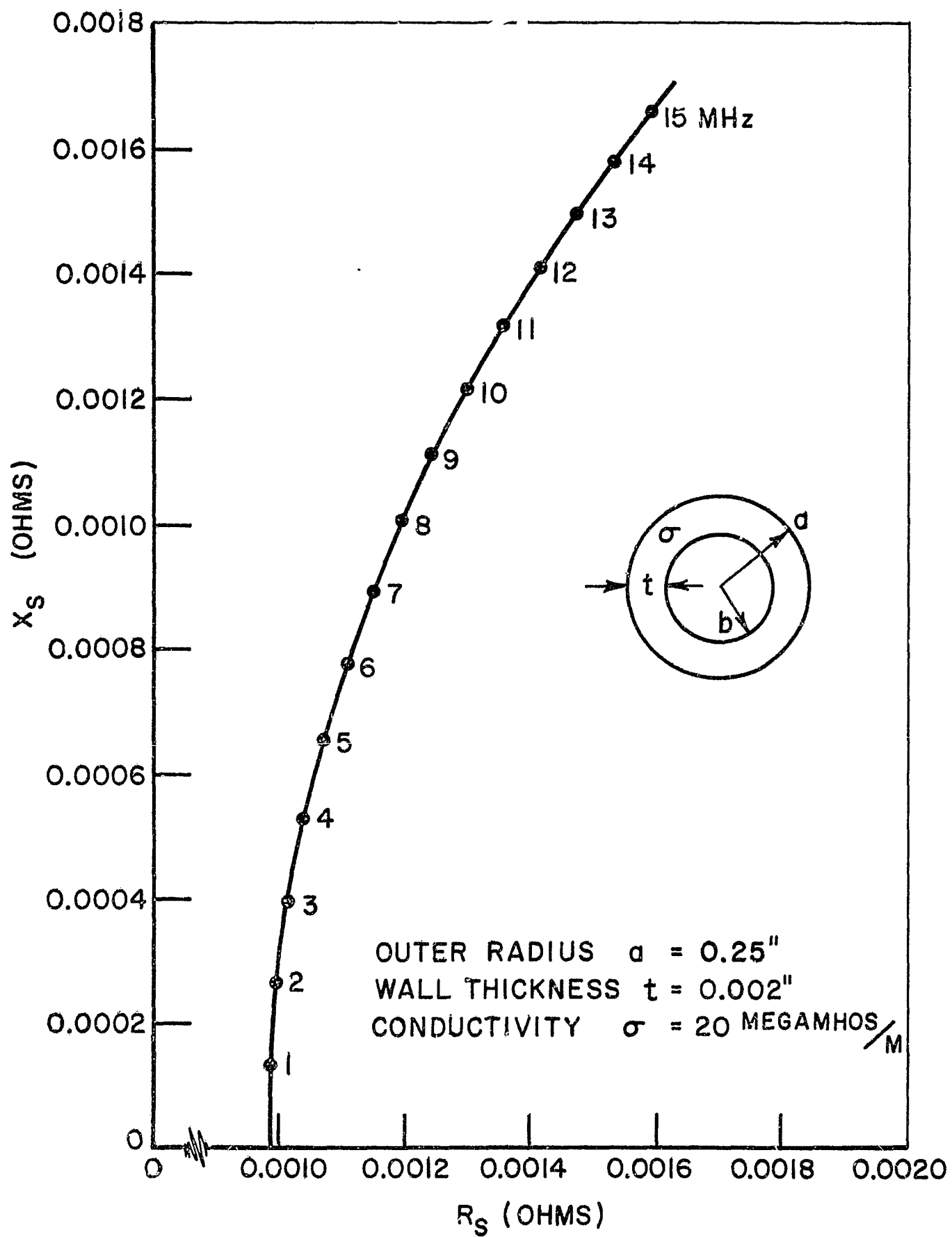


Fig. 14. Surface impedance Z_s of the thin-wall cylinders without holes.

VII. CURRENT DISTRIBUTION

As indicated in Fig. 15, I_1 and I_2 represent the current samples on the driven V and I'_1 and I'_2 are the corresponding samples on the floating V with capacitive load. The antenna terminals are located at the vertices, and the samples I_2 and I'_2 are defined at the midpoints of the arms. It is found that the calculated results are also applicable with terminals at the cylindrical surface of the satellite.

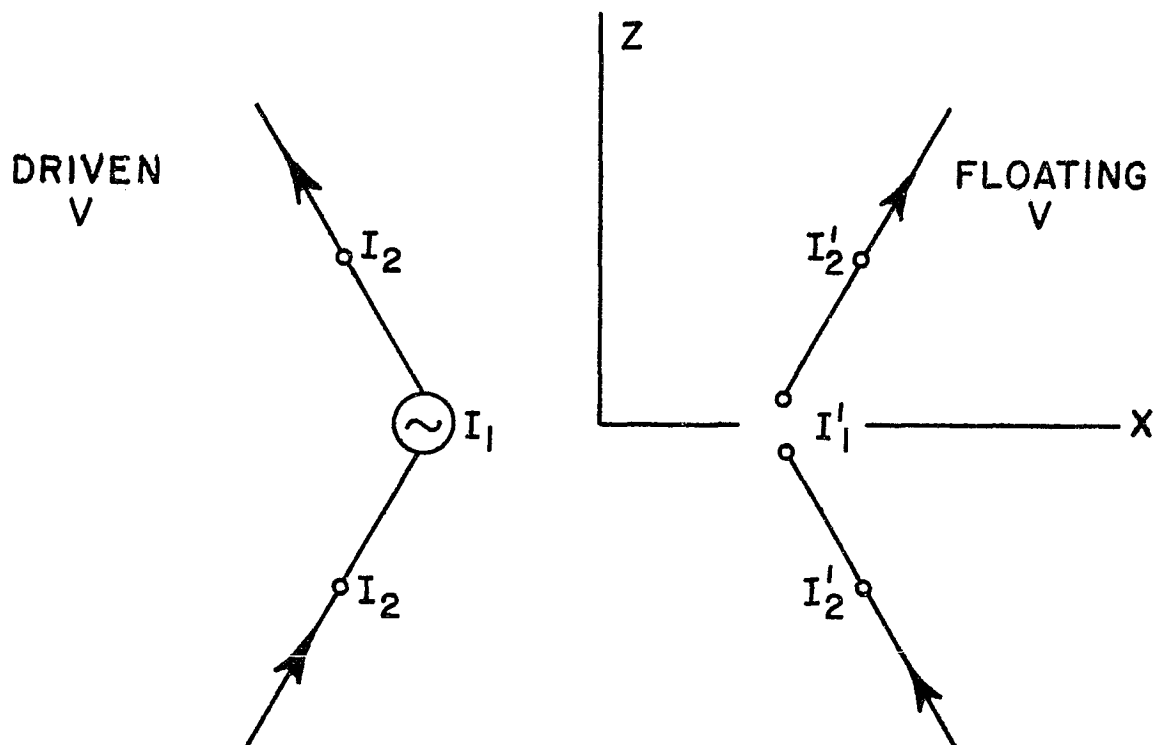


Fig. 15. The coupled V antennas and the coordinate system.

In the four-segment solution, the current distribution on the coupled V antennas is determined completely by the four samples and sinusoidal interpolation as in Eqs. (16) and (17). With a unit current generator applied to the driven antenna, $I_1 = 1$ and Tables I, II and III list the real and imaginary parts of I_2 , I'_1 and I'_2 .

VIII. IMPEDANCE

Tables IV, V and VI list the input impedance of the driven antenna. As in all the tables, these data include the effects of the floating V and imperfect conductivity.

IX. RADIATION EFFICIENCY

The radiation efficiency,¹² defined by the ratio of the radiated power to the input power, is listed in Table VII.

X. DIRECTIVITY

The directivity¹² is defined by the directive gain in the direction of the maximum. The data in Table VIII represent the largest directive gains encountered in the principal planes with ten-degree angular increments.

No experimental data are available for comparison with Table VIII. The directivity published by Schelkunoff¹ pertains to a single V antenna.

XI. ACCURACY AND LIMITATIONS

The N-segment induced emf technique was developed for accurate and efficient calculations of impedance, radiation efficiency and field patterns. No attempt is made to determine the precise current distributions in the gap region or near the ends of the wires. The limitations on wire radius are unknown, but the two-segment and four-segment solutions have proven accurate for thin wires (Fig. 7) and thicker wires (Figs. 11 and 12), respectively. As the radius a/λ or the length h/λ increases, the antenna is divided more finely into segments.

More definite information on the assured accuracy can be obtained best with additional computations and experimental measurements.

XII. SUMMARY

A multi-segment induced emf technique has been developed for thin-wire antenna and array problems. The technique, based on the reciprocity theorem and reaction concepts, is presented in this report. Several graphs are included to compare our two-segment calculations with Schelkunoff's results, four-segment calculations with experimental measurements performed at this laboratory, and six-segment calculations with Harrington's data. A careful study of this evidence, together with additional results not included herein, indicates that the computations for the ATS-E radio astronomy experiment have an accuracy within the normal range of experimental uncertainties.

Tables I through VIII present the current distributions, impedance, radiation efficiency and directivity for the wide V antenna. These include the effects of imperfect conductivity, the floating V, and the libration damper in its nominal position.

Figures A-1 through A-60 present in polar form the principal-plane antenna patterns for three V angles and twenty frequencies. For the convenience of the reader, these power patterns are normalized. The corresponding data for directive gain and power gain are supplied on magnetic tape with ten-degree angular increments.

The digital computer programs developed in this investigation are particularly efficient. With an IBM 7094 computer, the execution time was 6 minutes for the complete analysis of the ATS-E antenna characteristics.

TABLE I
Current distribution vs. frequency for $\psi = 124^\circ$

<u>Frequency</u>	<u>I₂</u>		<u>I₁</u>		<u>I₂</u>	
60 KHz	0.479	0.000	-0.013	0.000	0.001	-0.000
128	0.480	-0.000	-0.013	0.000	0.001	0.000
188	0.481	-0.000	-0.013	-0.000	0.001	-0.000
258	0.482	-0.000	-0.013	-0.000	0.001	-0.000
407	0.487	-0.000	-0.012	-0.000	0.001	-0.000
567	0.494	-0.000	-0.011	-0.000	0.003	-0.001
736	0.505	-0.001	-0.009	-0.001	0.005	-0.001
916	0.521	-0.002	-0.006	-0.002	0.008	-0.003
1104	0.541	-0.004	-0.002	-0.004	0.012	-0.005
1315	0.571	-0.007	0.003	-0.007	0.017	-0.010
1537	0.612	-0.012	0.011	-0.012	0.025	-0.018
1781	0.670	-0.021	0.022	-0.023	0.037	-0.033
1913	0.708	-0.028	0.029	-0.032	0.045	-0.047
2053	0.757	-0.038	0.038	-0.046	0.054	-0.067
2202	0.818	-0.054	0.050	-0.068	0.066	-0.101
2353	0.892	-0.075	0.061	-0.106	0.076	-0.157
2697	1.111	-0.157	0.006	-0.348	-0.030	-0.517
3086	1.835	-0.283	-0.610	0.271	-1.027	0.447
3546	3.082	-3.340	0.256	0.409	0.212	0.923
4102	-2.337	-1.659	-0.035	-0.192	0.204	-0.198

TABLE II
Current distribution vs. frequency for $\psi = 136^\circ$

<u>Frequency</u>	<u>I₂</u>		<u>I₁</u>		<u>I₂</u>	
60 KHz	0.480	-0.000	-0.018	0.000	0.000	0.000
128	0.480	-0.000	-0.018	0.000	0.000	0.000
188	0.481	-0.000	-0.018	-0.000	0.001	-0.000
258	0.483	-0.000	-0.017	-0.000	0.001	-0.000
407	0.487	-0.000	-0.017	-0.000	0.001	-0.000
567	0.495	-0.000	-0.015	-0.000	0.003	-0.001
736	0.506	-0.001	-0.013	-0.001	0.005	-0.002
916	0.522	-0.002	-0.009	-0.002	0.009	-0.003
1104	0.542	-0.004	-0.005	-0.004	0.013	-0.006
1315	0.572	-0.007	0.002	-0.007	0.020	-0.011
1537	0.613	-0.013	0.011	-0.014	0.030	-0.020
1781	0.671	-0.023	0.026	-0.026	0.045	-0.038
1913	0.710	-0.031	0.035	-0.036	0.056	-0.053
2053	0.758	-0.042	0.048	-0.053	0.069	-0.077
2202	0.819	-0.059	0.063	-0.080	0.085	-0.117
2353	0.891	-0.084	0.080	-0.125	0.102	-0.184
2697	1.090	-0.177	0.026	-0.416	-0.003	-0.616
3086	1.784	-0.195	-0.761	0.183	-1.267	0.304
3546	3.334	-3.328	0.190	0.580	0.029	1.226
4102	-2.389	-1.631	0.003	-0.221	0.309	-0.195

TABLE III
Current distribution vs. frequency for $\psi = 154^\circ$

<u>Frequency</u>	<u>I_2</u>		<u>I_1'</u>		<u>I_2'</u>	
60 KHz	0.480	0.000	-0.029	0.000	-0.002	-0.000
128	0.480	-0.000	-0.029	-0.000	-0.002	-0.000
188	0.481	-0.000	-0.029	-0.000	-0.002	-0.000
258	0.483	-0.000	-0.028	-0.000	-0.001	-0.000
407	0.488	-0.000	-0.027	-0.000	-0.001	-0.000
567	0.495	-0.000	-0.025	-0.000	0.001	-0.001
736	0.506	-0.001	-0.022	-0.001	0.004	-0.002
916	0.522	-0.002	-0.018	-0.002	0.008	-0.003
1104	0.543	-0.004	-0.012	-0.004	0.014	-0.006
1315	0.573	-0.008	-0.003	-0.008	0.024	-0.012
1537	0.613	-0.014	0.010	-0.015	0.037	-0.022
1781	0.672	-0.025	0.030	-0.029	0.058	-0.043
1913	0.711	-0.034	0.044	-0.042	0.073	-0.061
2053	0.759	-0.047	0.062	-0.062	0.094	-0.089
2202	0.819	-0.067	0.085	-0.095	0.120	-0.137
2353	0.890	-0.097	0.114	-0.151	0.152	-0.220
2697	1.058	-0.219	0.081	-0.325	0.072	-0.770
3086	1.601	-0.060	-0.948	-0.047	-1.559	-0.059
3546	4.099	-2.817	-0.153	0.846	-0.699	1.651
4102	-2.637	-1.530	0.069	-0.247	0.529	-0.161

TABLE IV
Impedance vs. frequency for $\psi = 124^{\circ}$

<u>Frequency</u>	<u>R</u>	<u>X</u>
60 KHz	0.84	-19332.3
128	0.96	- 9038.0
188	1.13	- 6129.2
258	1.42	- 4437.0
407	2.36	- 2753.4
567	3.89	- 1908.7
736	6.17	- 1395.2
916	9.47	- 1037.0
1104	14.12	- 768.1
1315	21.21	- 535.1
1537	31.65	- 333.2
1781	48.32	- 137.0
1913	60.66	- 35.6
2053	77.39	71.4
2202	100.88	187.4
2353	133.16	309.1
2697	250.63	592.0
3086	301.79	1343.9
3546	3272.10	2495.4
4102	1374.56	- 2273.9

TABLE V
Impedance vs. frequency for $\psi = 136^0$

<u>Frequency</u>	<u>R</u>	<u>X</u>
60 KHz	0.84	-19386.7
128	0.97	- 9063.2
188	1.17	- 6146.1
258	1.49	- 4448.9
407	2.51	- 2760.2
567	4.19	- 1912.7
736	6.69	- 1397.3
916	10.33	- 1037.7
1104	15.46	- 767.4
1315	23.32	- 533.2
1537	34.94	- 330.0
1781	53.66	- 132.5
1913	67.65	- 30.6
2053	86.78	76.9
2202	113.98	192.9
2353	151.98	313.4
2697	294.01	569.3
3086	206.95	1260.6
3546	3248.85	2747.0
4102	1358.06	- 2318.4

TABLE VI
Impedance vs. frequency for $\psi = 154^\circ$

<u>Frequency</u>	<u>R</u>	<u>X</u>
60 KHz	0.85	-19410.4
128	0.99	- 9074.1
188	1.20	- 6153.2
258	1.54	- 4453.9
407	2.66	- 2762.8
567	4.49	- 1913.9
736	7.22	- 1397.5
916	11.20	- 1037.0
1104	16.84	- 765.9
1315	25.56	- 530.7
1537	38.60	- 326.4
1781	60.03	- 127.3
1913	76.38	- 24.4
2053	99.23	84.1
2202	132.67	200.9
2353	181.33	321.0
2697	383.97	535.6
3086	80.87	991.3
3546	2690.51	3441.9
4102	1275.67	- 2496.0

TABLE VII
Radiation efficiency vs. frequency for the three ν angles

<u>Frequency</u>	<u>124⁰</u>	<u>136⁰</u>	<u>154⁰</u>
60 KHz	3.9%	4.3%	4.6%
128	15.6	16.9	18.1
188	28.6	30.5	32.3
258	43.0	45.3	47.4
407	65.3	67.4	69.1
567	78.6	80.1	81.4
736	86.2	87.3	88.2
916	90.7	91.5	92.1
1104	93.5	94.1	94.5
1315	95.4	95.8	96.2
1537	96.7	97.0	97.3
1781	97.6	97.8	98.0
1913	97.9	98.1	98.3
2053	98.2	98.4	98.6
2202	98.5	98.6	98.8
2353	98.7	98.8	99.0
2697	98.9	99.0	99.2
3086	97.5	96.2	89.7
3546	99.1	99.0	98.6
4102	99.3	99.2	99.1

TABLE VIII
Directivity vs. frequency for the three V angles

<u>Frequency</u>	<u>124⁰</u>	<u>136⁰</u>	<u>154⁰</u>
60 KHz	1.500	1.500	1.500
128	1.500	1.500	1.500
188	1.500	1.500	1.500
258	1.500	1.500	1.500
407	1.502	1.503	1.504
567	1.505	1.507	1.509
736	1.510	1.512	1.516
916	1.516	1.520	1.525
1104	1.524	1.530	1.537
1315	1.536	1.546	1.556
1537	1.555	1.567	1.581
1781	1.584	1.602	1.620
1913	1.606	1.629	1.651
2053	1.638	1.666	1.690
2202	1.687	1.722	1.745
2353	1.766	1.811	1.823
2697	2.336	2.365	2.220
3086	3.247	3.340	3.537
3546	2.597	2.924	3.157
4102	2.498	2.924	3.300

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APPENDIX I

SPACECRAFT EFFECT ON IMPEDANCE

Figure 16 shows our experimental results for the admittance of a V monopole over a ground plane, and Figs. 17 and 18 show the effect of mounting the antenna on a spherical spacecraft. The measurements were performed at 375 MHz with a Hewlett-Packard 803A Impedance Bridge. Image theory can be employed to relate these data to the admittance of a V dipole with angle ψ of 120° .

In these experiments, the monopoles were brass rods with a radius of $1/16$ inch ($a = 0.002\lambda$). The admittance is referred to the ground-plane surface in Fig. 16 and the spherical surface in Figs. 17 and 18. The monopole length h is measured from the ground plane in Fig. 16 and from the spherical surface in Figs. 17 and 18. The spacecraft radius is 2.5 cm (0.03125λ) in Fig. 17 and 5 cm (0.0625λ) in Fig. 18.

The coaxial feed was accomplished via cylindrical holes (with diameter 0.28 inch) drilled through the solid aluminum hemispheres.

On the ATS-E satellite, the cylindrical spacecraft has a radius of 2.5 ft (ranging from about 0.00015λ at 60 KHz to 0.01λ at 4 MHz). Thus the ATS-E spacecraft is considerably smaller (in comparison with the wavelength) than those in Figs. 17 and 18. The ATS-E spacecraft is also much smaller in comparison with the antenna length.

It is observed that spherical and cylindrical spacecraft (with equal radii) have similar effects on the impedance. Furthermore, the impedance varies smoothly with the spacecraft radius.

Figures 16, 17 and 18 yield no quantitative data on the ATS-E configuration. However, they permit an estimate that the spacecraft will shift the resonant frequency by less than 40 KHz.

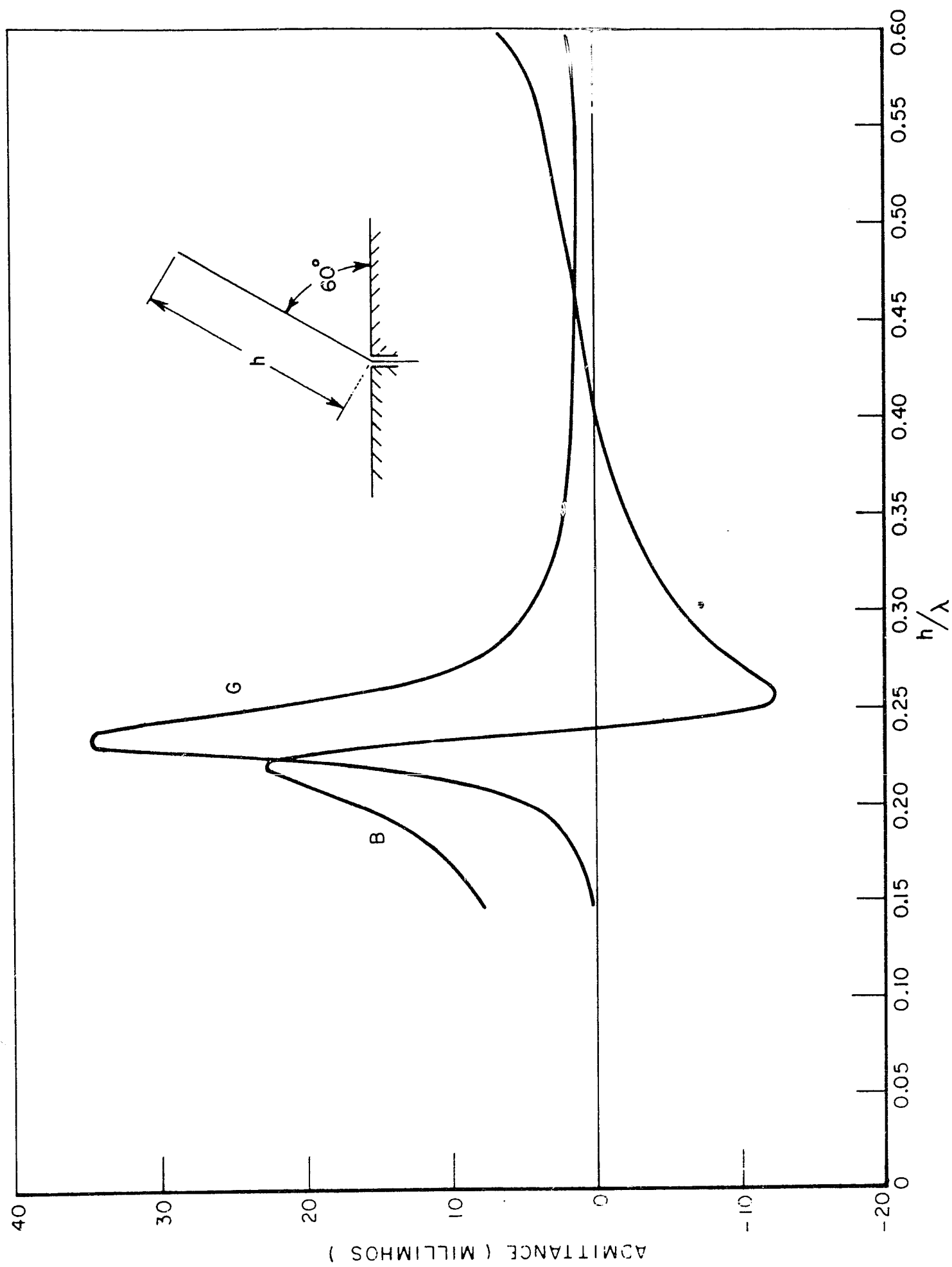


Fig. 16. Measured admittance of V monopole over ground plane.

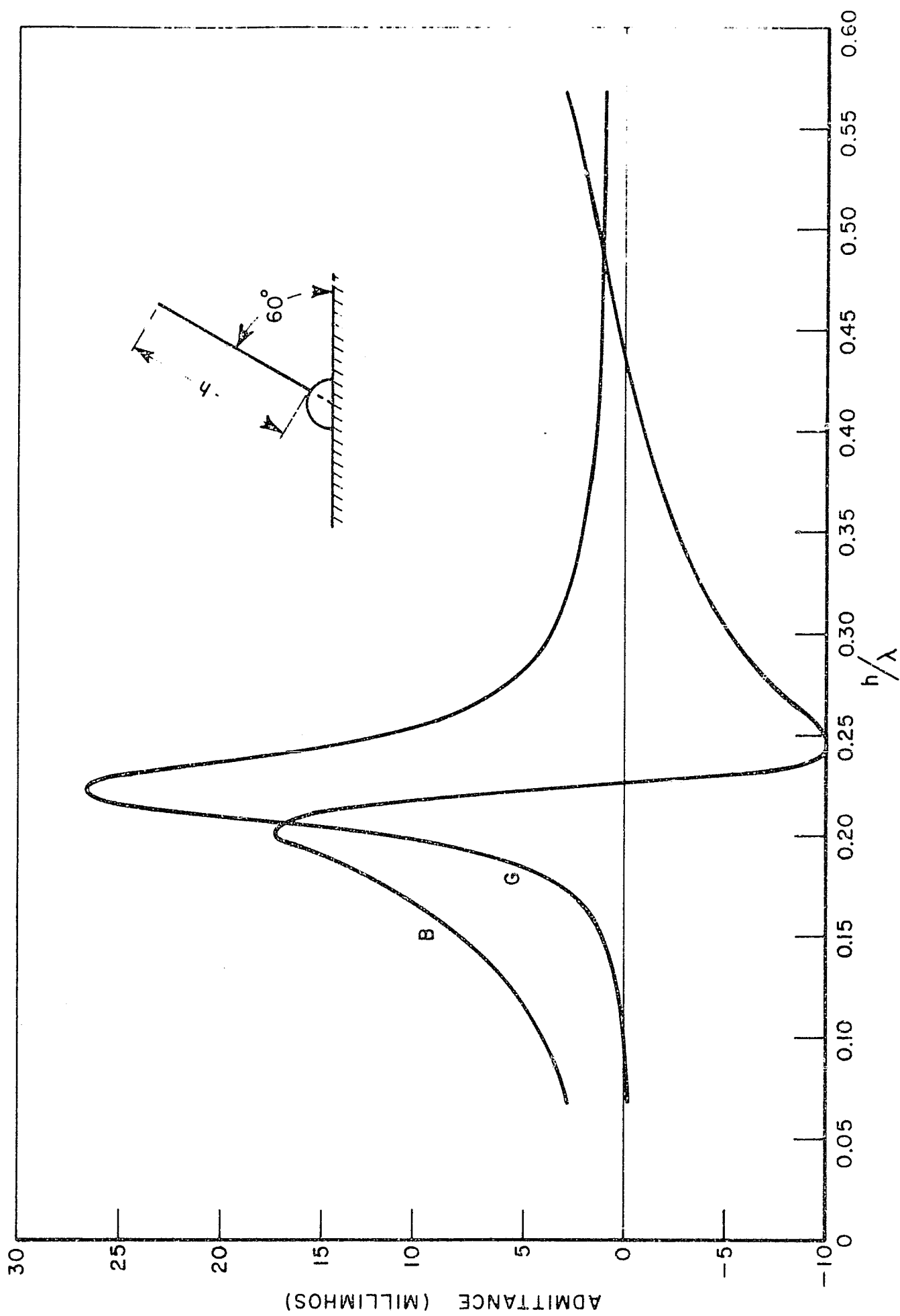


Fig. 17. Measured admittance of V monopole on conducting hemisphere with radius 0.03125λ .

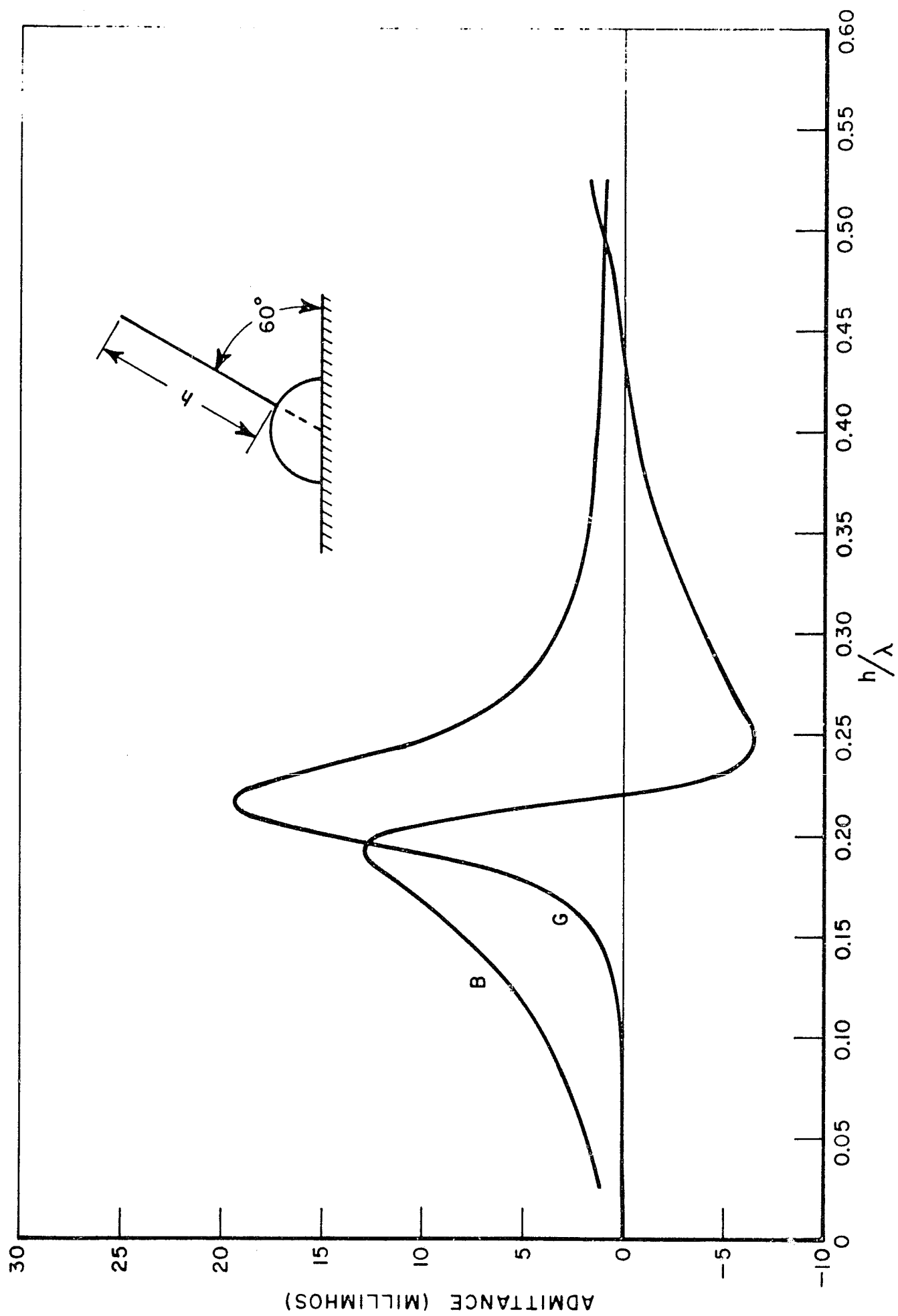


Fig. 18. Measured admittance of V monopole on conducting hemisphere with radius 0.0625λ .

APPENDIX II

THE MAGNETIC TAPE

Figure 19 illustrates the rectangular (x,y,z) and spherical (r, θ , ϕ) coordinate systems employed for the radiation patterns of the V antenna system on the ATS-E satellite. As indicated in Fig. 15, the V antennas lie in the xz plane and the vertex of the floating V is on the positive x axis.

The calculated data for the principal-plane patterns are tabulated on magnetic tape. (In addition, the normalized power patterns are presented graphically in Appendix III.) Figure 20 shows the key statements in a Fortran IV program for reading this tape and writing the data in hardcopy form. The symbols in this program are defined as follows:

PSI	V angle ψ in degrees
FKC	Frequency in KHz
EFFIC	Radiation efficiency
Z1	Input impedance in ohms
TH	θ in degrees
PHI	ϕ in degrees
GD	Directive gain $G_d(\theta, \phi)$
GP	Power gain $G_p(\theta, \phi)$

The directive gain is defined in the usual manner.¹² The power gain is the product of the directive gain and the radiation efficiency.

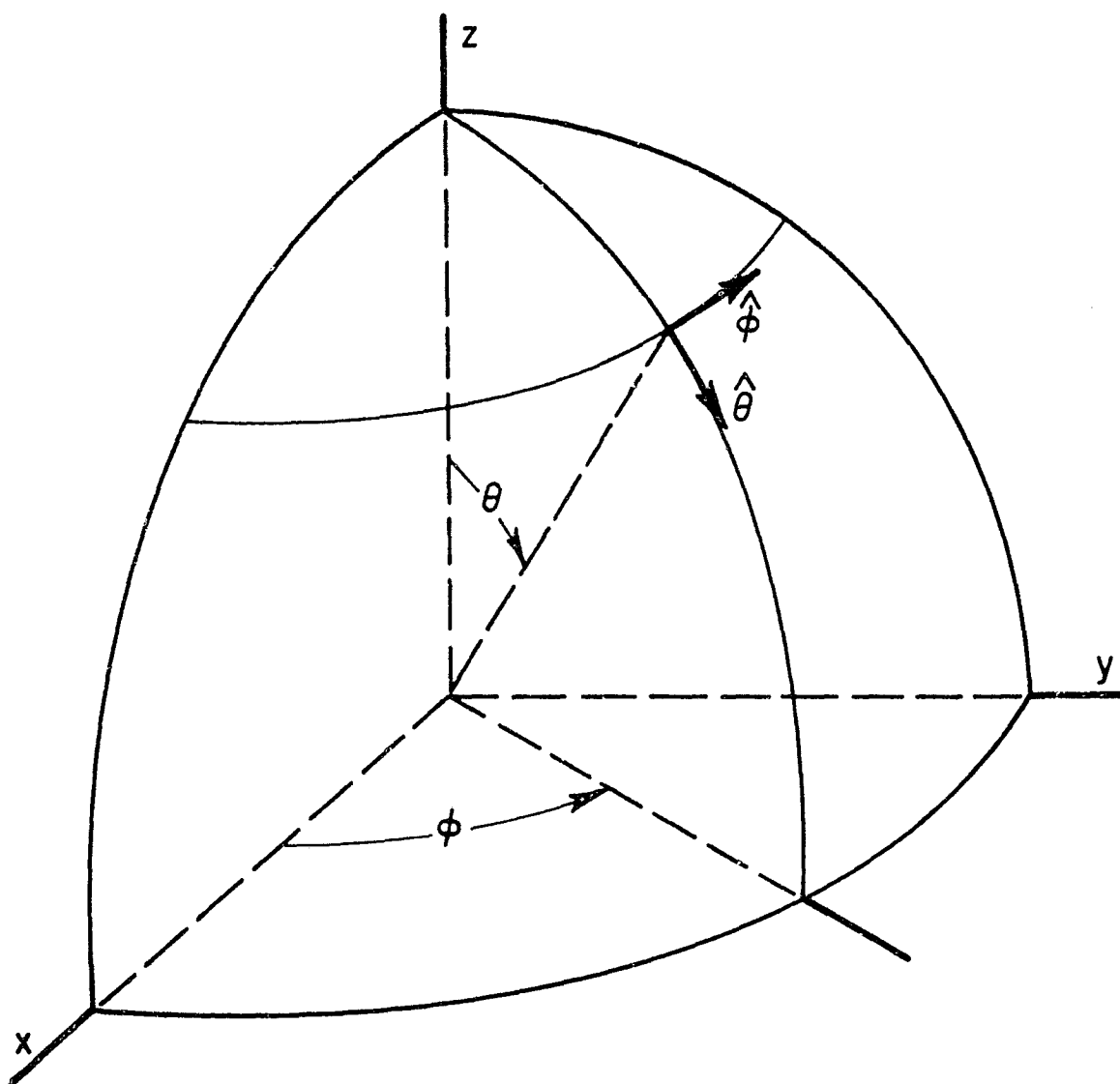


Fig. 19. The rectangular and spherical coordinate systems.

```

$*      MOUNT NASB2619 ON UNIT 7
$FILE      -UNIT07-,A(1),BCD,INPUT,BLK=22,MOUNT,LIST
3        FORMAT(6F15.8)
        COMPLEX Z1
        REWIND 7
        DO 100 IPSI=1,3
        NO 100 NFK=1,20
        READ (7,3)PSI,FKC,EFFIC,Z1
        WRITE (6,3)PSI,FKC,EFFIC,Z1
        DO 100 NPR=1,3
        DO 100 NT=1,19
        READ (7,3)TH,PHI,GD,DP
        WRITE (6,3)TH,PHI,GD,GP
100      CONTINUE
        REWIND 7

```

Fig. 20. The most important statements in a computer program for reading the magnetic tape.

APPENDIX III PRINCIPAL-PLANE PATTERNS

Figures A1 through A60 show the principal-plane radiation patterns of the V antenna system on the ATS-E satellite. These calculated power patterns are shown in polar form with ten-degree angular increments. With the libration damper in the nominal position, the field has two planes of symmetry: the xy and xz planes. Therefore, only one-half of each pattern is shown.

The frequency and the V angle are specified in the caption of each figure. For each of the three principal-plane patterns, the coordinate axes are identified in Fig. A1. In each of the figures the xy-plane pattern is at the top, the xz-plane pattern in the middle, and the yz-plane pattern at the bottom.

The data in these figures represent the normalized directive-gain patterns. The normalization factors are listed in Table VIII.

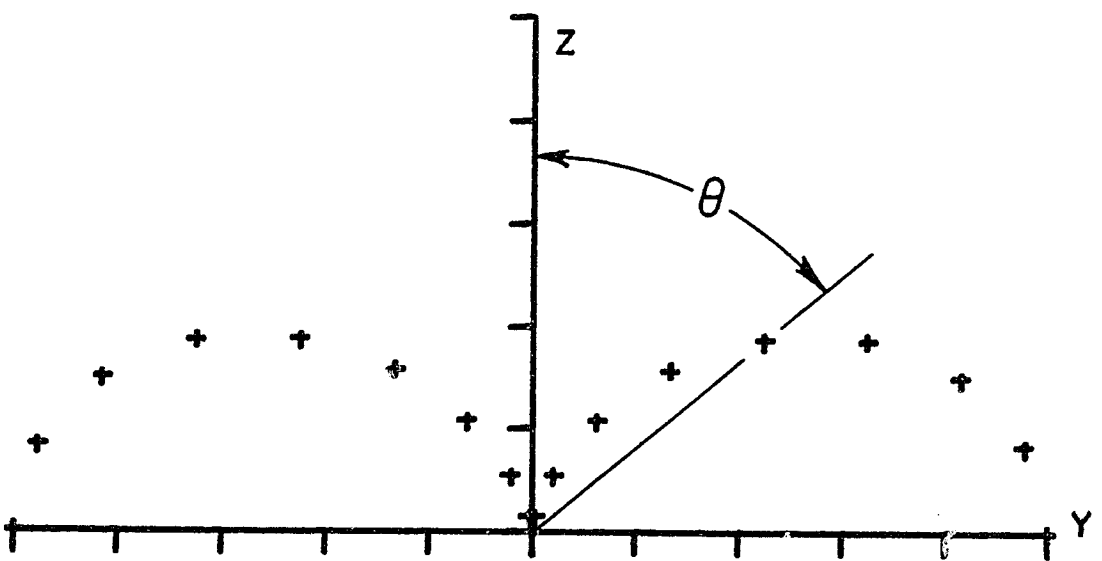
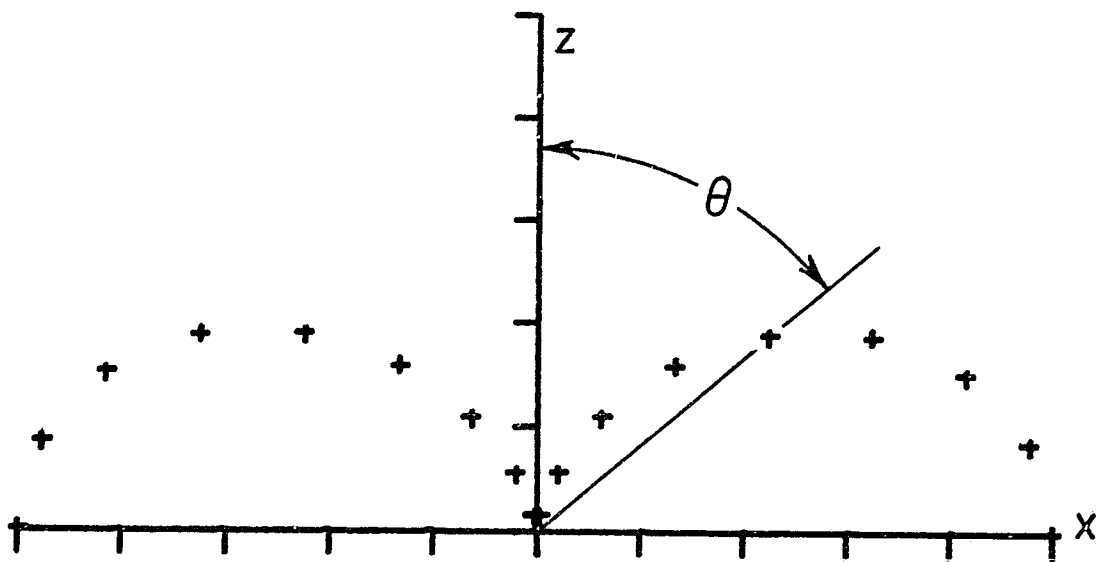
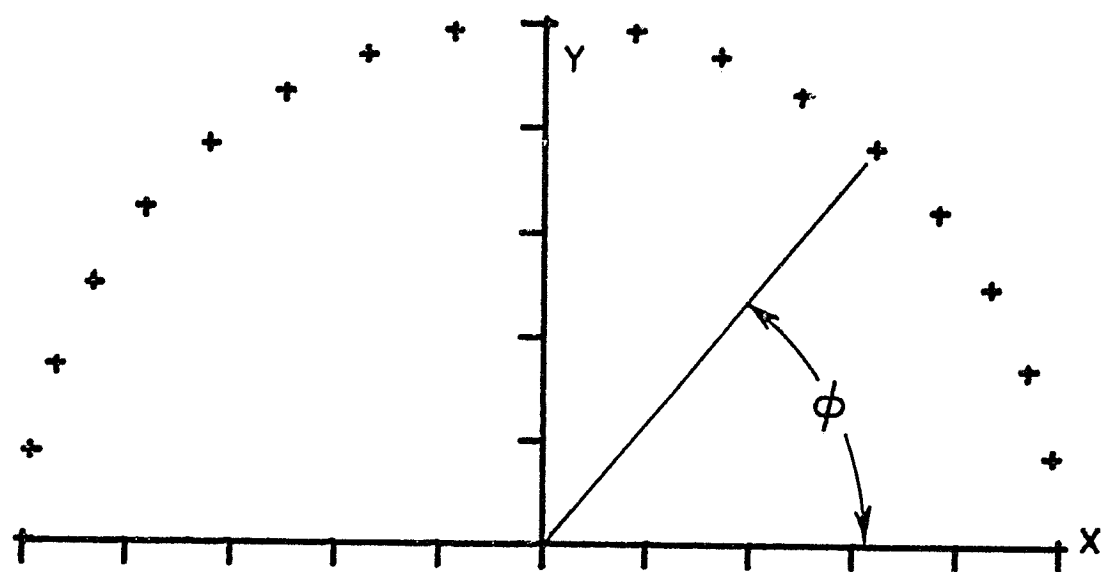


FIG. A1. FREQ.= 60 KHZ, V ANGLE= 124 DEG.

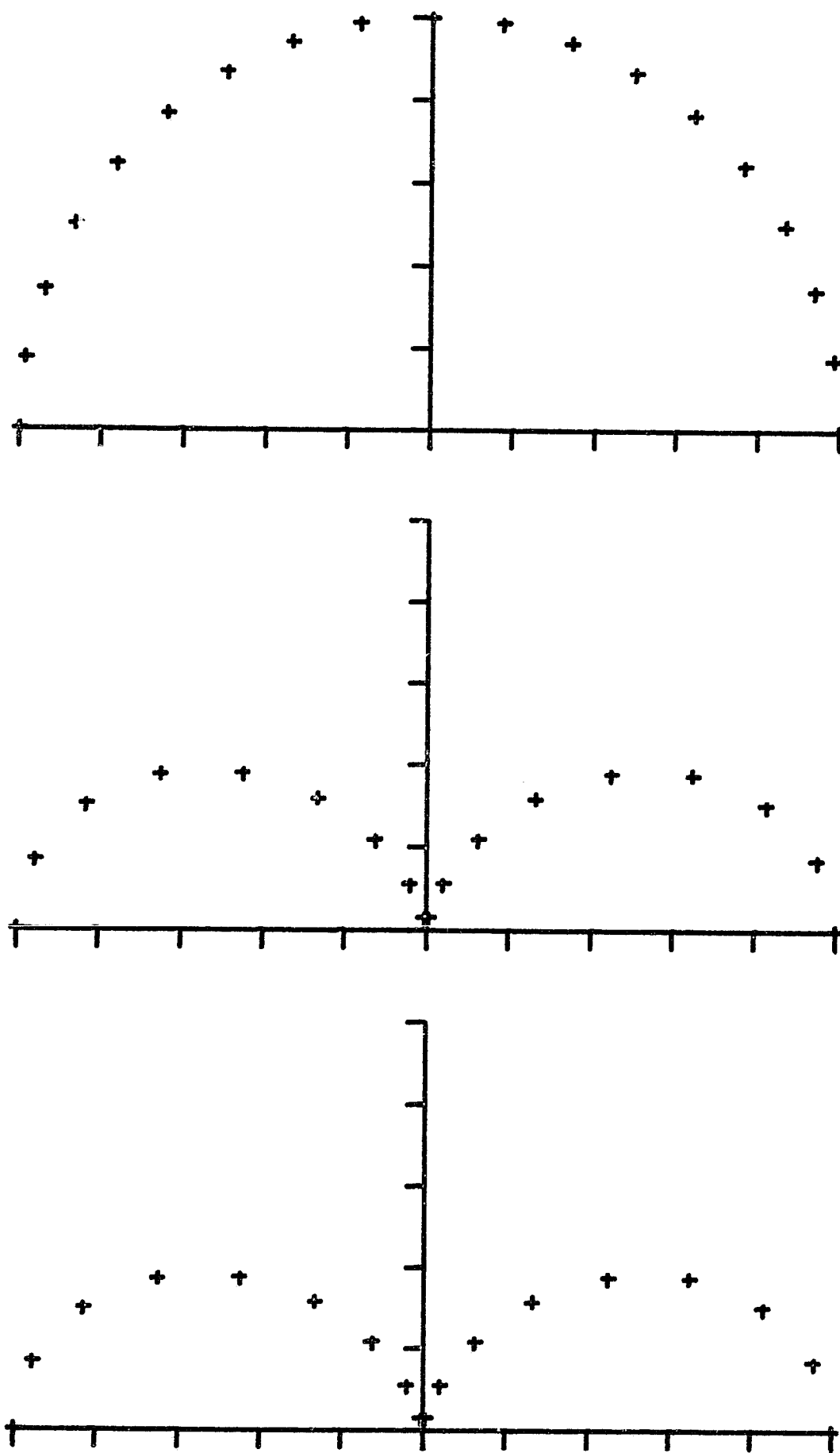


FIG. A2.

FREQ.= 128 KHZ, V ANGLE= 124 DEG.

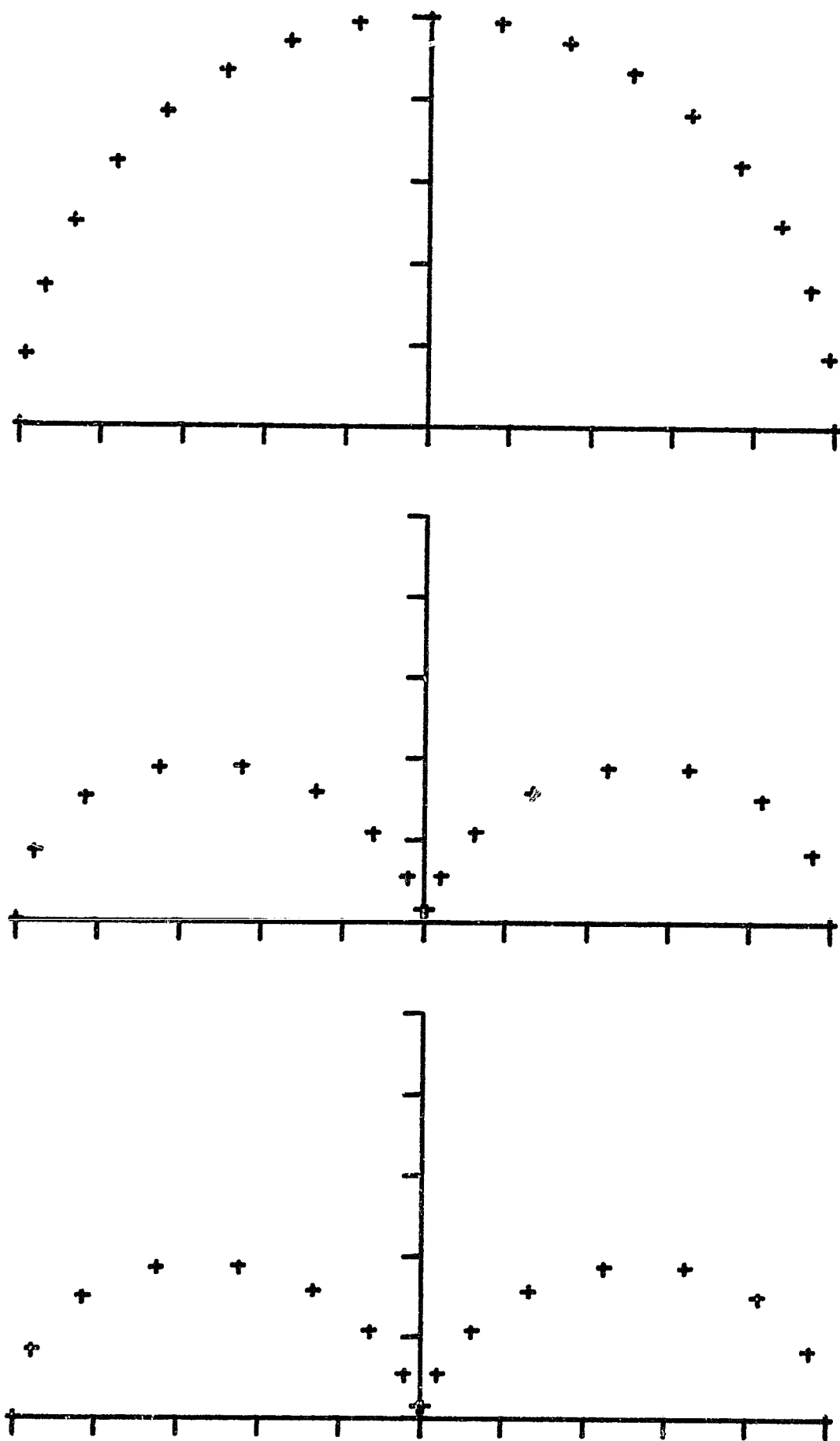


FIG. A3.

FREQ.= 188 KHZ, V ANGLE= 124 DEG.

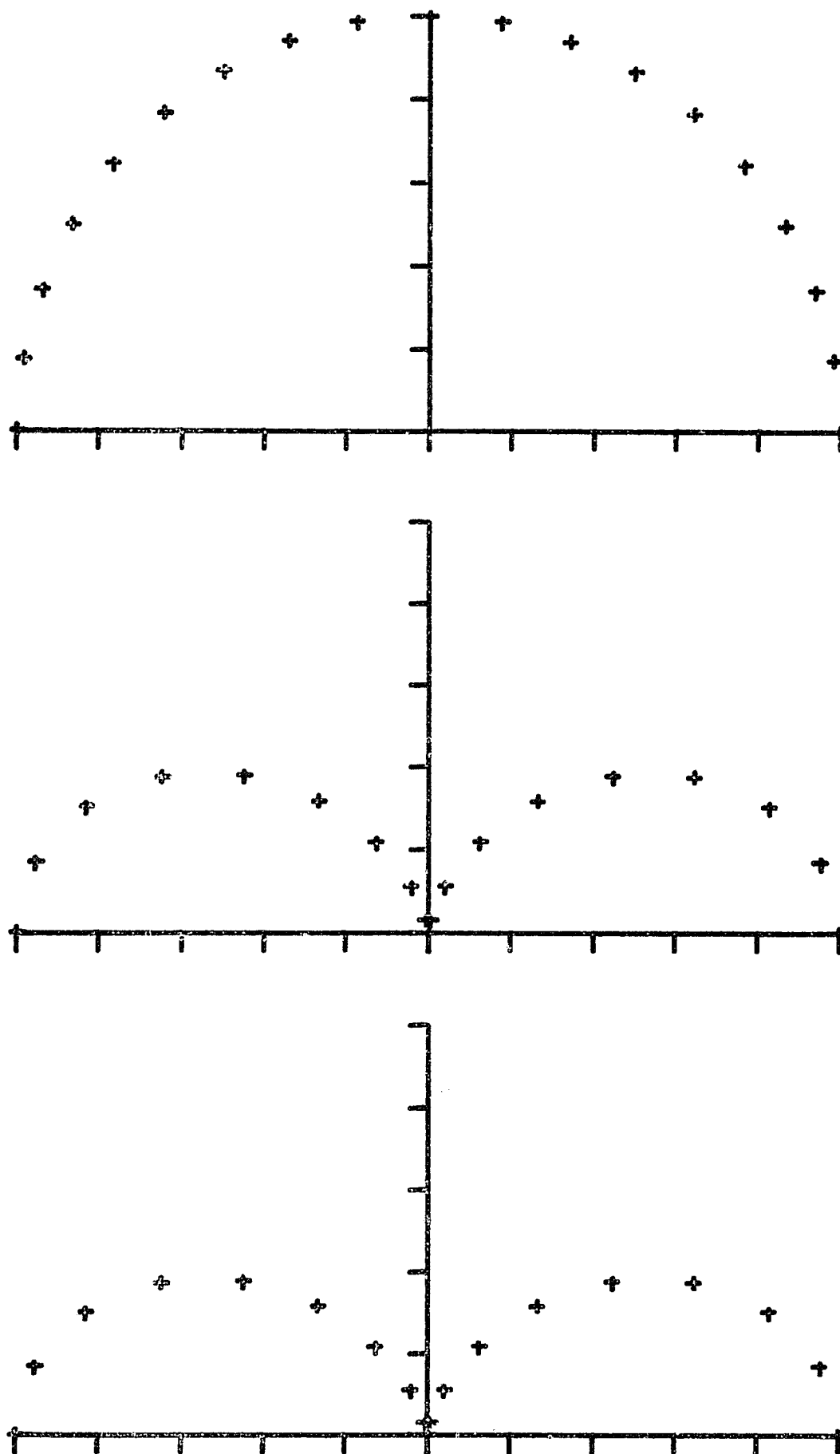


FIG. A4.

FREQ.= 258 KHZ, V ANGLE= 124 DEG.

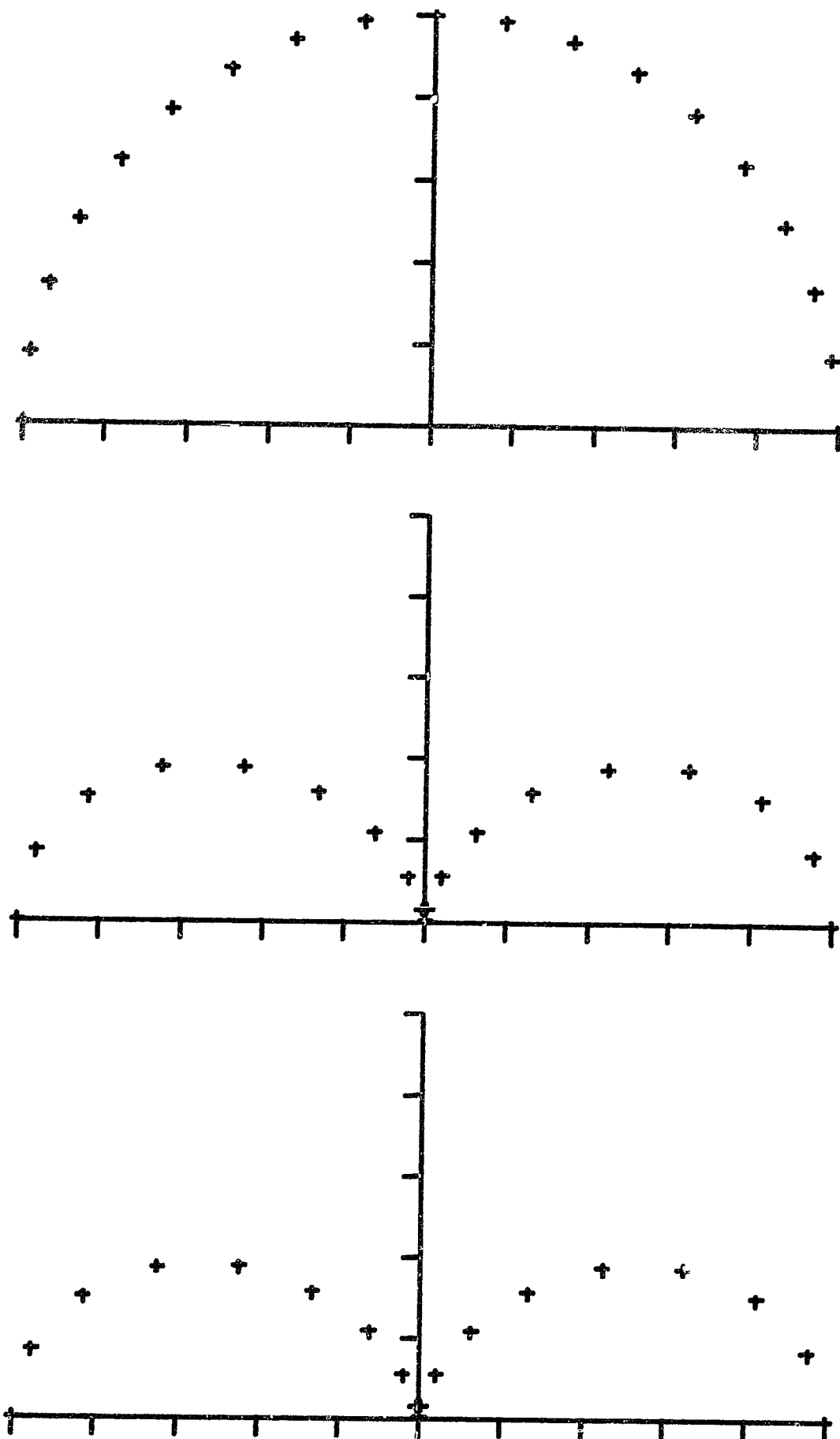


FIG. A5.

FREQ.=407 KHZ, V ANGLE=124 DEG.

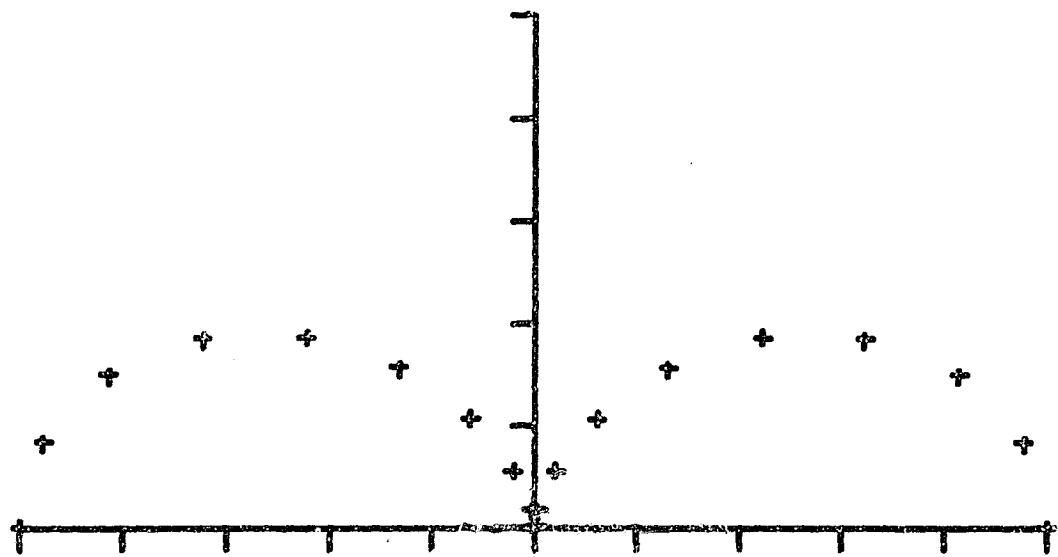
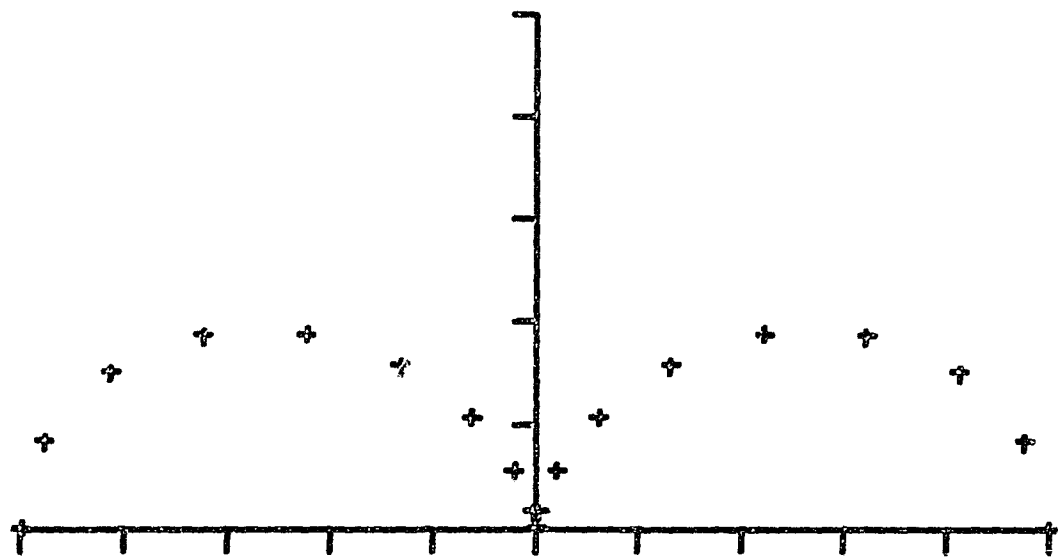
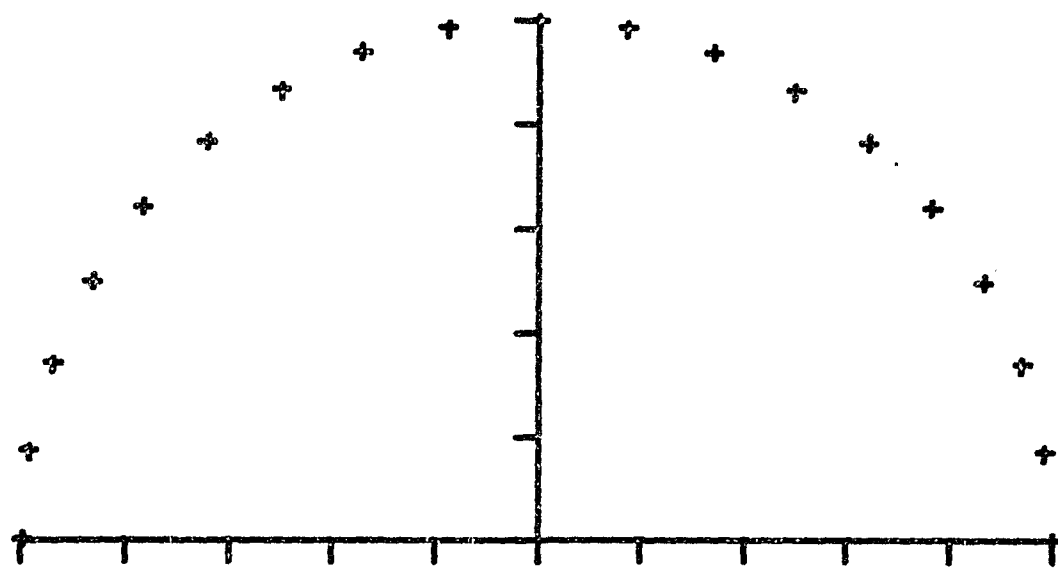


FIG. A6.

FREQ.=567 KHZ, V ANGLE=124 DEG.

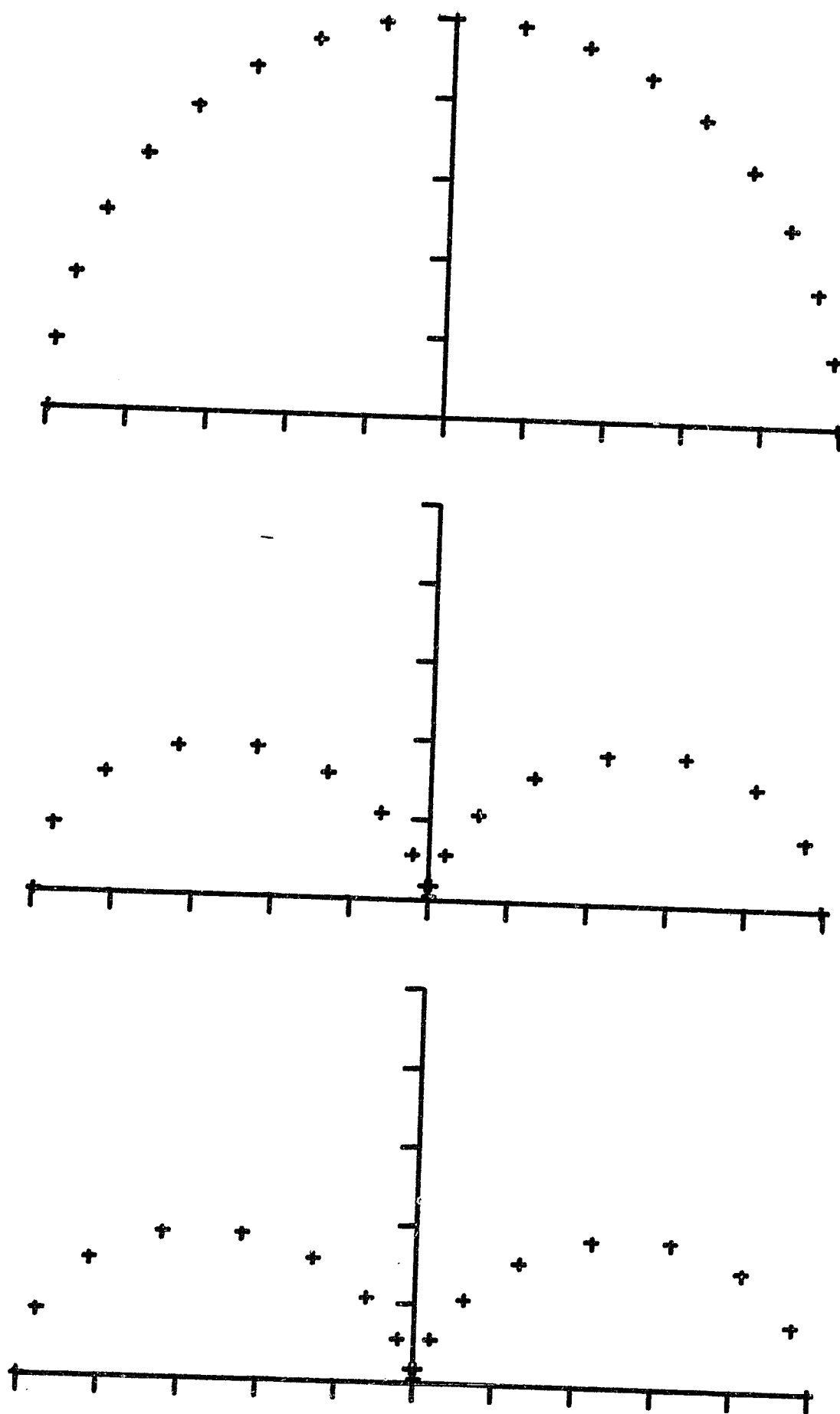


FIG. A7.

FREQ.= 736 KHZ, V ANGLE= 124 DEG.

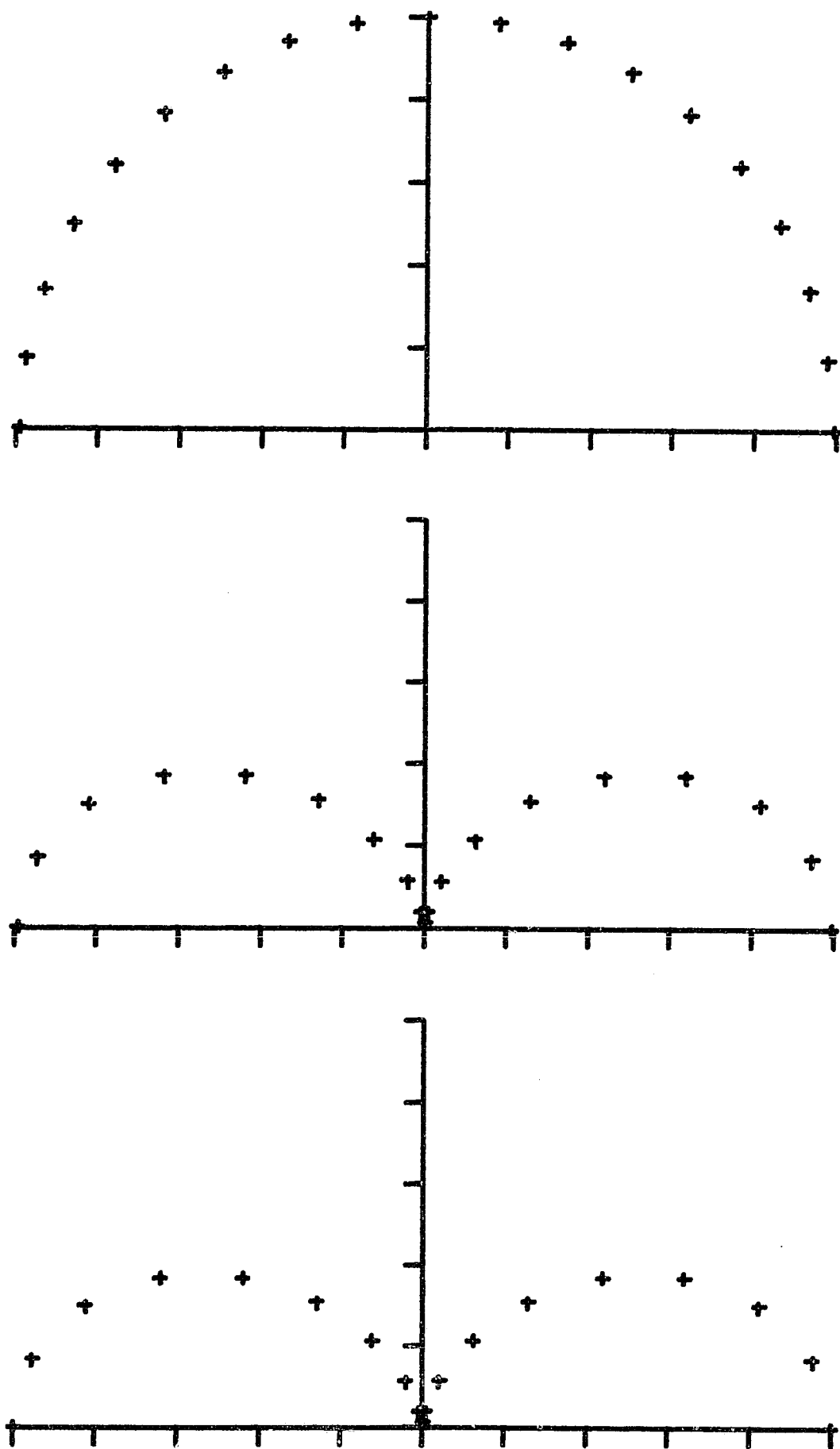


FIG. A8.

FREQ.=916 KHZ. V ANGLE=124 DEG.

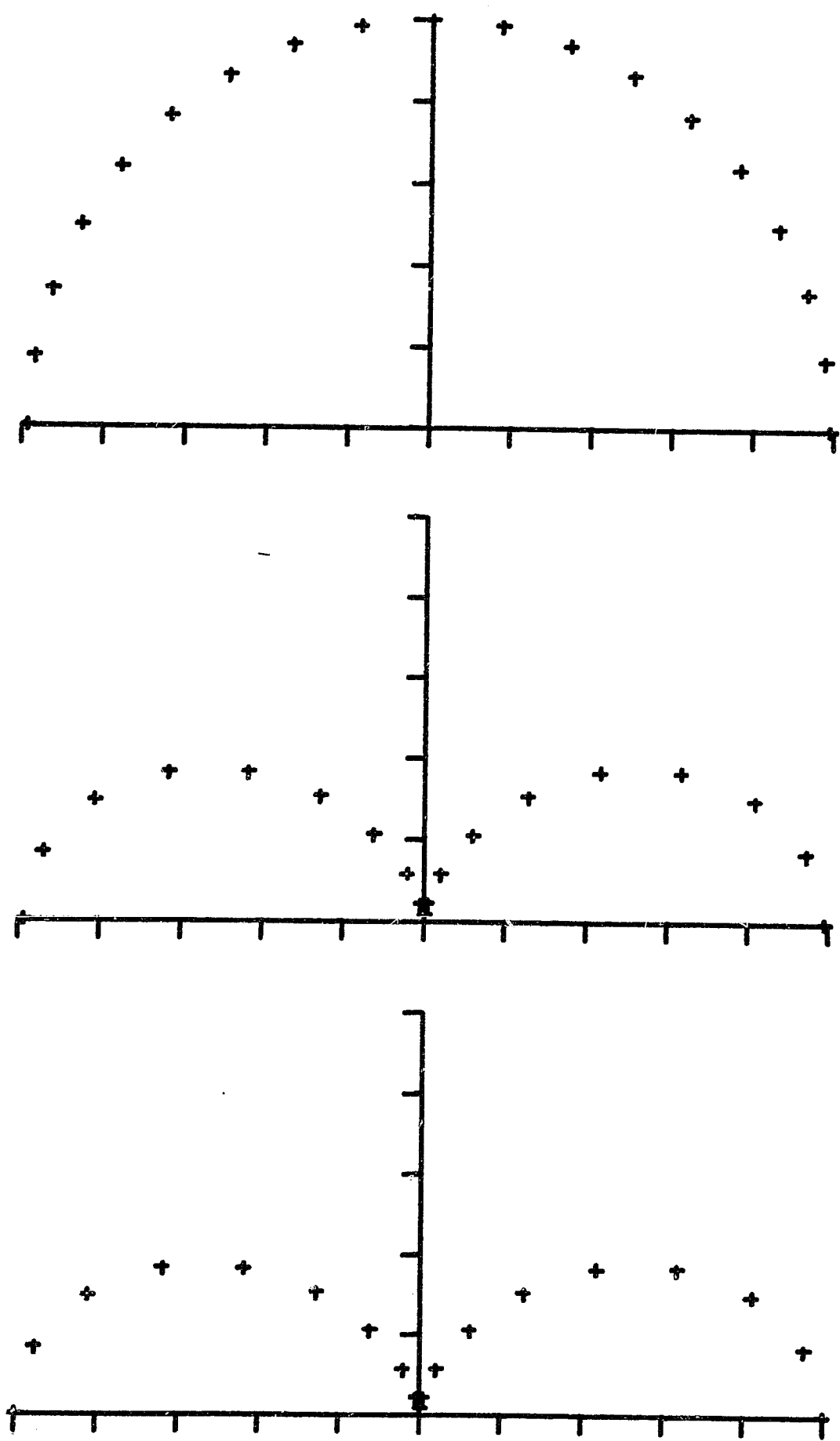


FIG. A9.

FREQ.=1104 KHZ, V ANGLE=124 DEG.

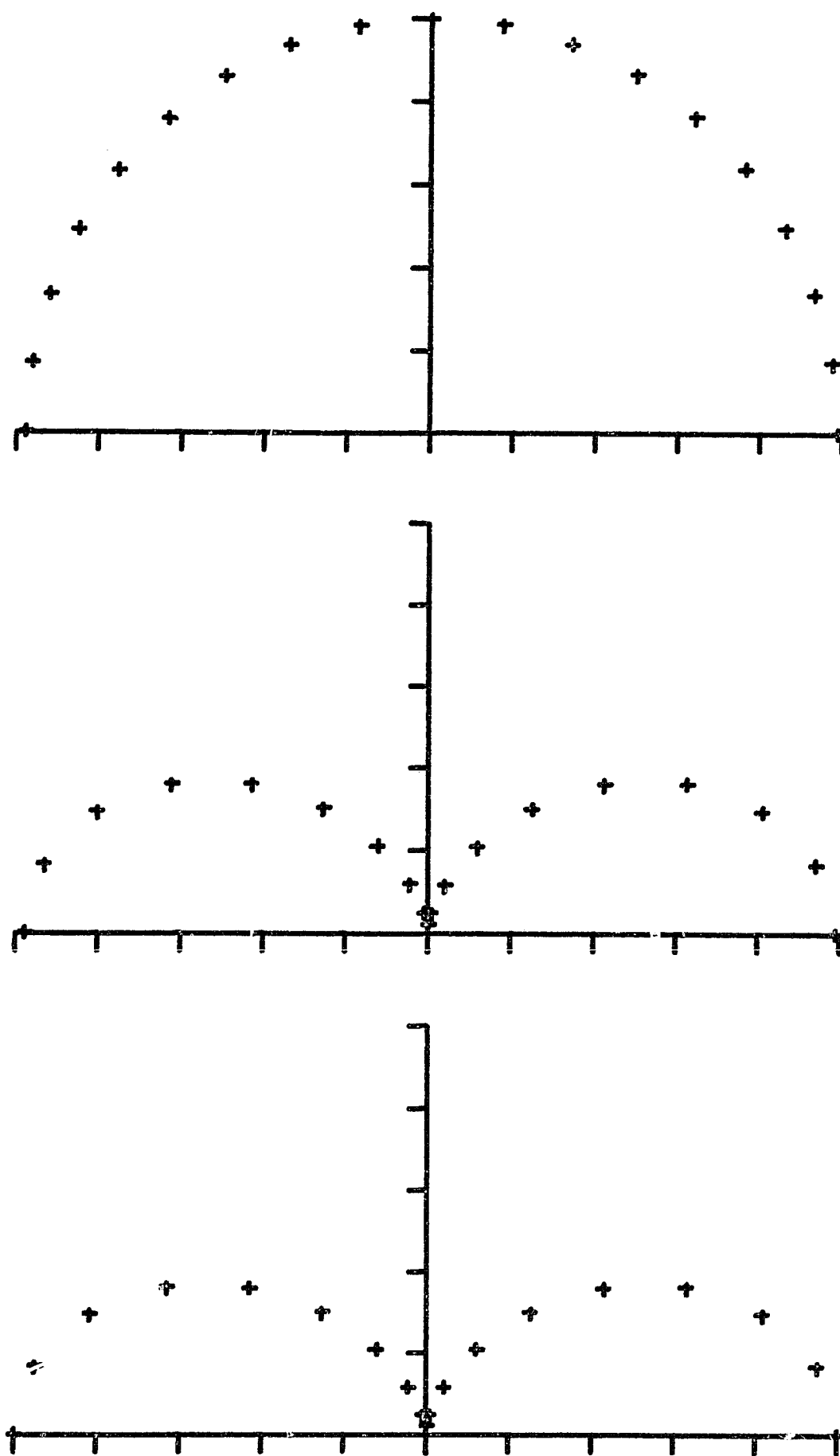


FIG. A10.

FREQ.=1315 KHZ, V ANGLE=124 DEG.

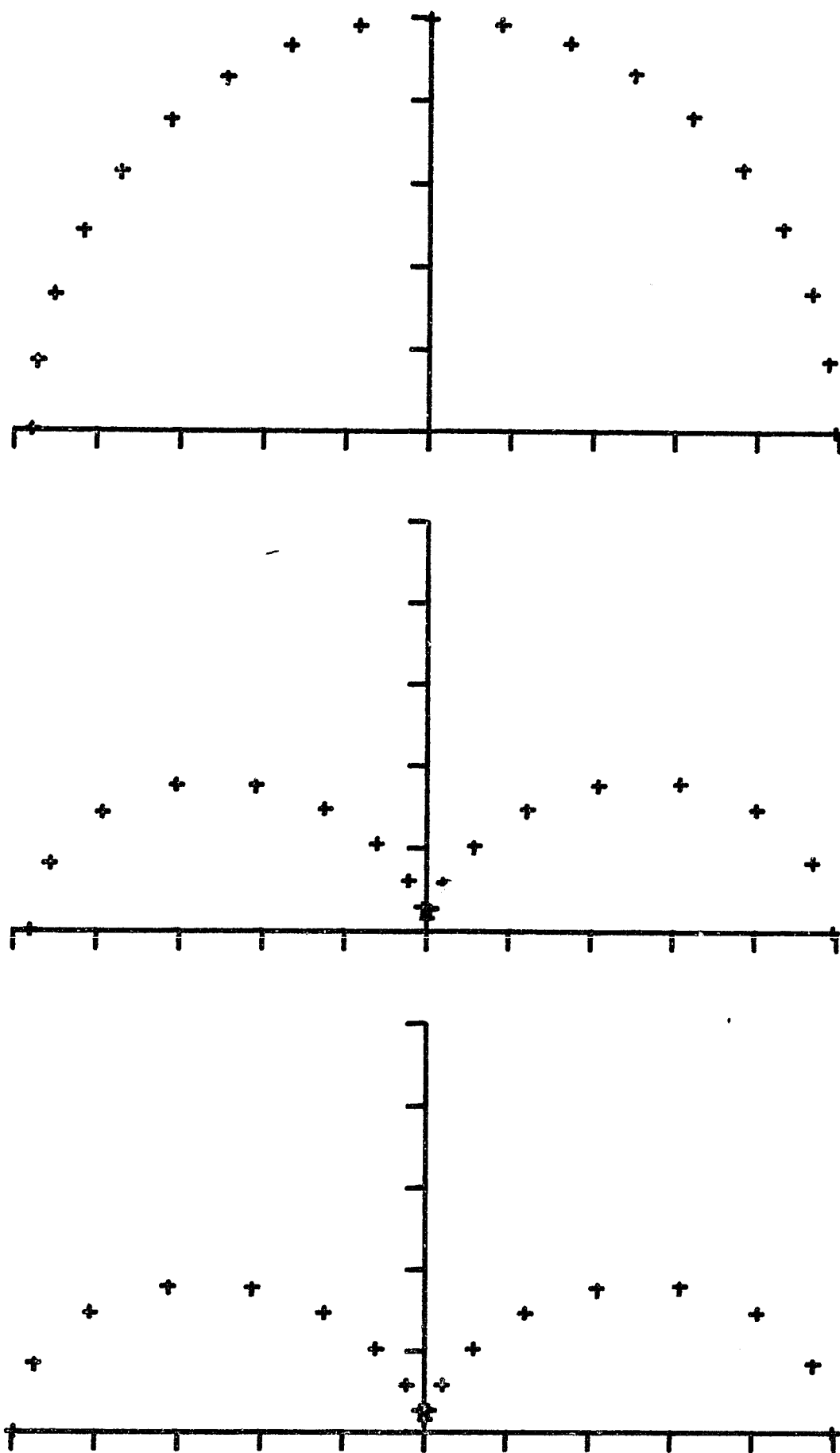


FIG. A11.

FREQ.=1537 KHZ. V ANGLE=124 DEG.

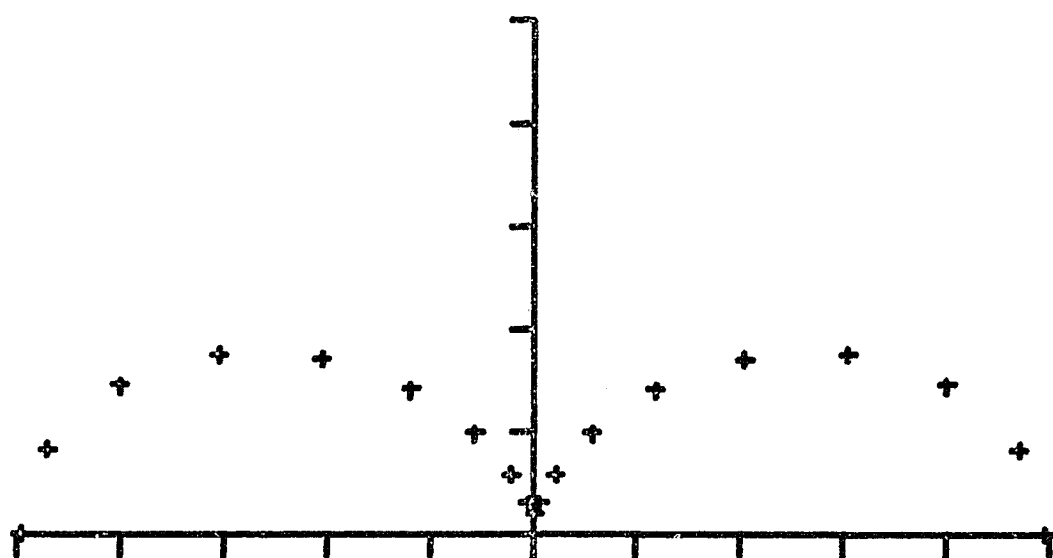
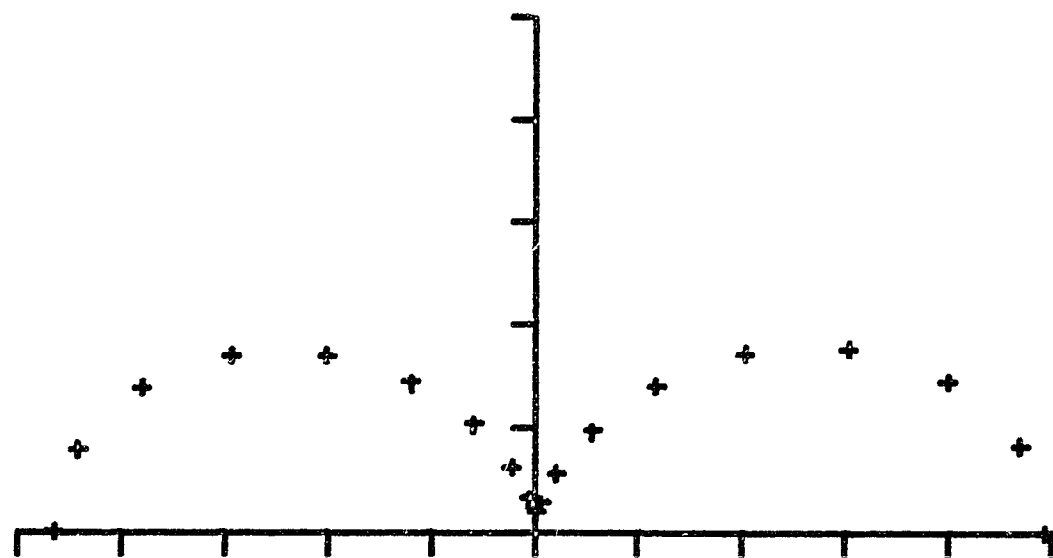
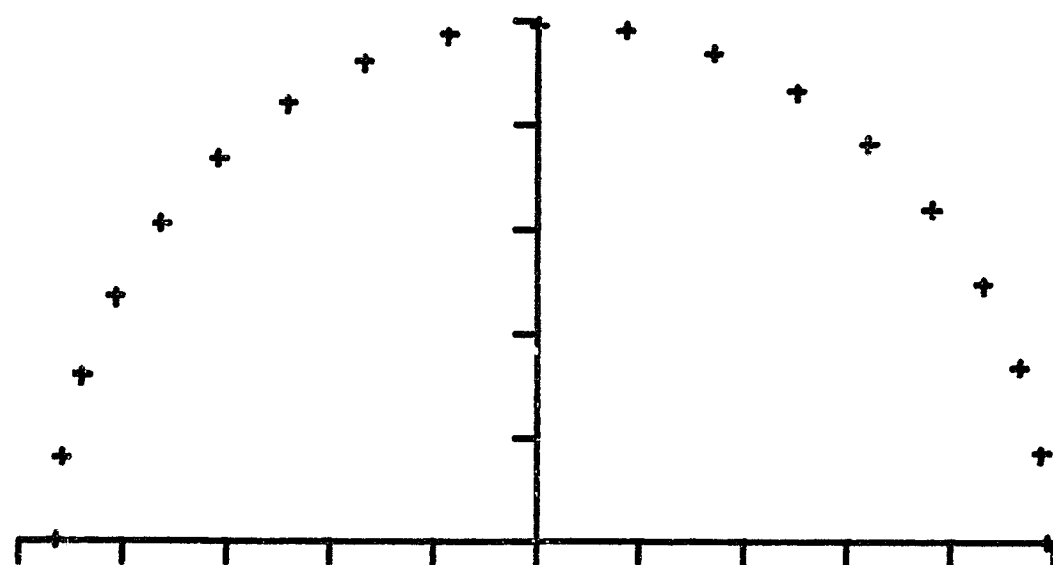


FIG. A12.

FREQ.=1781 KHZ, V ANGLE=124 DEG.

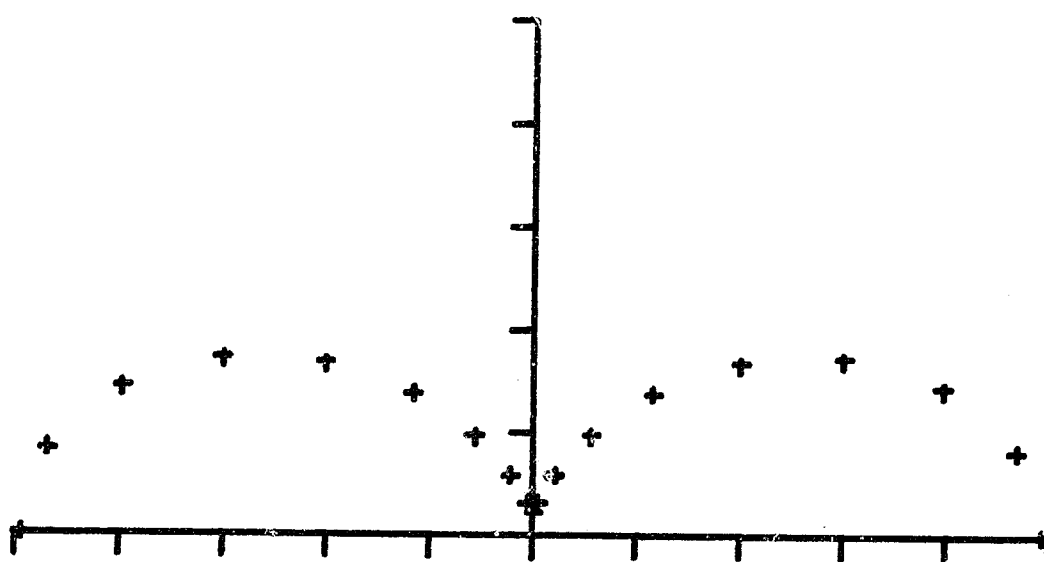
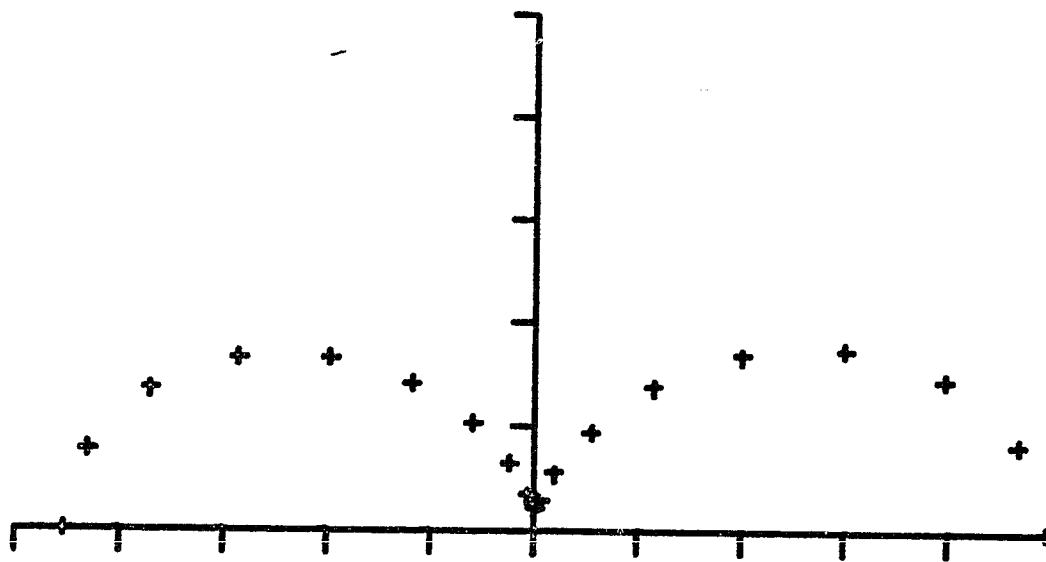
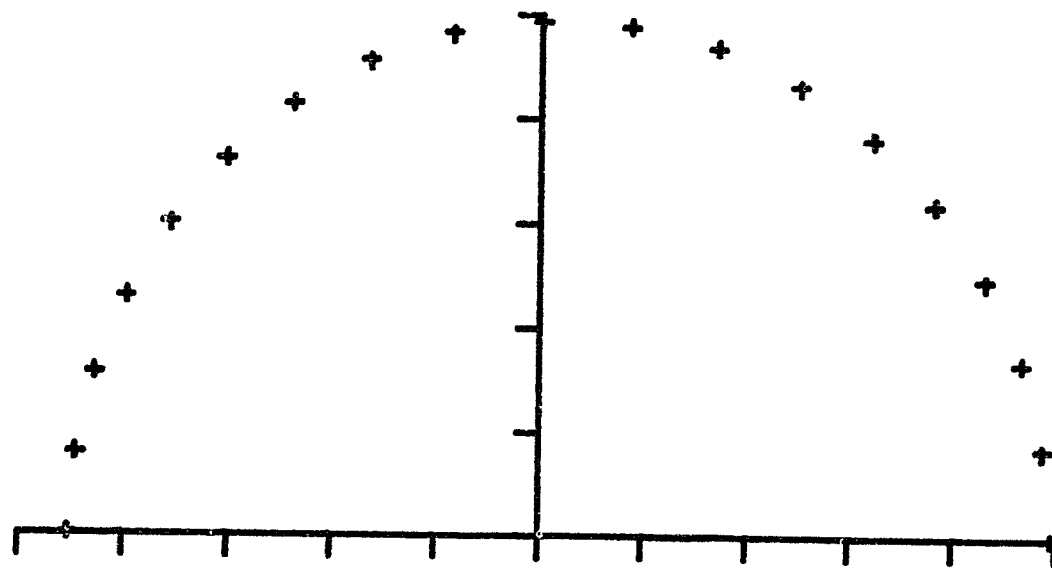


FIG. A13.

FREQ.=1913 KHZ, V ANGLE=124 DEG.

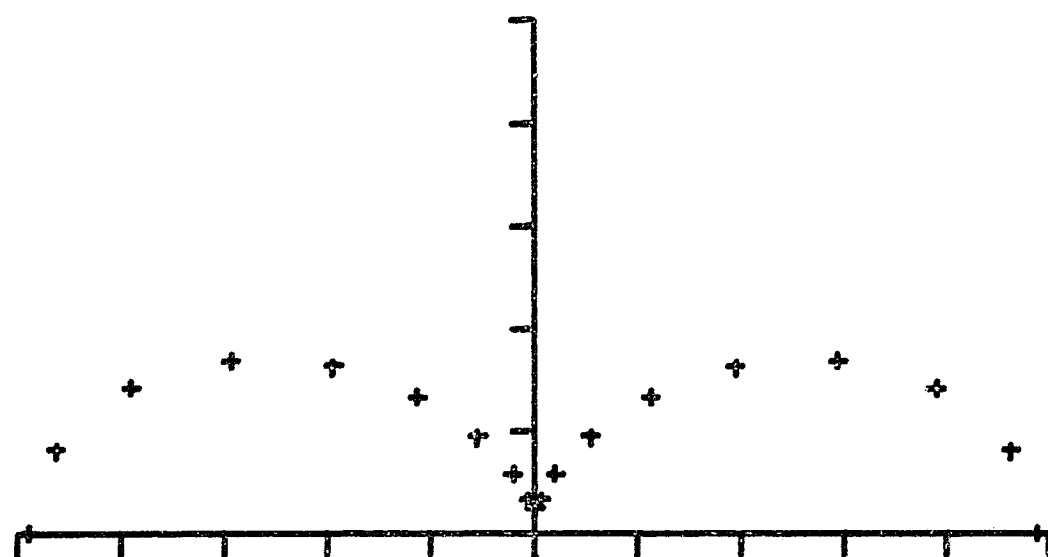
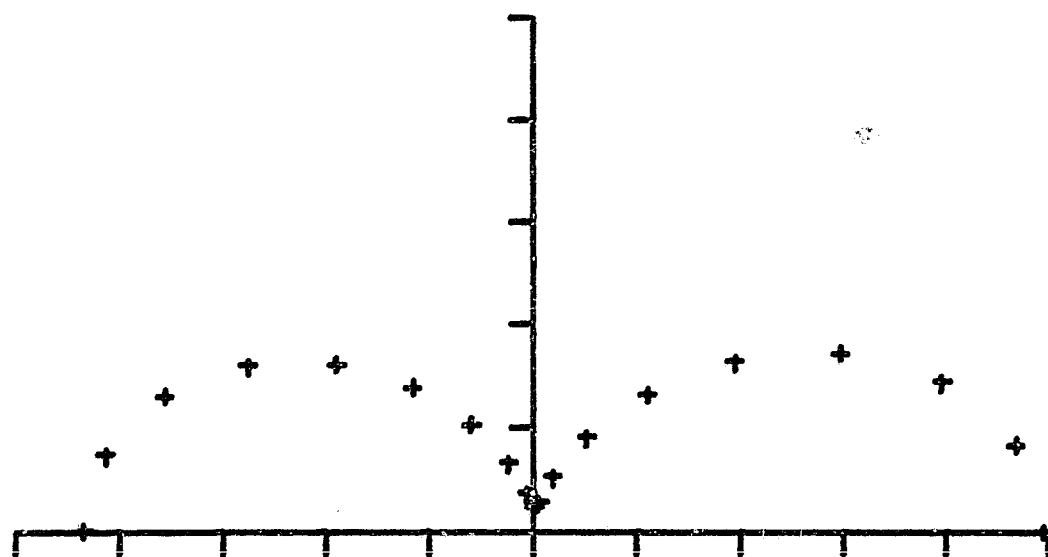
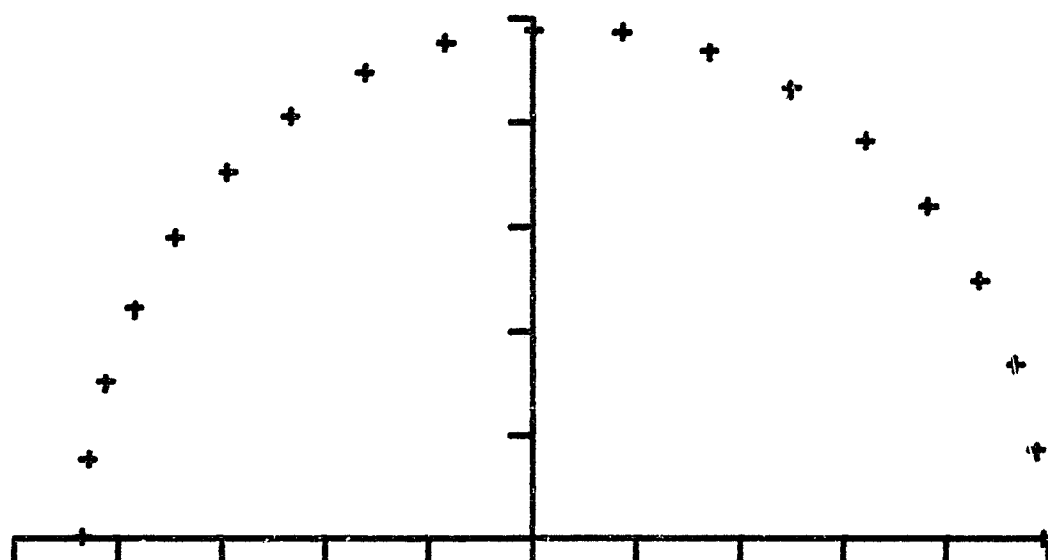


FIG. A14.

FREQ.=2053 KHZ, V ANGLE=124 DEG.

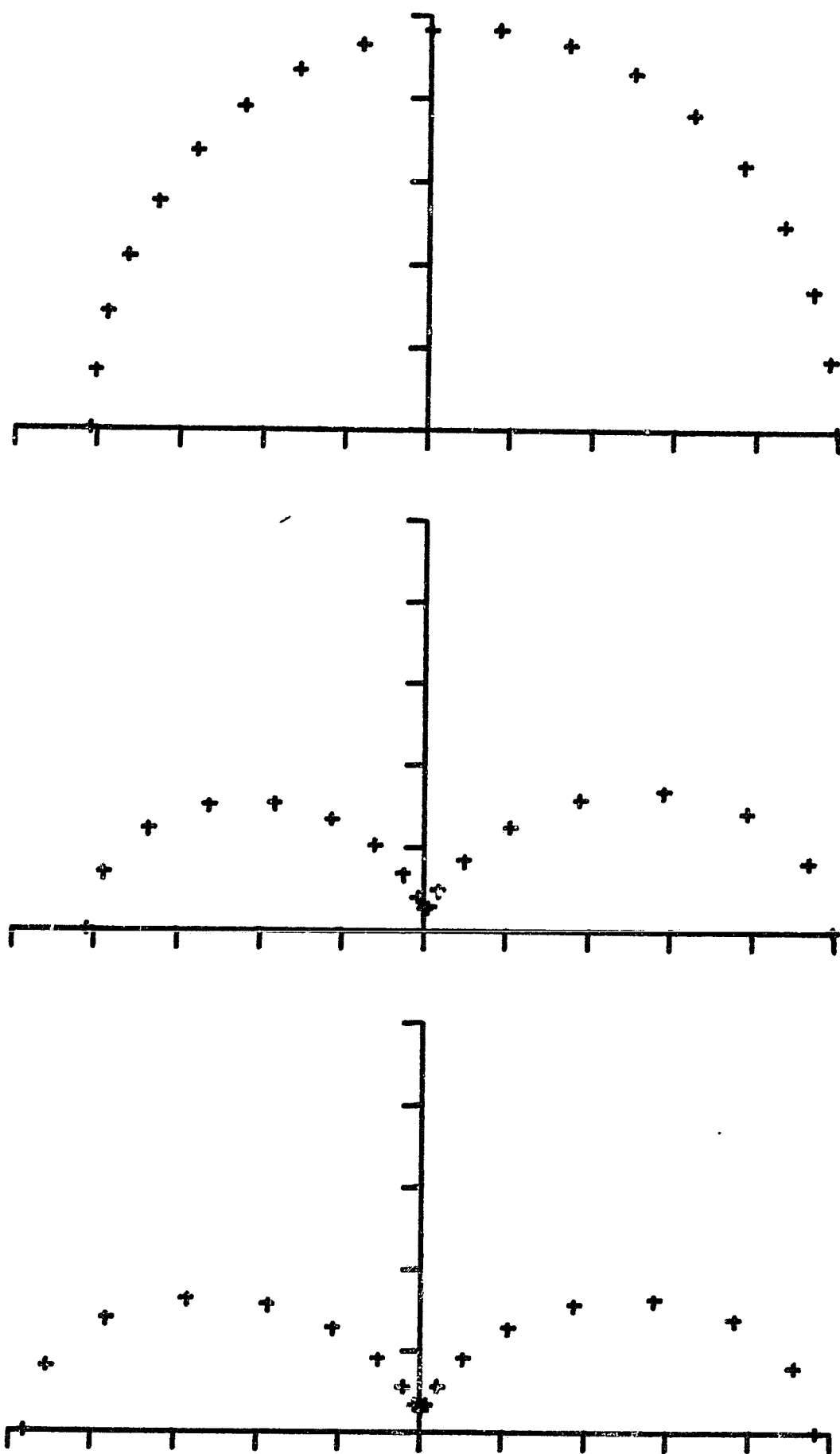


FIG. A15.

FREQ.=2202 KHZ, V ANGLE=124 DEG.

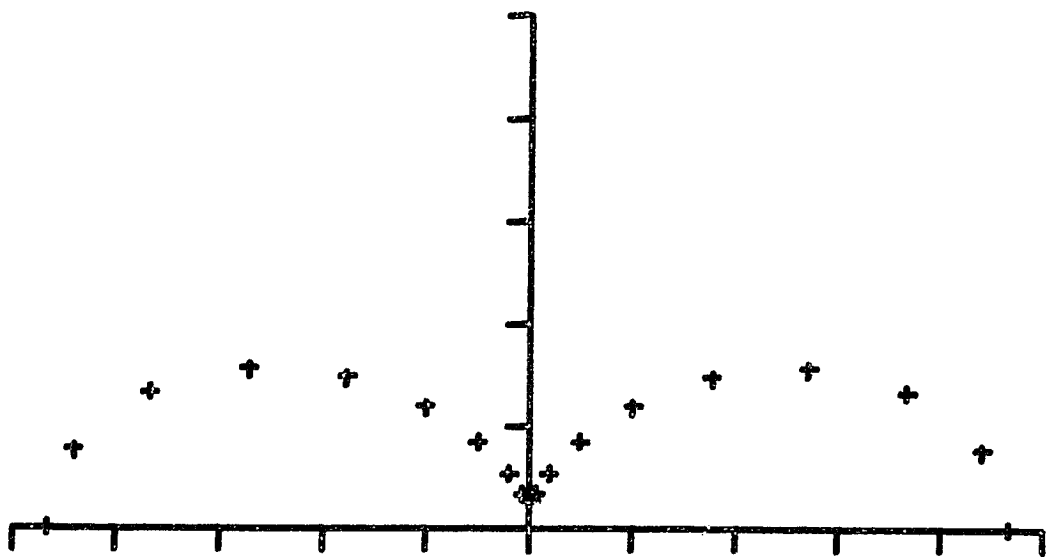
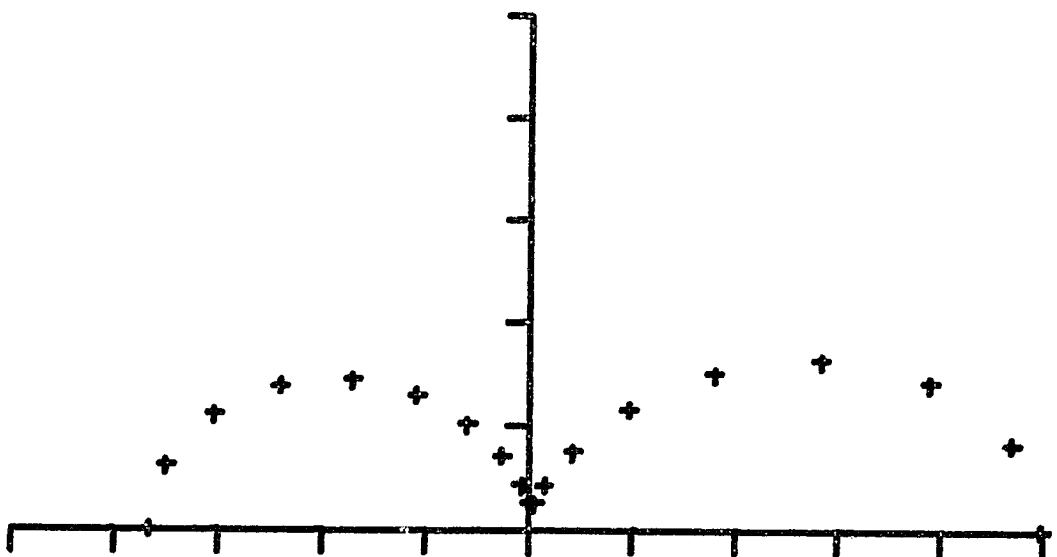
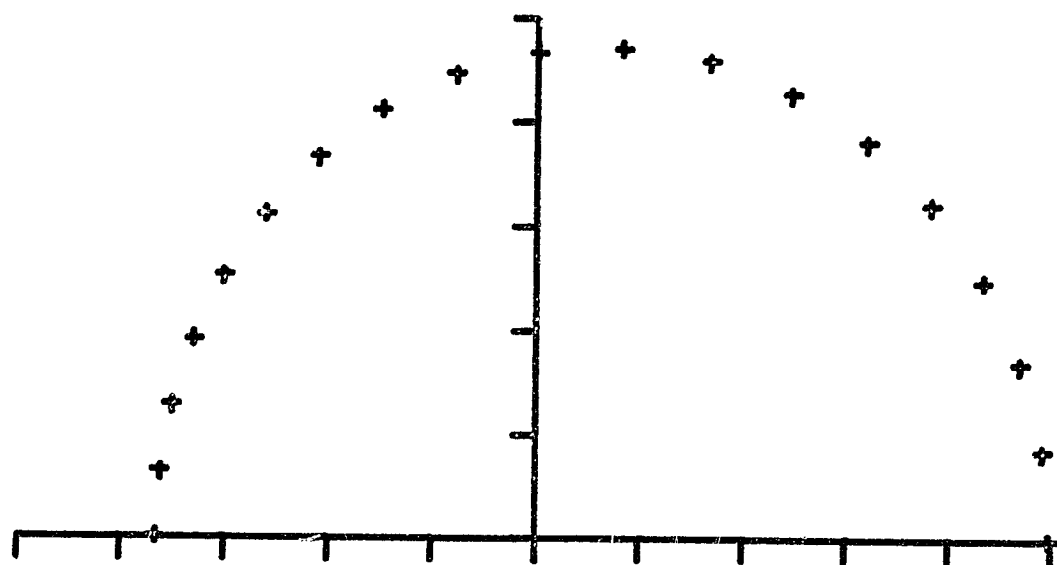


FIG. A16.

FREQ.=2353 KHZ, V ANGLE=124 DEG.

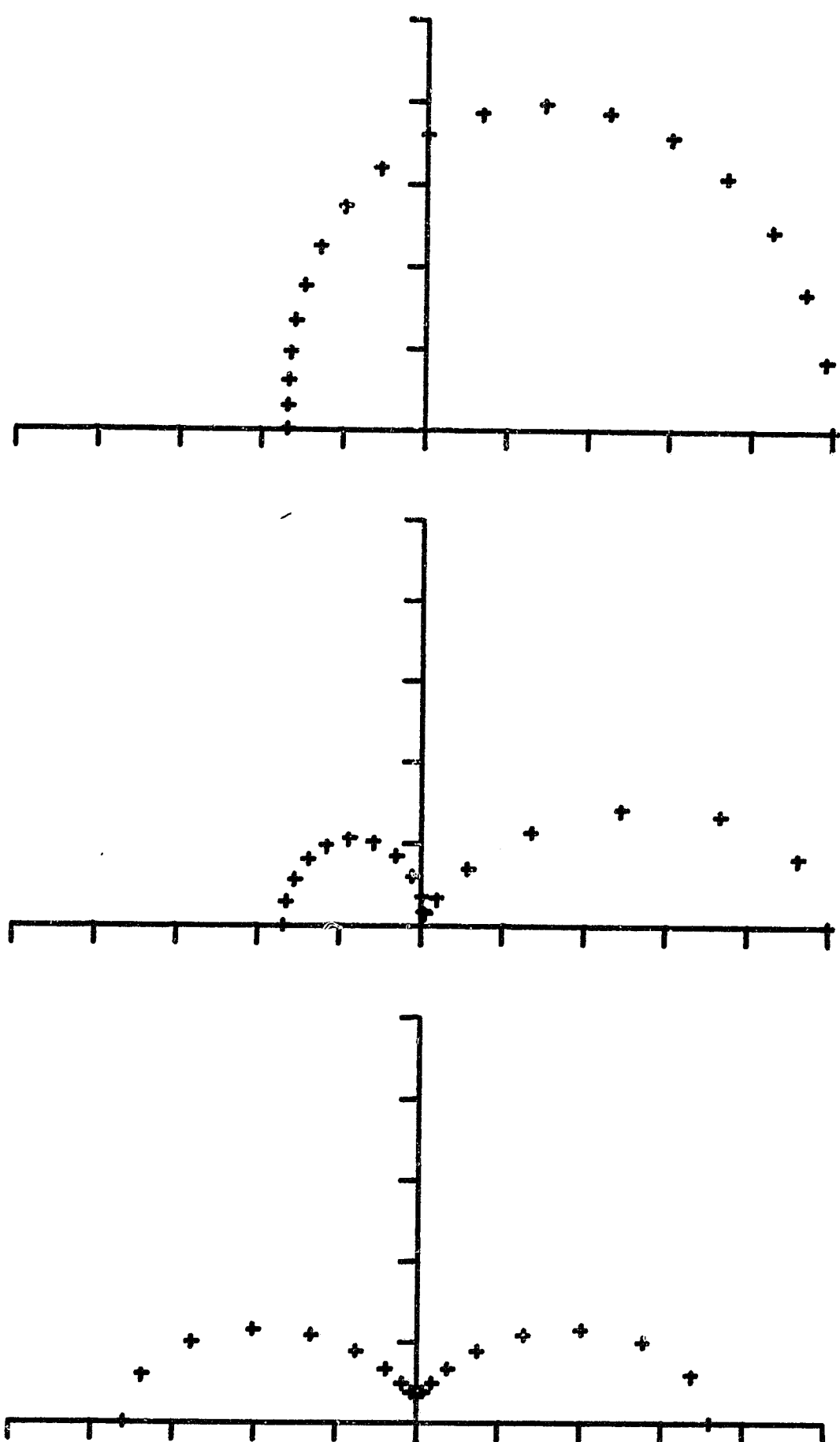


FIG. A17.

FREQ.=2697 KHZ, V ANGLE=124 DEG.

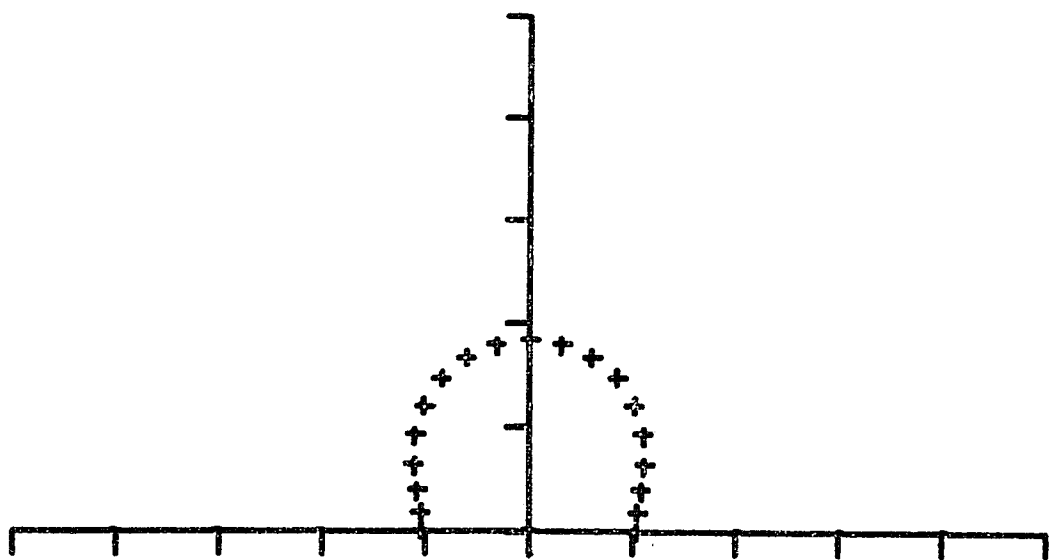
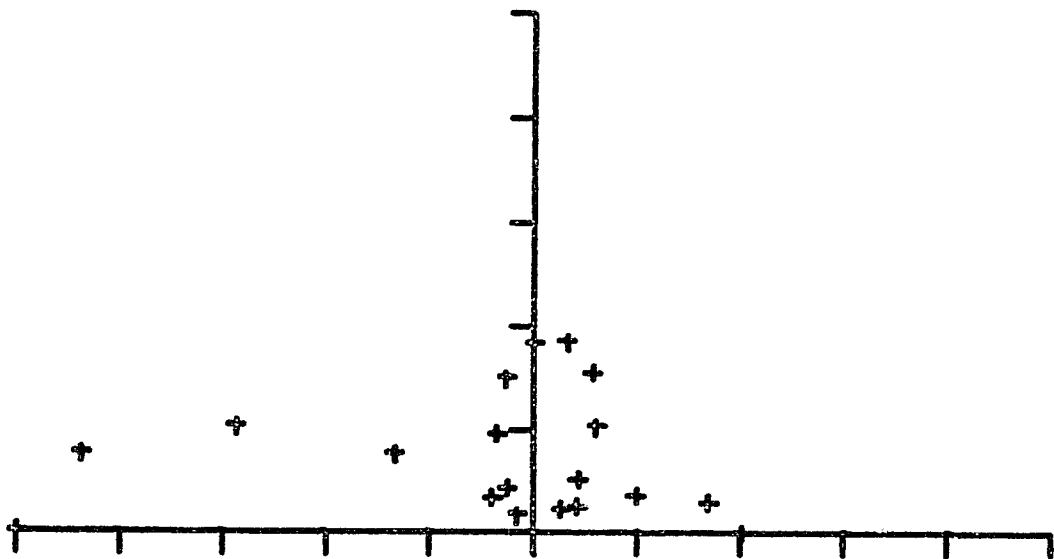
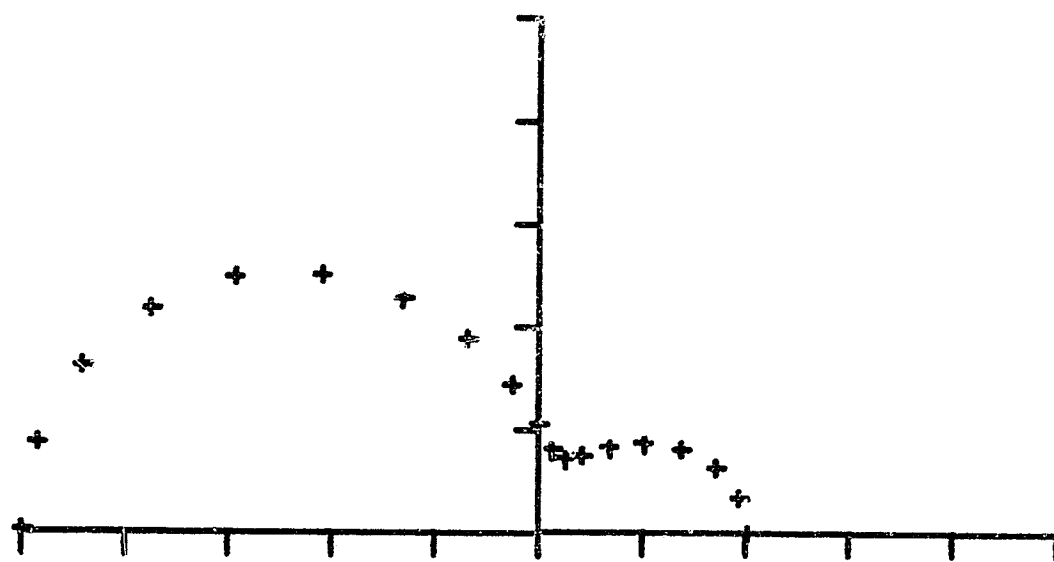


FIG. A18.

FREQ.=3086 KHZ. V ANGLE=124 DEG.

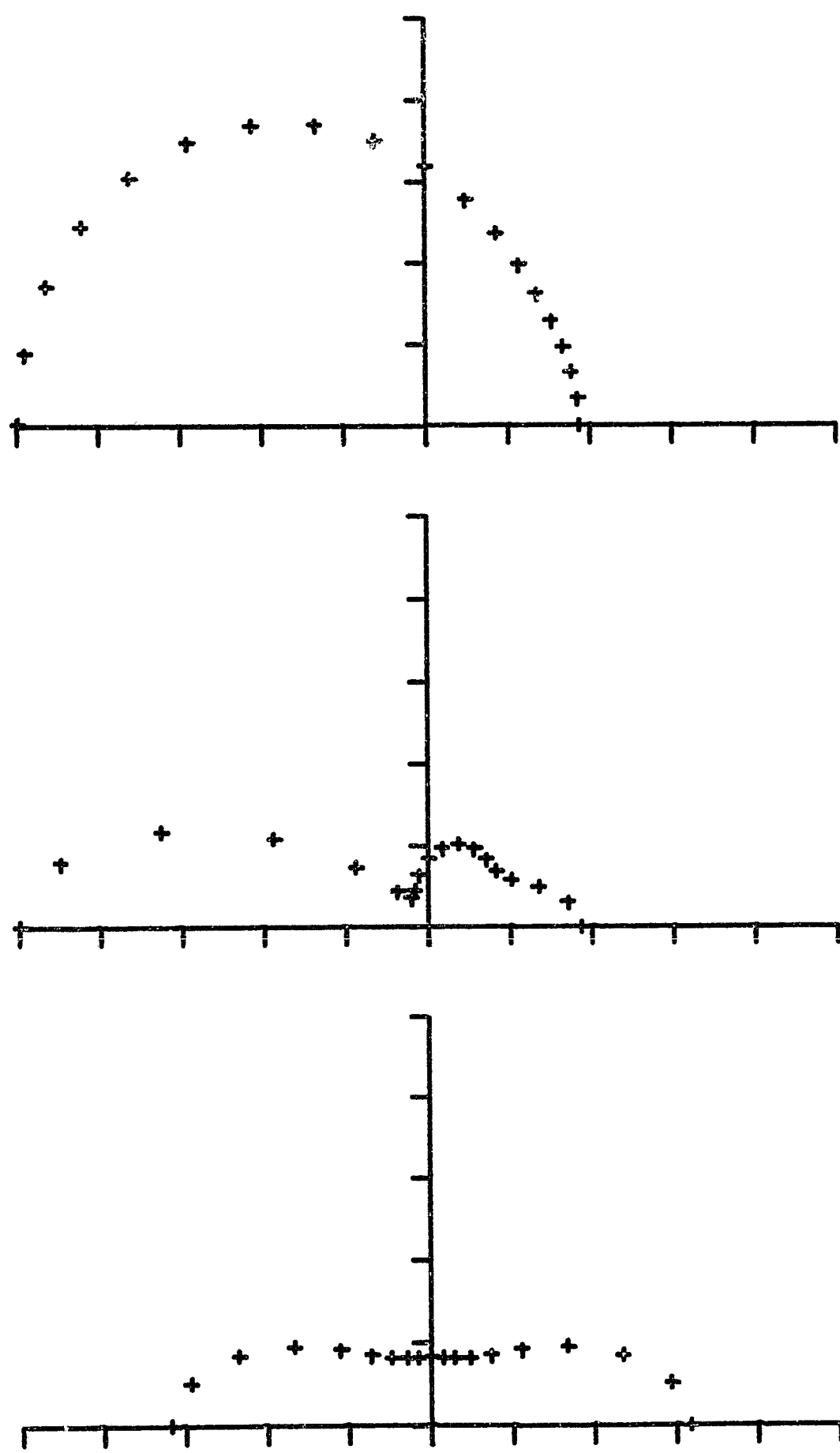


FIG. A19.

FREQ.=3546 KHZ. V ANGLE=124 DEG.

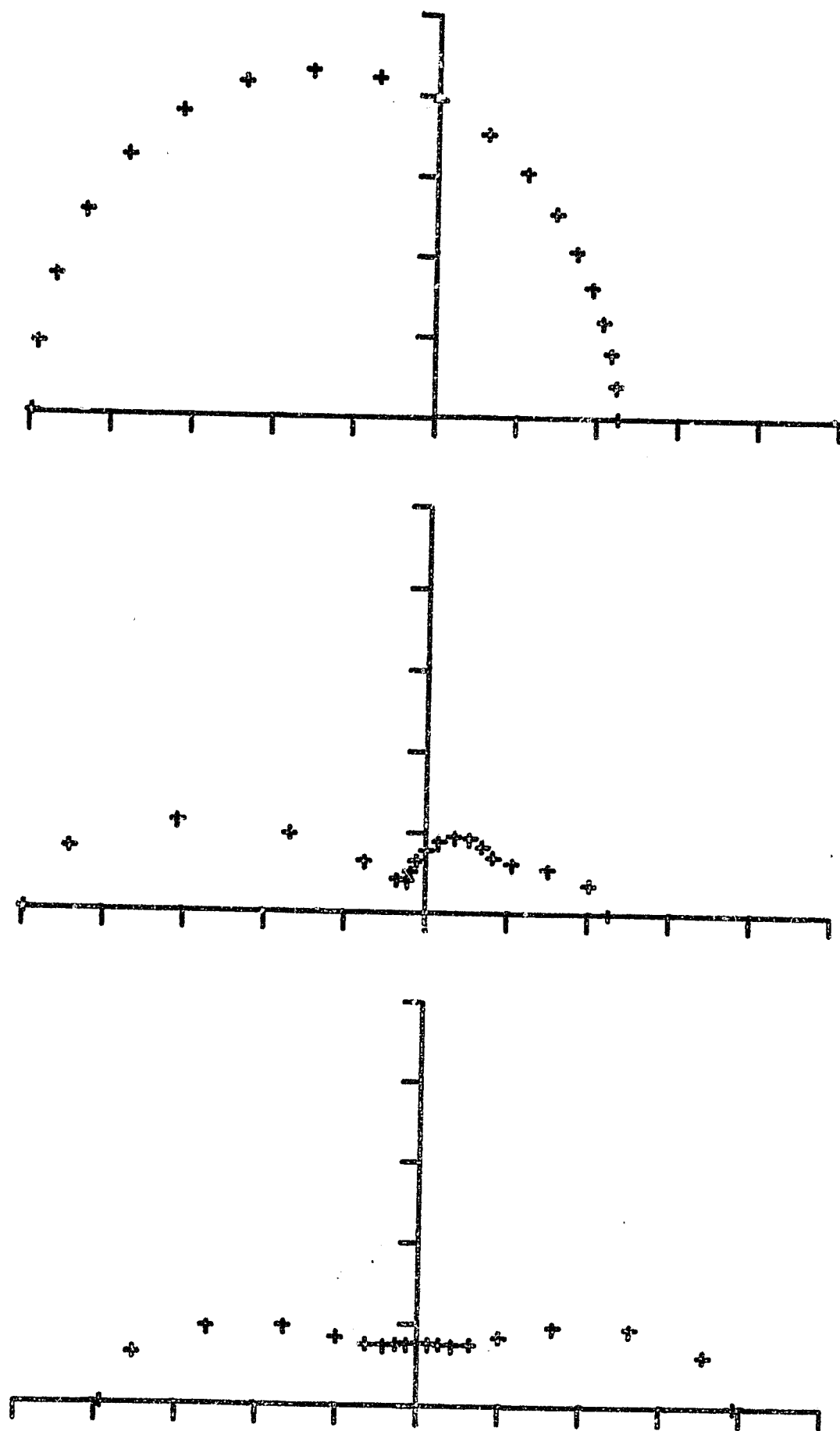


FIG. A20.

FREQ.=4102 KHZ. V ANGLE=124 DEG.

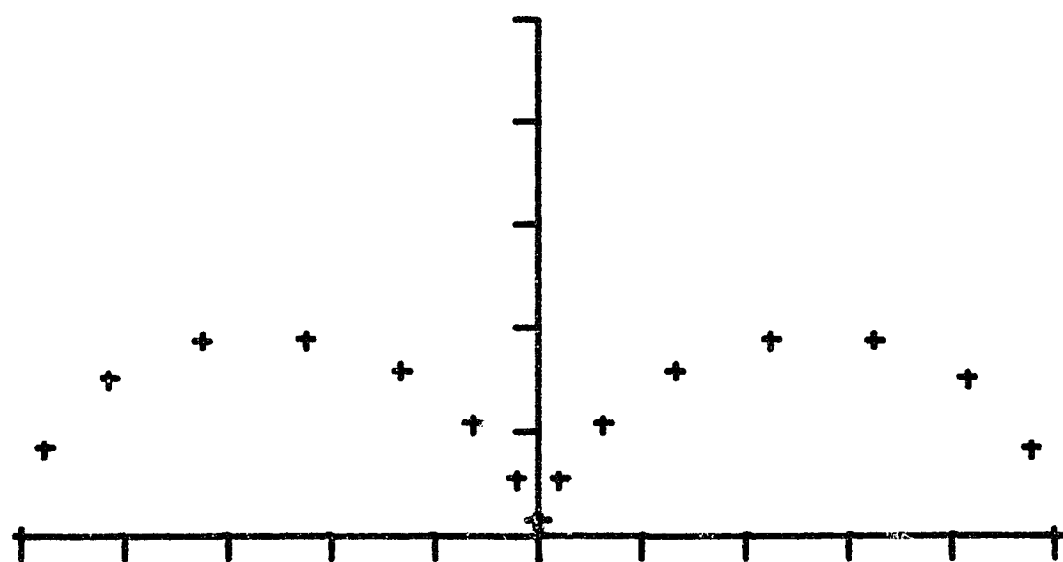
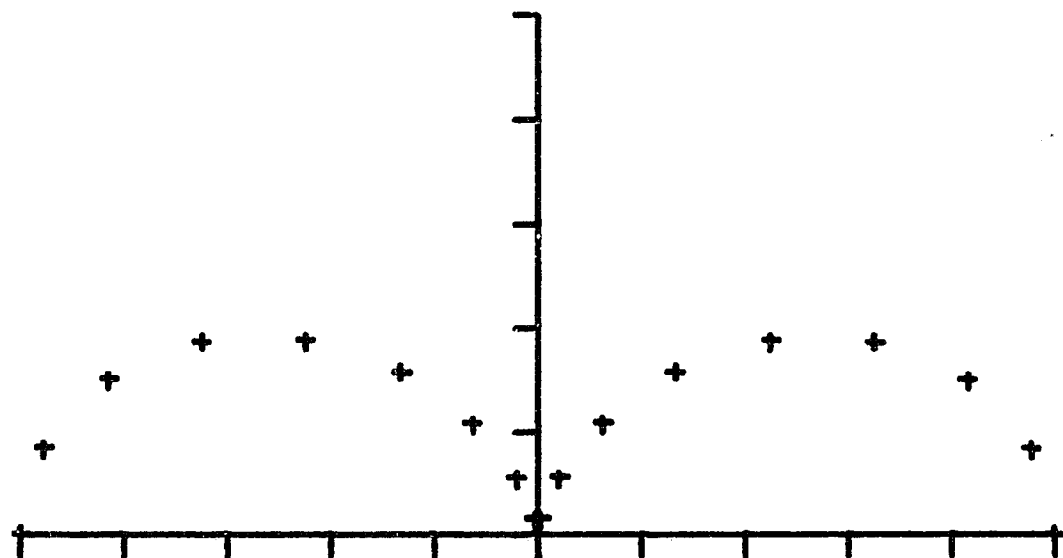
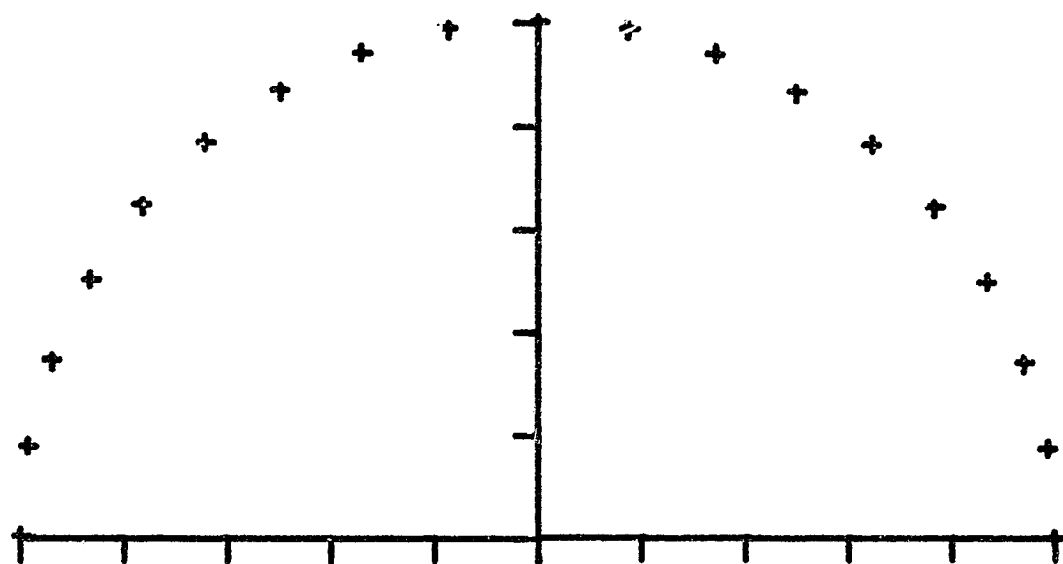


FIG. A21.

FREQ.=60

KHZ, V ANGLE=136 DEG.

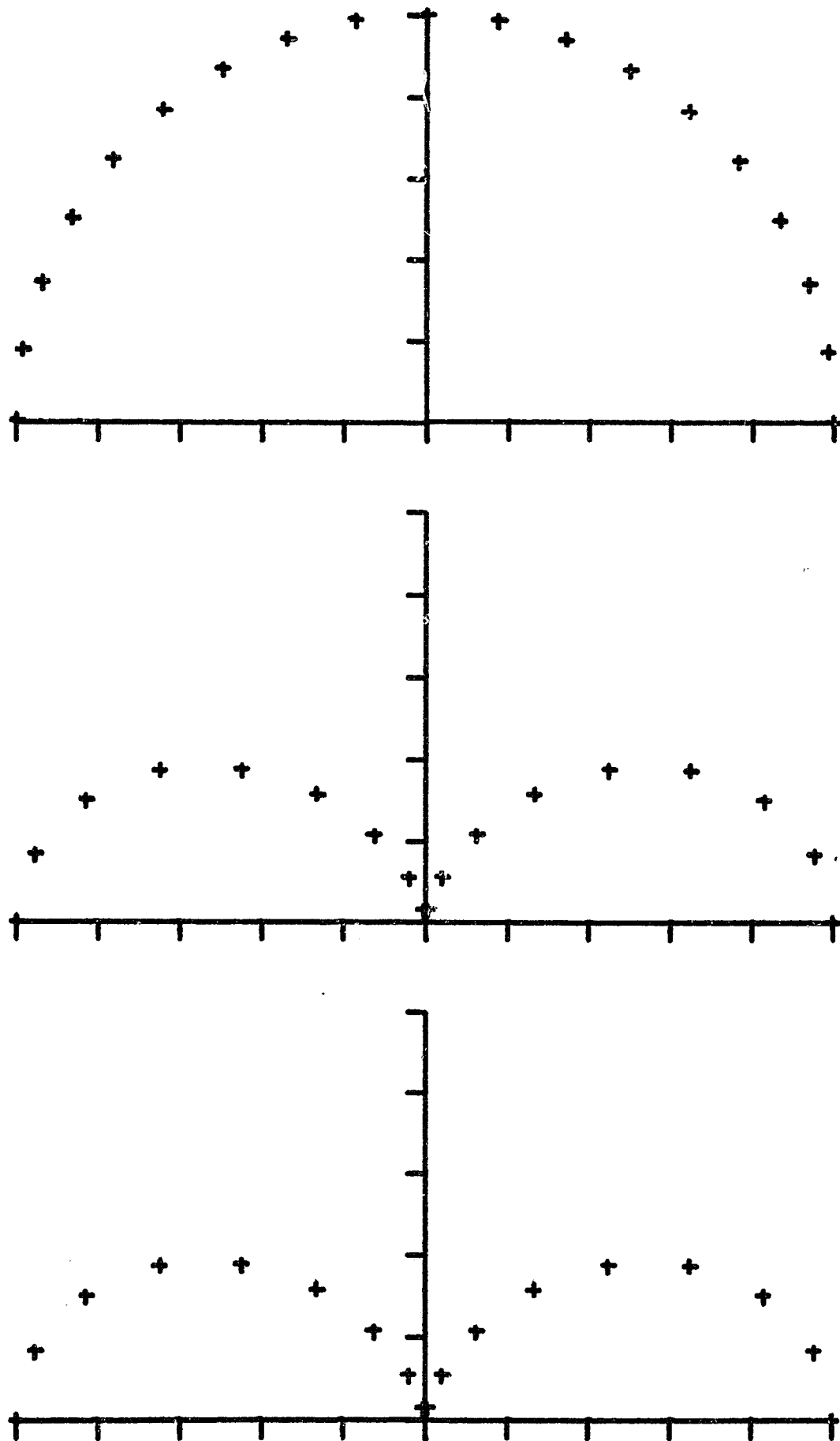


FIG. A22.

FREQ.=128 KHZ. V ANGLE=136 DEG.

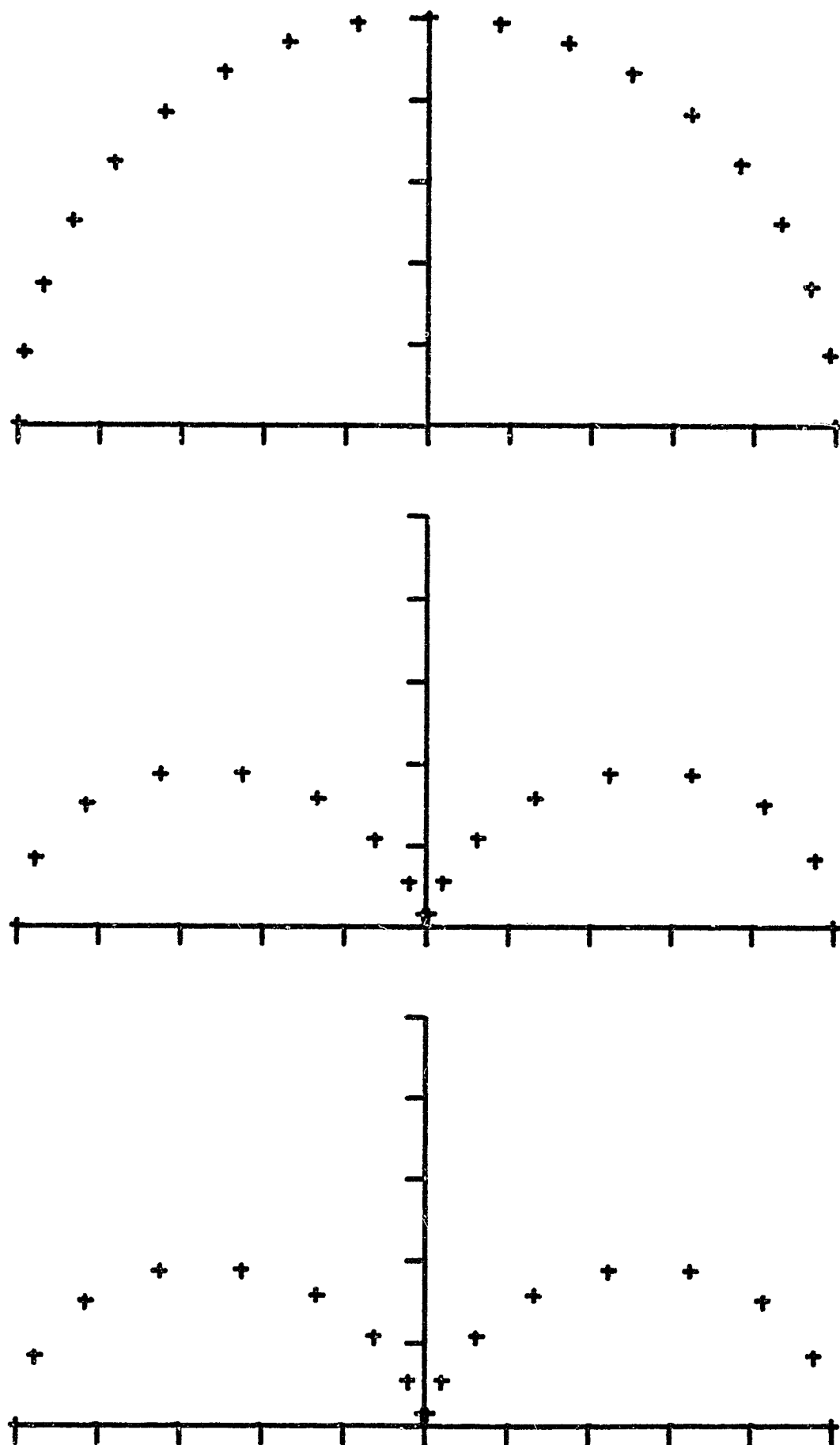


FIG. A23.

FREQ.=188 KHZ, V ANGLE=136 DEG.

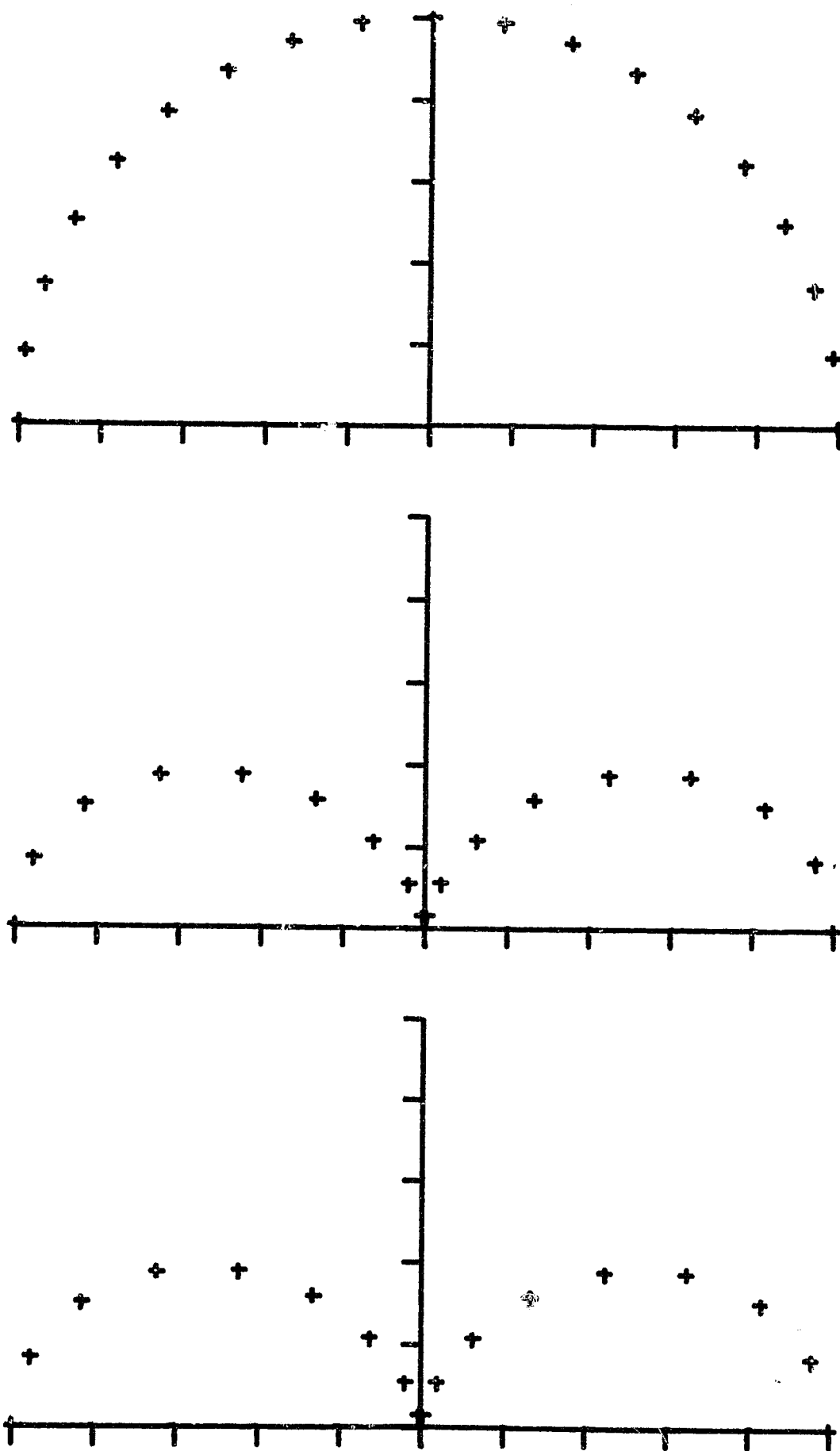


FIG. A24.

FREQ.=258 KHZ. V ANGLE=136 DEG.

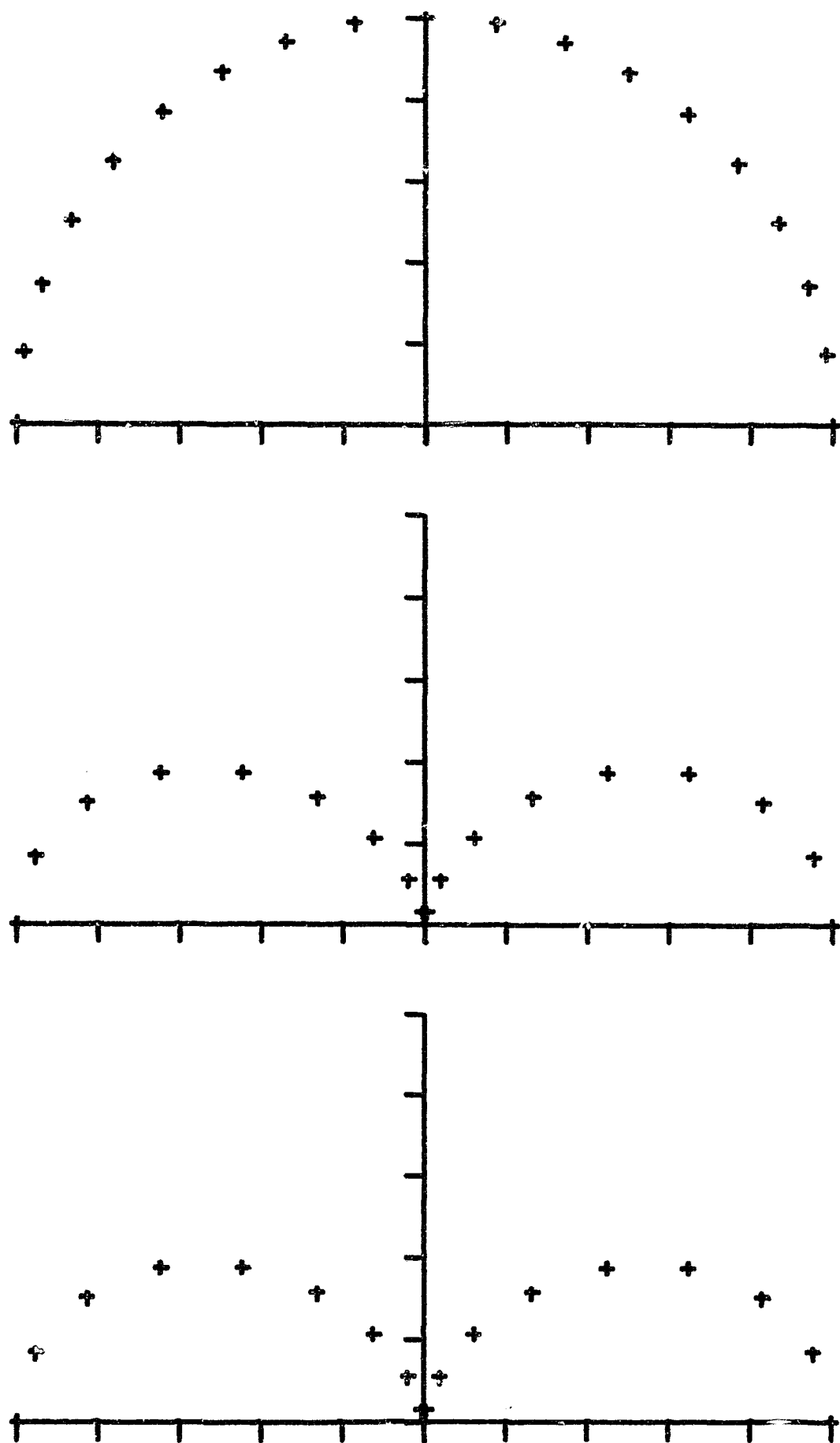


FIG. A25.

FREQ.=407 KHZ, V ANGLE=136 DEG.

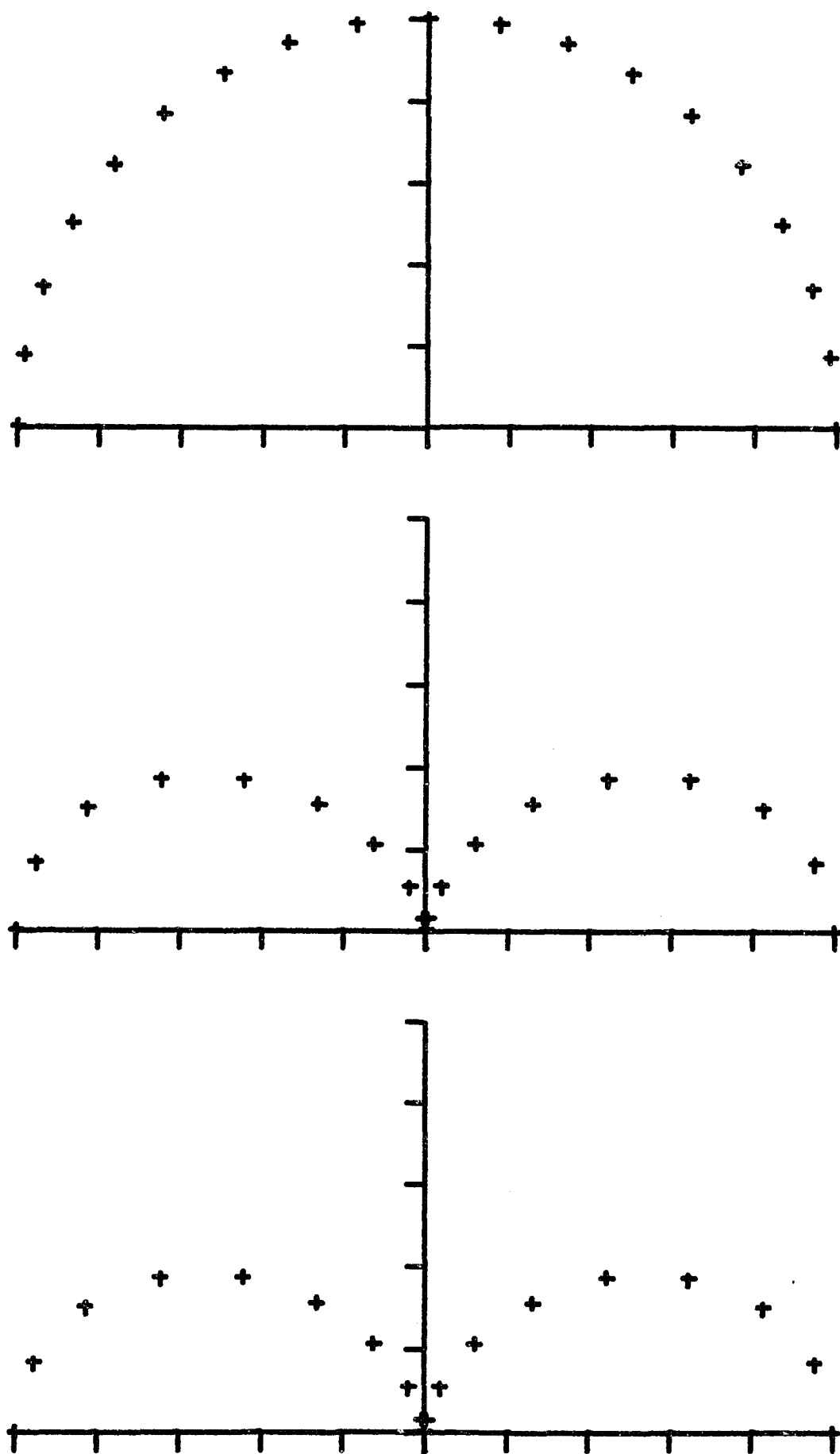


FIG. A26.

FREQ.=567 KHZ, V ANGLE=136 DEG.

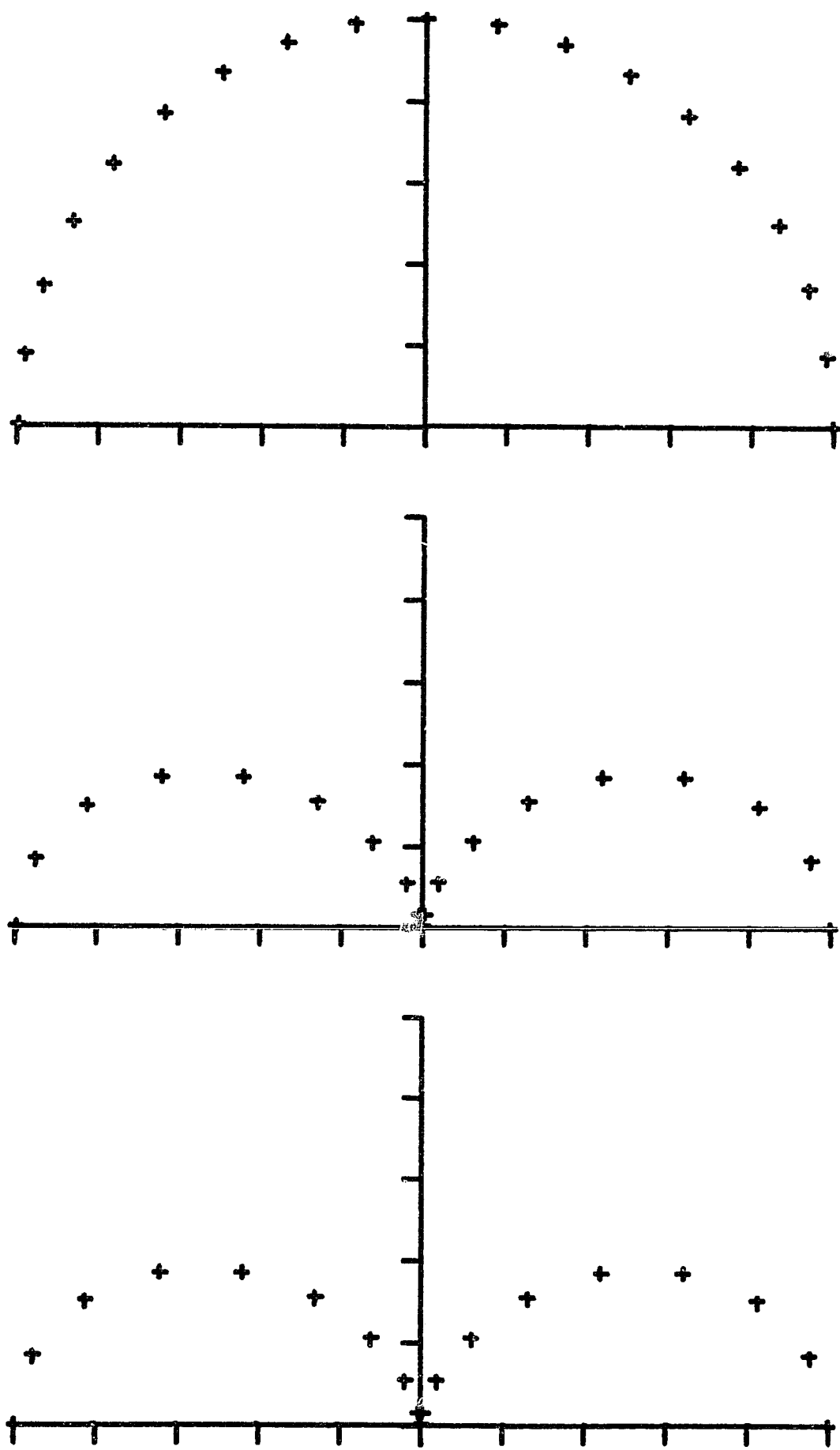


FIG. A27. FREQ.=736 KHZ. V ANGLE=136 DEG.

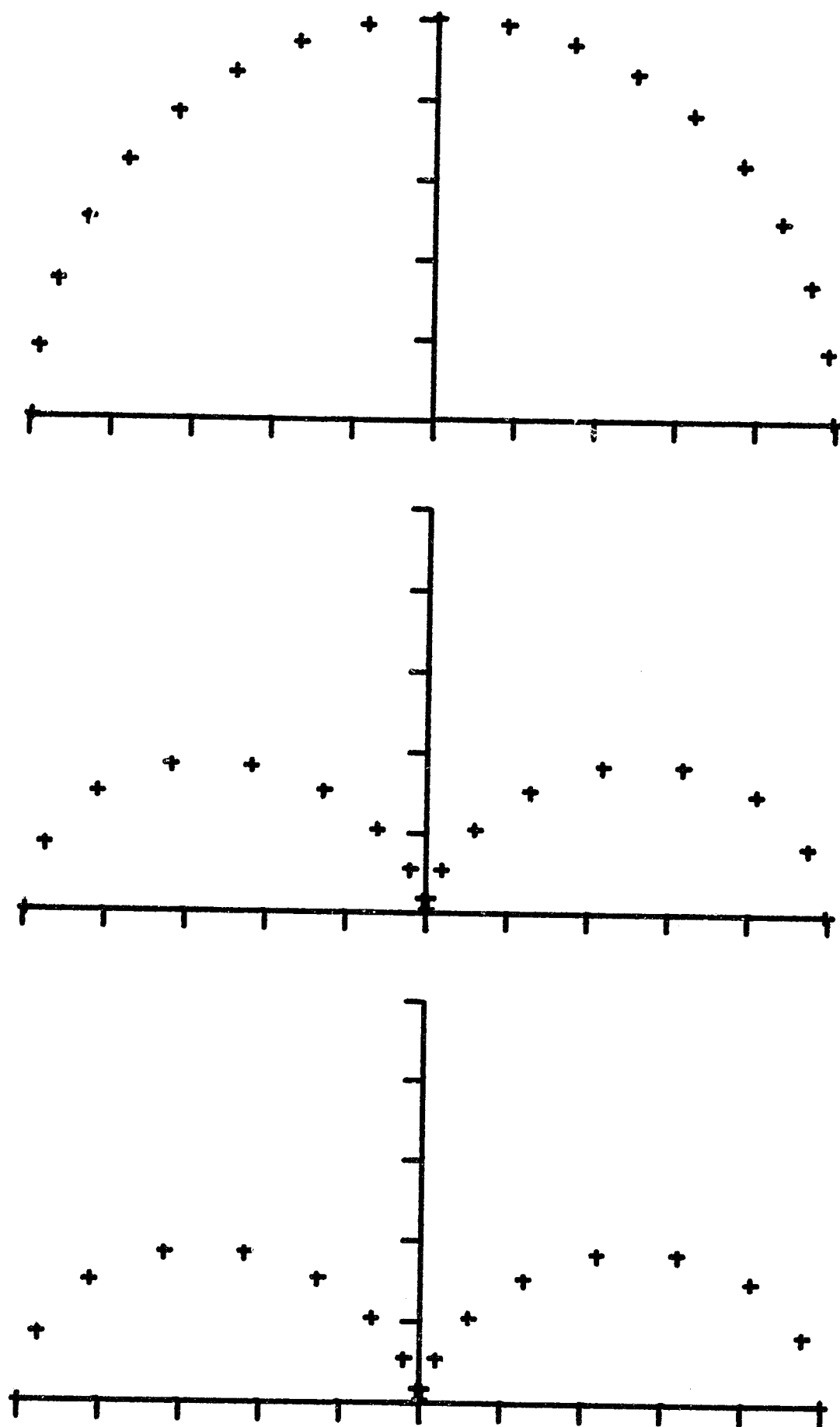


FIG. A28. FREQ.=916 KHZ, V ANGLE=136 DEG.

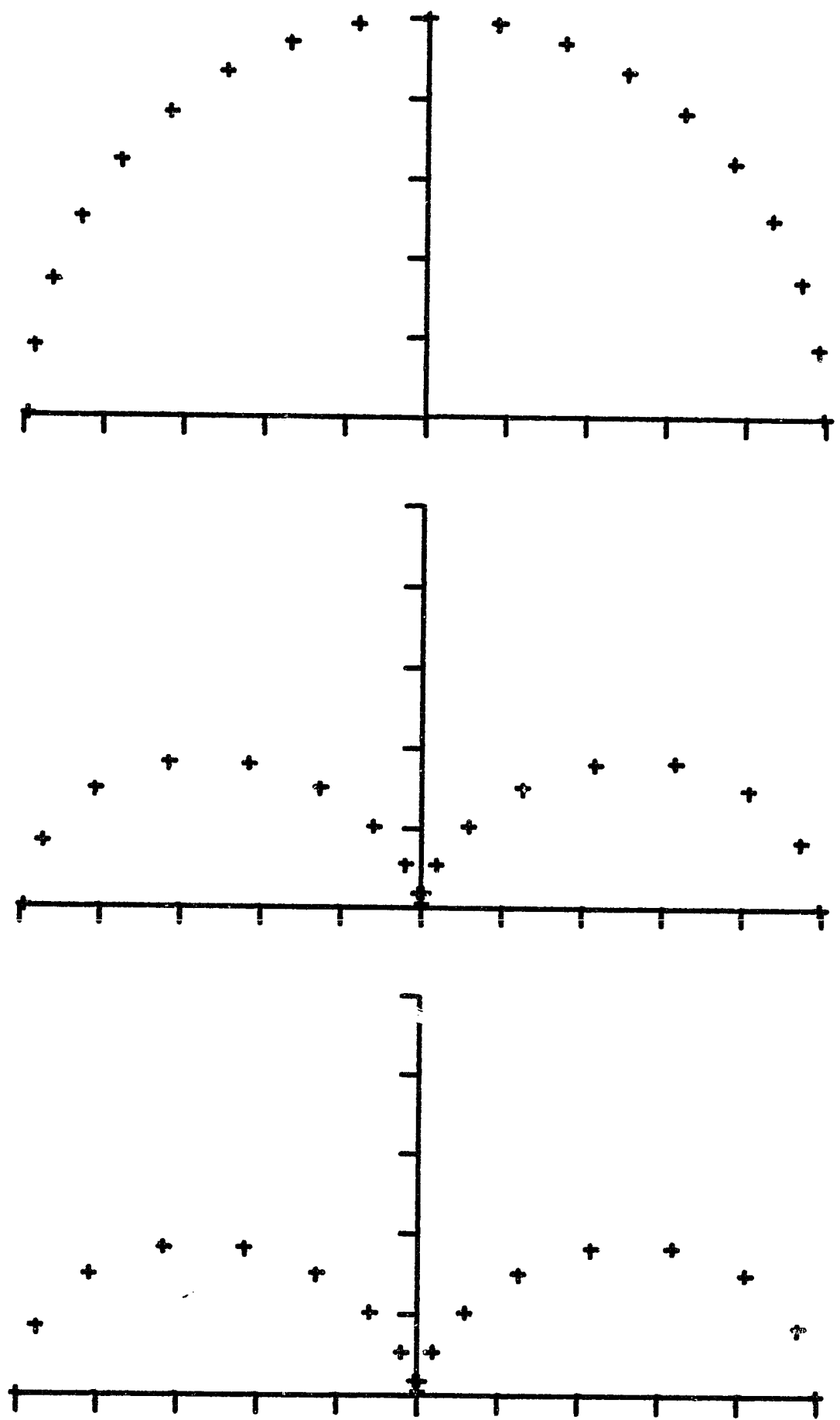


FIG. A29.

FREQ.=1104 KHZ, V ANGLE=136 DEG.

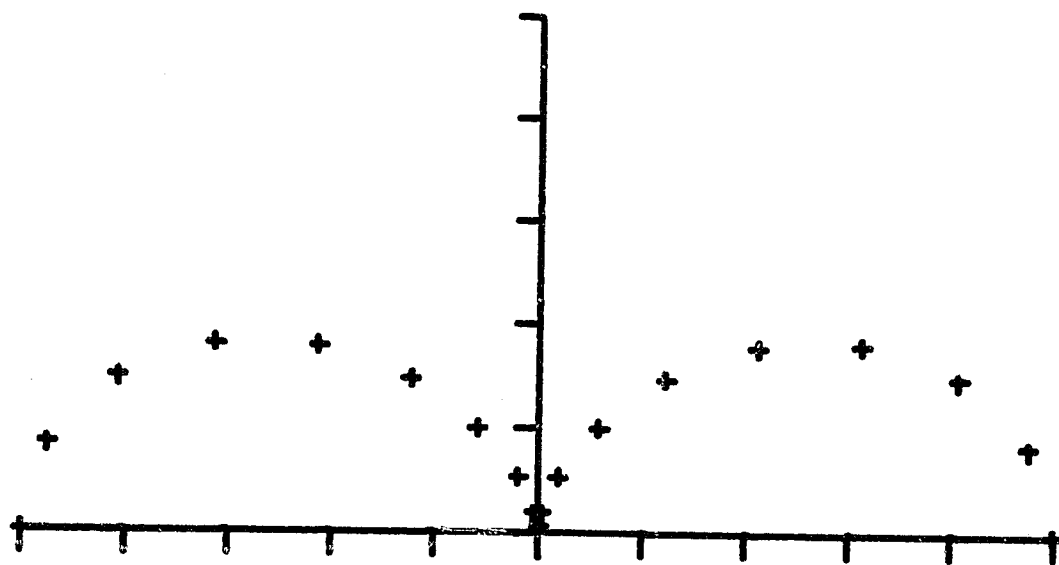
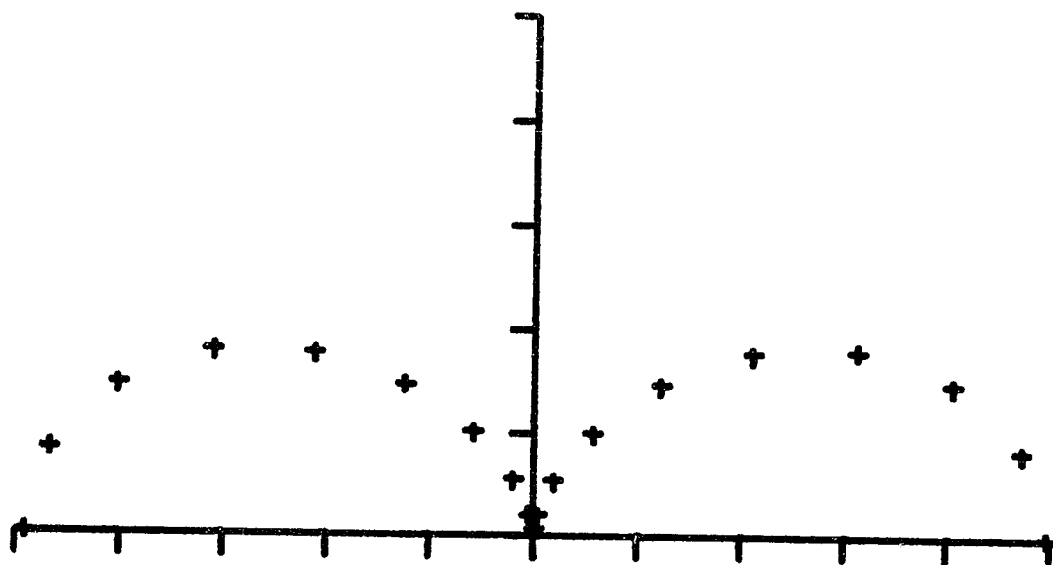
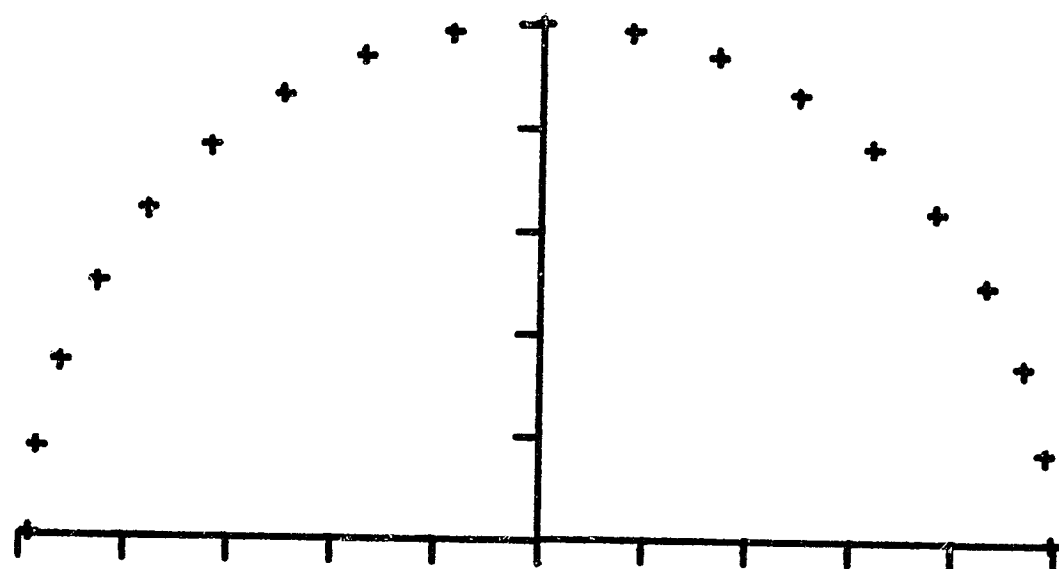


FIG. A30. FREQ.= 1315 KHZ, V ANGLE=136 DEG.

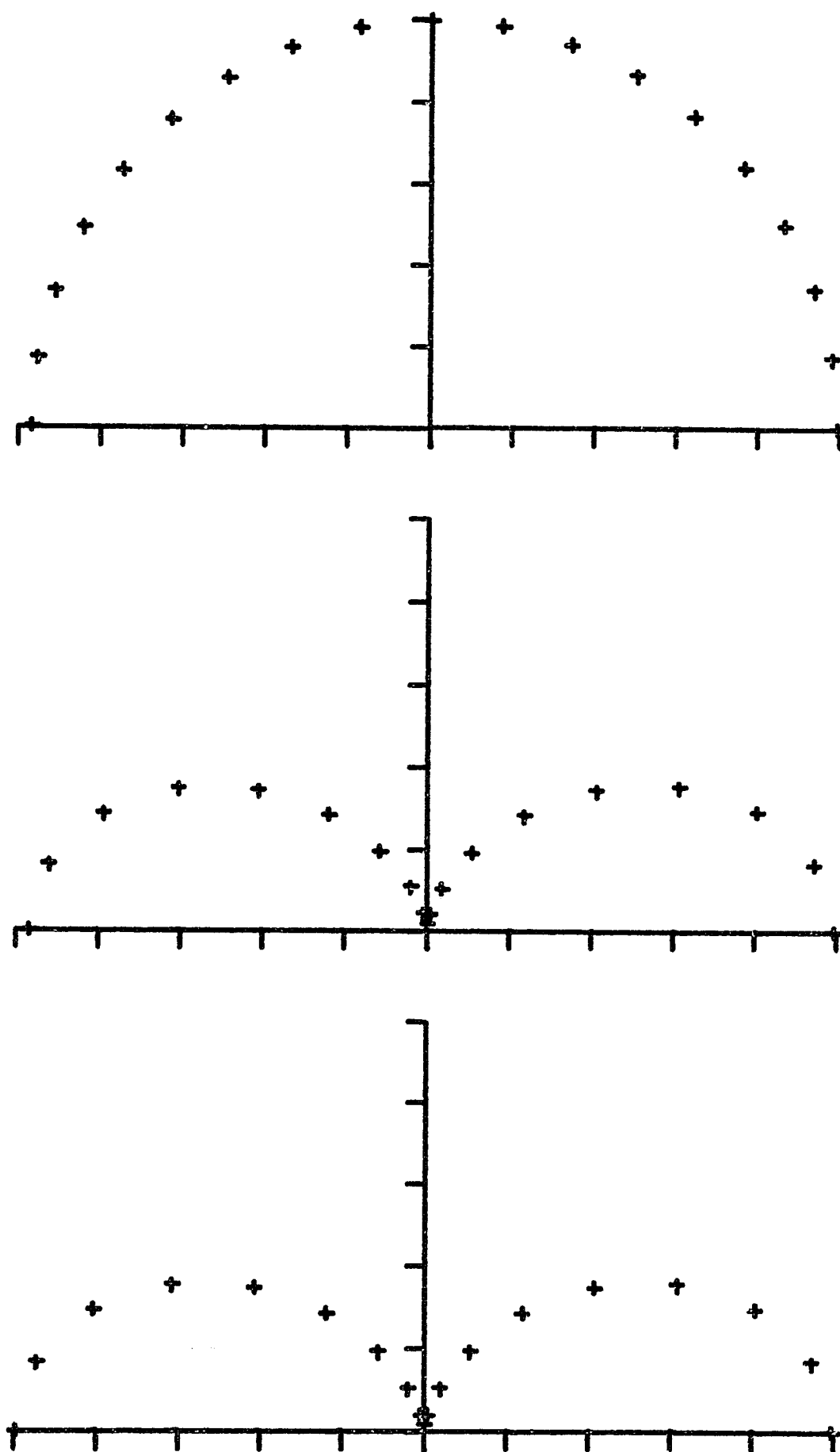


FIG. A31.

FREQ.=1537 KHZ. V ANGLE=136 DEG.

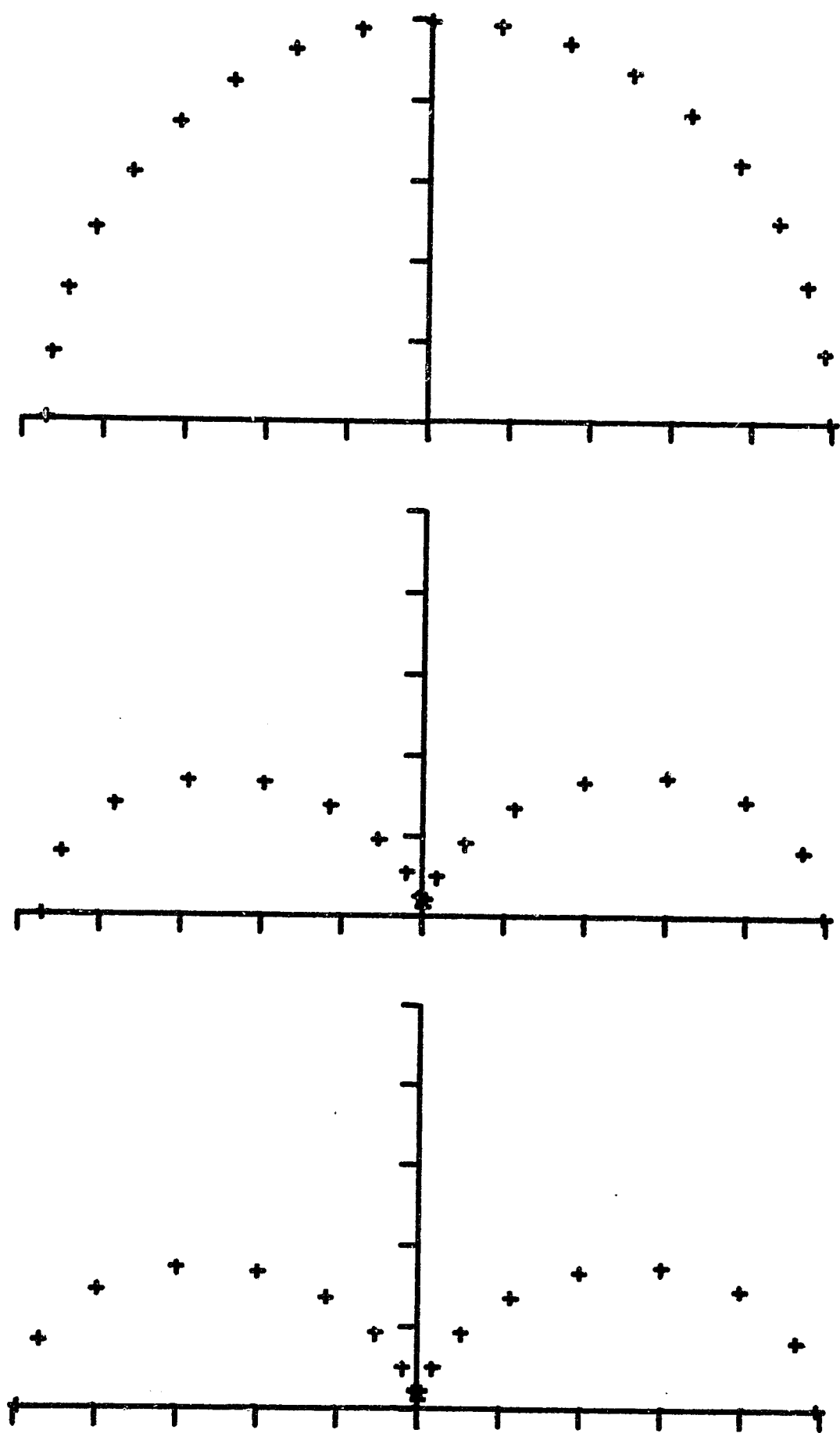


FIG. A32.

FREQ.=1781 KHZ, V ANGLE=136 DEG.

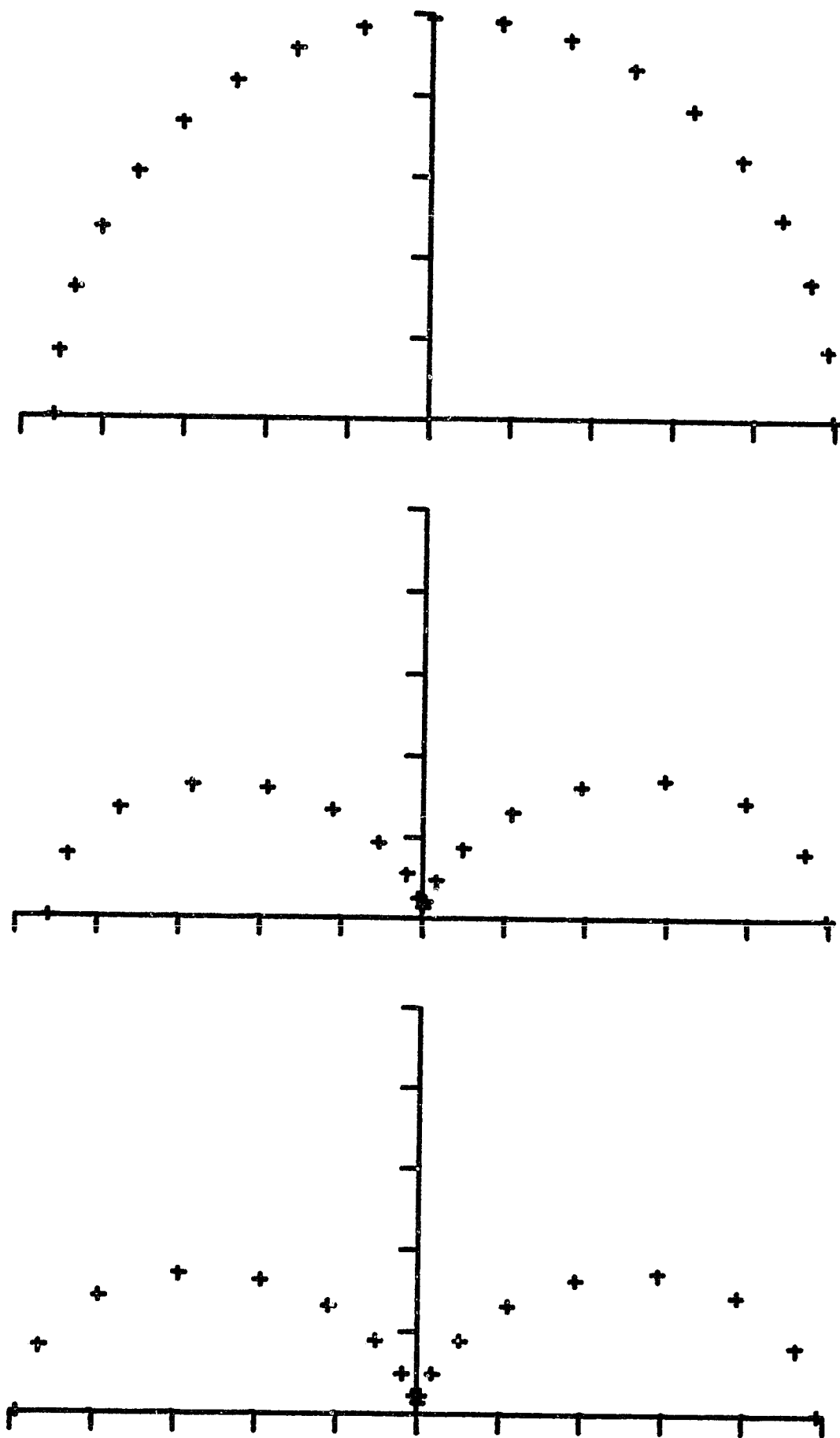


FIG. A33.

FREQ.=1913 KHZ, V ANGLE=136 DEG.

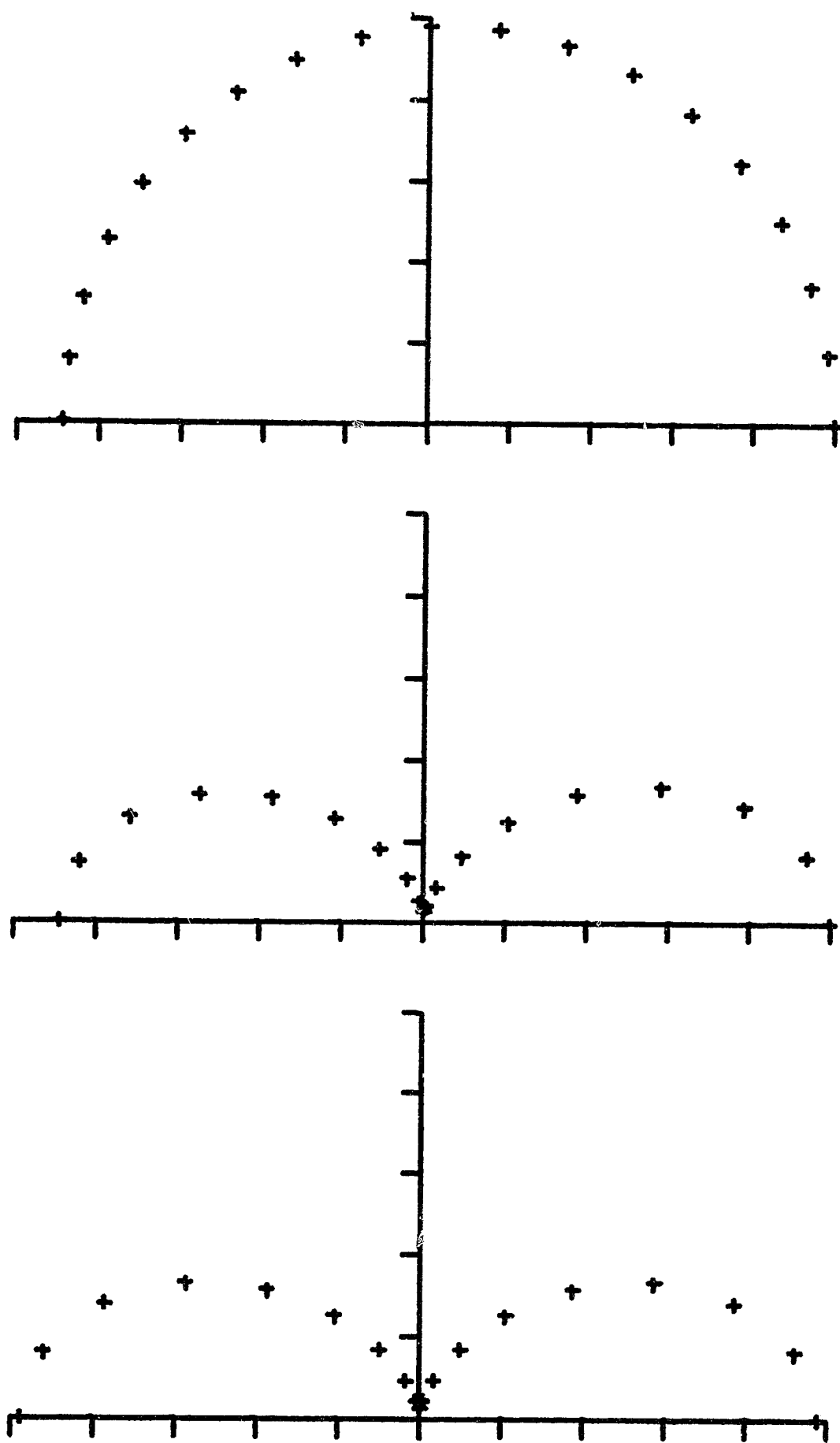


FIG. A34.

FREQ.=2053 KHZ, V ANGLE=136 DEG.

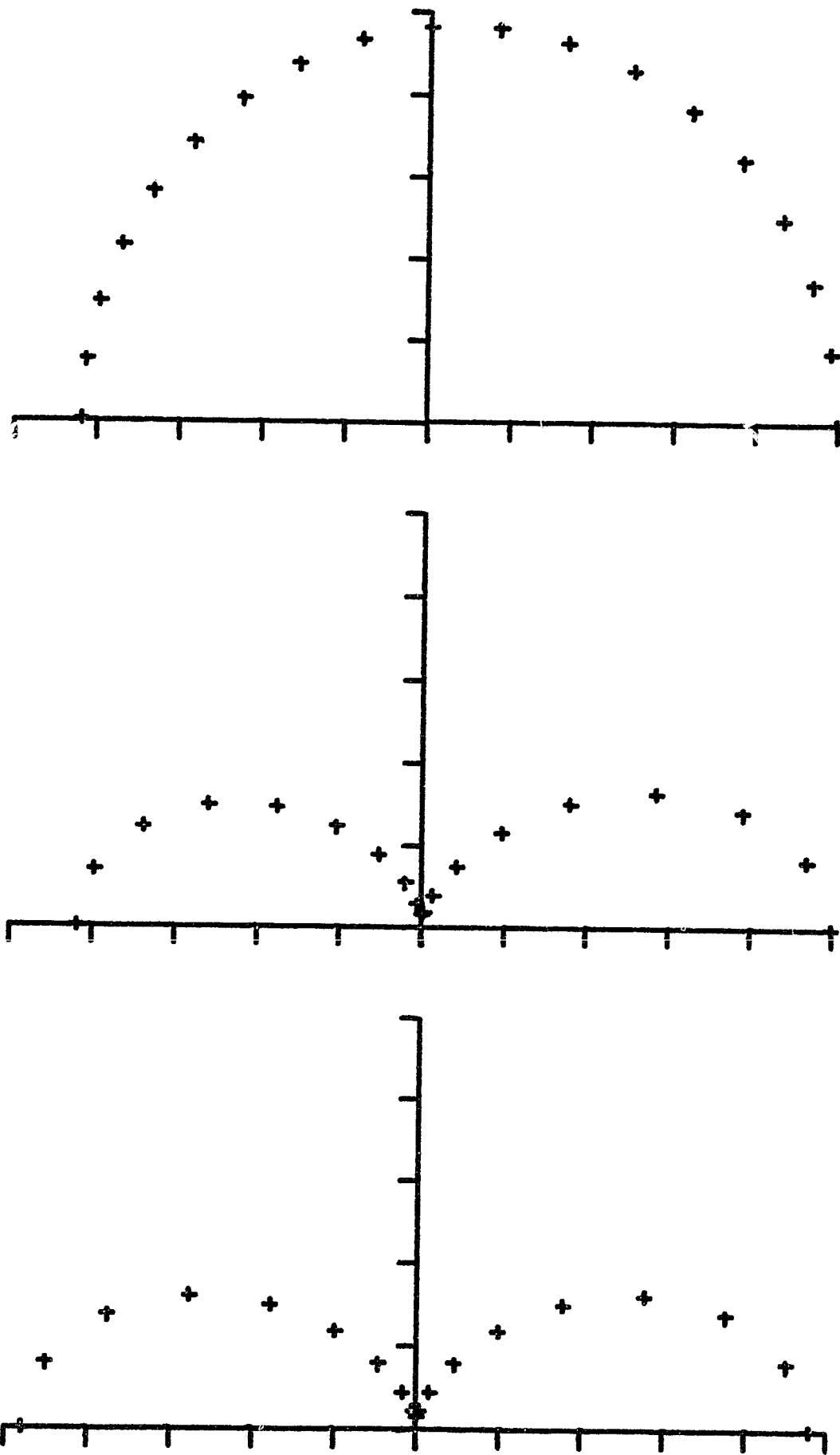


FIG. A35,

FREQ.=2202 KHZ, V ANGLE=136 DEG.

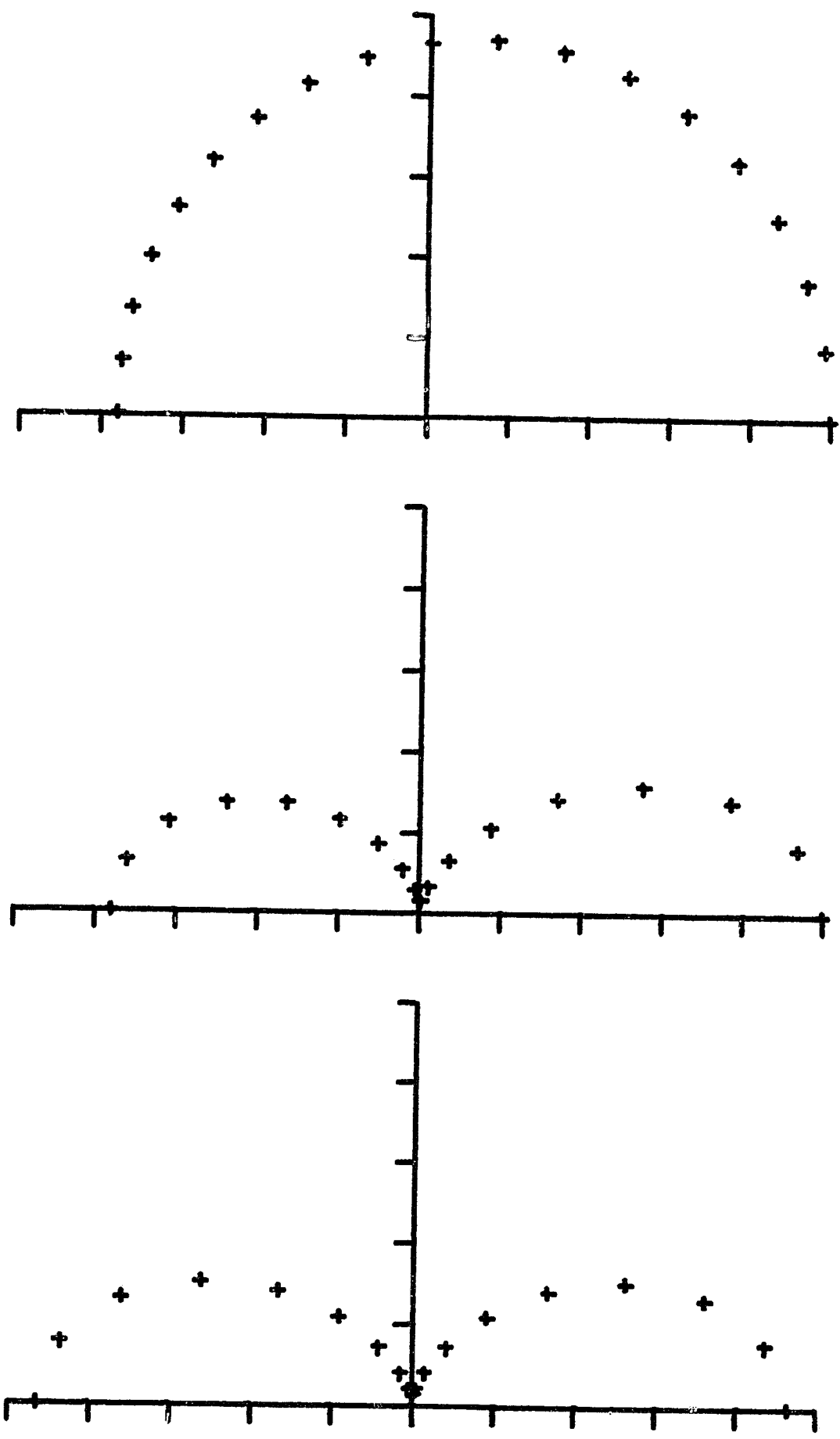


FIG. A36. FREQ.=2353 KHZ, V ANGLE=136 DEG.

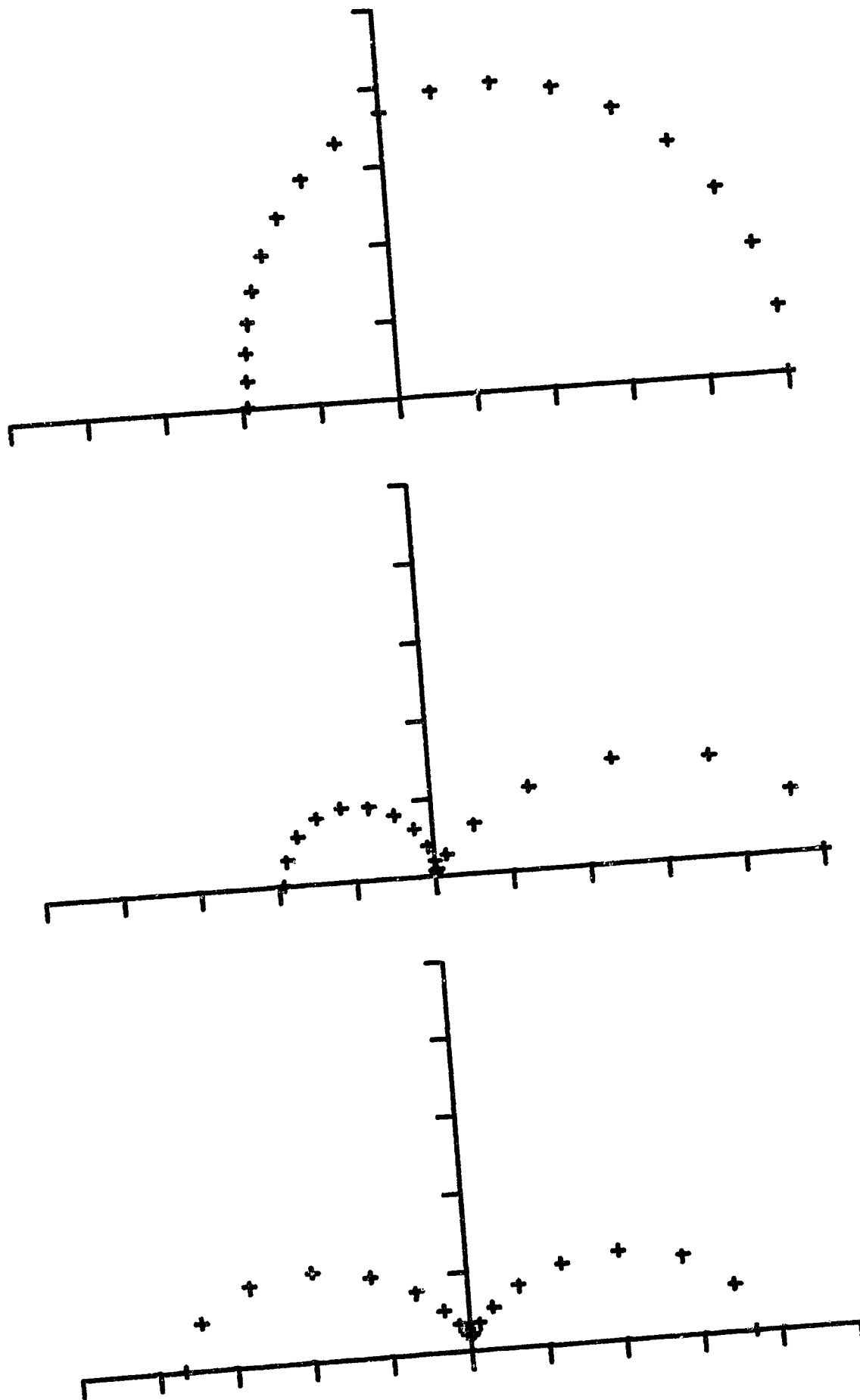


FIG. A37.

FREQ.=2697 KHZ. V ANGLE=136 DEG.

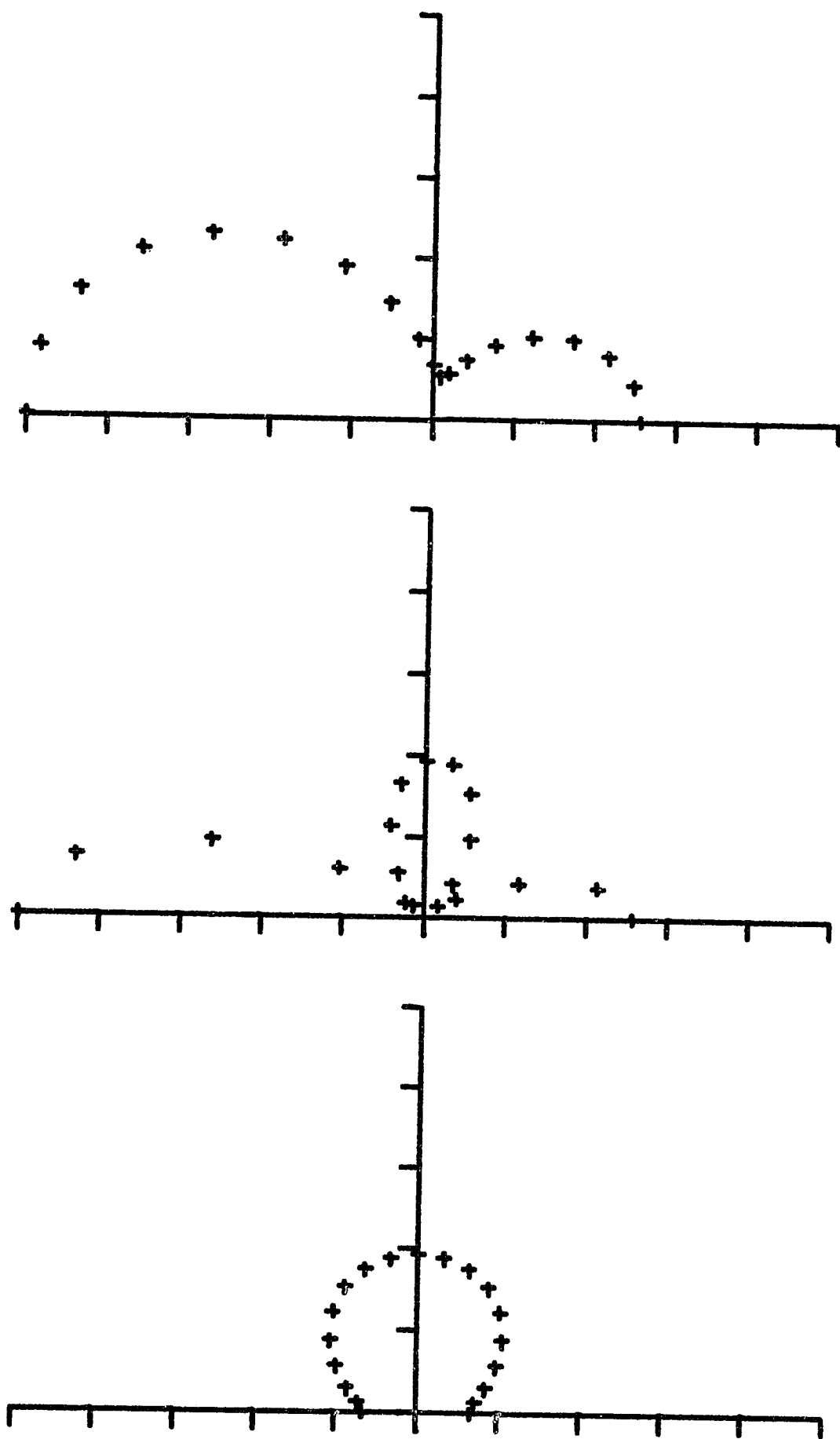


FIG. A38.

FREQ.=3086 KHZ. V ANGLE=136 DEG.

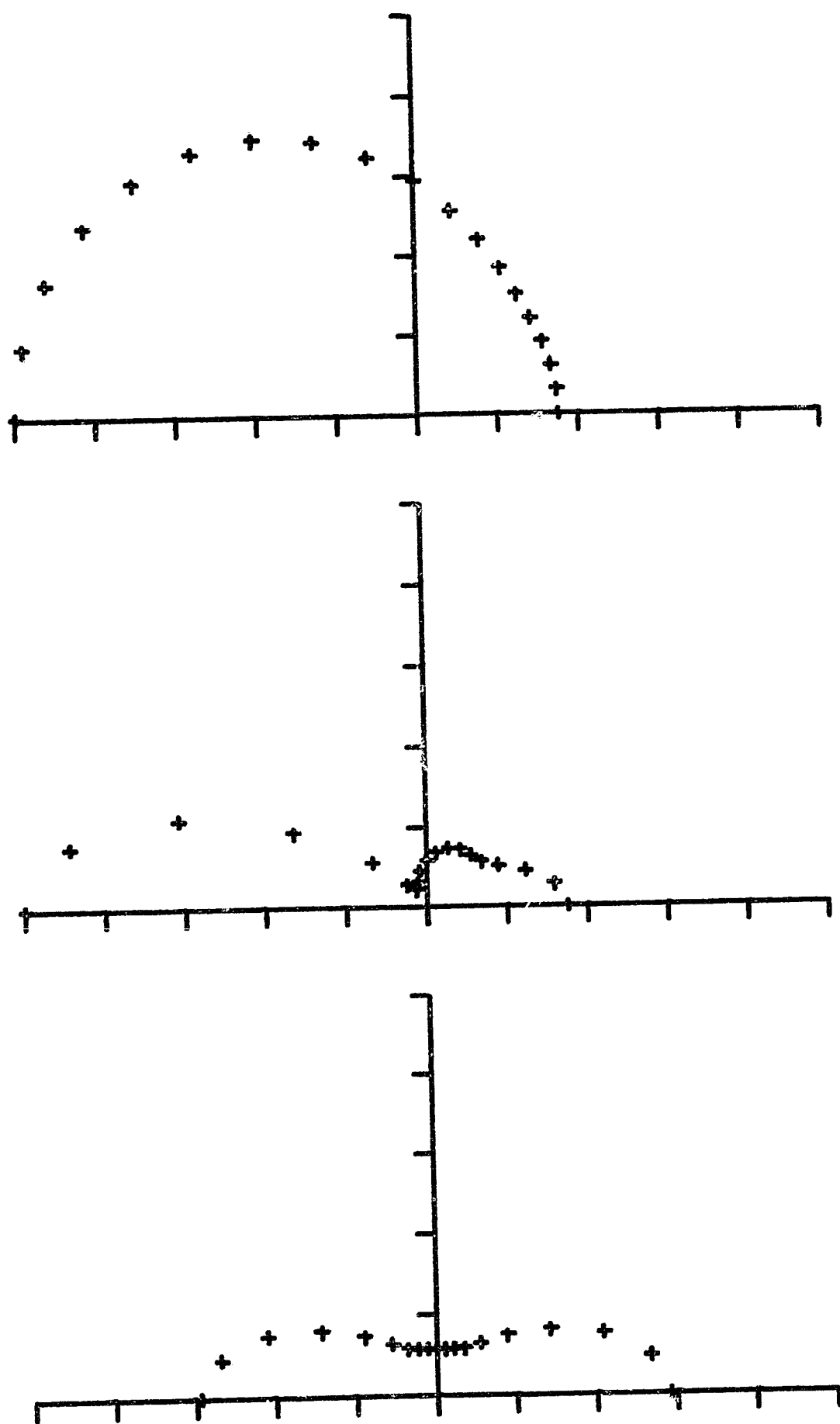


FIG. A39.

FREQ.=3546 KHZ. V ANGLE=136 DEG.

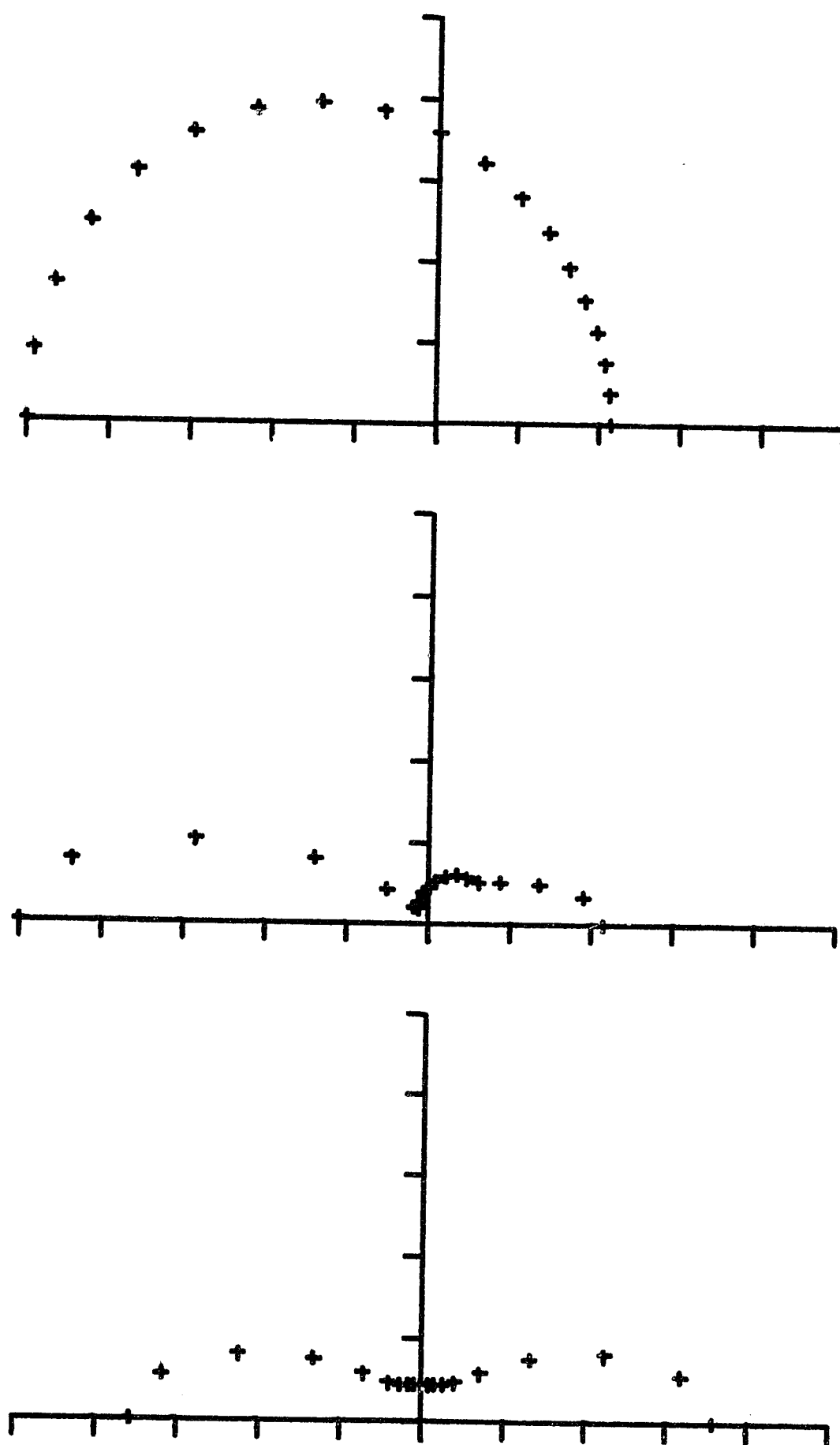


FIG. A40.

FREQ.=4102 KHZ, V ANGLE=136 DEG.

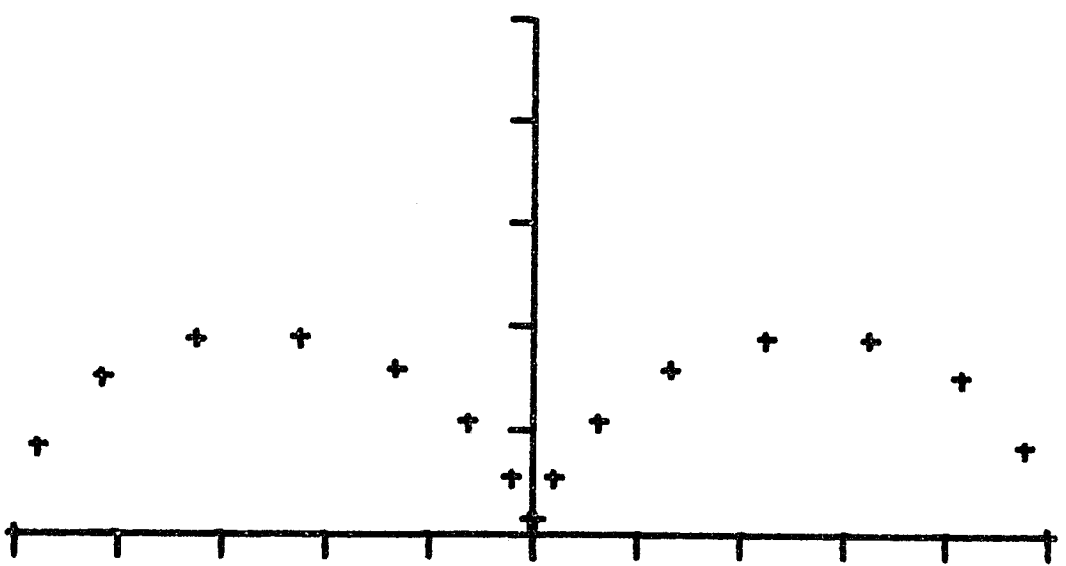
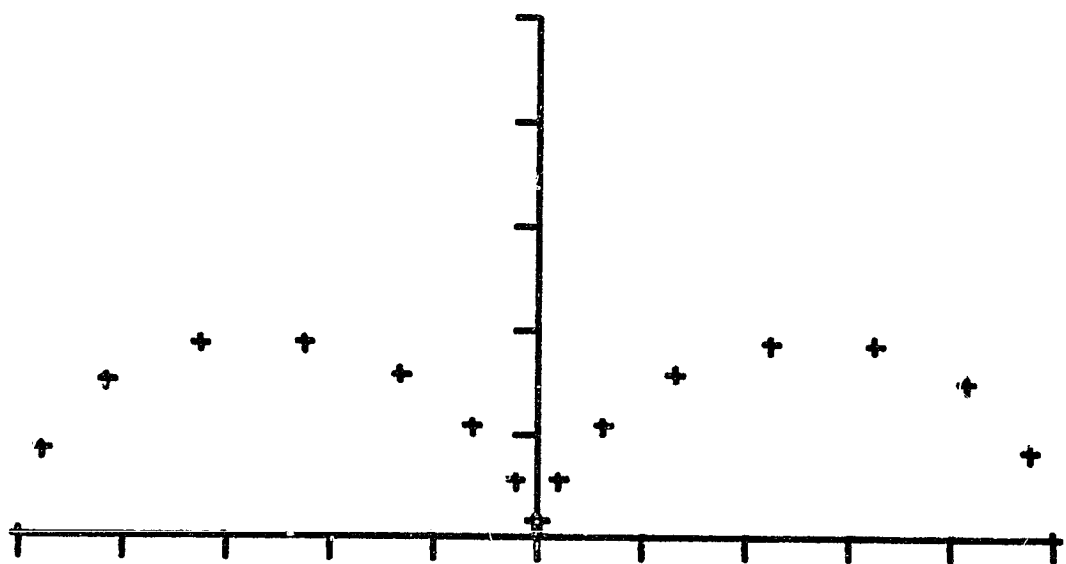
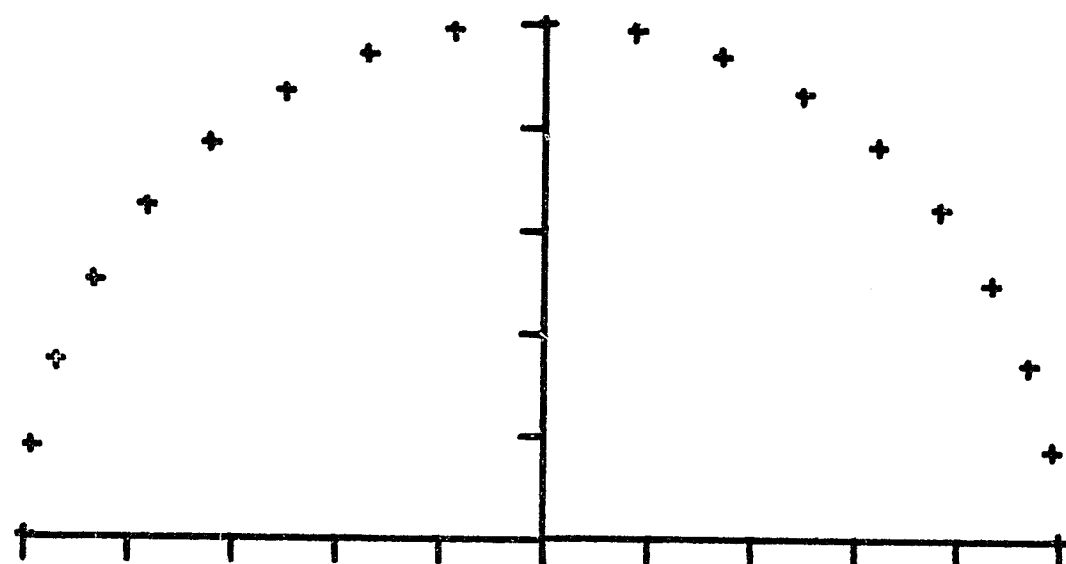


FIG. A41. FREQ.=60 KHZ. V ANGLE=154 DEG.

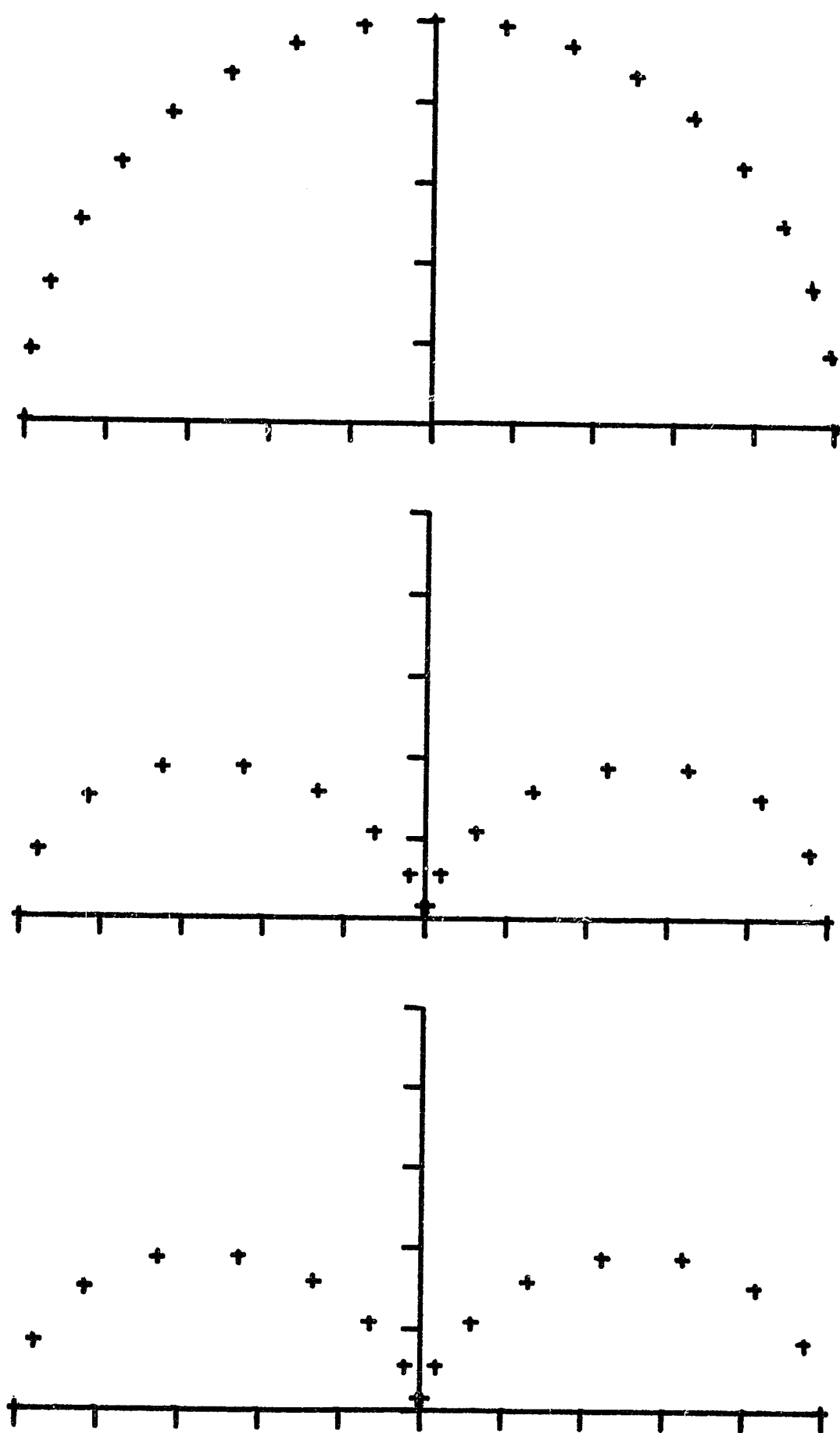


FIG. A42. FREQ.=128 KHZ. V ANGLE=154 DEG.

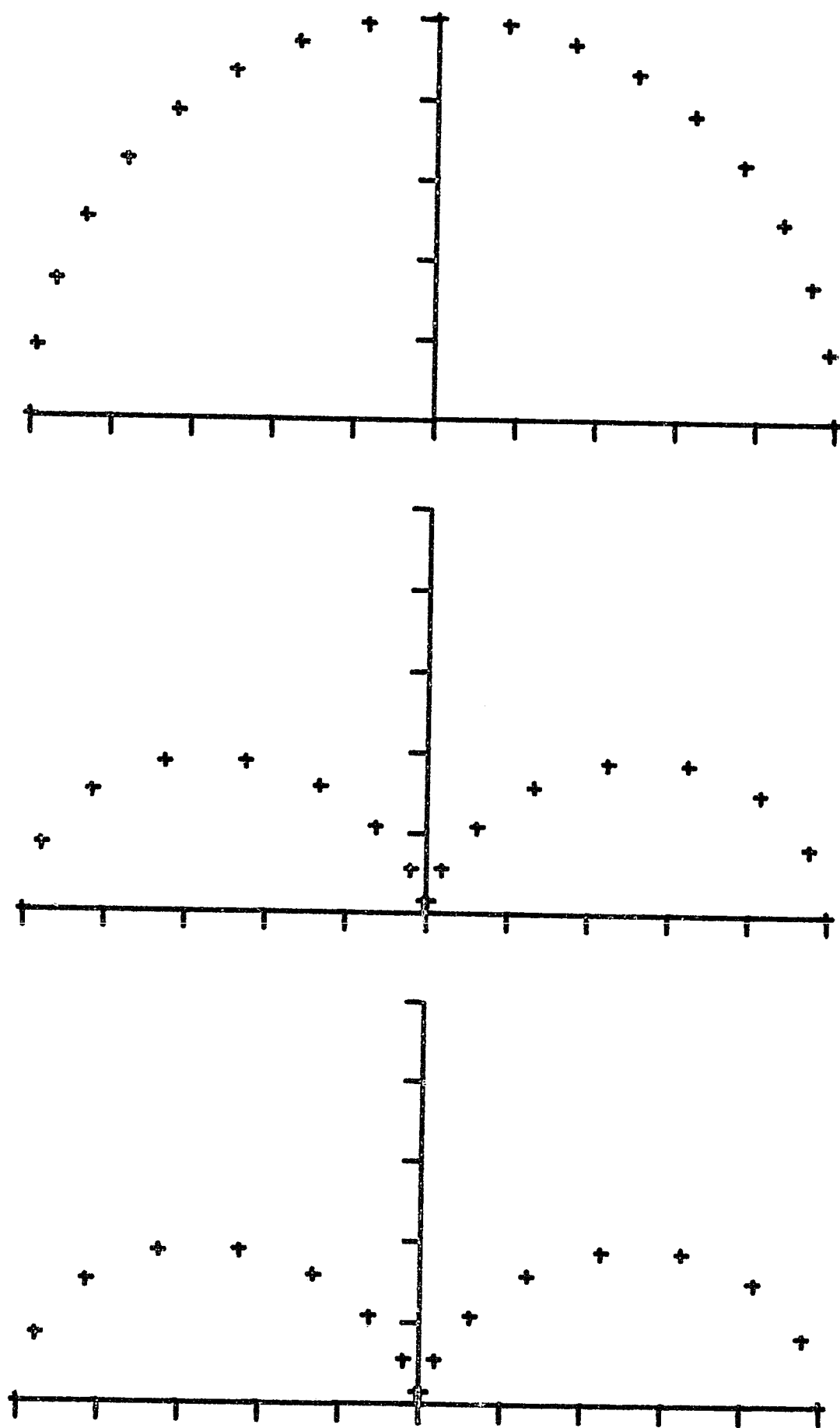


FIG. A43.

FREQ.=188 KHZ. V ANGLE=154 DEG.

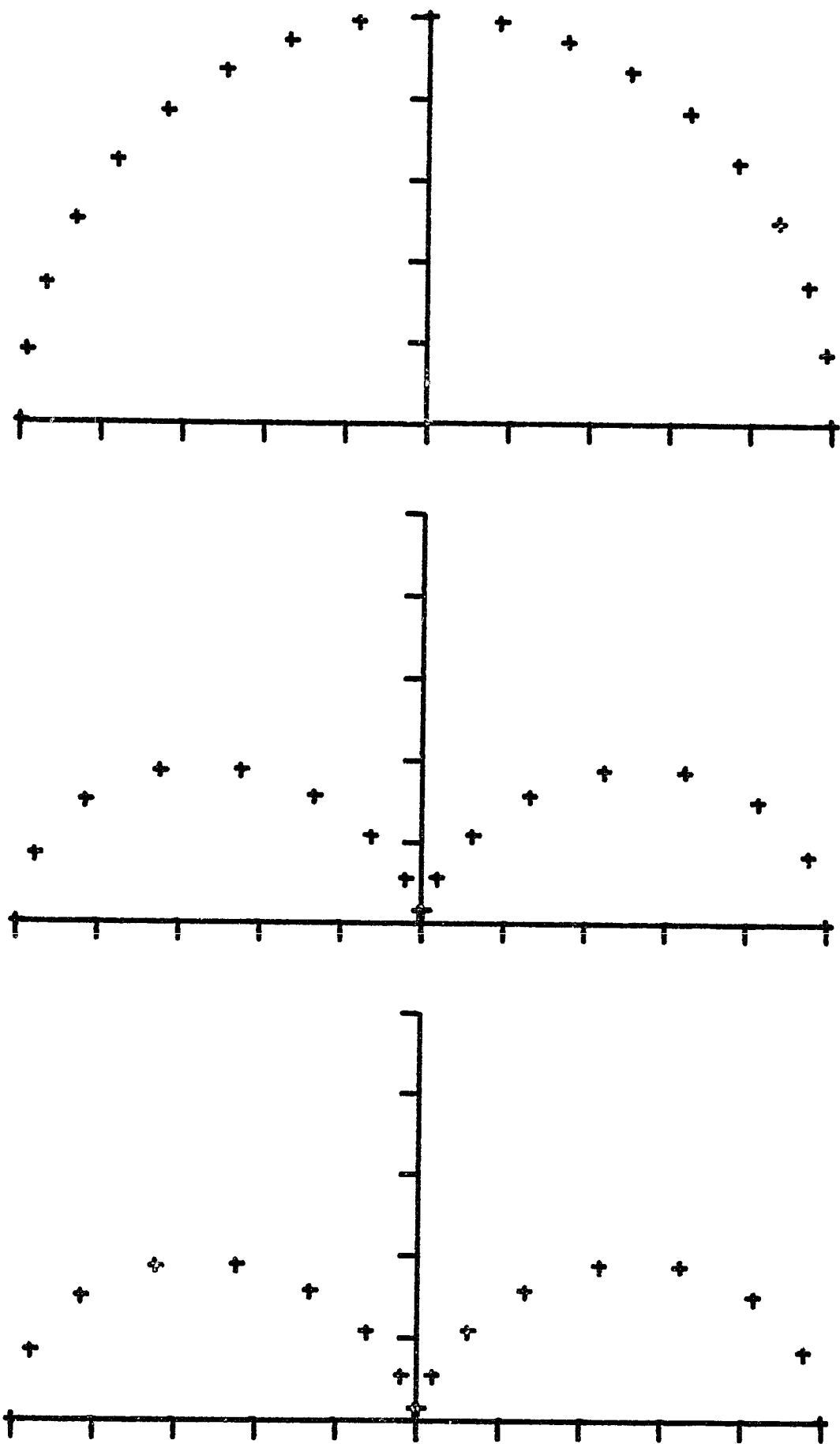


FIG. A44.

FREQ.=258 KHZ, V ANGLE=154 DEG.

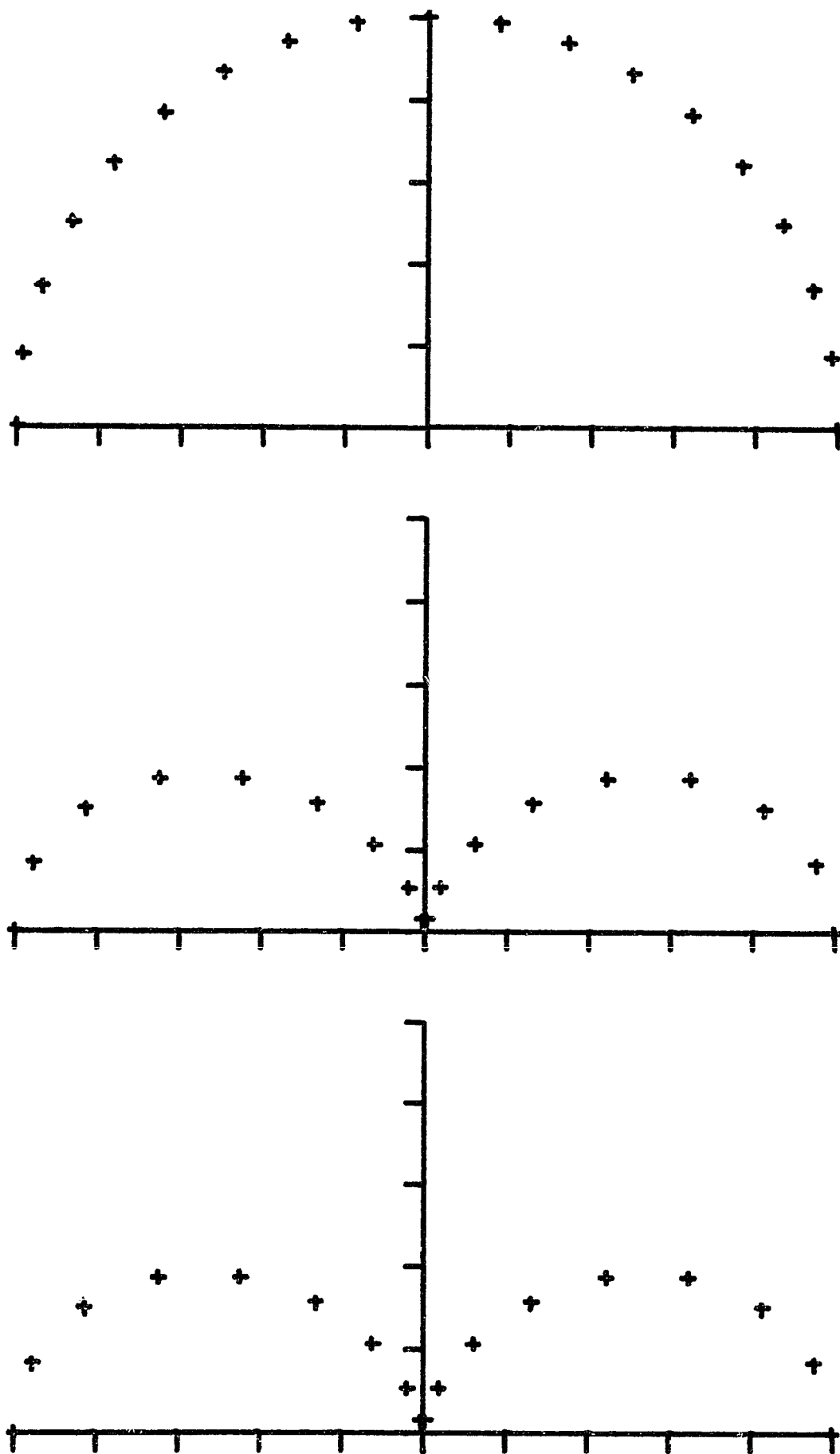


FIG. A45.

FREQ.=407 KHZ. V ANGLE=154 DEG.

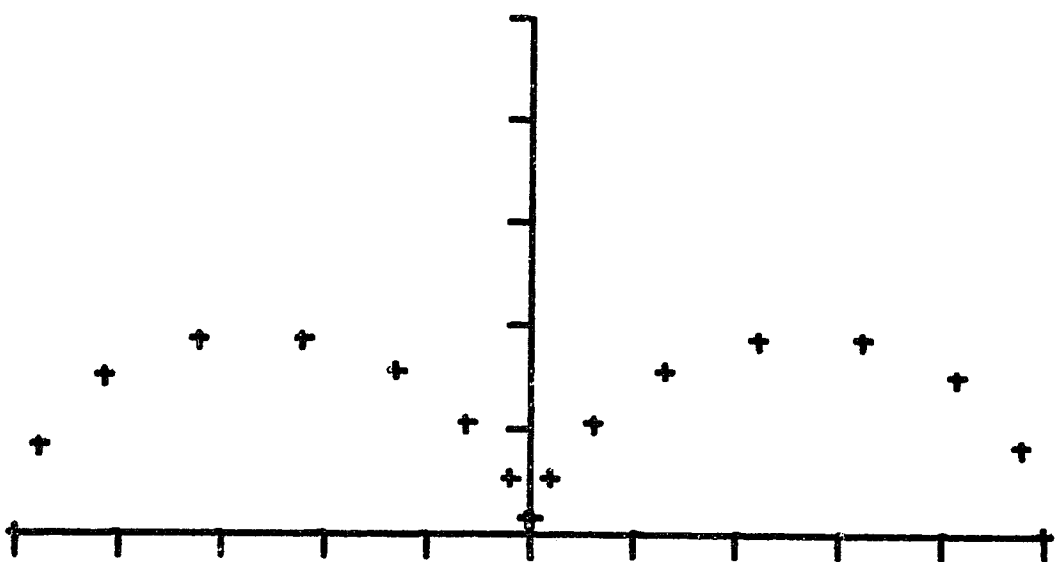
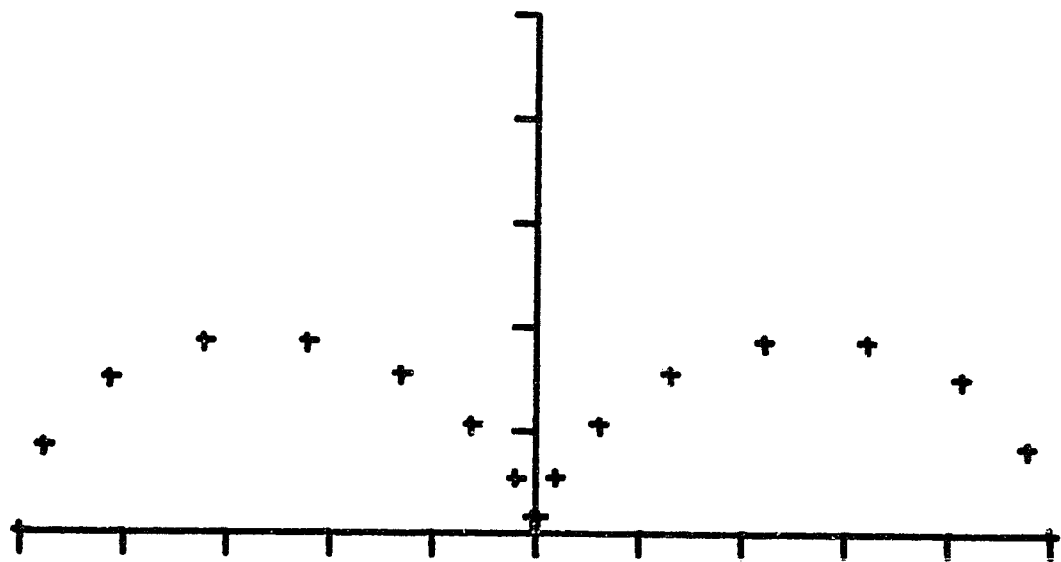
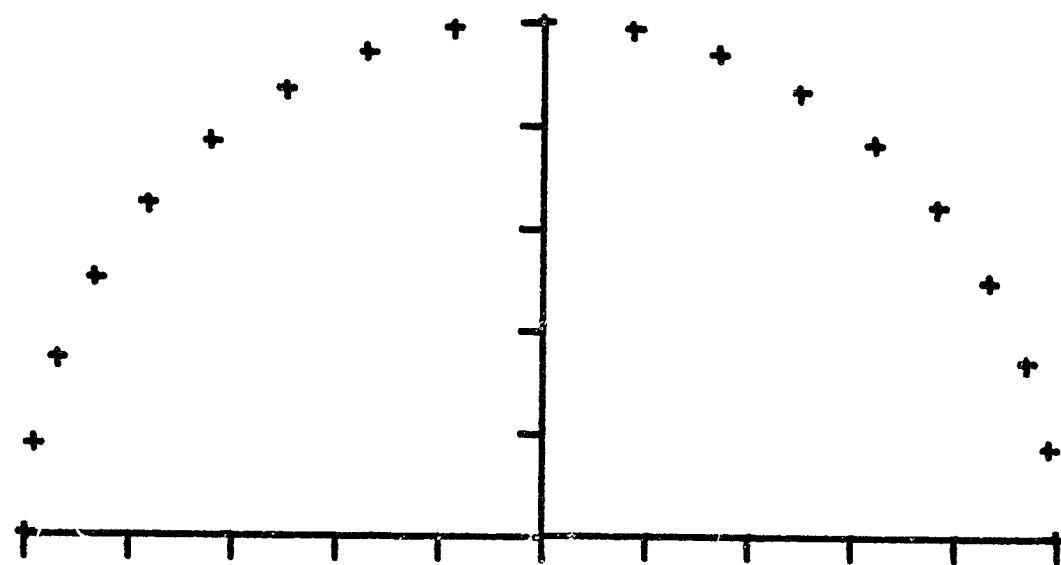


FIG. A46. FREQ.=567 KHZ, V ANGLE=154 DEG.

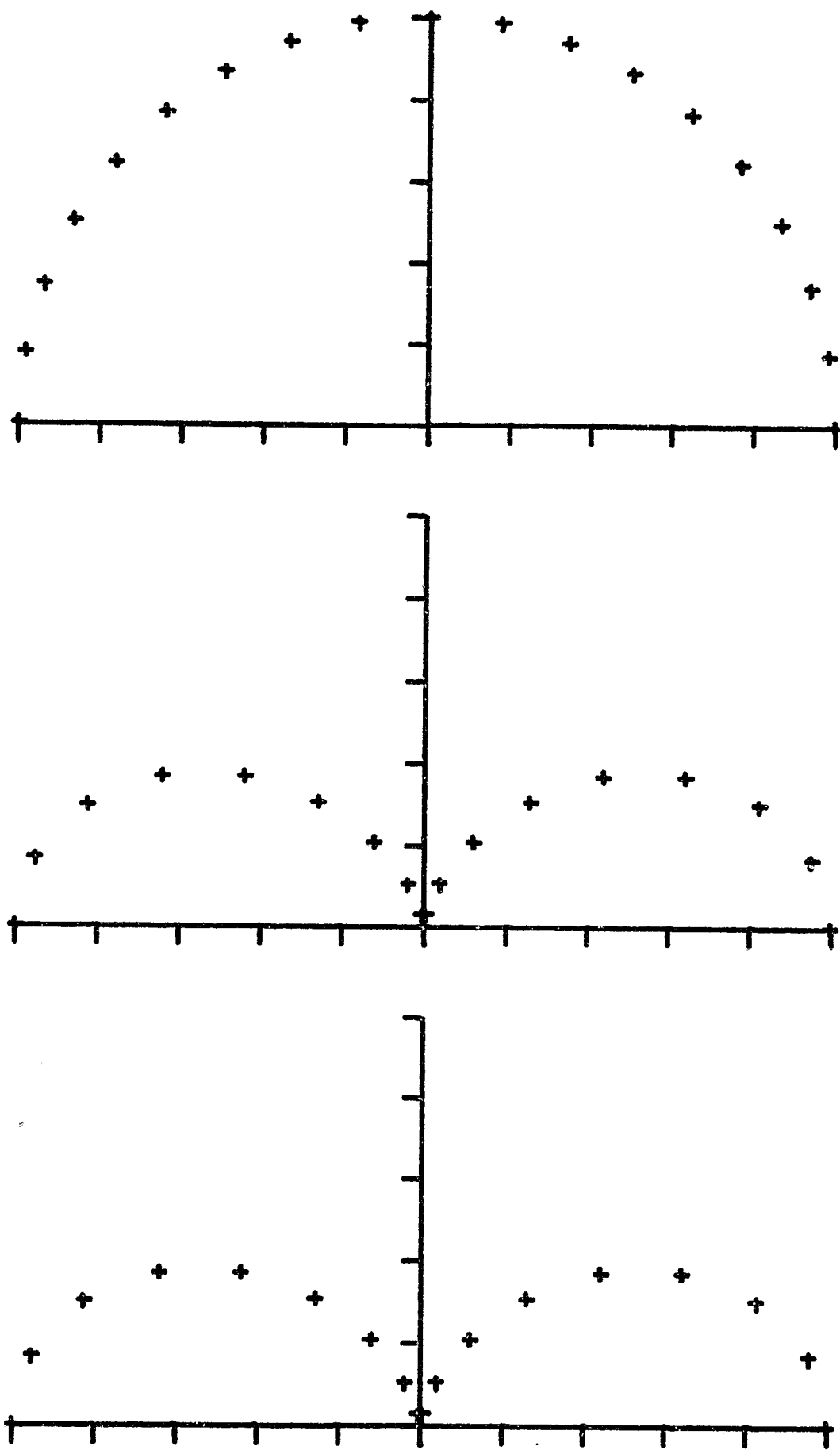


FIG. A47.

FREQ.=736 KHZ, V ANGLE=154 DEG.

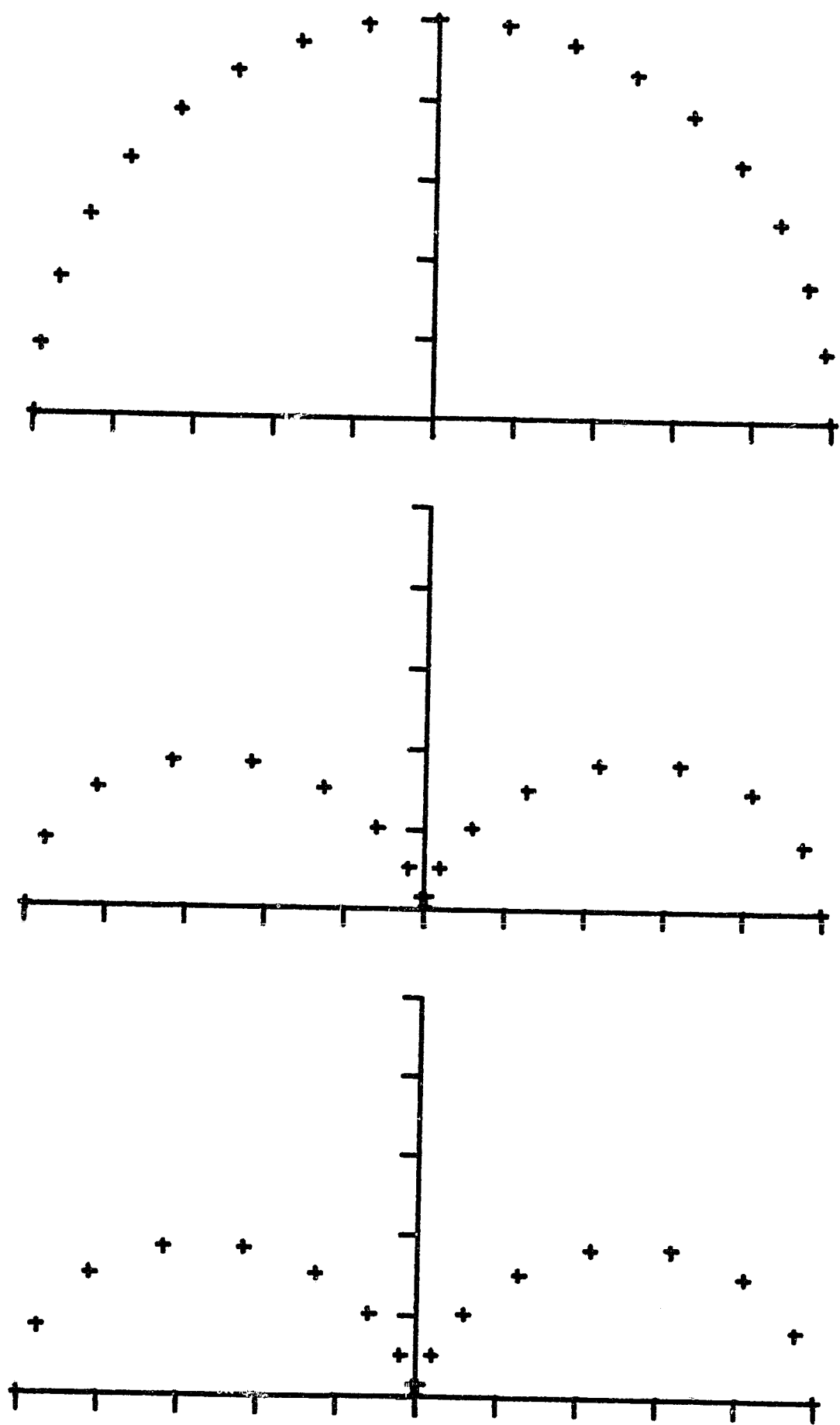


FIG. A48.

FREQ.=916 KHZ. V ANGLE=154 DEG.

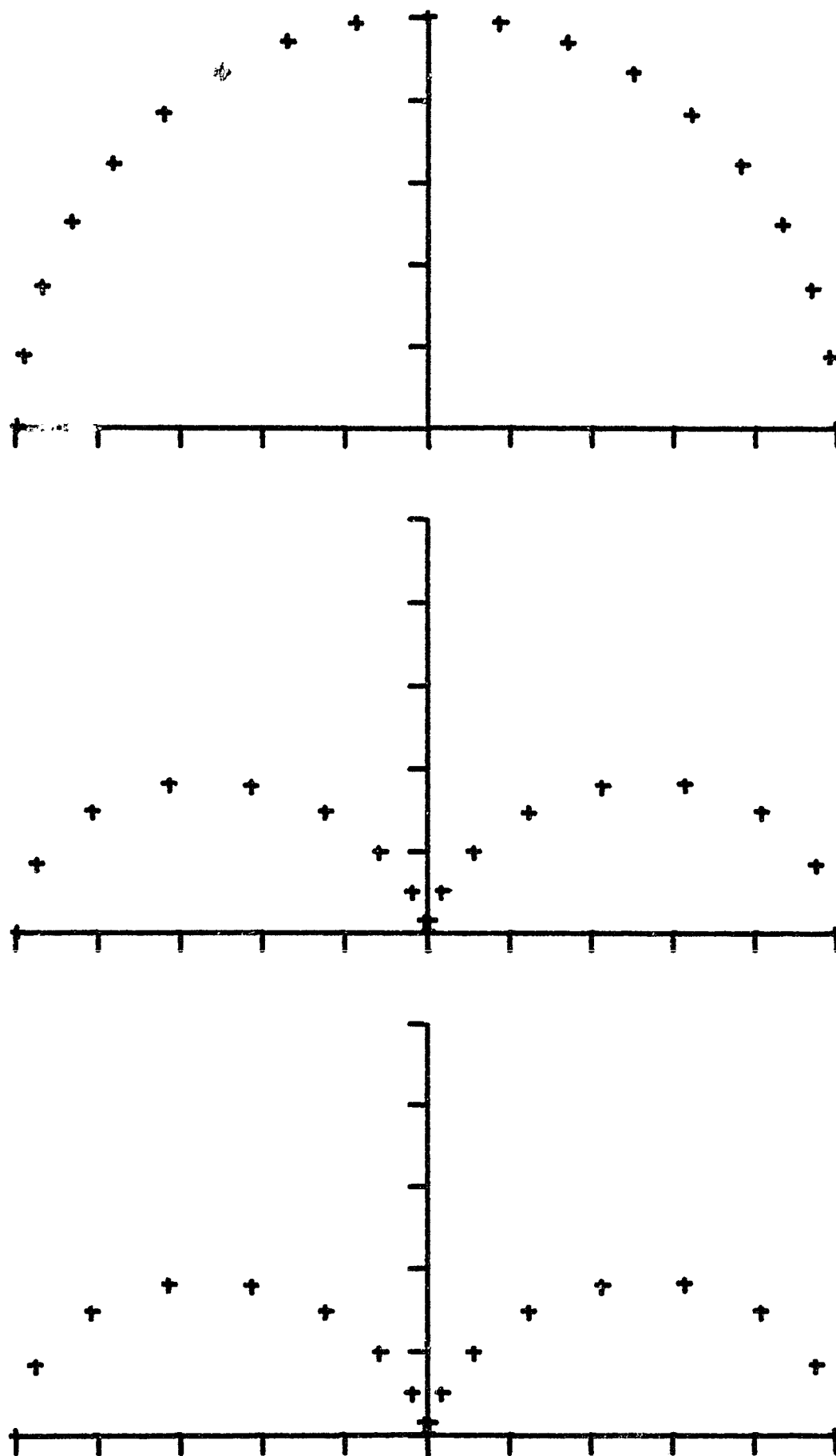


FIG. A49.

FREQ.=1104 KHZ. V ANGLE=154 DEG.

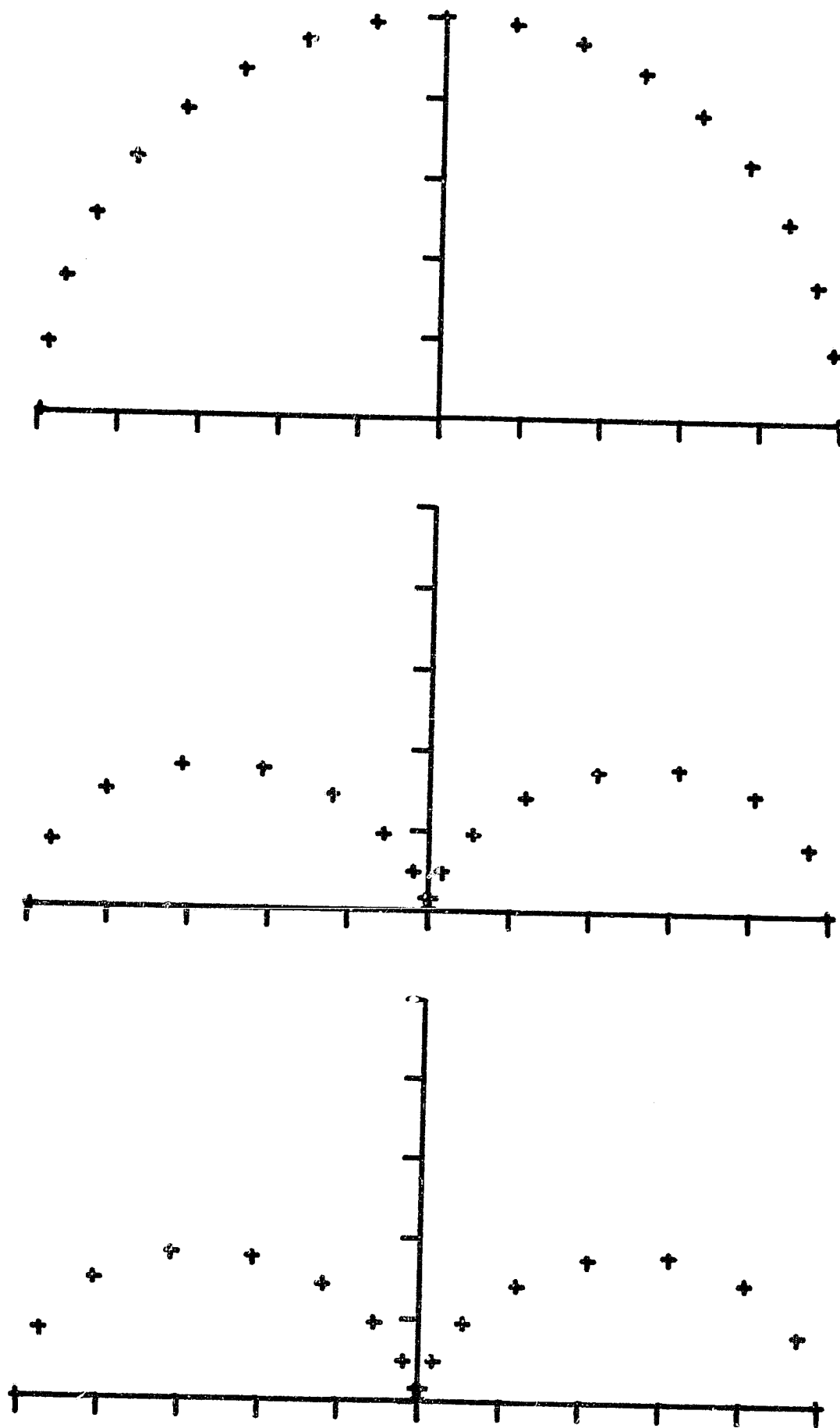


FIG. A50.

FREQ.=1315 KHZ. V ANGLE=154 DEG.

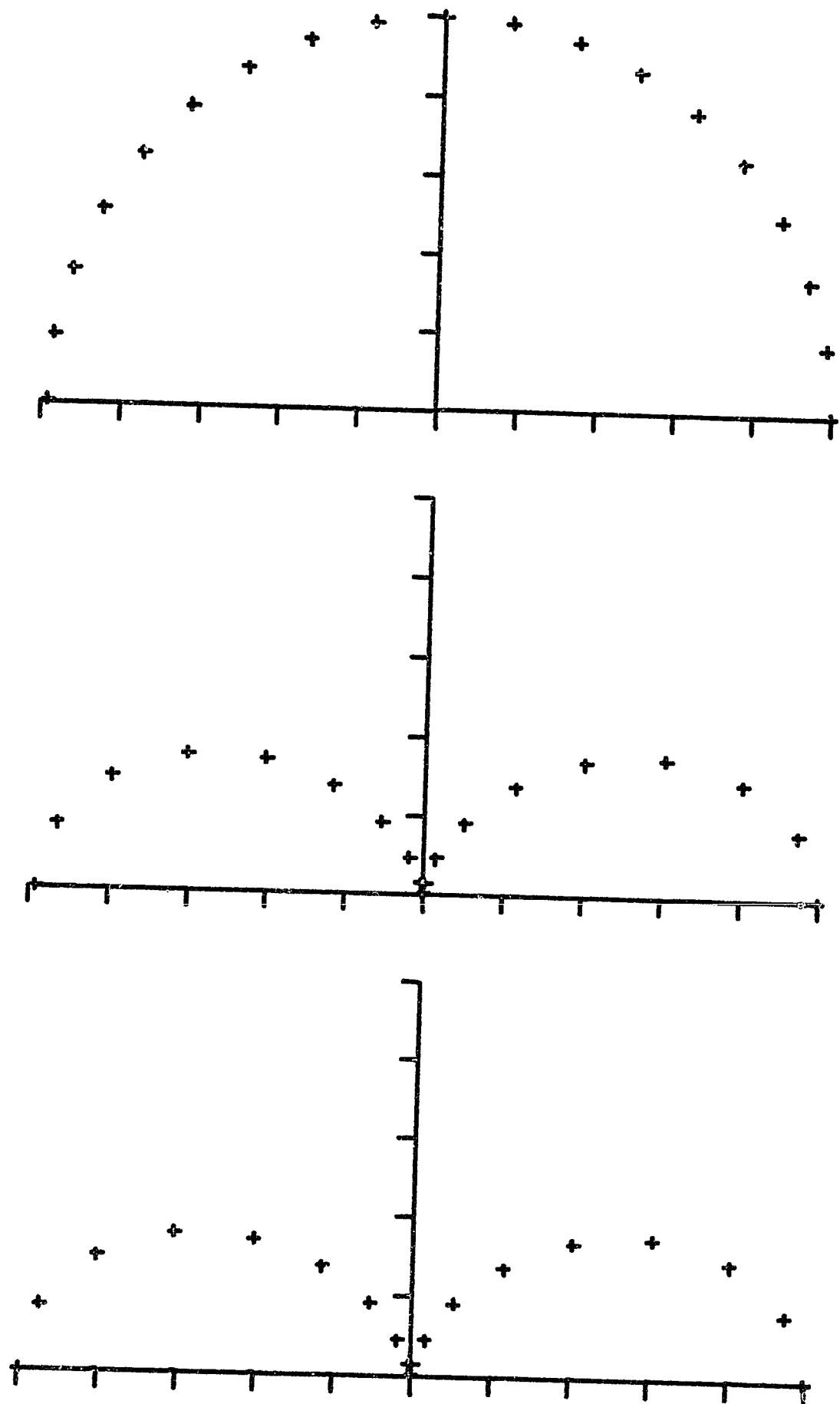


FIG. A51.

FREQ.=1537 KHZ. V ANGLE=154 DEG.

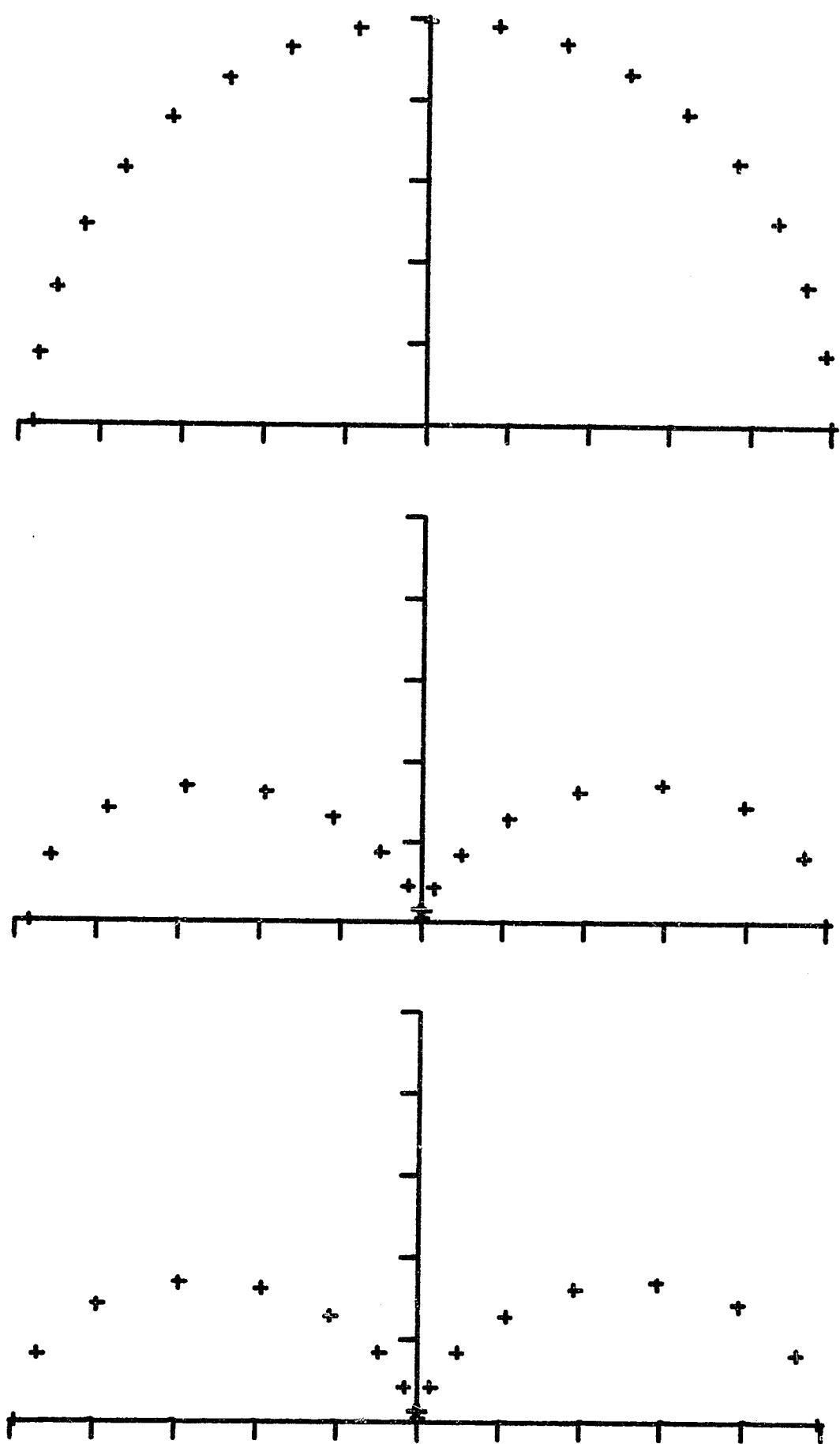


FIG. A52.

FREQ.=1781 KHZ, V ANGLE=154 DEG.

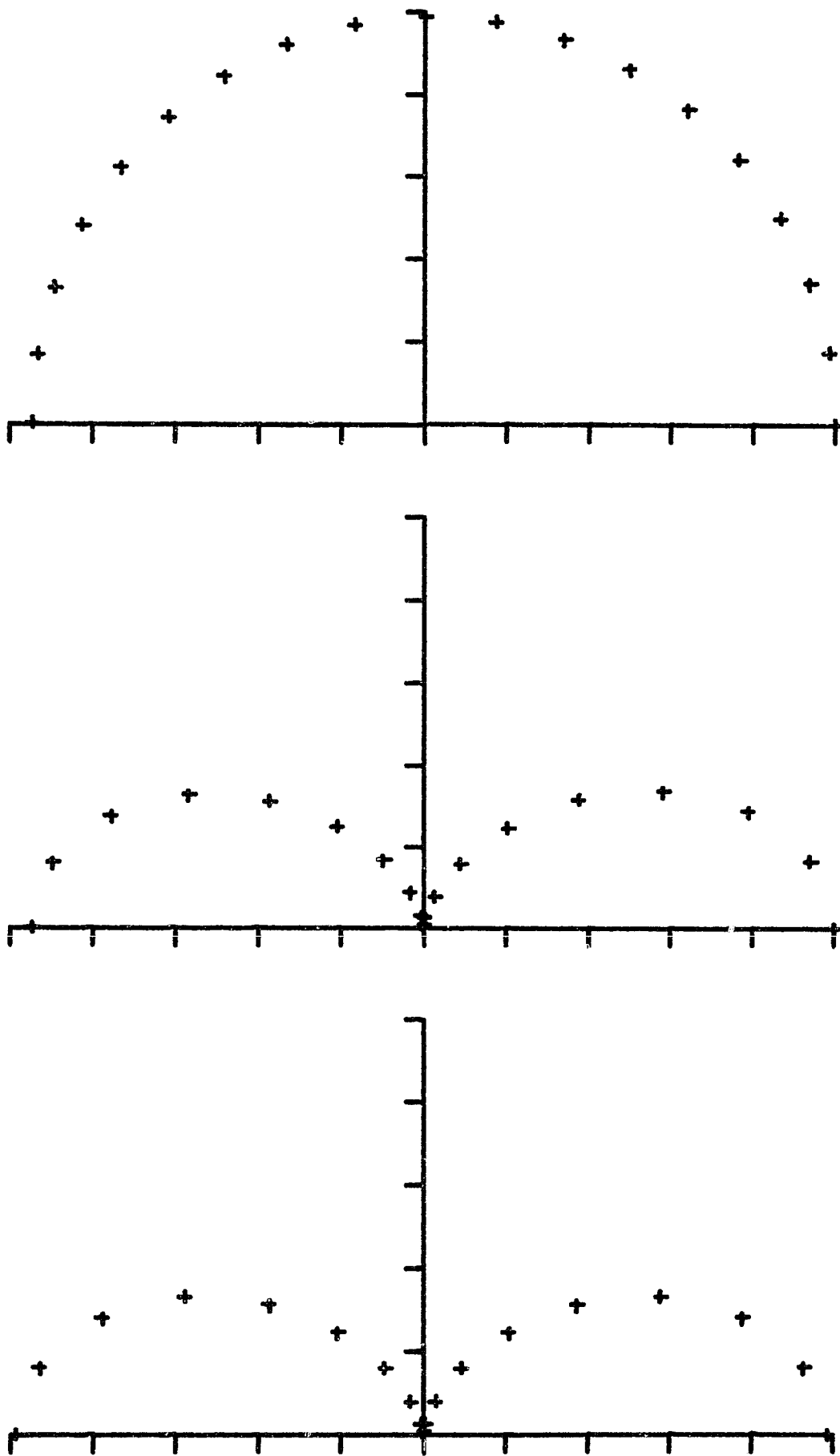


FIG. A53.

FREQ.=1913 KHZ. V ANGLE=154 DEG.

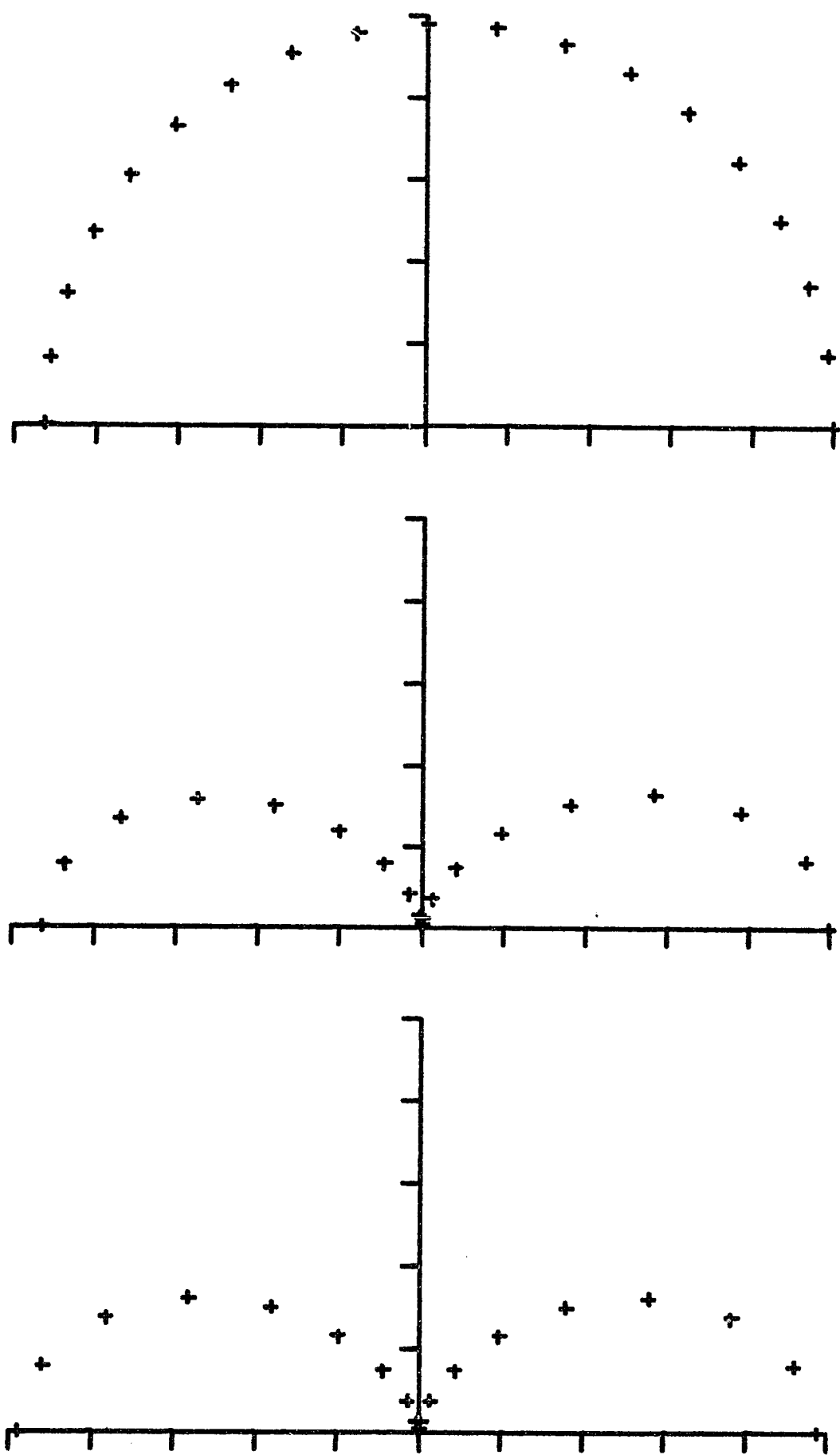


FIG. A54. FREQ.=2053 KHZ, V ANGLE=154 DEG.

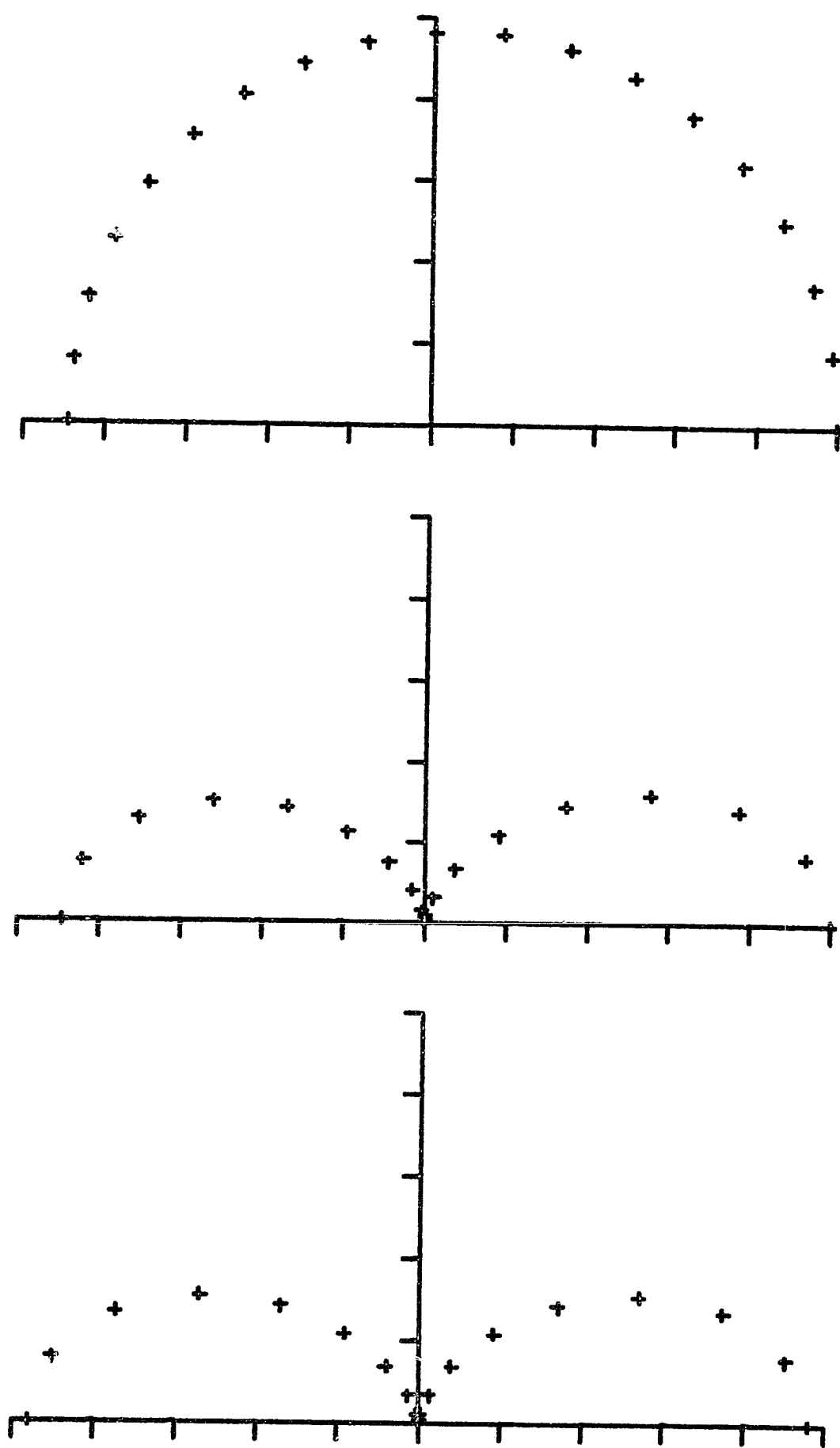


FIG. A55.

FREQ.=2202 KHZ, V ANGLE=154 DEG.

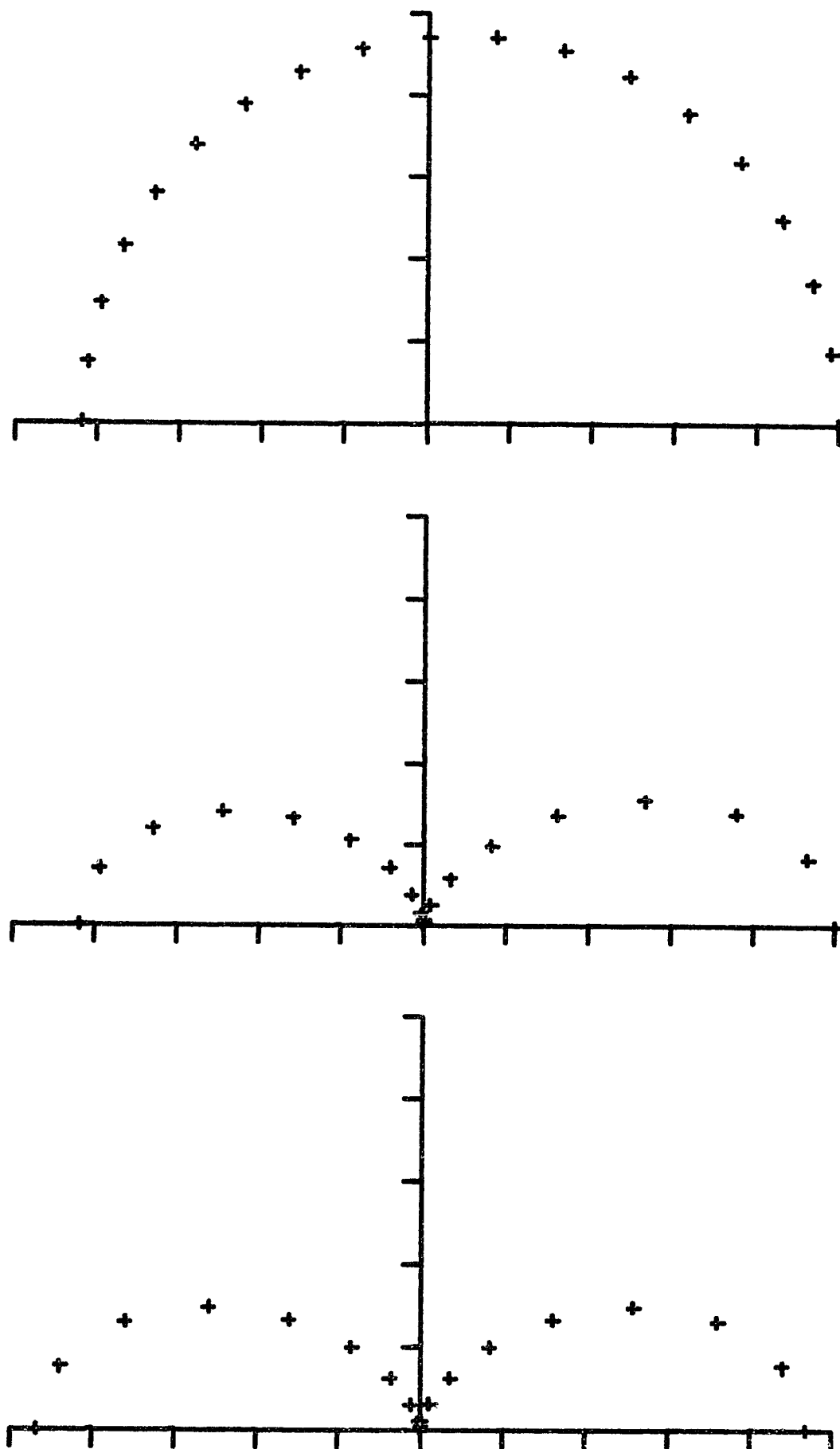


FIG. A56.

FREQ.=2353 KHZ, V ANGLE=154 DEG.

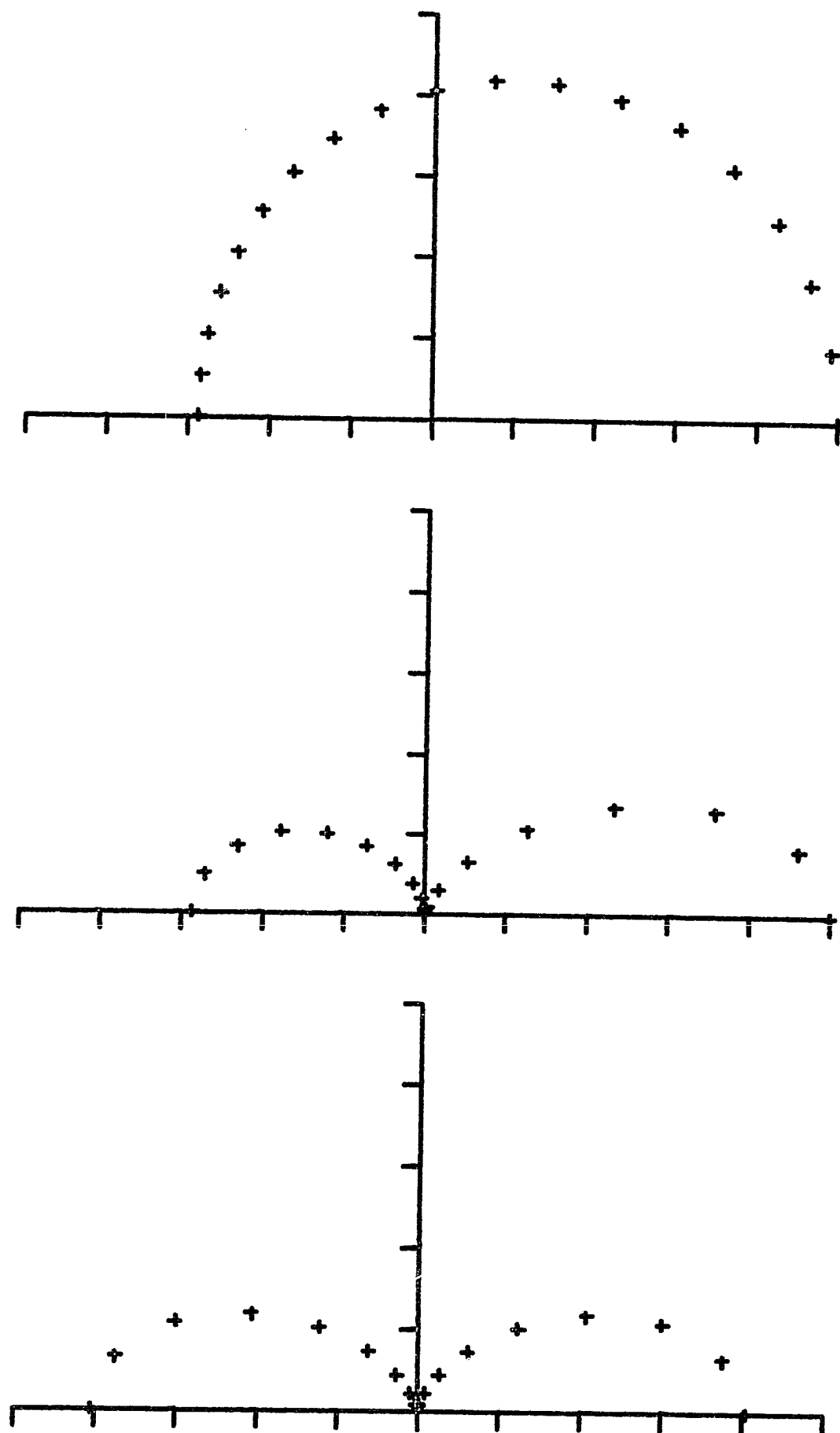


FIG. A57.

FREQ.=2697 KHZ, V ANGLE=154 DEG.

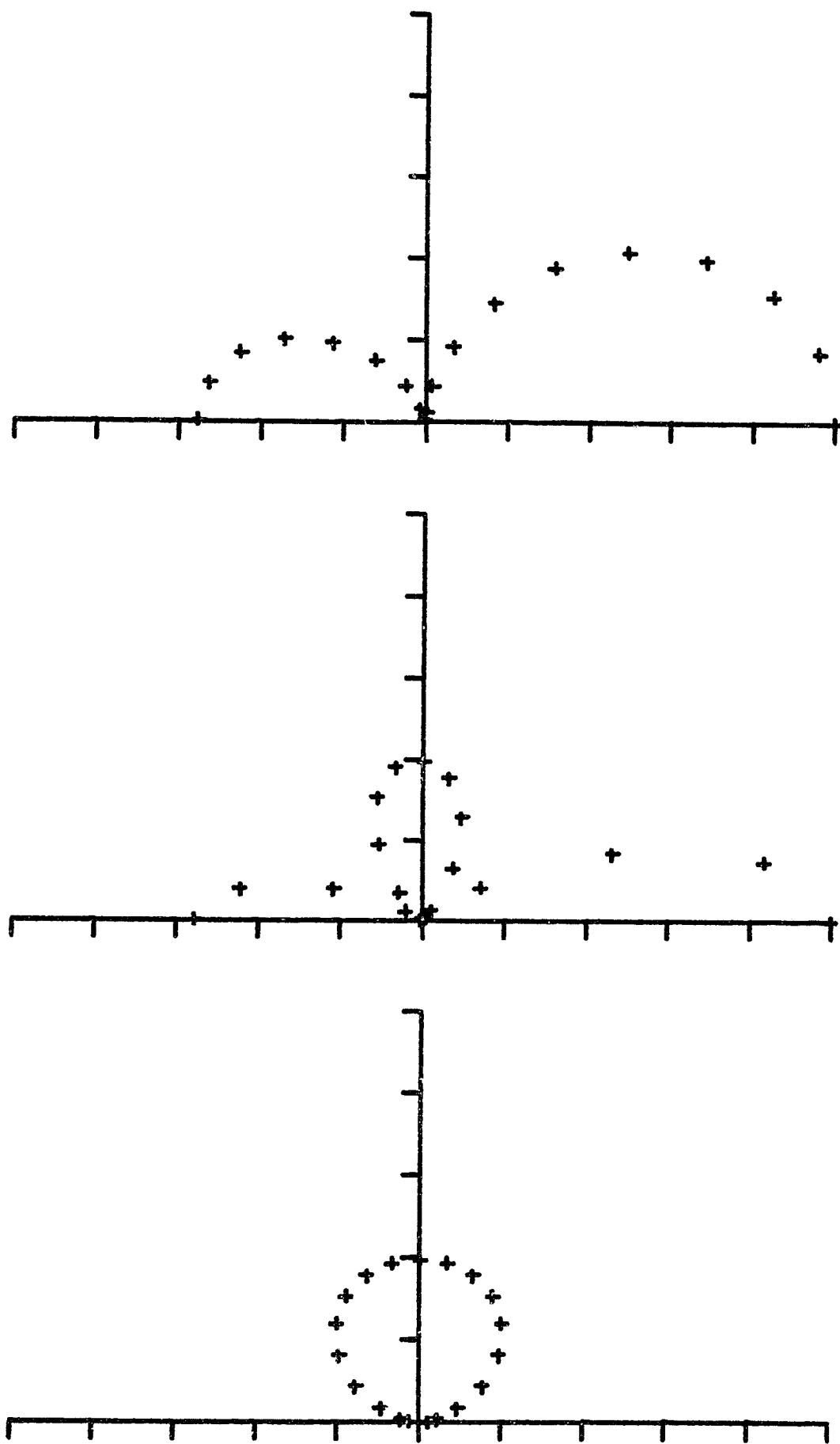


FIG. A58.

FREQ.= 3086 KHZ. V ANGLE= 154 DEG.

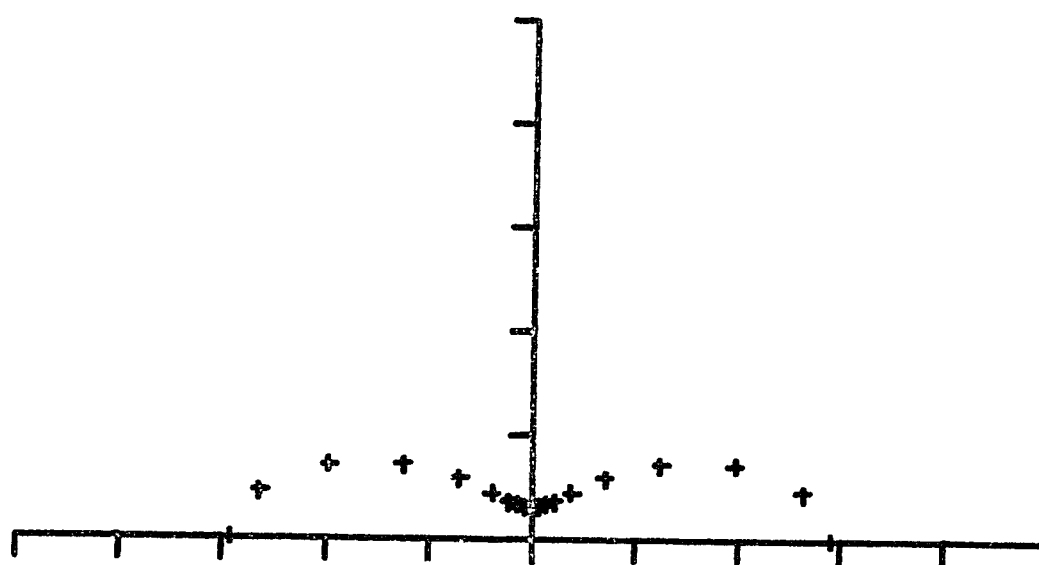
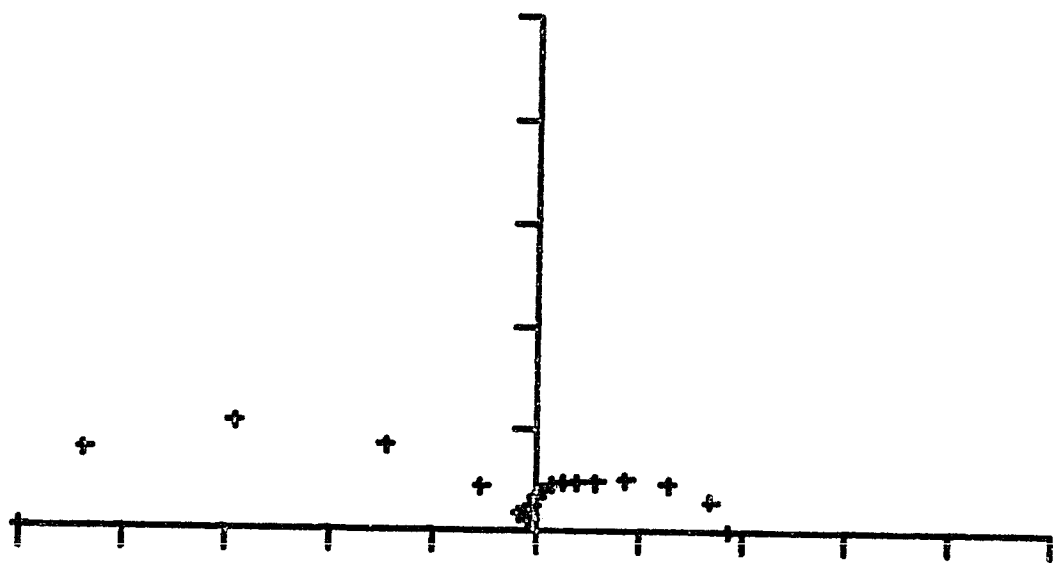
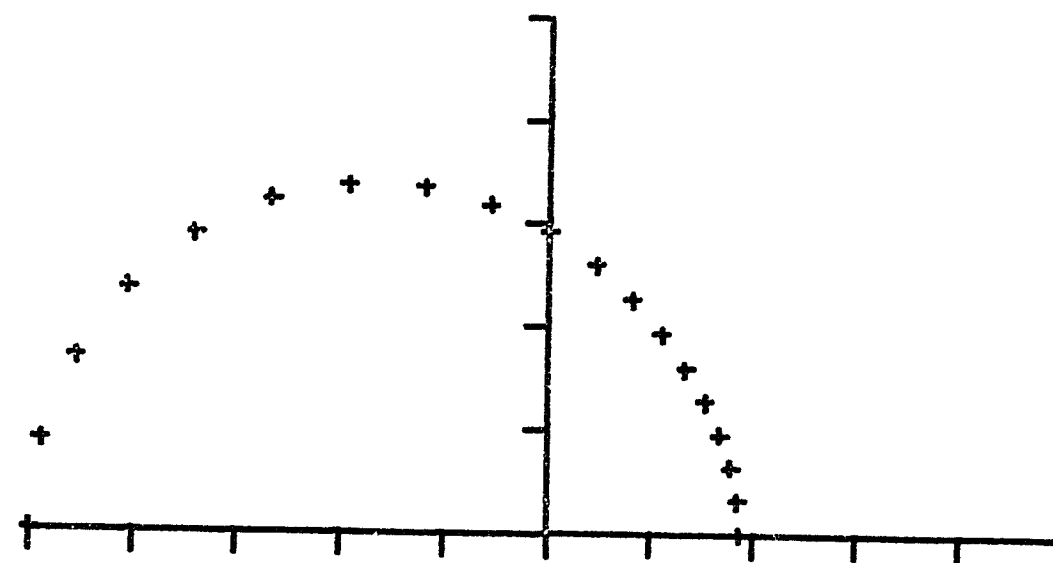


FIG. A59.

FREQ.= 3546 KHZ, V ANGLE= 154 DEG.

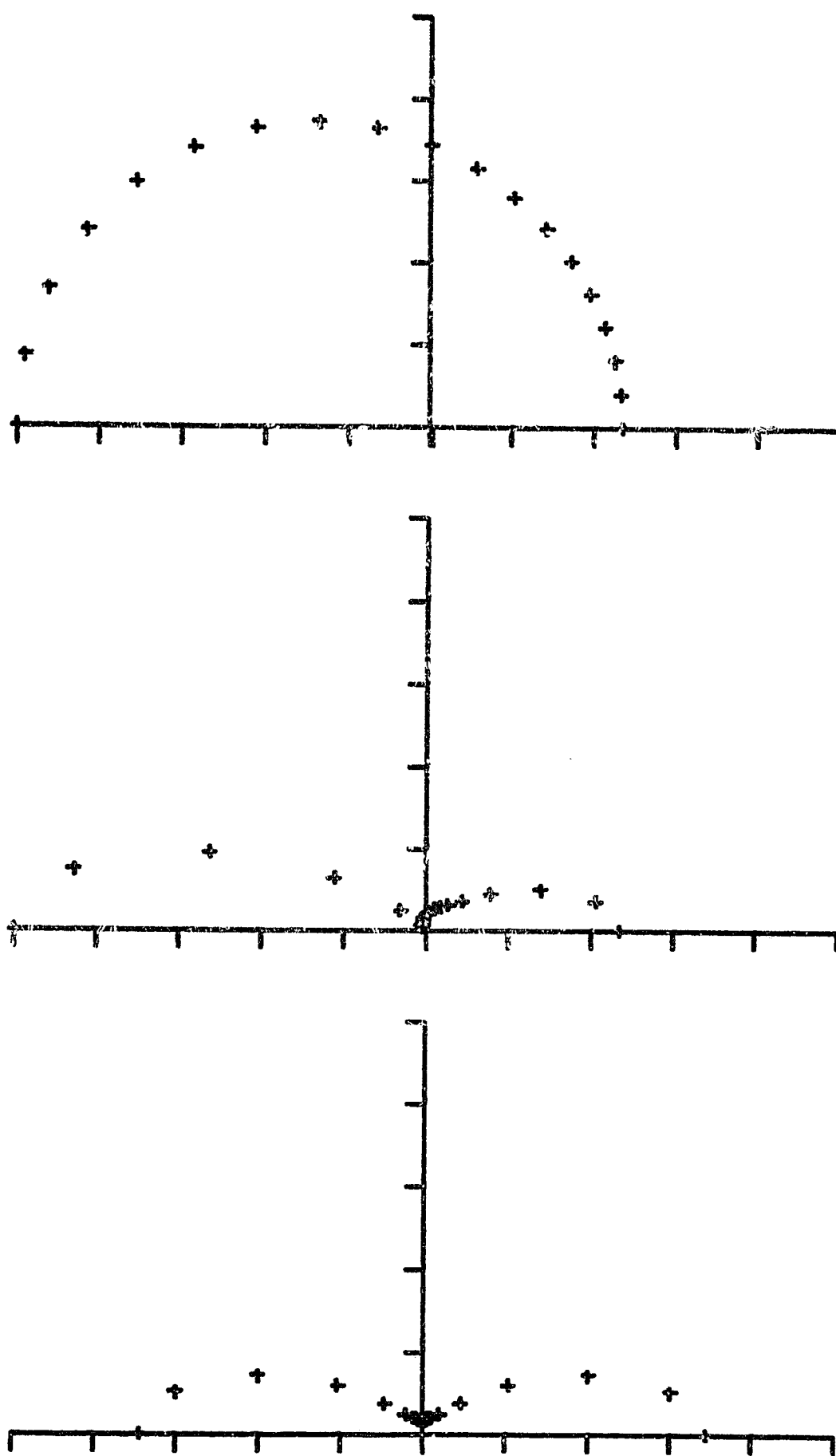


FIG. A60.

FREQ.=4102 KHZ, V ANGLE=154 DEG.