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CW MEASUREMENTS OF RIGHT CIRCULAR  
CONES

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Michigan University

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by

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The measured backscattering characteristics of two metallic right circular cones, with and without absorbing pads on their bases, are shown in 328 patterns. The absorber pads were used to reduce second order diffraction across the base of the cones. Measurements were carried out at closely spaced frequencies from 8.0 to 12.0 GHz for both horizontal and vertical polarizations, using a CW cancellation method.

## CW MEASUREMENTS OF RIGHT CIRCULAR CONES

The intent of this report is to display in a convenient format the measured backscattering characteristics of a pair of metallic right circular cones. The original purpose of the measurements was to collect a comprehensive body of data to be used in analyzing the diffraction of electromagnetic waves by the base of a cone and to provide experimental tests of theoretical work that has been in progress for several years at the Radiation Laboratory. Having performed the measurements, it occurred to us that others might also find the data useful and we decided to publish the data for the benefit of all.

The cones were machined from cold-rolled aluminum billets and care was taken to maintain sharp tips and sharp edges where the slanted sides meet the base. Their half-angles were  $15.00 \pm 0.05$  and  $40.00 \pm 0.05$  degrees and their base diameters were  $3.937 \pm 0.001$  and  $6.010 \pm 0.002$  inches, respectively. The large half-angle of the latter model was chosen to provide a substantial range in aspect angle over which the entire rim of the base remains visible. A short cylindrical beaded foam pedestal was cemented to each cone to speed their installation on and removal from a beaded foam support column used in the measurements. The cones were measured both with and without circular pads of Emerson and Cuming AN-73 absorbing material cemented to their bases, whose purpose was to reduce second order diffraction across the base.

The measurements were carried out at X-band frequencies in a large anechoic chamber using the time-honored CW cancellation method. A stable signal was produced by the use of a phase-locked frequency stabilizer and residual chamber reflections were cancelled by means of a reference signal sample of controllable phase and amplitude. A single pyramidal antenna was used as transmitter and receiver, hence the measured returns are proportional to the target's backscattering cross section. The received signal was detected by a superheterodyne receiver and recorded on a conventional antenna pattern recorder.

The recorded patterns were calibrated by a substitution method, in which the target obstacle is removed and replaced by a known scatterer, leaving all equipment gain settings undisturbed. We used a precision aluminum sphere 2.945 inches in diameter for calibration and, based on its theoretical radar cross section, we have marked each pattern with a reference line whose amplitude is 10 square wavelengths. This line extends horizontally across the entire pattern.

The frequencies used in the measurements ranged from 8.0 to 12.0 GHz and were nominally spaced 0.1 GHz apart, producing a total of 41 frequencies. Occasionally the klystron signal source failed to produce the necessary power at the desired frequency, whereupon the frequency was shifted slightly in order to achieve more satisfactory operation. However, the frequency was always measured, whatever it turned out to be (with an estimated accuracy of better than 0.01 GHz), and the measured value was multiplied by the constants 1.047922 and 1.599698 in order to obtain the electrical circumference  $ka = 2\pi a/\lambda$  of the  $15^\circ$  and  $40^\circ$  cones, respectively, at each frequency. Each pattern is prominently labelled with this value.

The cone targets were installed on the support column with their axes in a horizontal plane and the column was rotated about a vertical axis. The angular scale shown at the bottom of each pattern is the aspect angle subtended by the line of sight and the cone axis, with zero degrees being nose-on incidence. The traces are not always perfectly centered on the patterns, but the misalignment is seldom greater than 0.5 degree. Total aspect angle coverage was limited to slightly more than 90 degrees on either side of nose-on, sufficient to include at least the first two side lobes beyond the specular flash from the side of the cone.

Both horizontal and vertical polarizations were used and the various combinations of frequency, polarization, model and model condition (with or without absorber pad) produced a total of 328 patterns. The patterns of the 15-degree cone are reproduced on pages 10 through 91 and those of the 40-degree cone are reproduced on pages 94 through 175. The format used in displaying the patterns is simple and convenient: when the reader turns to any page he will be looking at a collection of four patterns. The pair on the left-hand page is for horizontal polarization and

the pair on the right for vertical. The upper pattern on either page is for the bare object and the lower for the object having the absorber pad cemented to its base.

The measurements were started off with horizontal polarization at the highest frequency (12.0 GHz) and the models were initially bare. After patterns of the bare objects had been recorded, the absorber pads were applied and another pair of patterns recorded. The frequency was then decremented 0.1 GHz and the absorber-treated models measured again; the pads were removed and another pair of patterns taken. This procedure was followed until the lowest frequency had been reached, whereupon the polarization was rolled over to the vertical. Then, with alternate application and removal of the pads, the frequency was advanced by 0.1 GHz increments until the highest frequency had been completed. We mention this measurement sequence so that the reader will be aware that although the patterns in a given set are physically adjacent to each other on the pages of this report, the time interval separating them may have been several days. In a few instances the frequency used for the vertical polarization was not quite the same as for horizontal and the reader will perceive occasional slight differences in the  $ka$  values displayed for a complete set of patterns; see pages 168 and 169, for example.

In order to give the reader some feeling for the consistency of the data, we have abstracted from the patterns the radar cross sections of the cones at nose-on and specular aspects, and these are displayed in Figs. 1 through 3. The values plotted in Fig. 1 are the means of the horizontal and vertical nose-on cross sections when adjusted according to the 10 square wavelength calibration line on the patterns. The circles are datum points for the bare objects and the squares for the absorber-treated models. The marked undulatory pattern traced out by the bare 15-degree cone cross sections shows that a significant contribution arises from second order diffraction across the shadowed base. The application of the absorber pad reduces this source of return, as evidenced by the more gentle undulation, but does not completely suppress it. The fact that minima and maxima exchange positions shows, in addition, that the absorber also changes the phase of the cross-base diffraction.

The corresponding variations in the 40-degree cone data are weaker than those for the 15-degree cone and, aside from what seem to be random errors, the

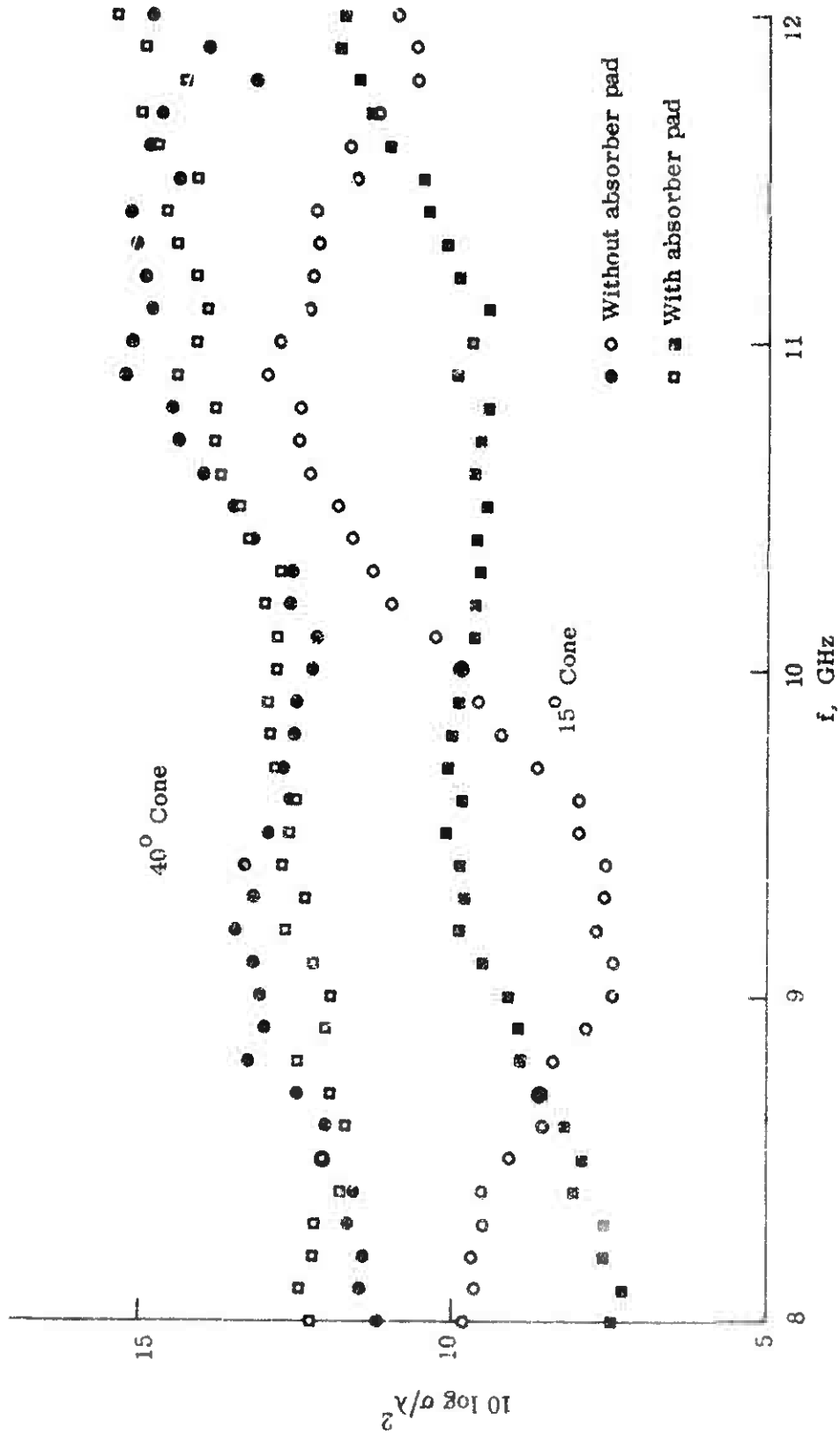


Figure 1: Summary of Nose-on Measurements.

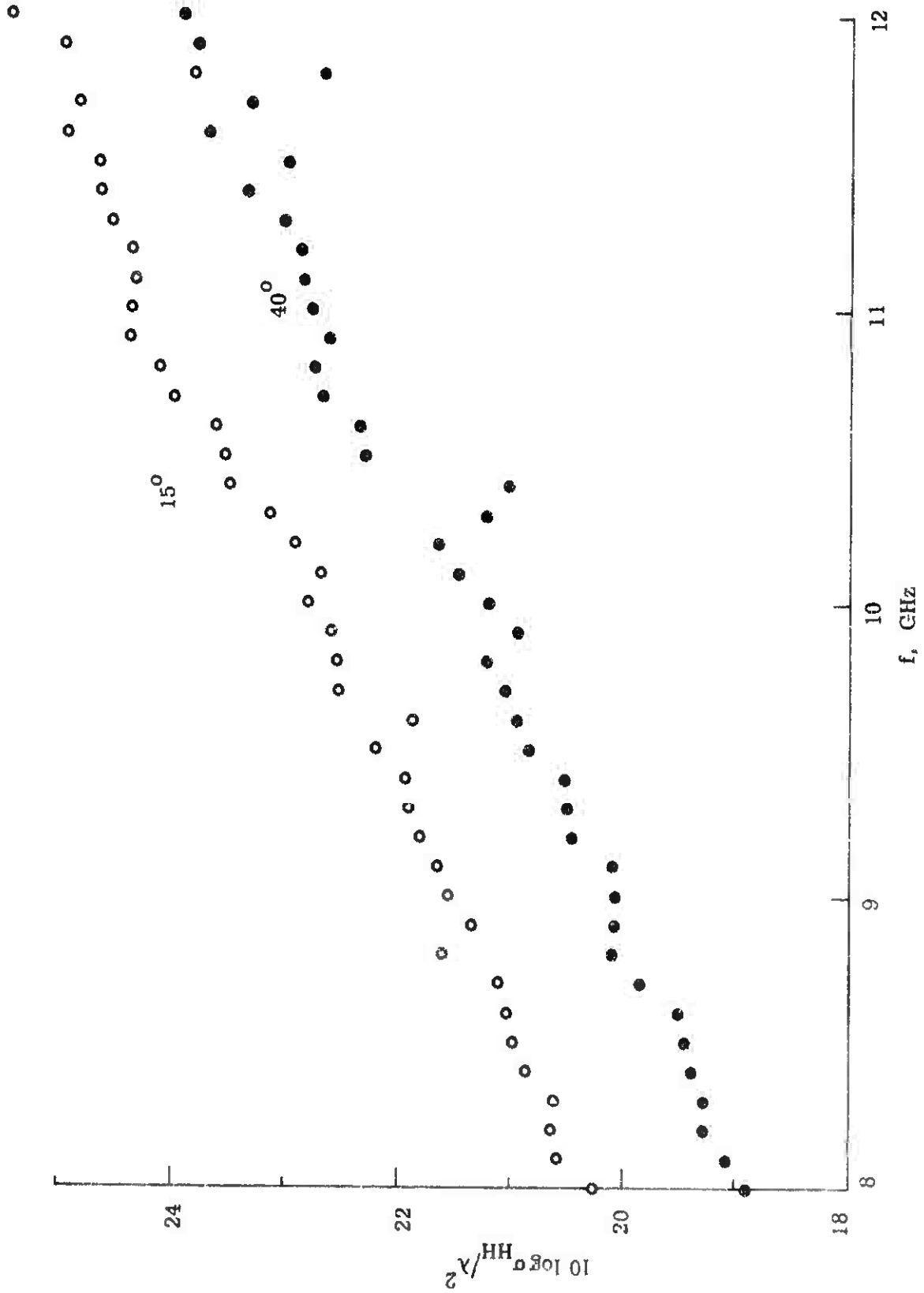


Figure 2: Specular Radar Cross Sections for Horizontal Polarization.

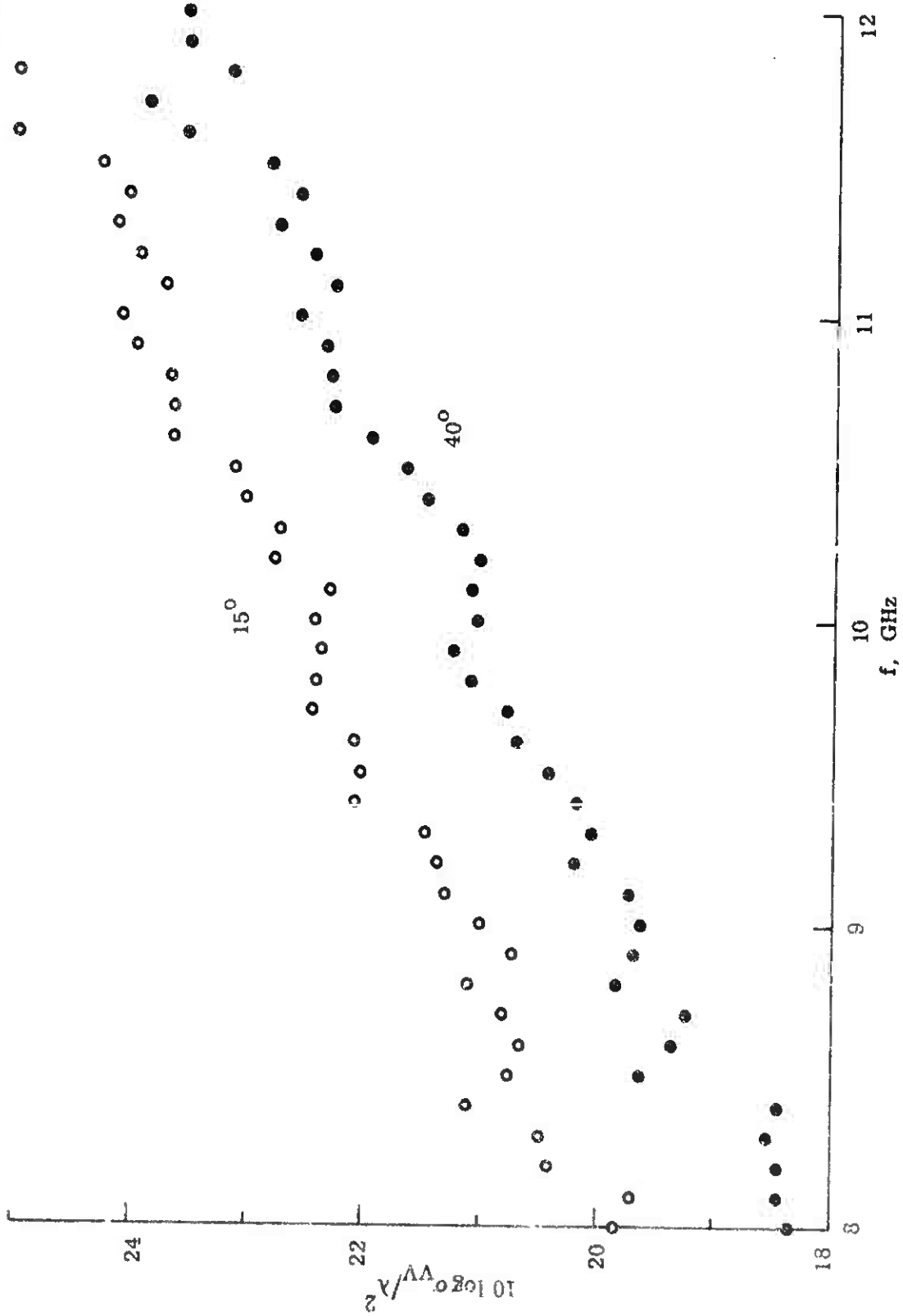


Figure 3: Specular Radar Cross Section for Vertical Polarization.

absorber pad produces a reasonably smoothly increasing cross section with increasing frequency. The results suggest that the larger cone has a smaller second order contribution than the smaller cone. Note that all four data sets take simultaneous jumps at certain frequencies (e.g., 9.2, 10.9, 11.2 GHz), while only those for one cone or the other do so at other frequencies (e.g., 8.8, 10.2, 11.8 GHz).

The specular radar cross sections of the cones are shown as functions of frequency in Fig. 2 for horizontal polarization in Fig. 3 for vertical. In both figures the upper string of datum points are those of the 15-degree cone and the lower data, of the 40-degree cone. The reader will immediately note the displacement of several datum points from the prevailing trend, notably those at 10.4 and 11.8 GHz in Fig. 2, and those at 8.4 and 10.7 GHz in Fig. 3. Undoubtedly the calibration levels of the patterns that produced these points should be adjusted, but we leave it to the reader to decide precisely how much adjustment is required. Aside from the disparities noted above, the data as a complete set seem to be accurate within 0.5 dB. Finally, a close comparison of Figs. 2 and 3 show that the specular returns for vertical polarization are on the average about 0.25 dB lower than those for horizontal polarization. We believe this to be a real difference, and not due to a consistent experimental error between the polarizations.

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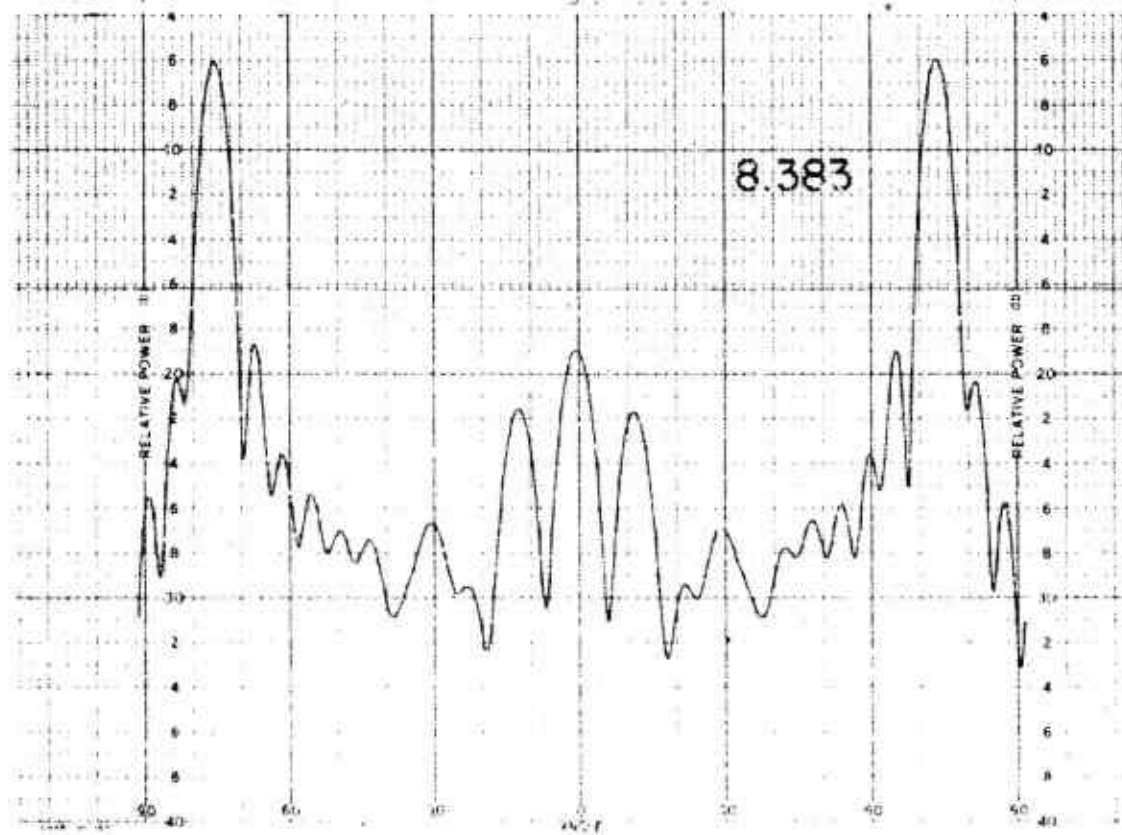
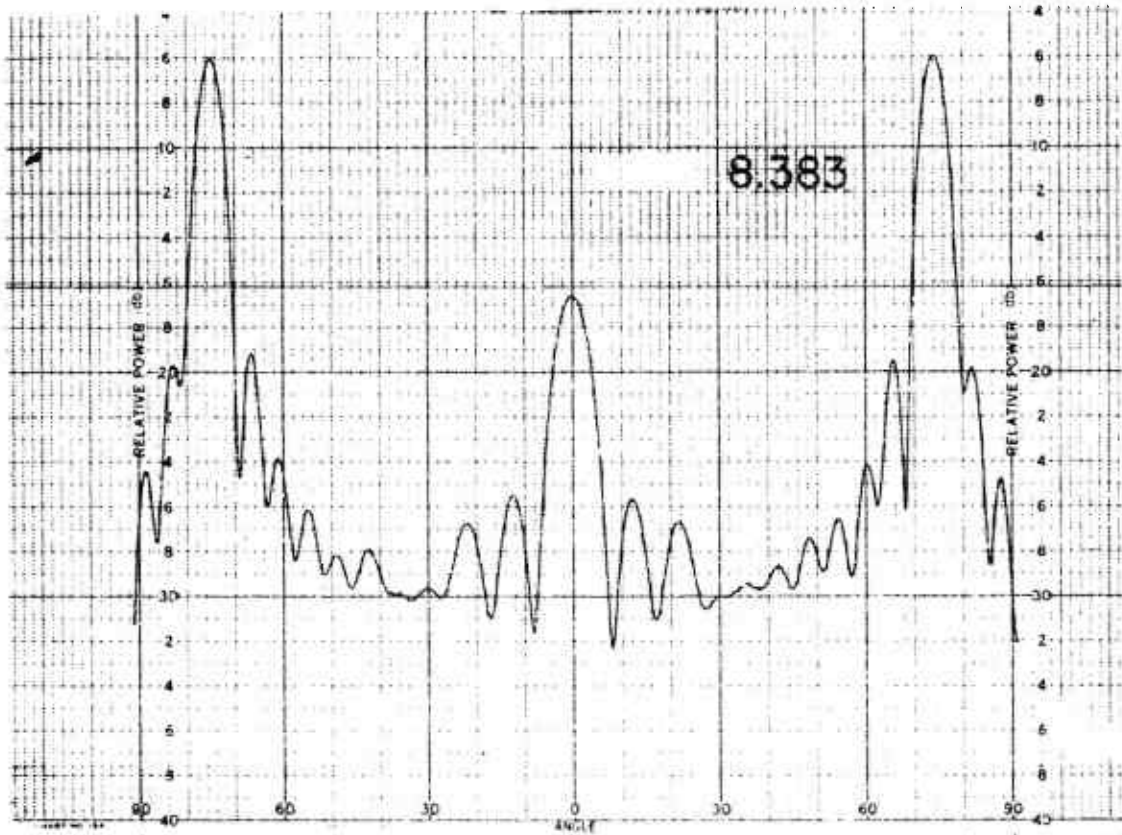
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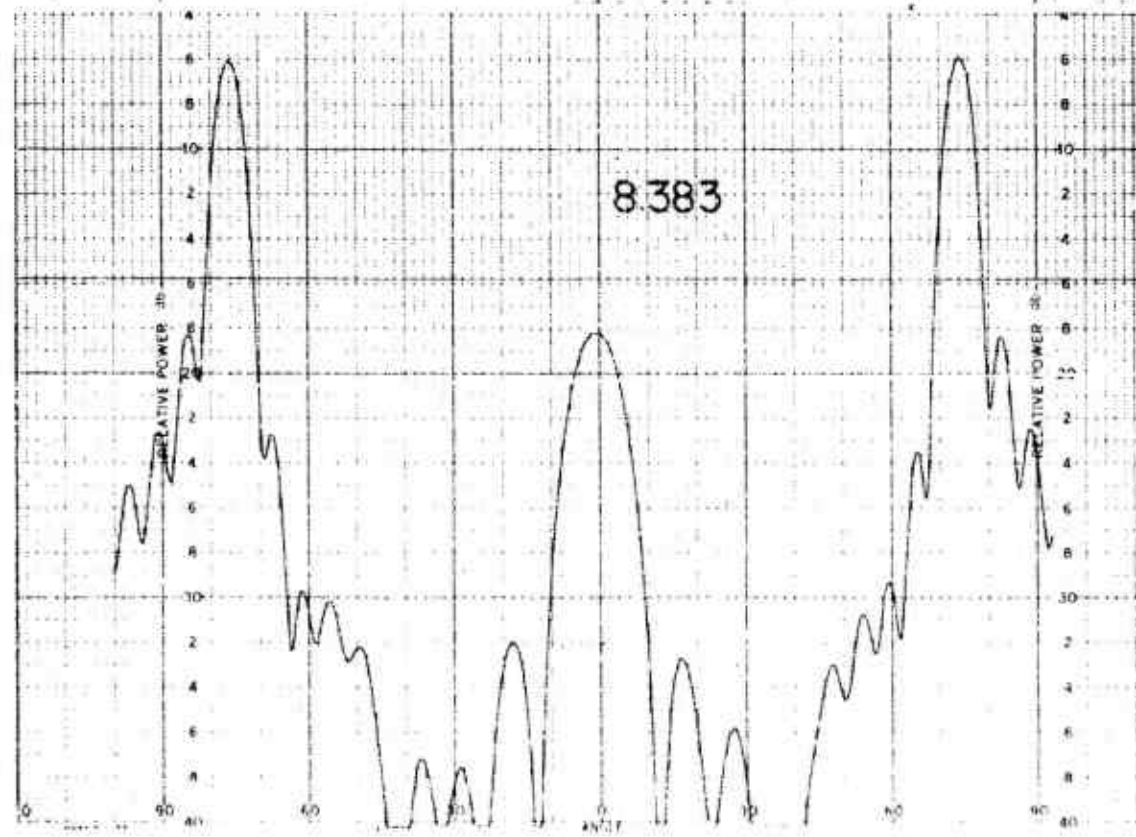
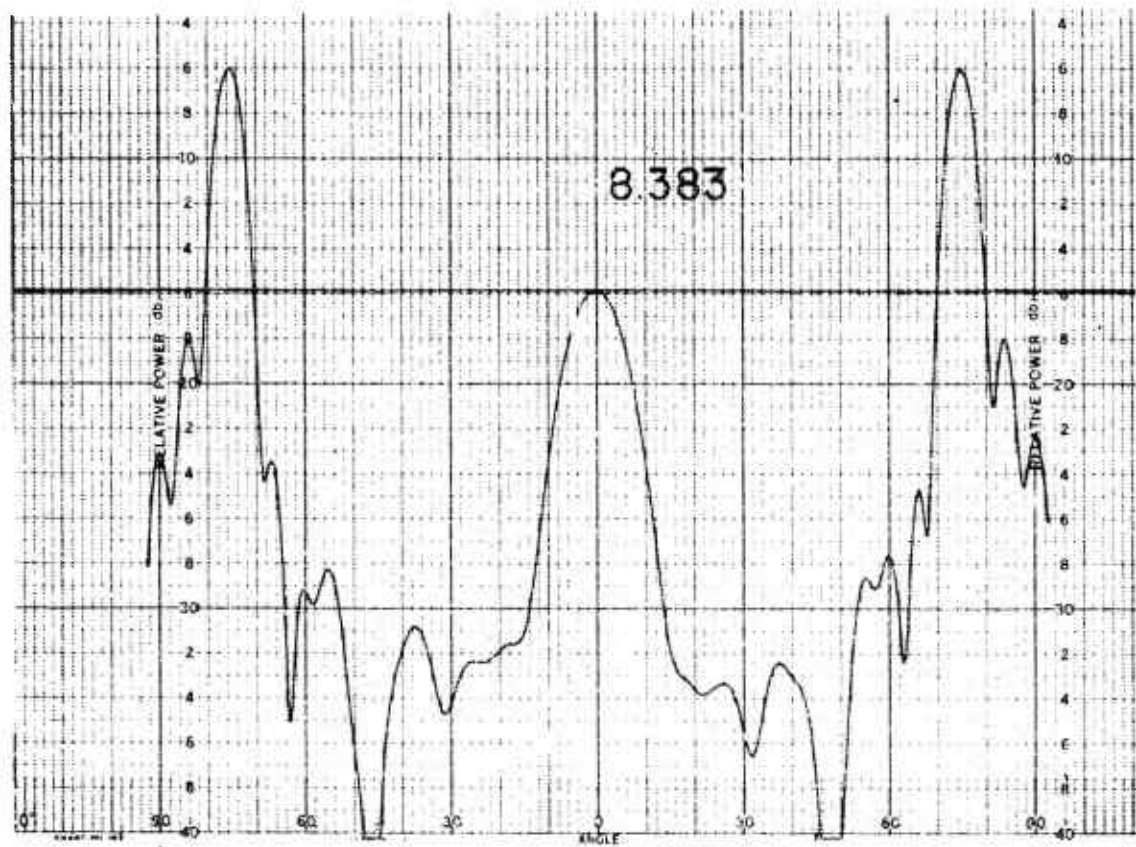
15° CONE

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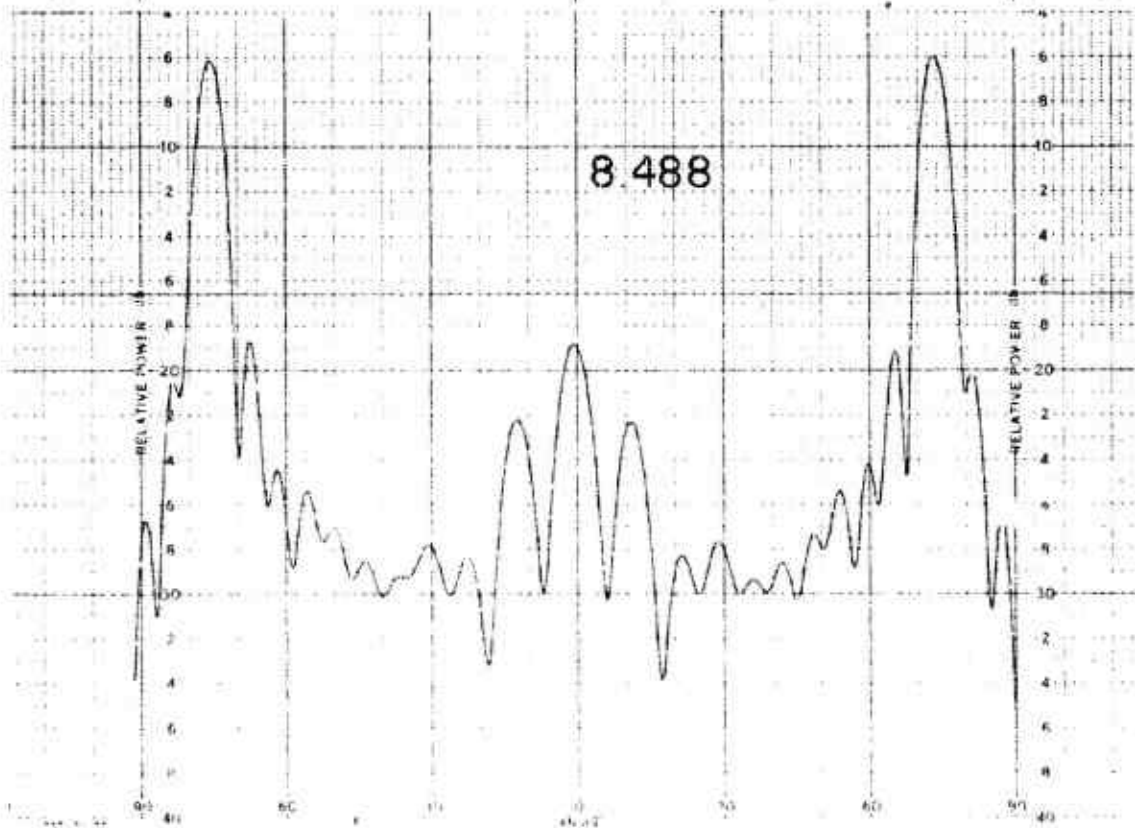
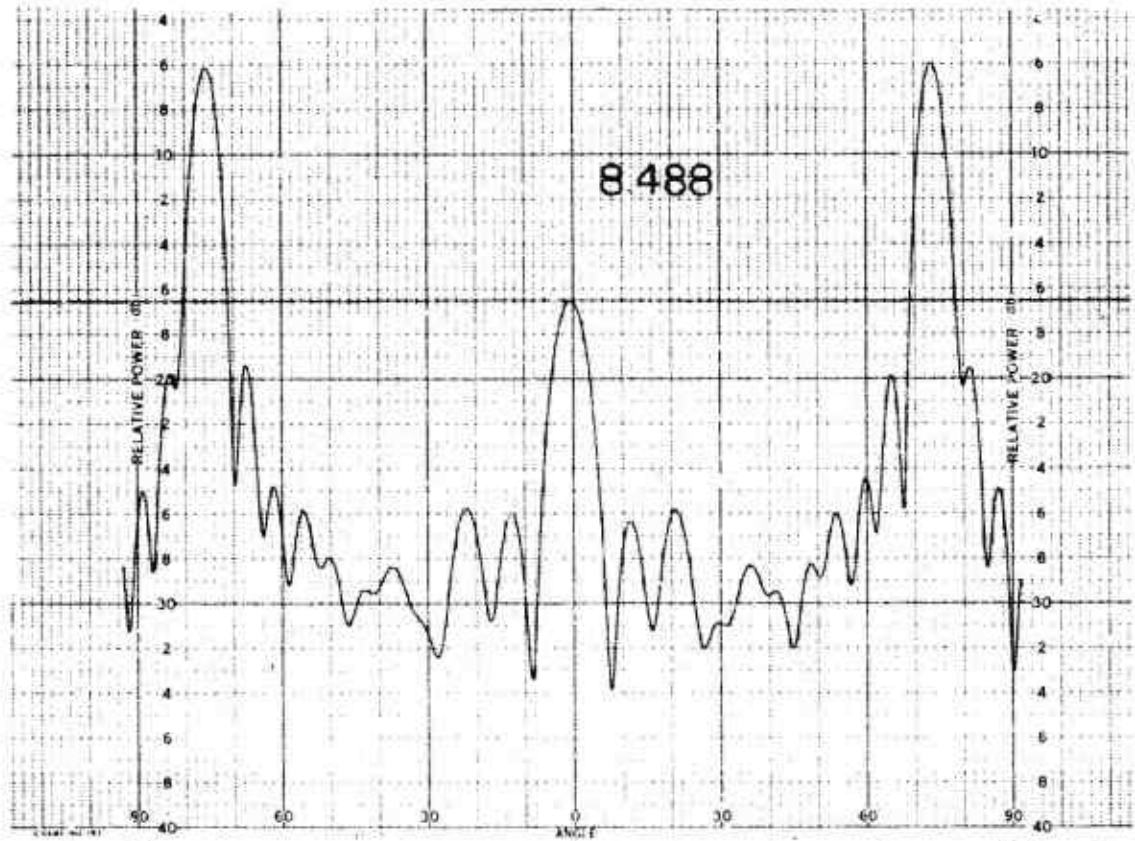
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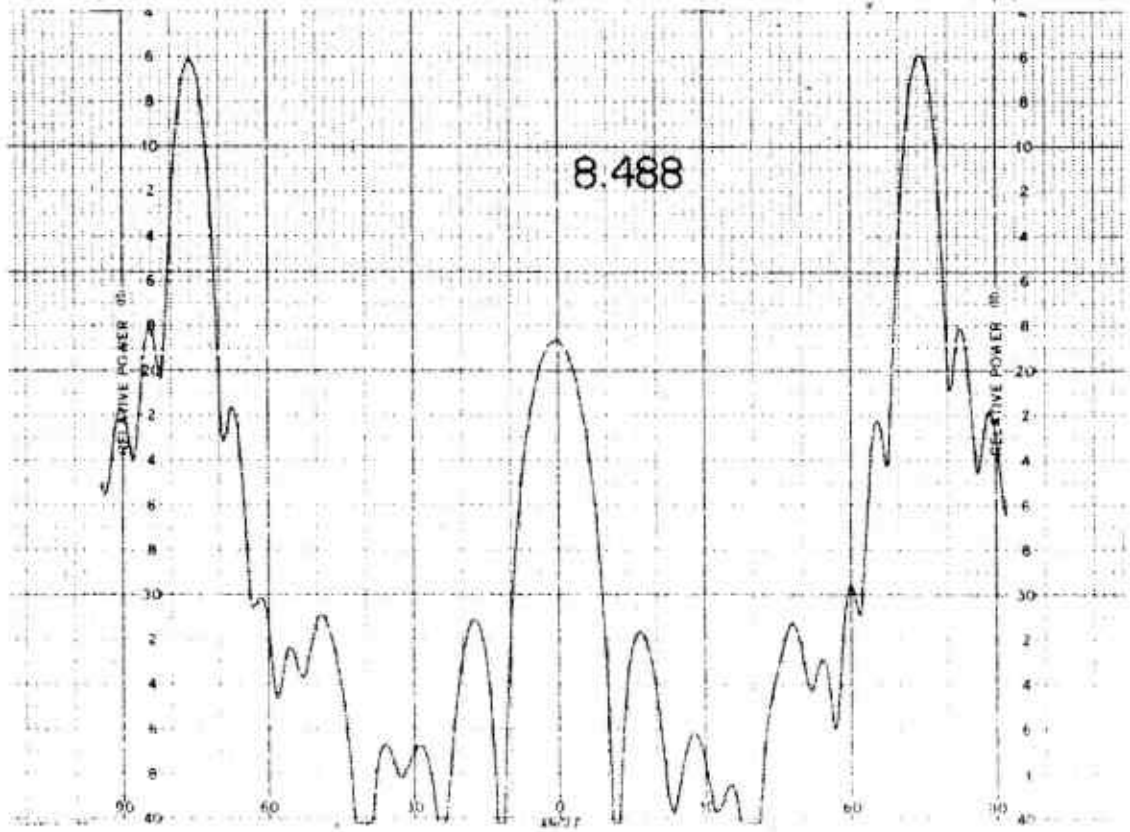
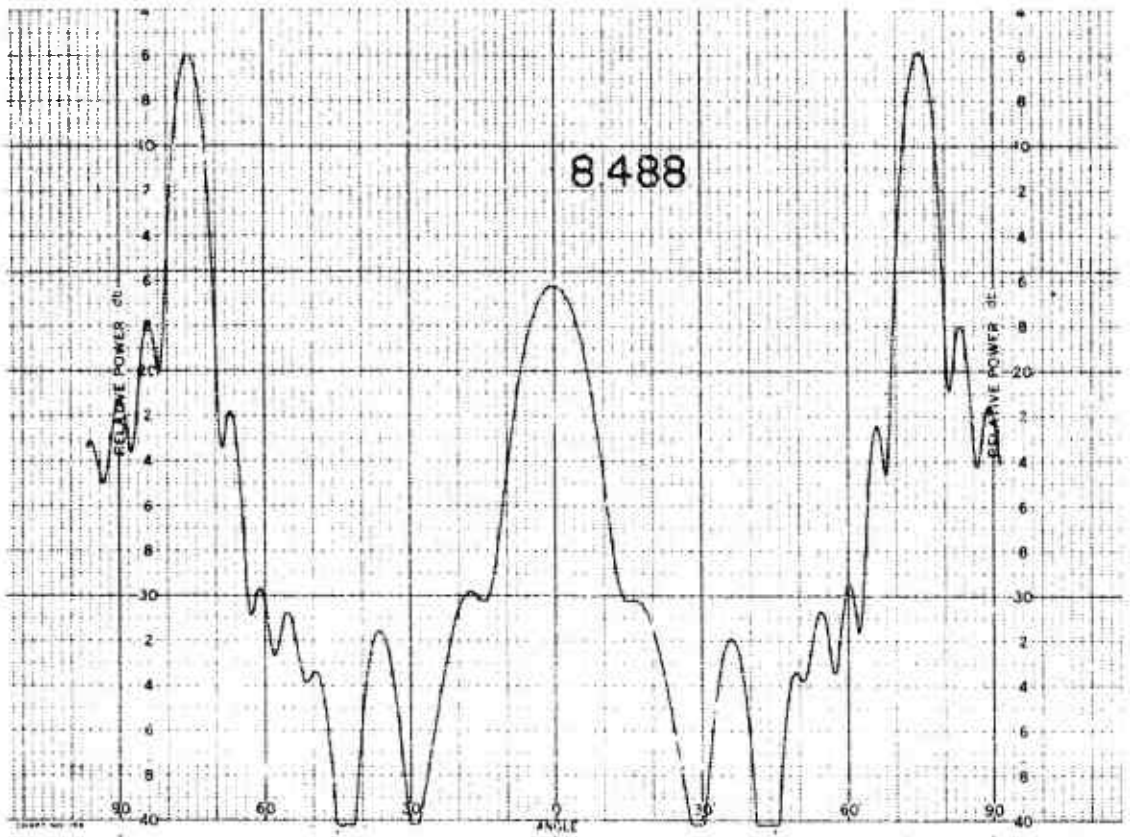
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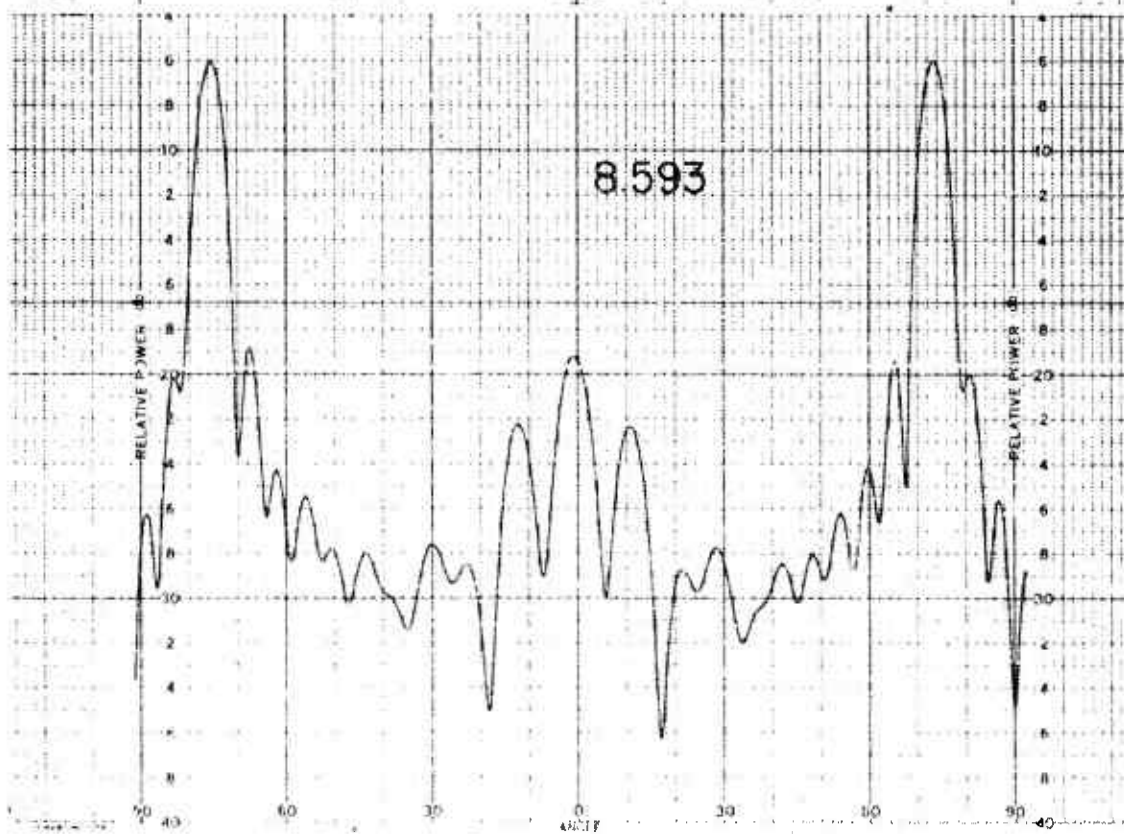
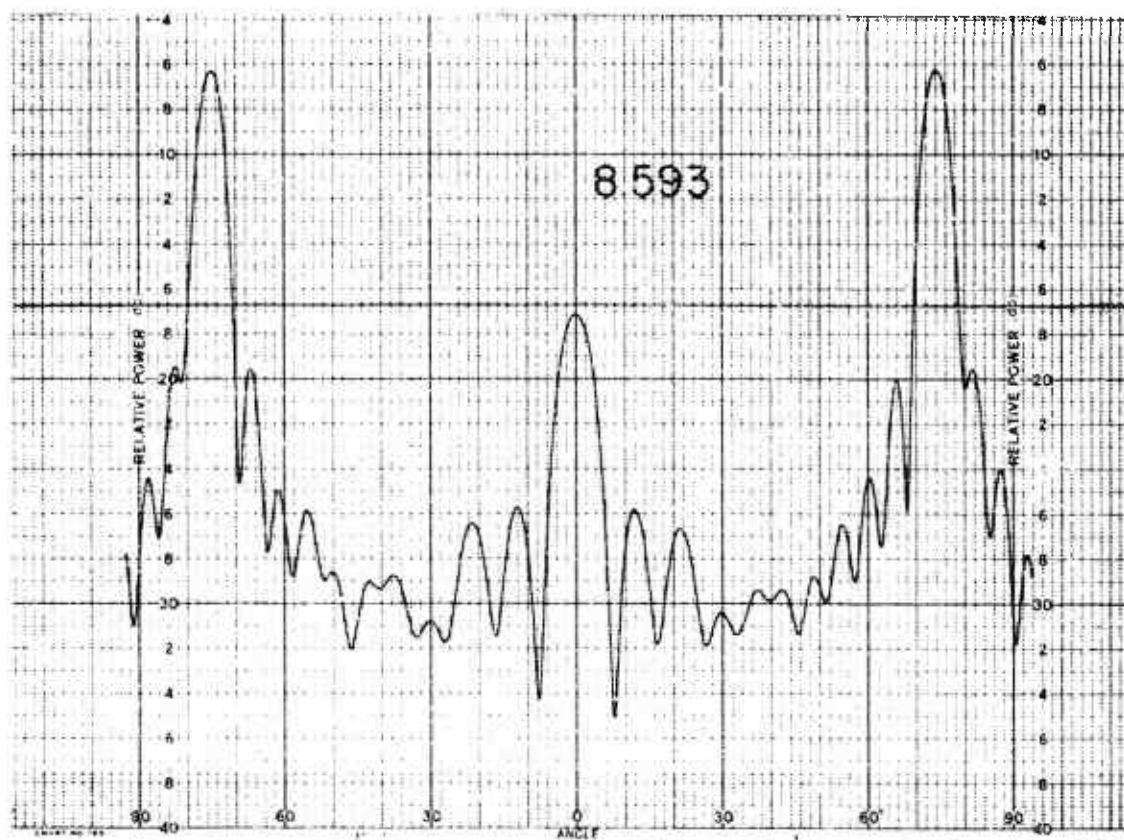
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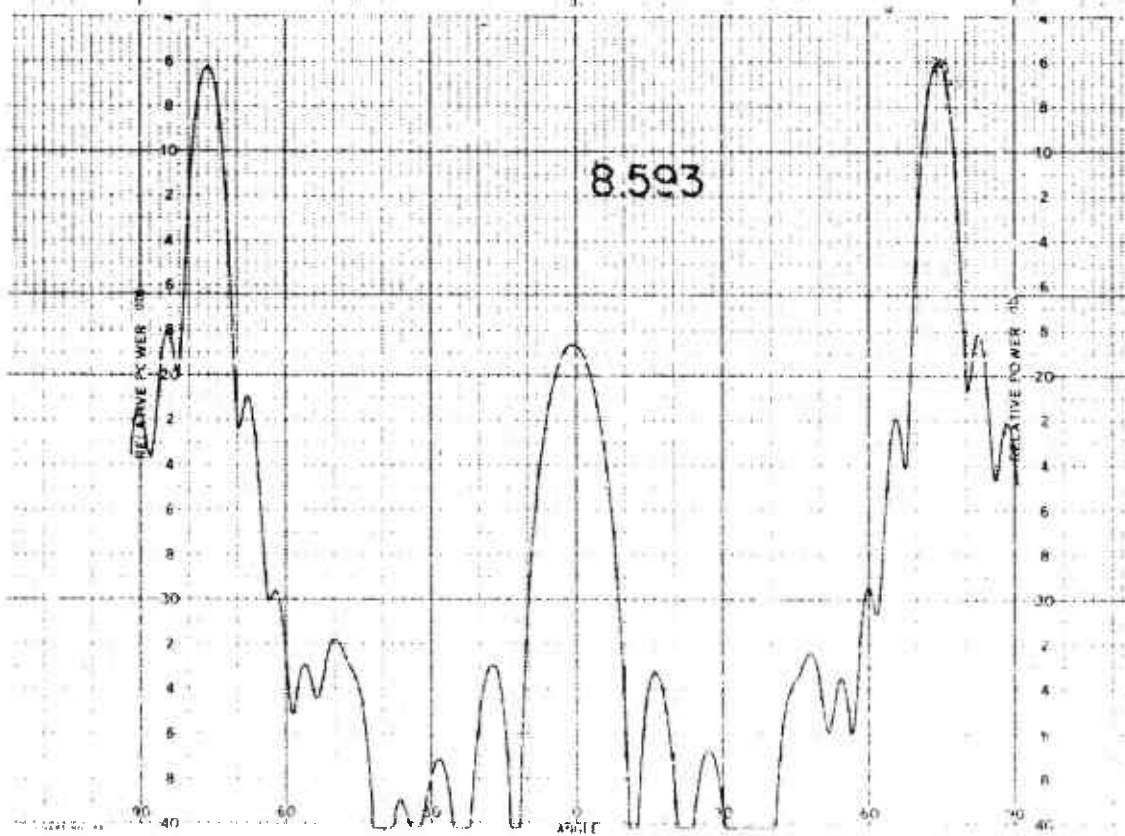
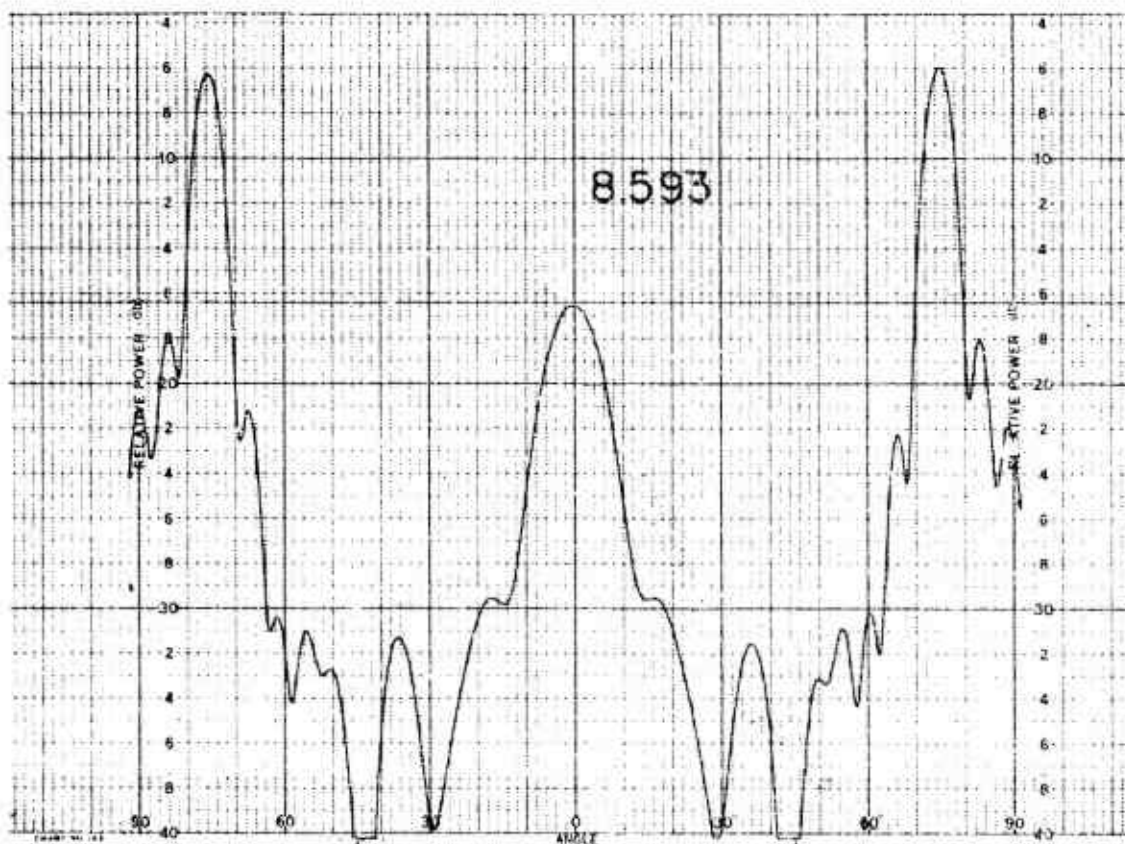
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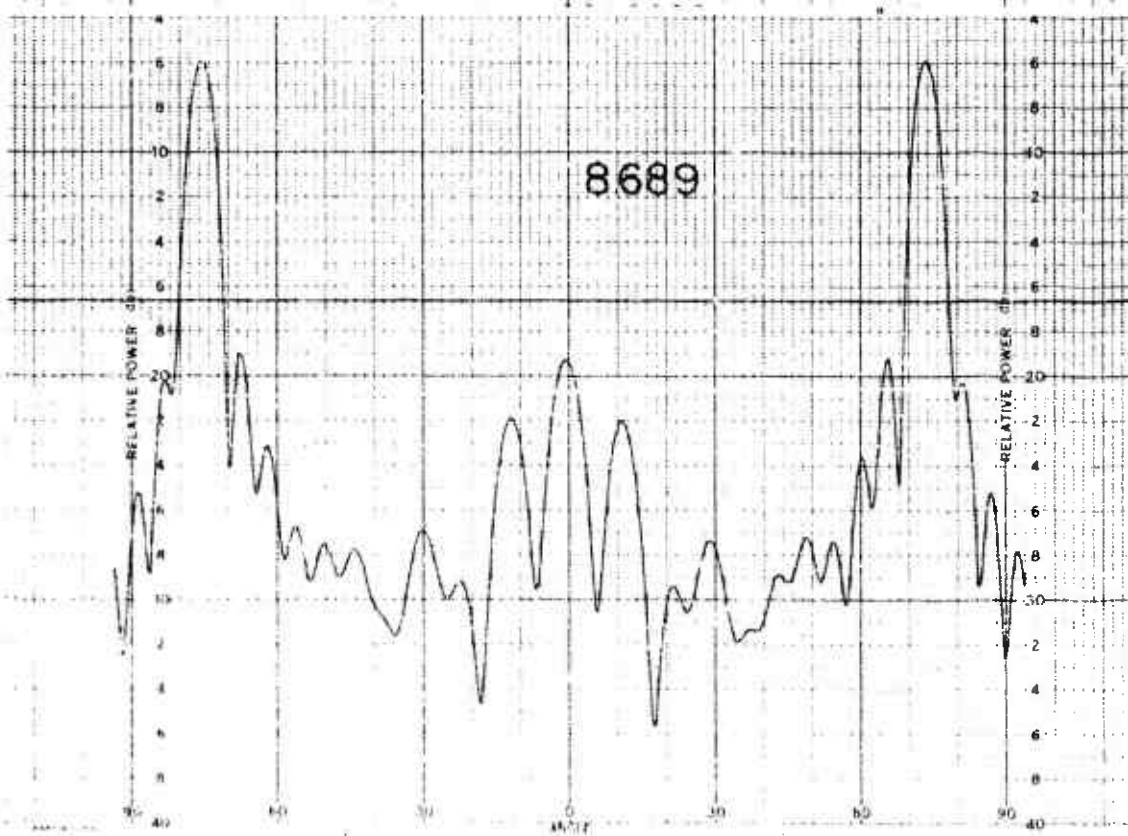
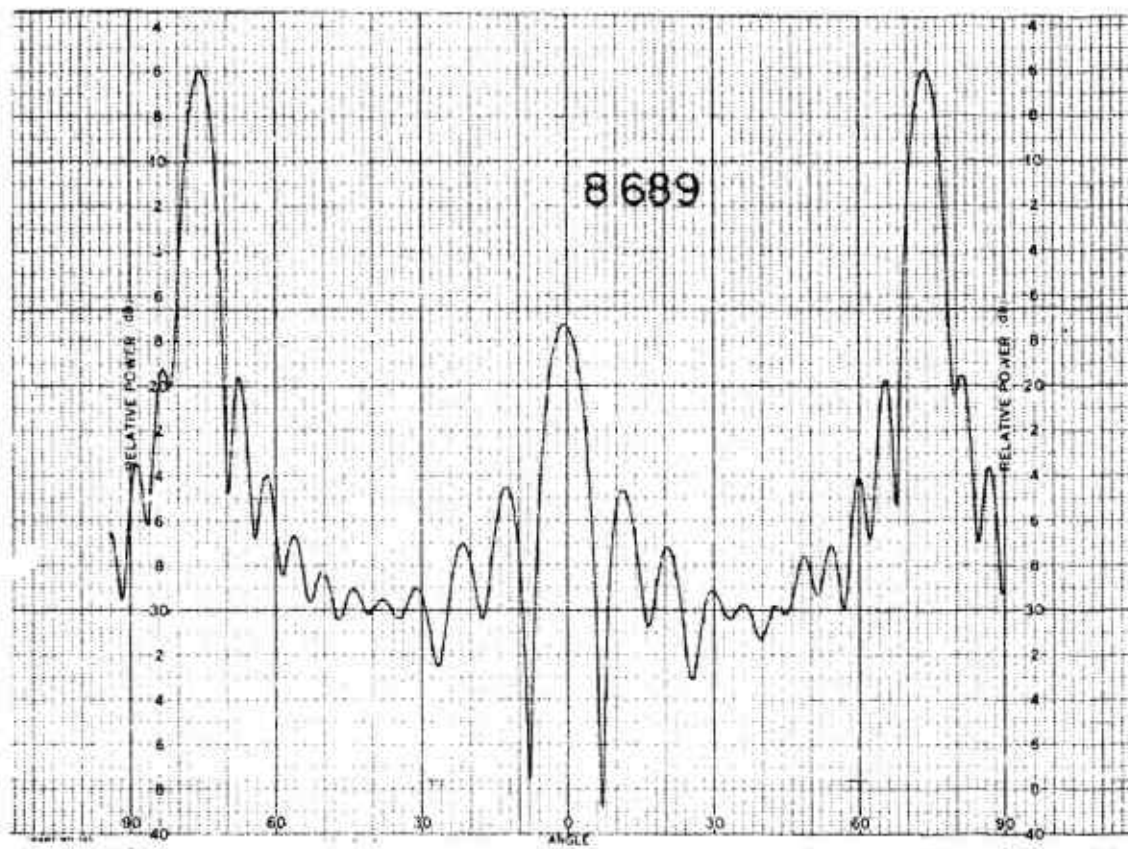
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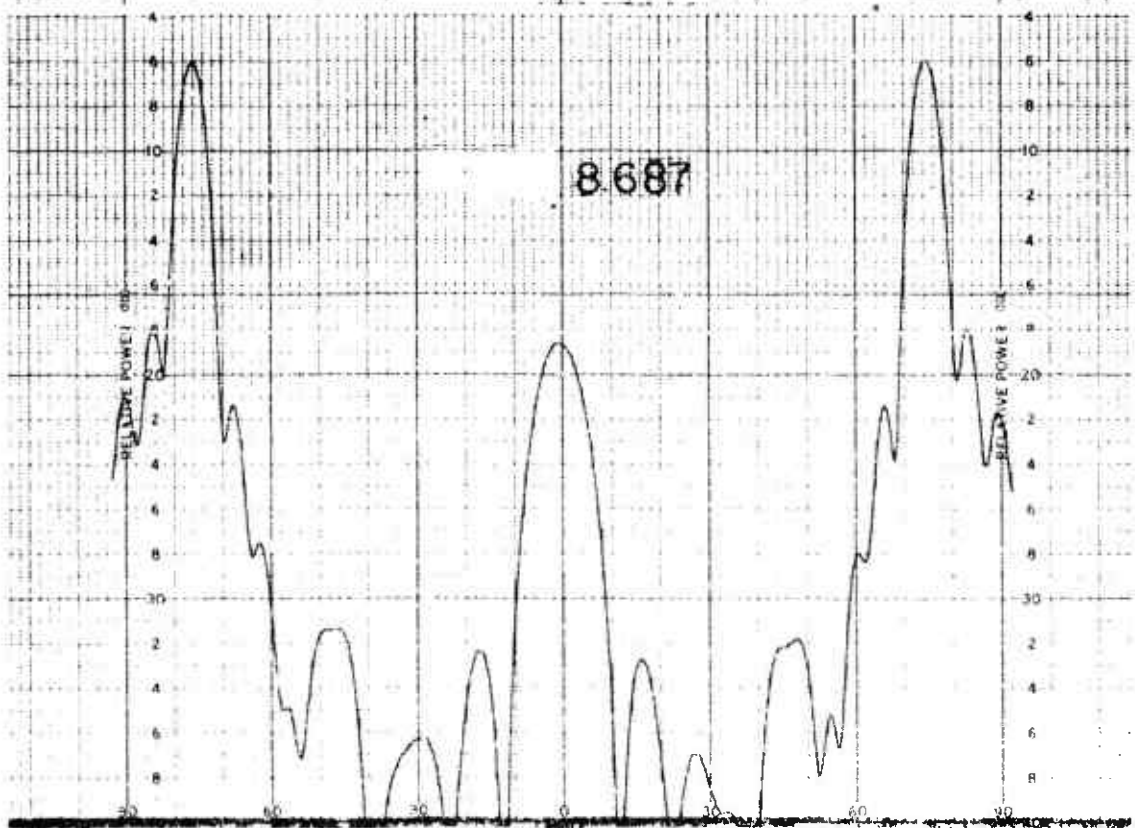
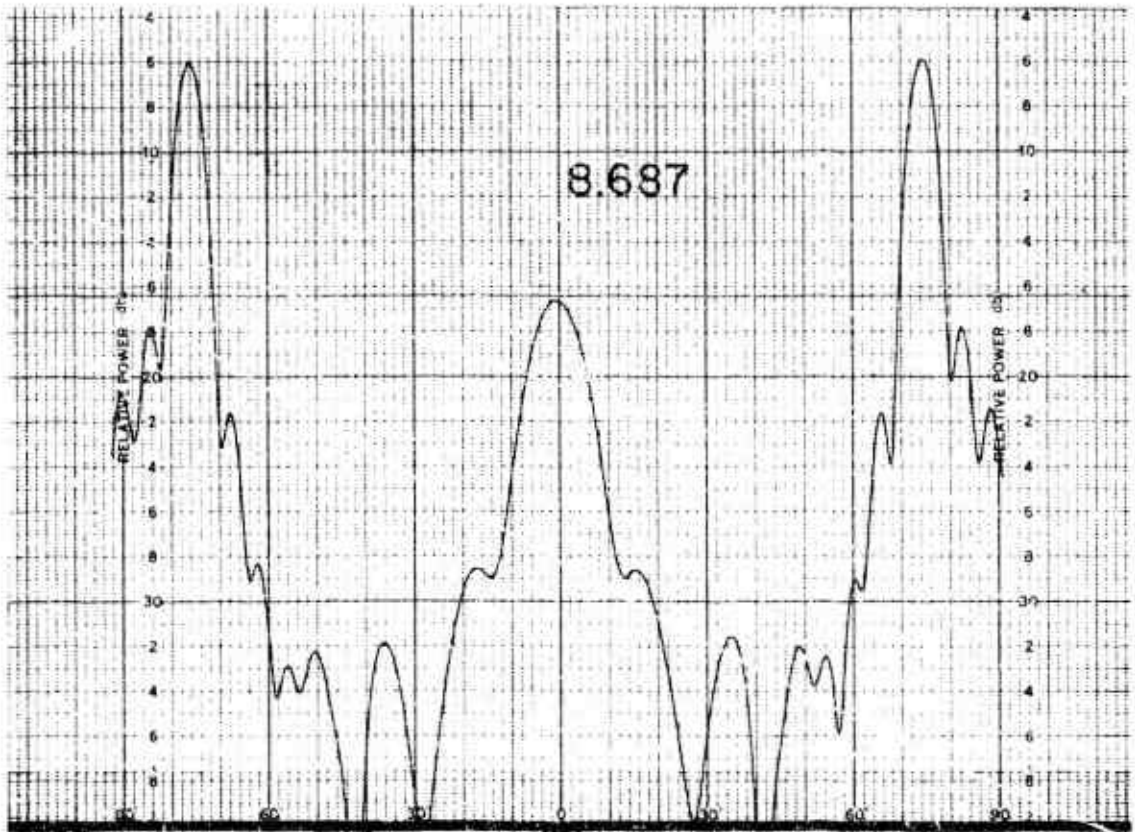
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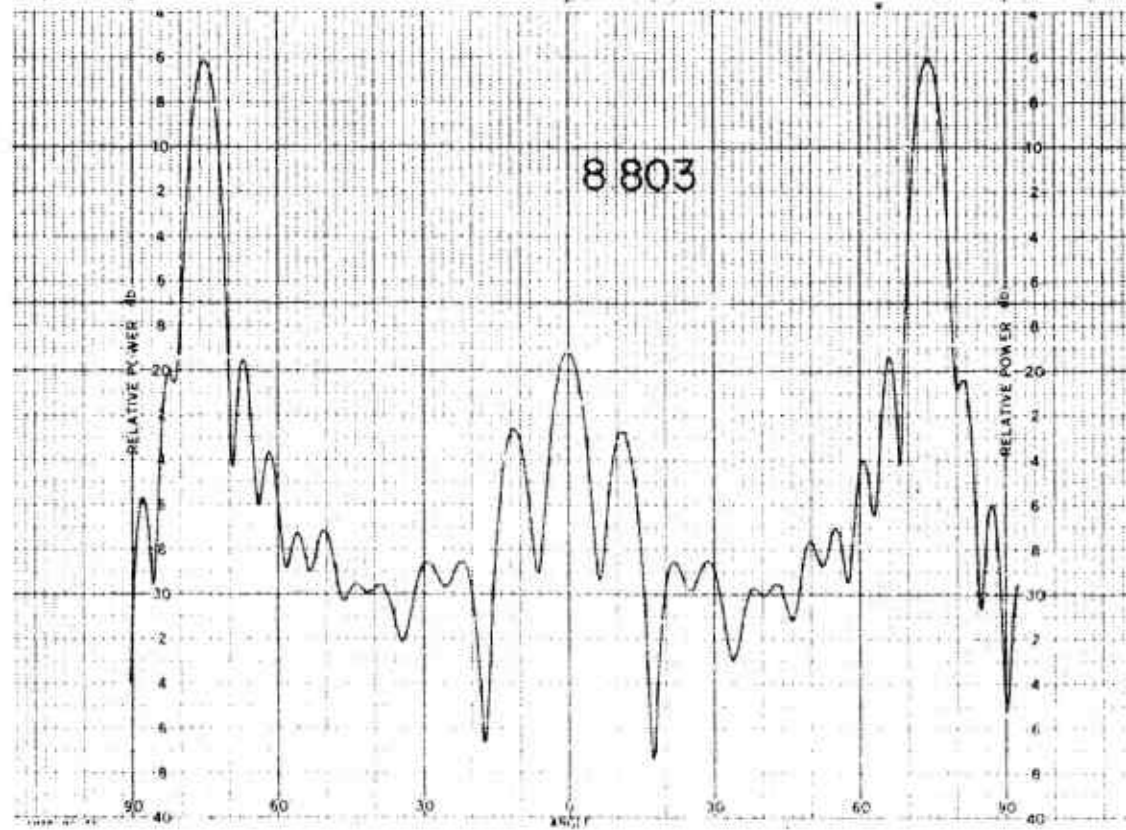
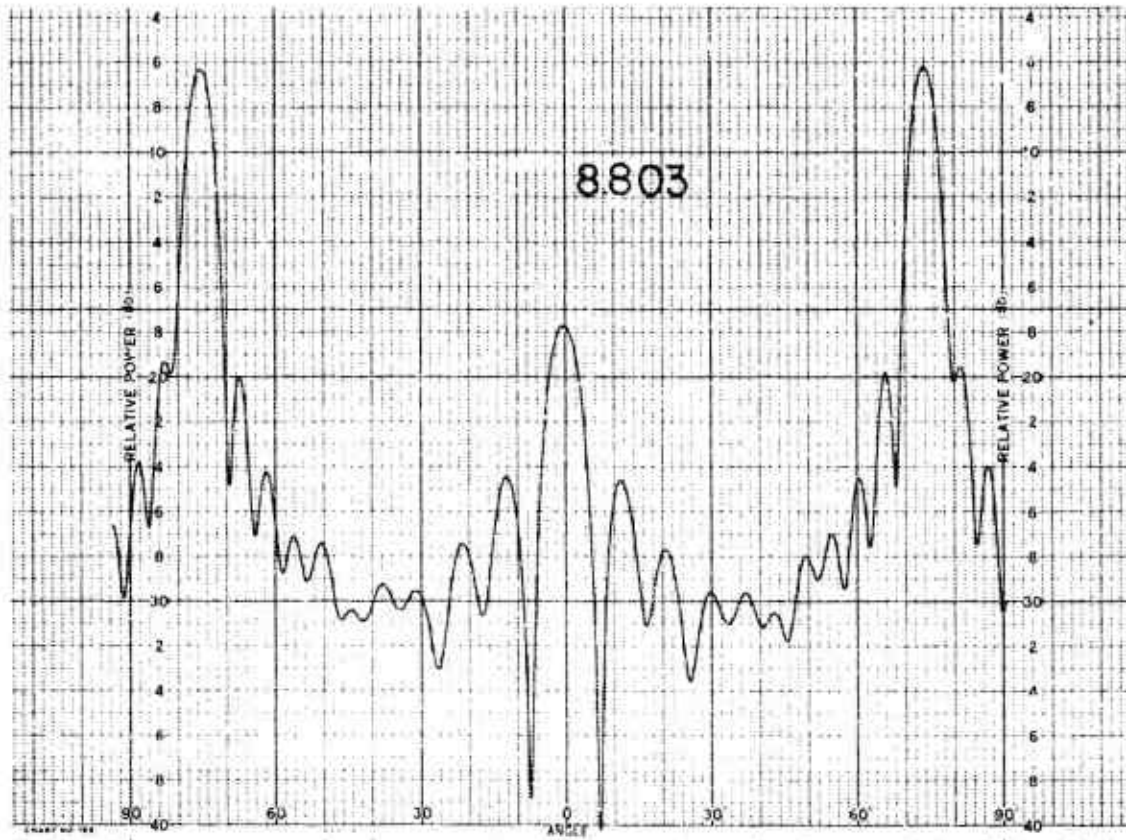
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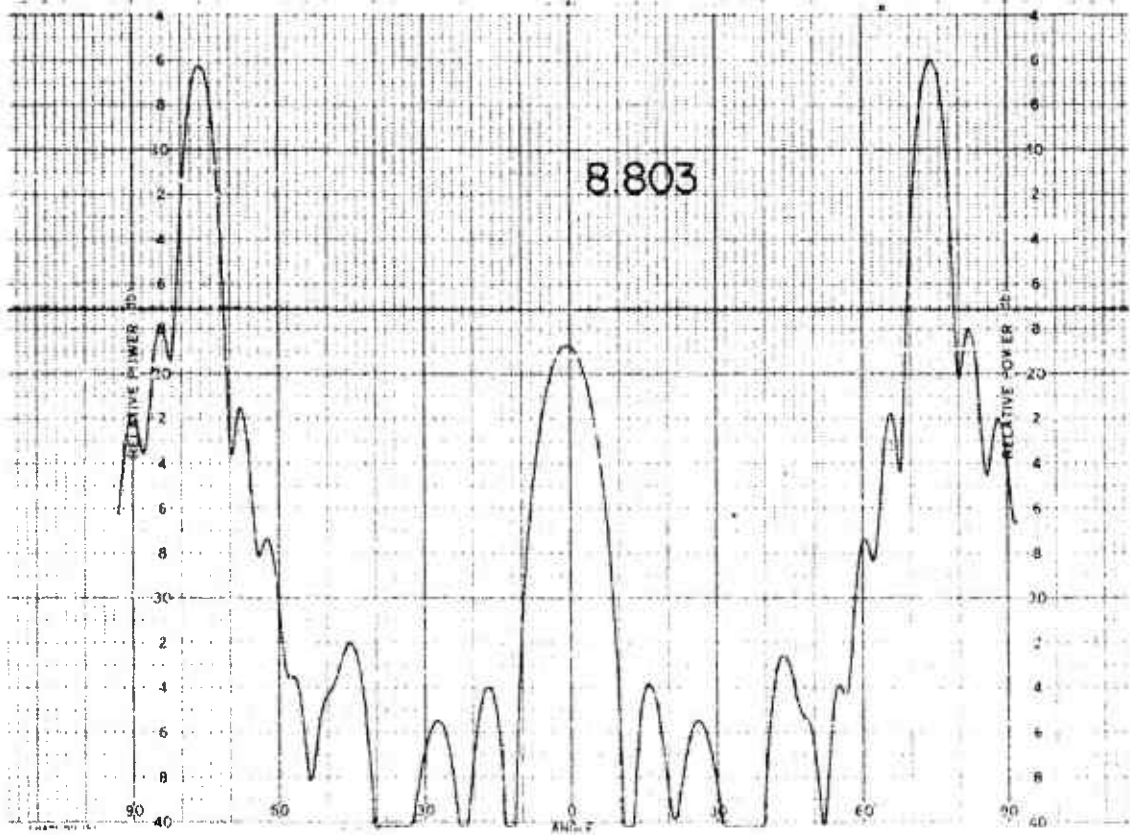
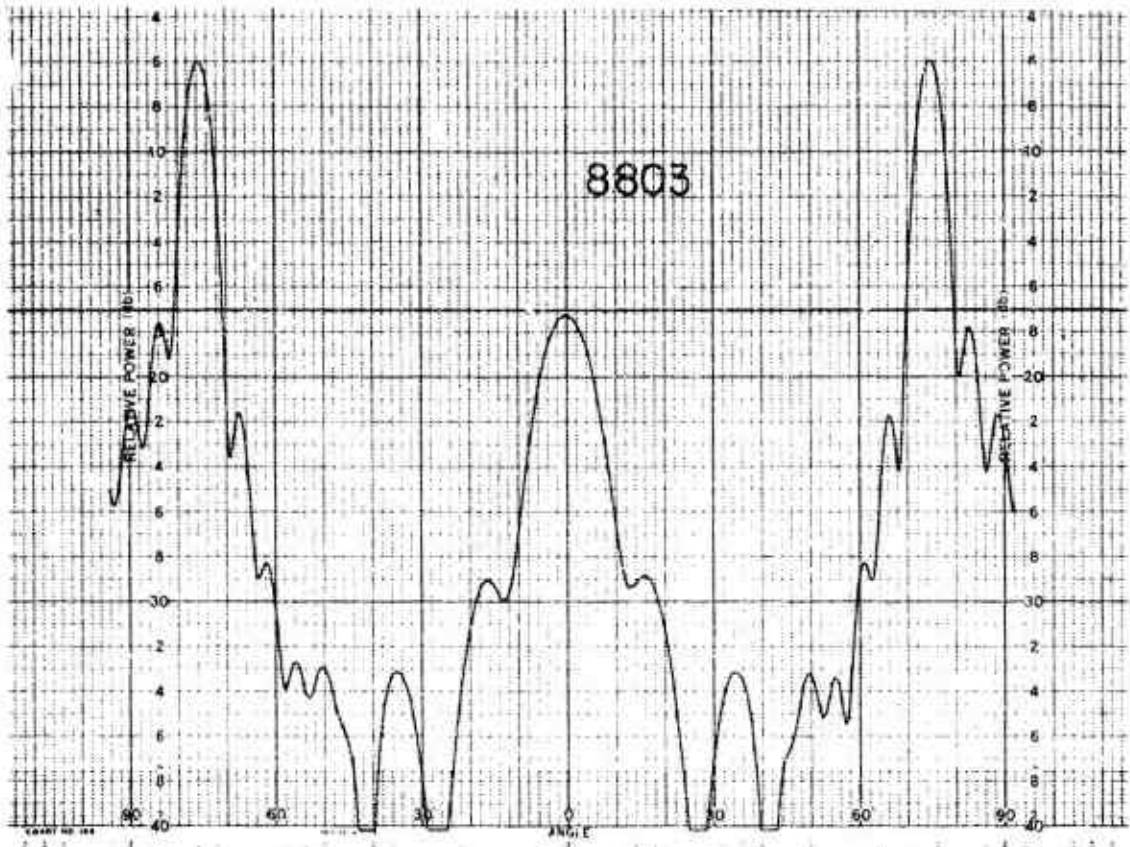
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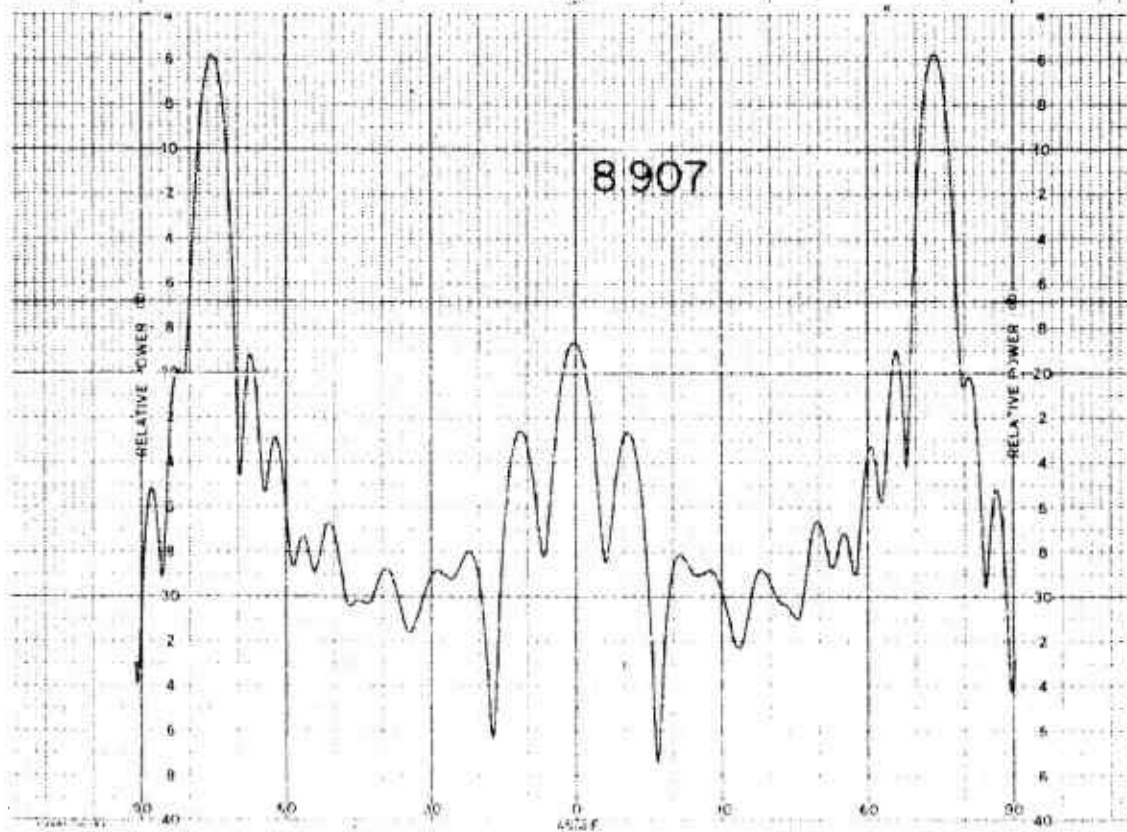
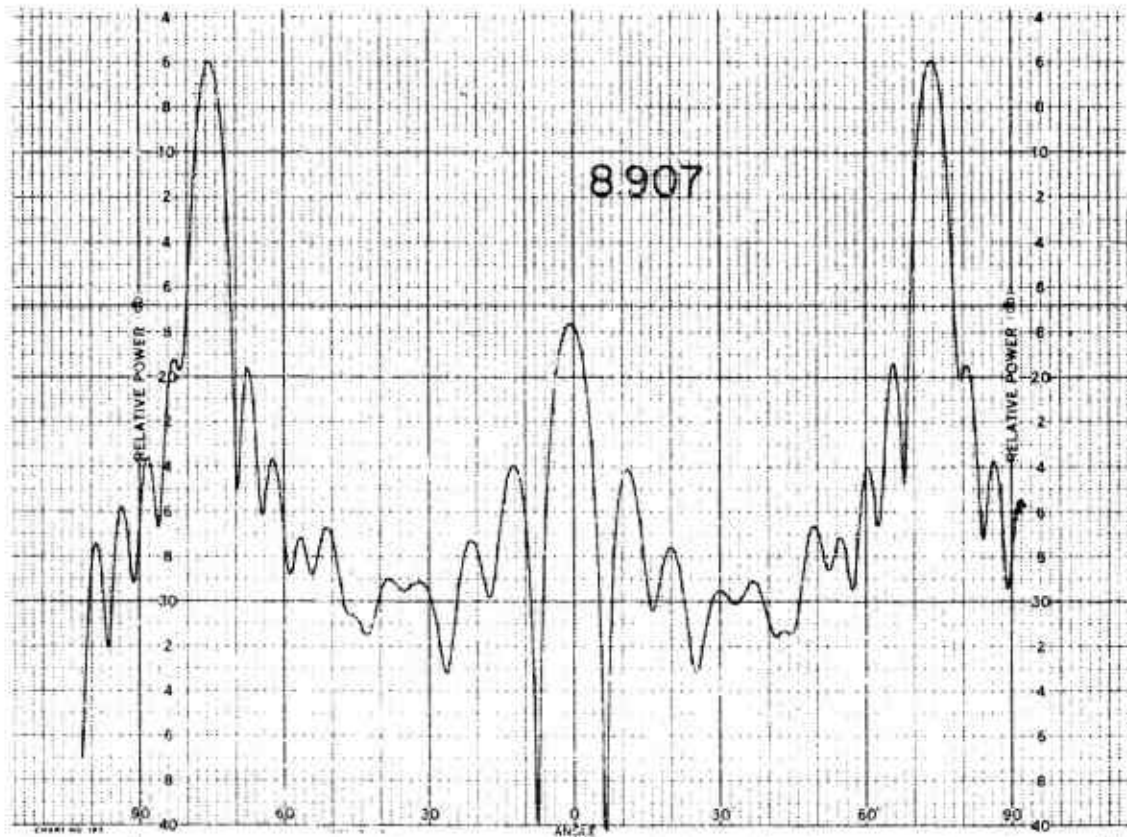
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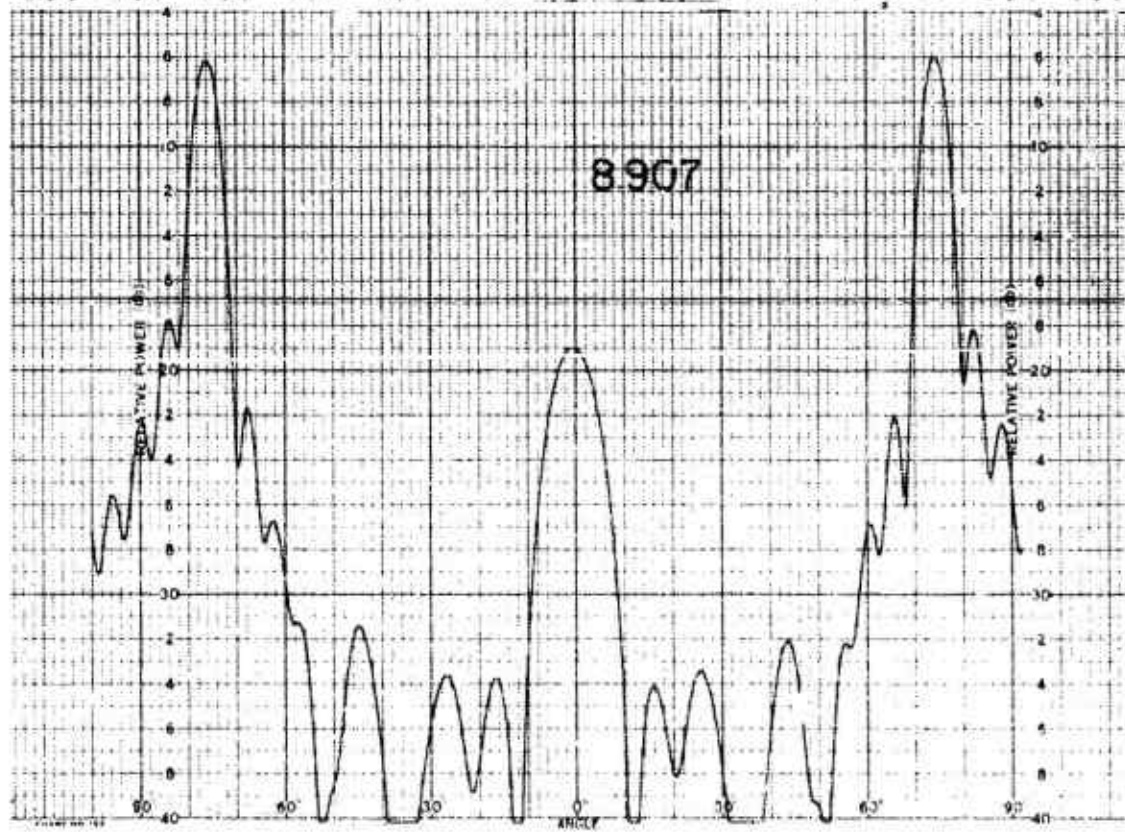
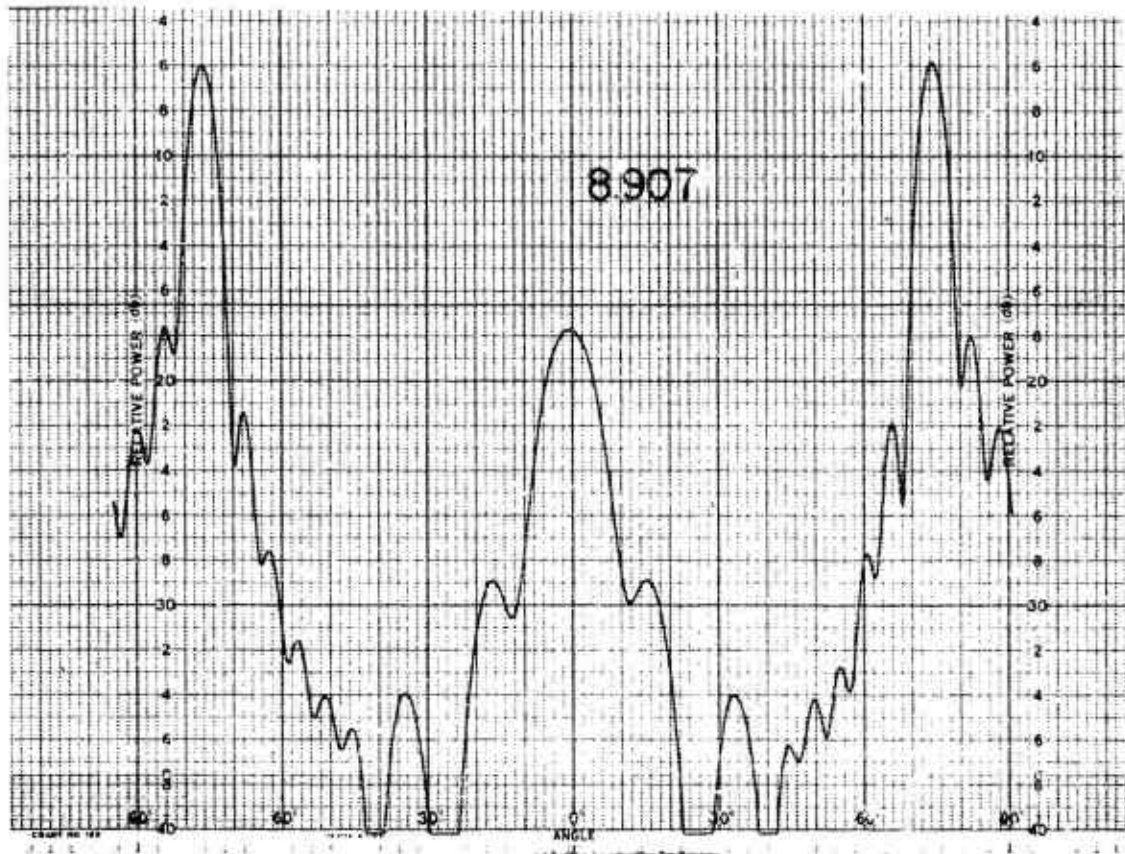
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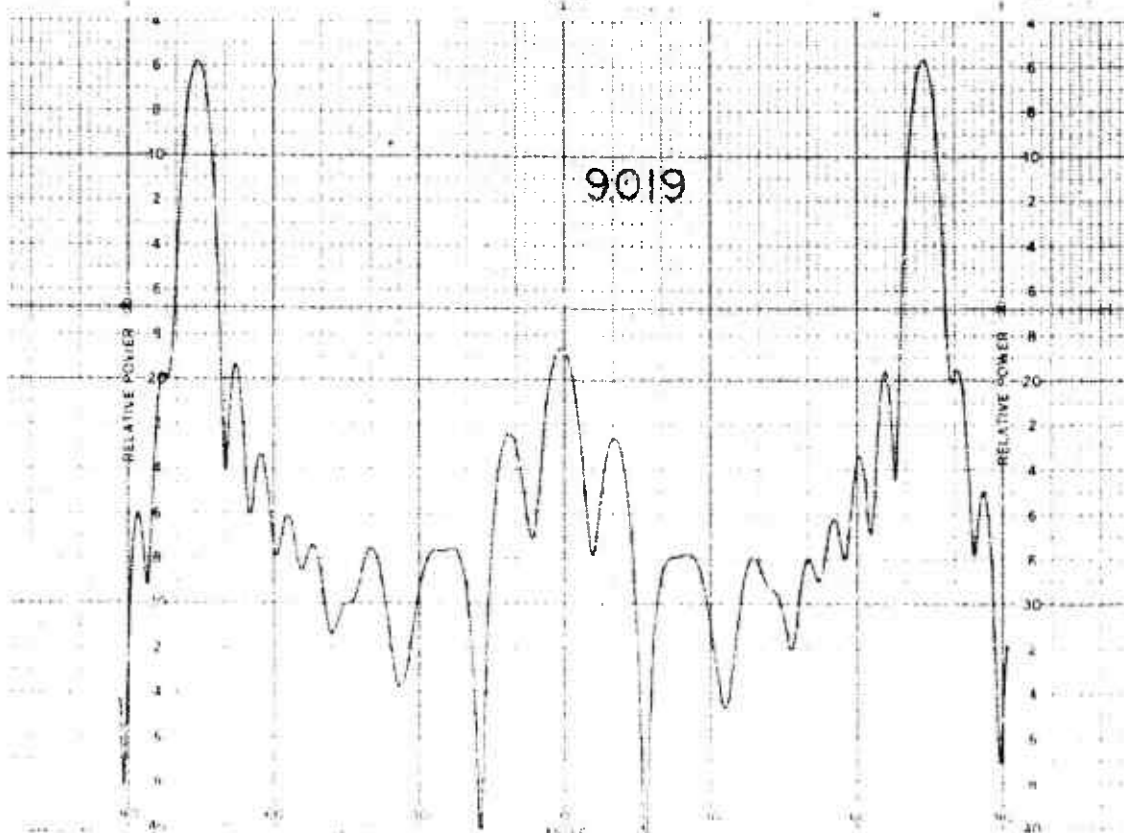
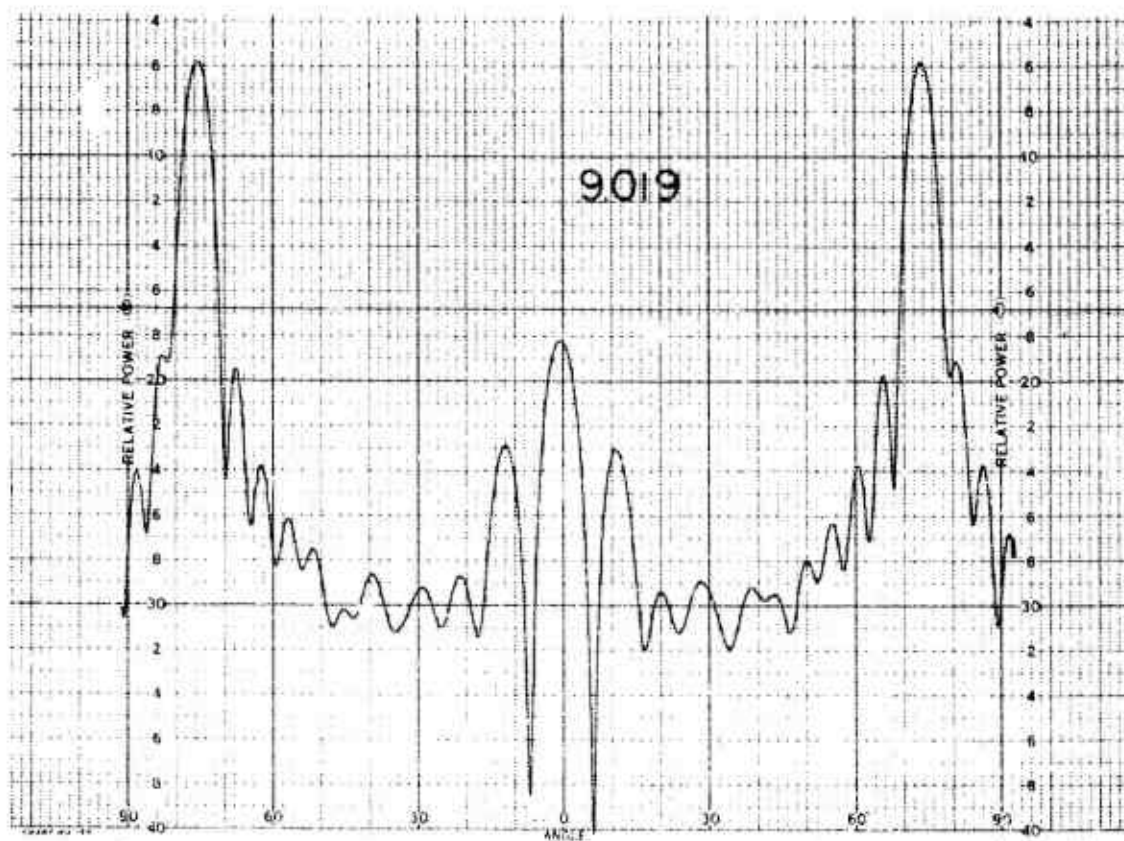
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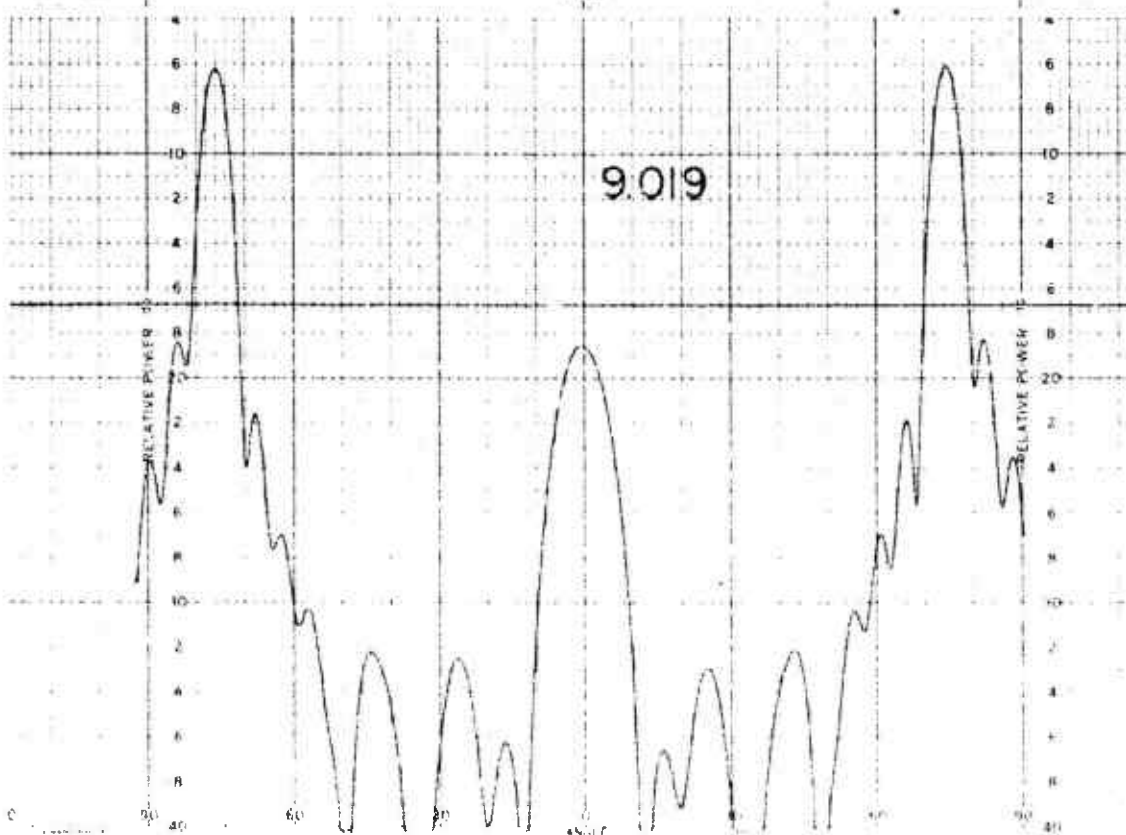
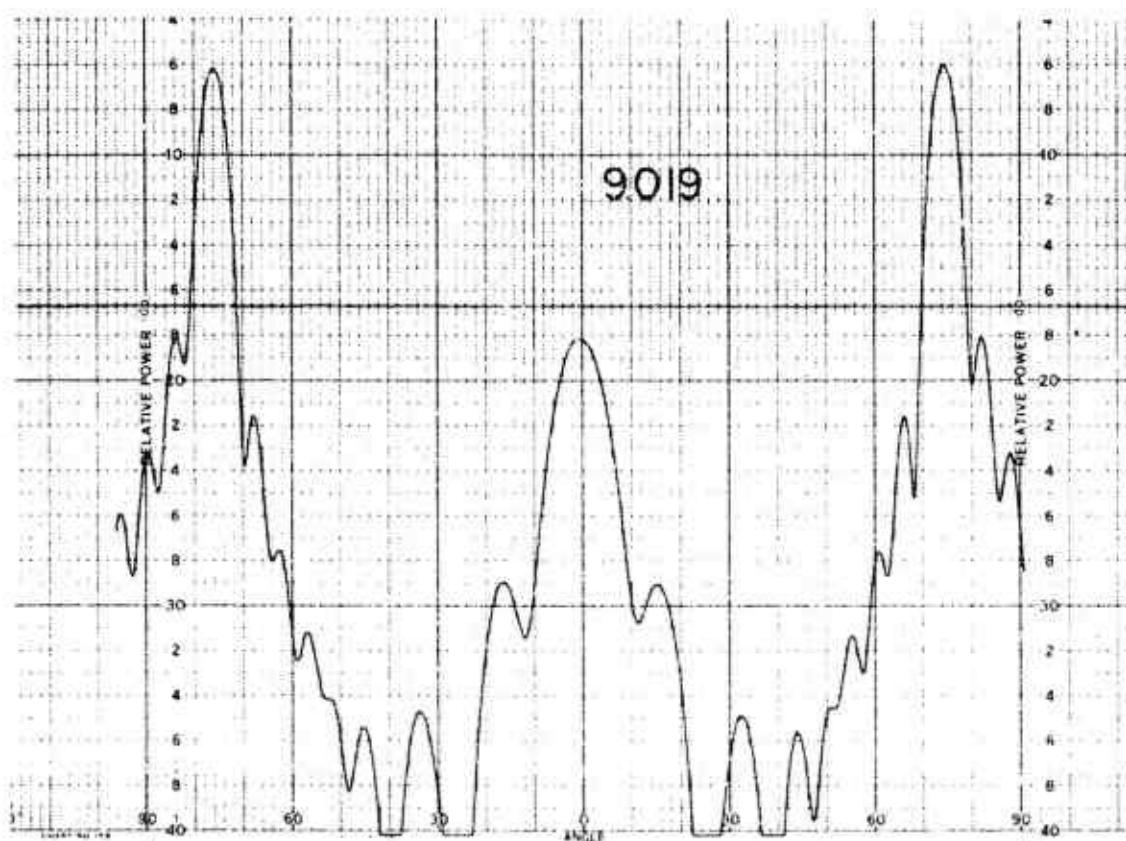
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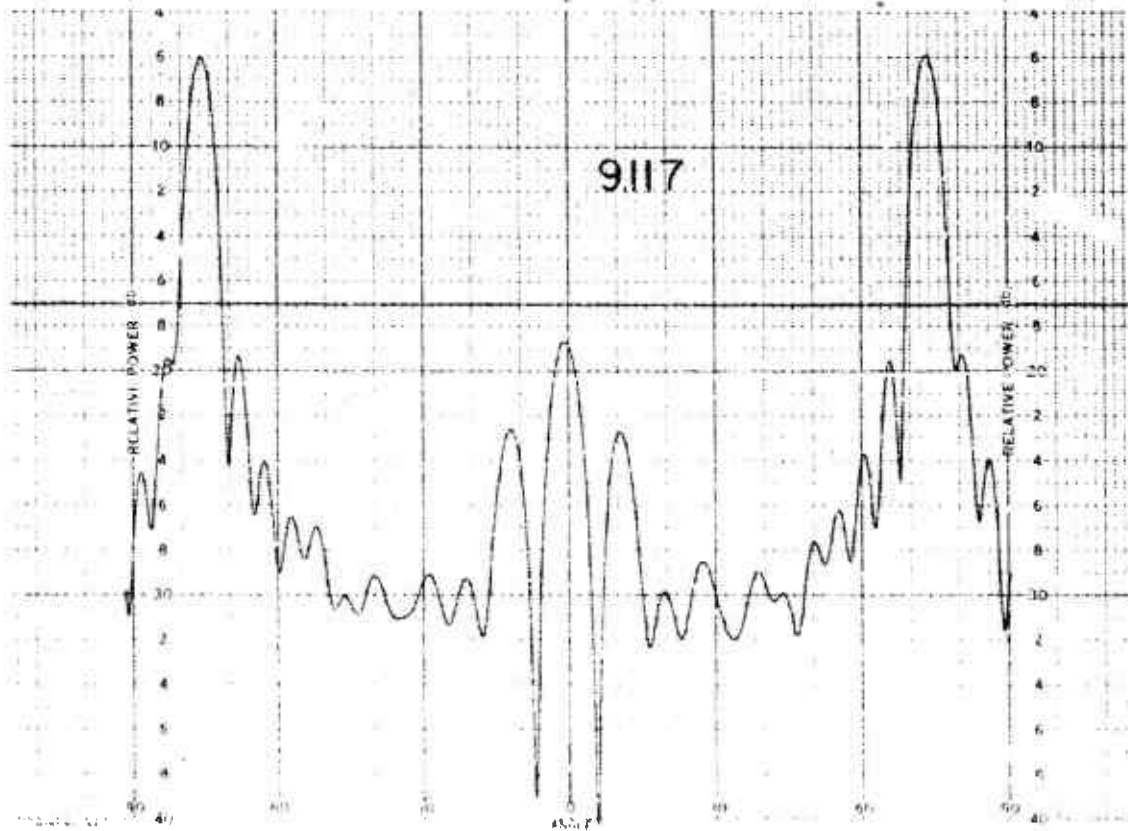
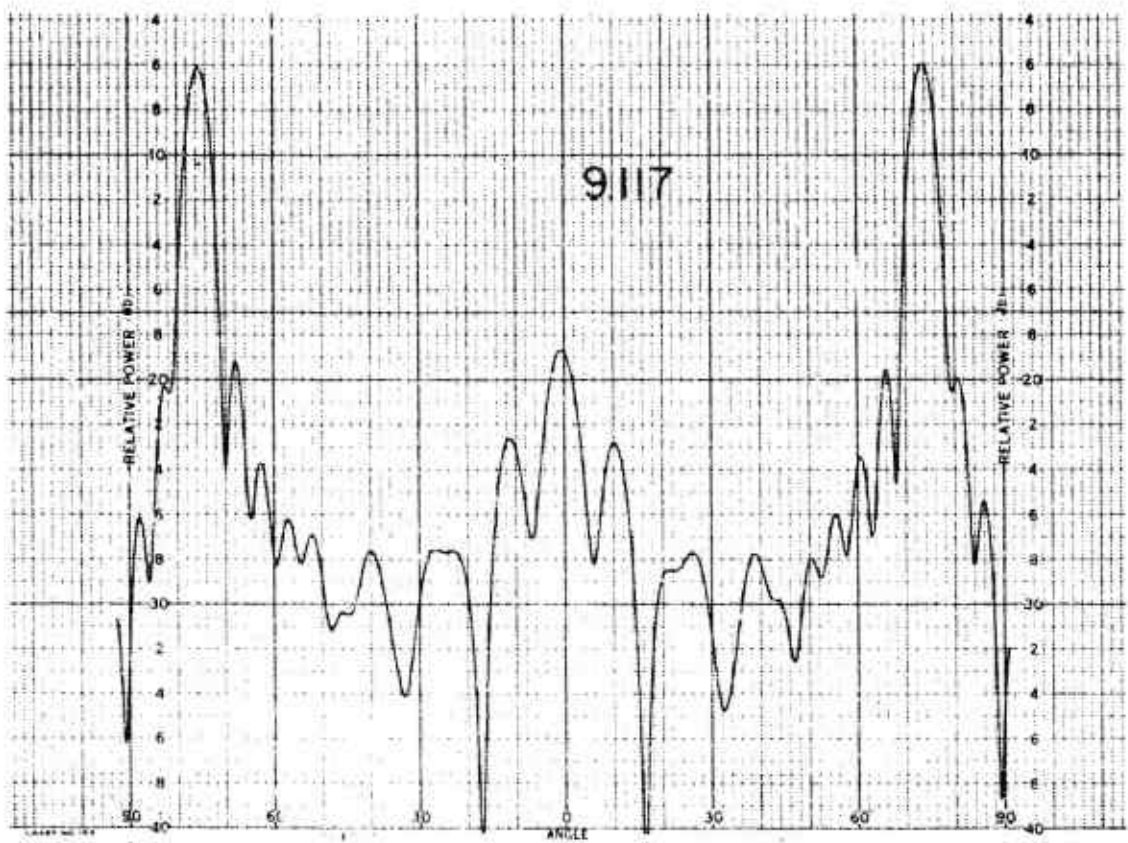
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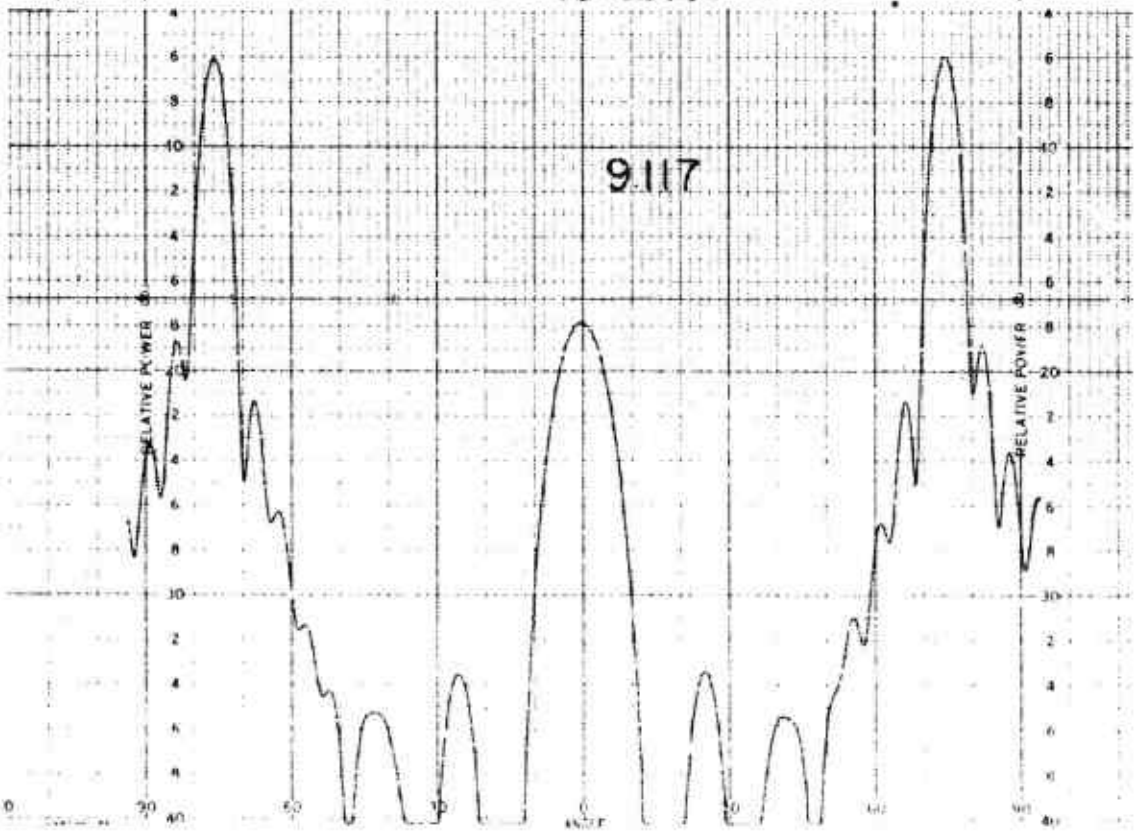
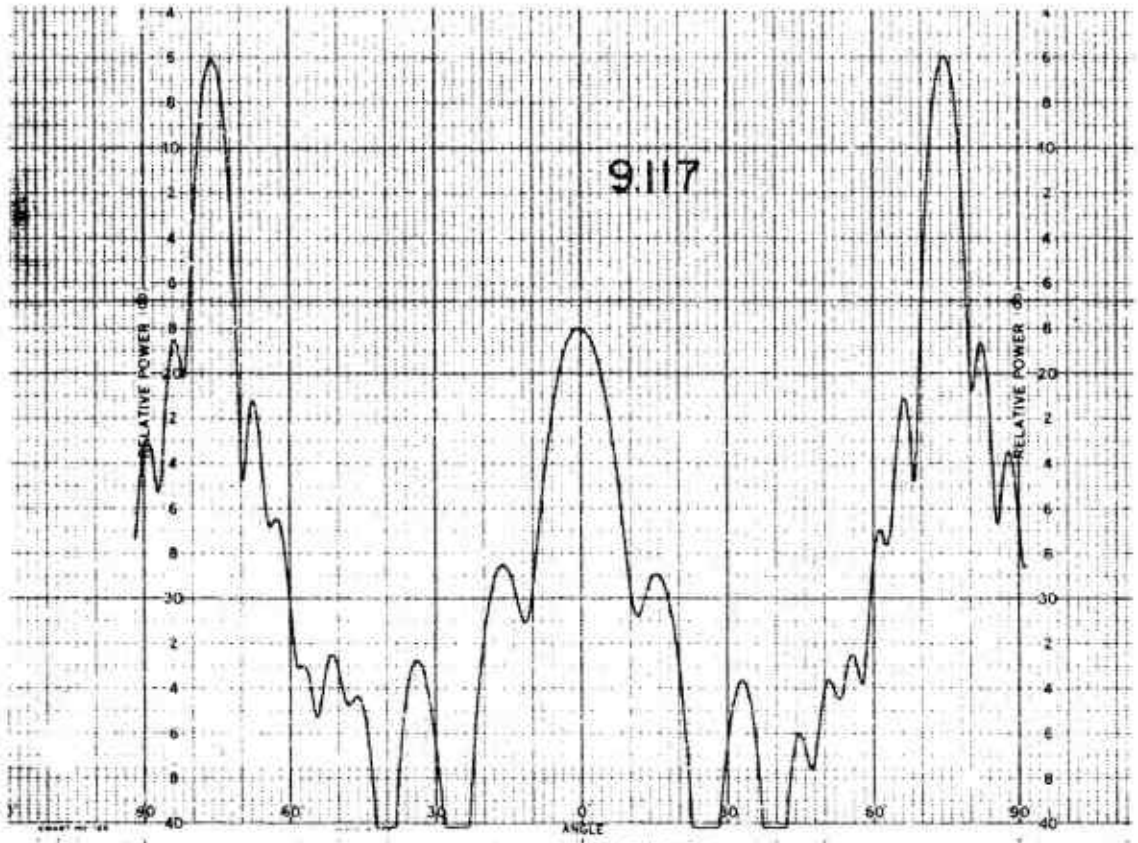
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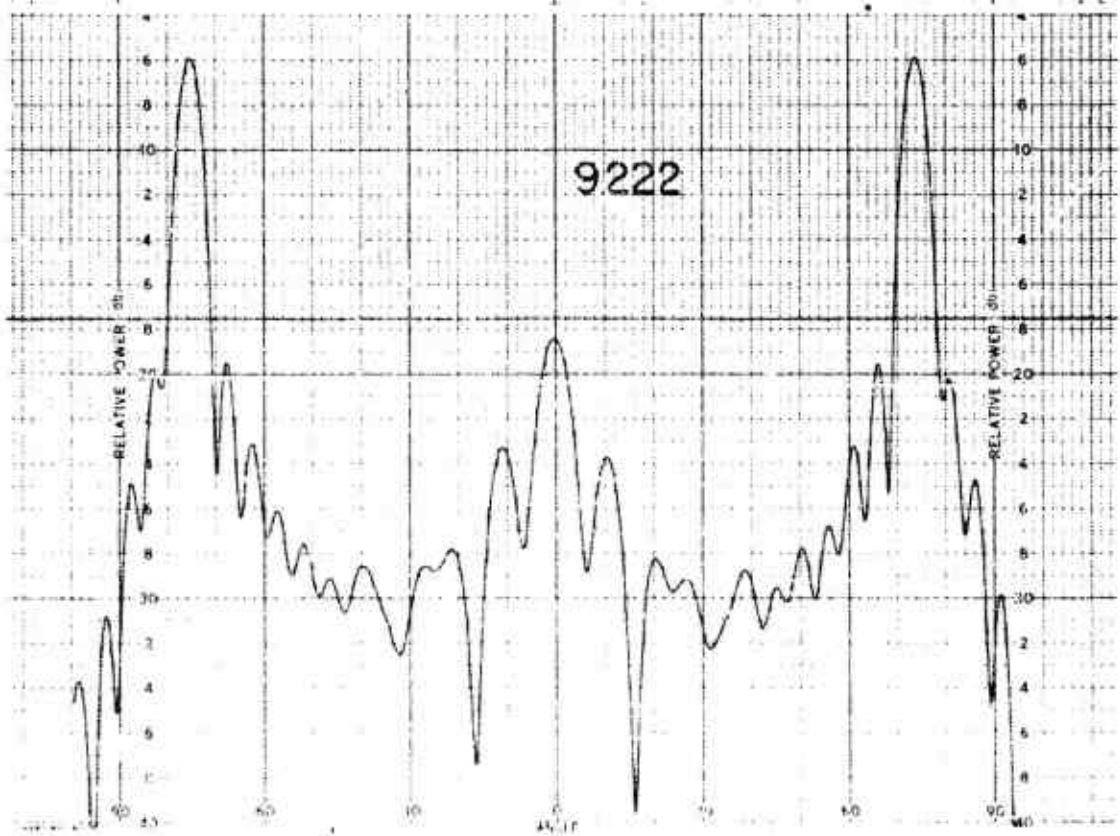
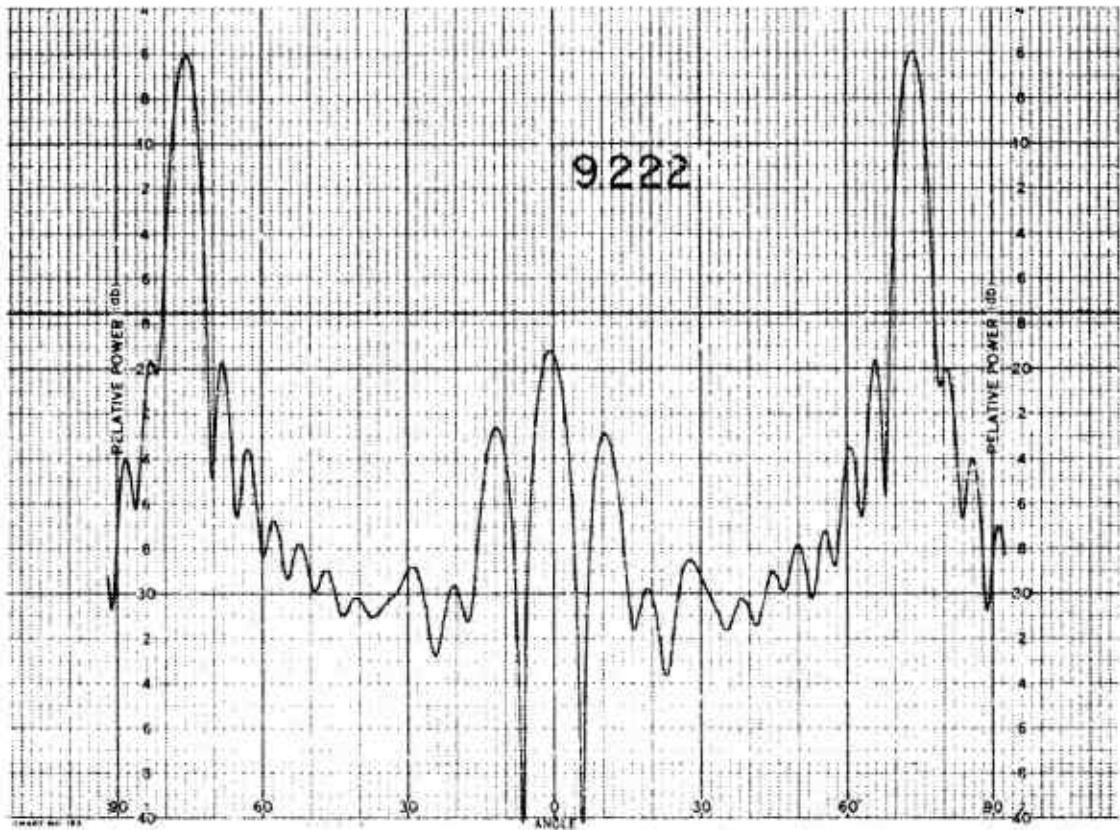
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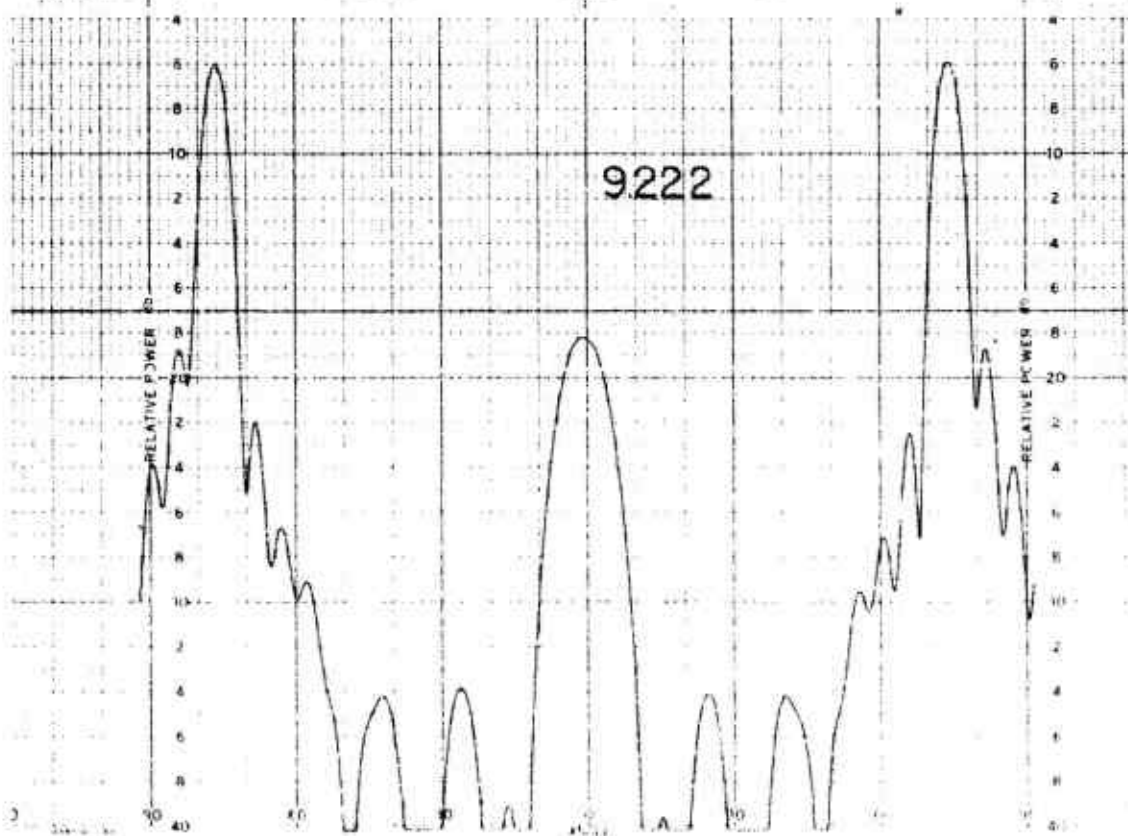
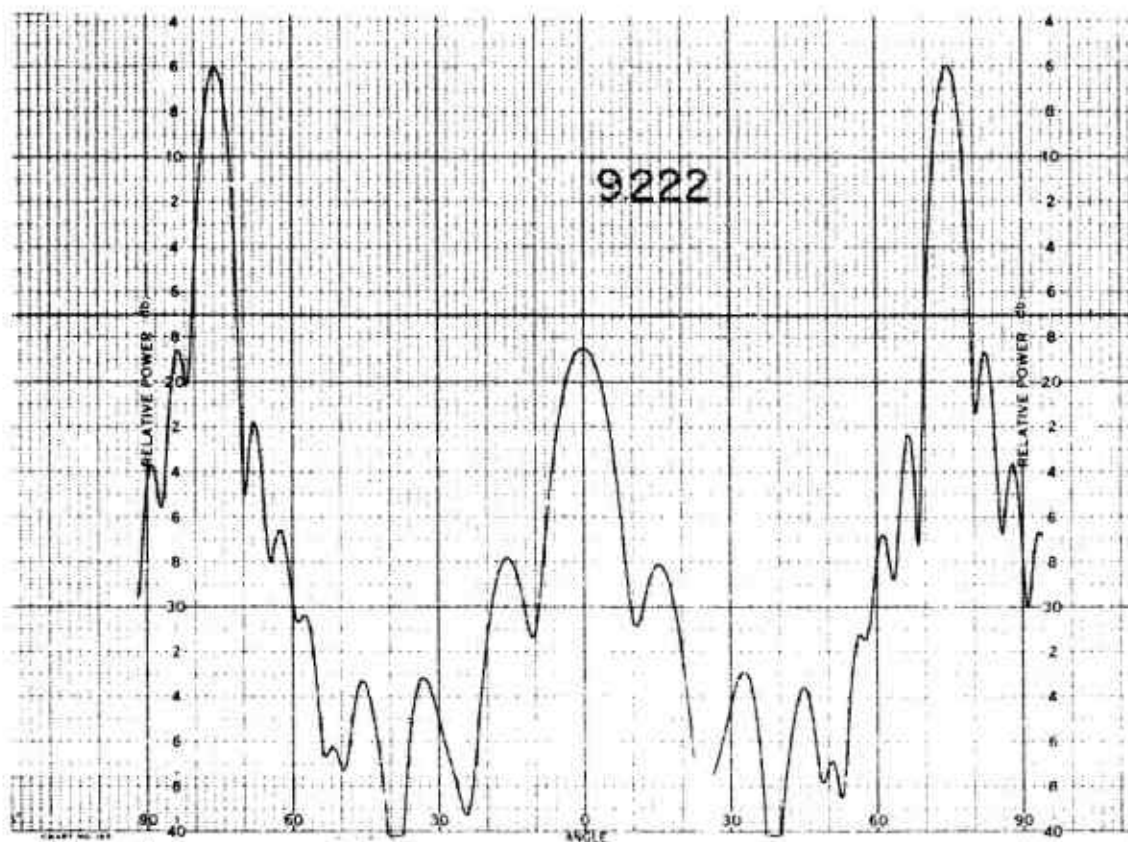
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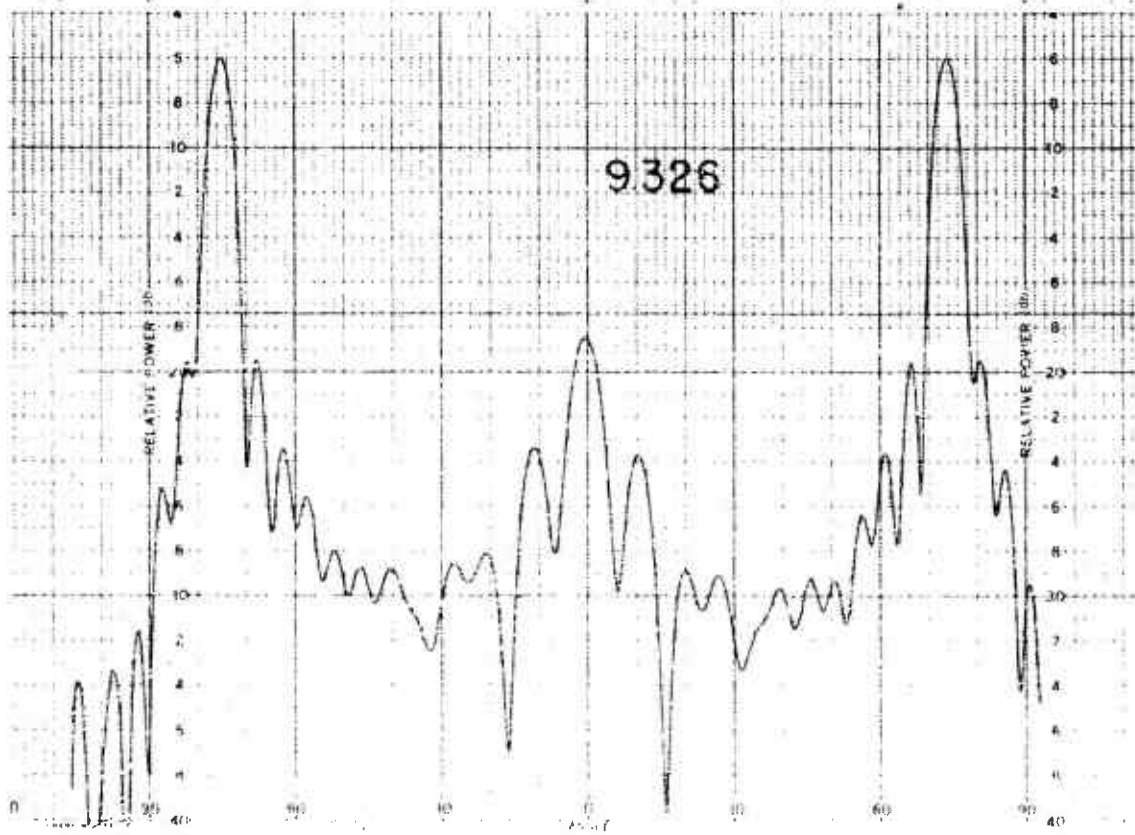
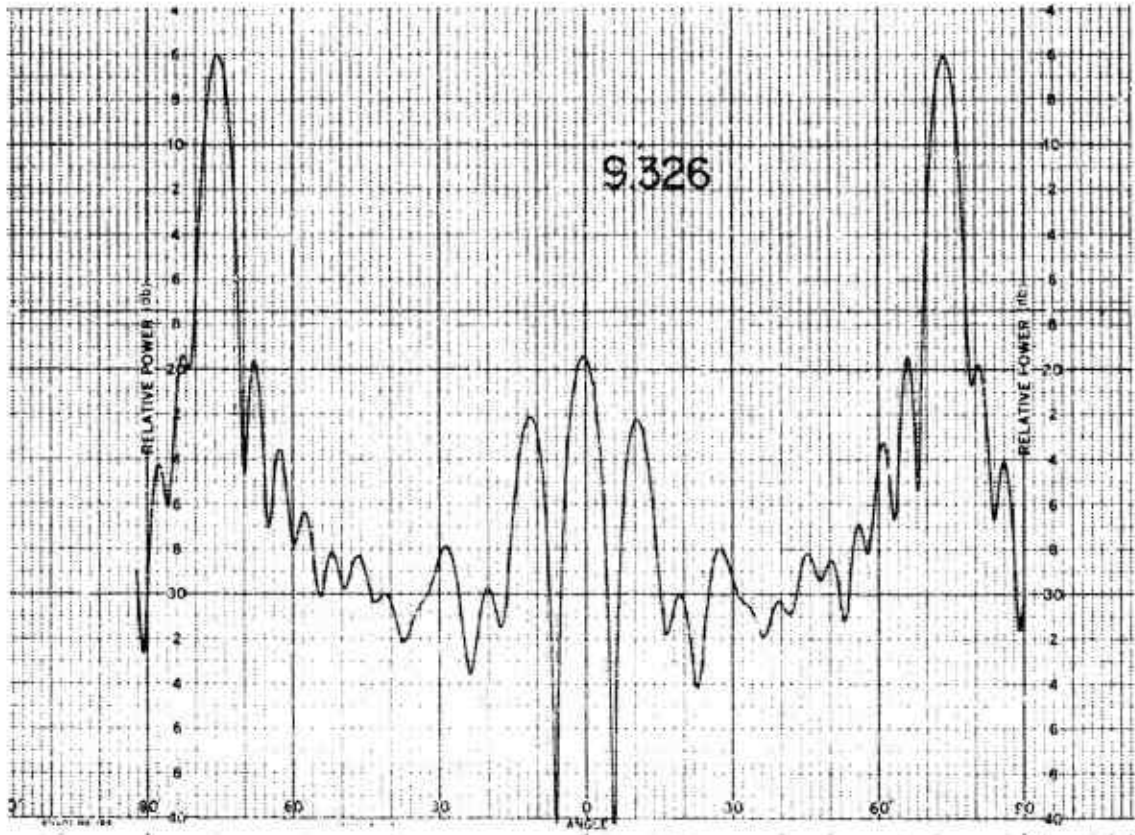
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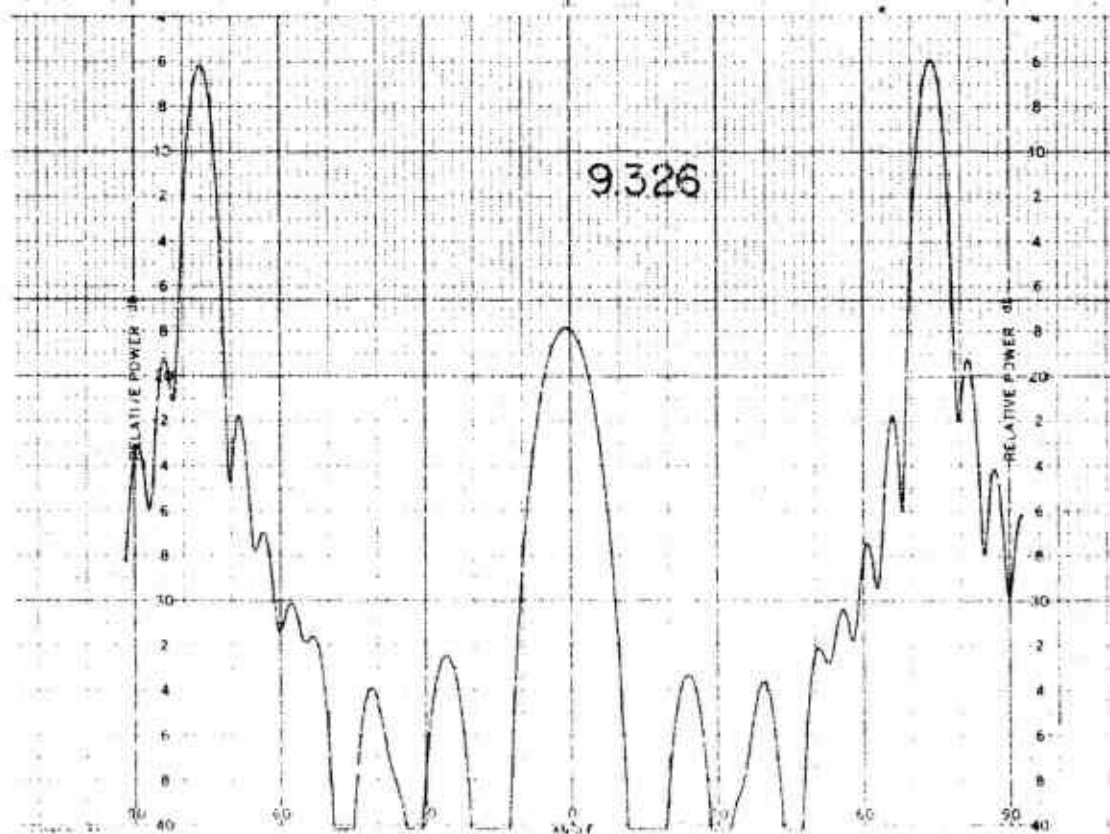
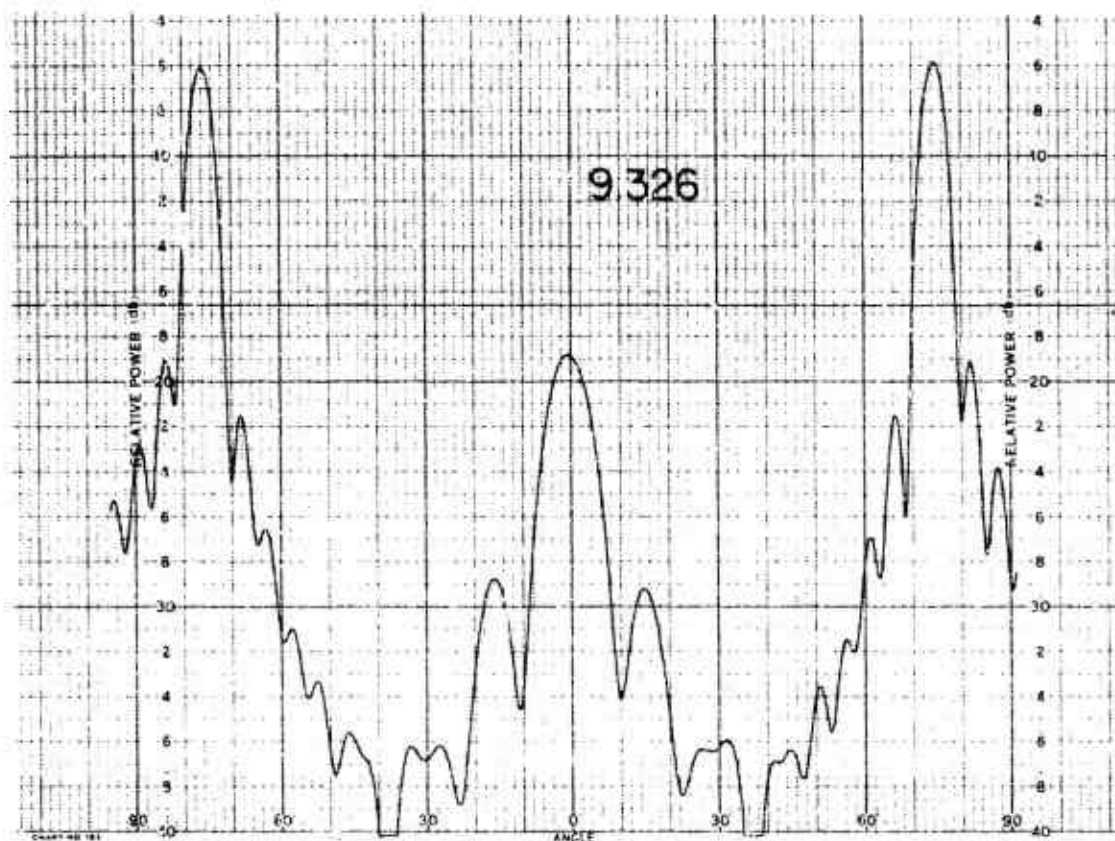
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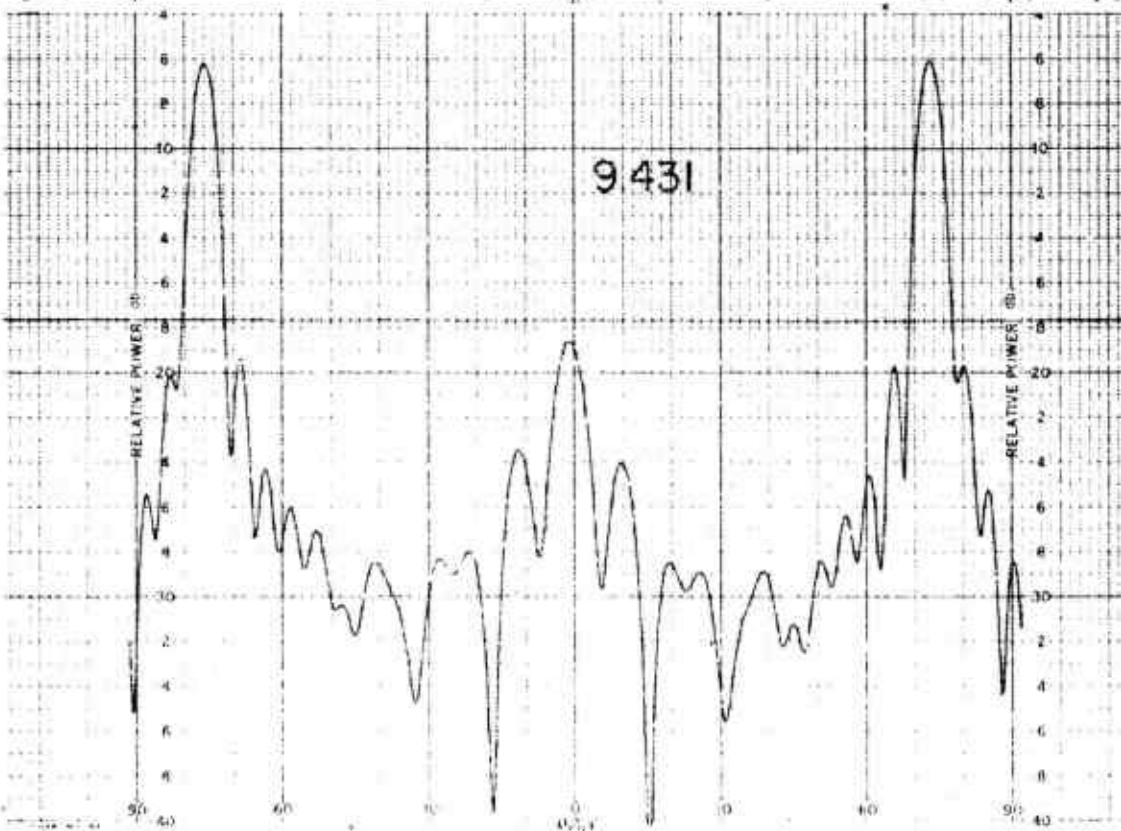
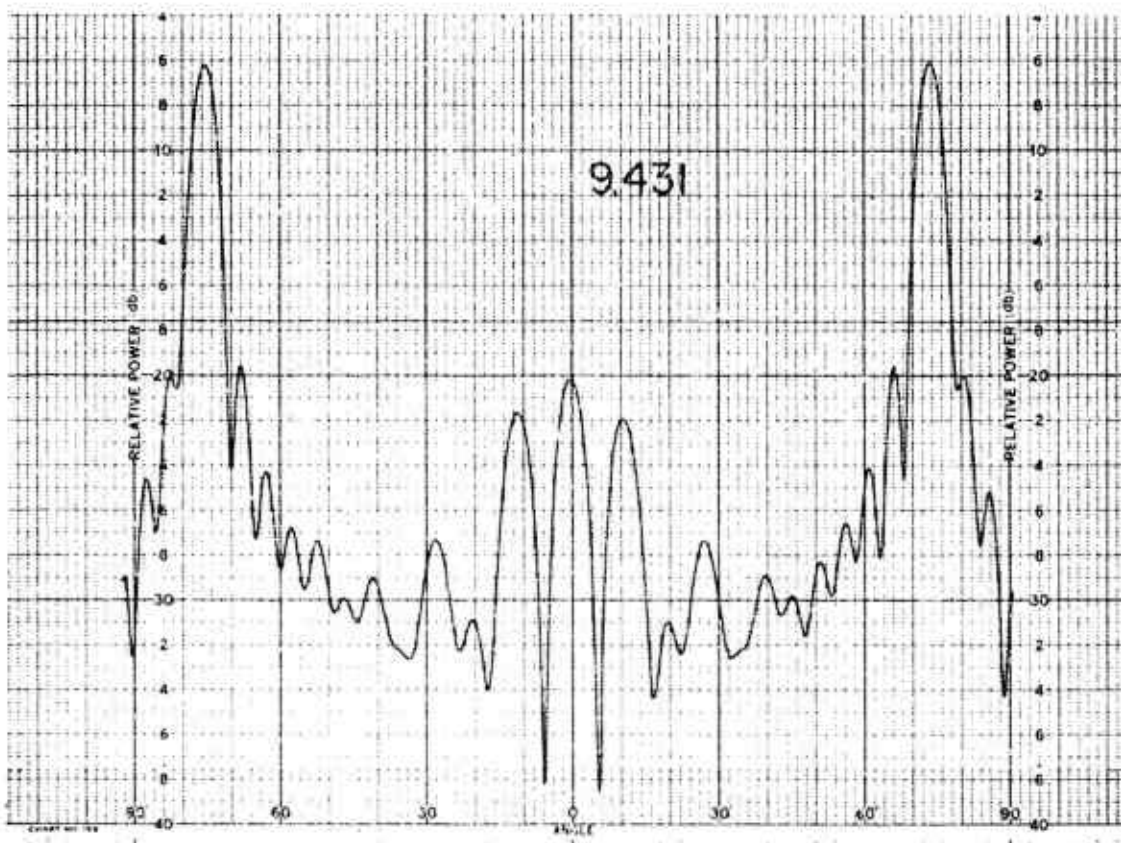
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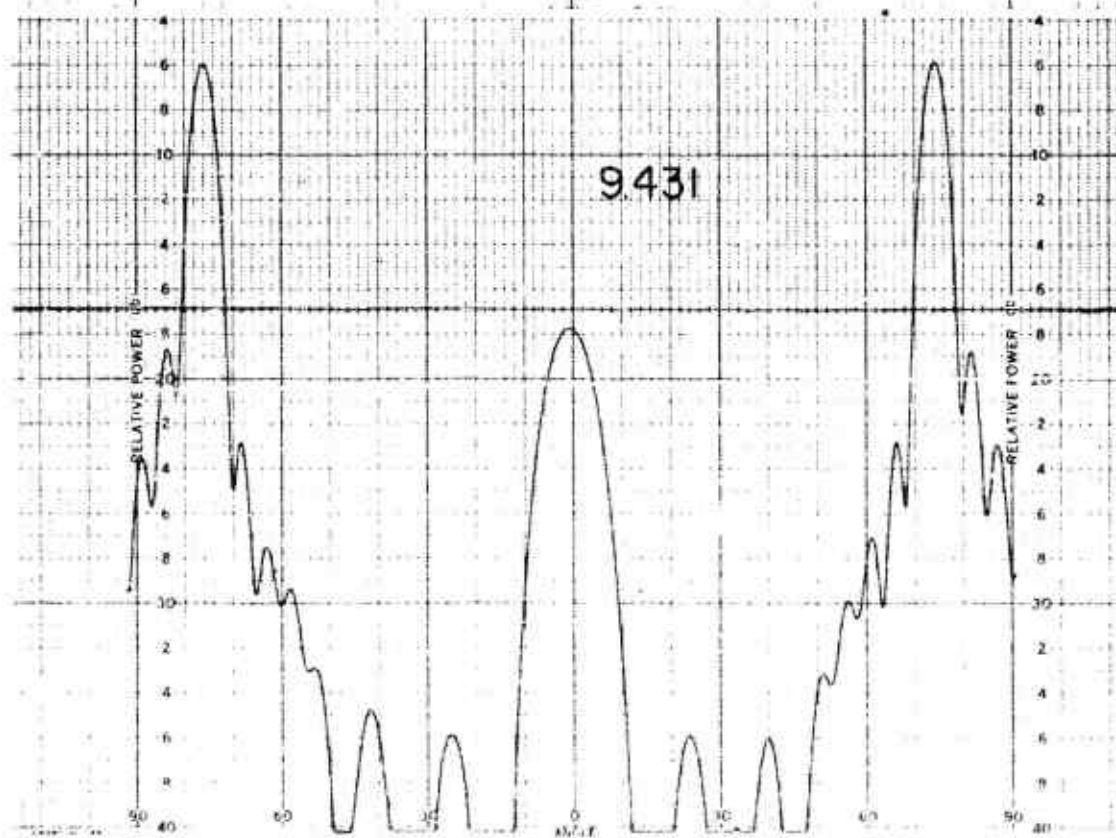
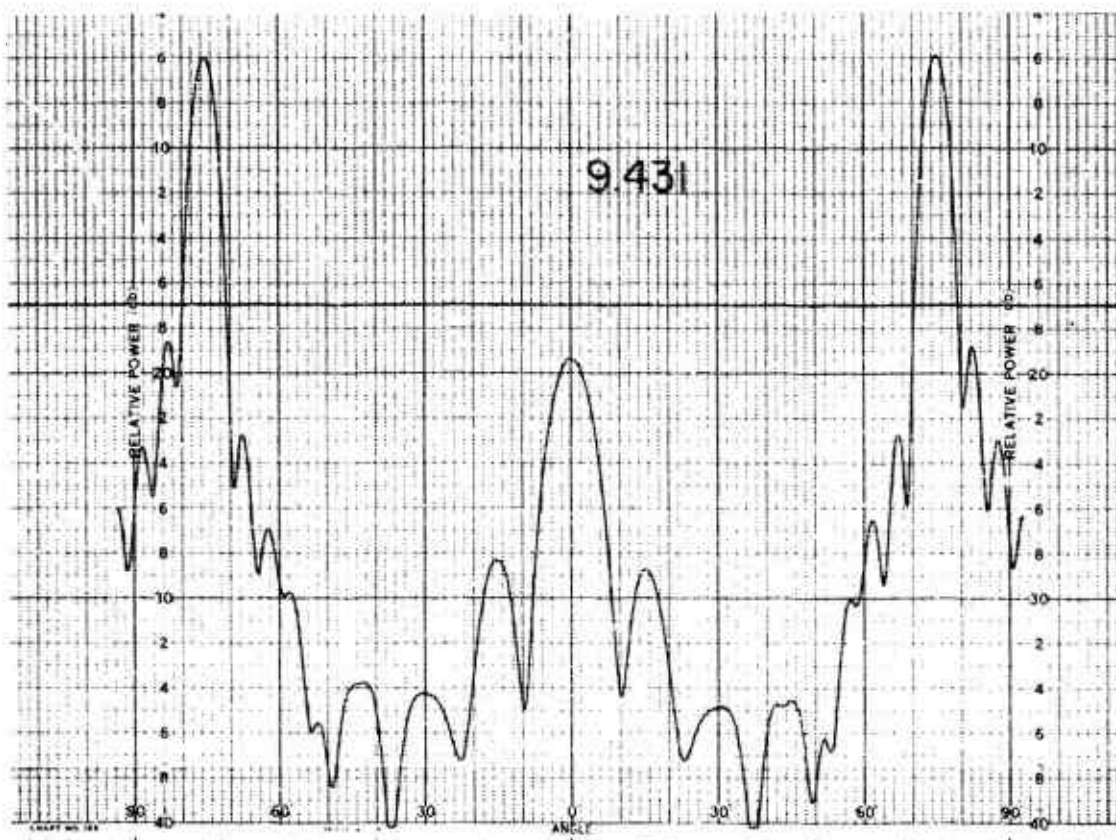
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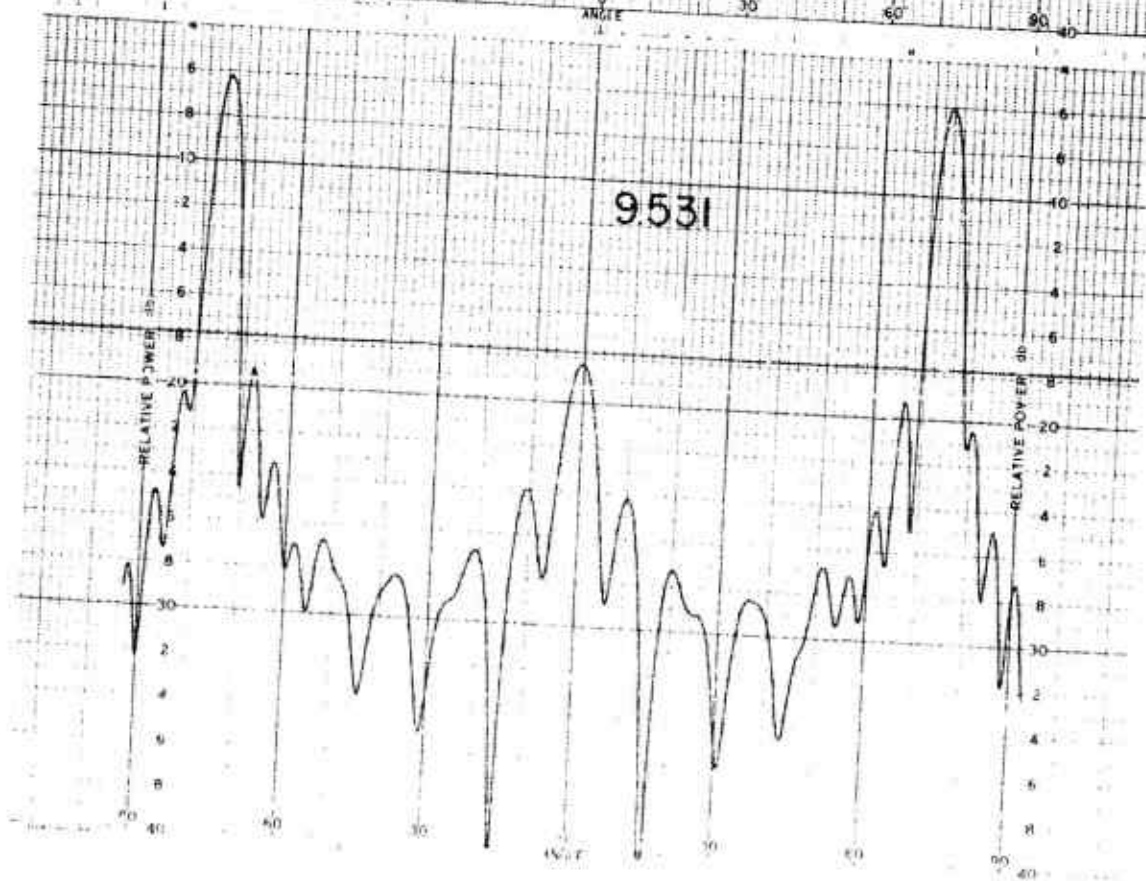
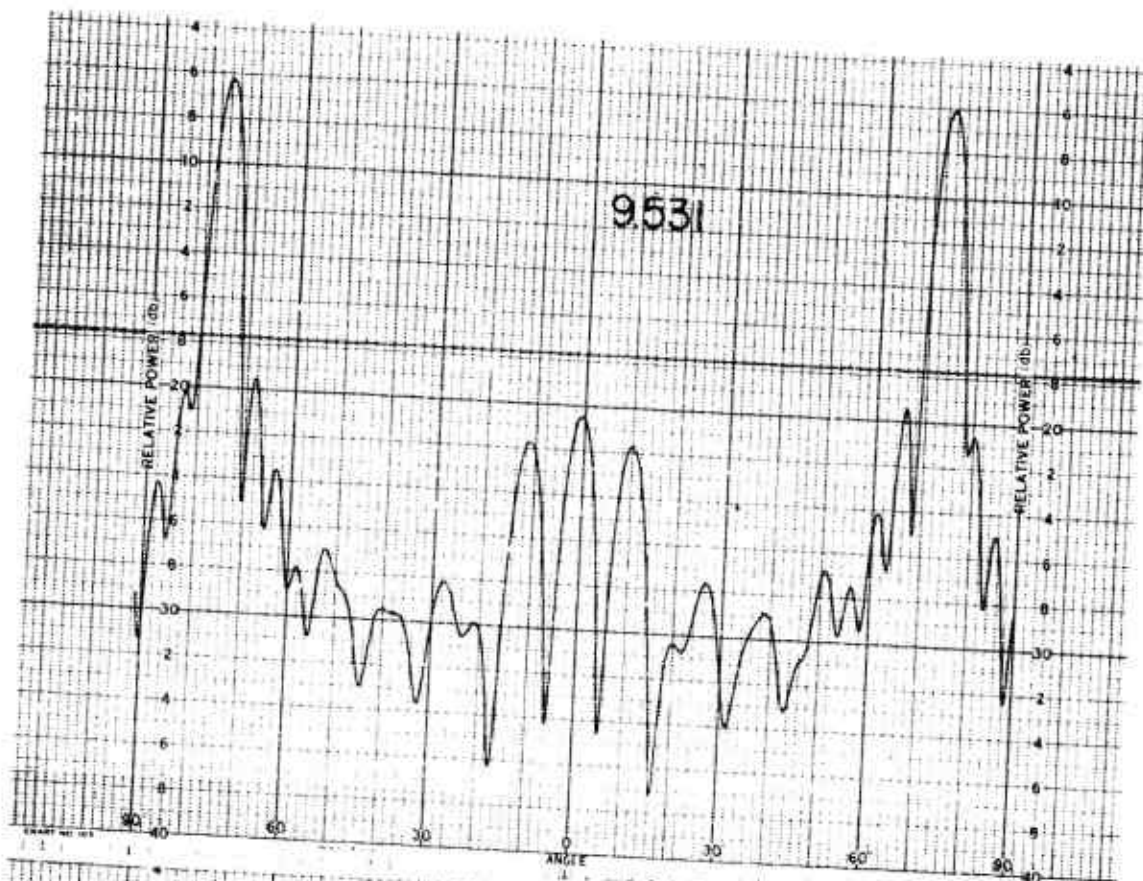
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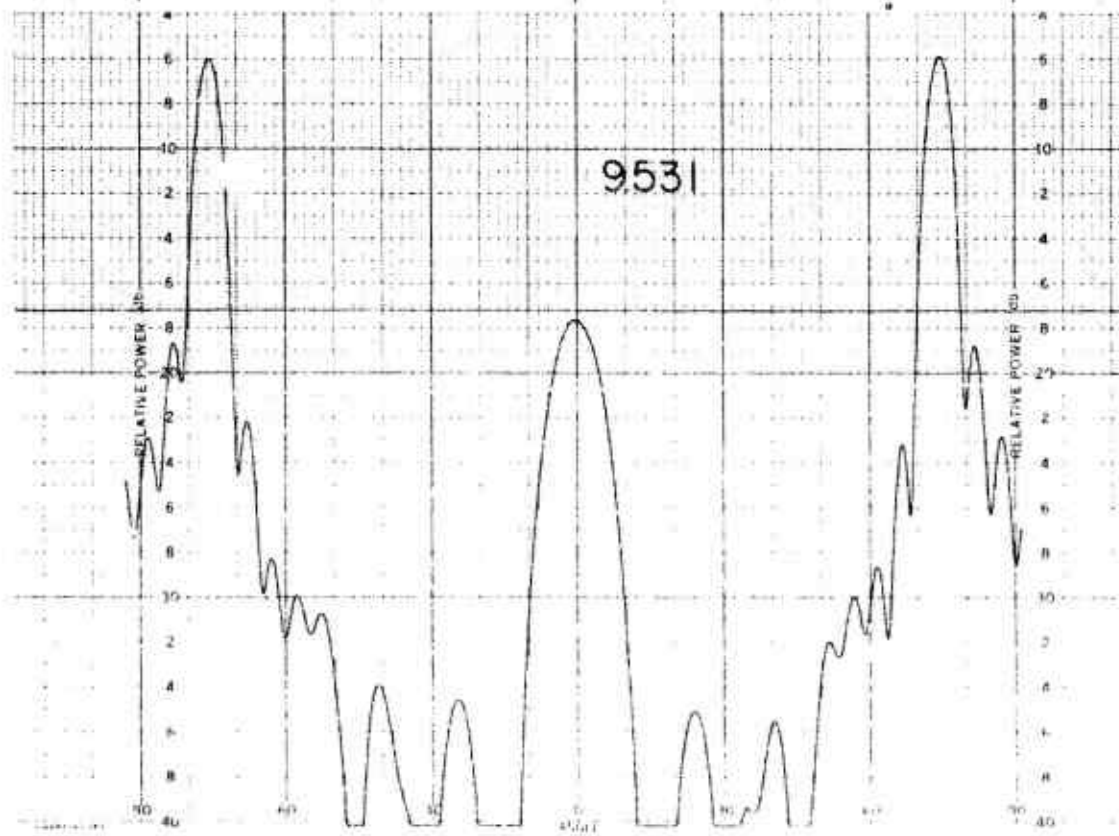
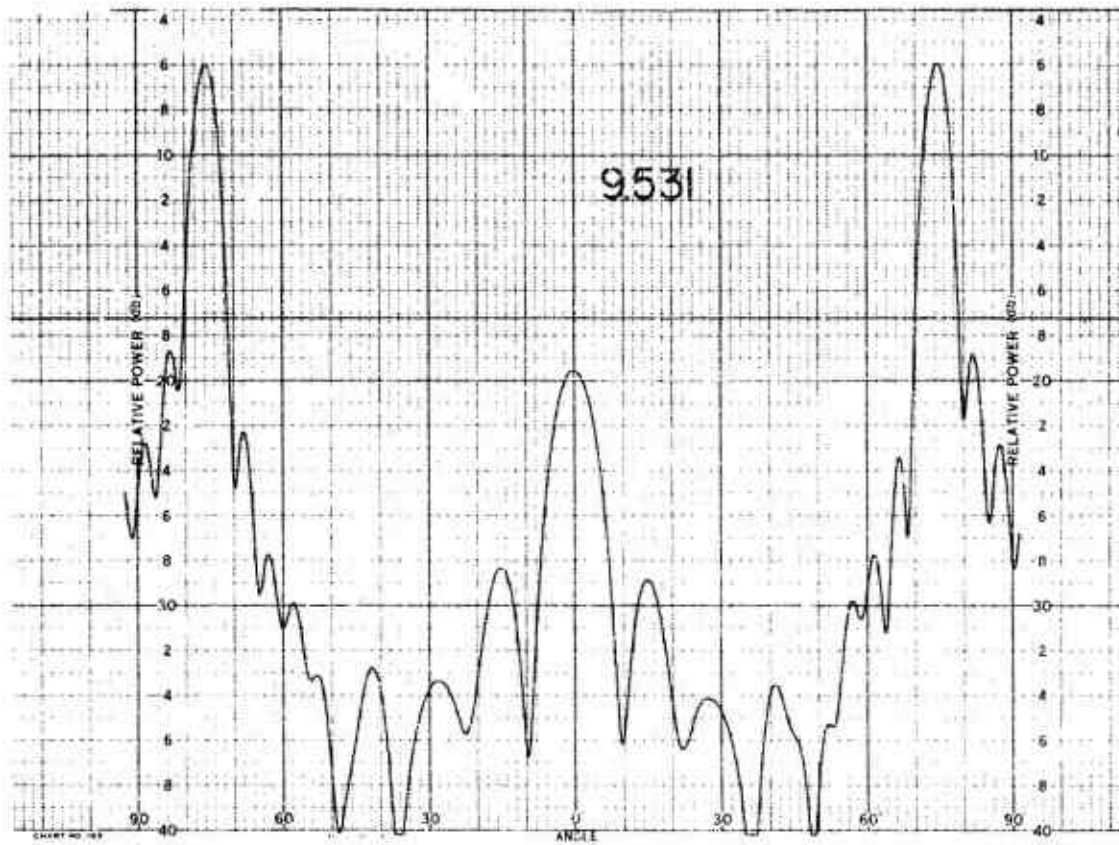
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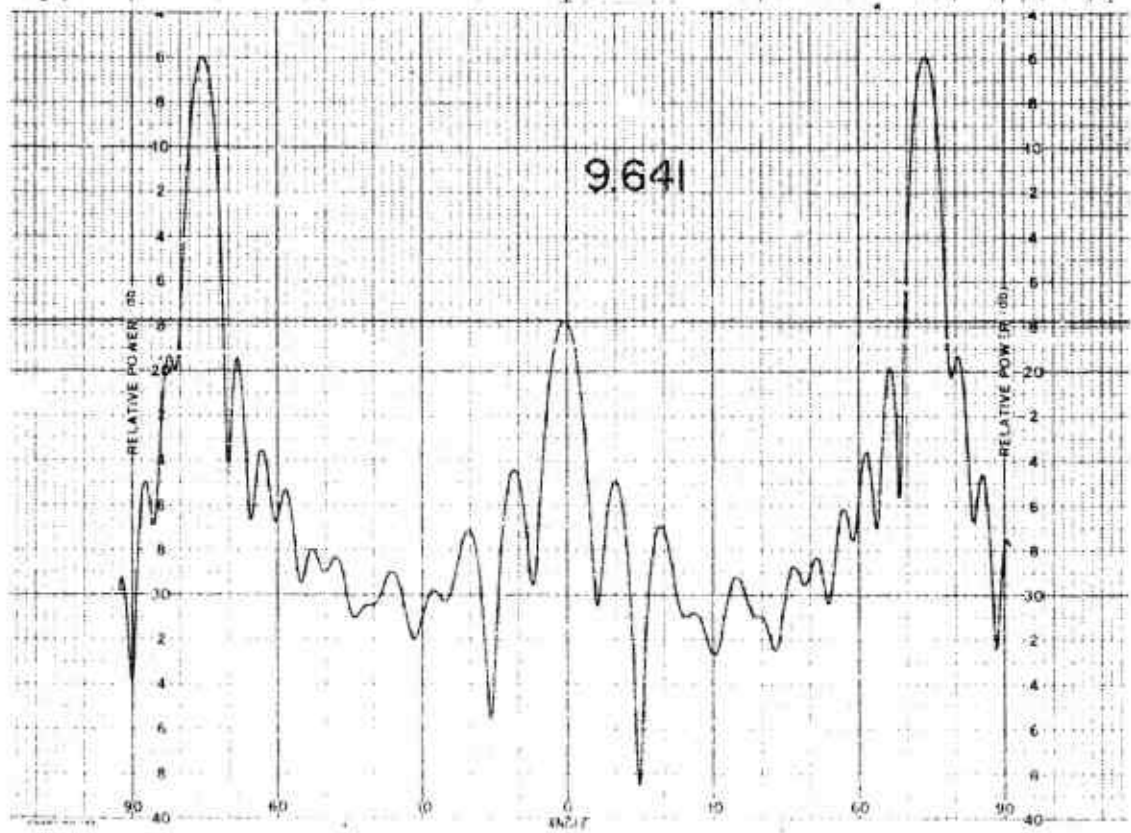
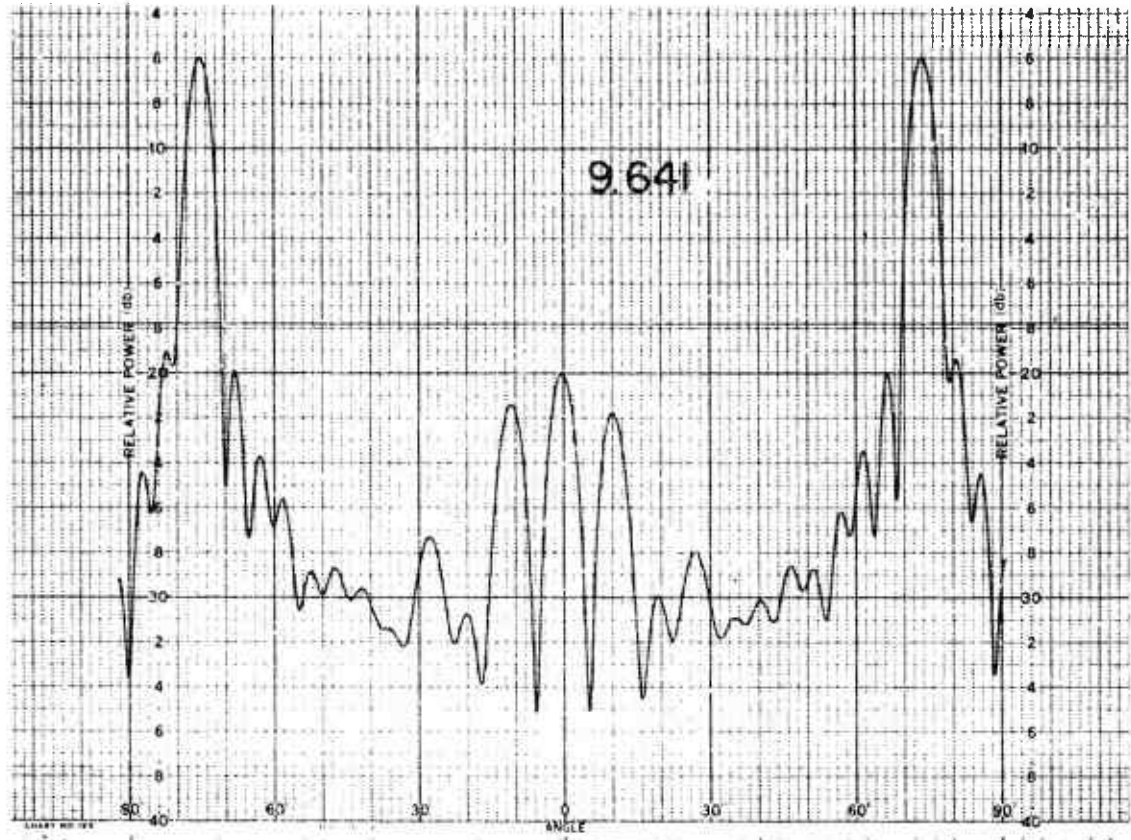
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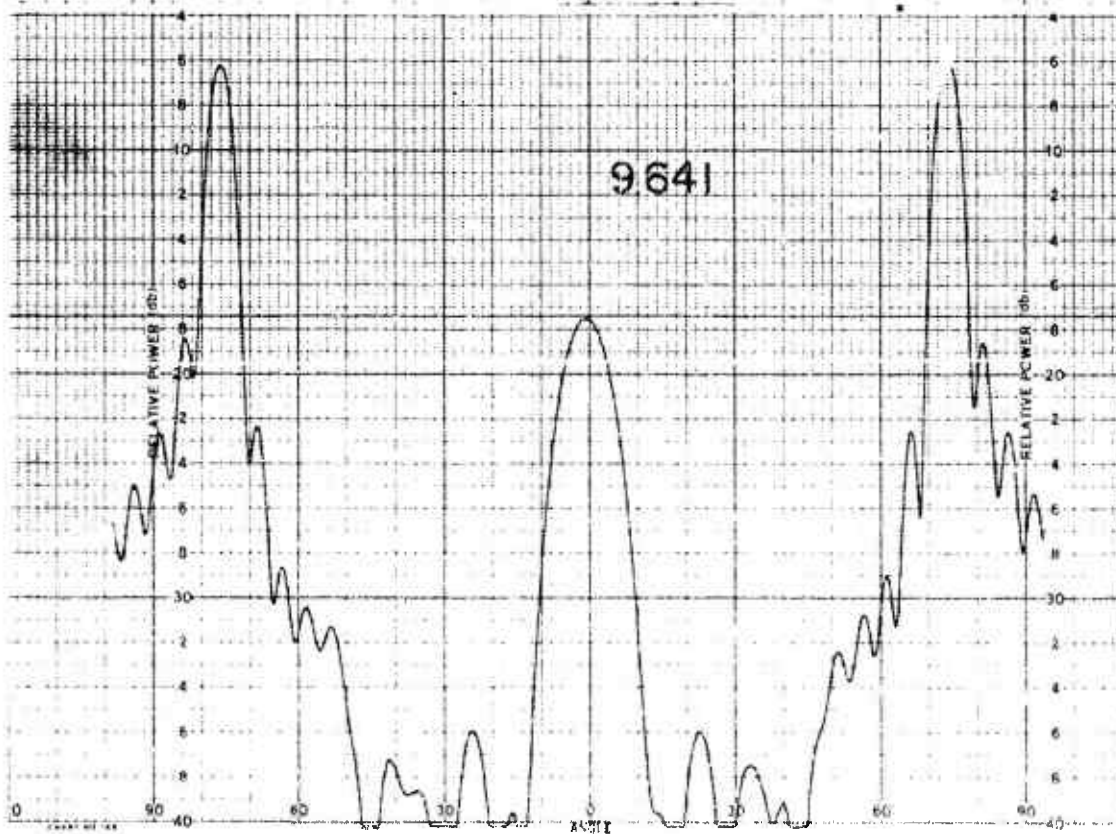
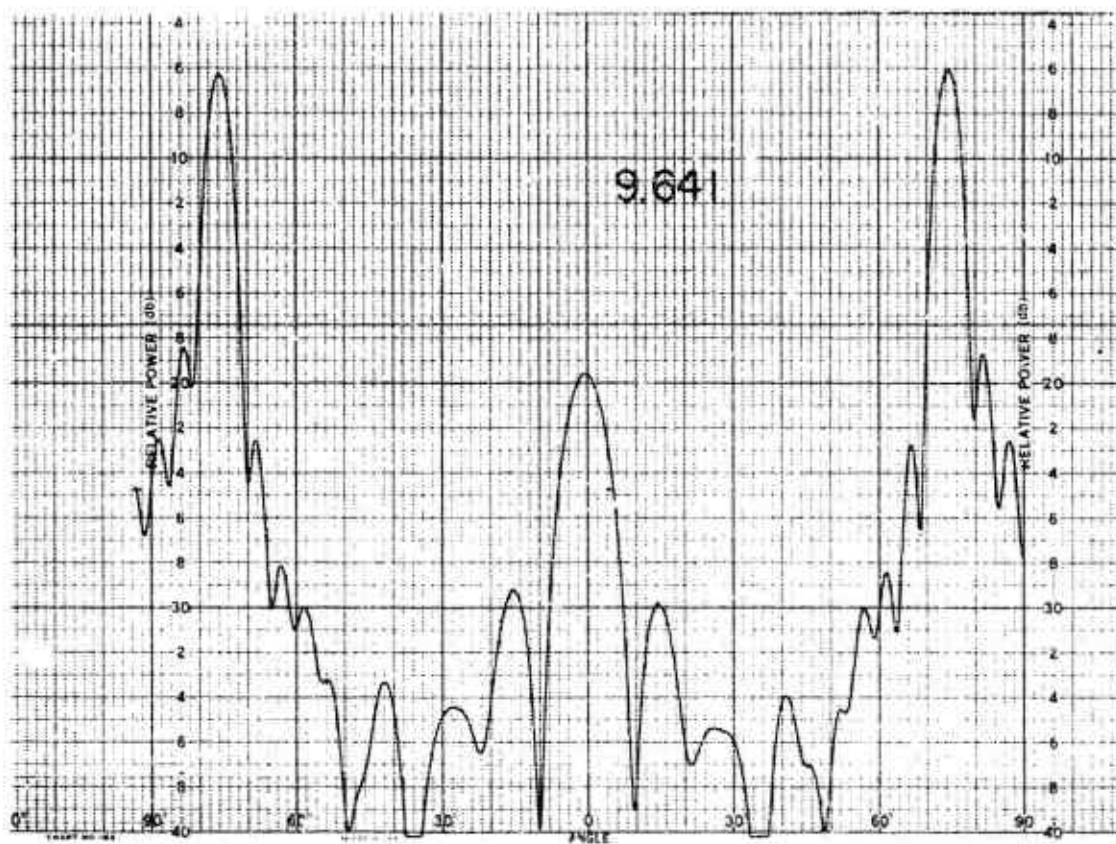
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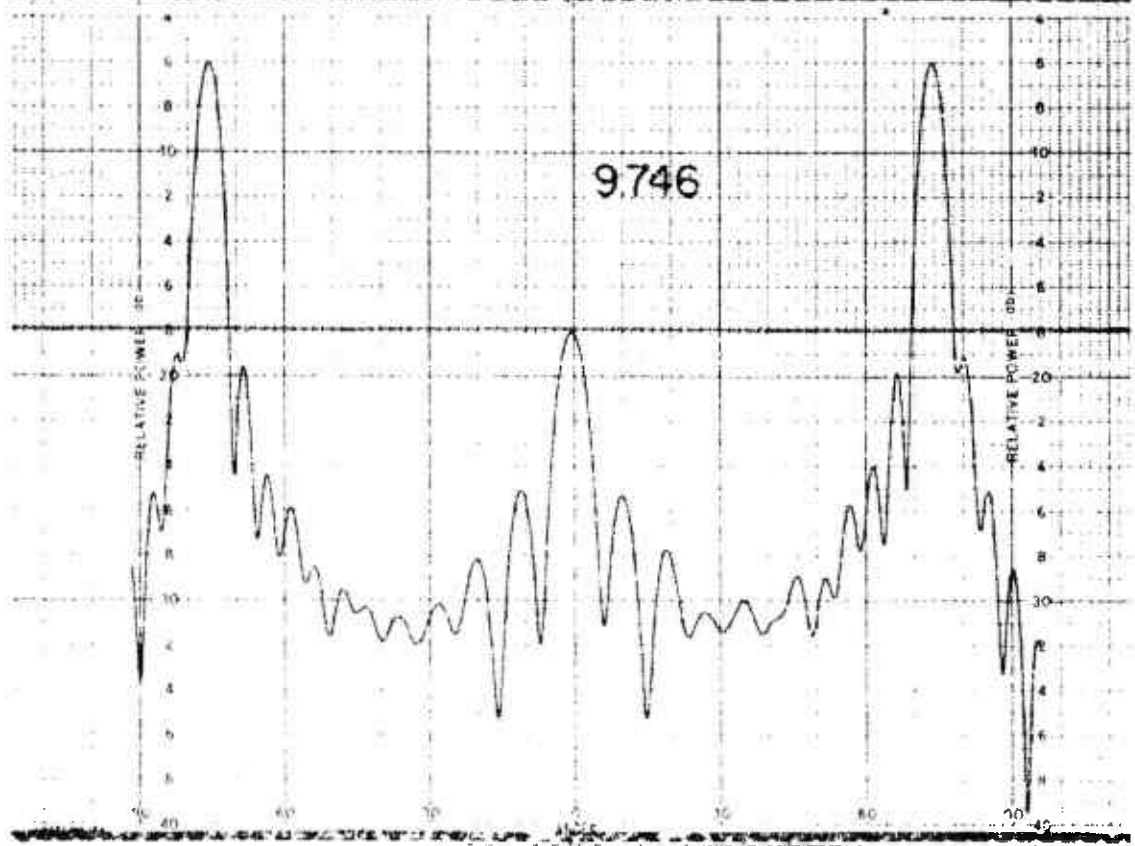
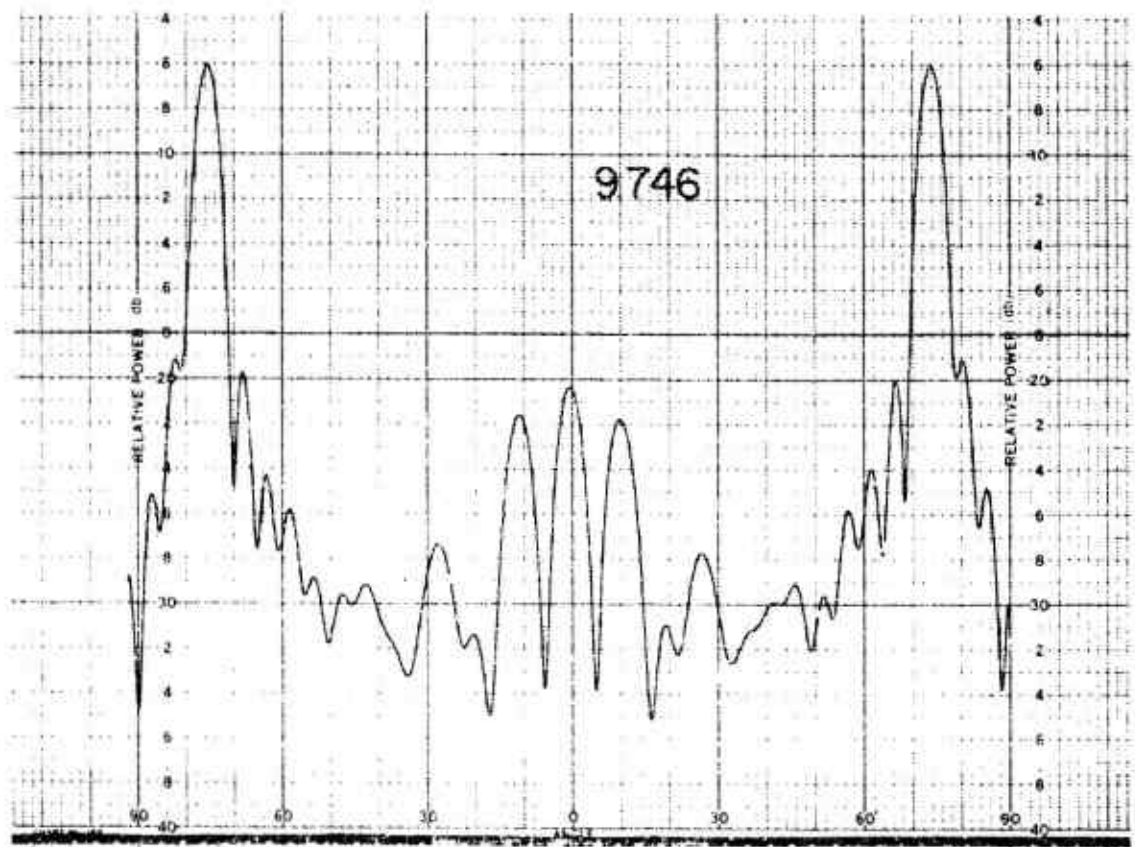
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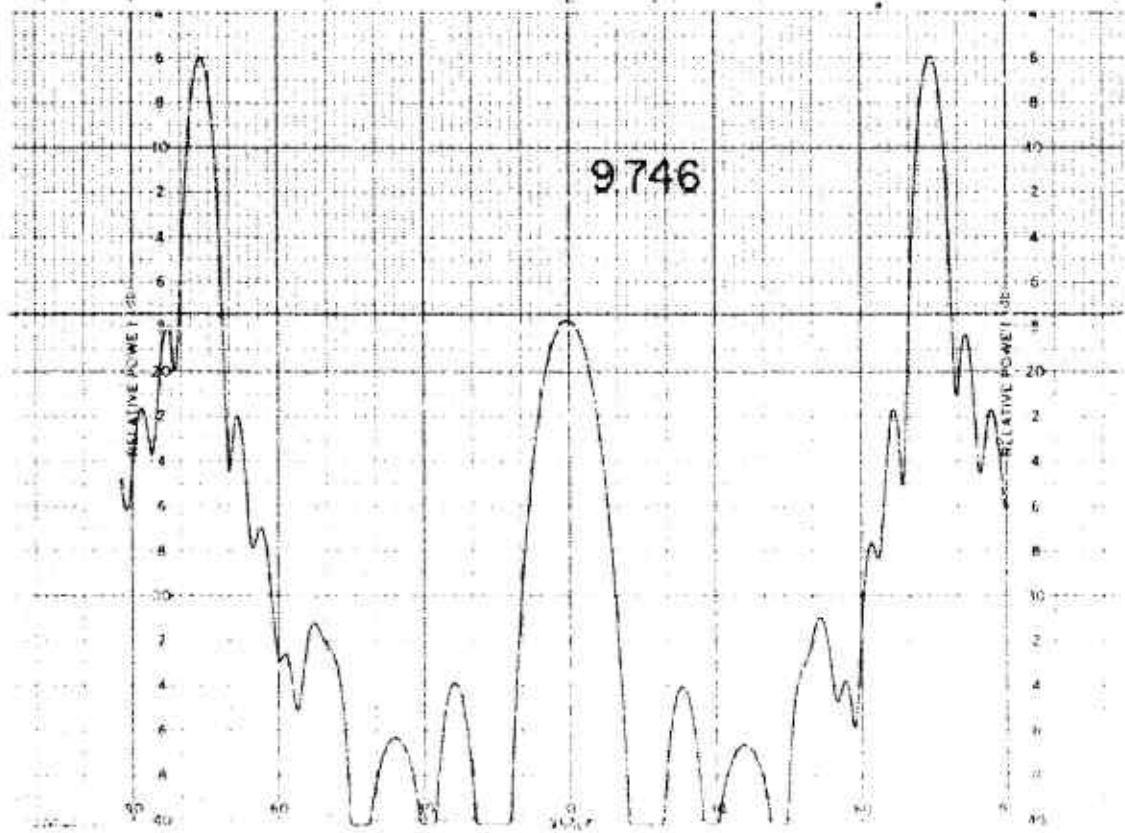
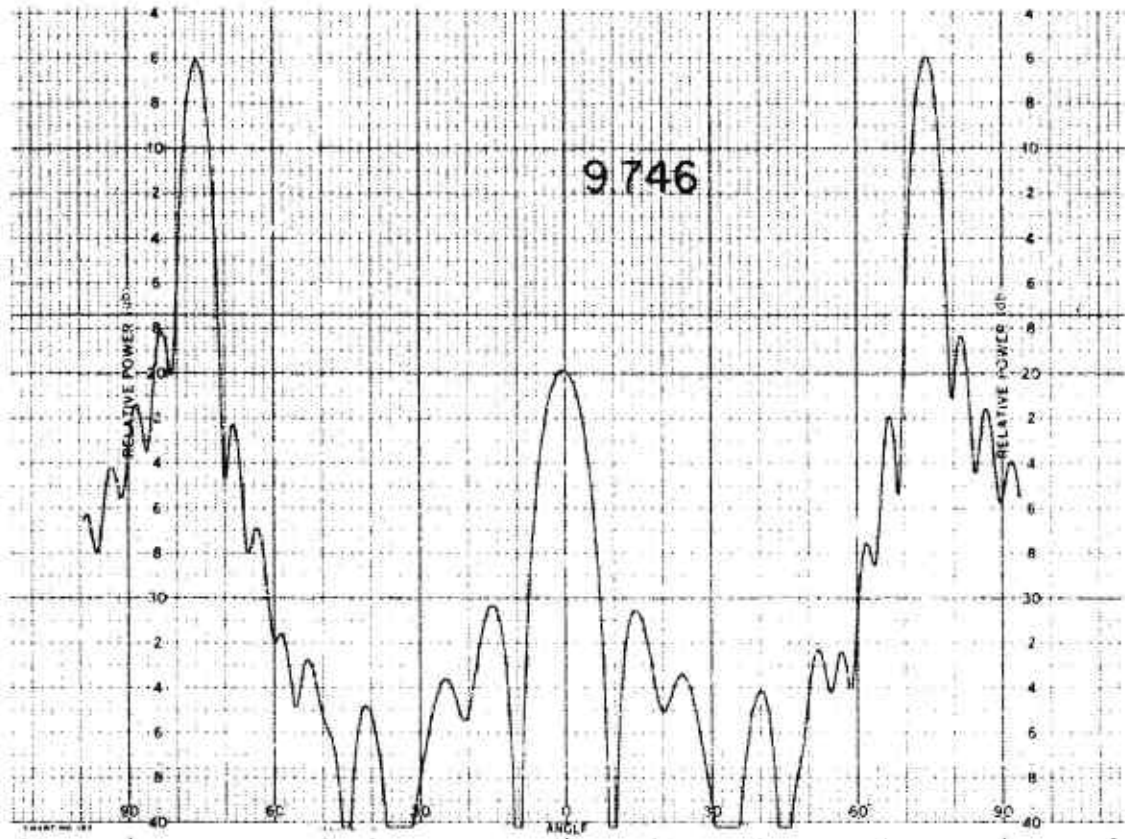
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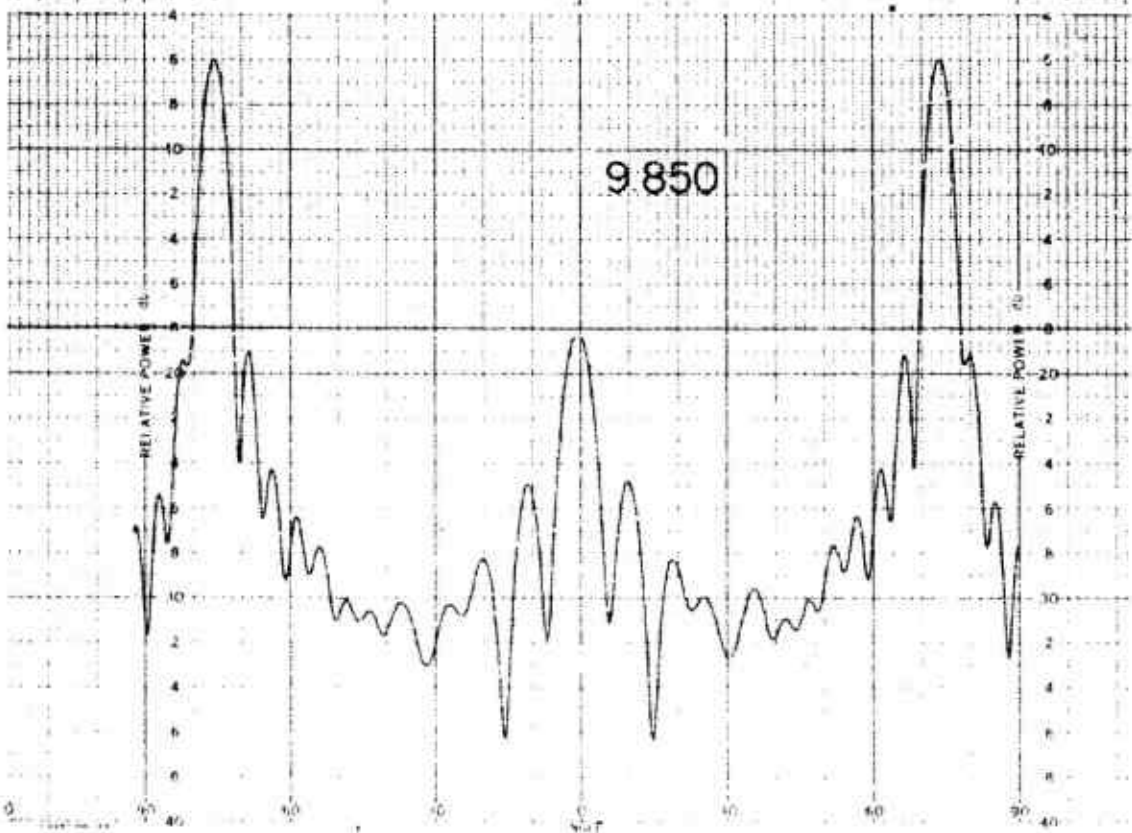
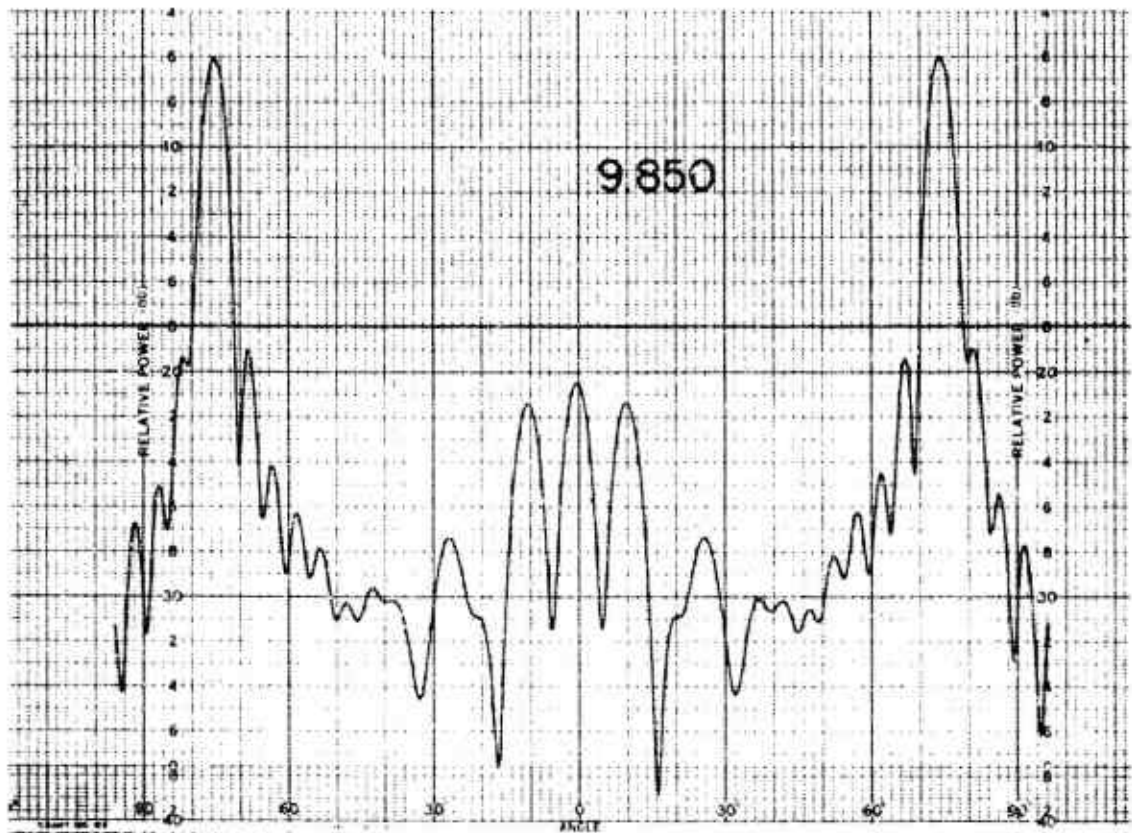
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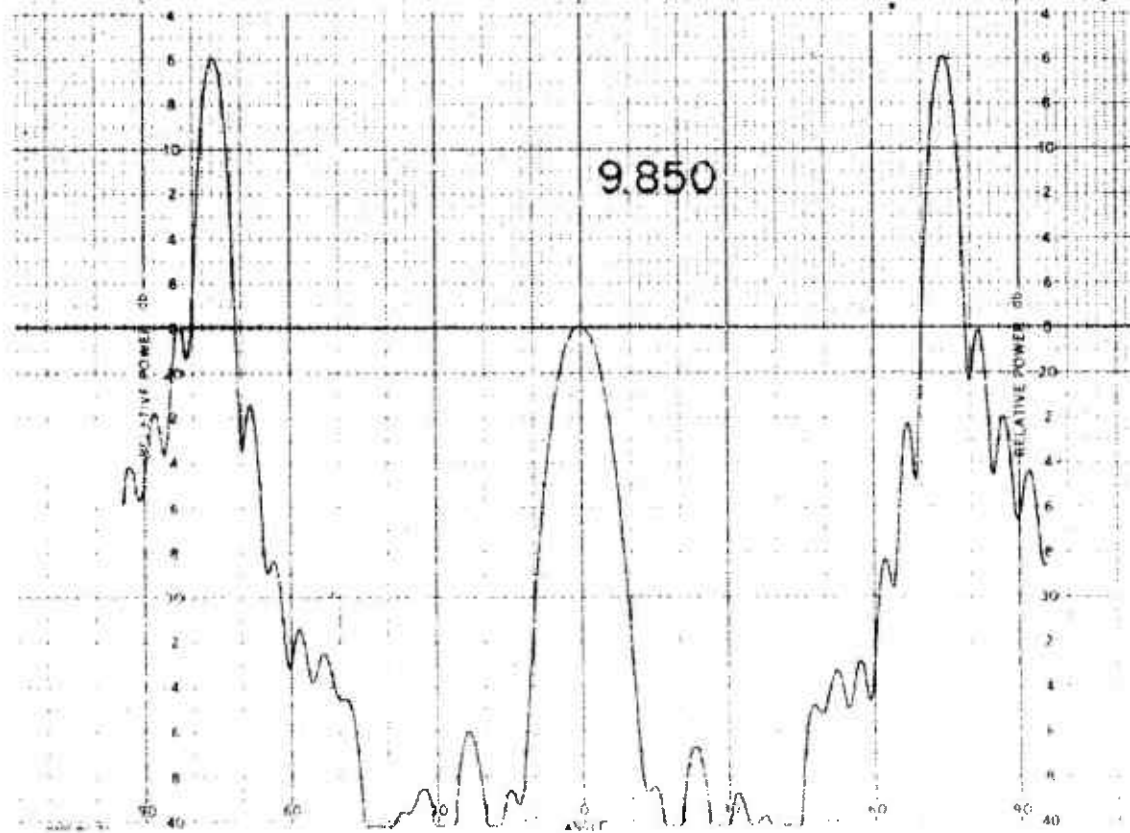
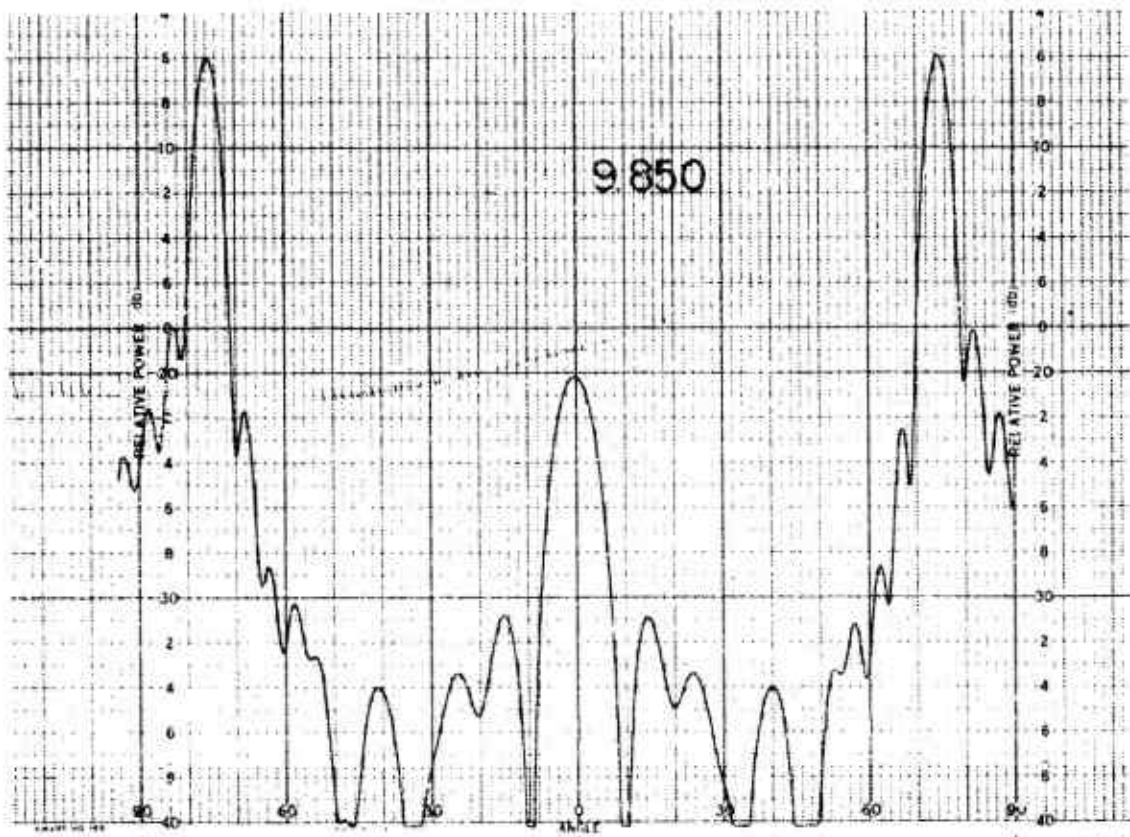
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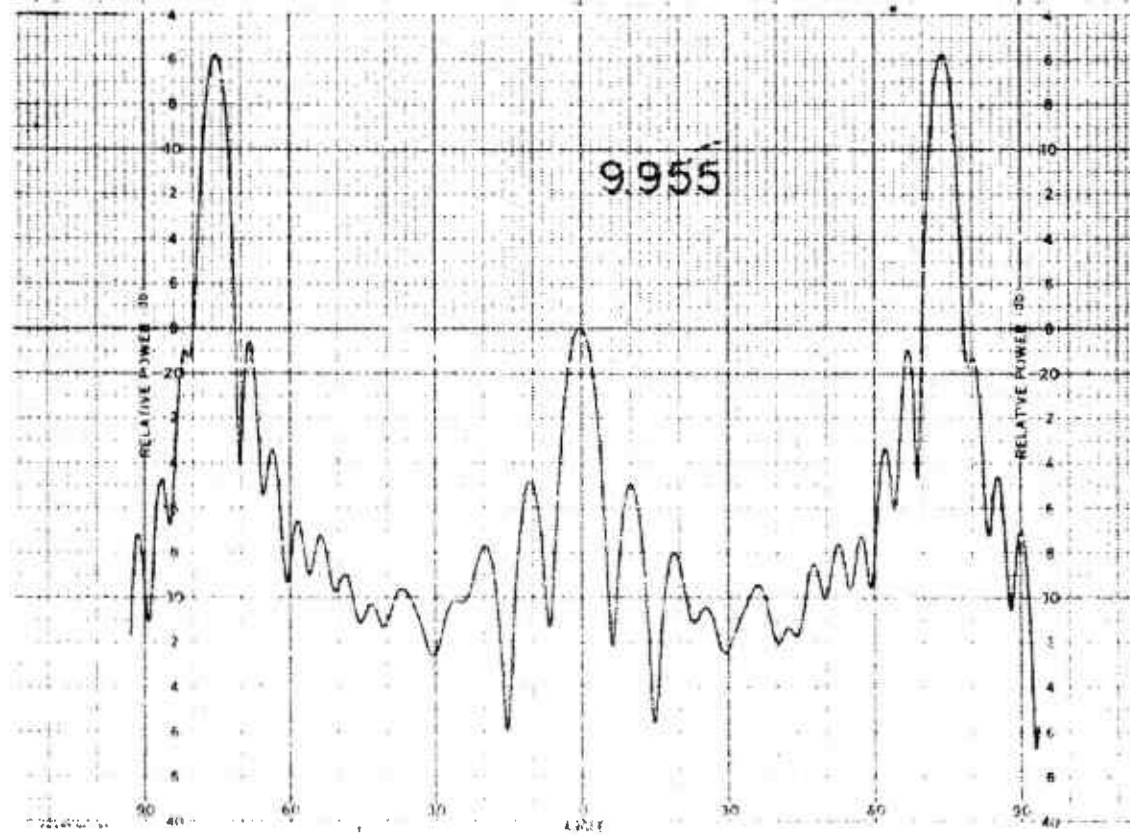
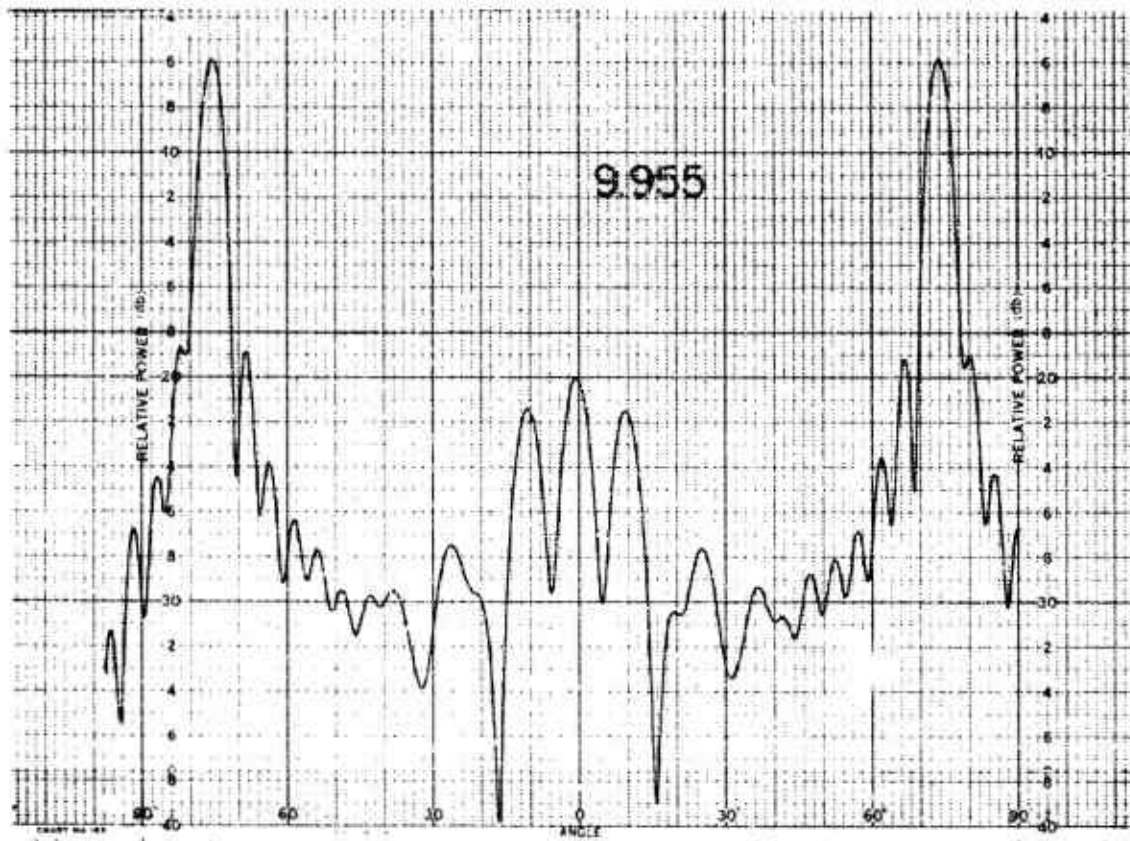
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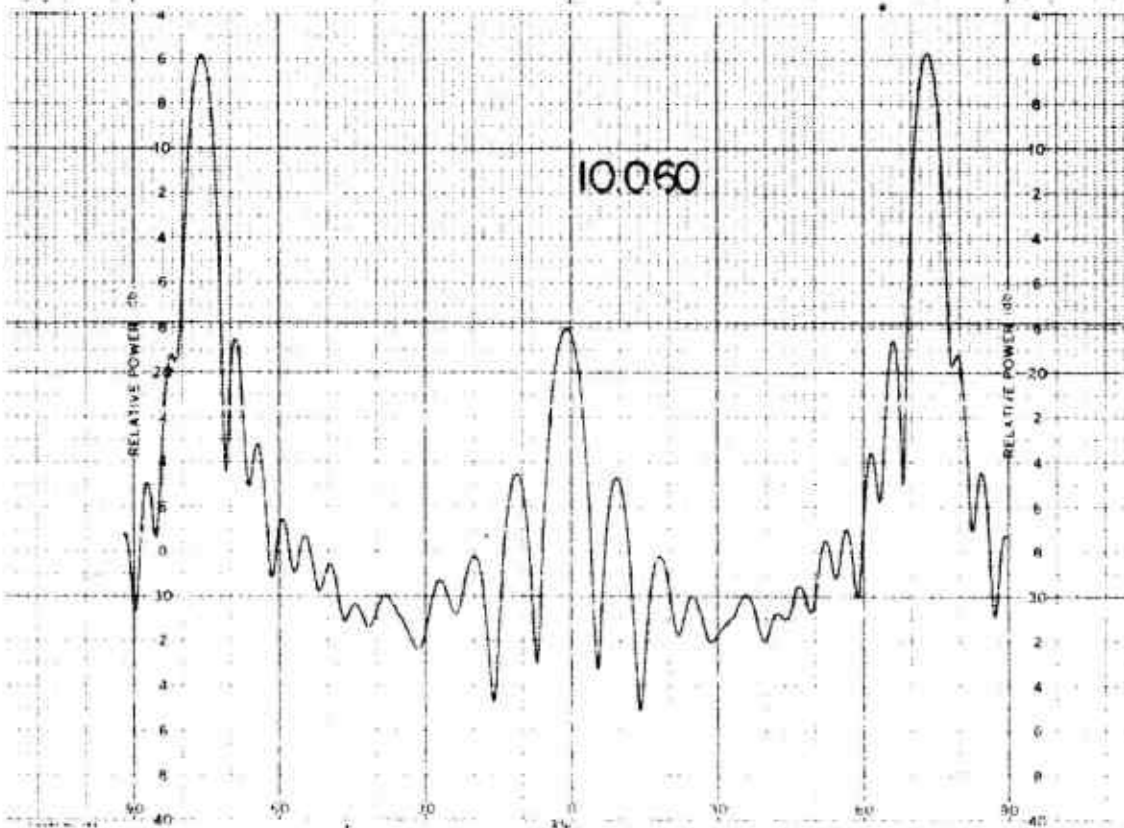
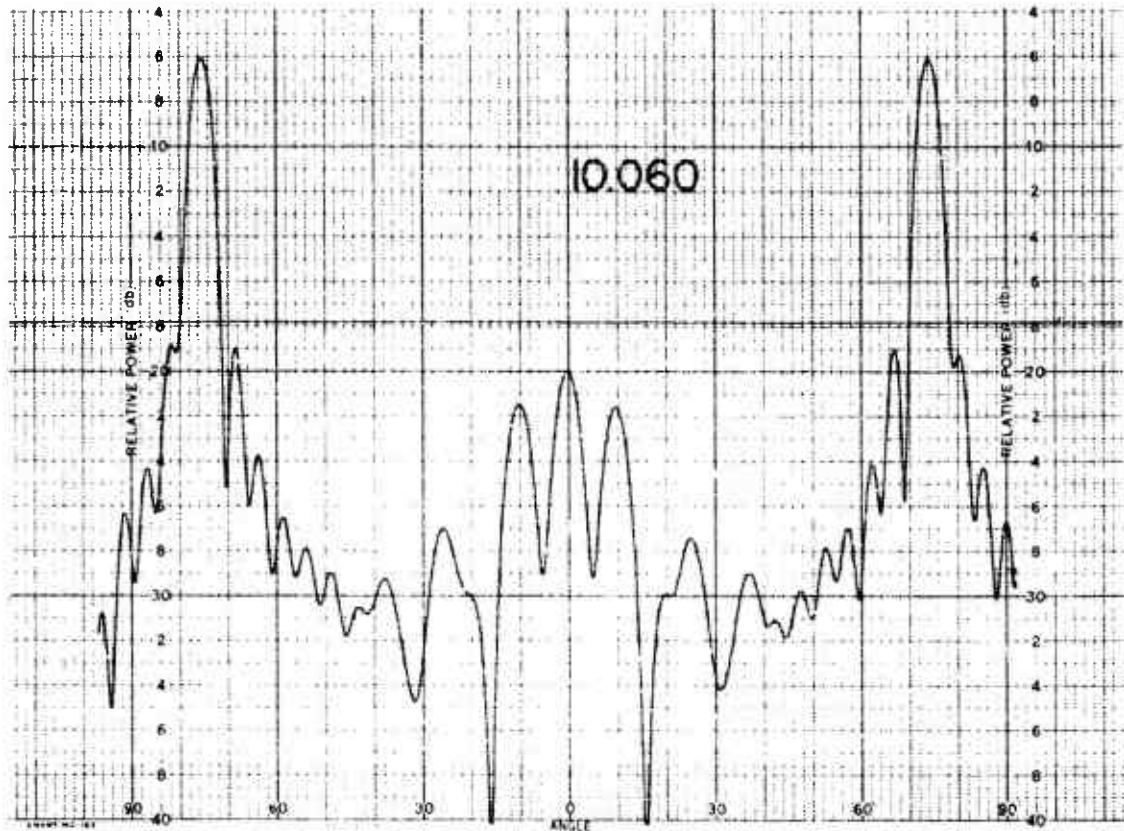
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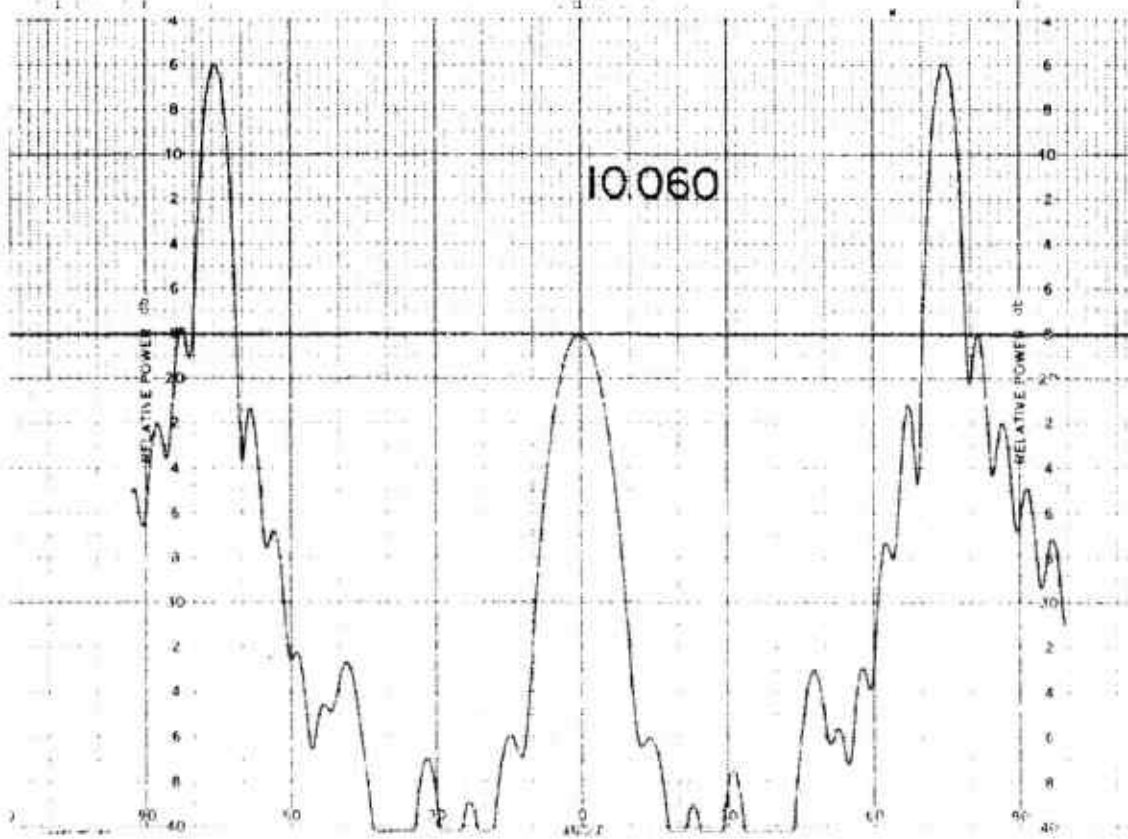
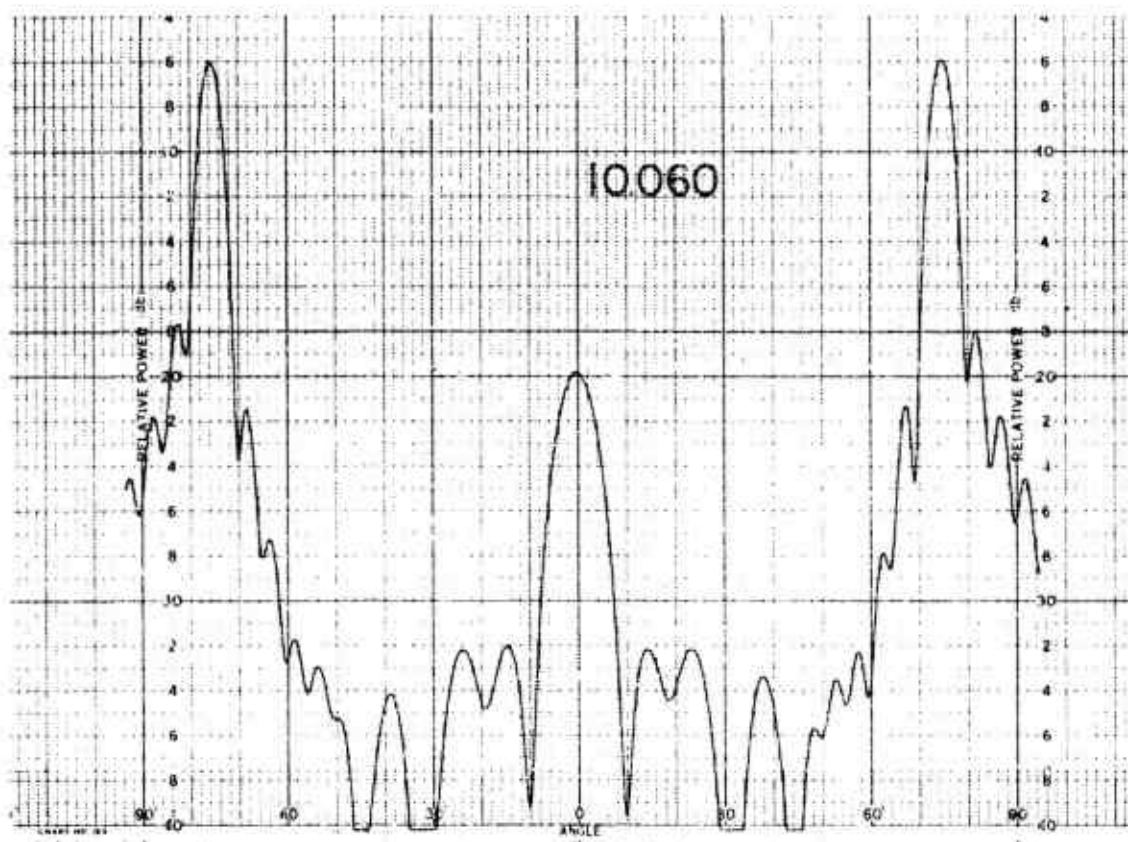
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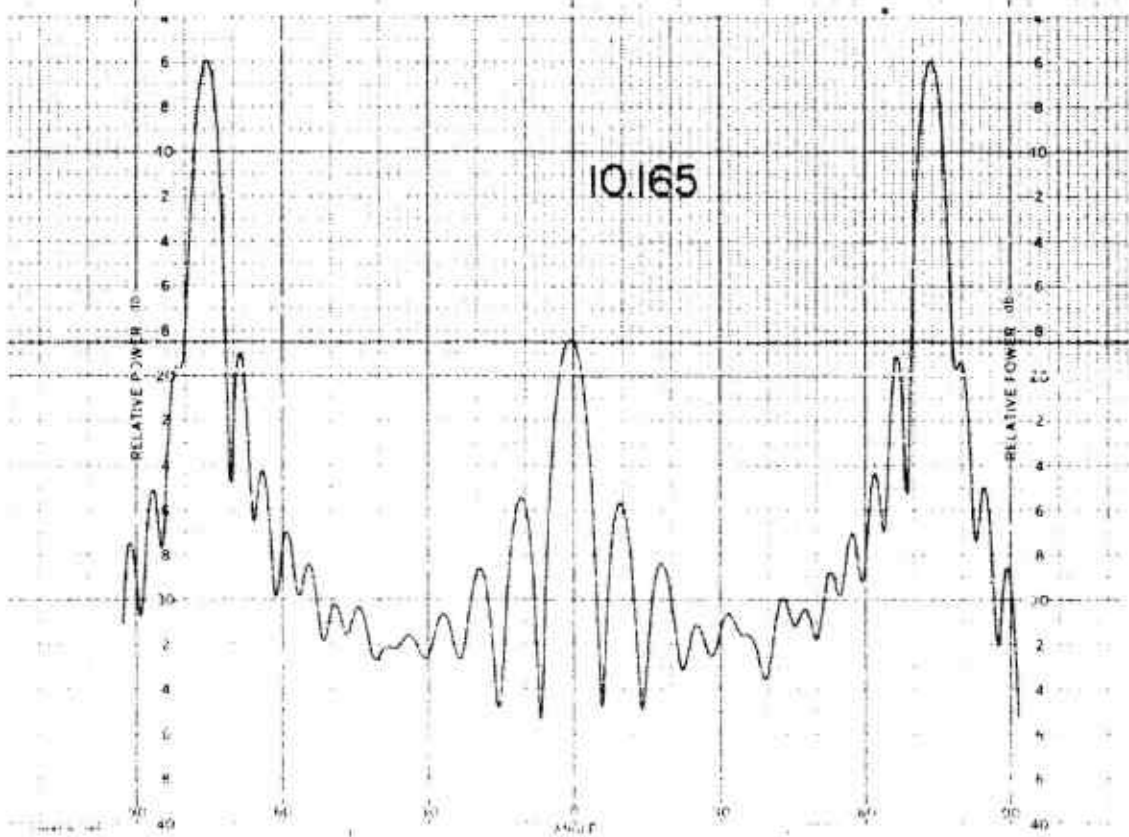
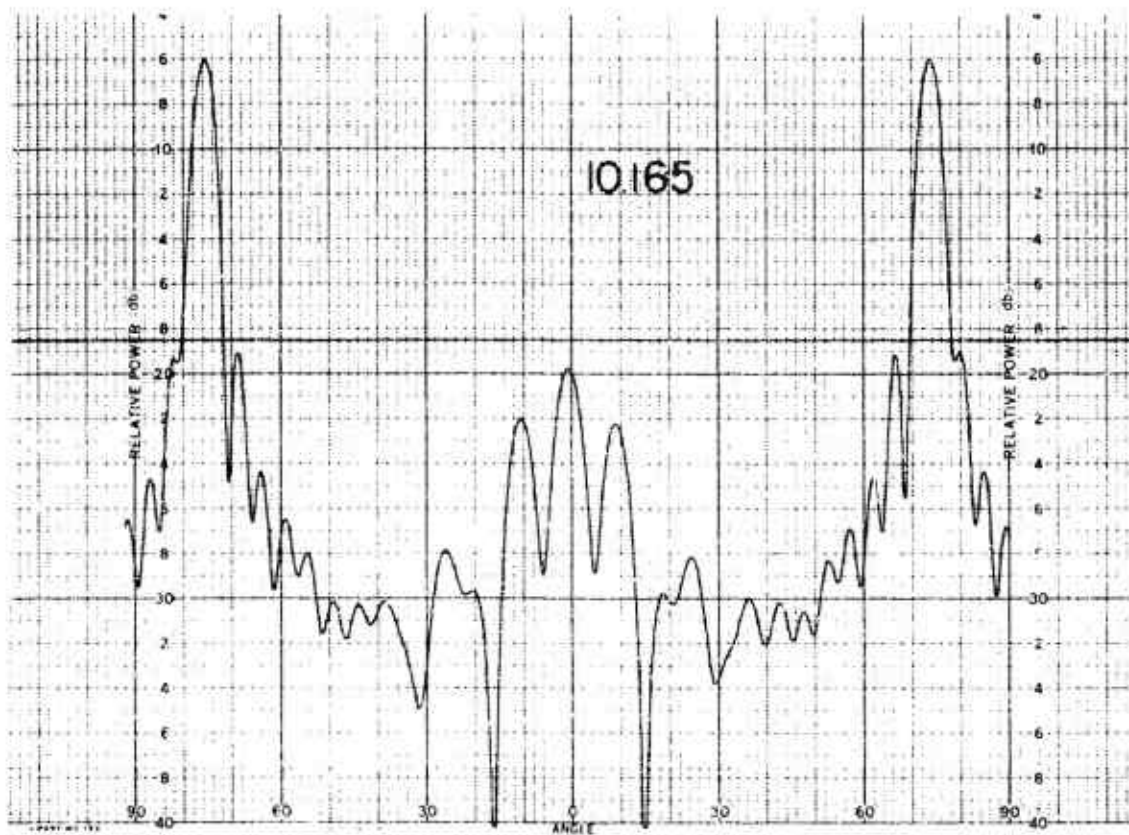




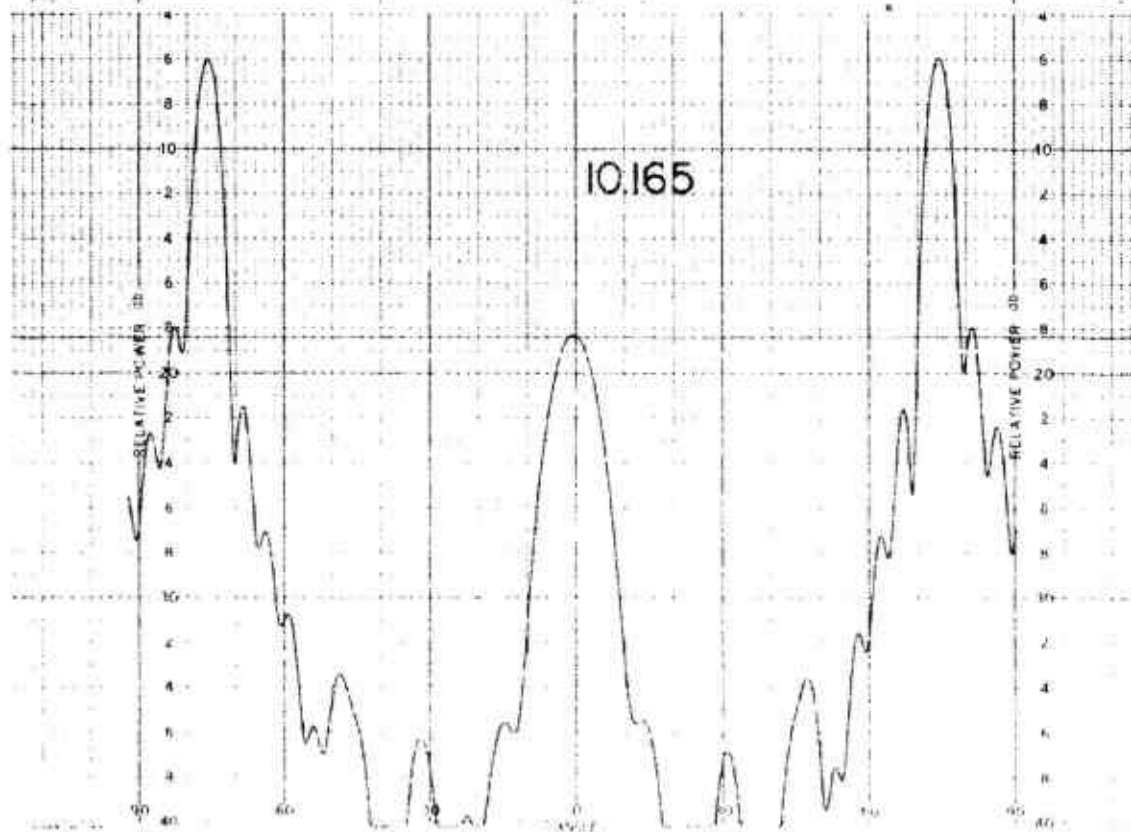
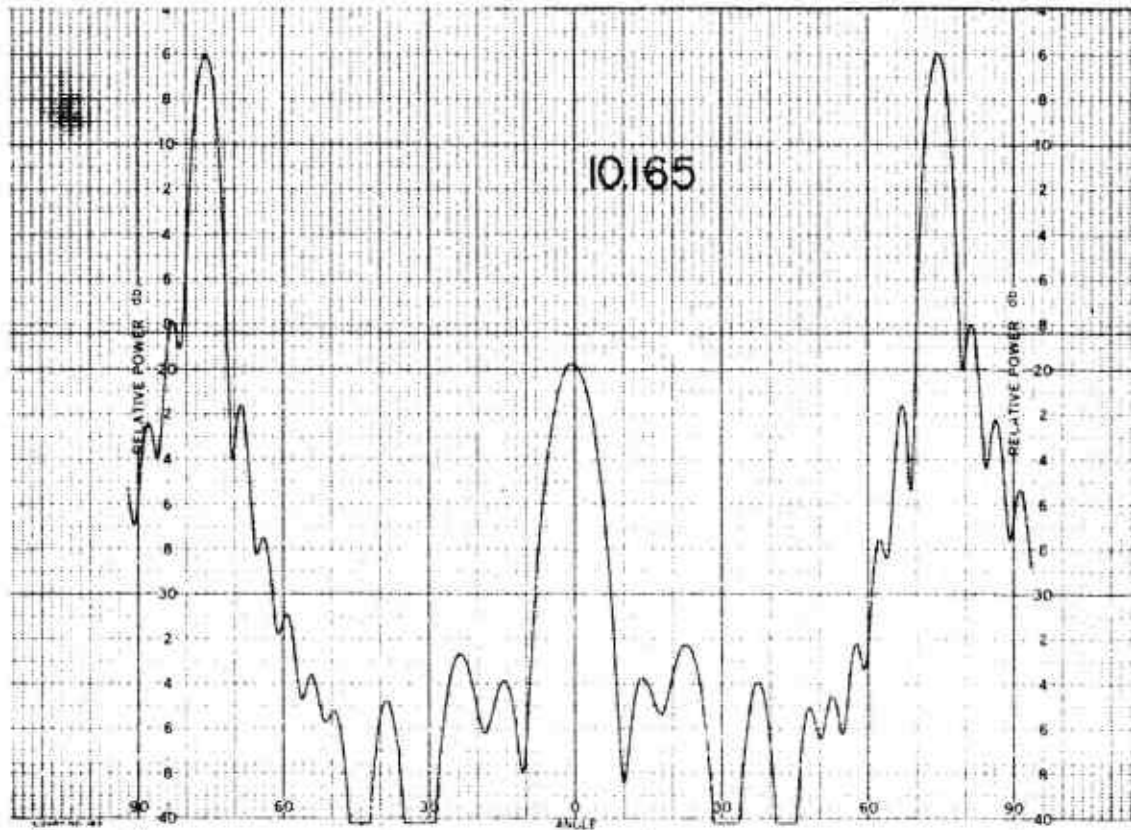
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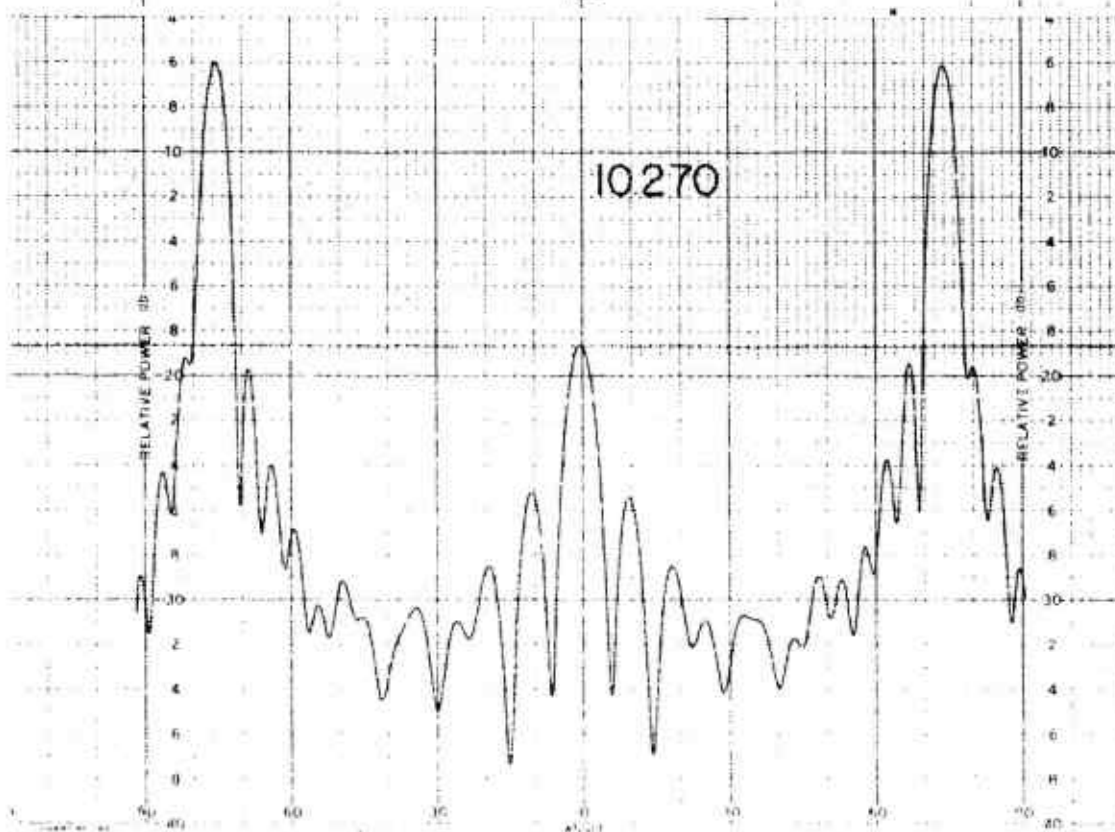
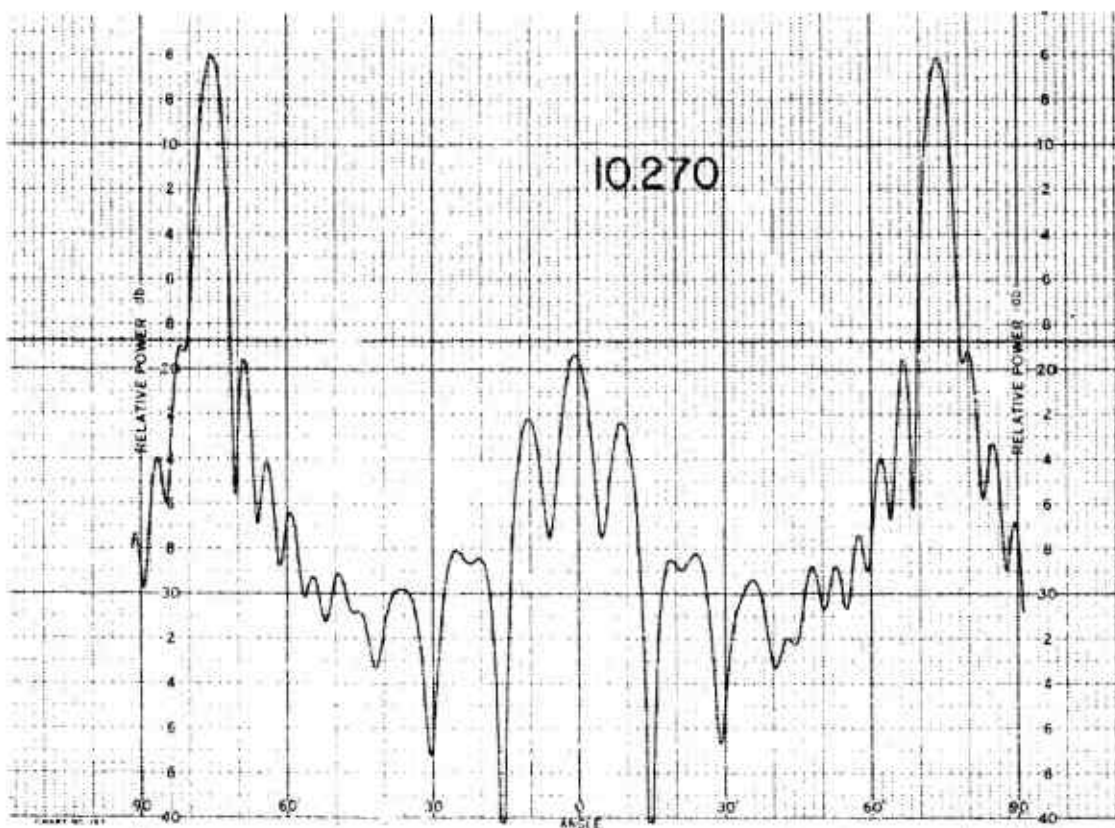
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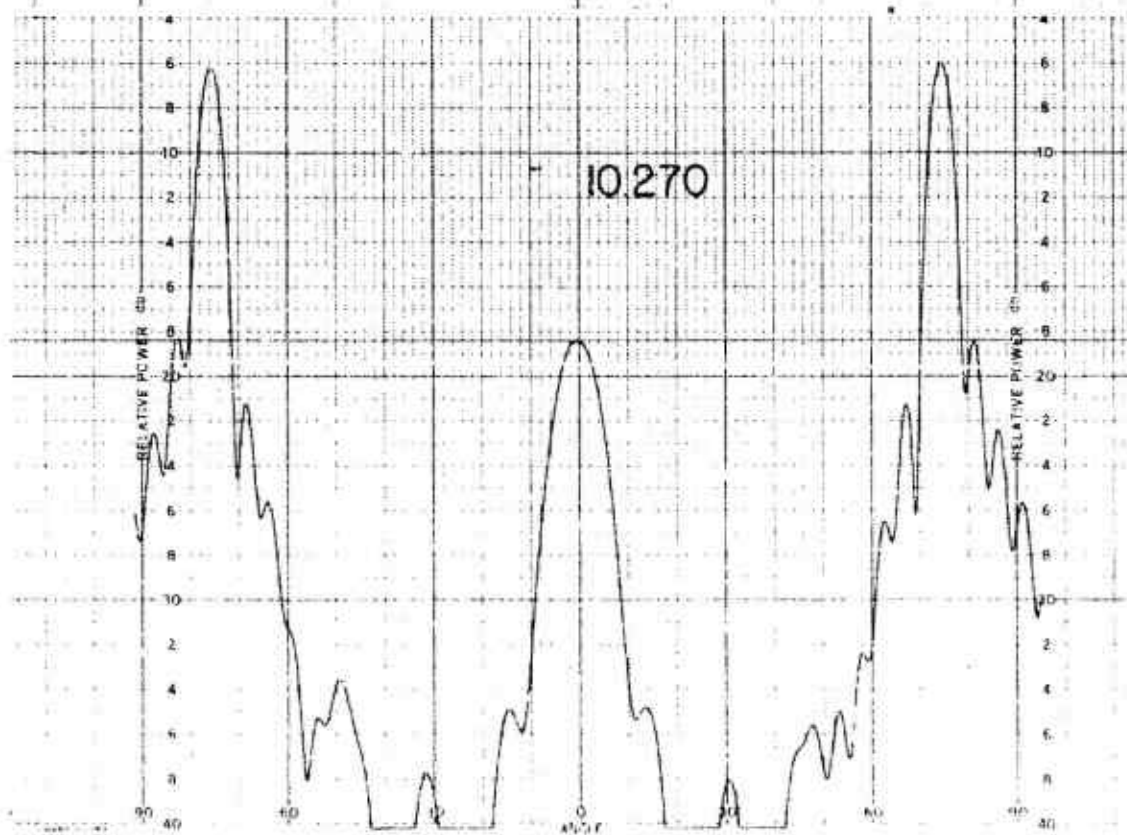
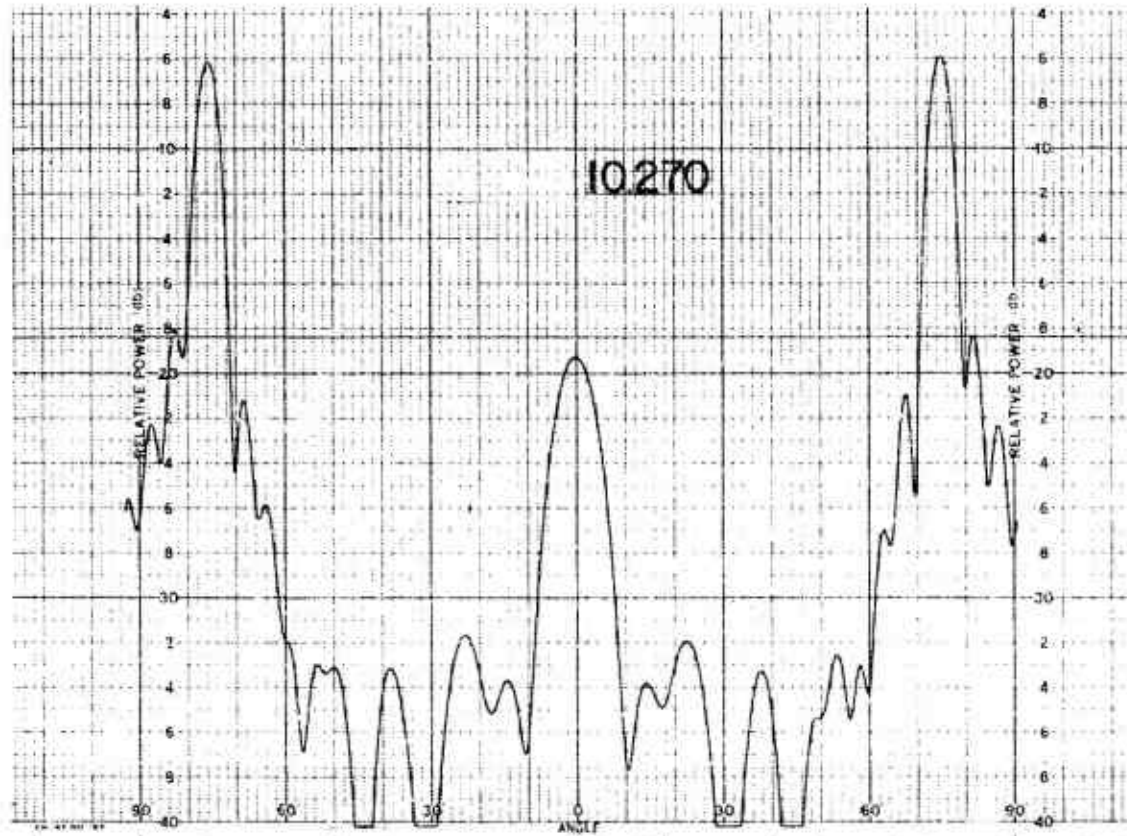
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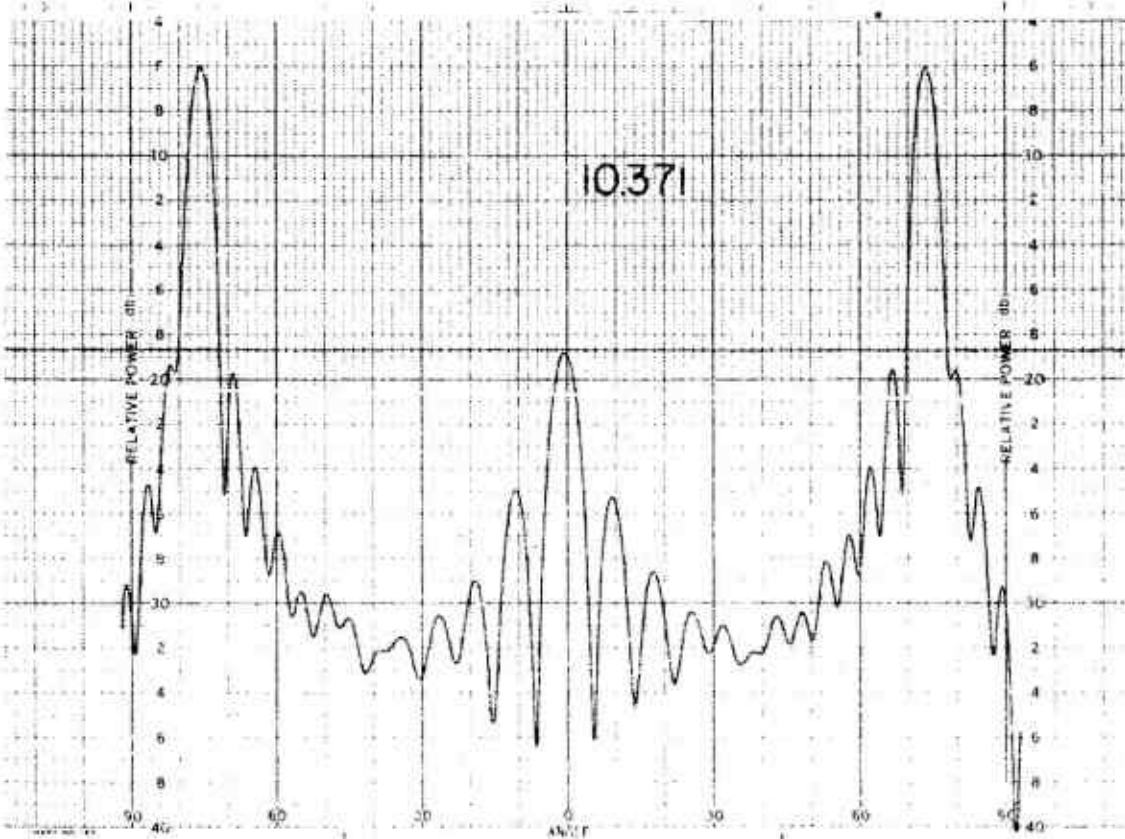
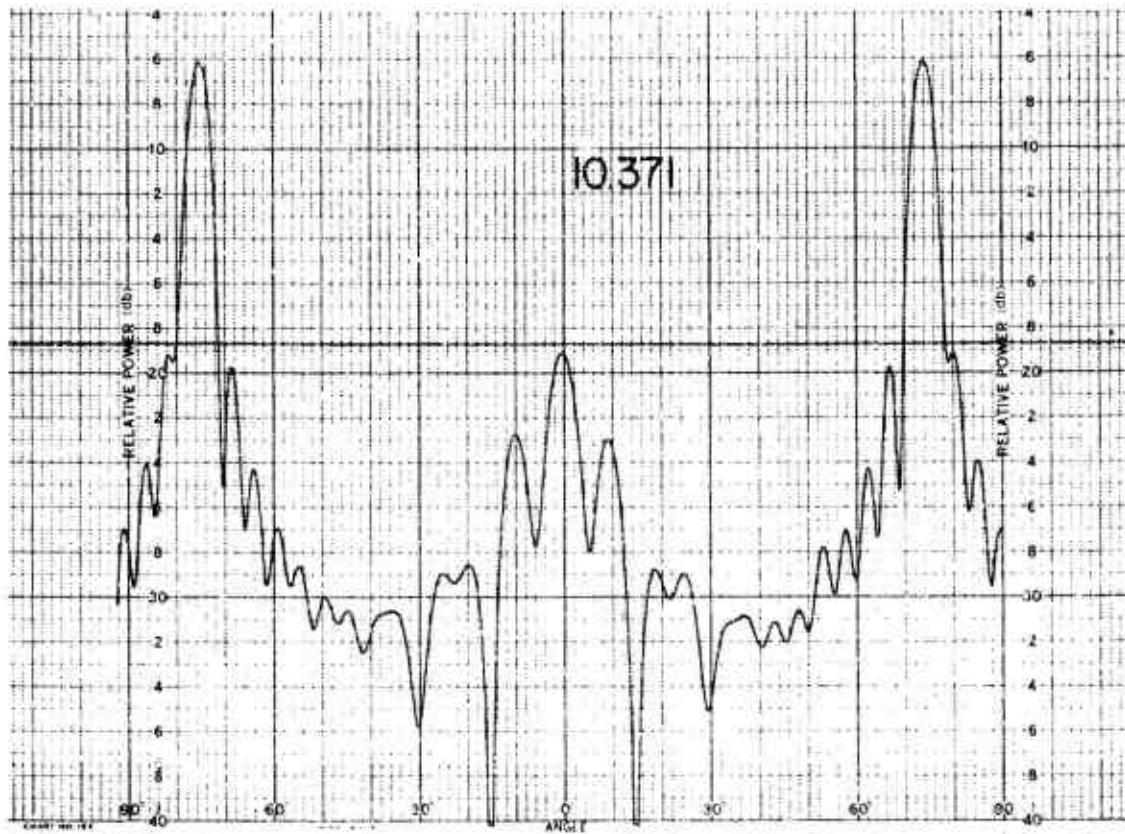
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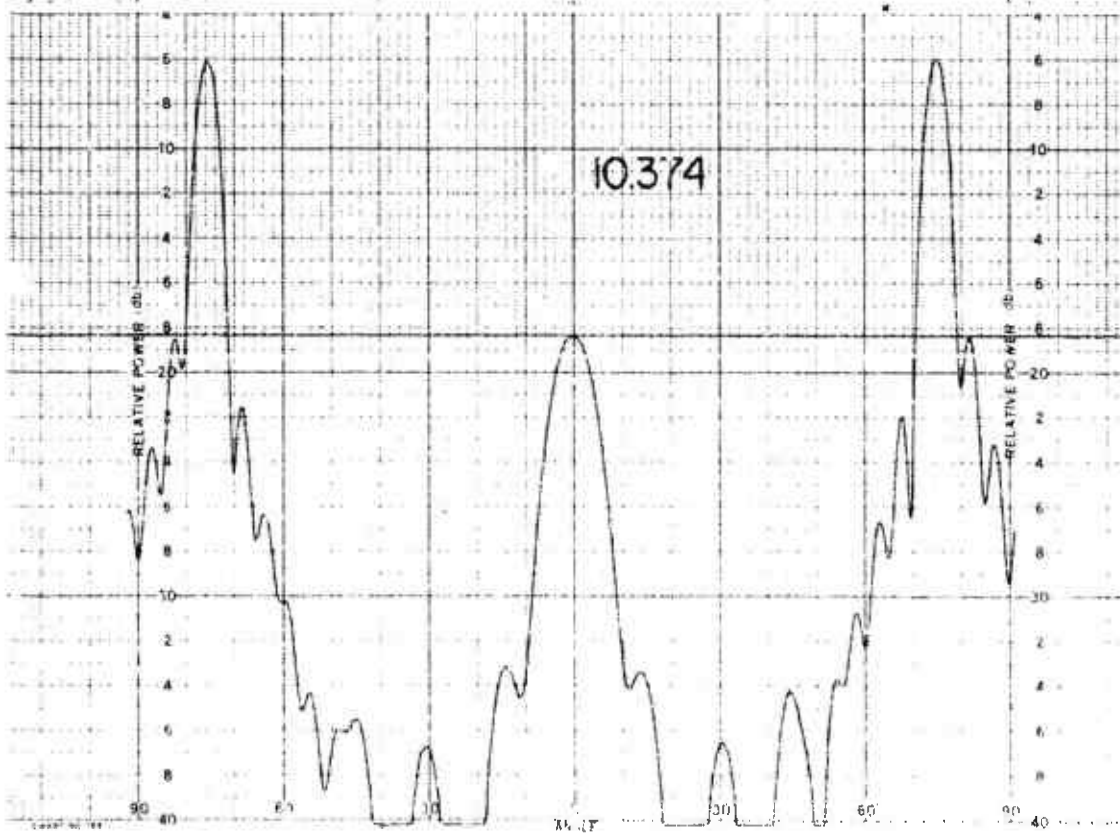
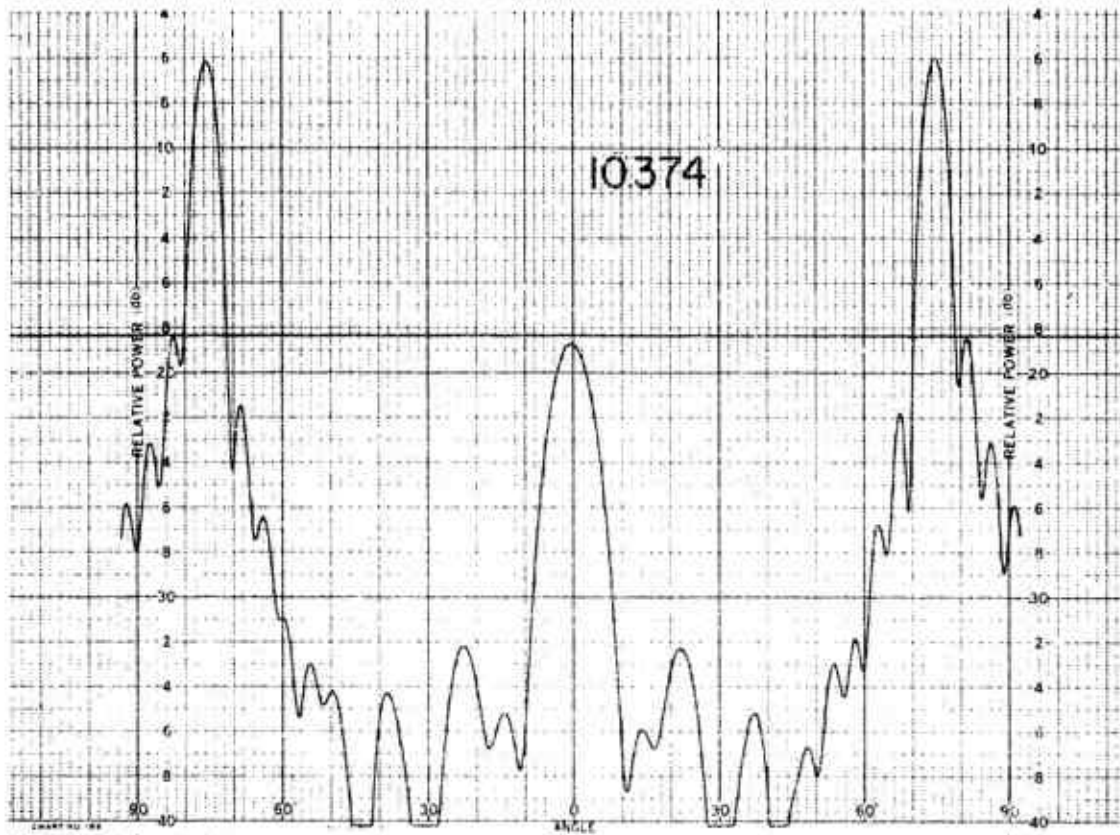
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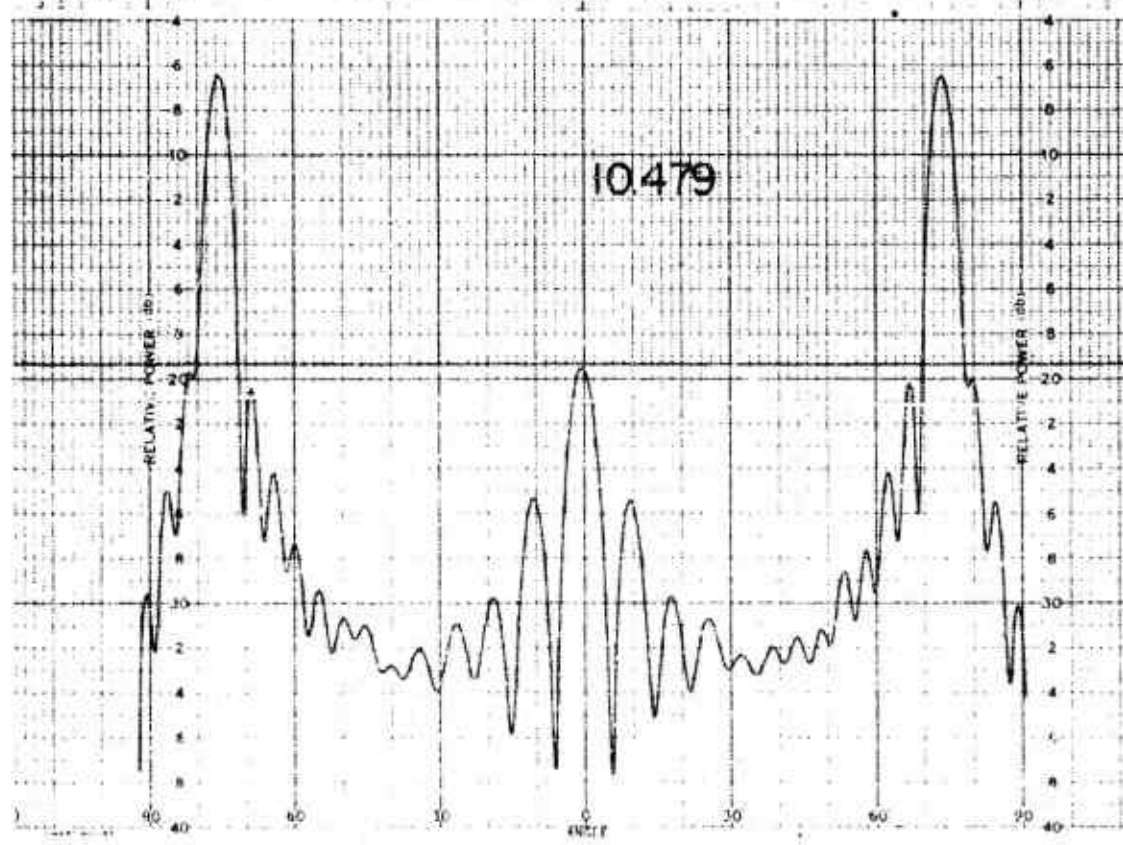
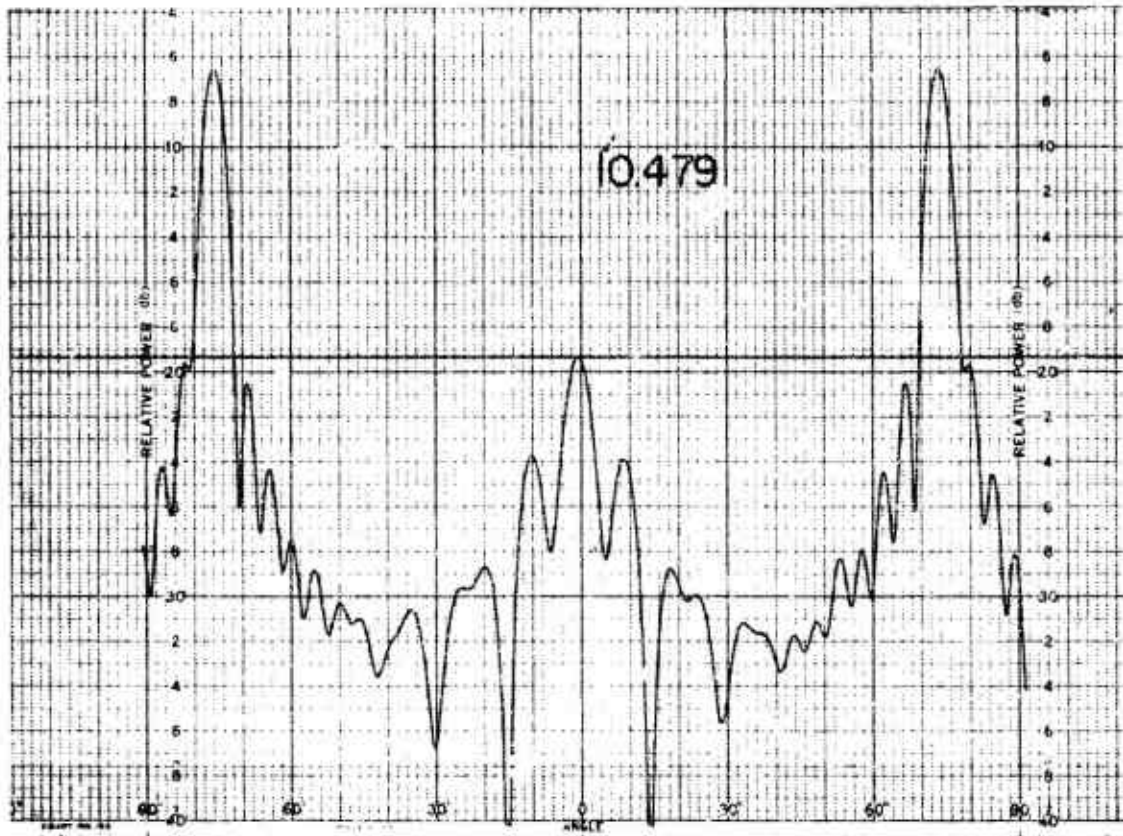
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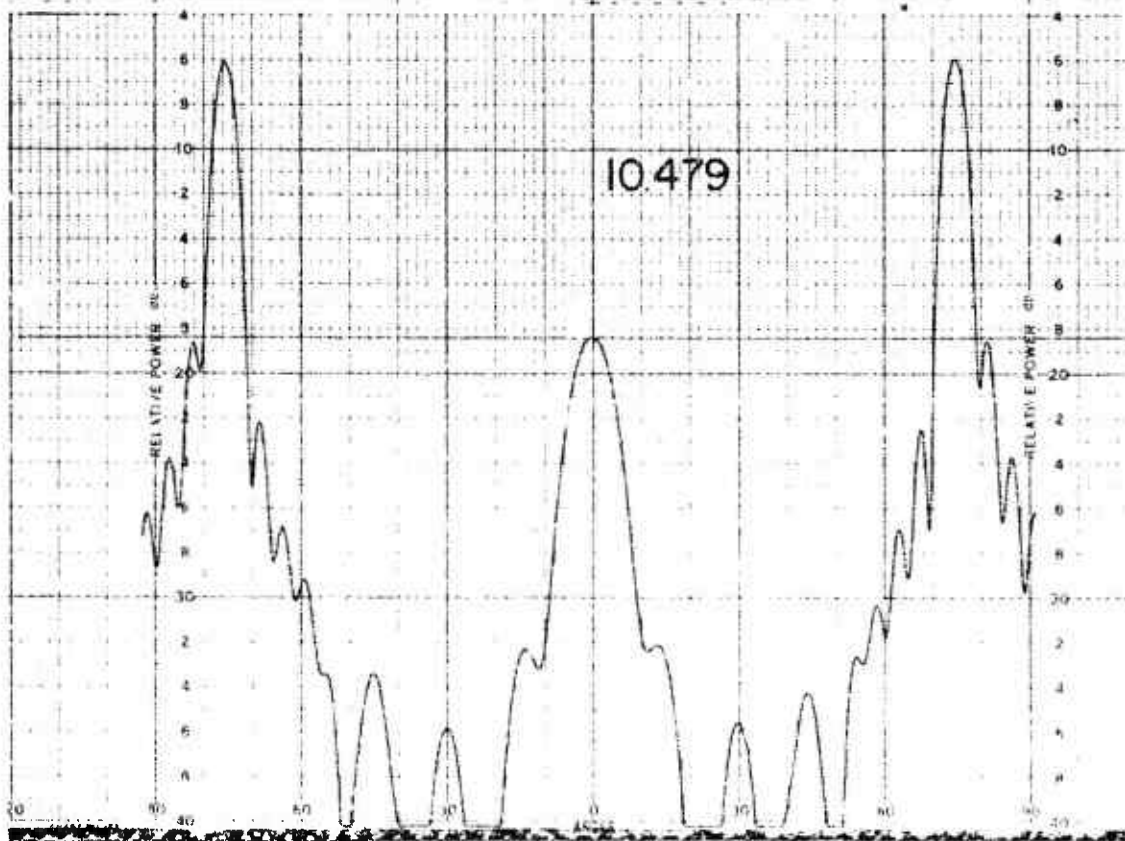
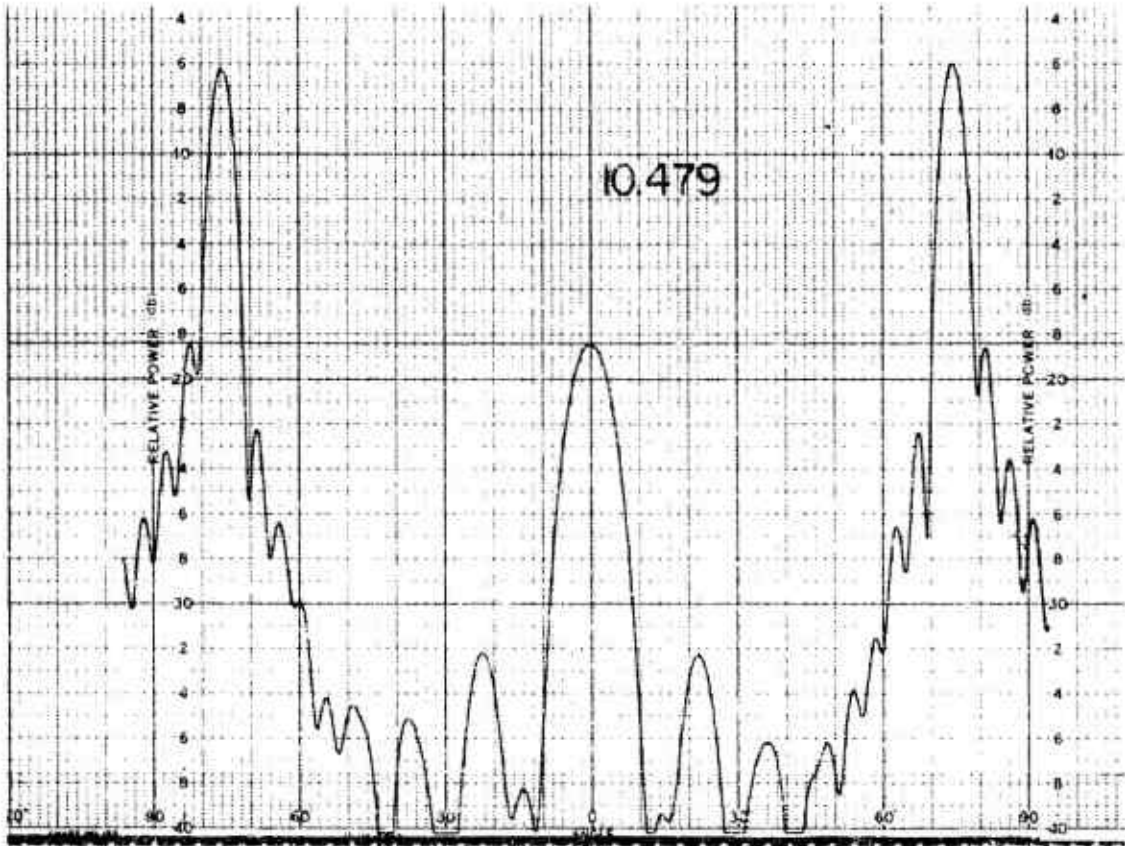
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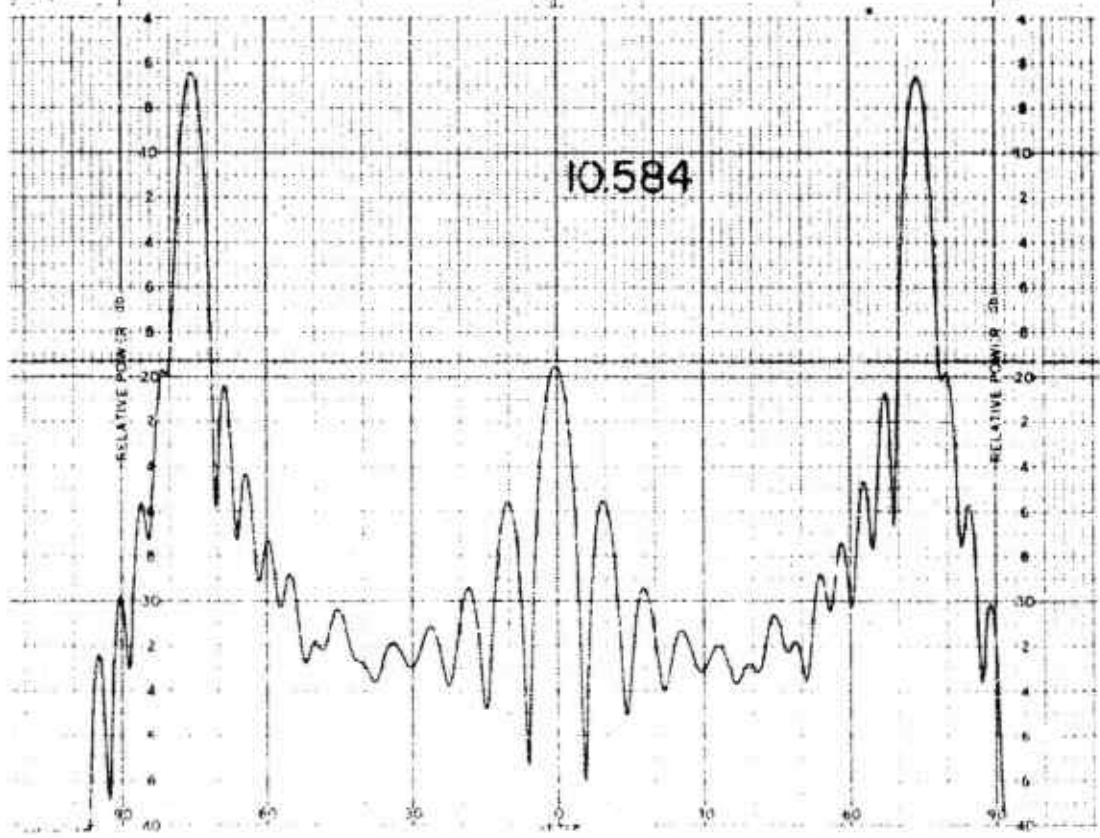
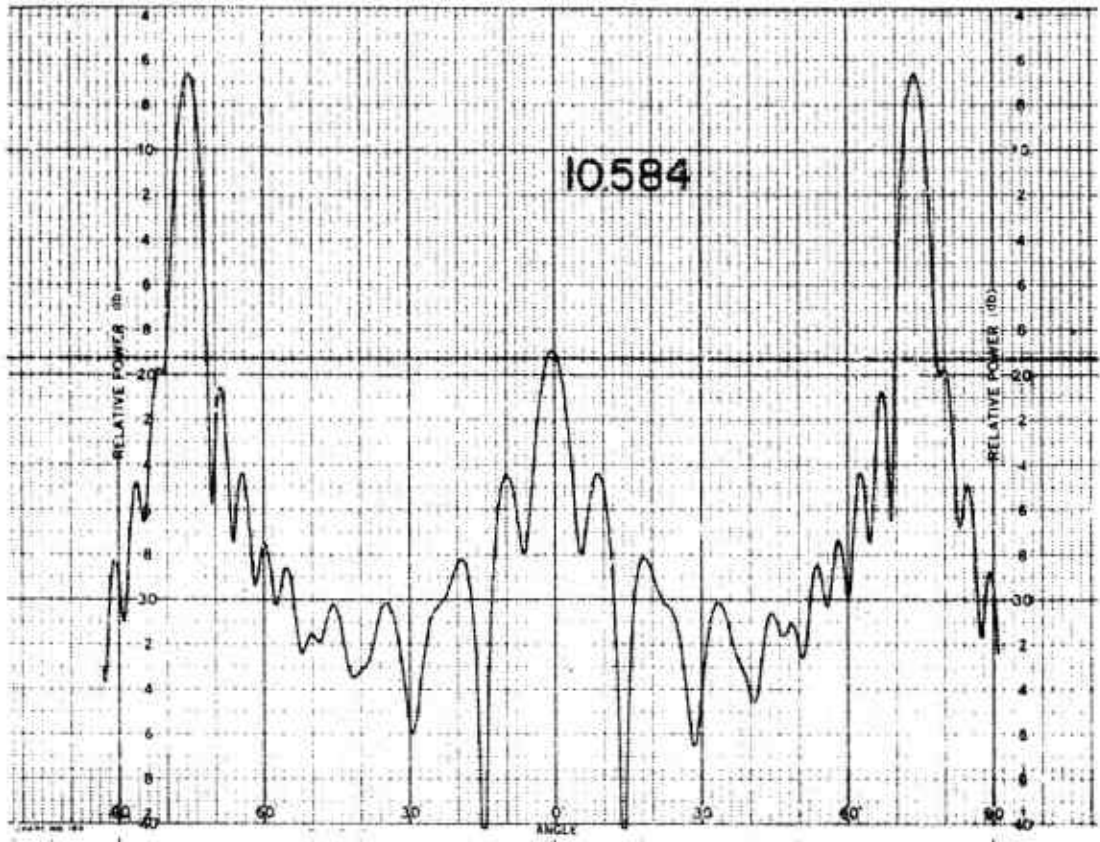
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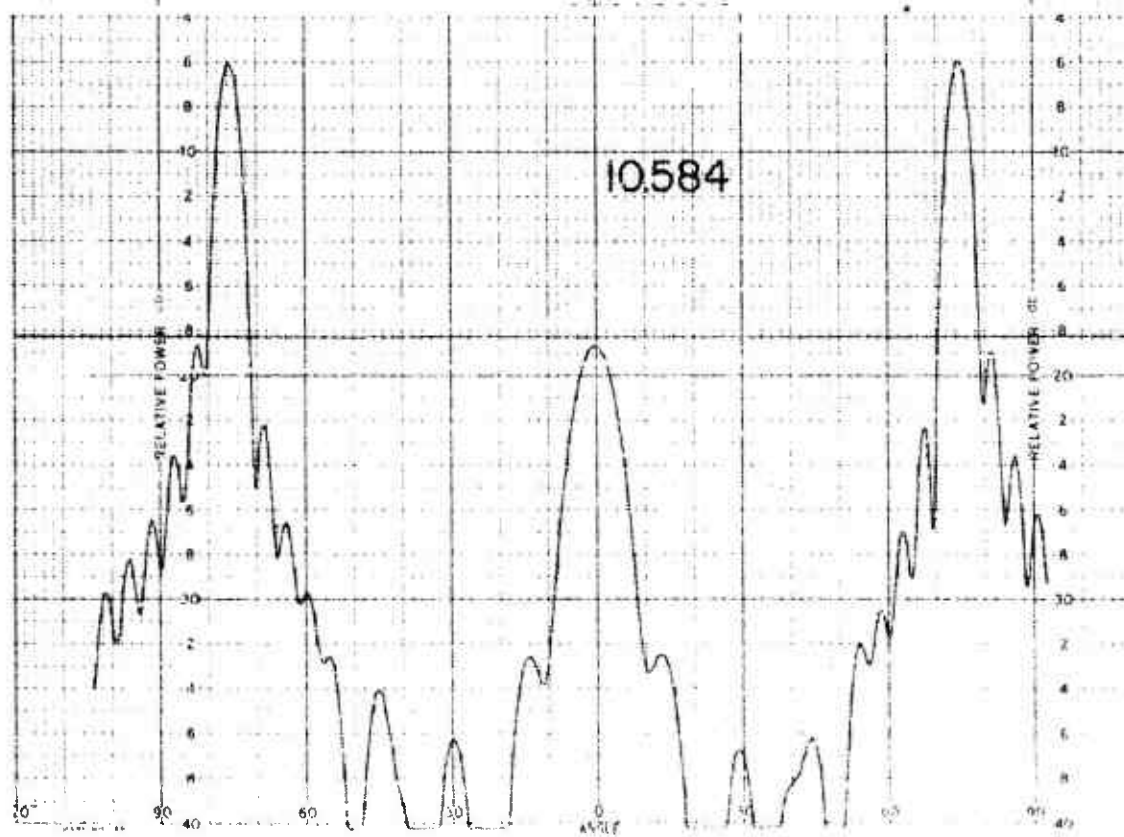
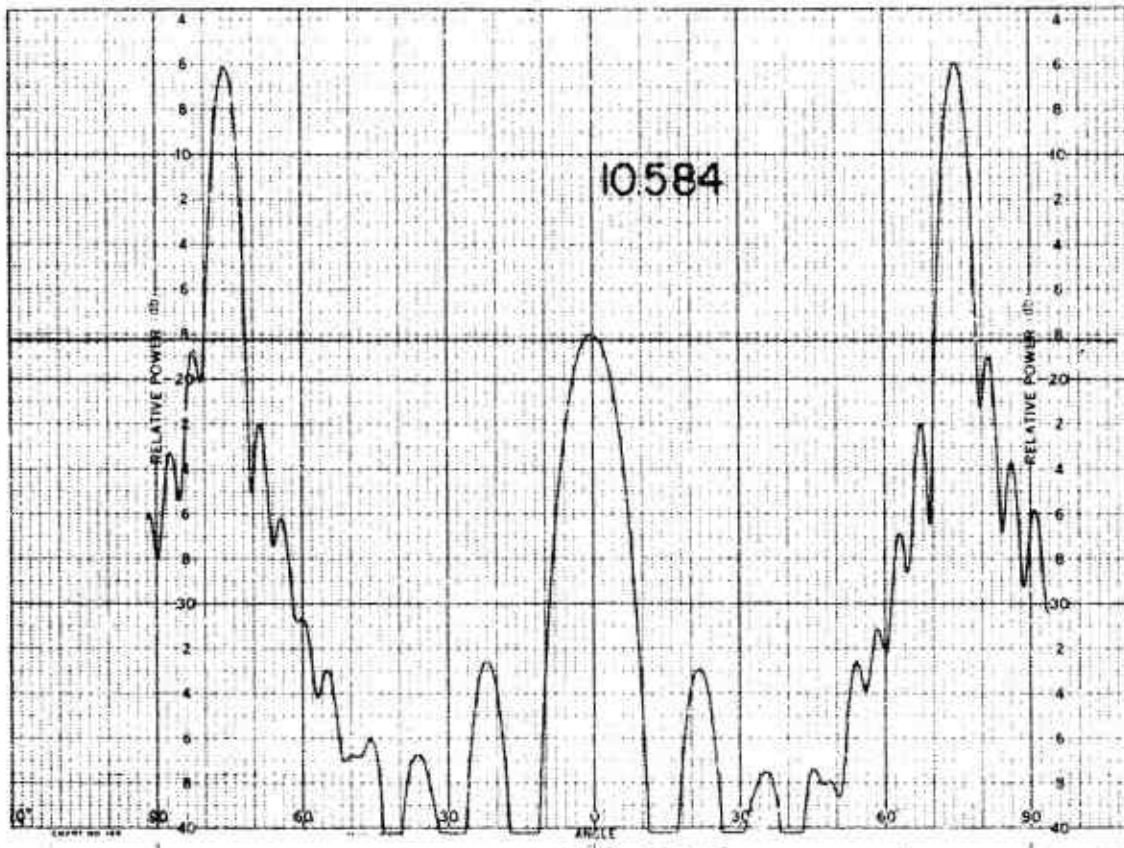
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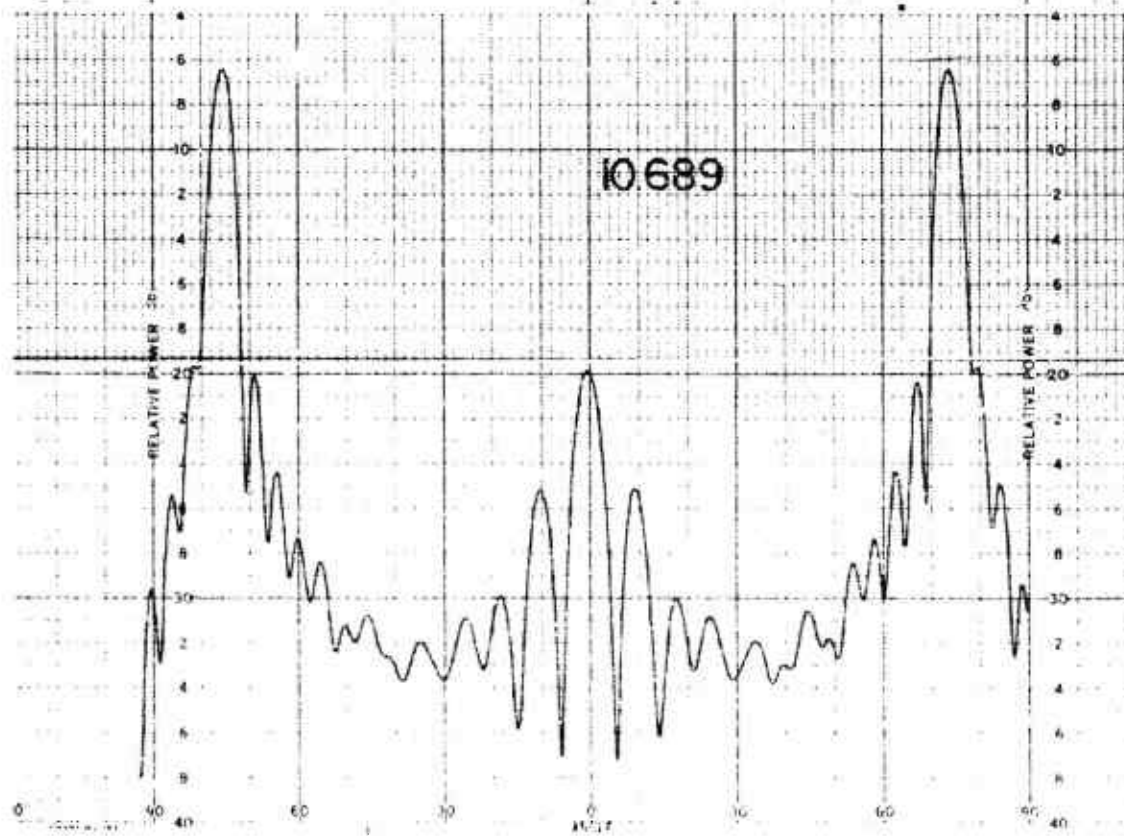
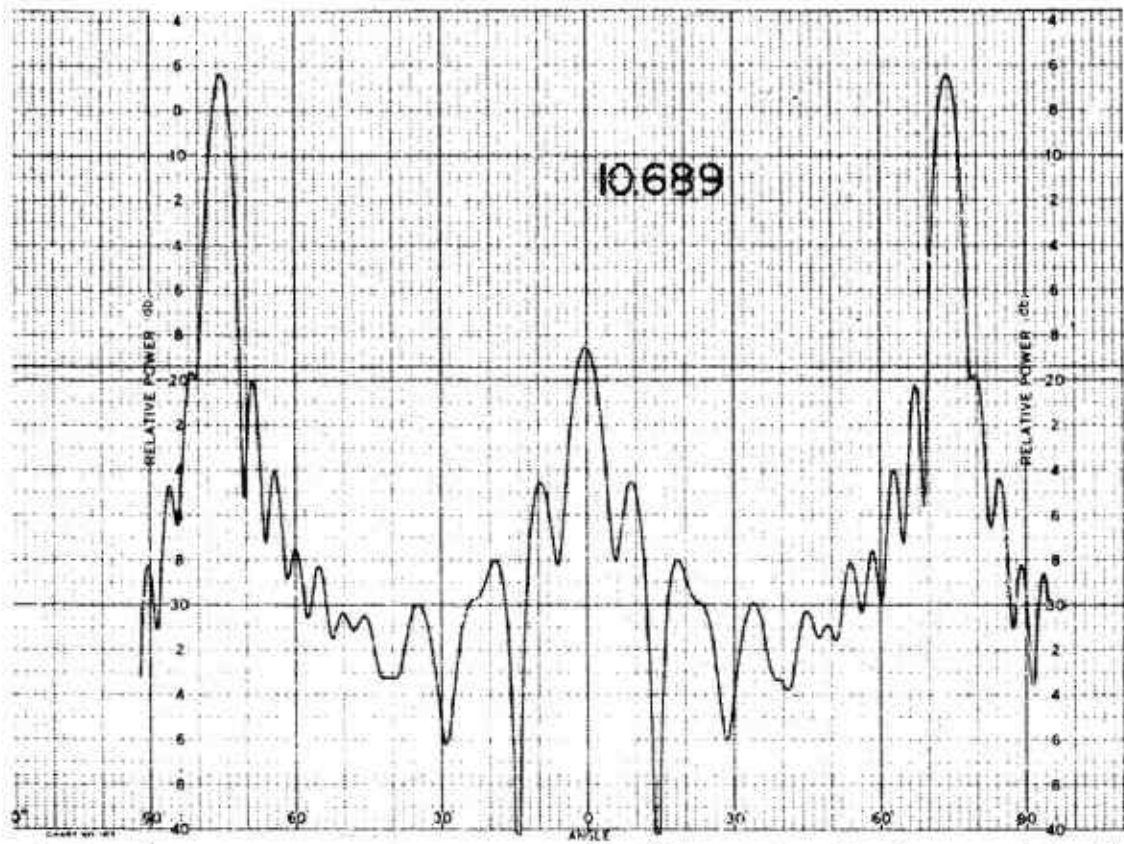
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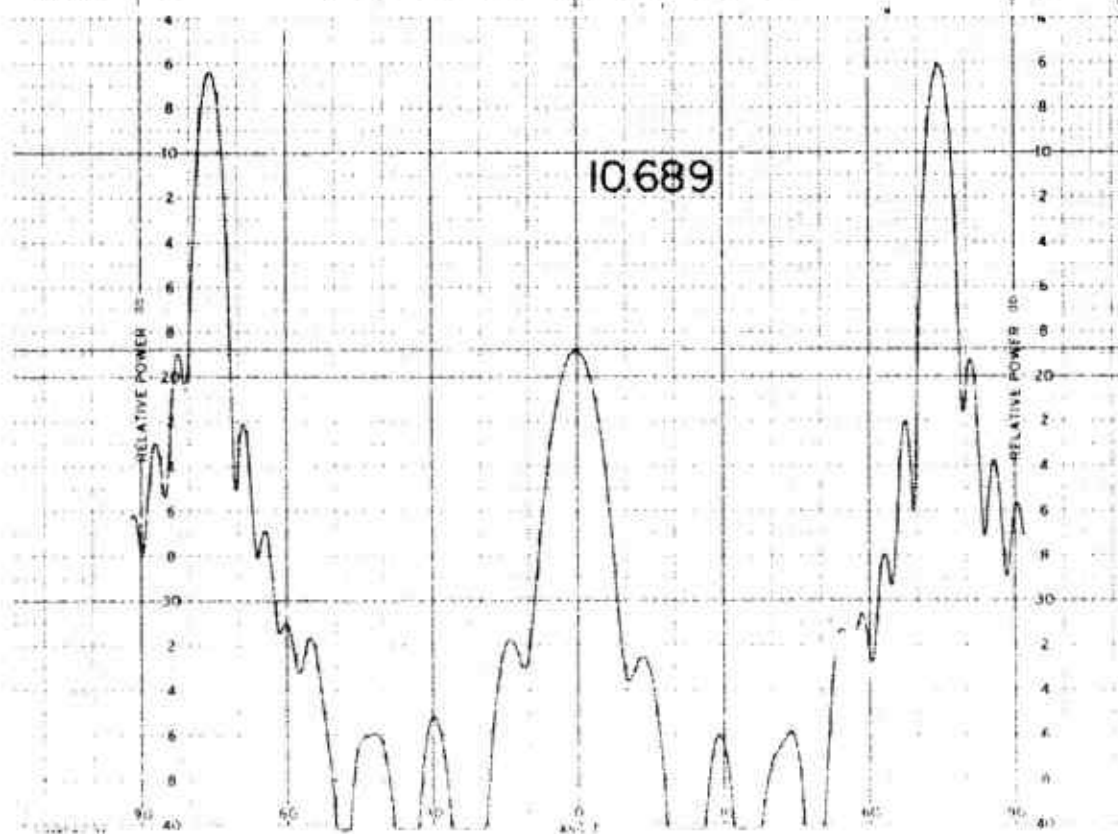
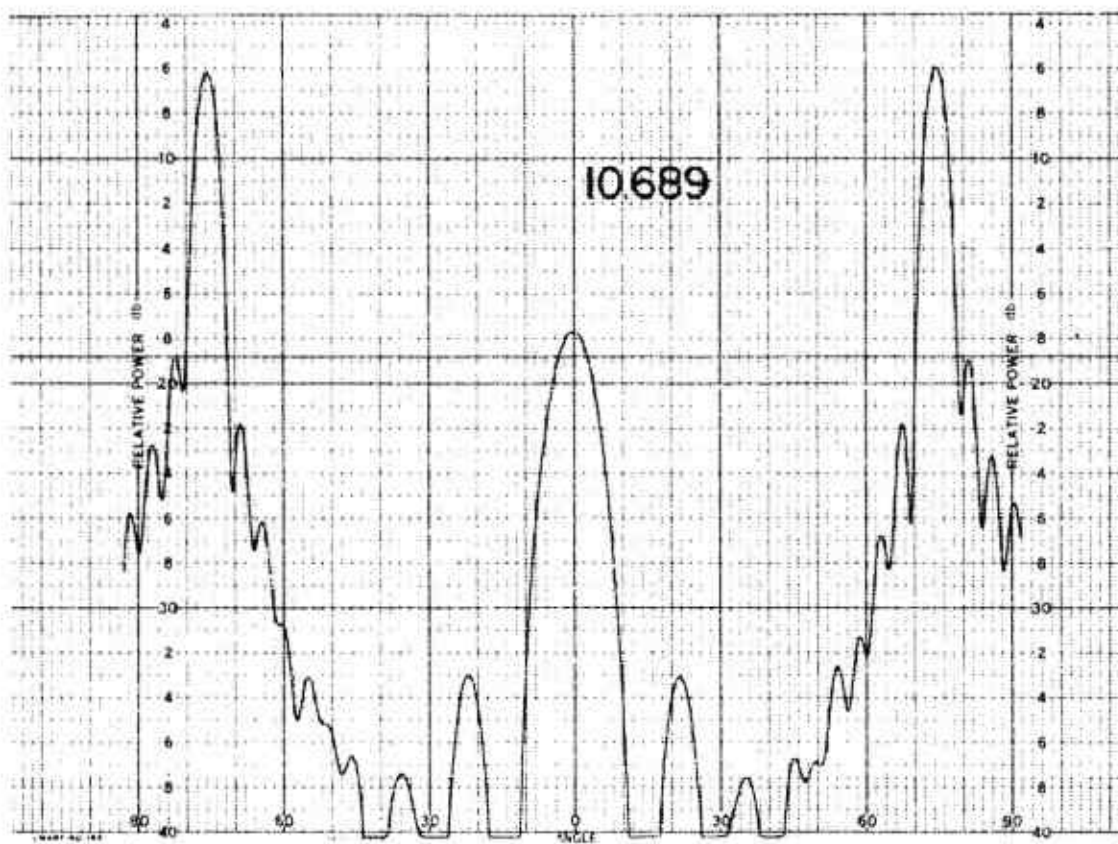
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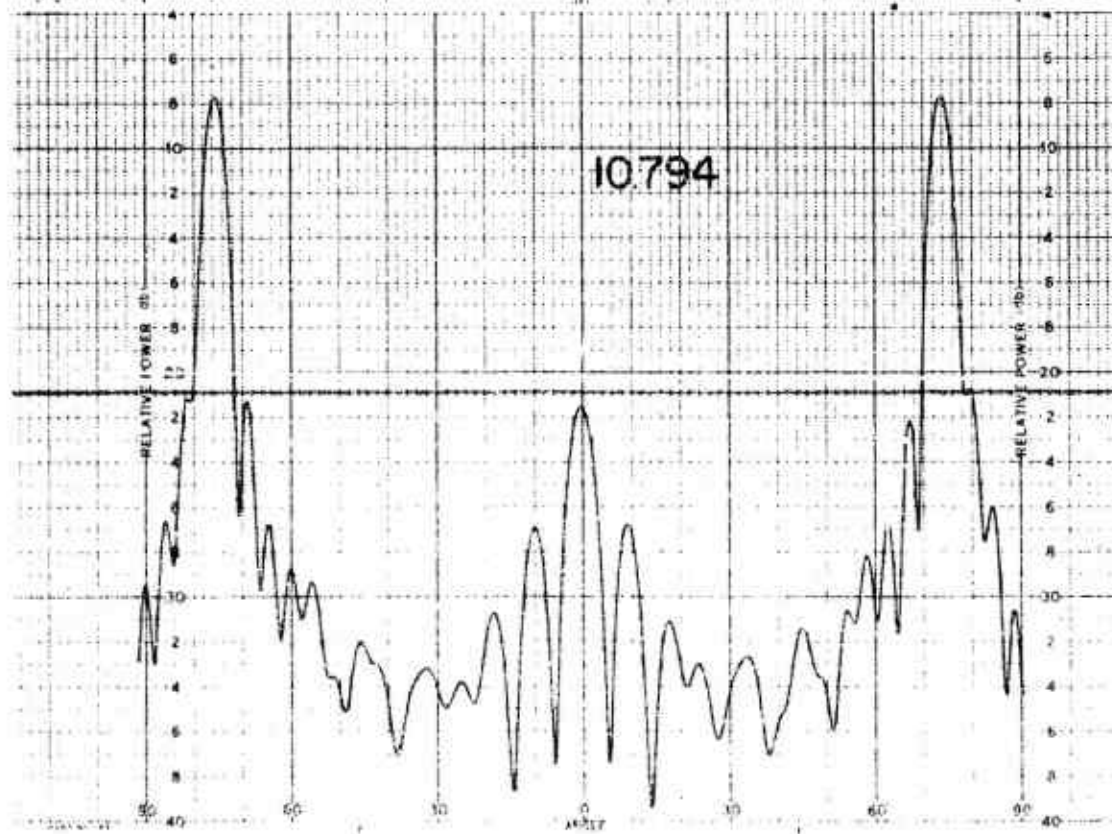
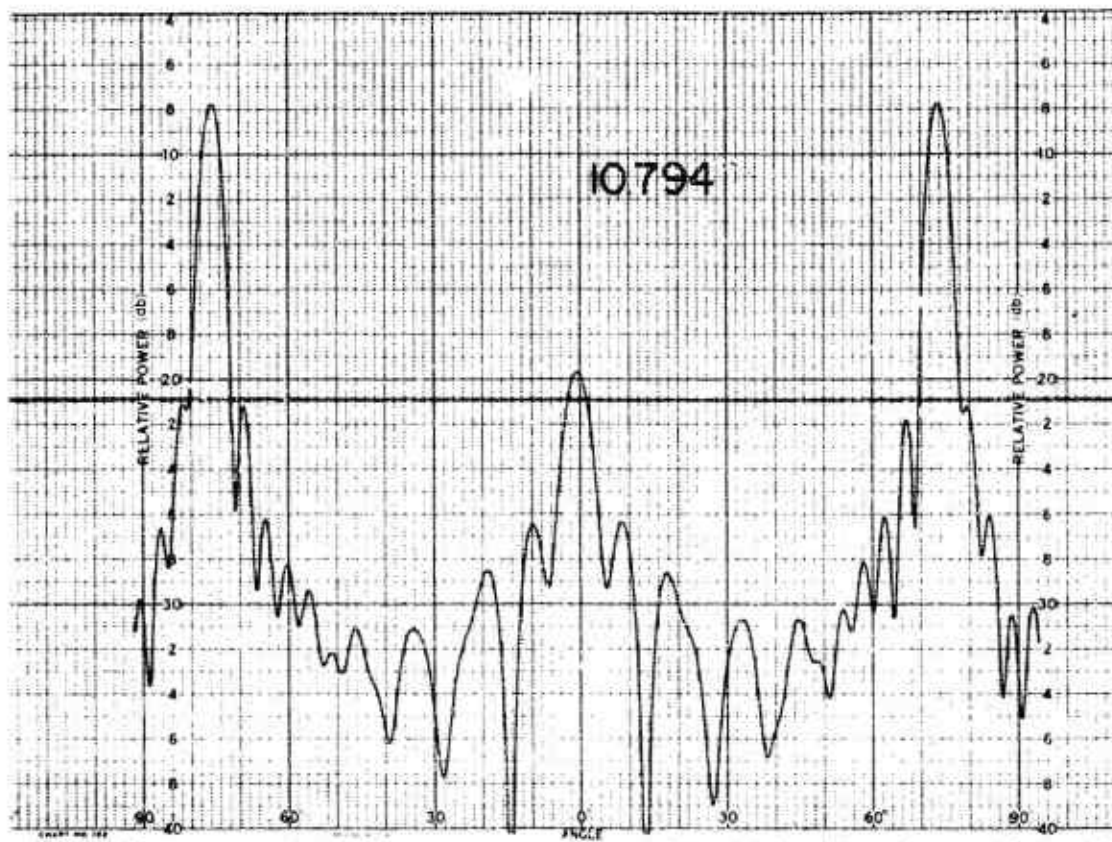
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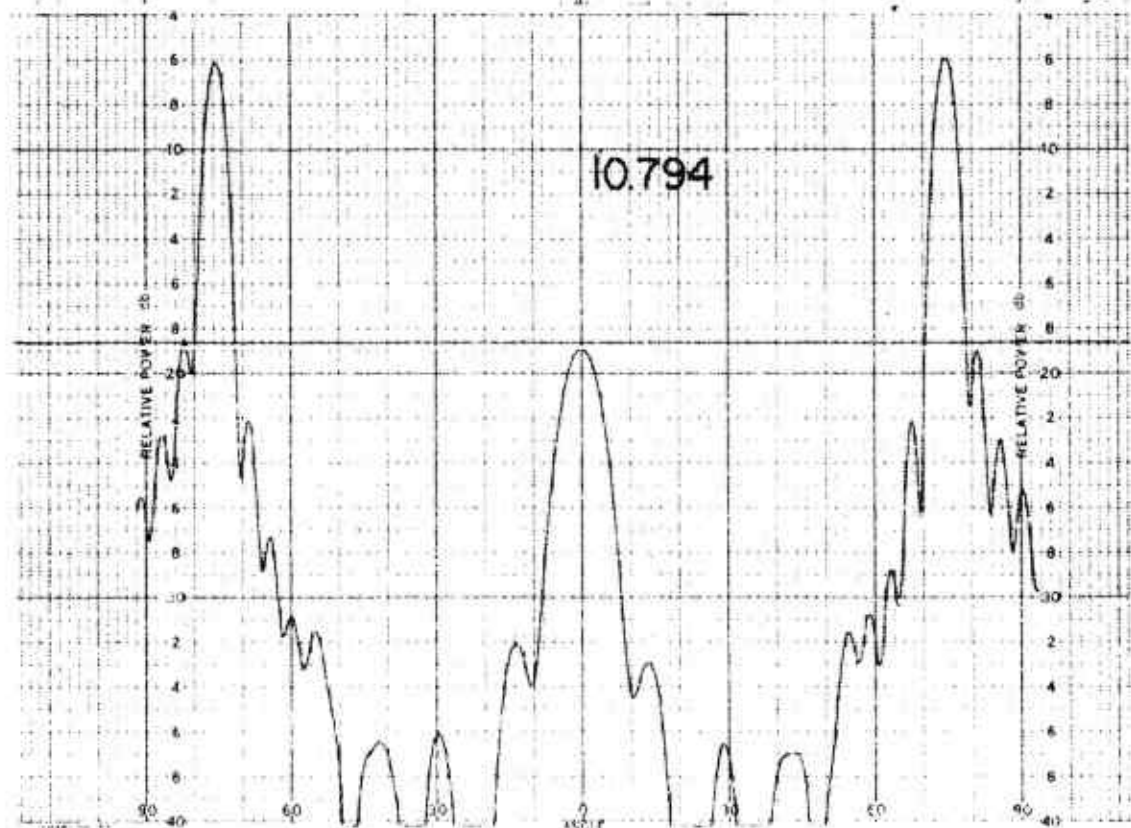
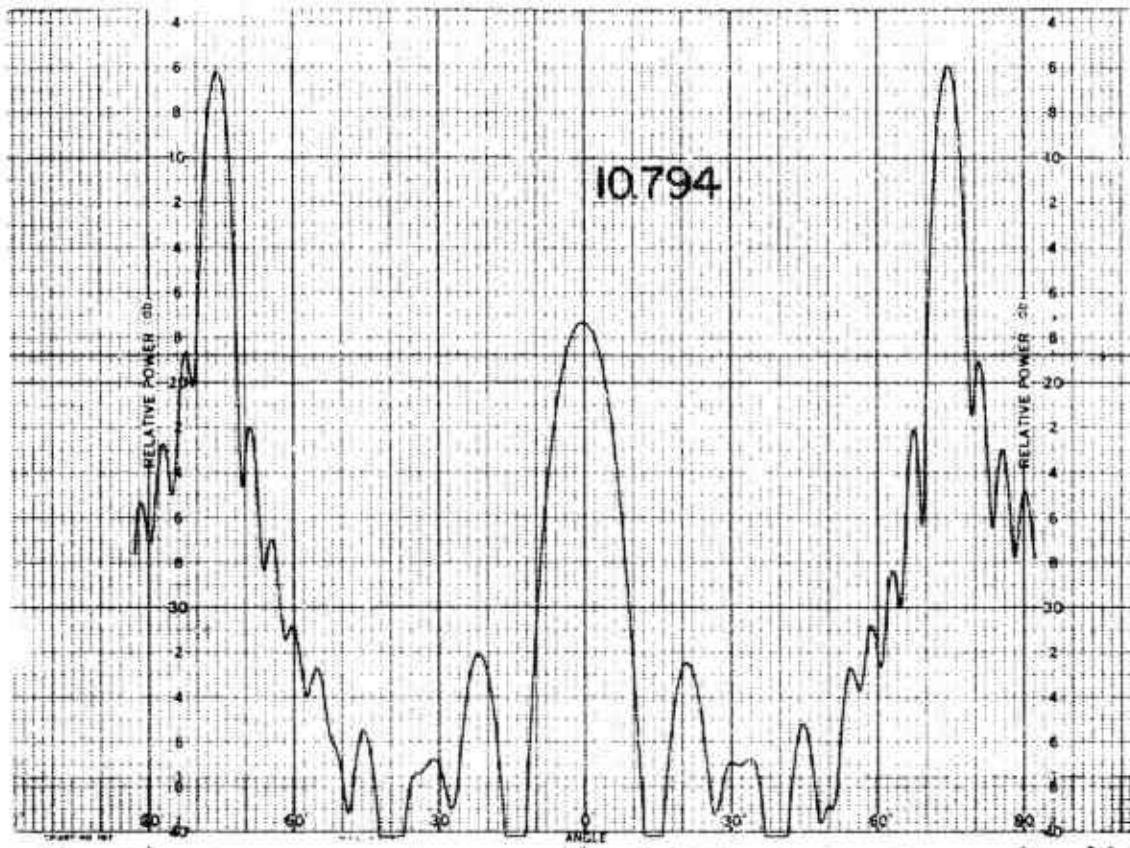
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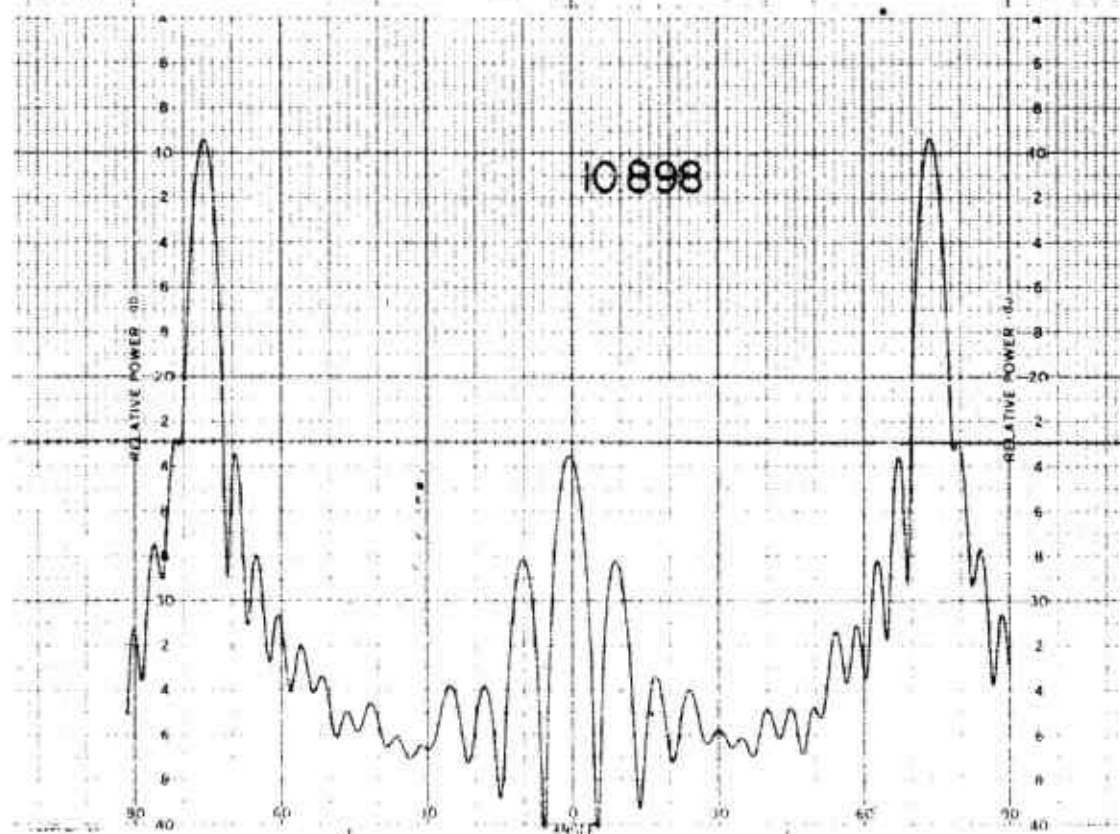
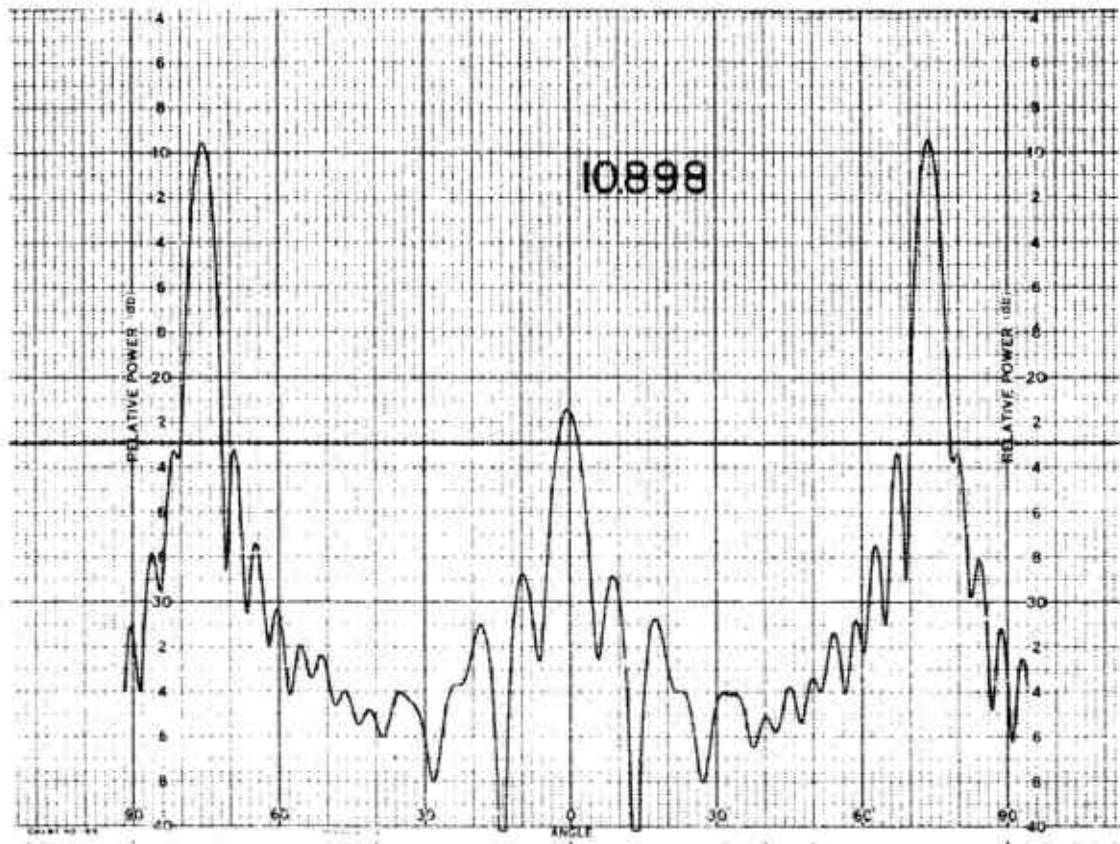
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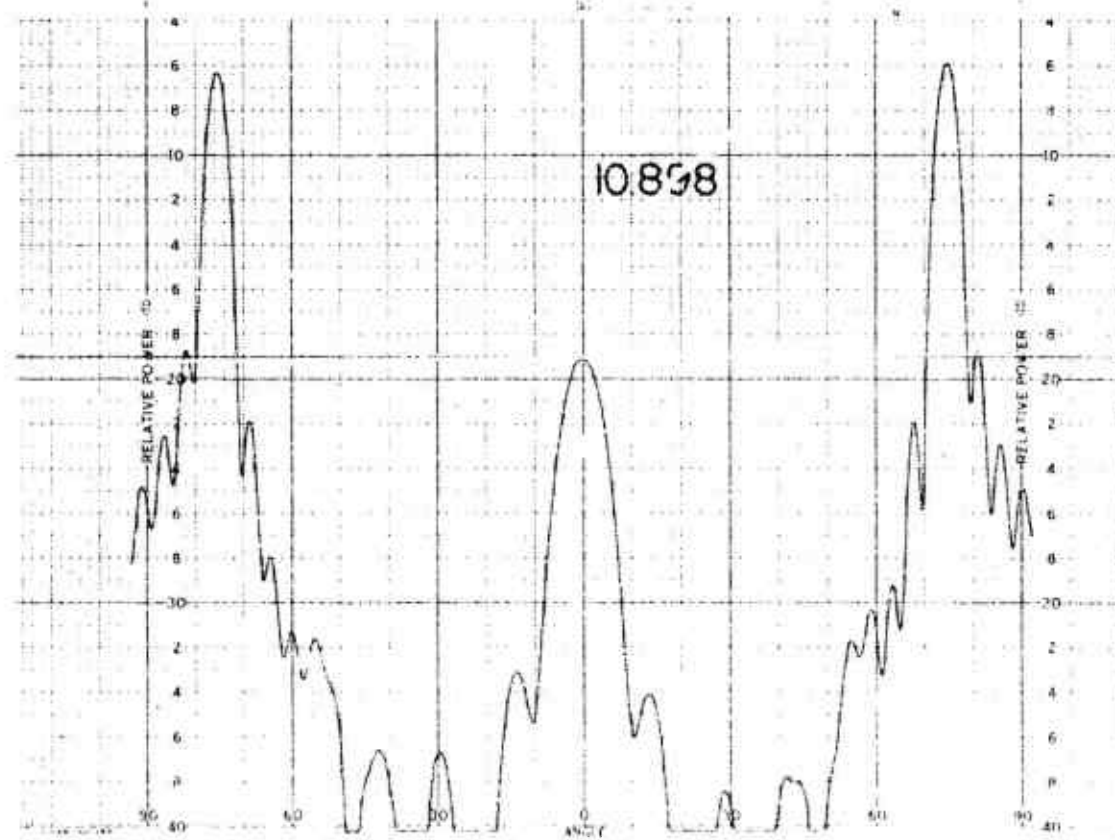
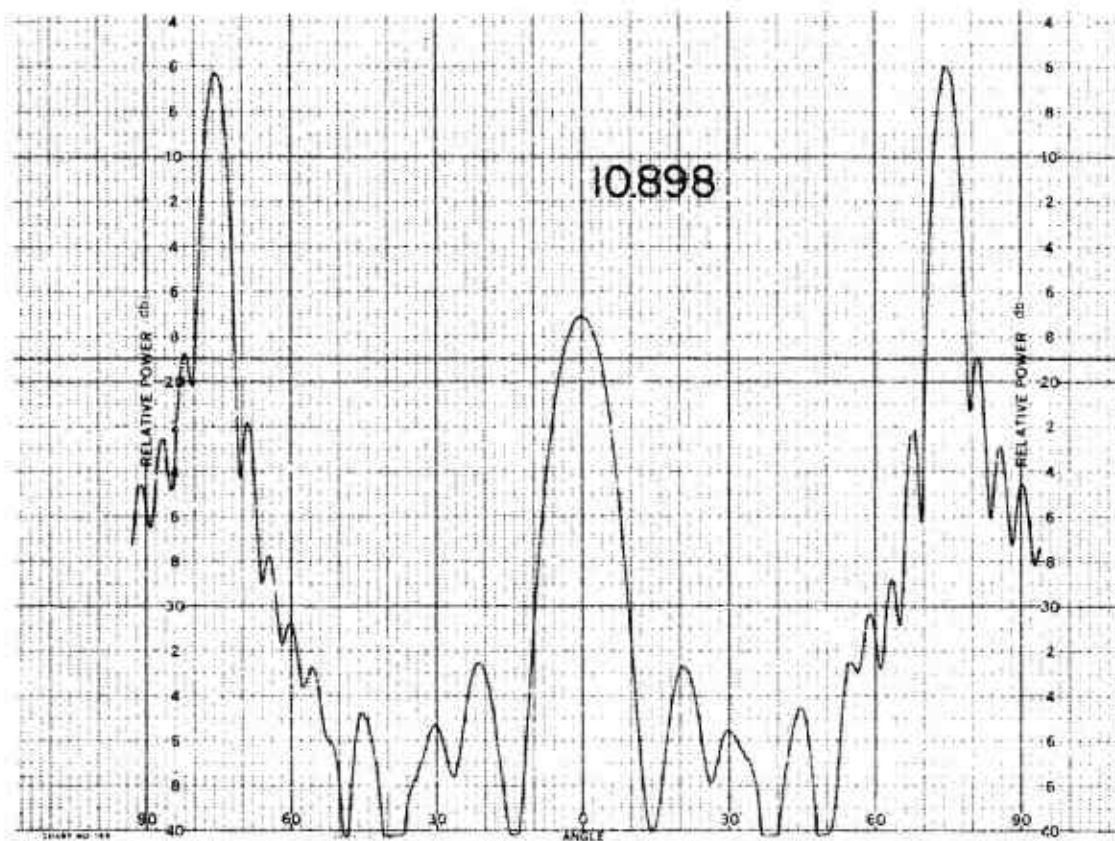
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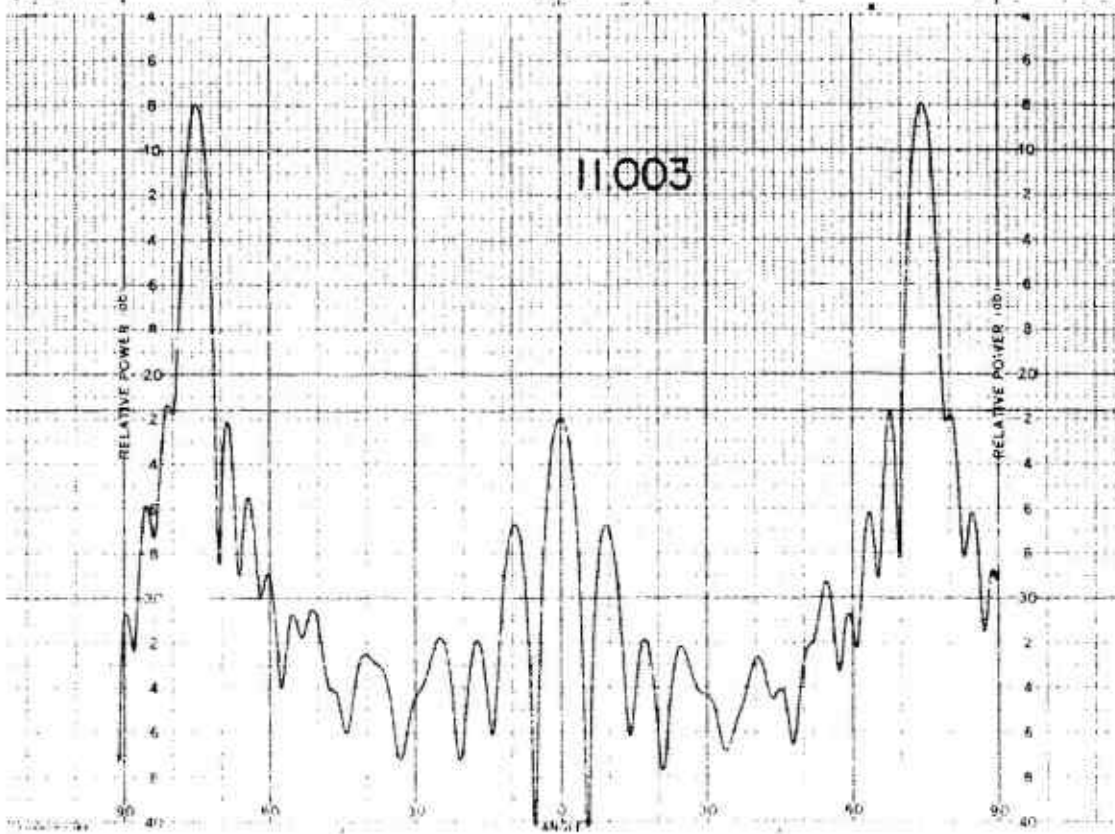
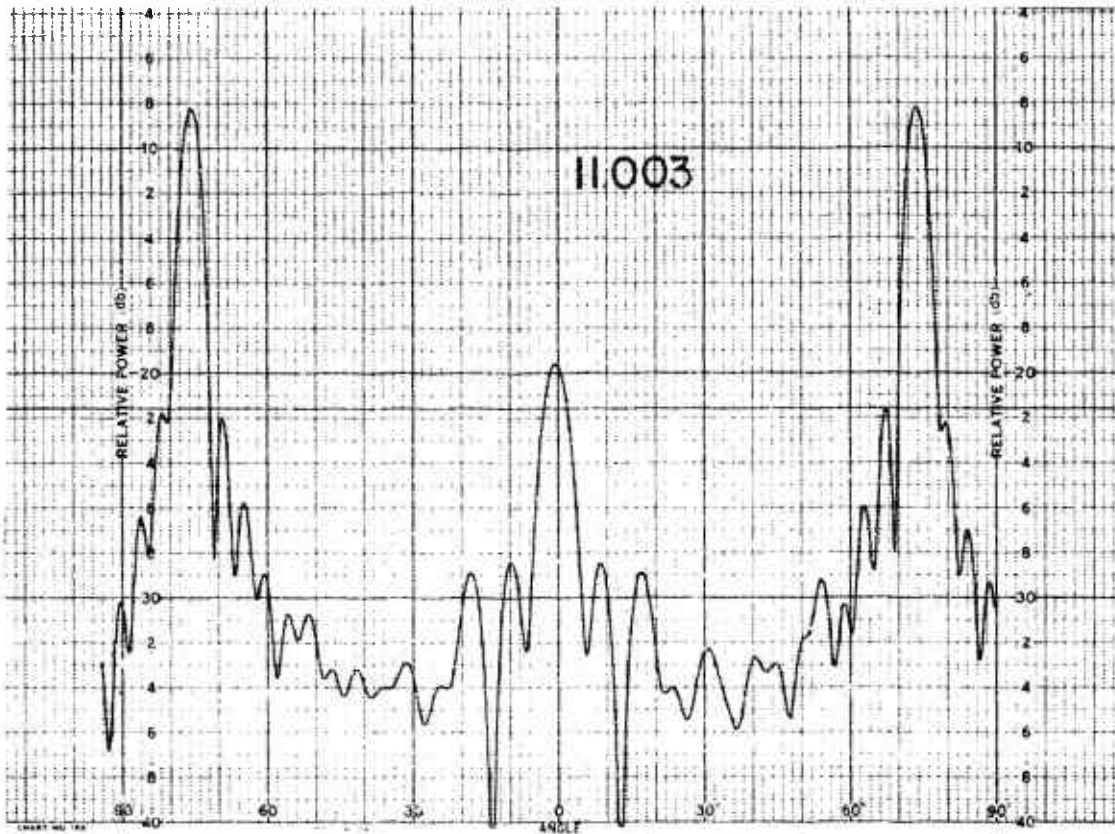
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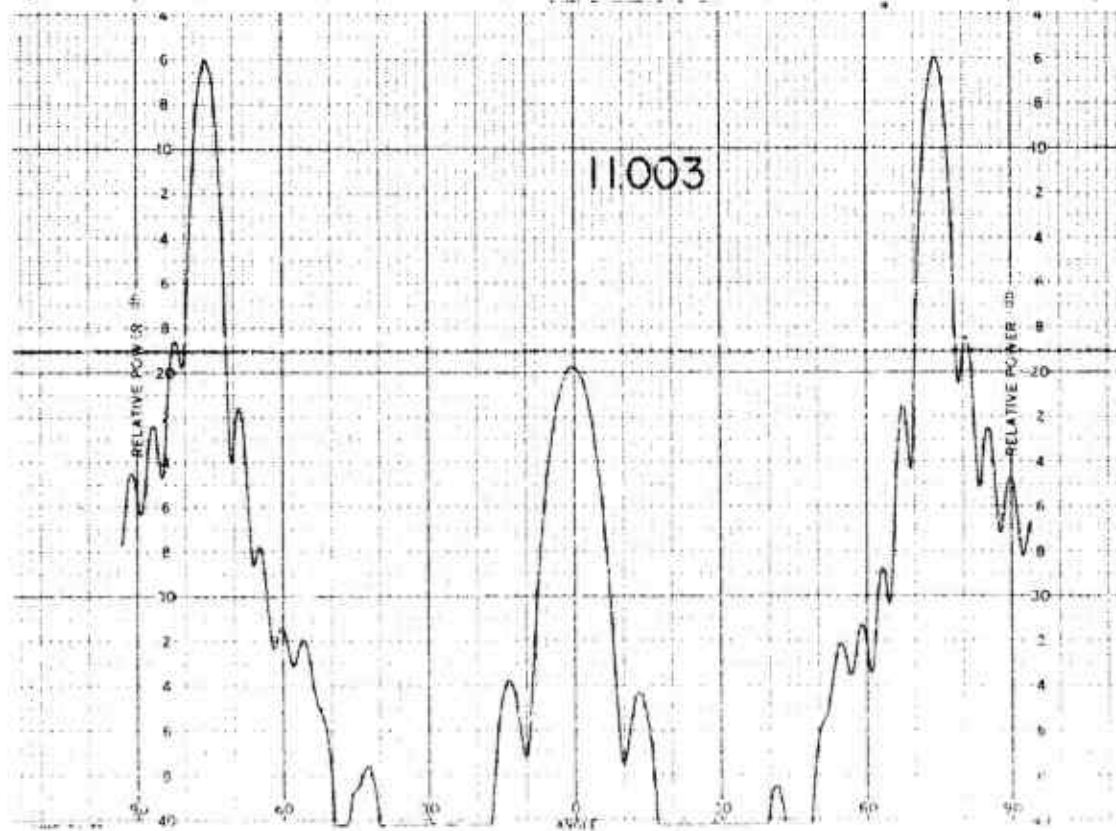
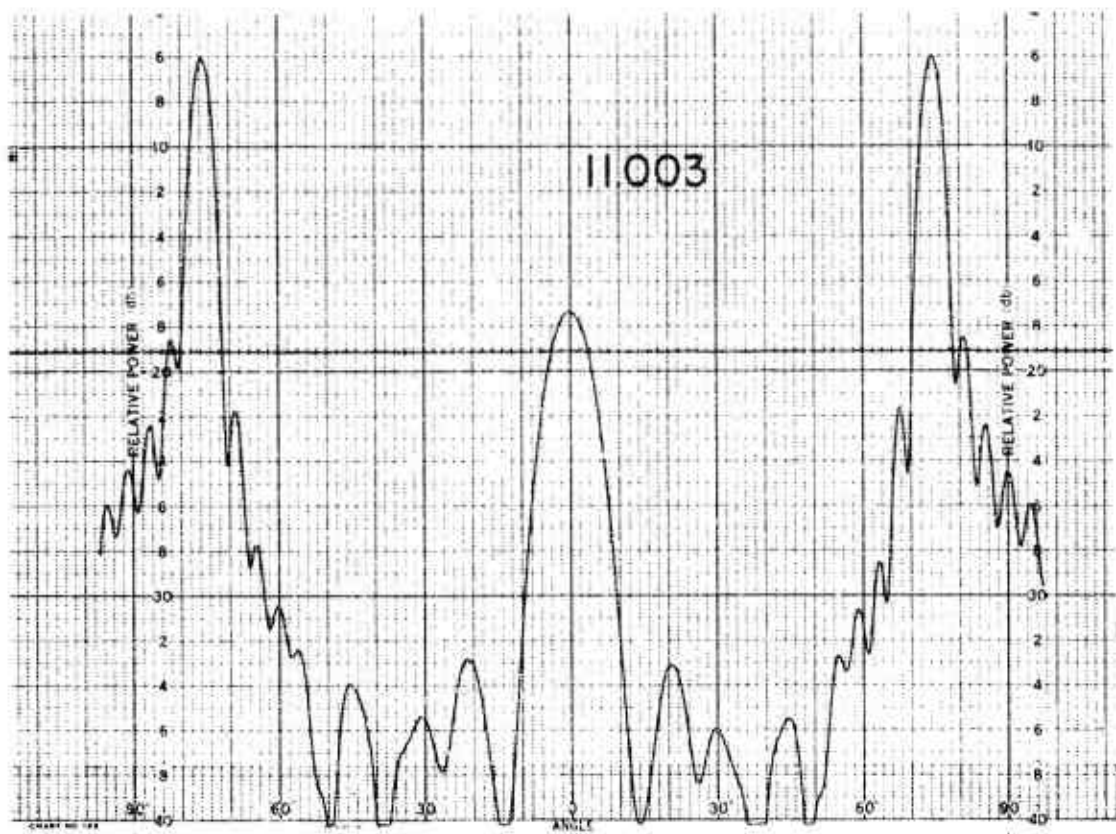
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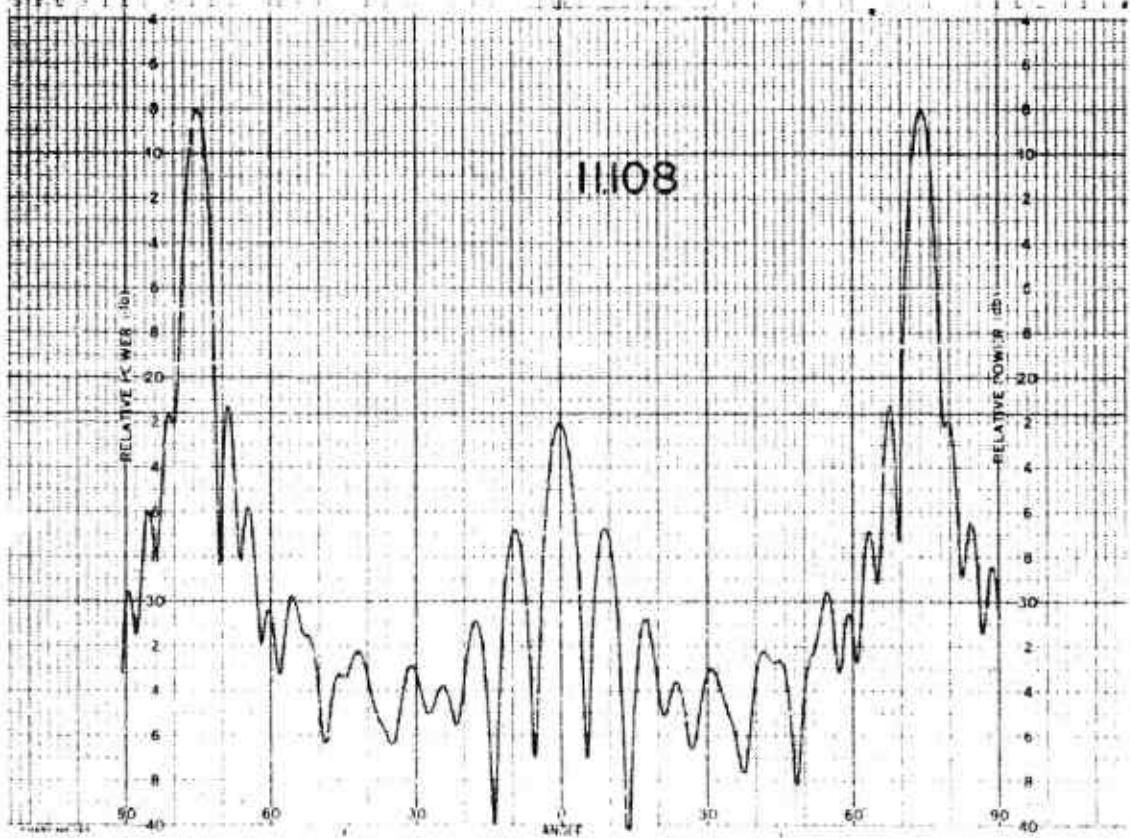
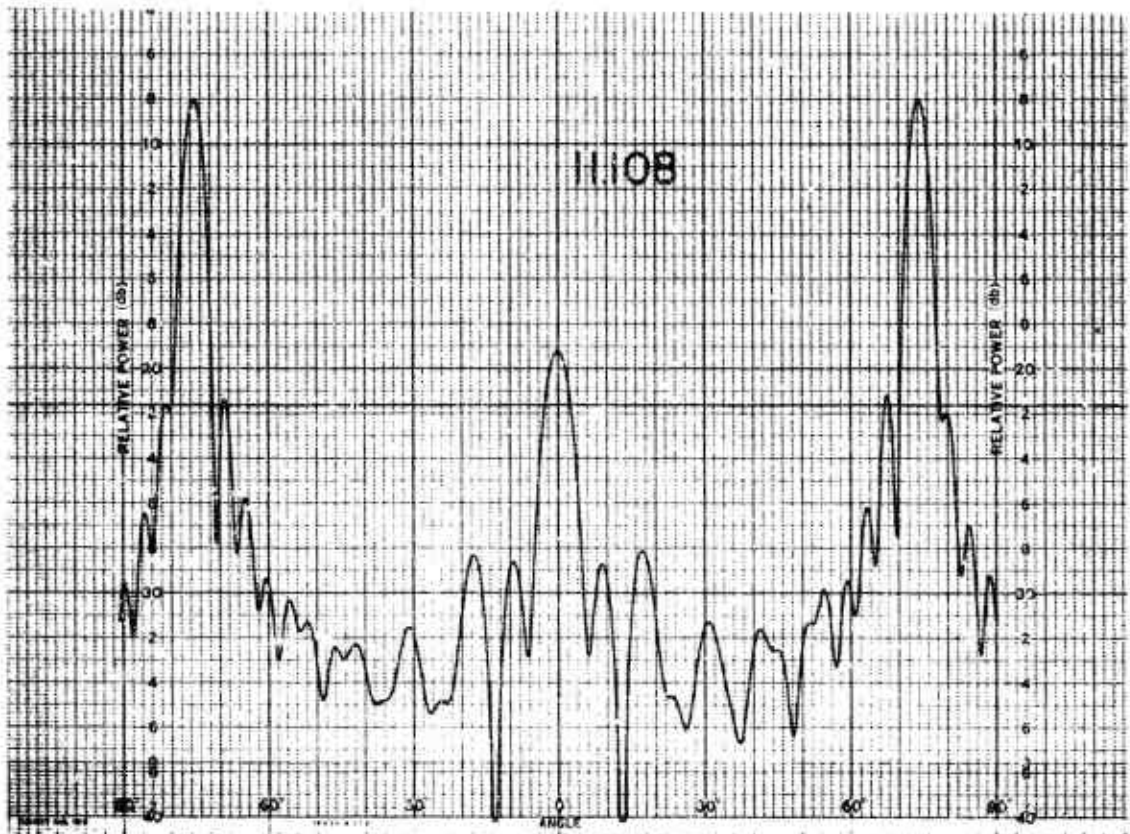
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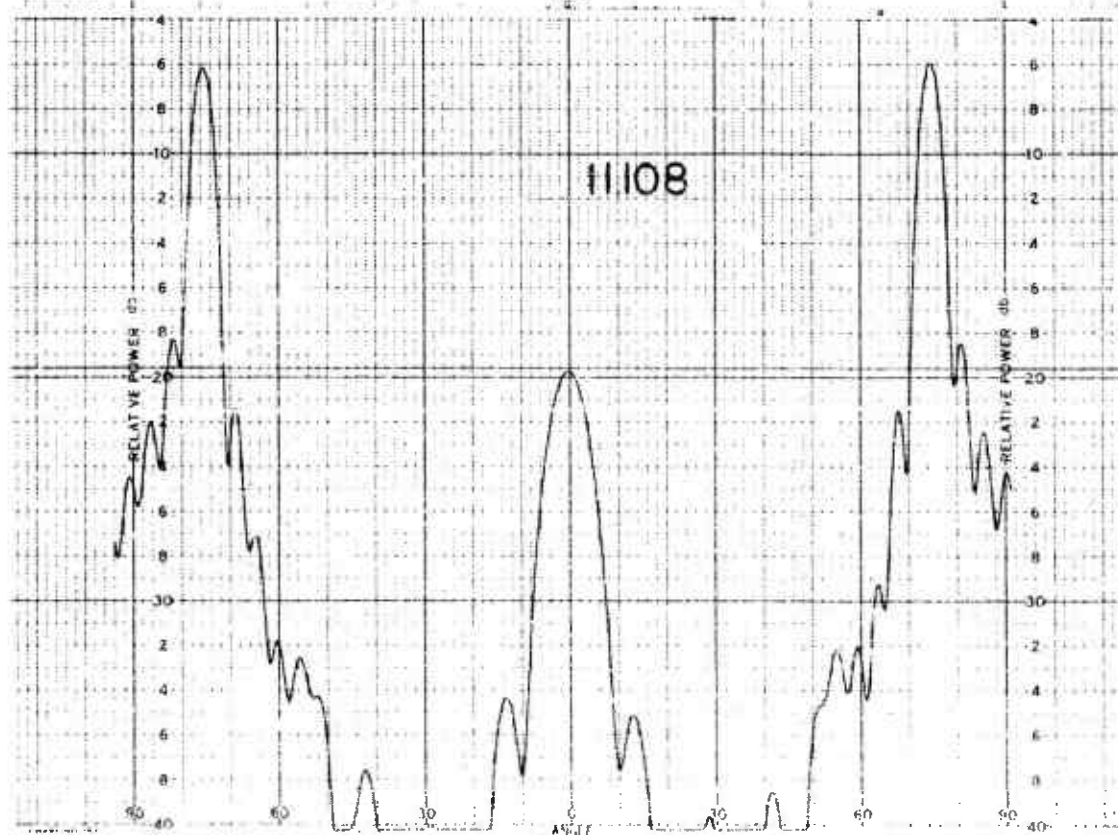


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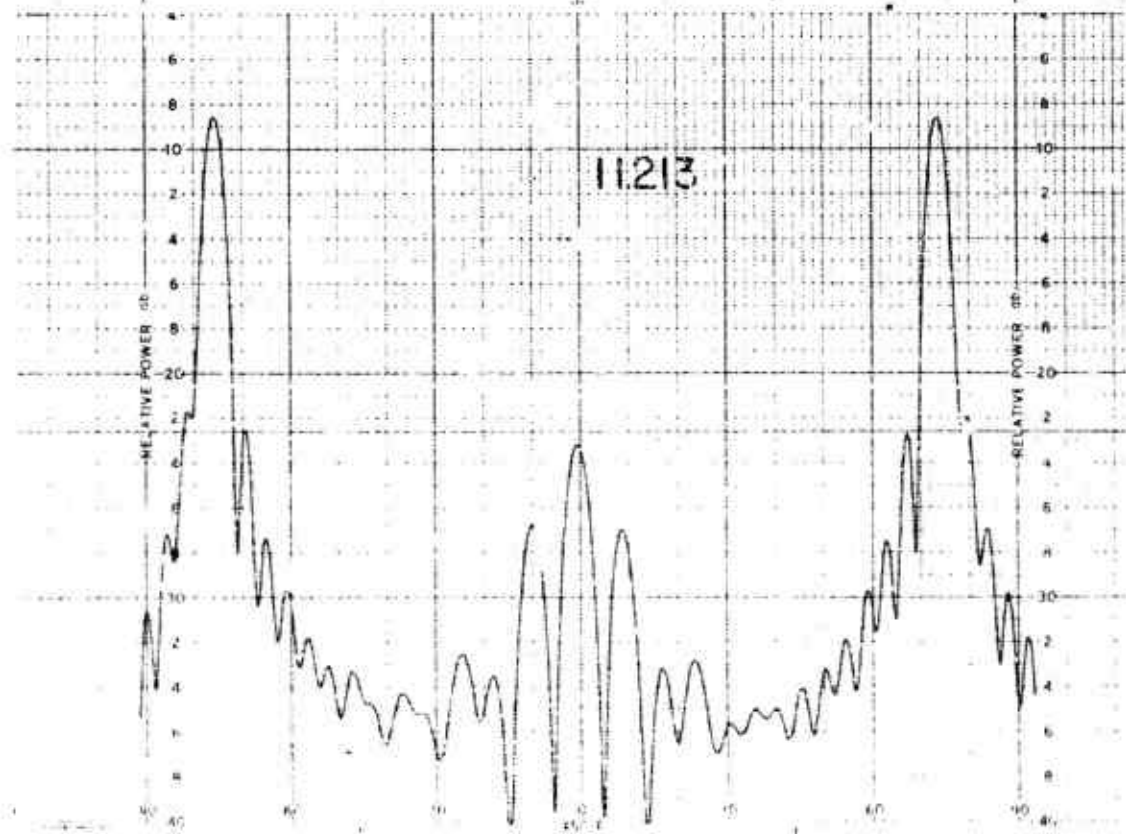
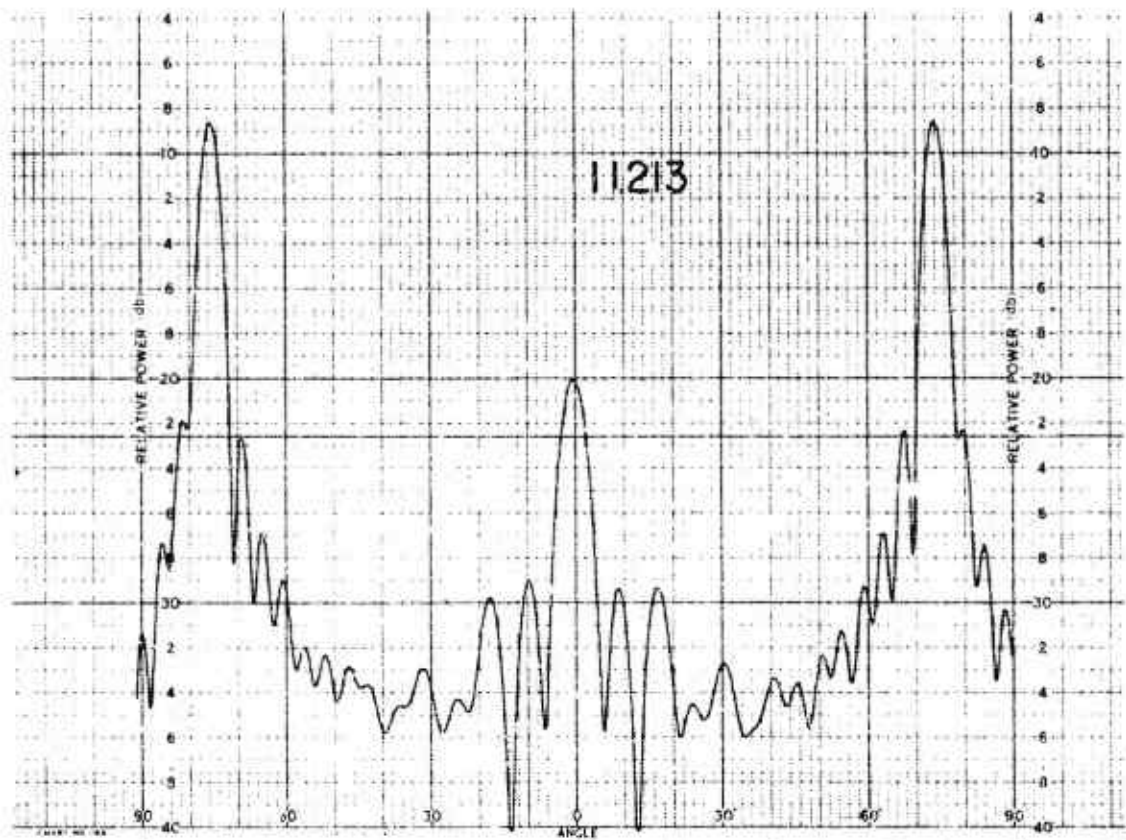


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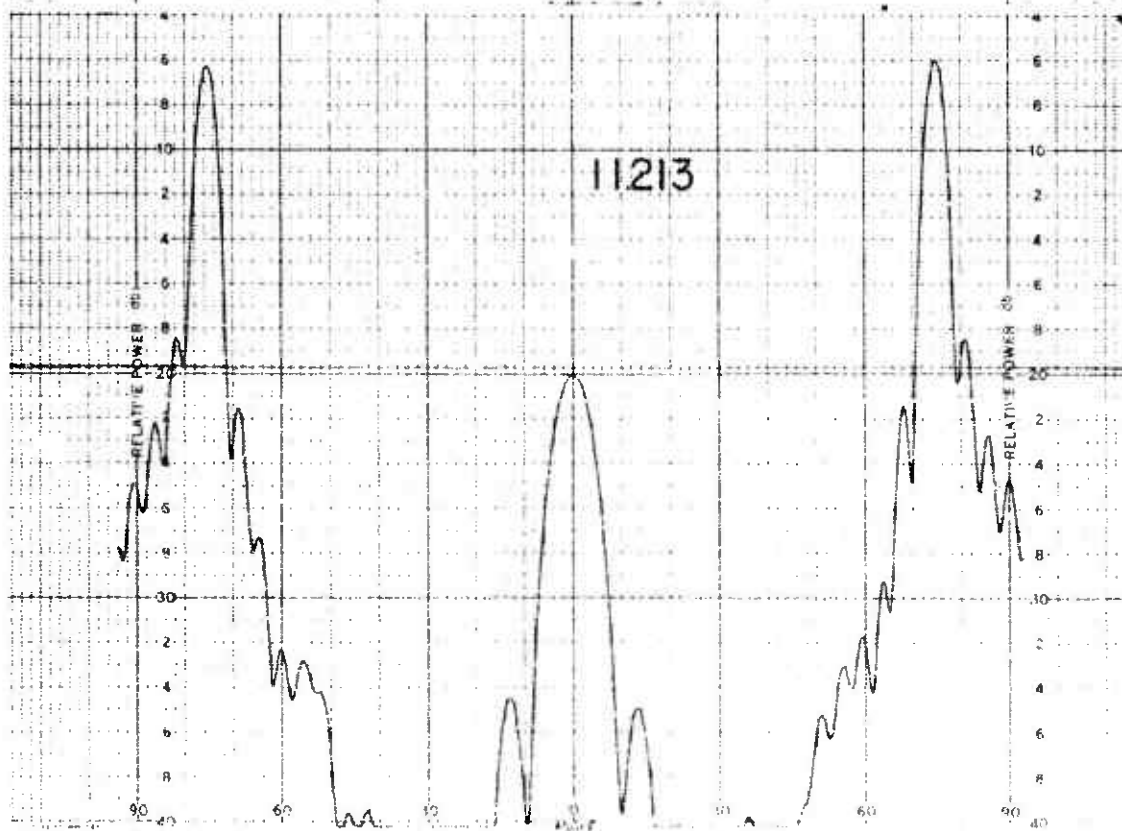
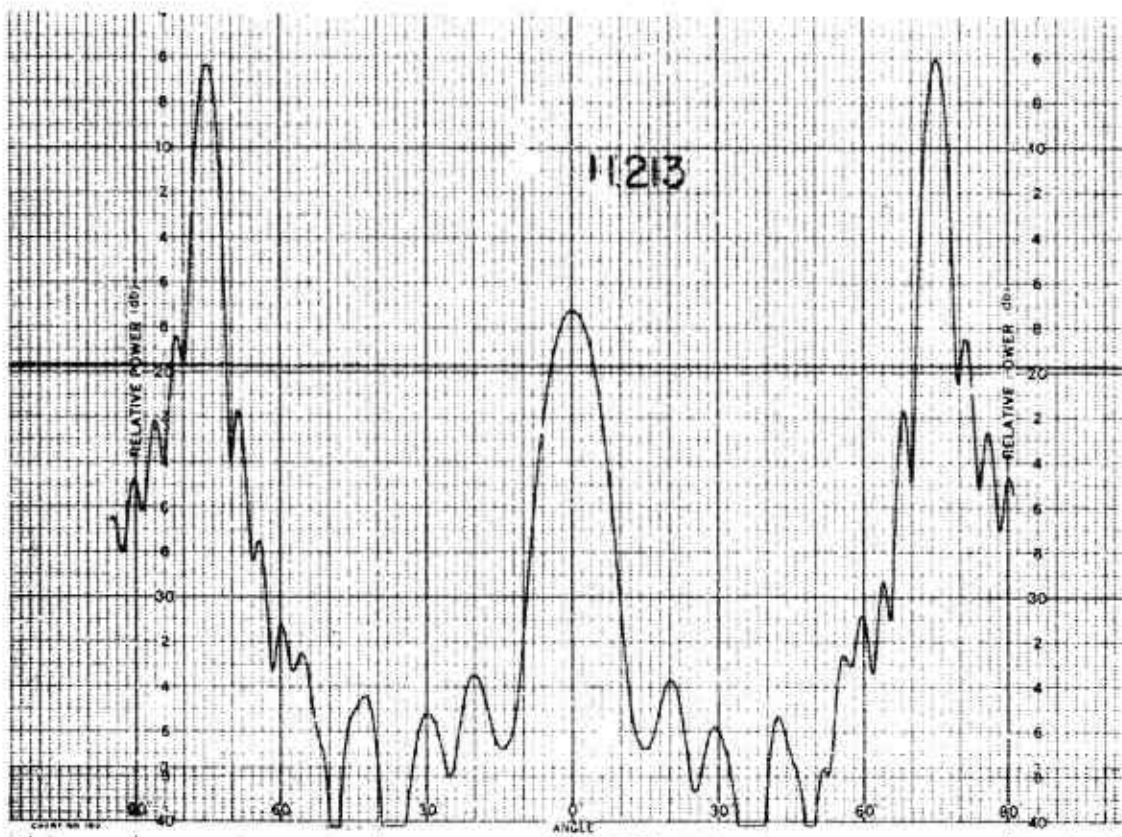




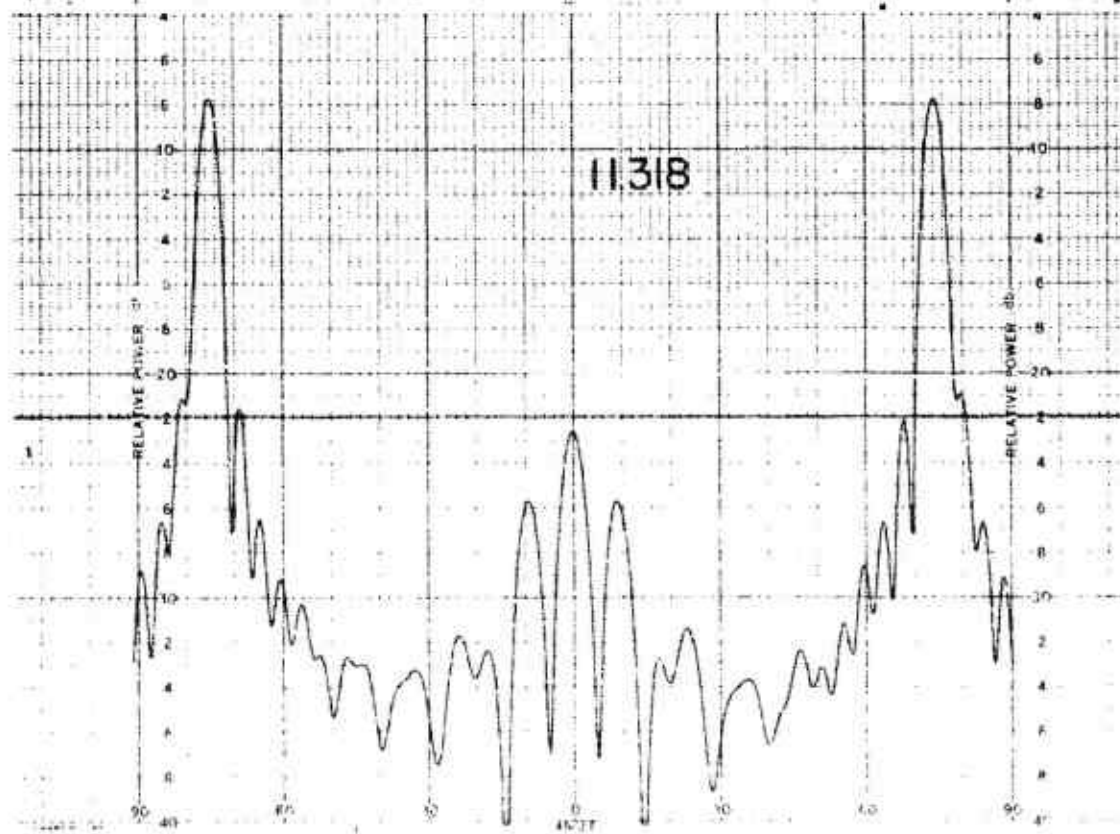
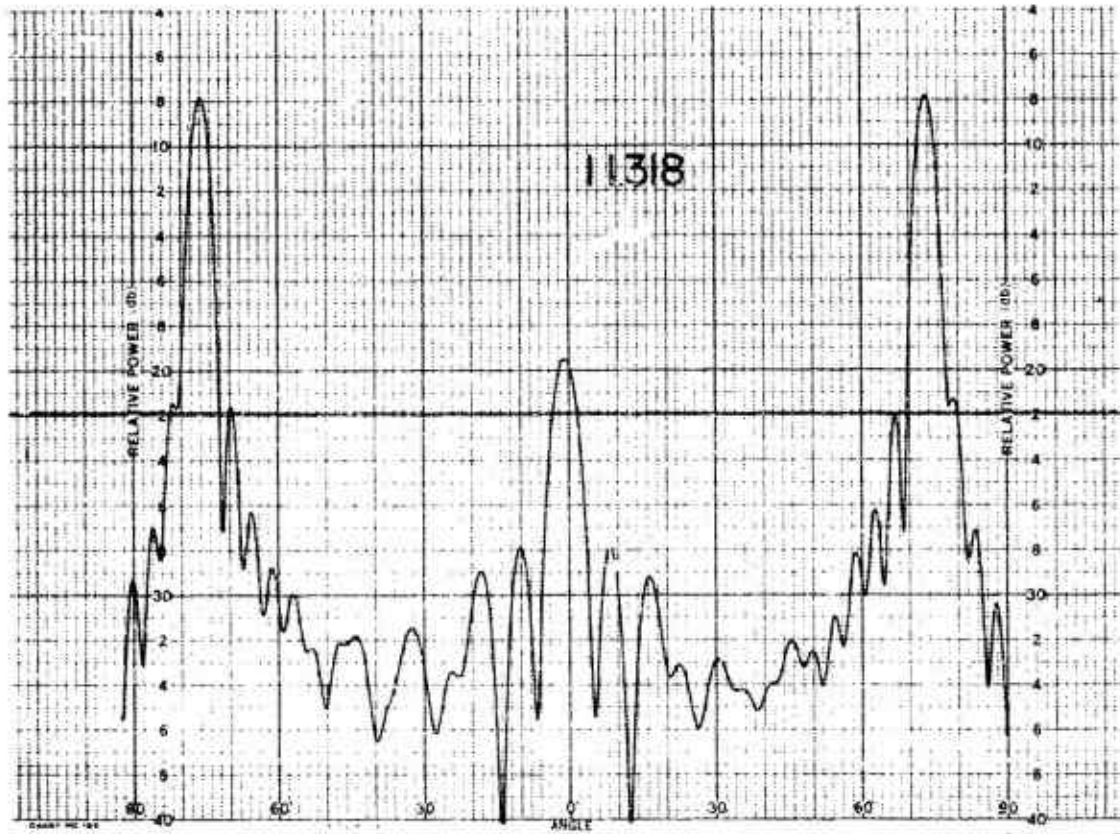
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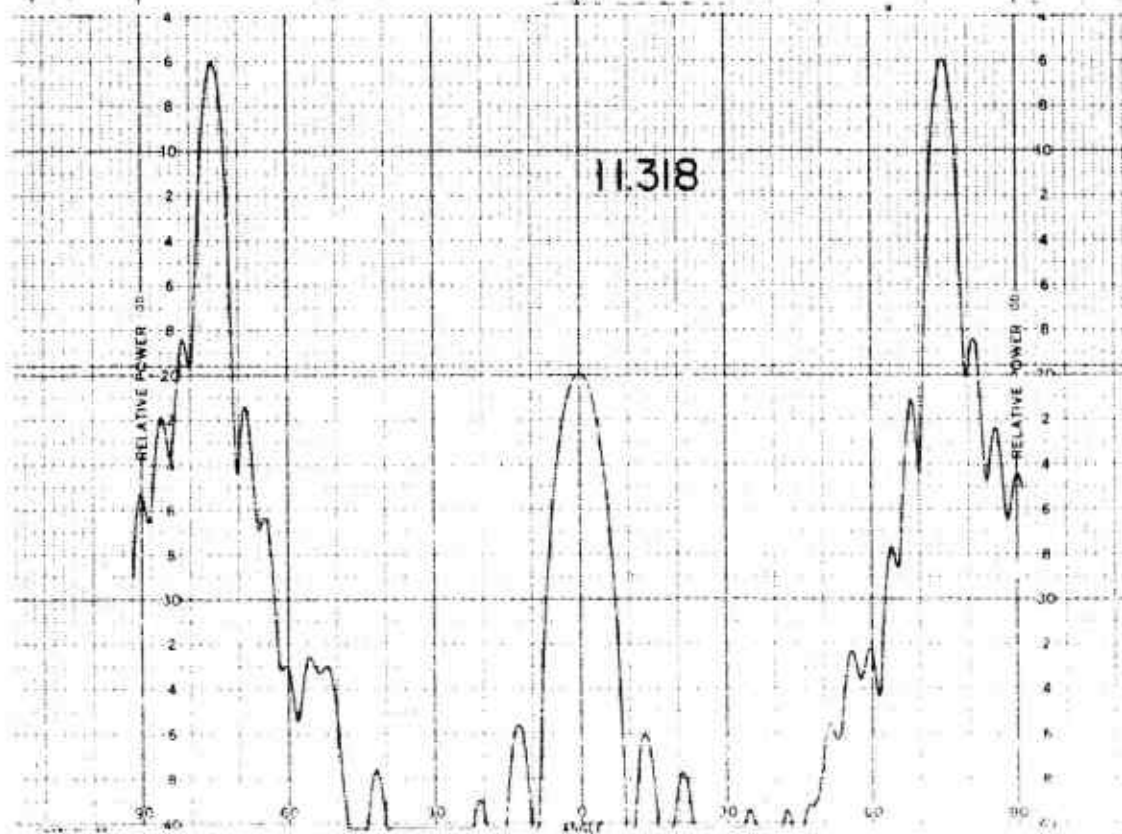
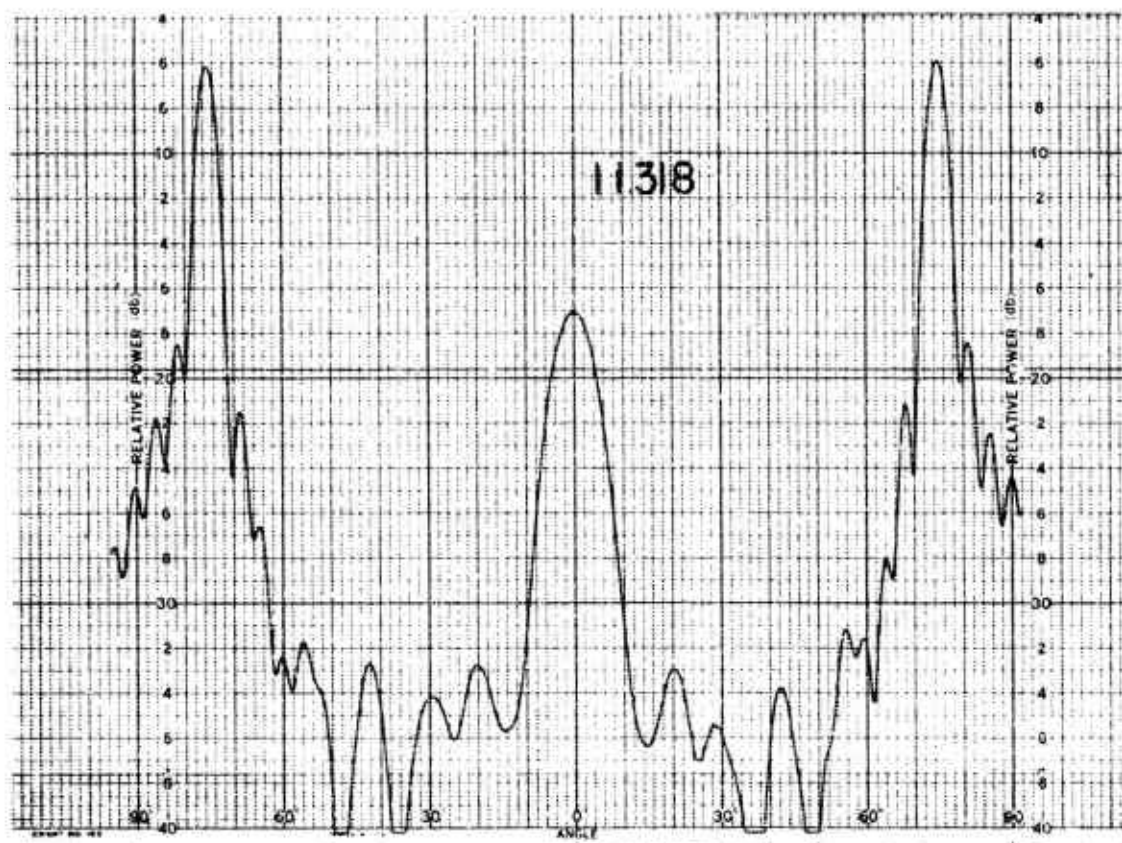
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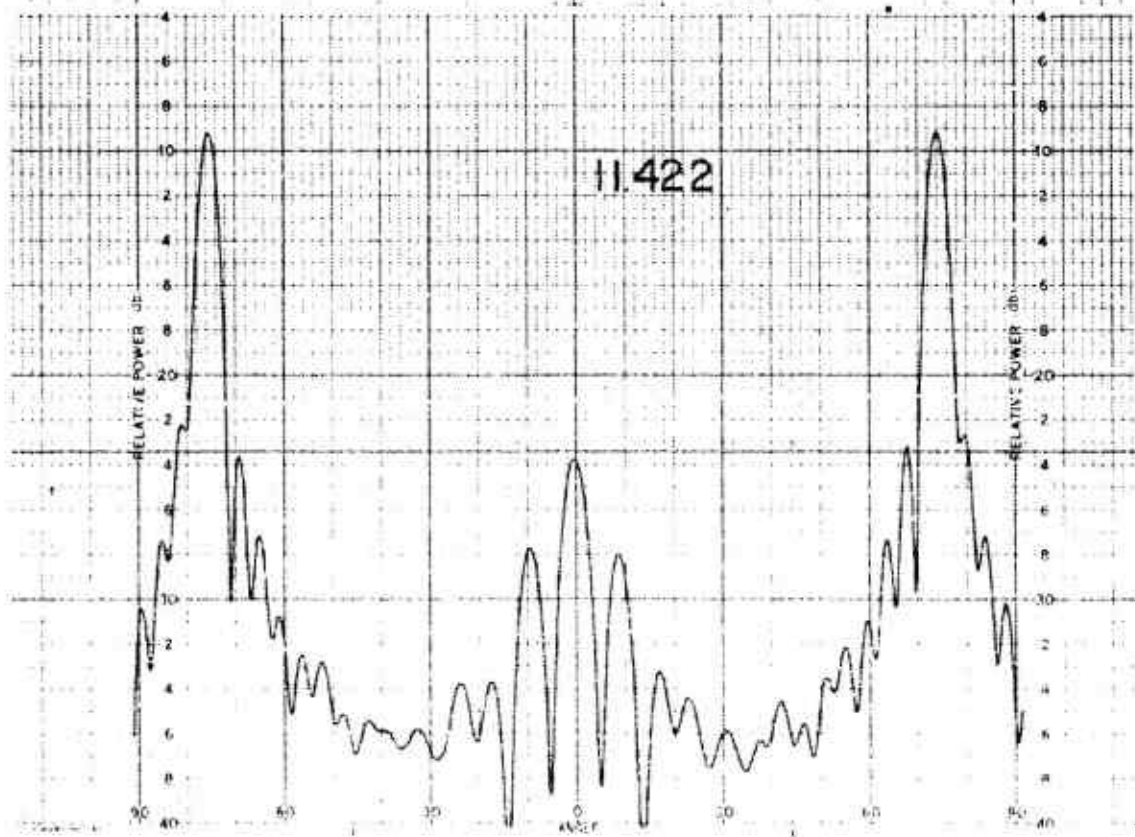
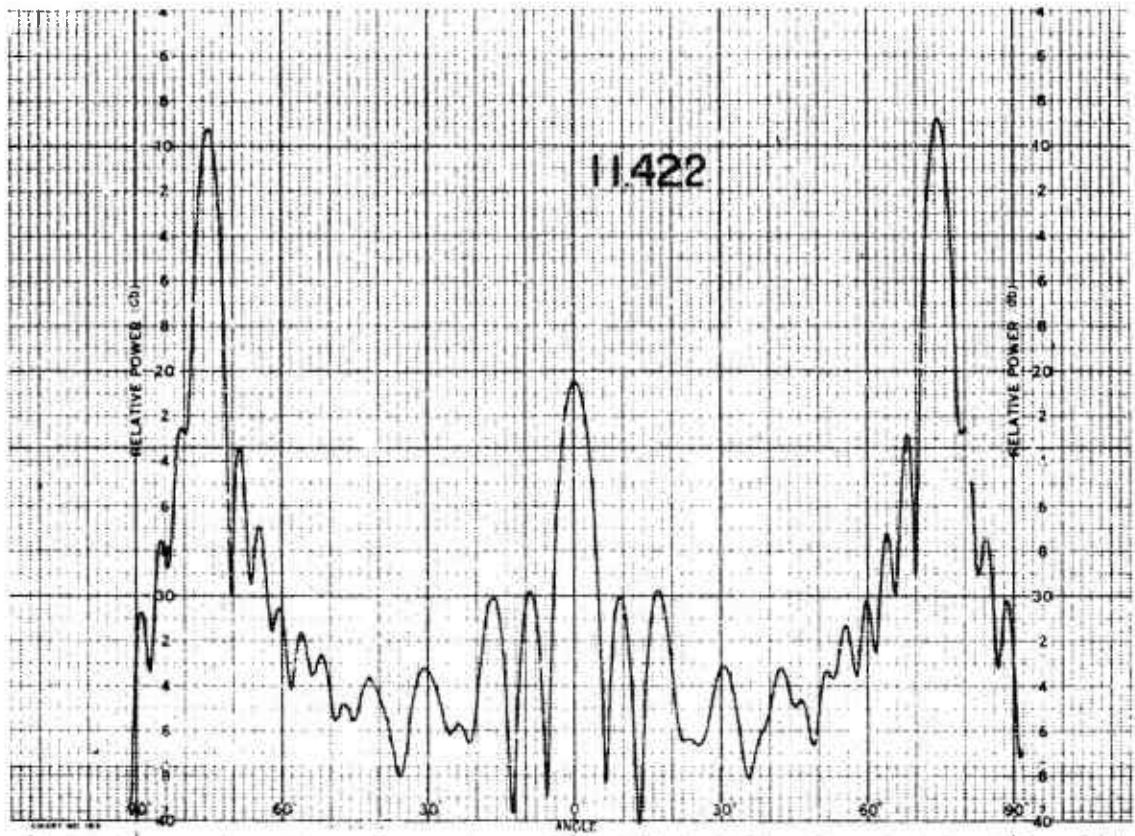
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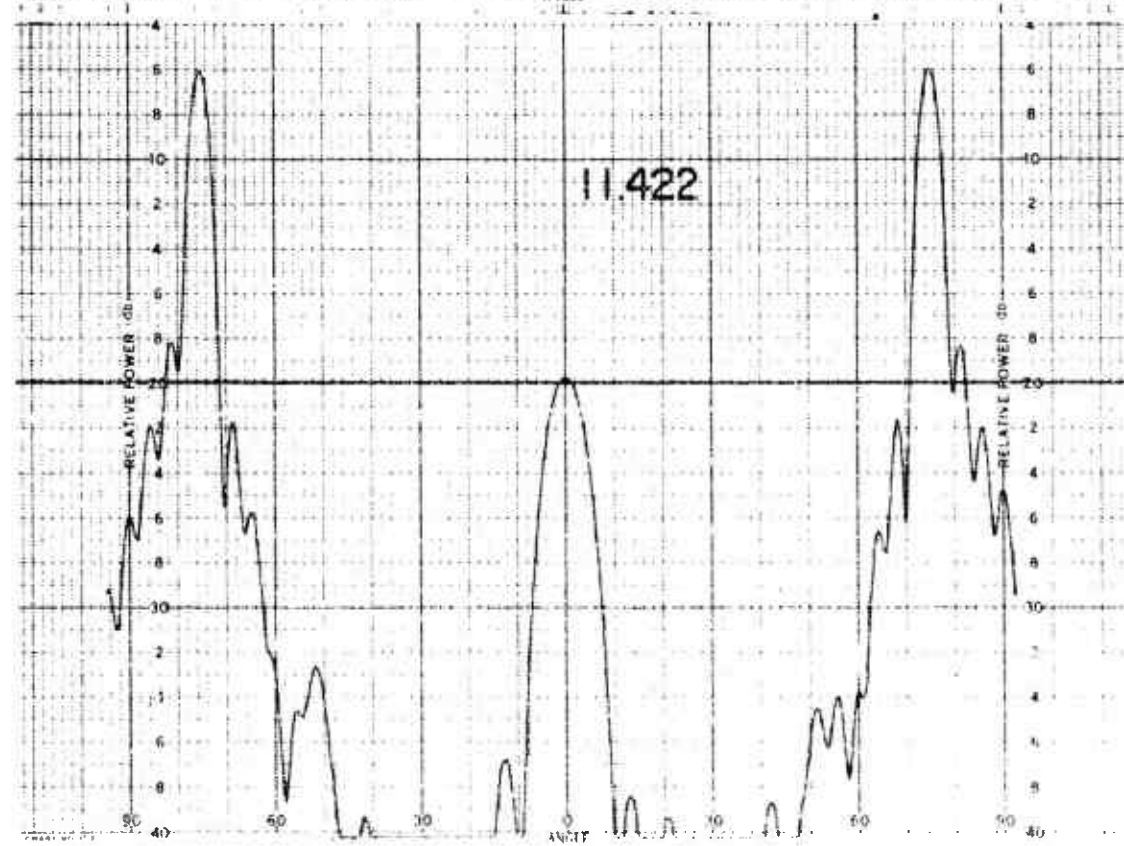
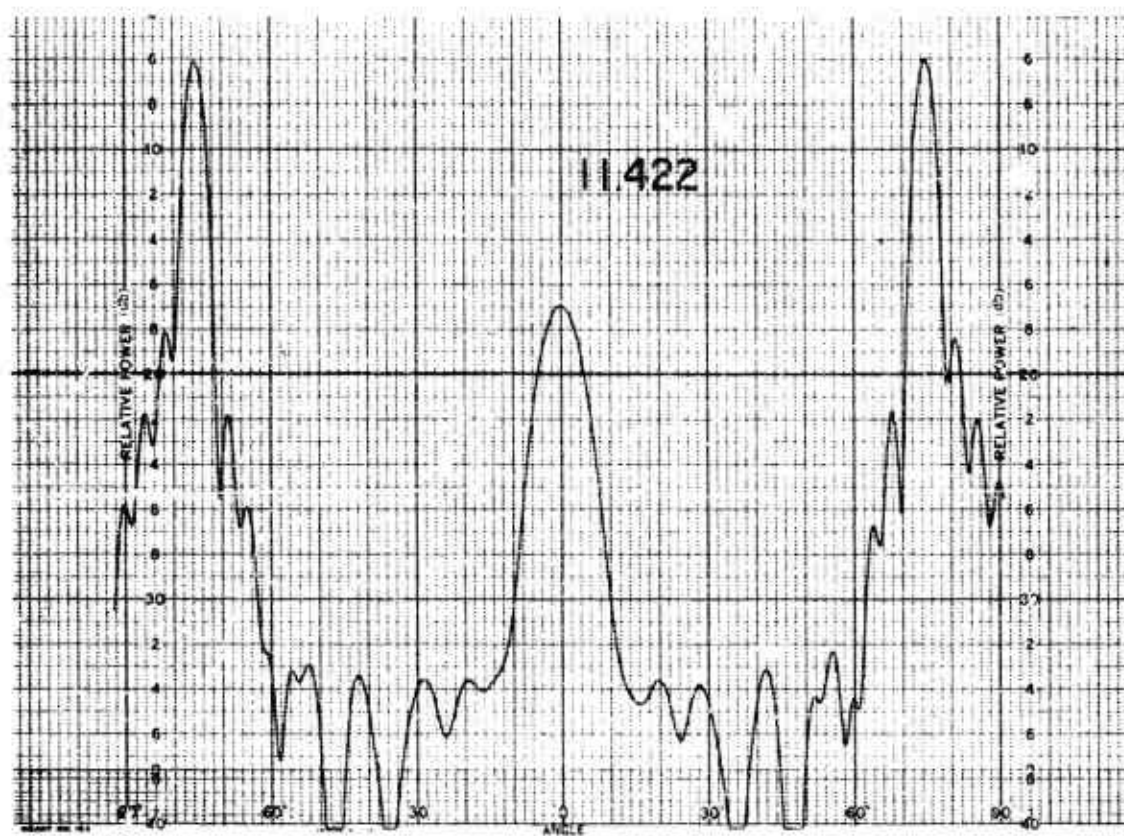
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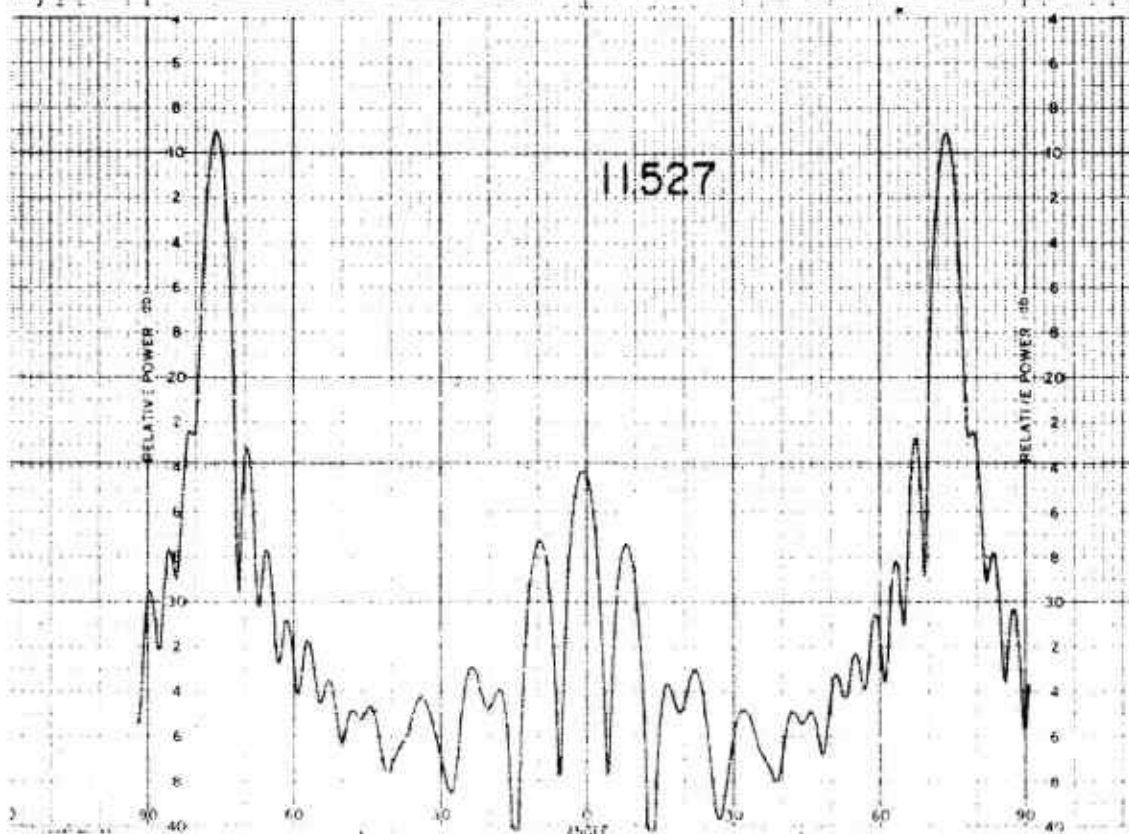
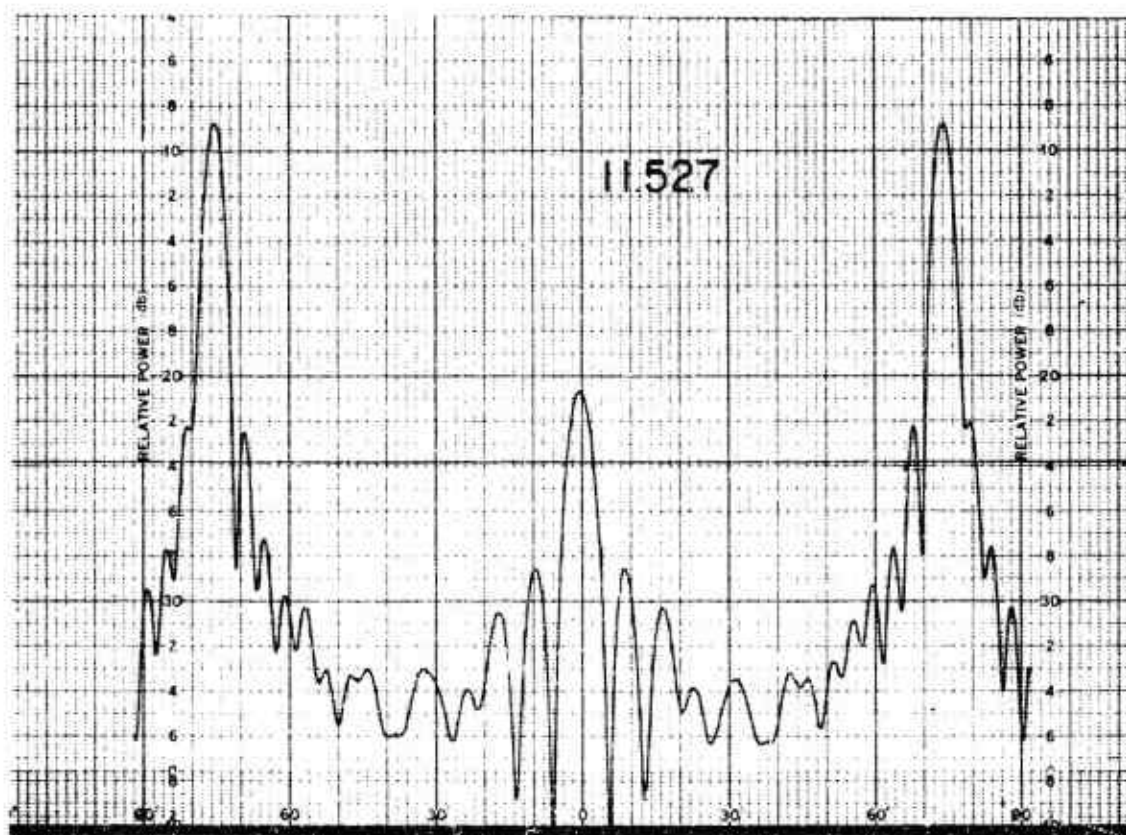
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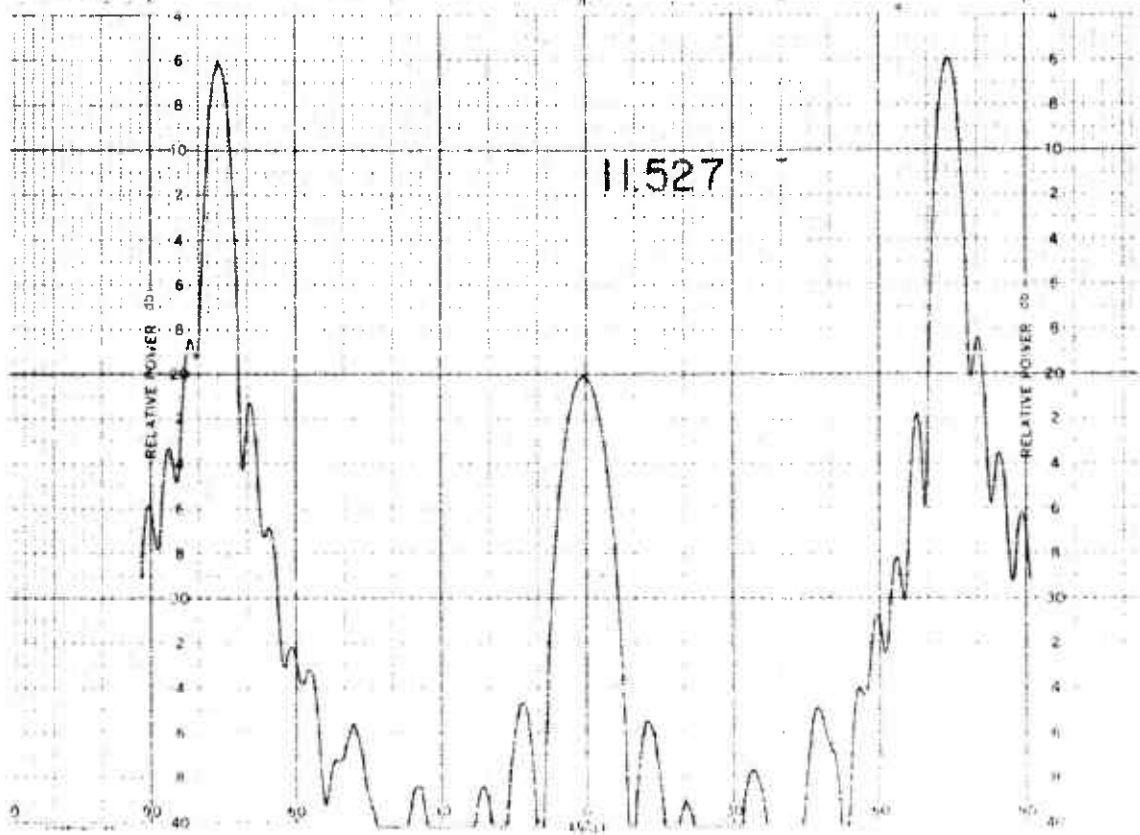
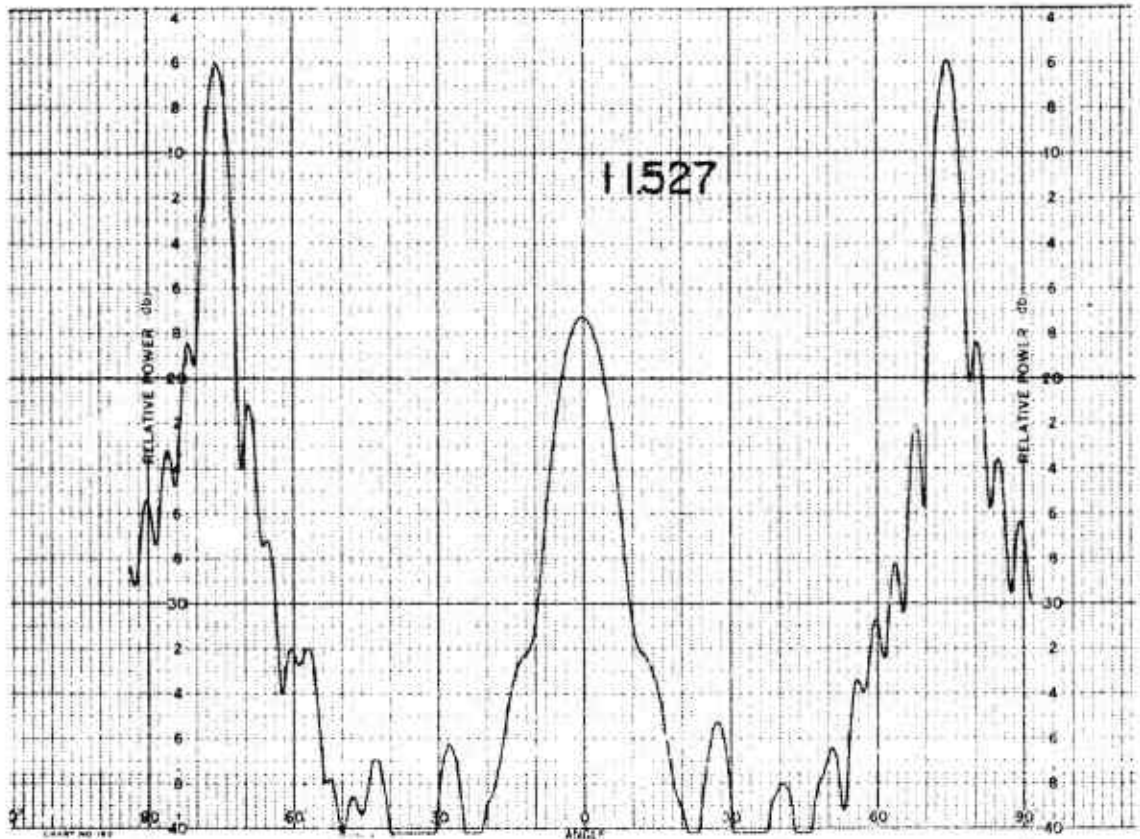
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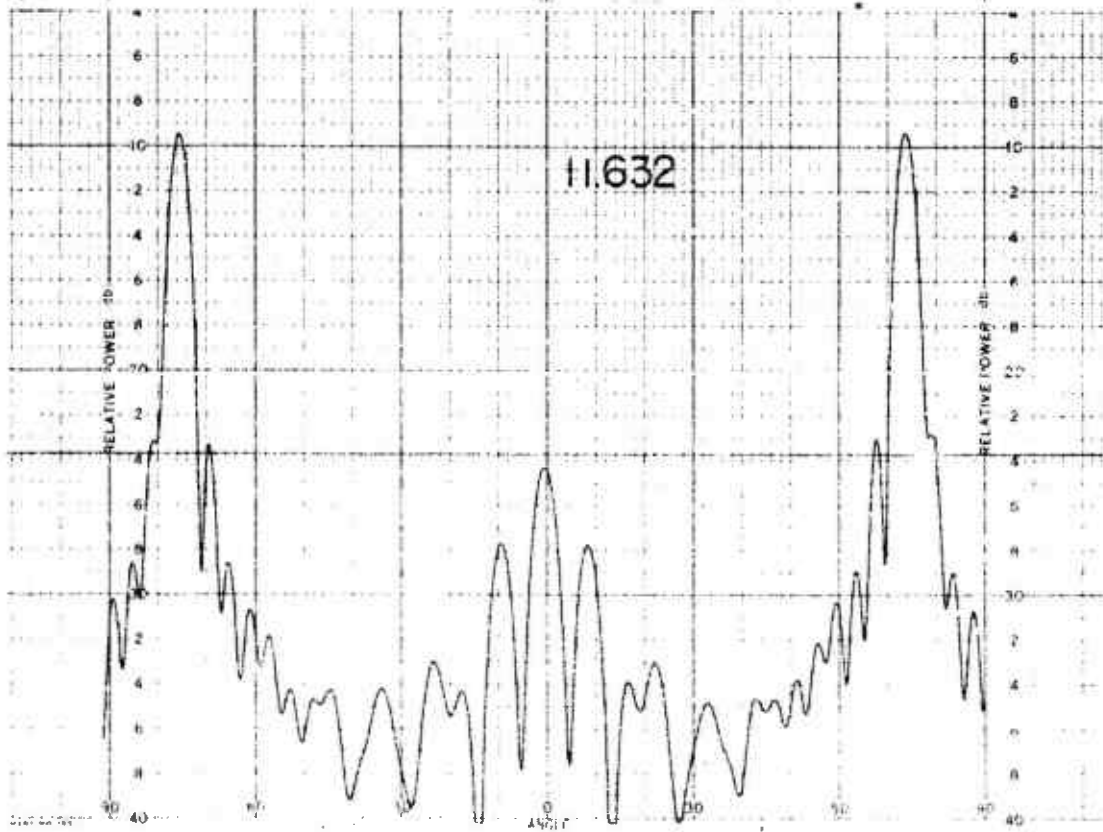
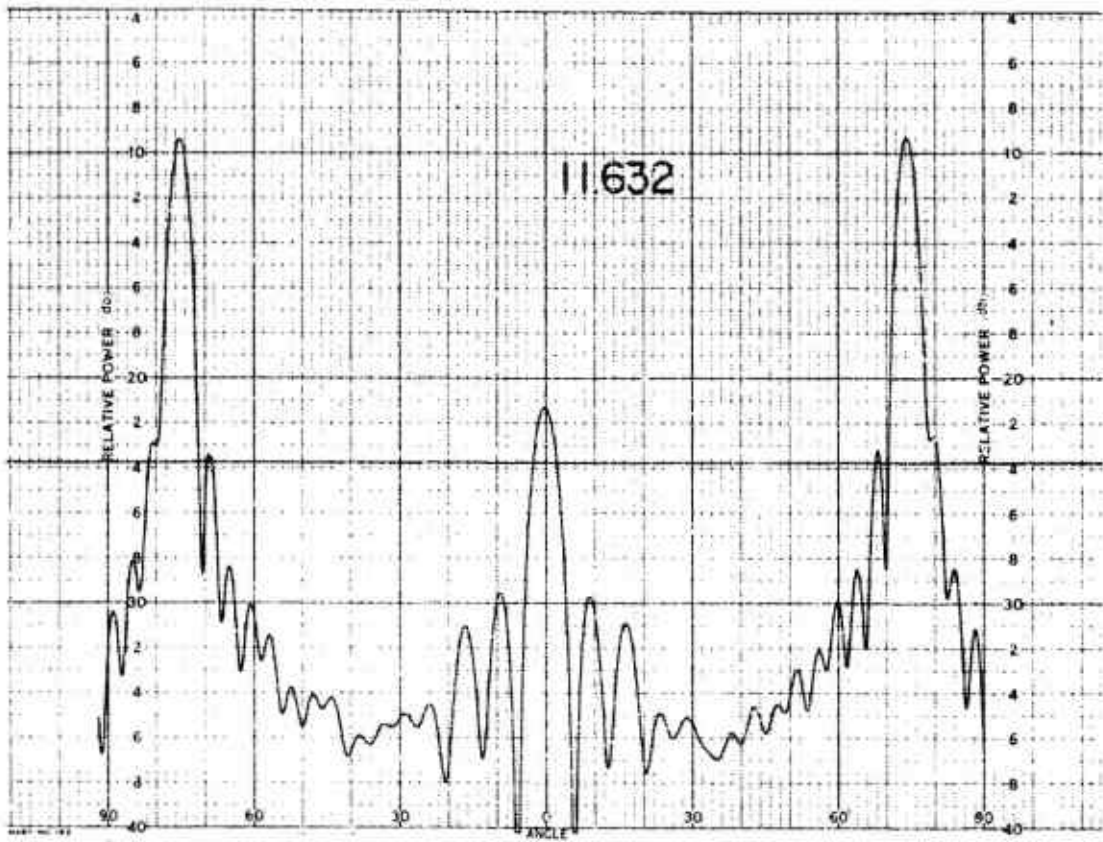
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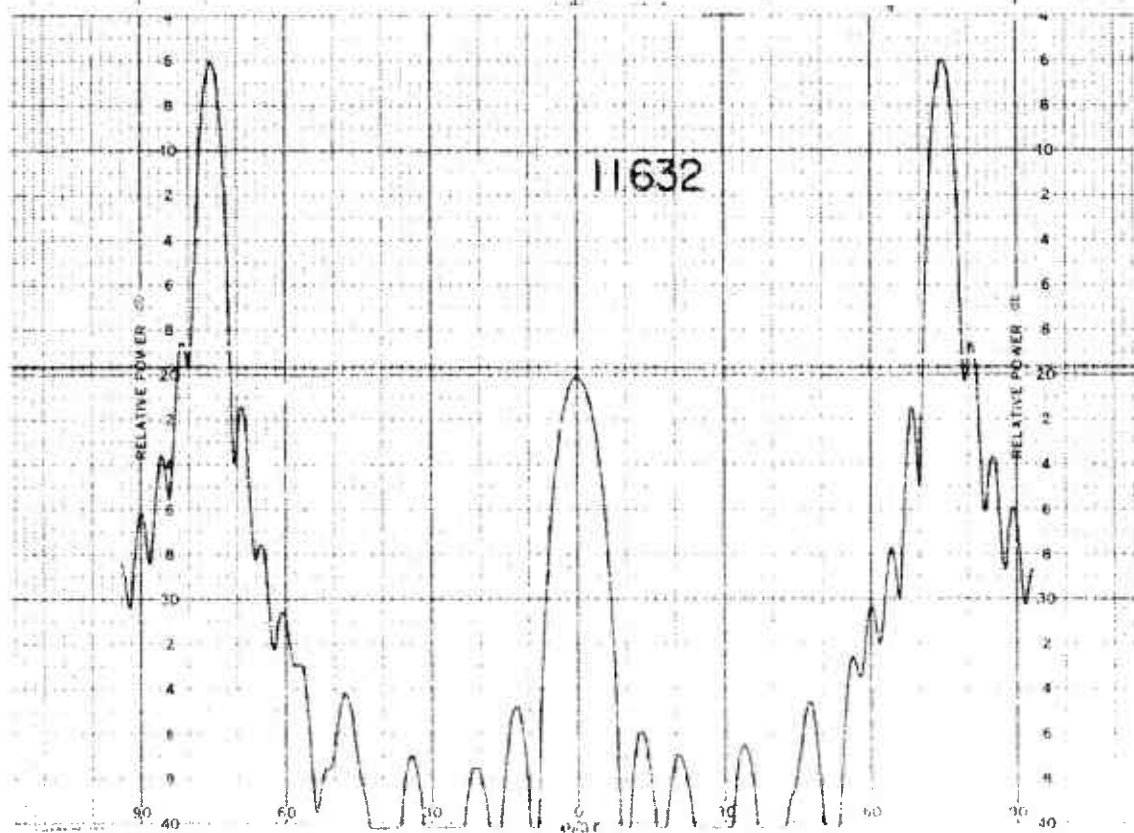
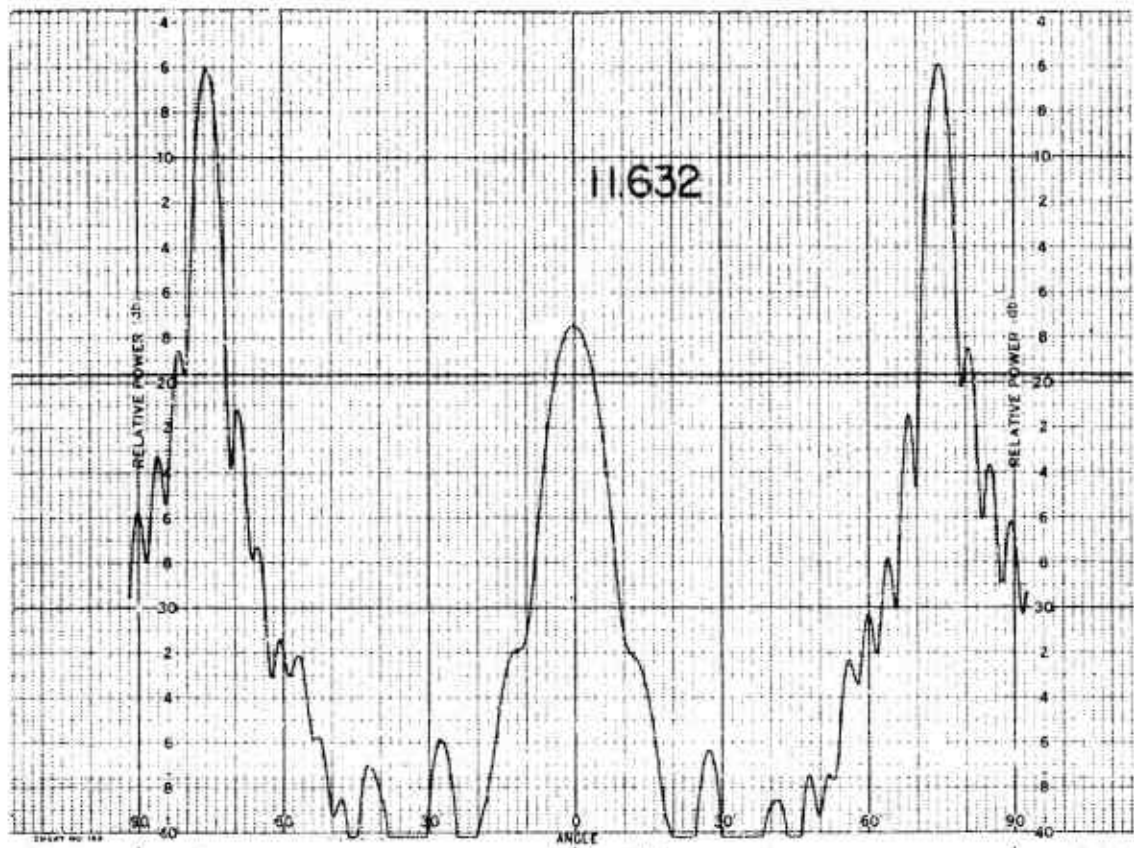
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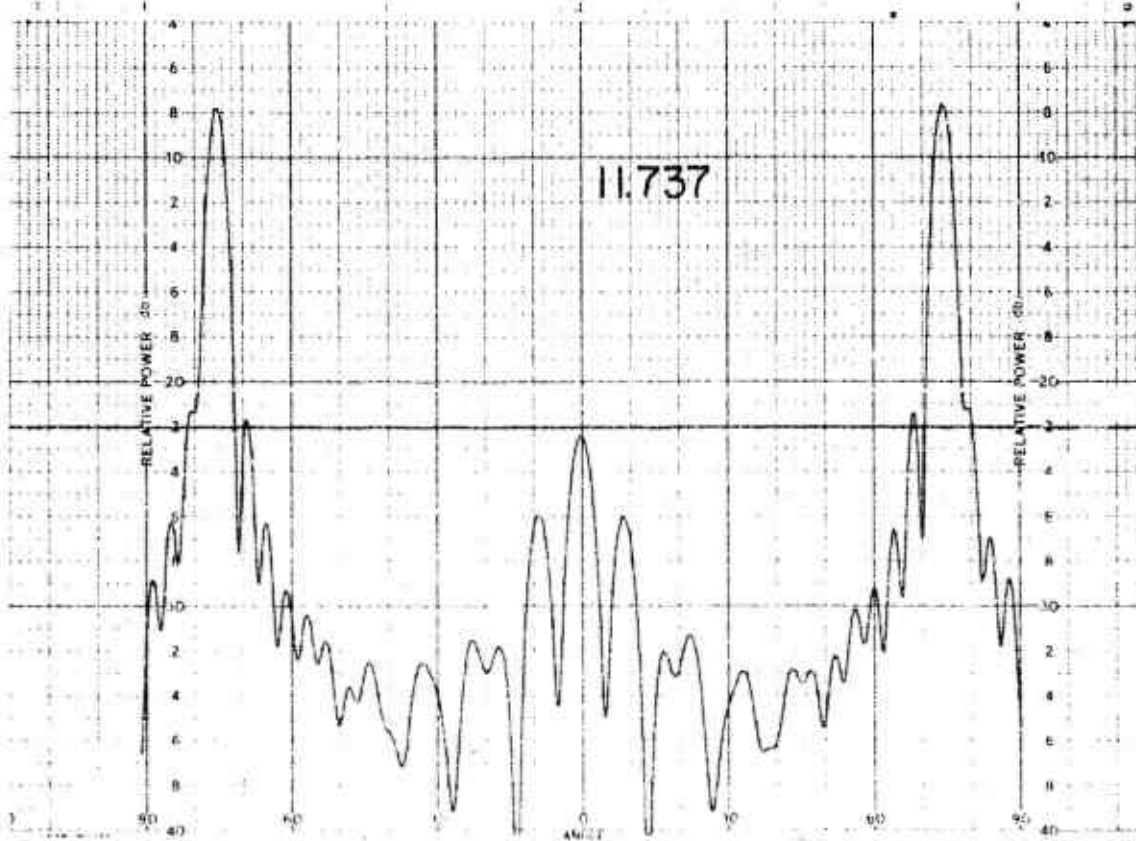
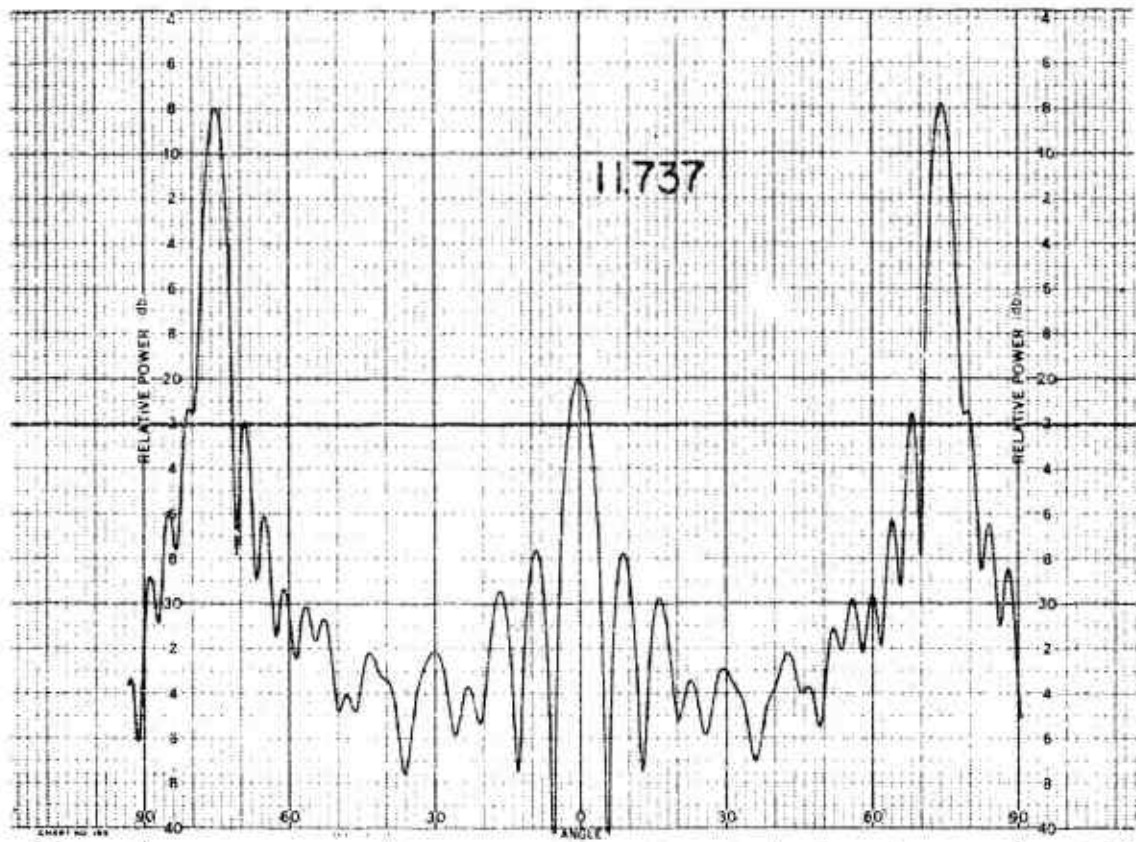
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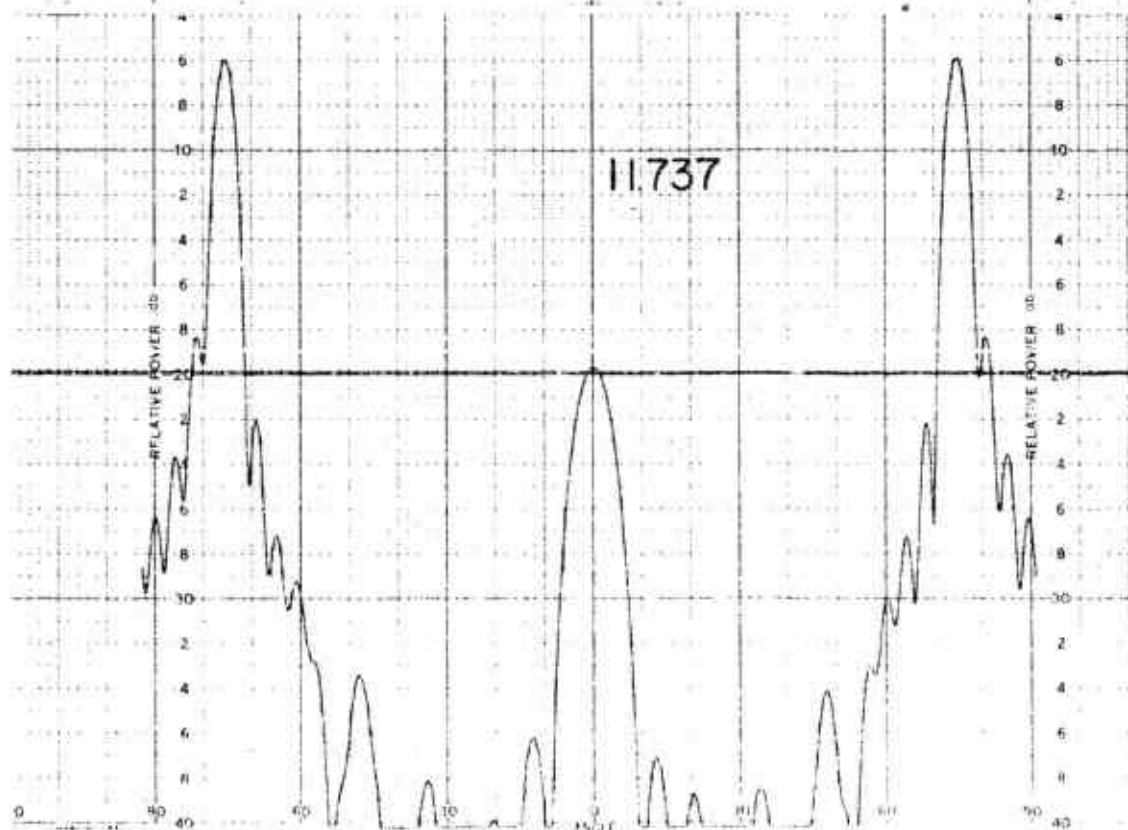
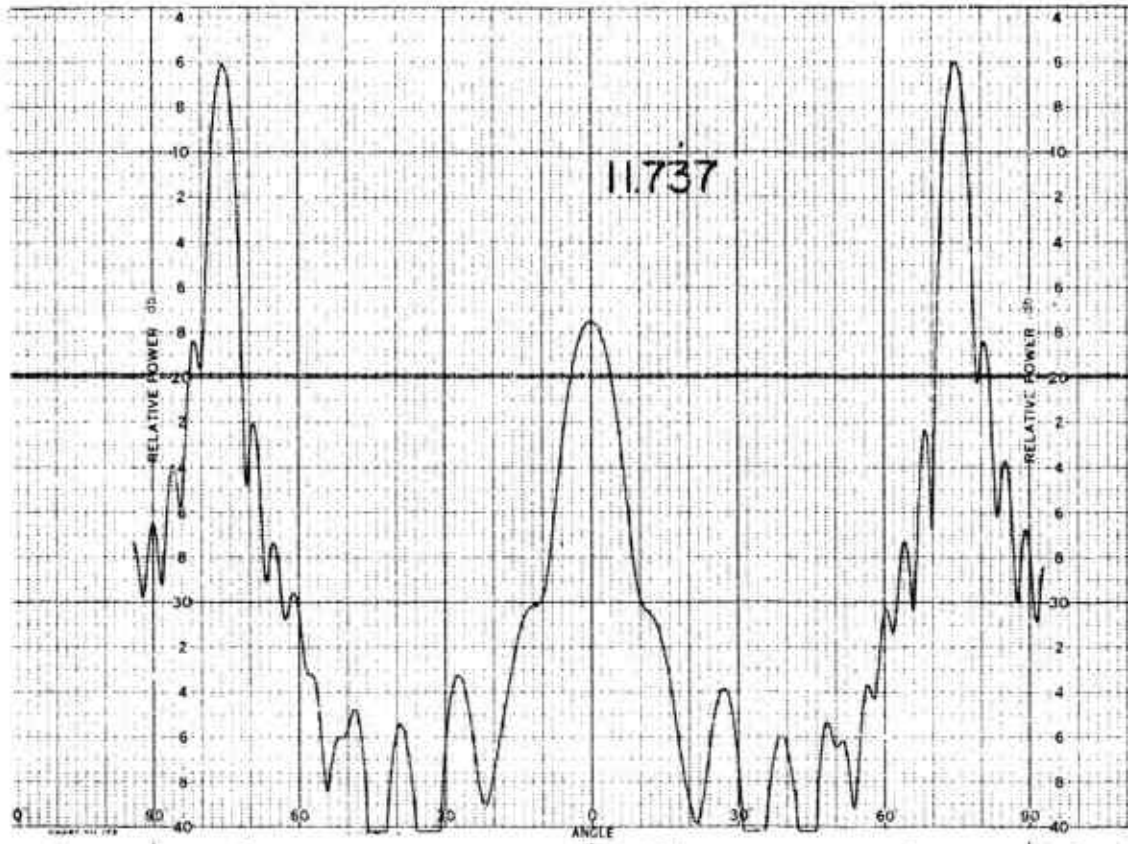
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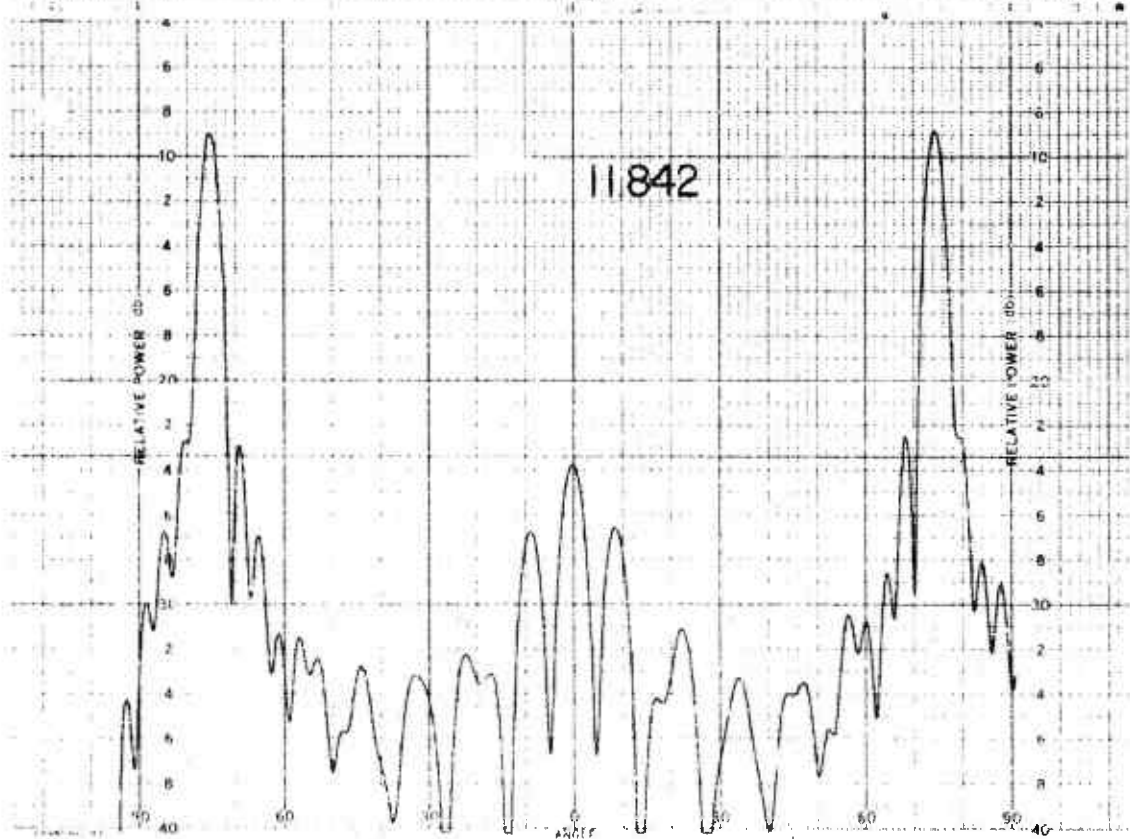
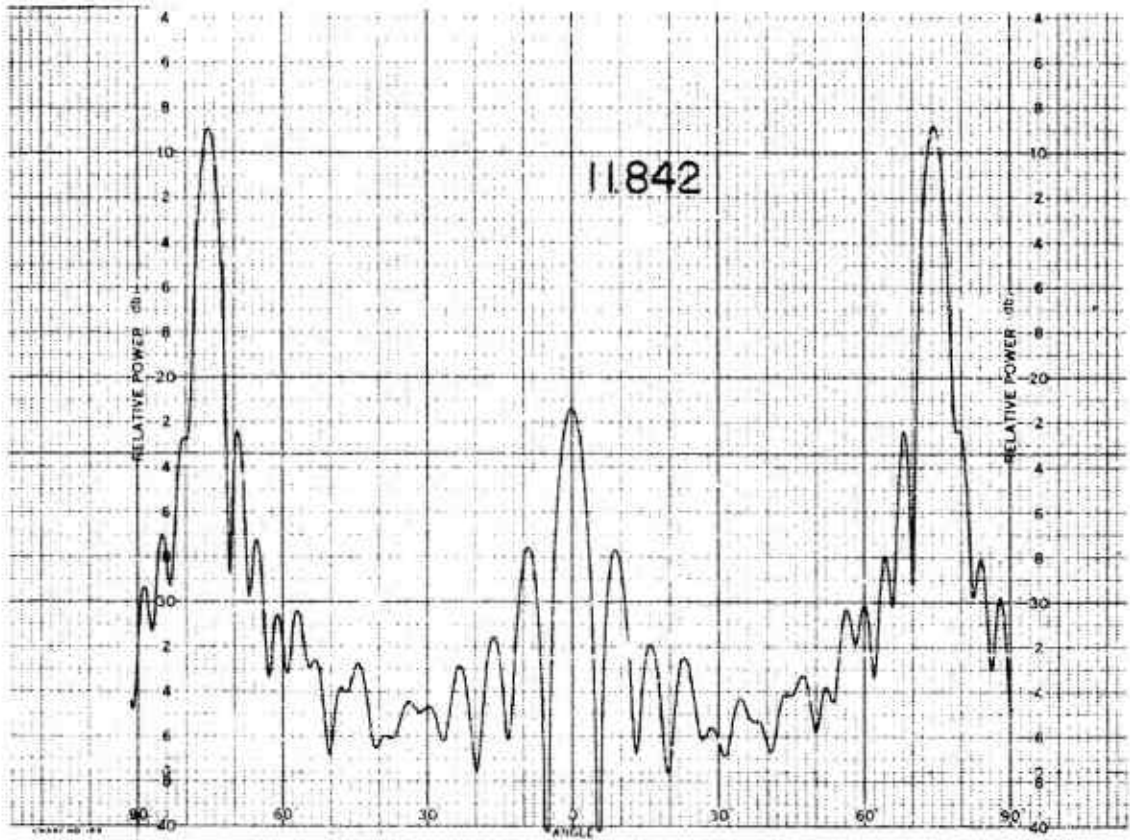
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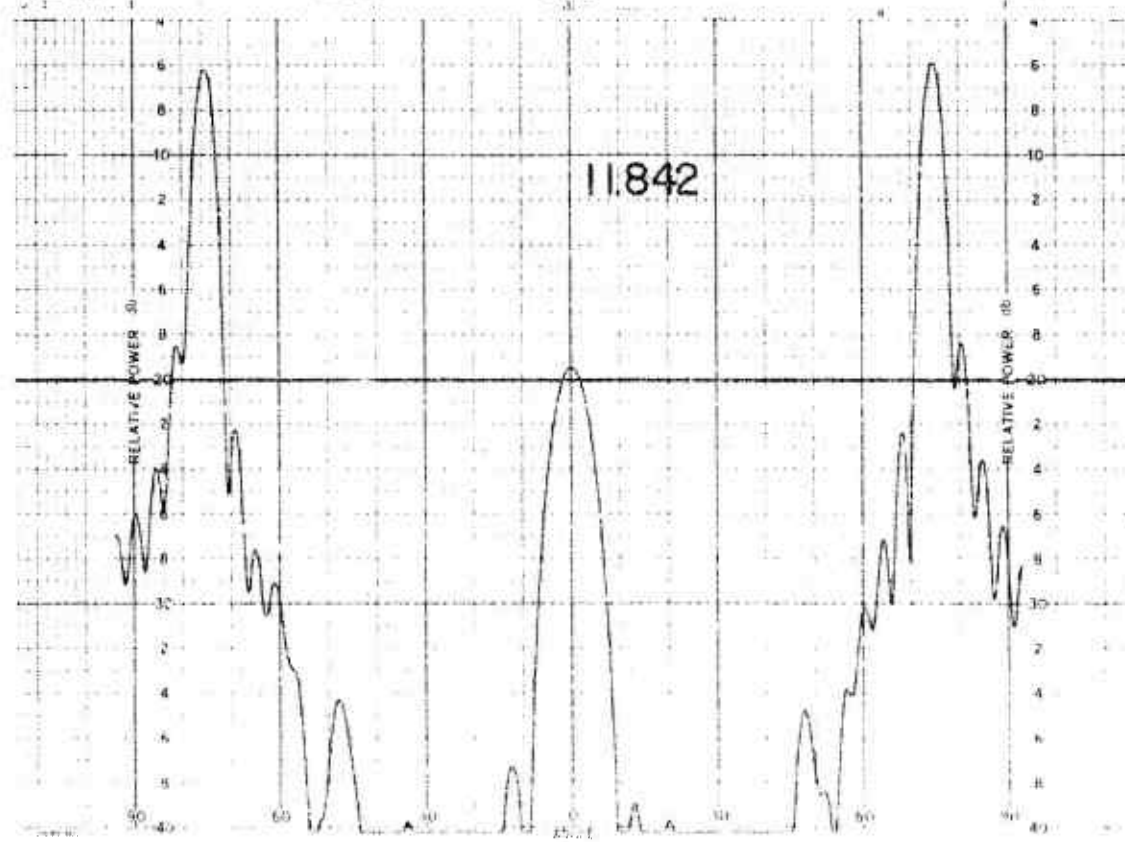
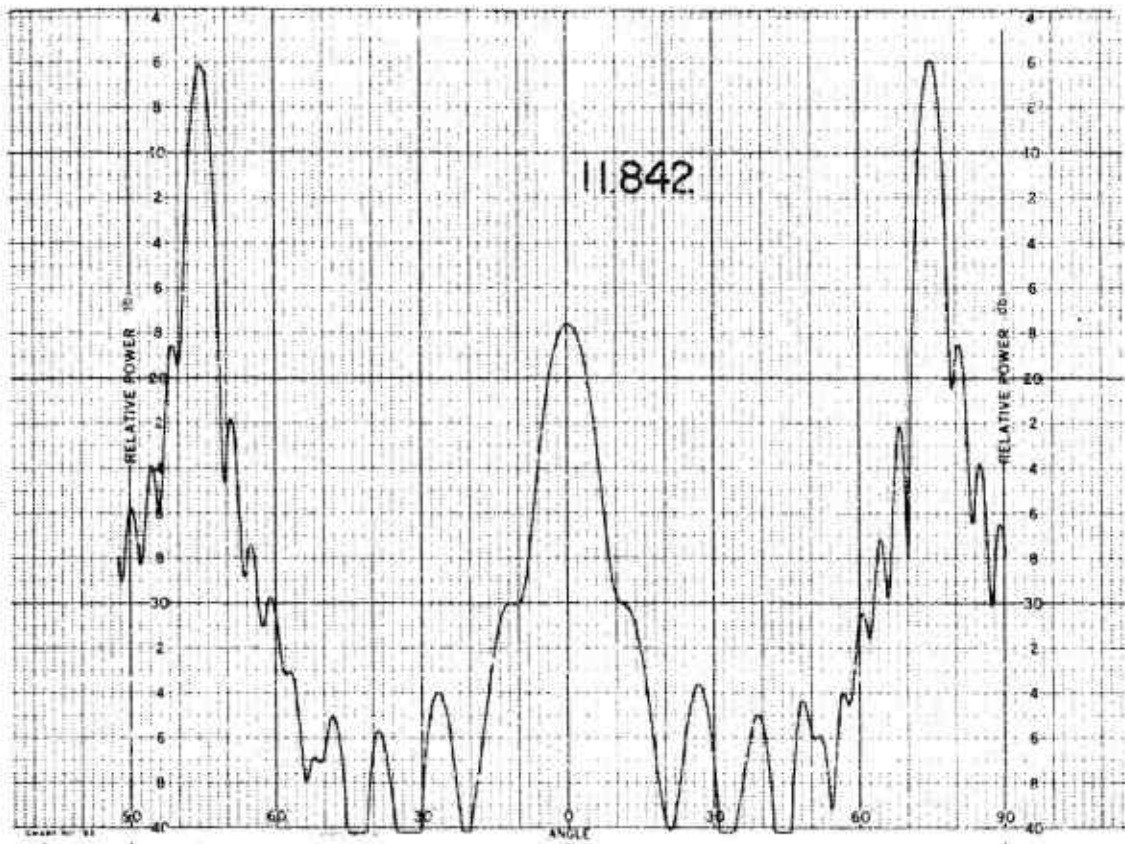
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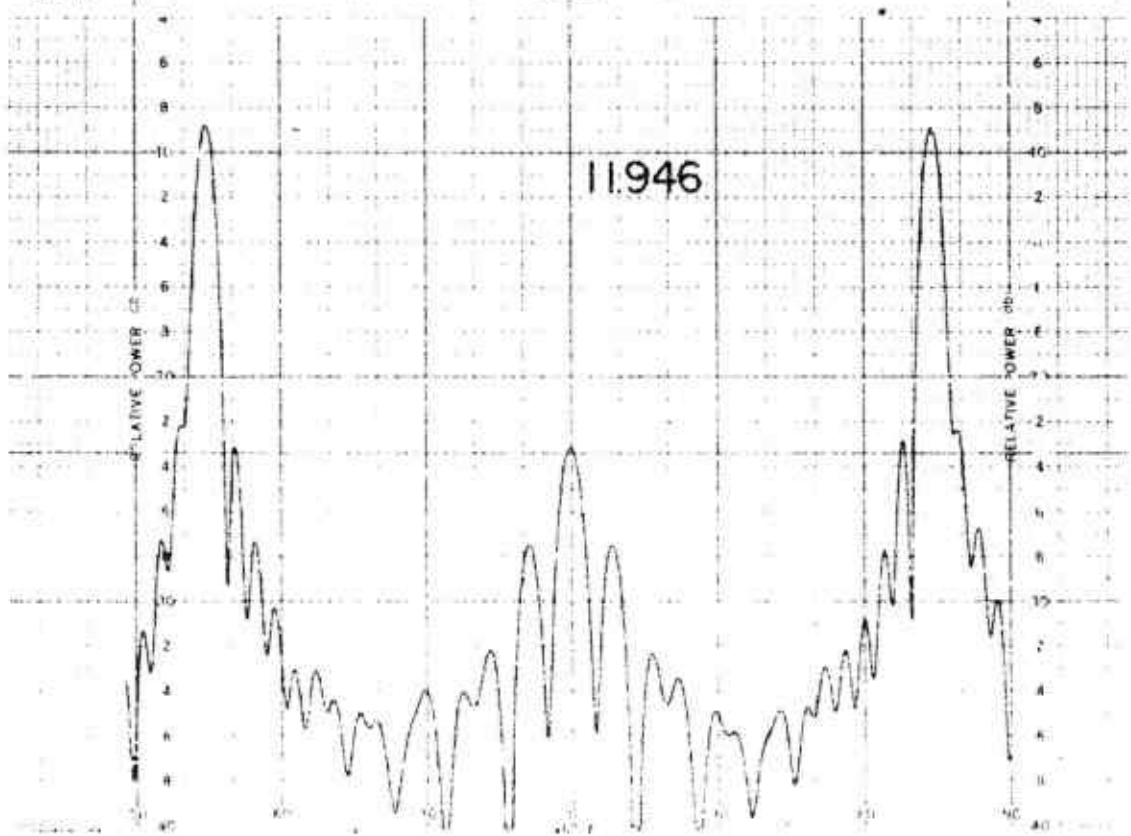
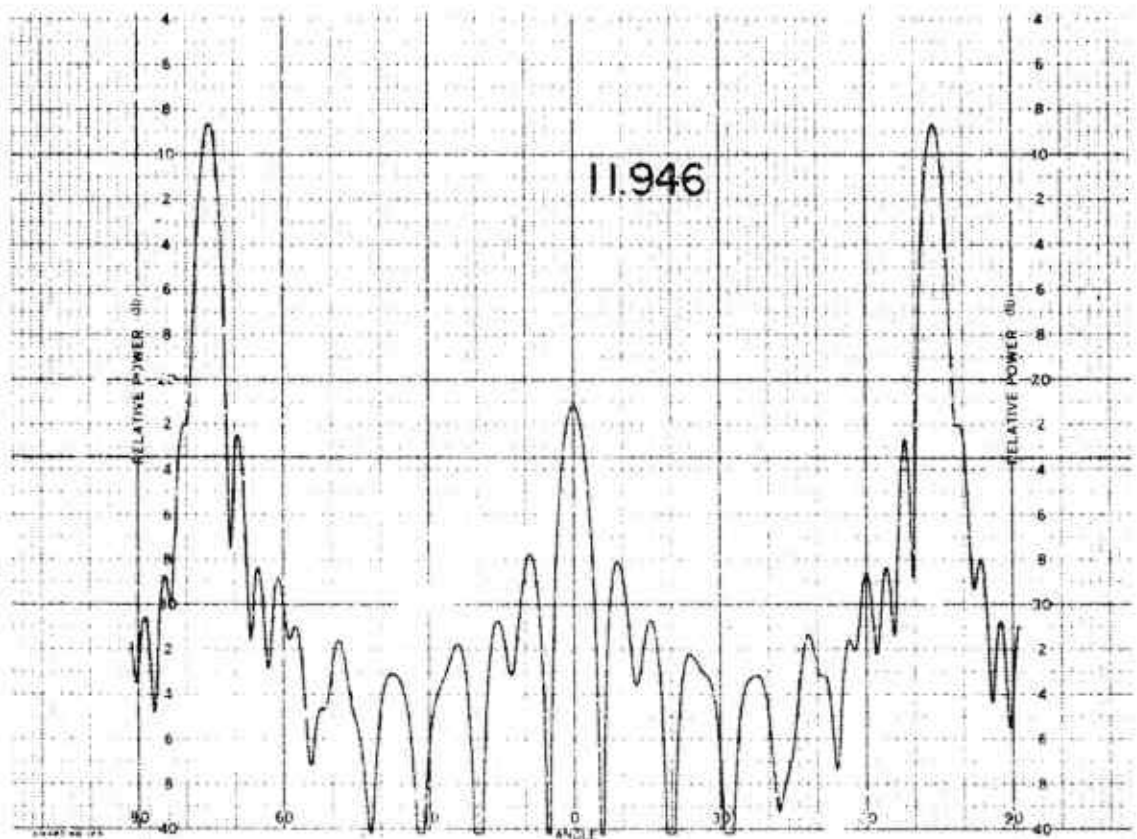
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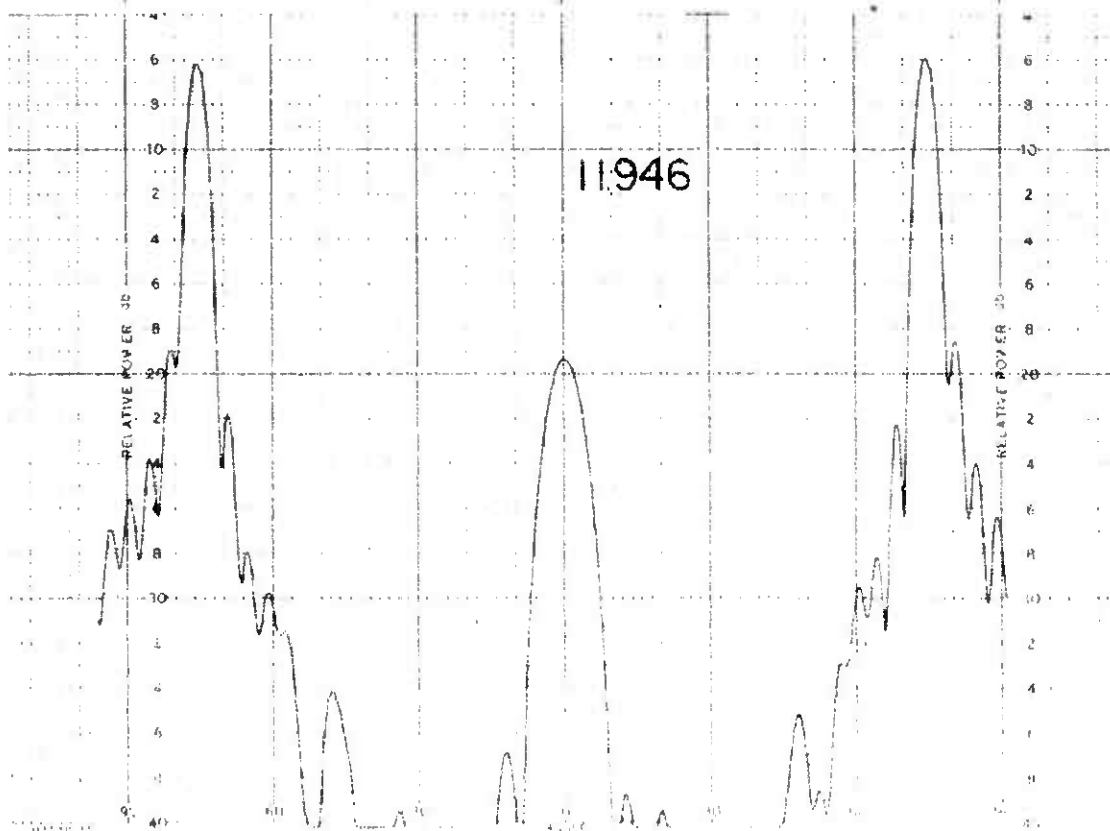
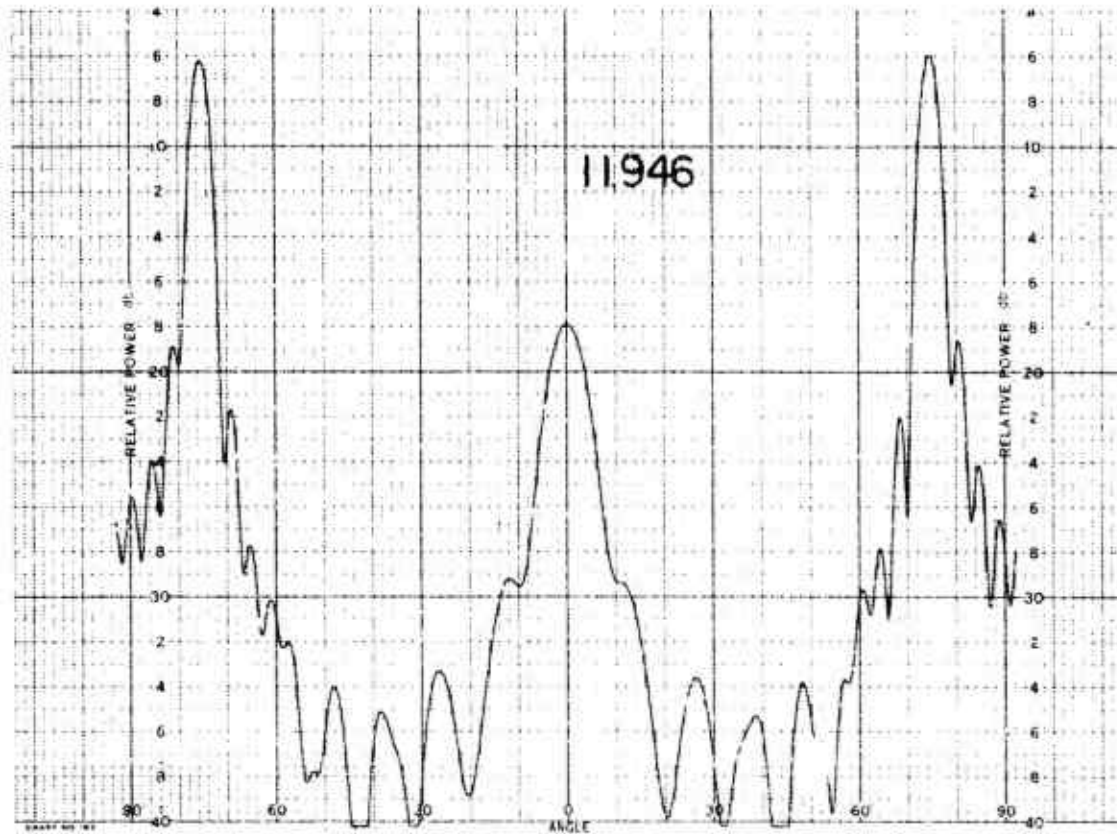
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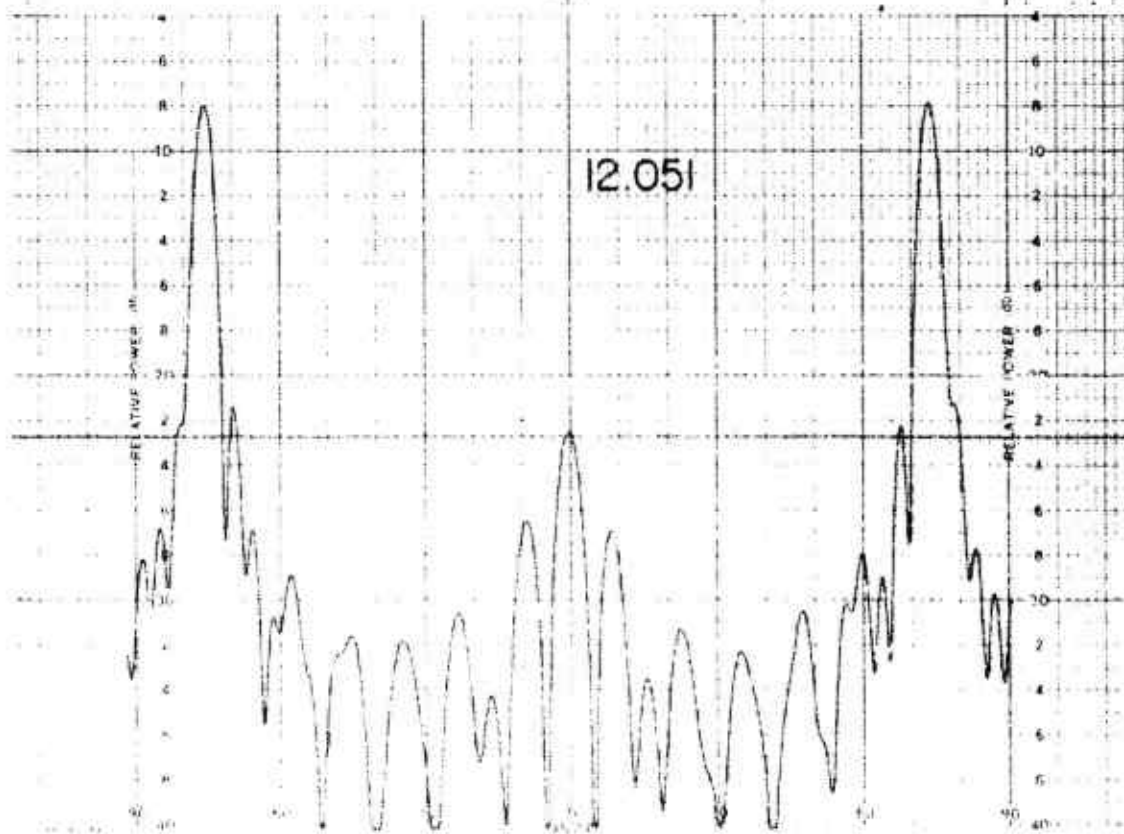
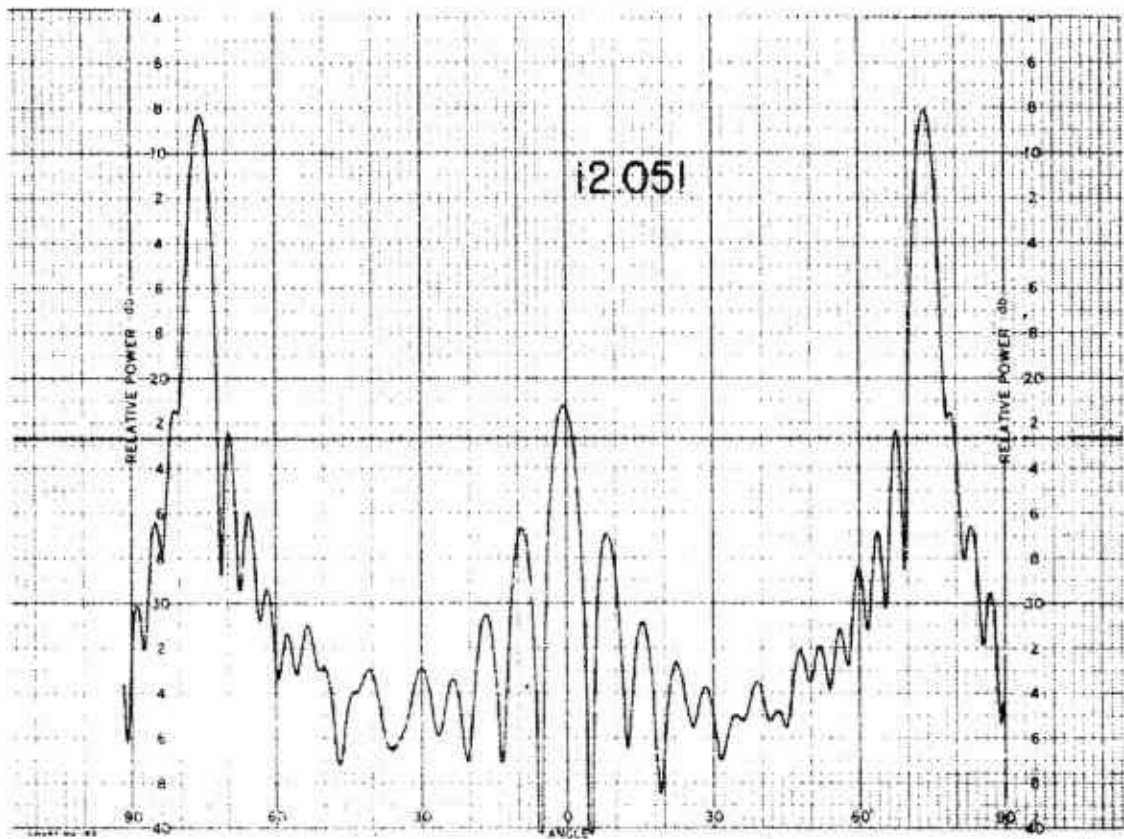
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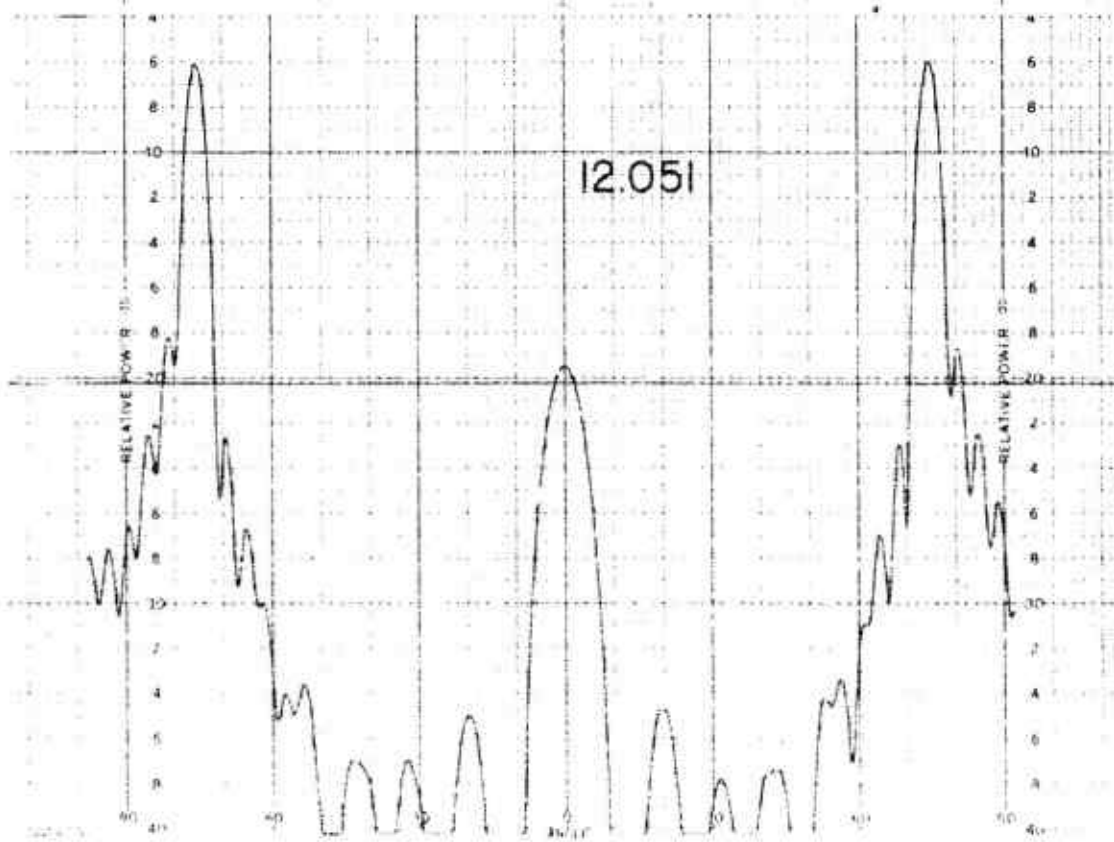
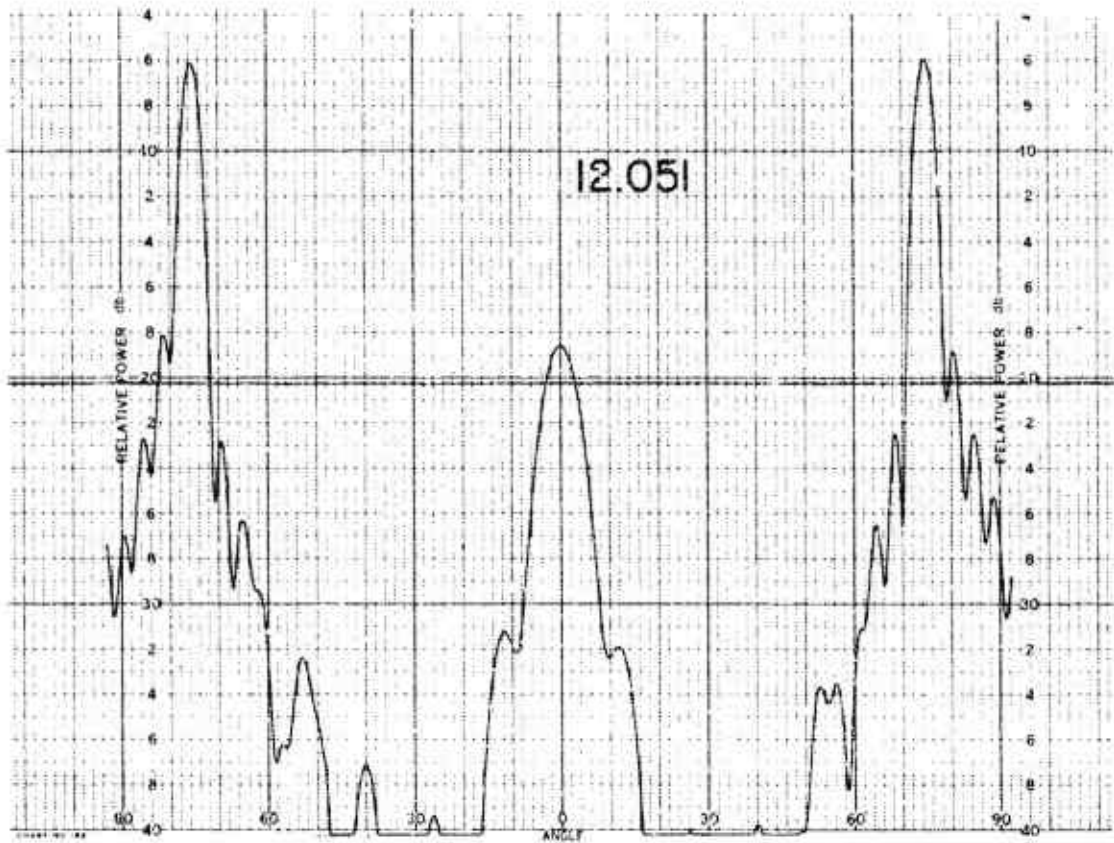
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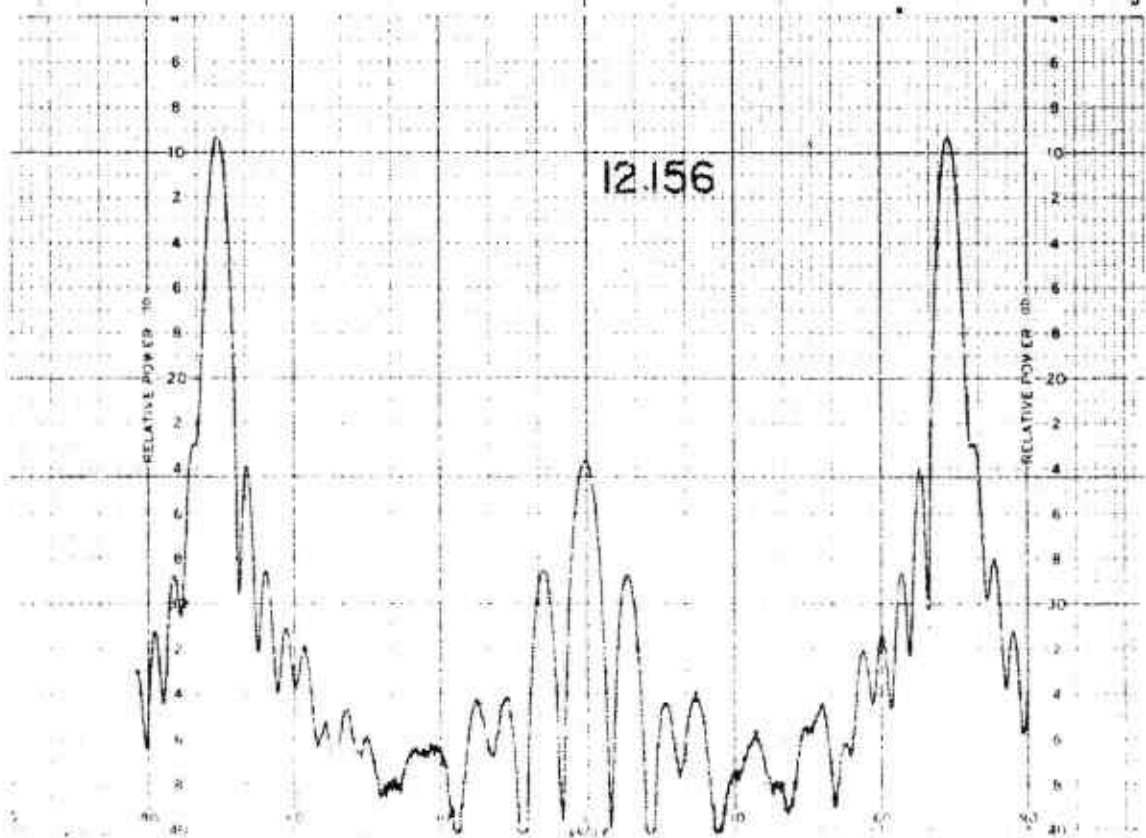
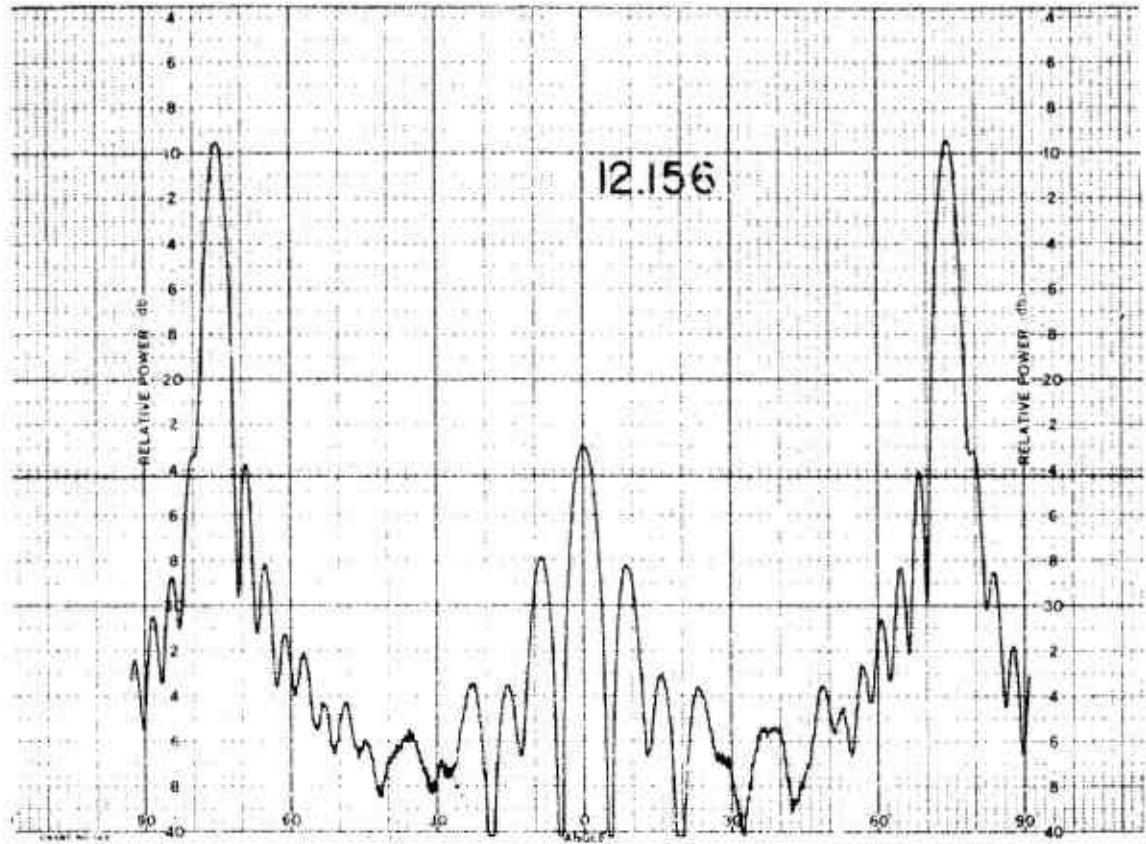
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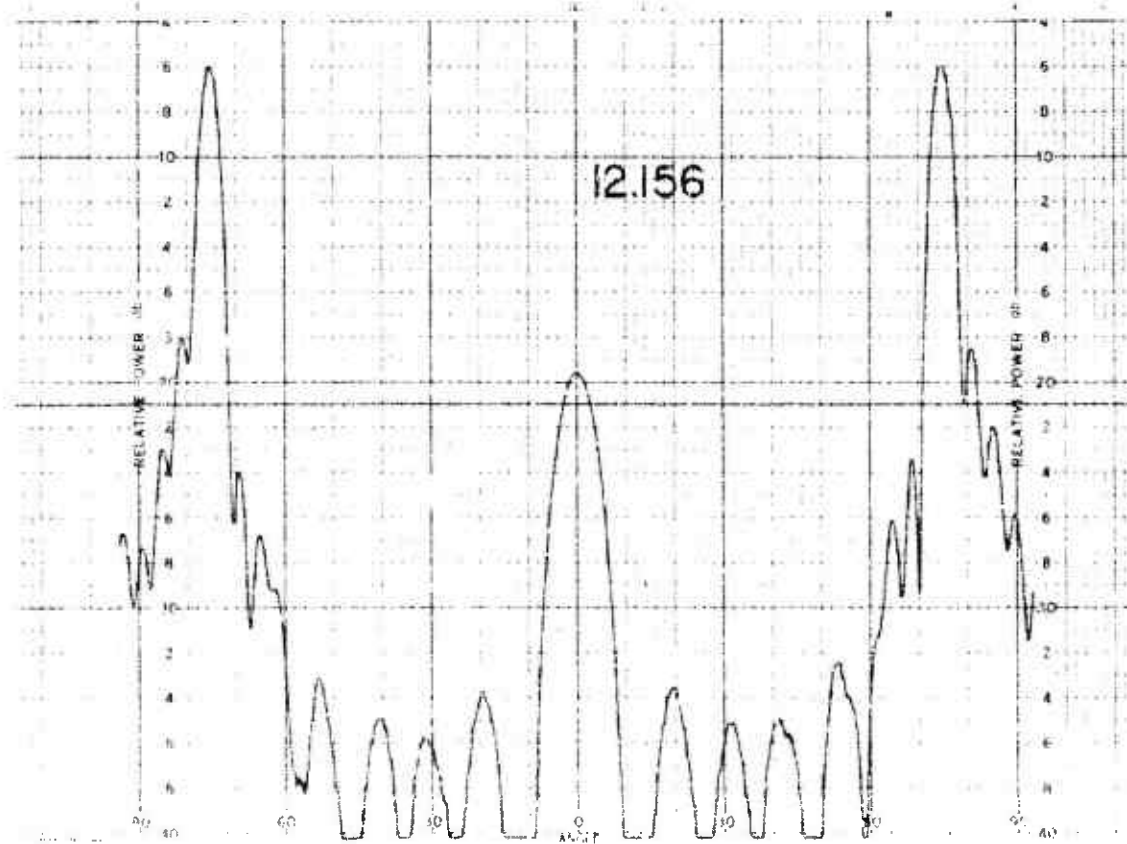
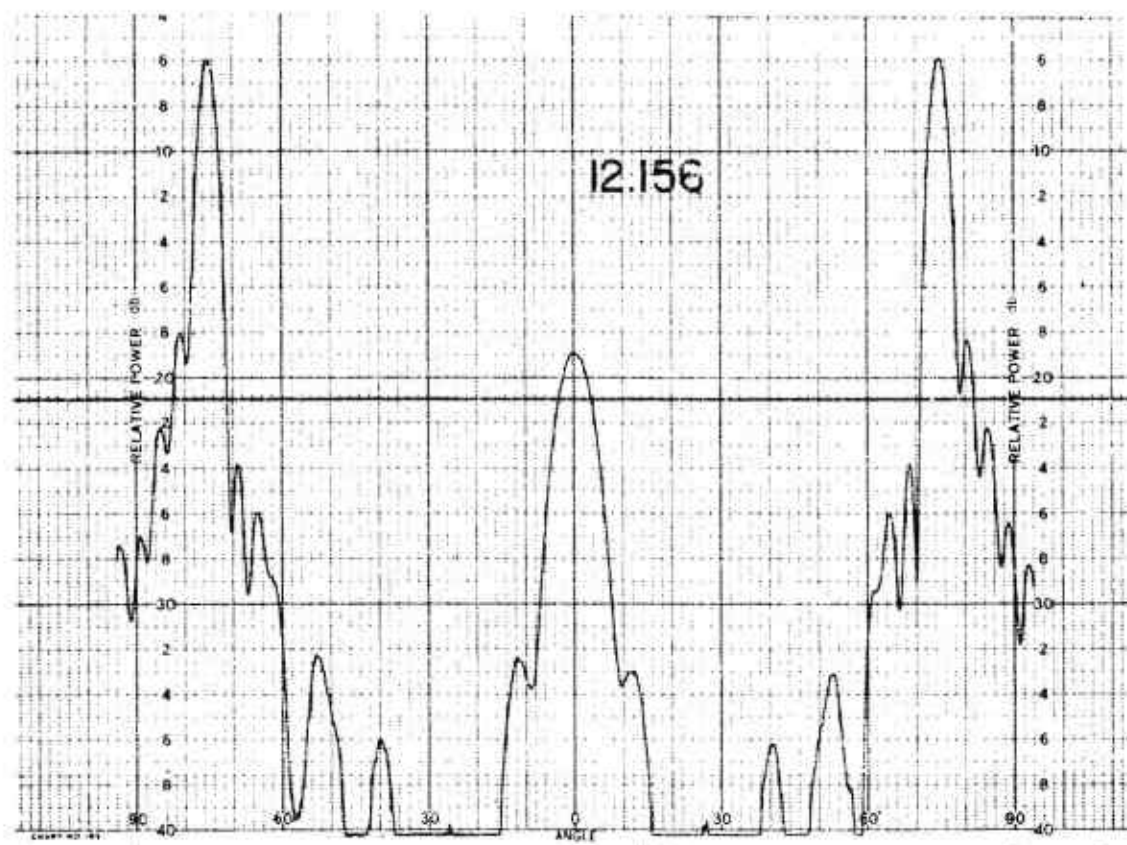
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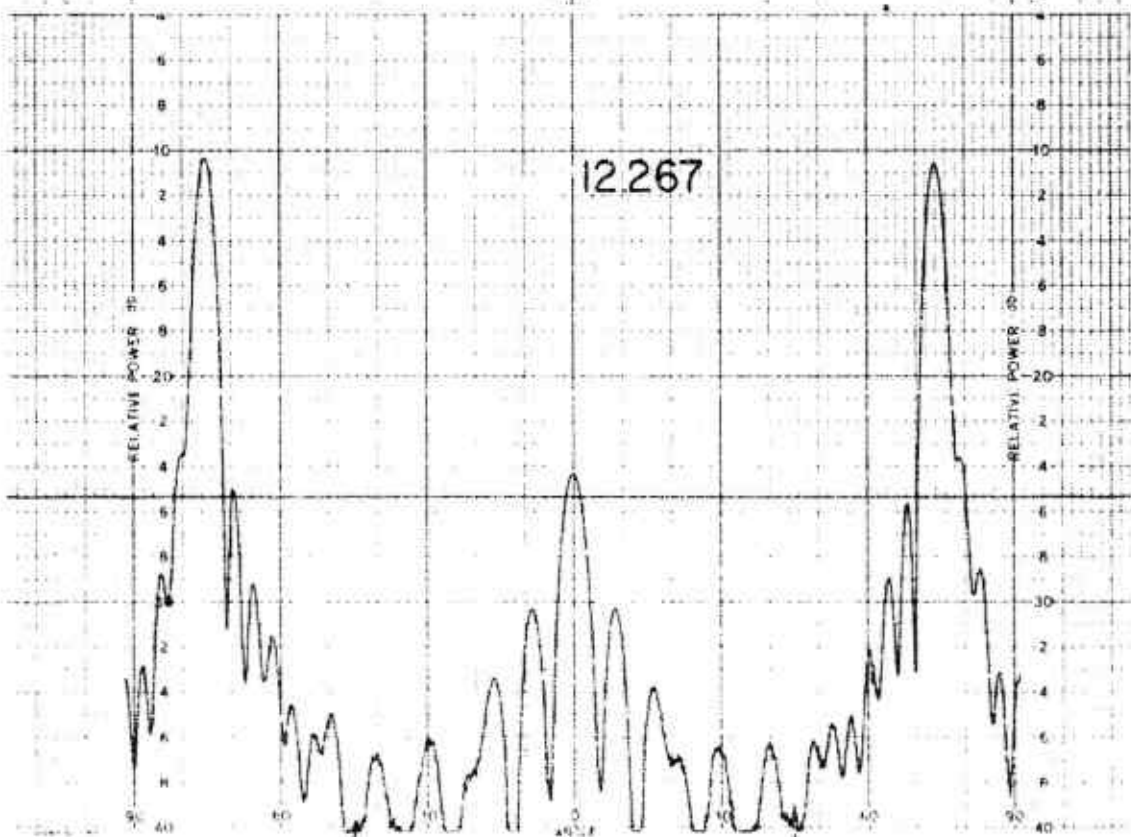
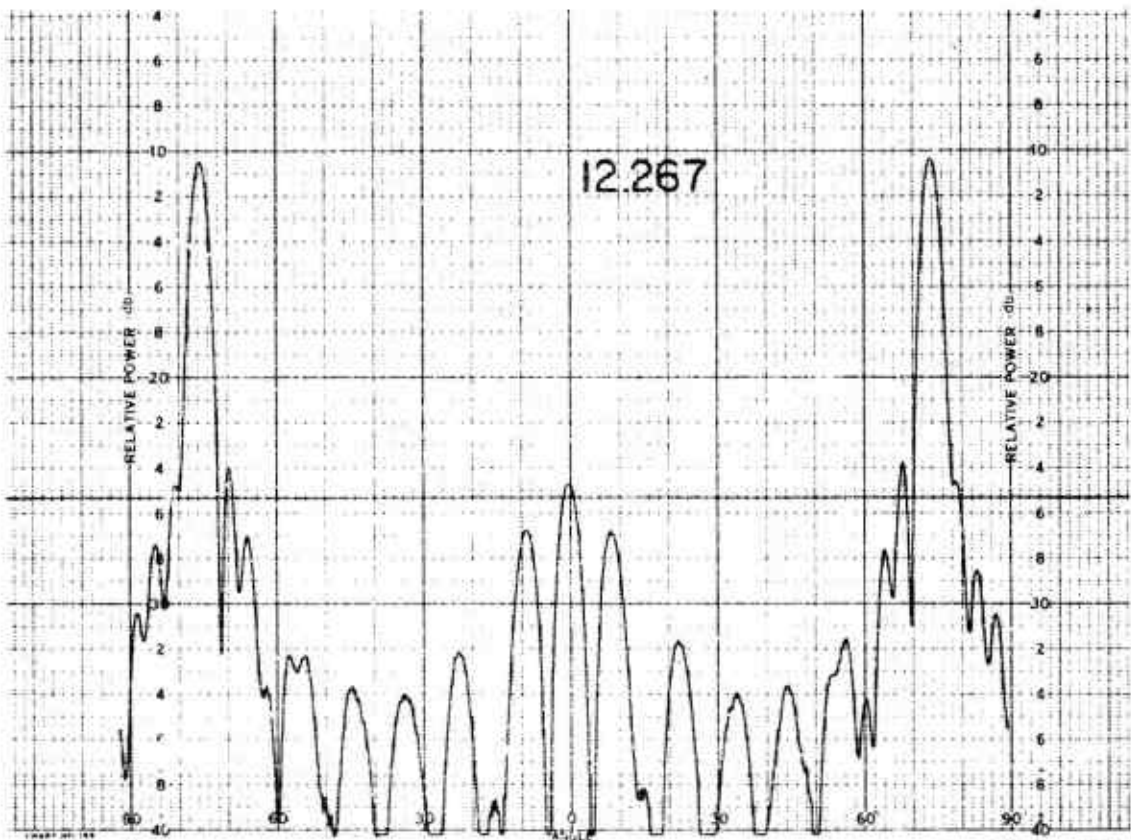
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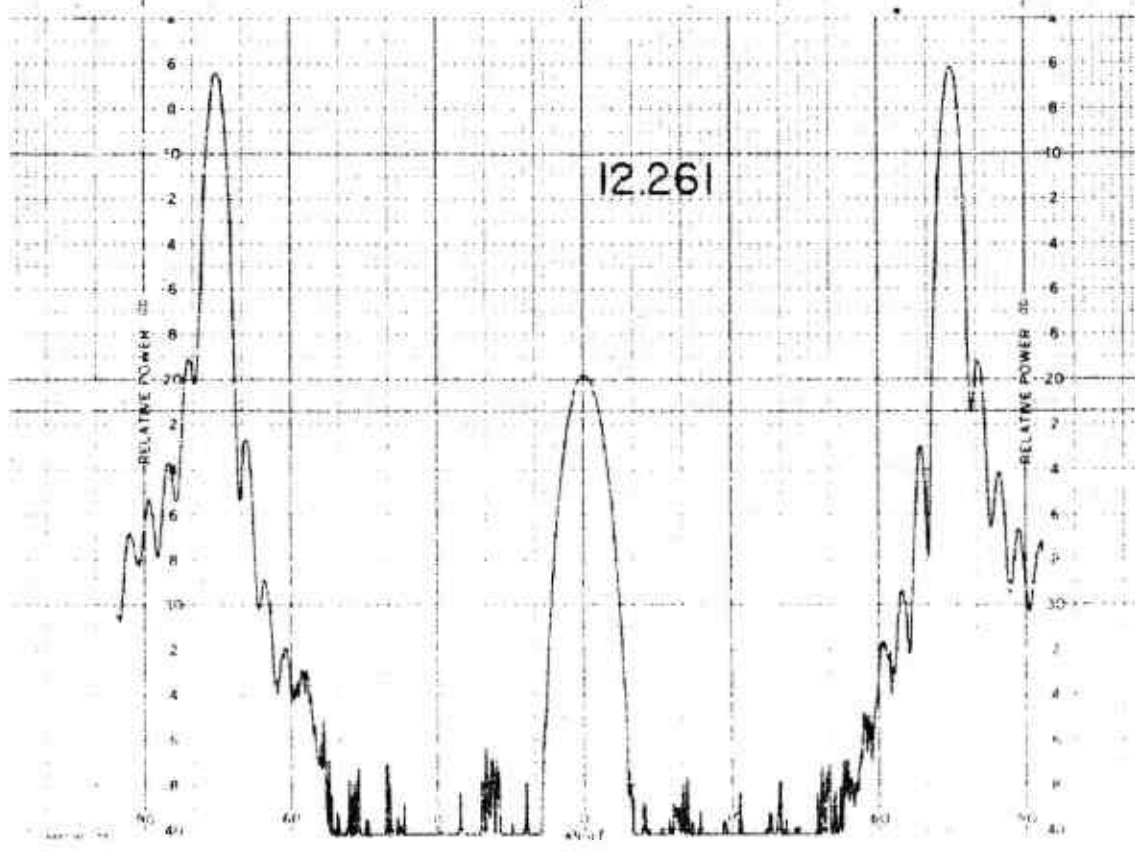
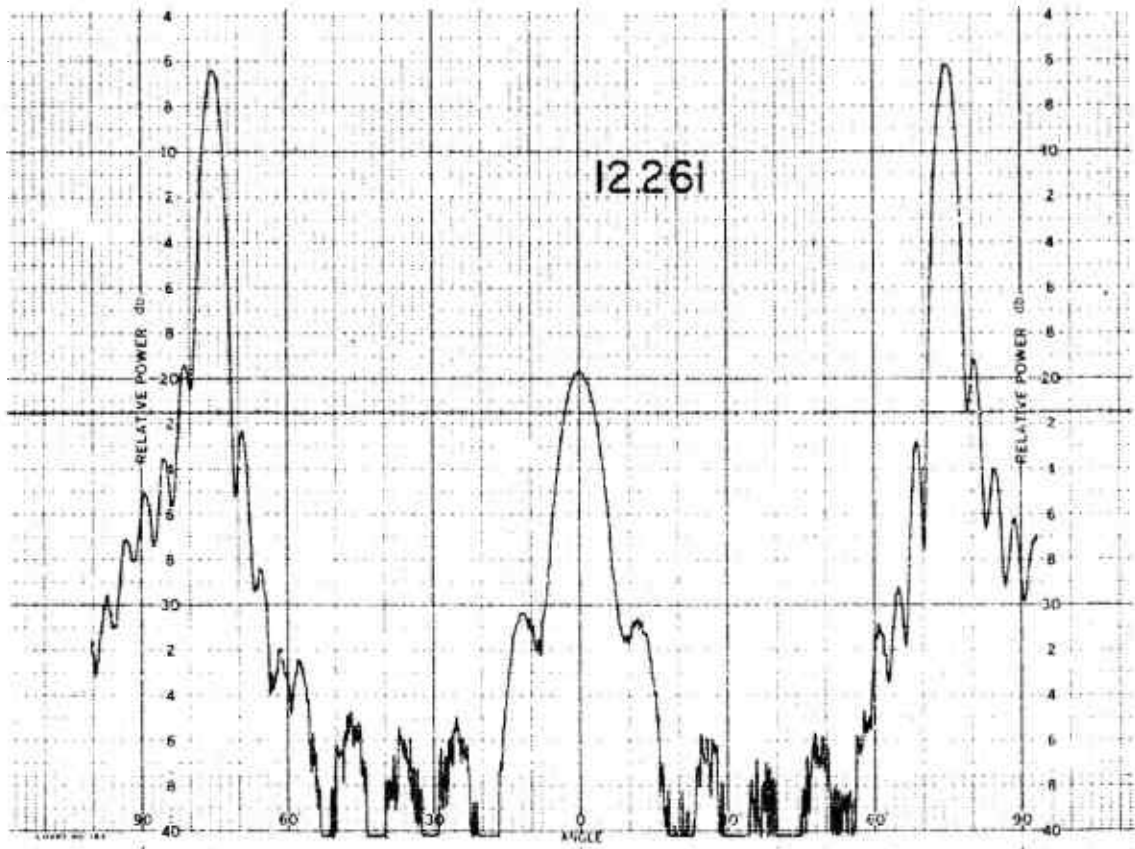
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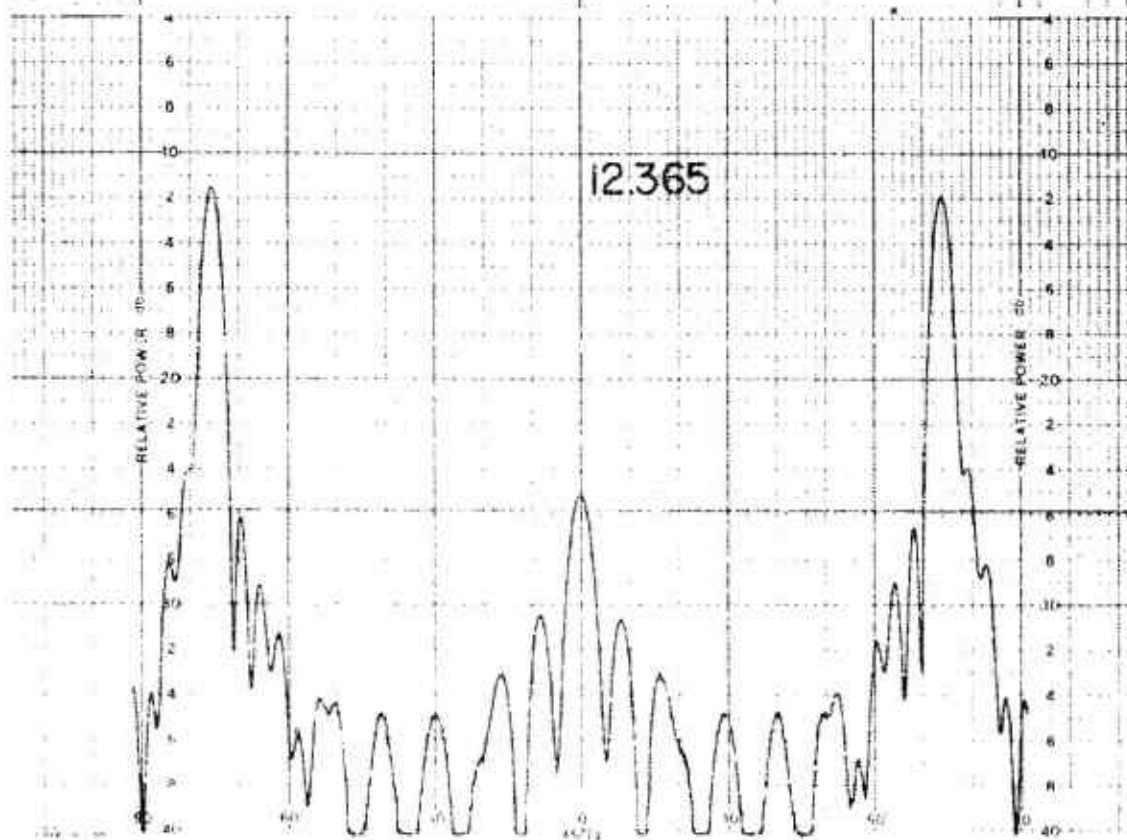
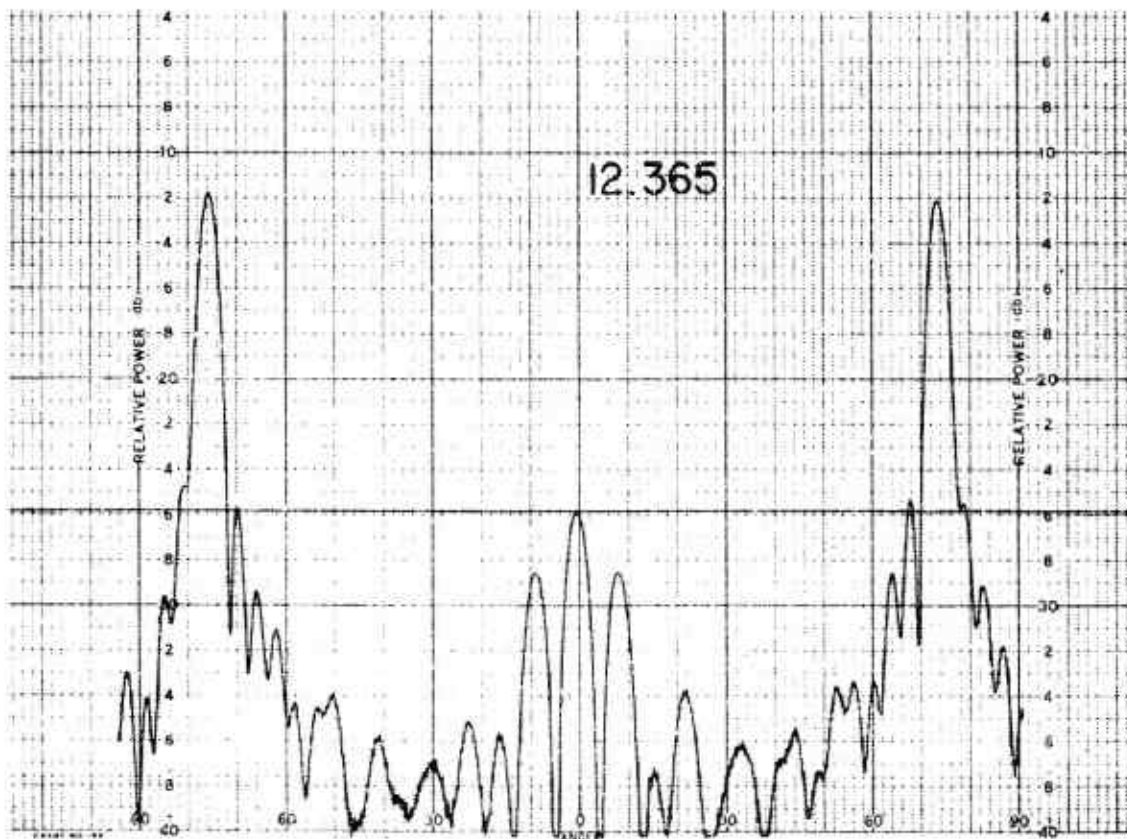
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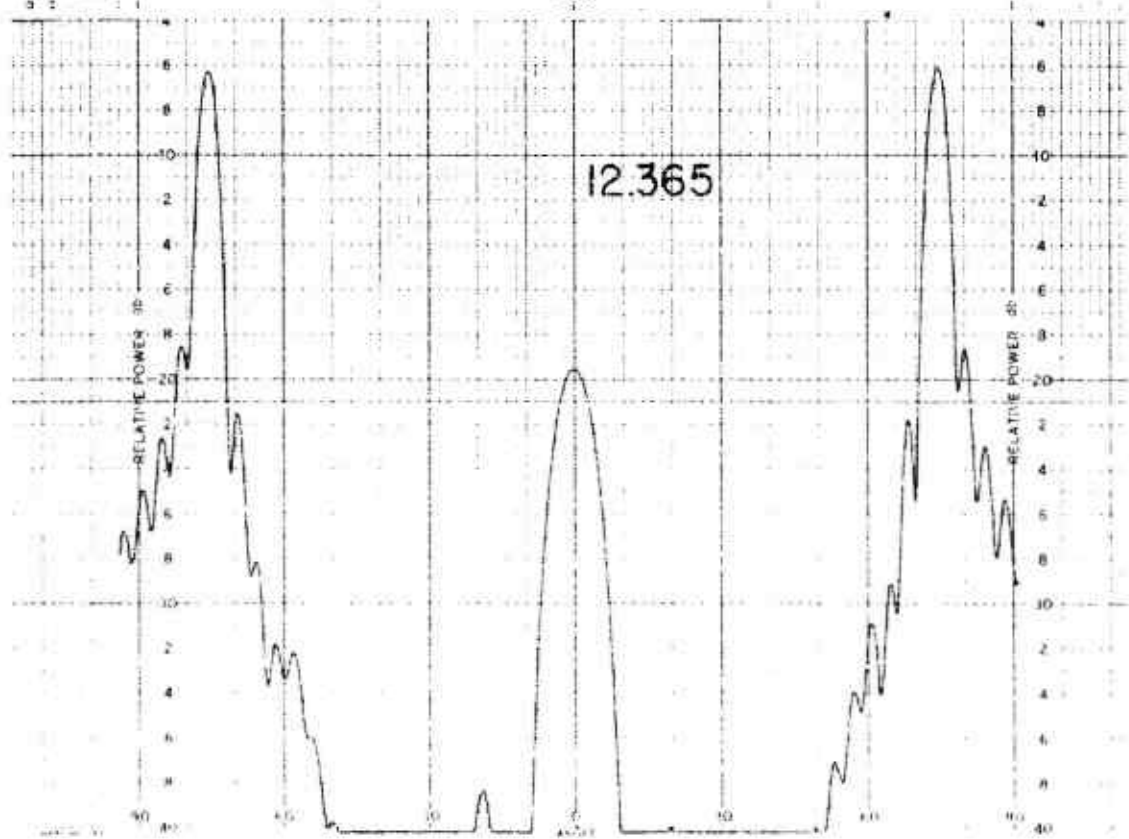
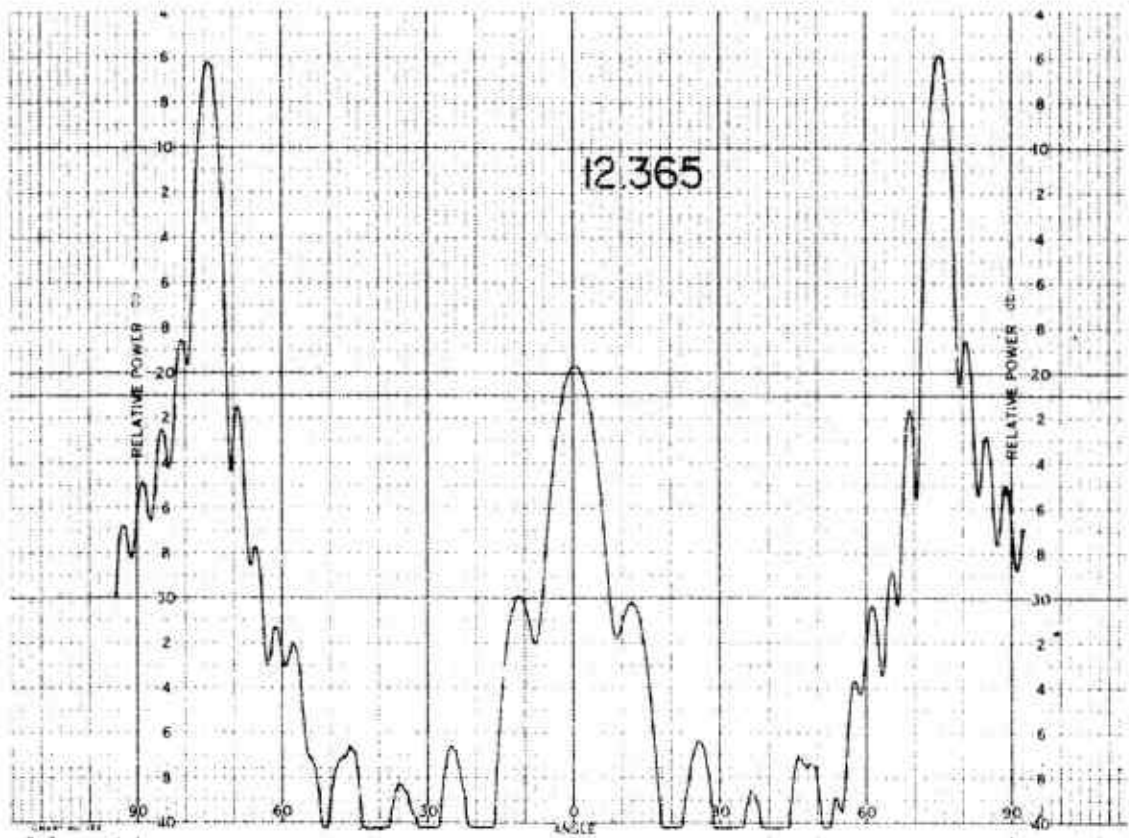
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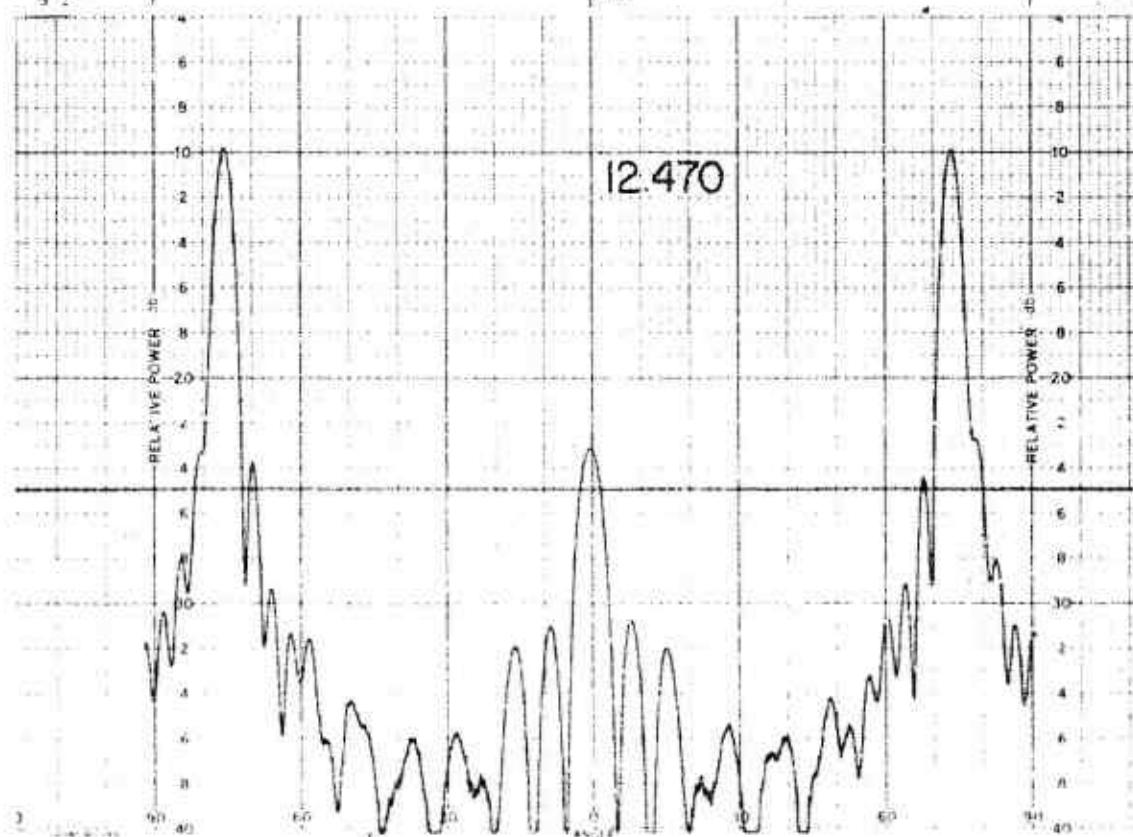
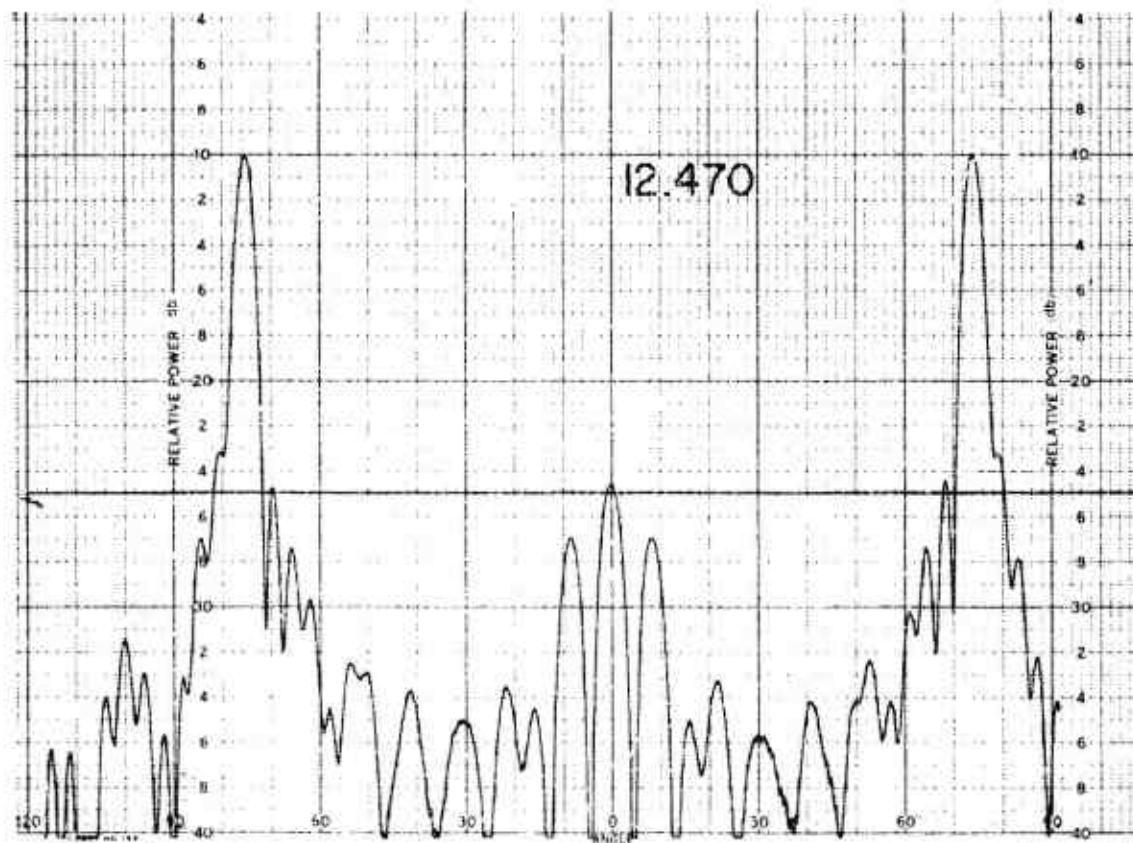


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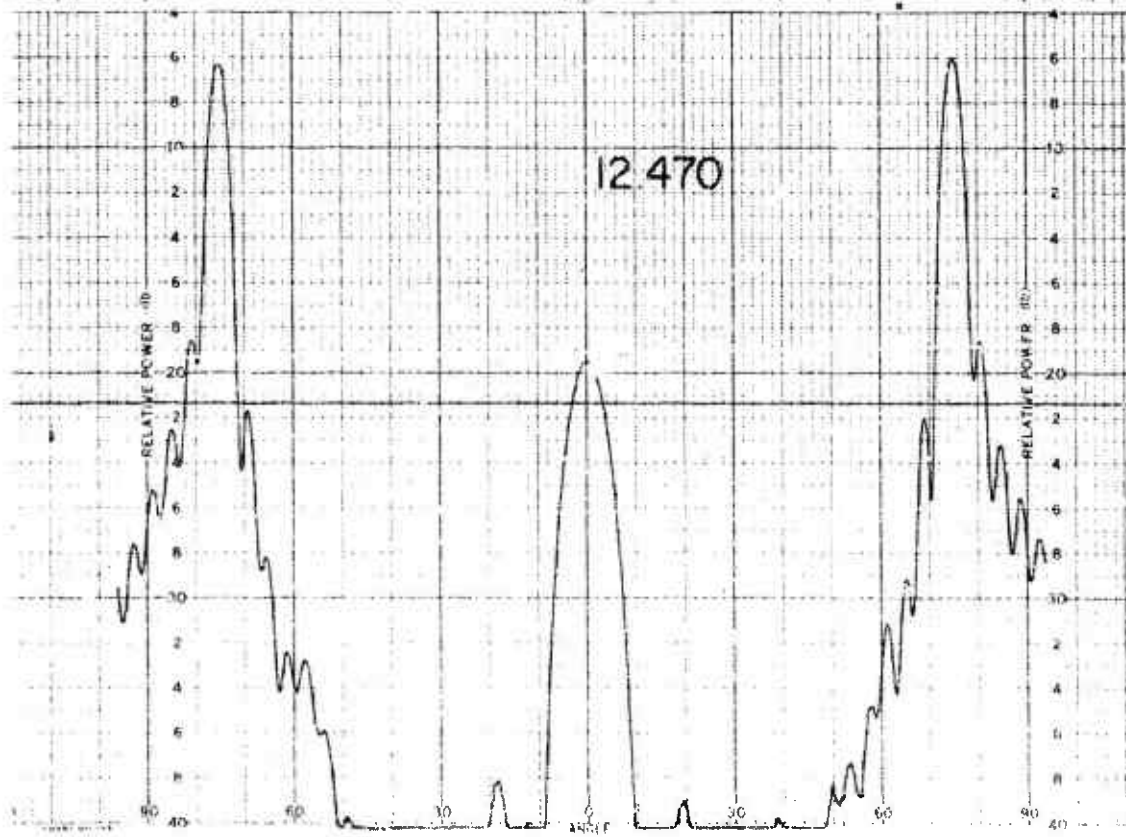
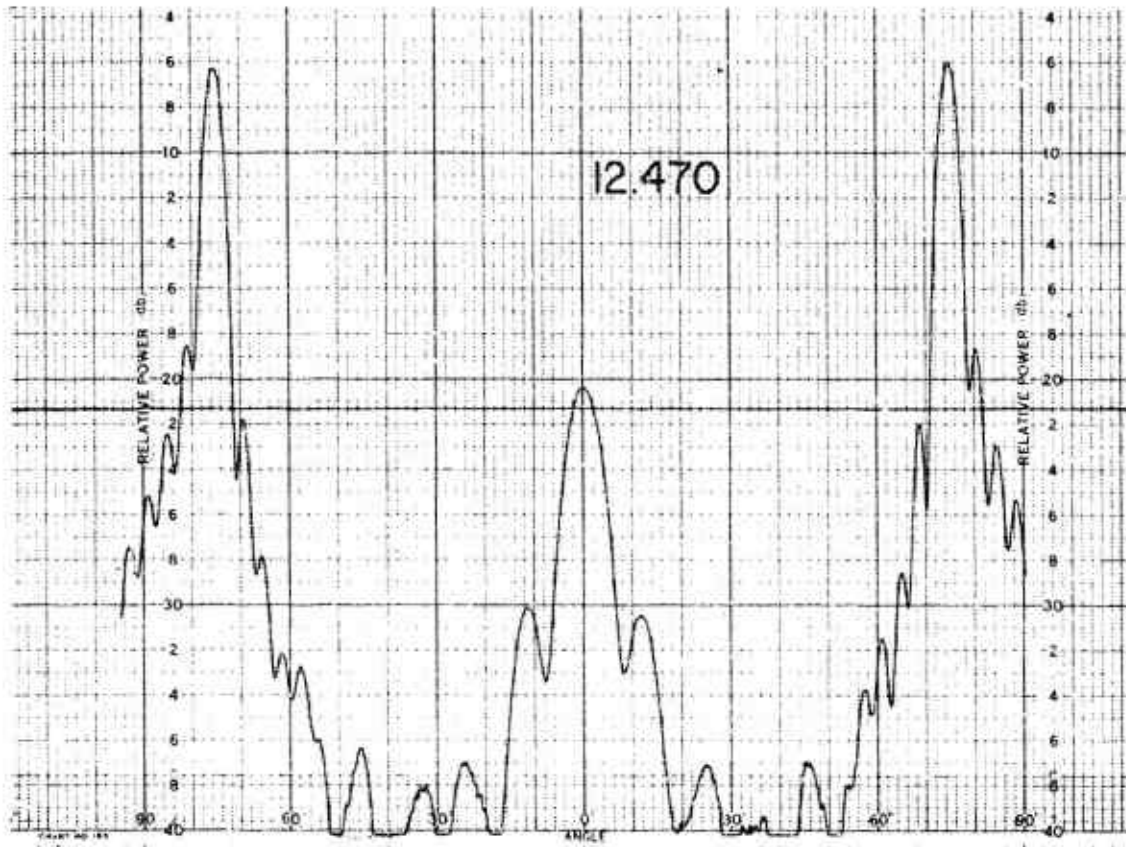


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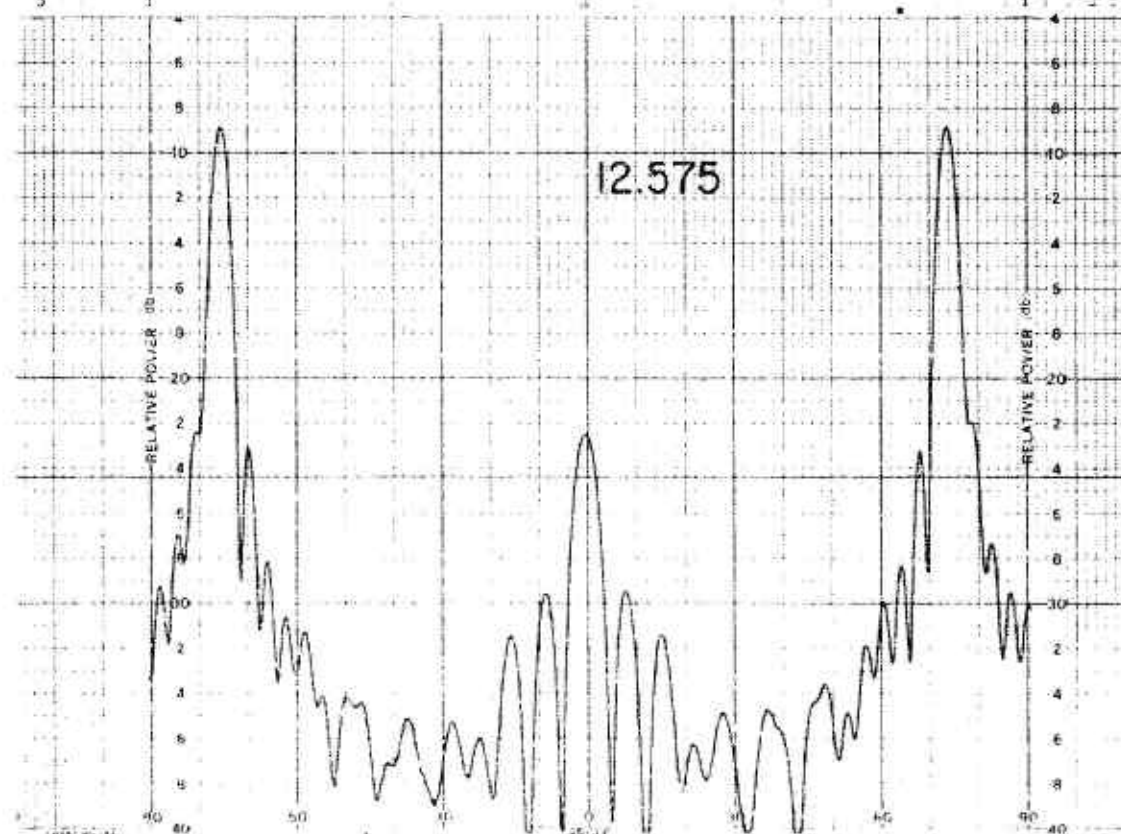
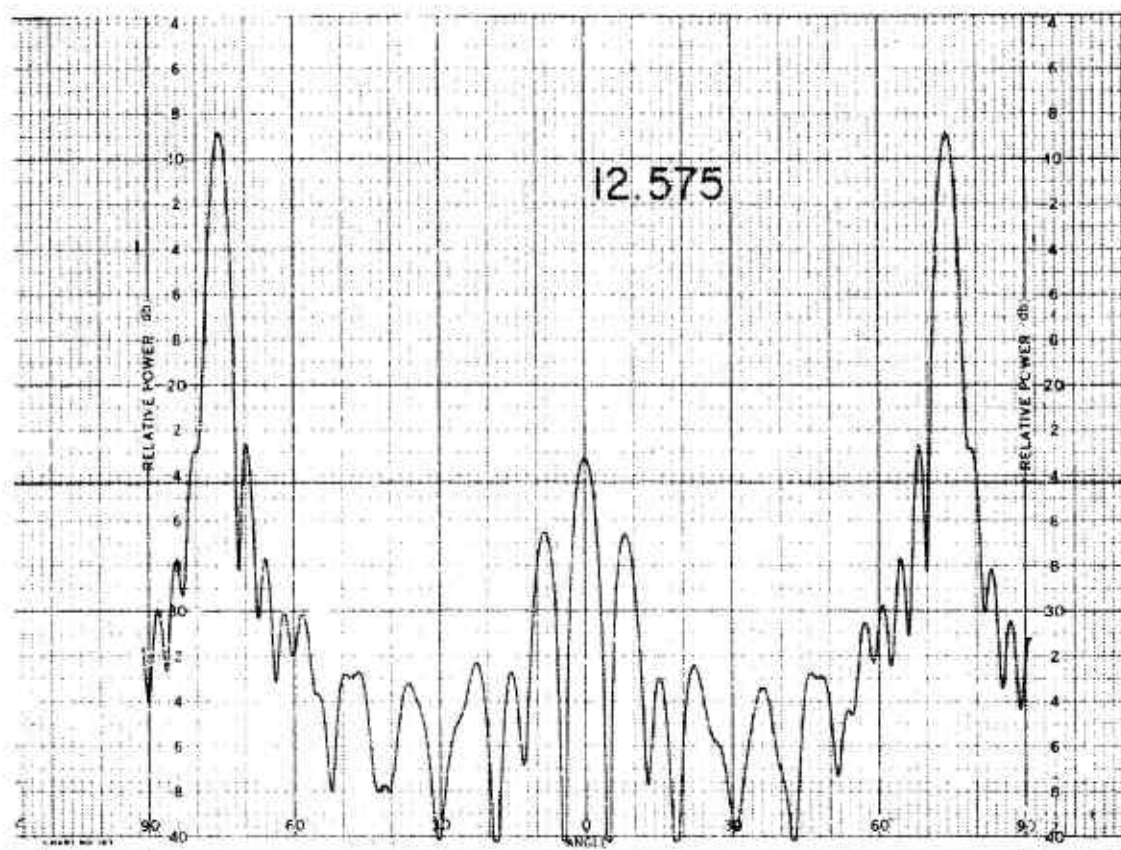




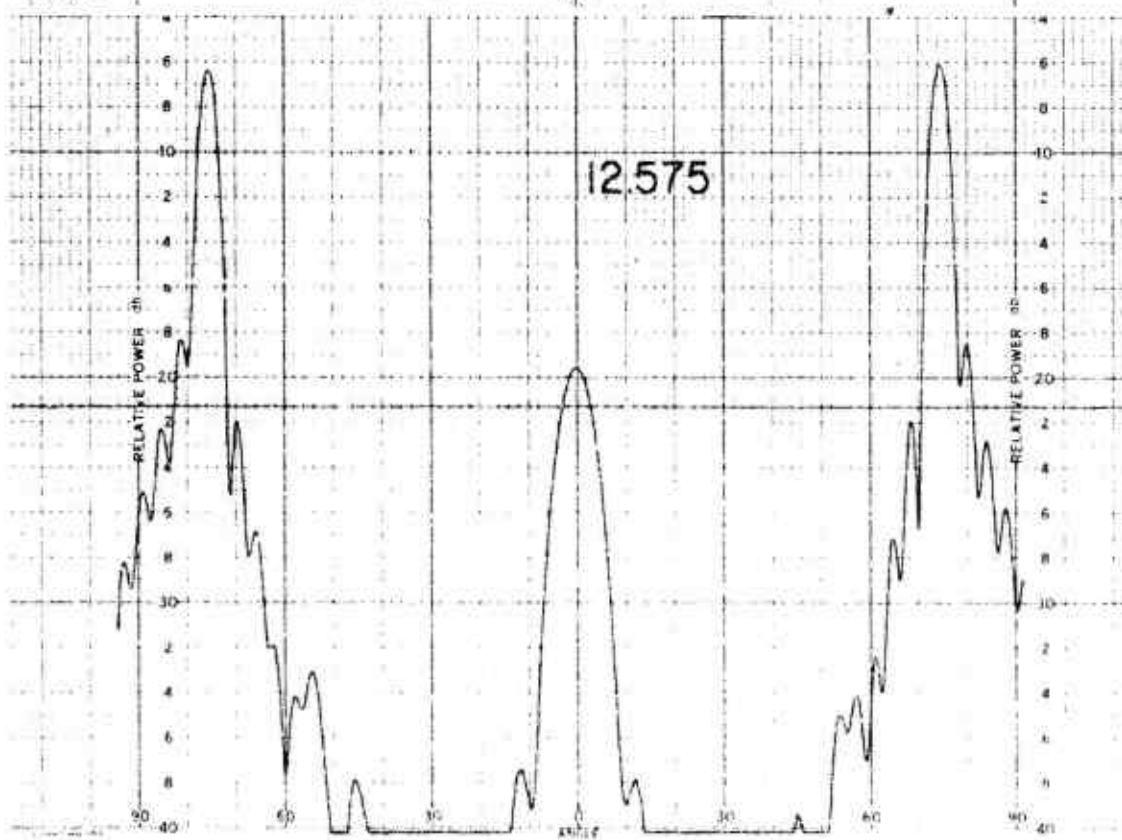
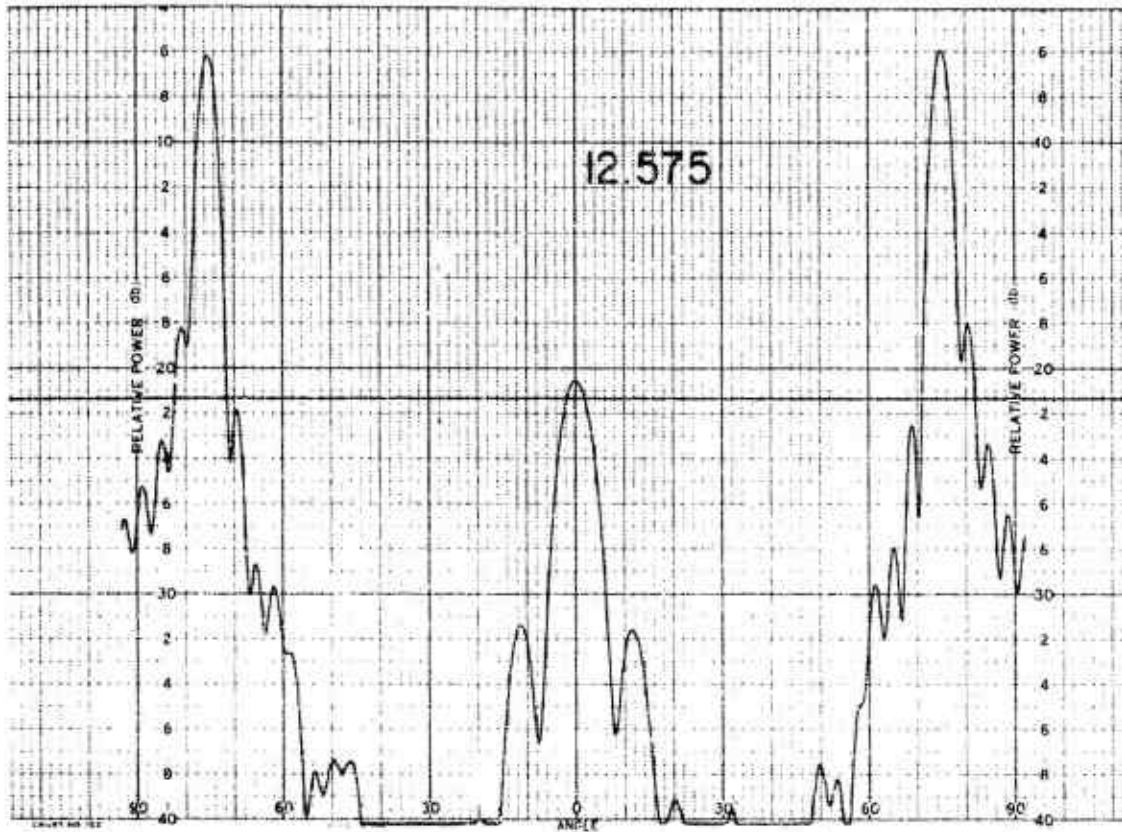
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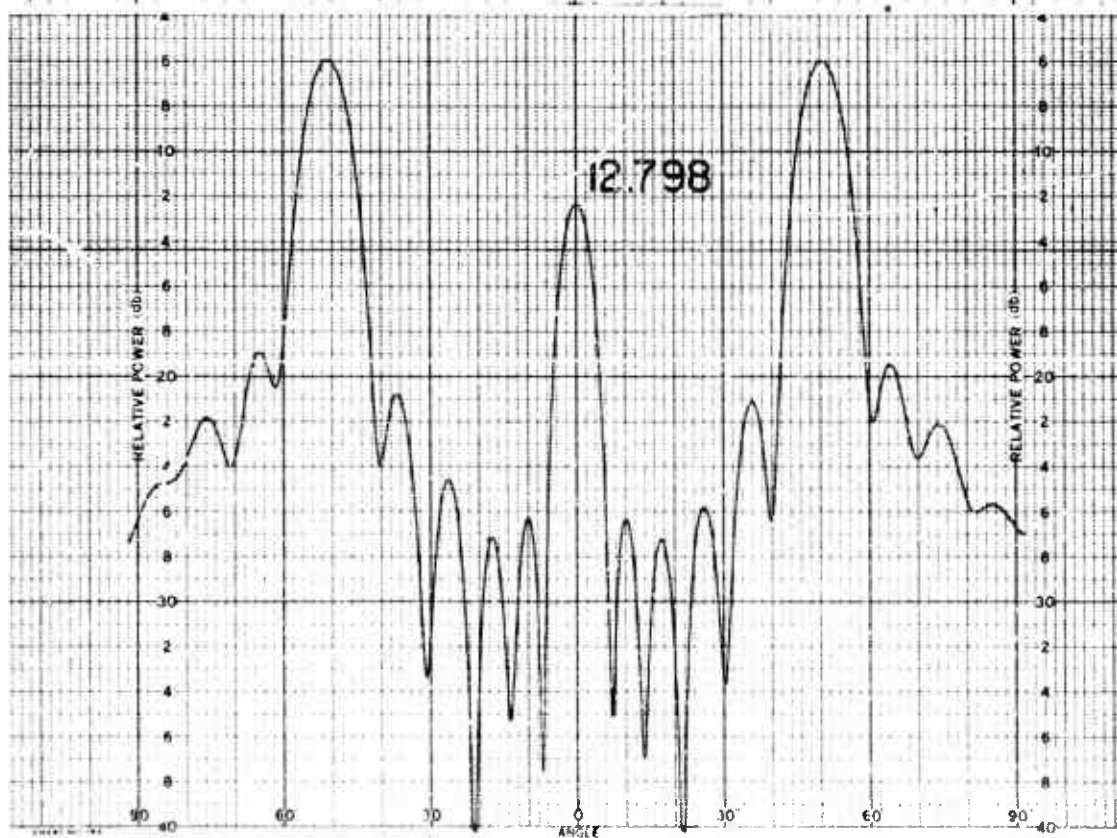
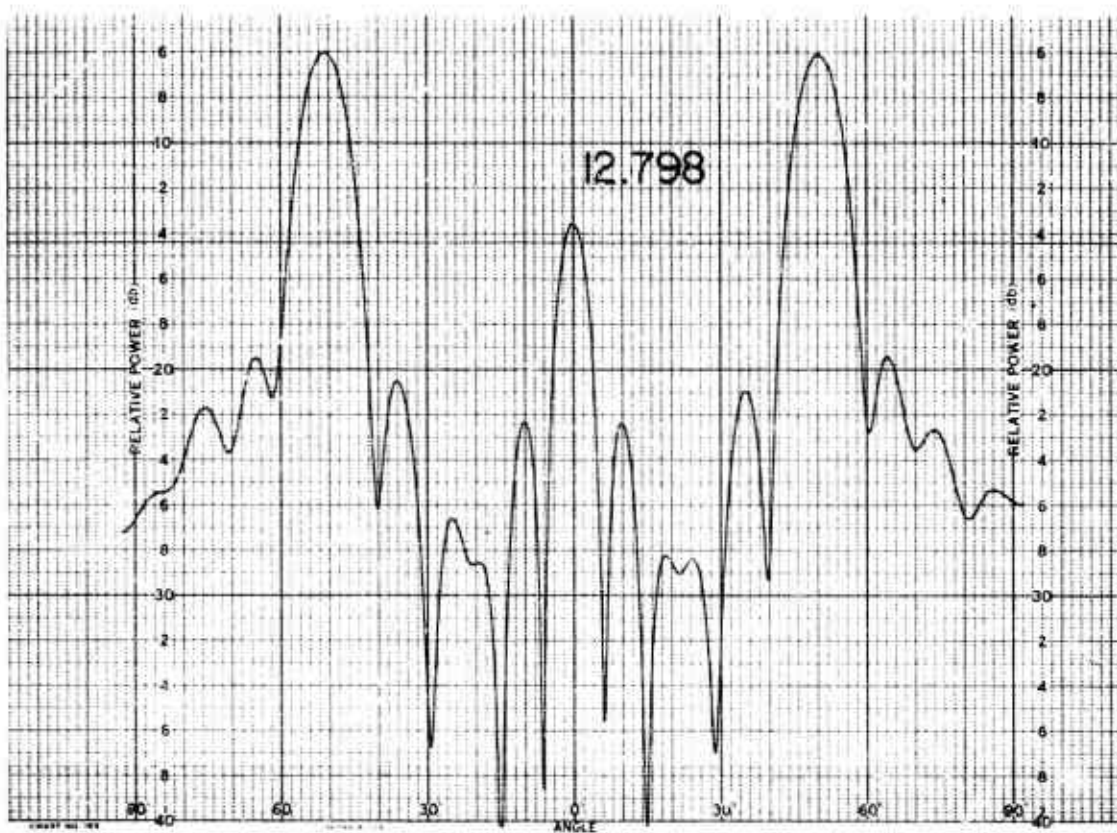


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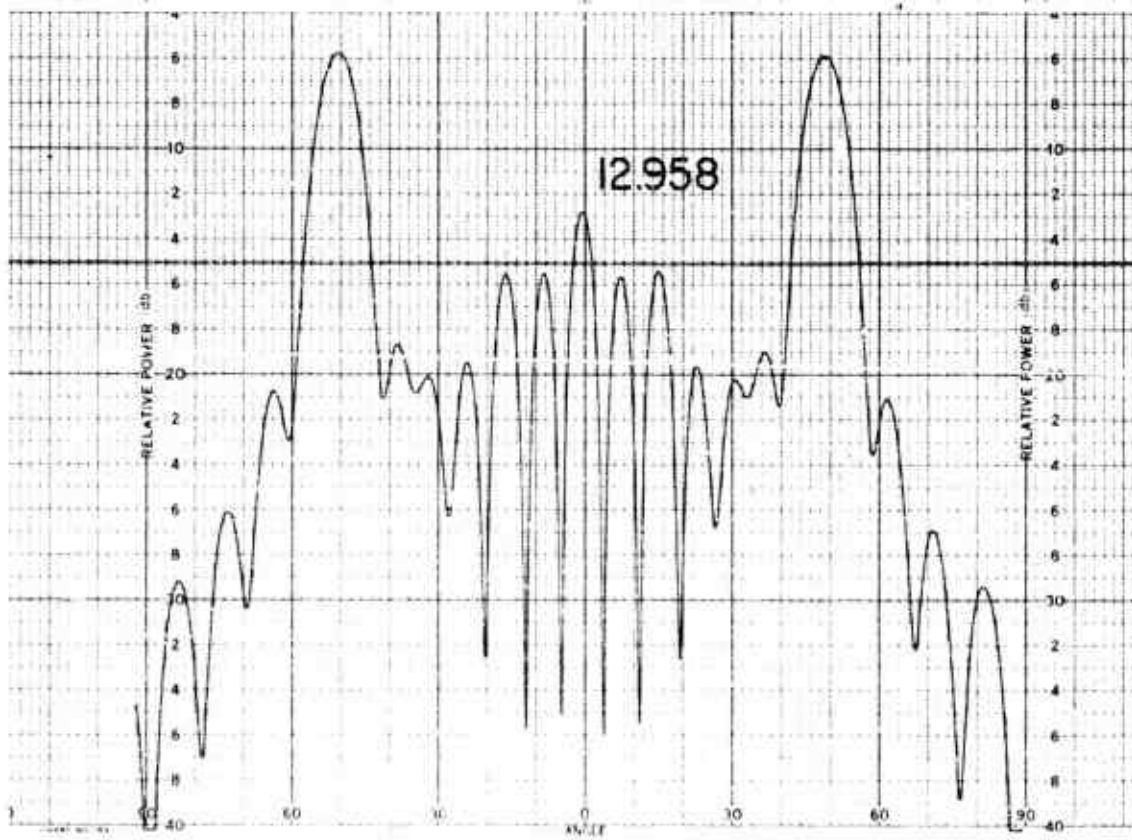
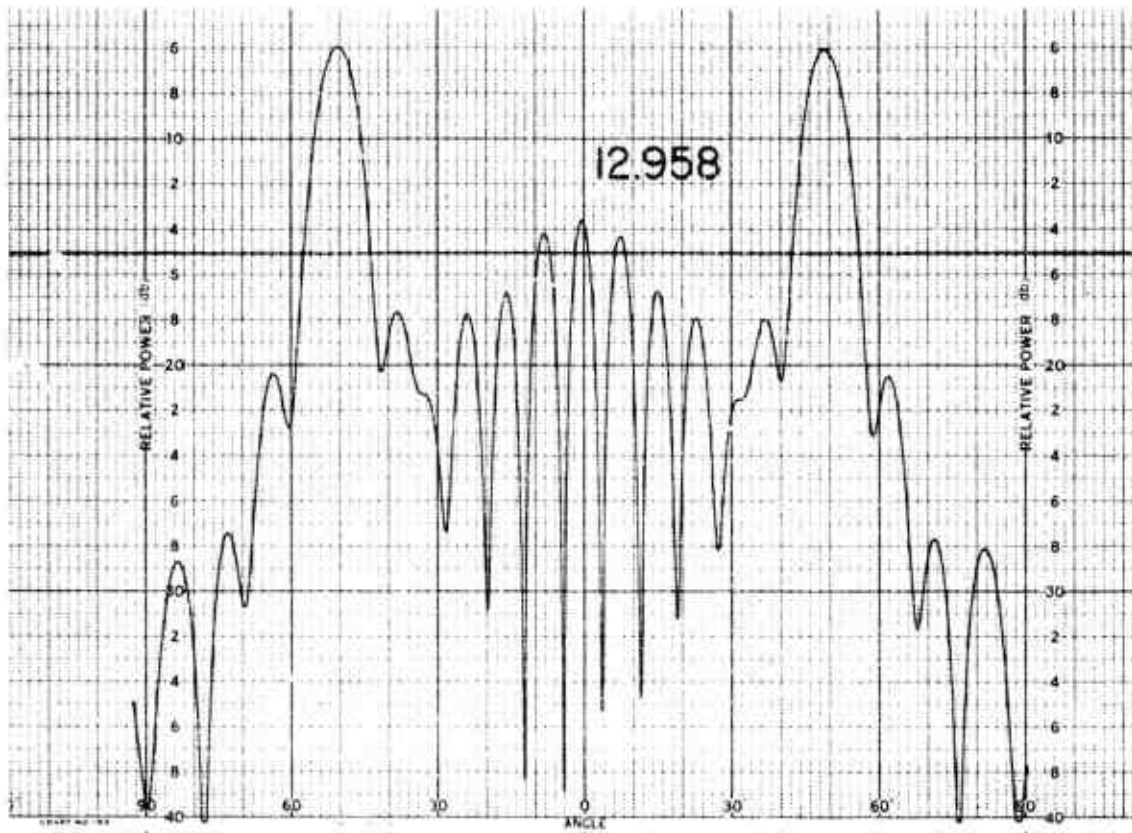
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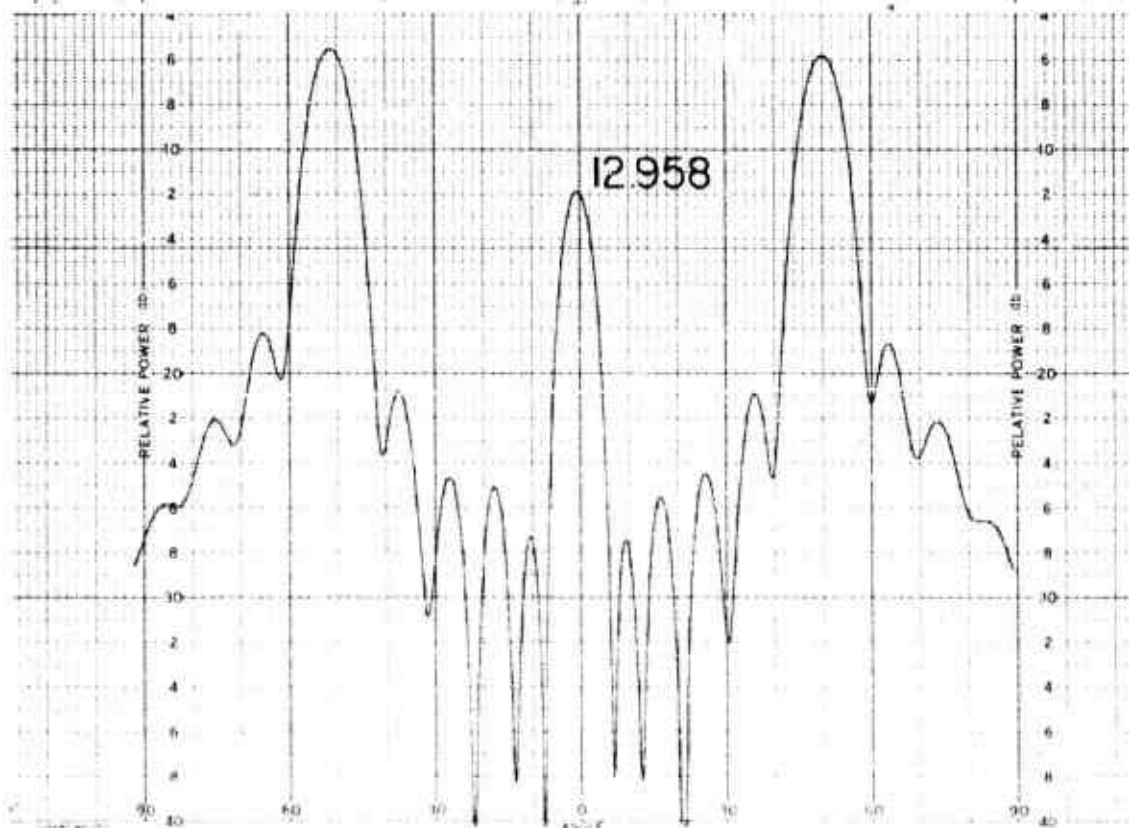
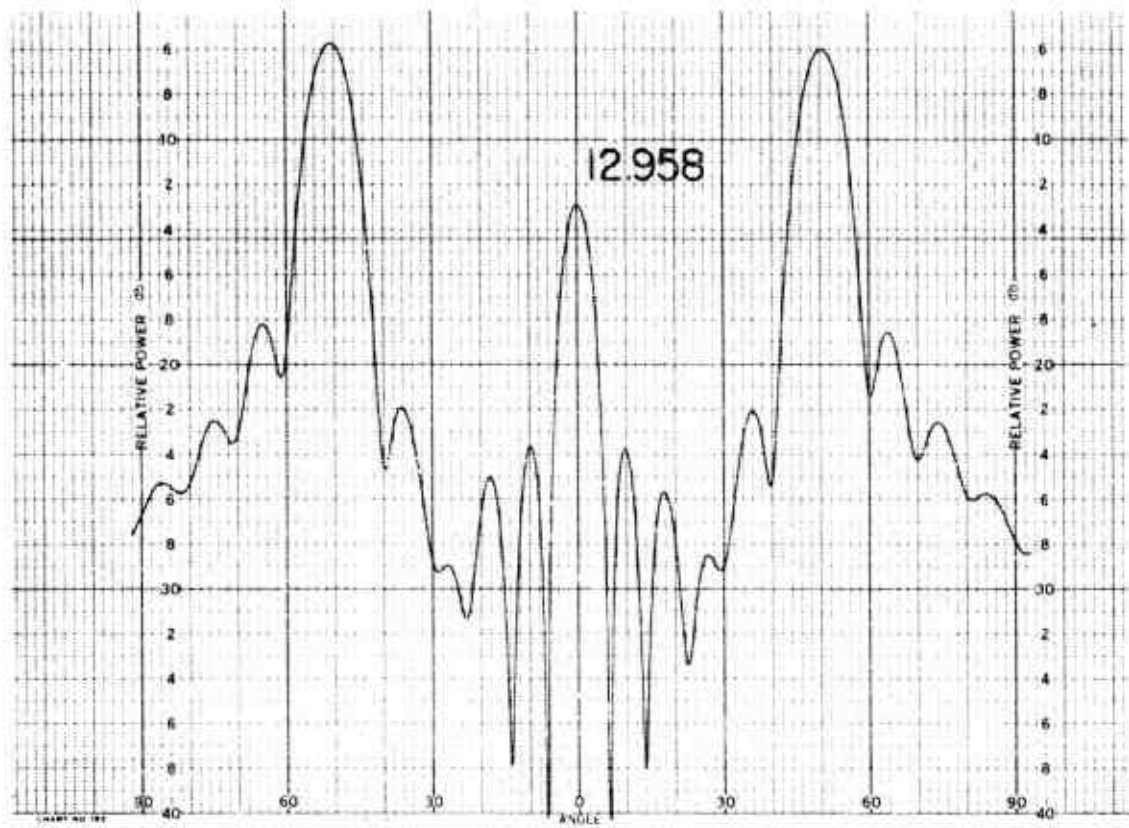
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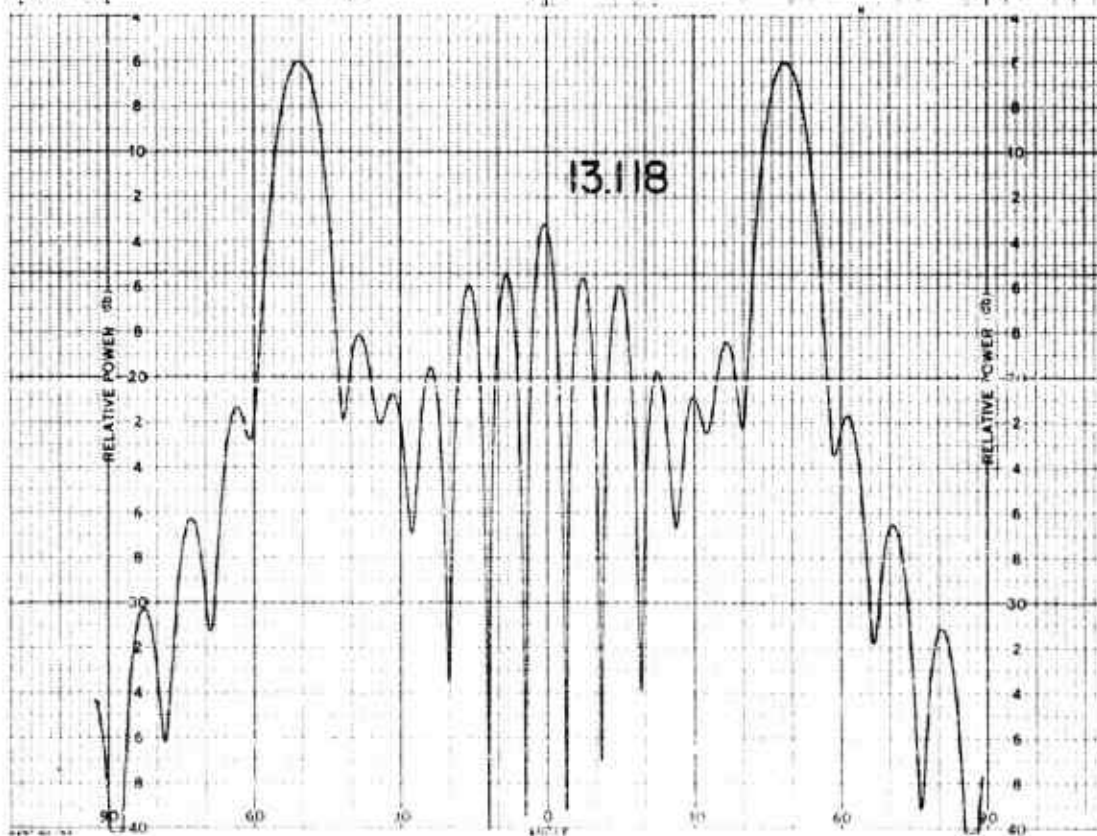
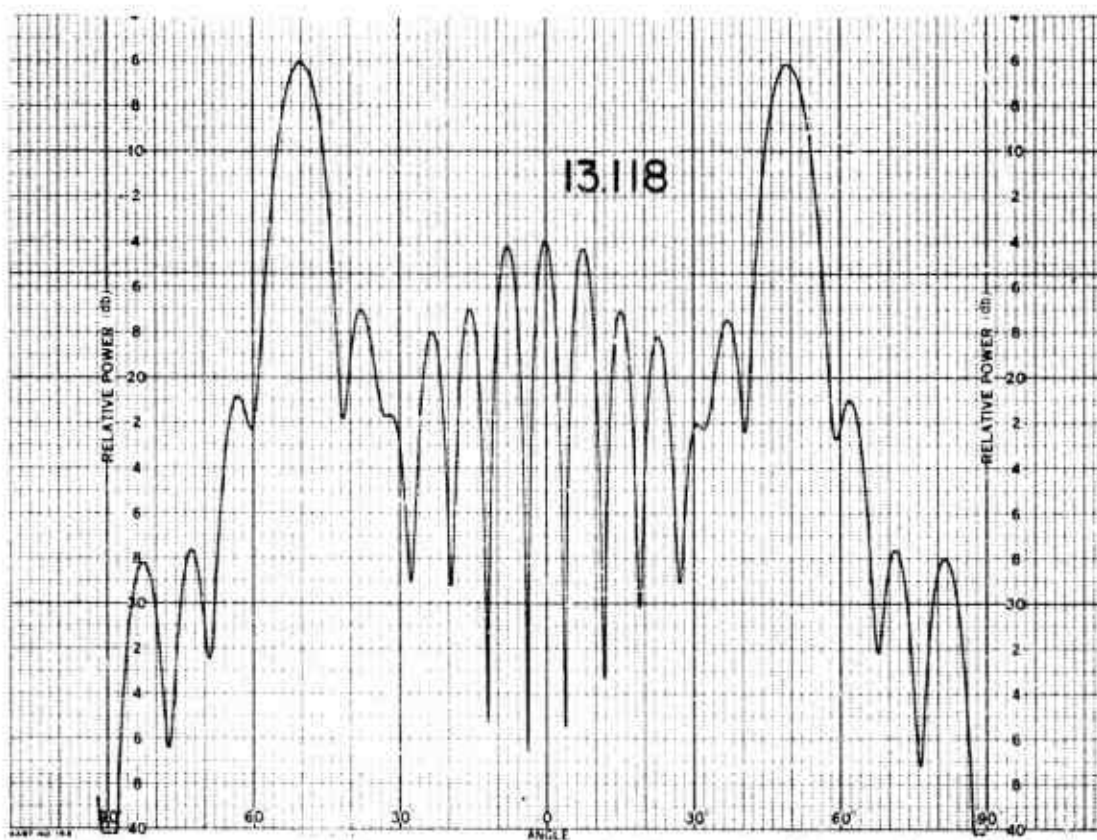
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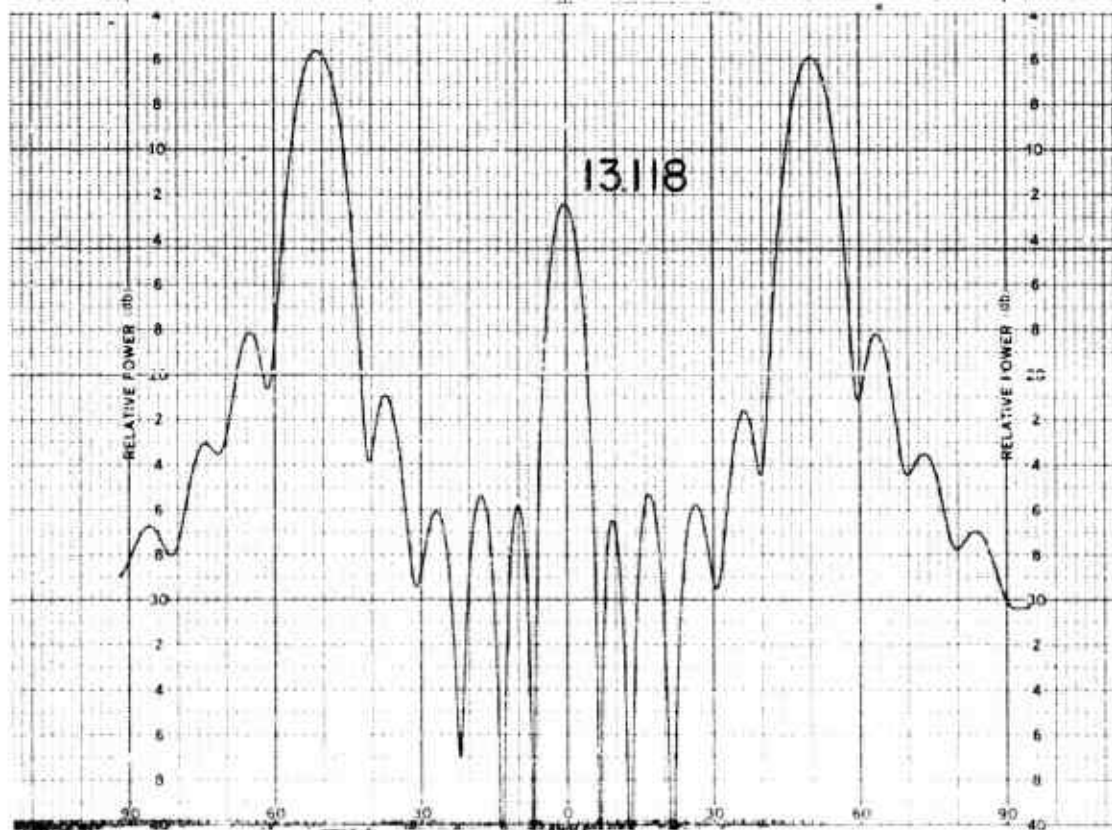
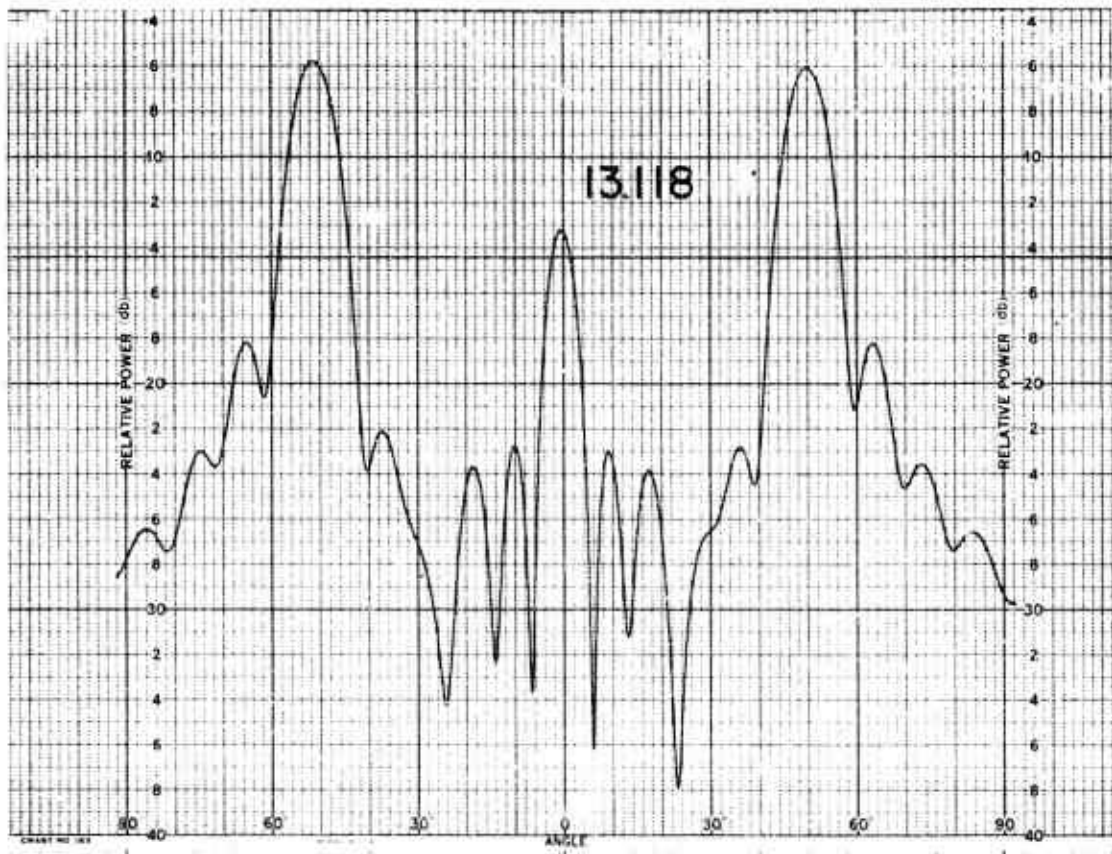
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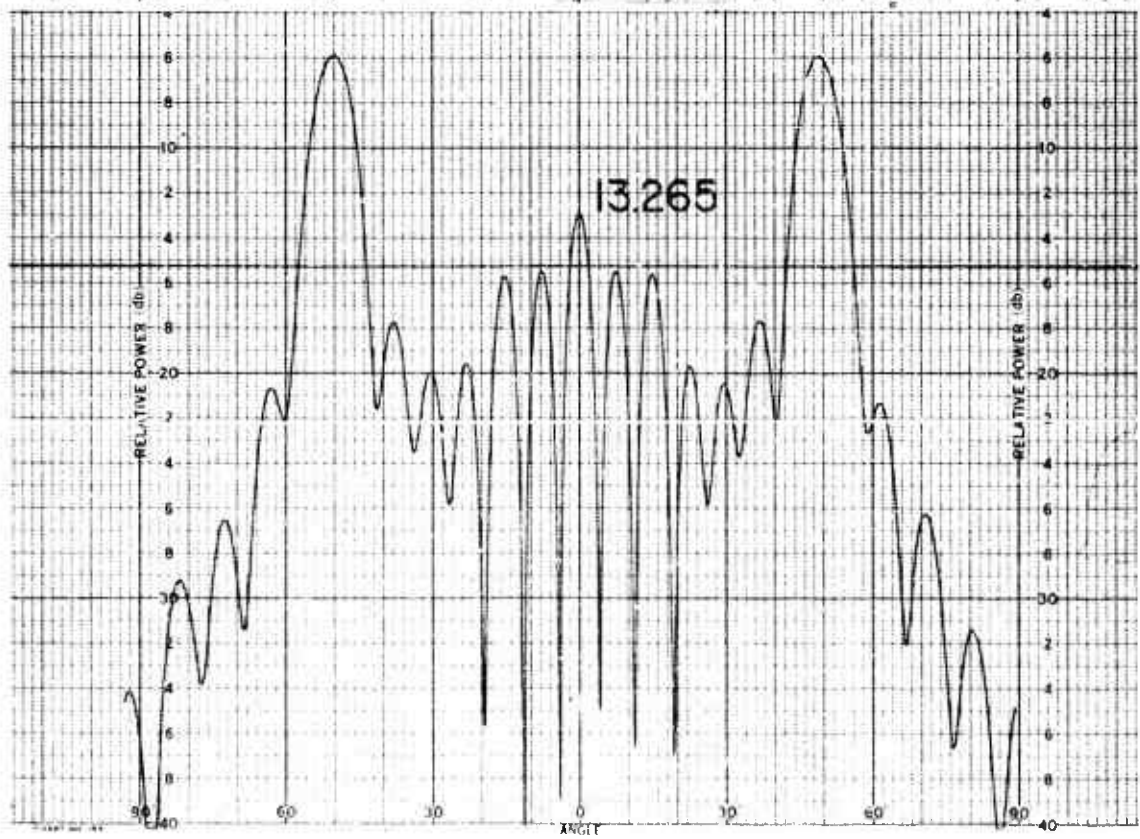
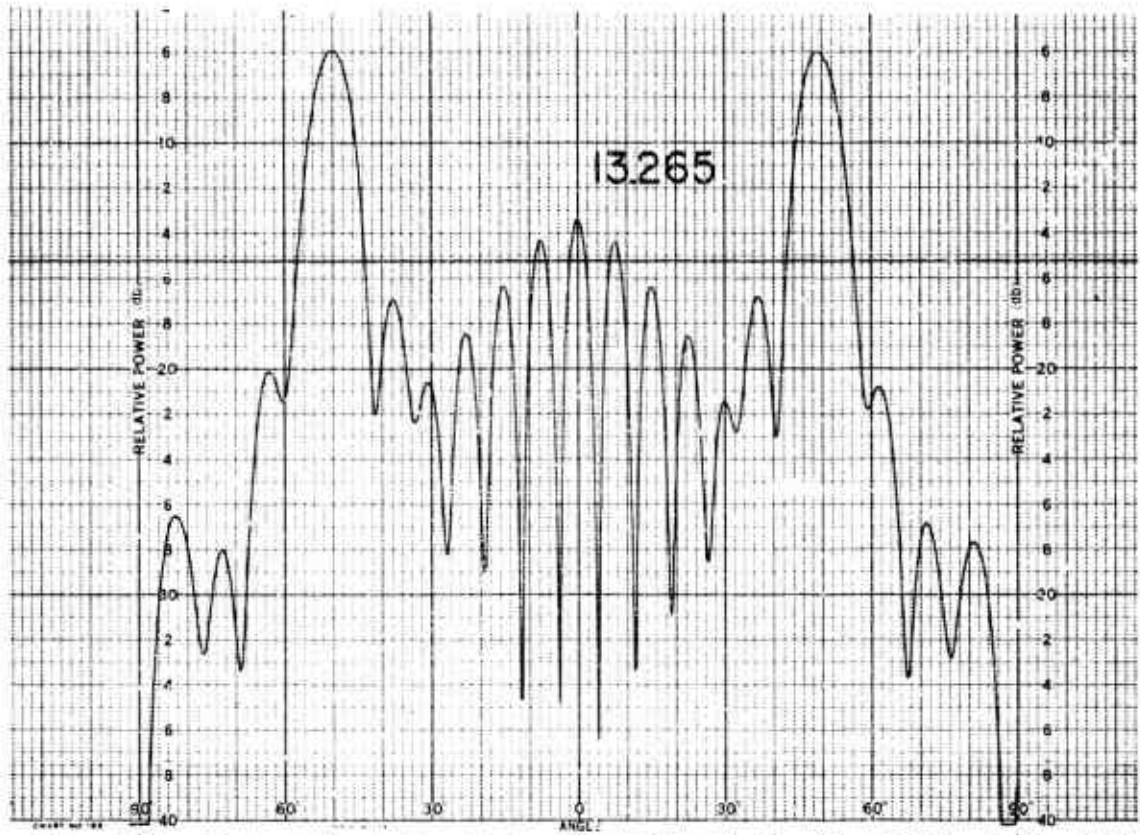
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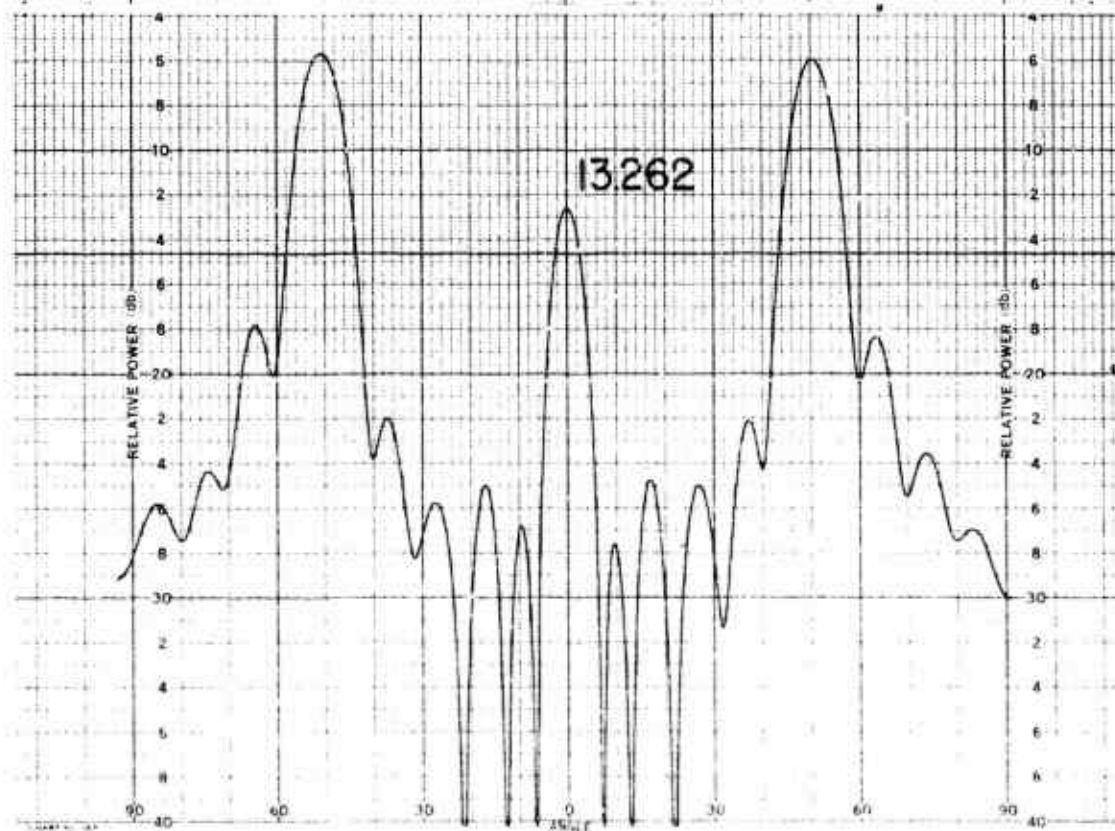
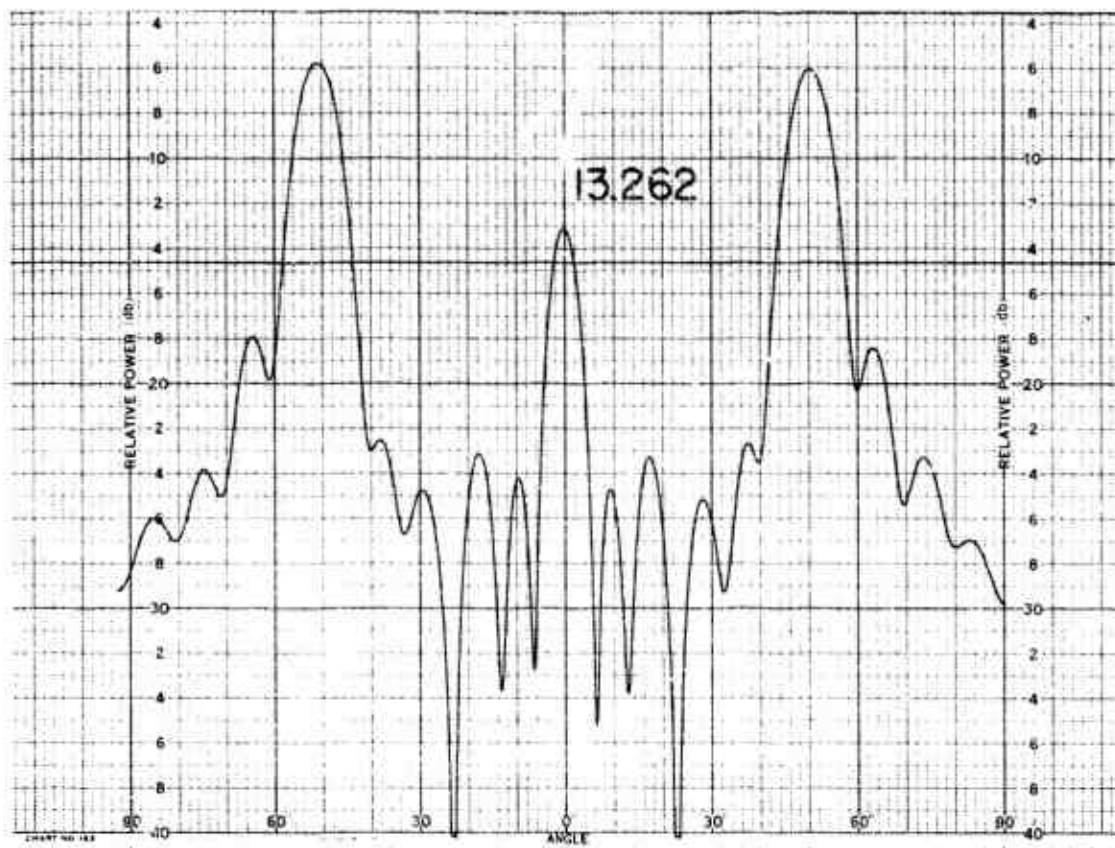
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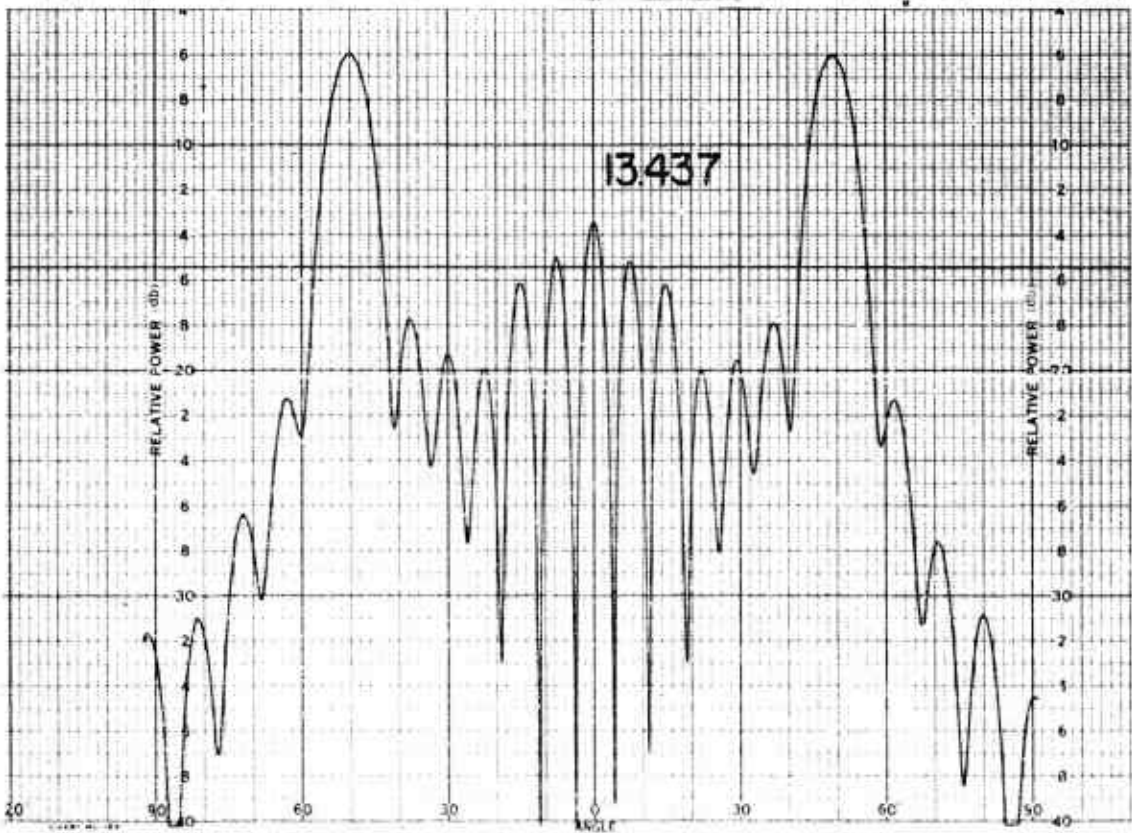
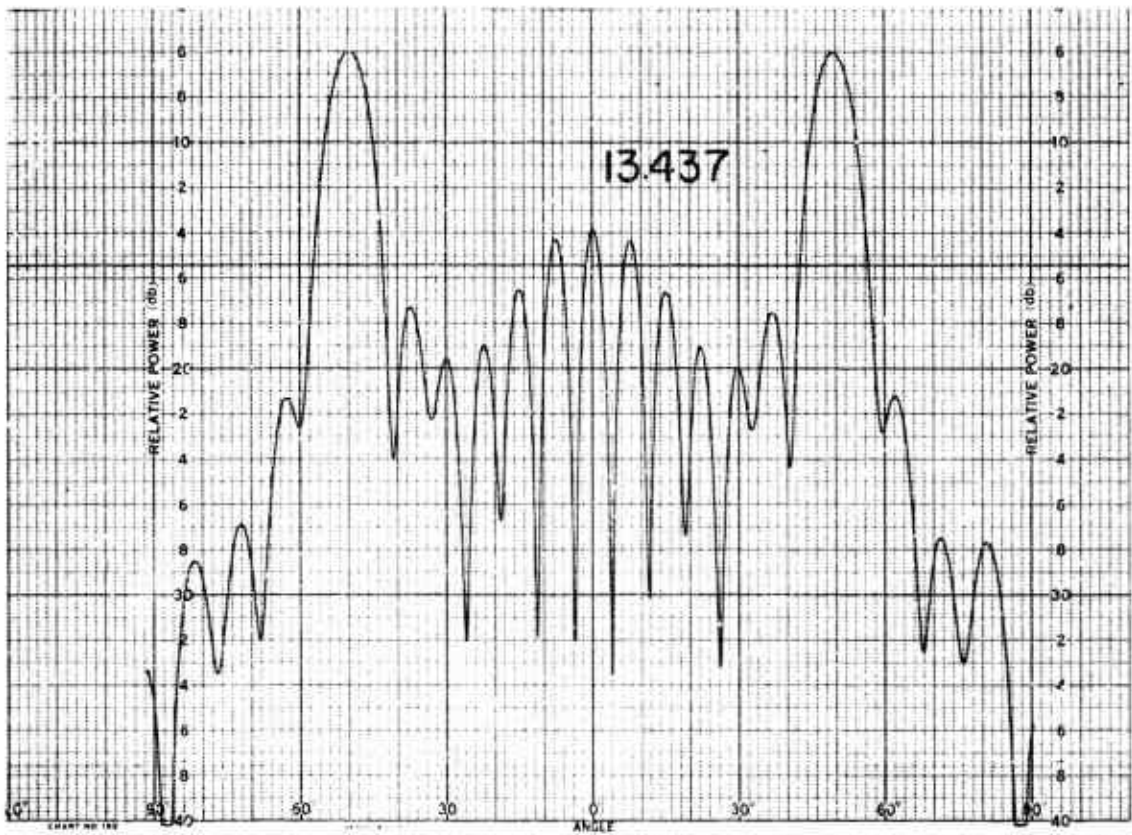
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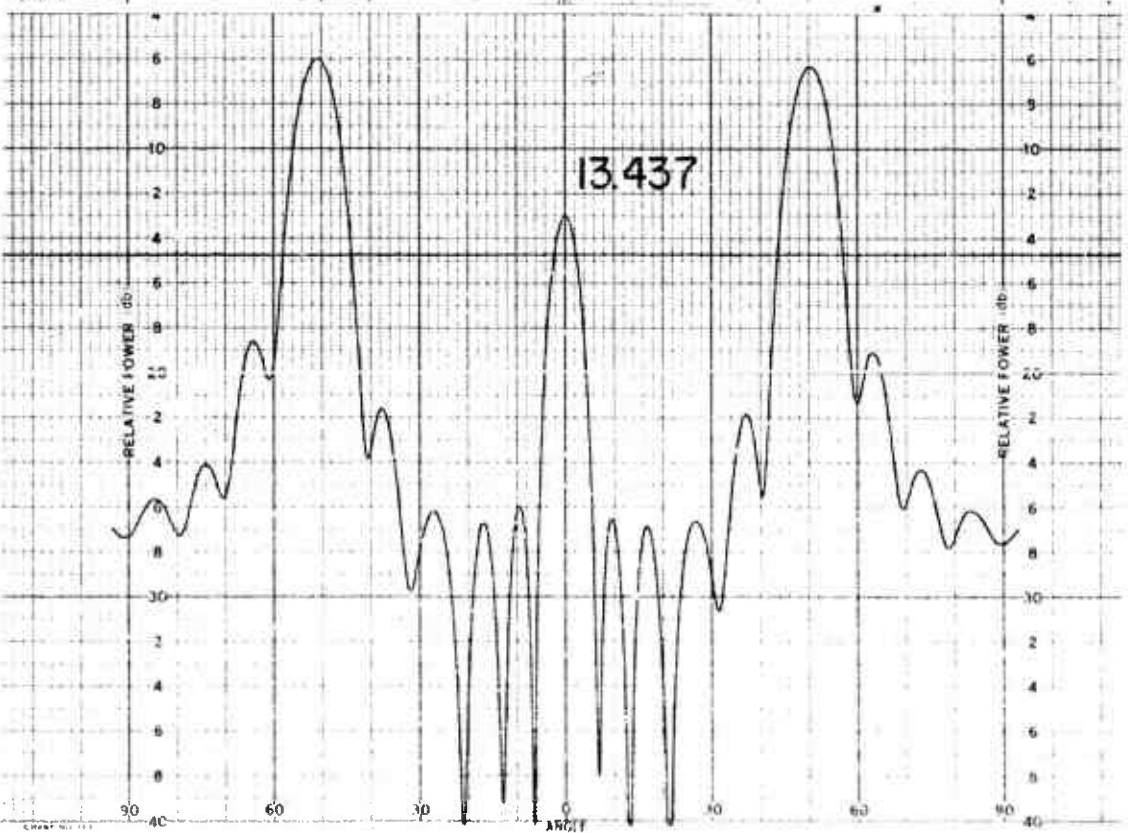
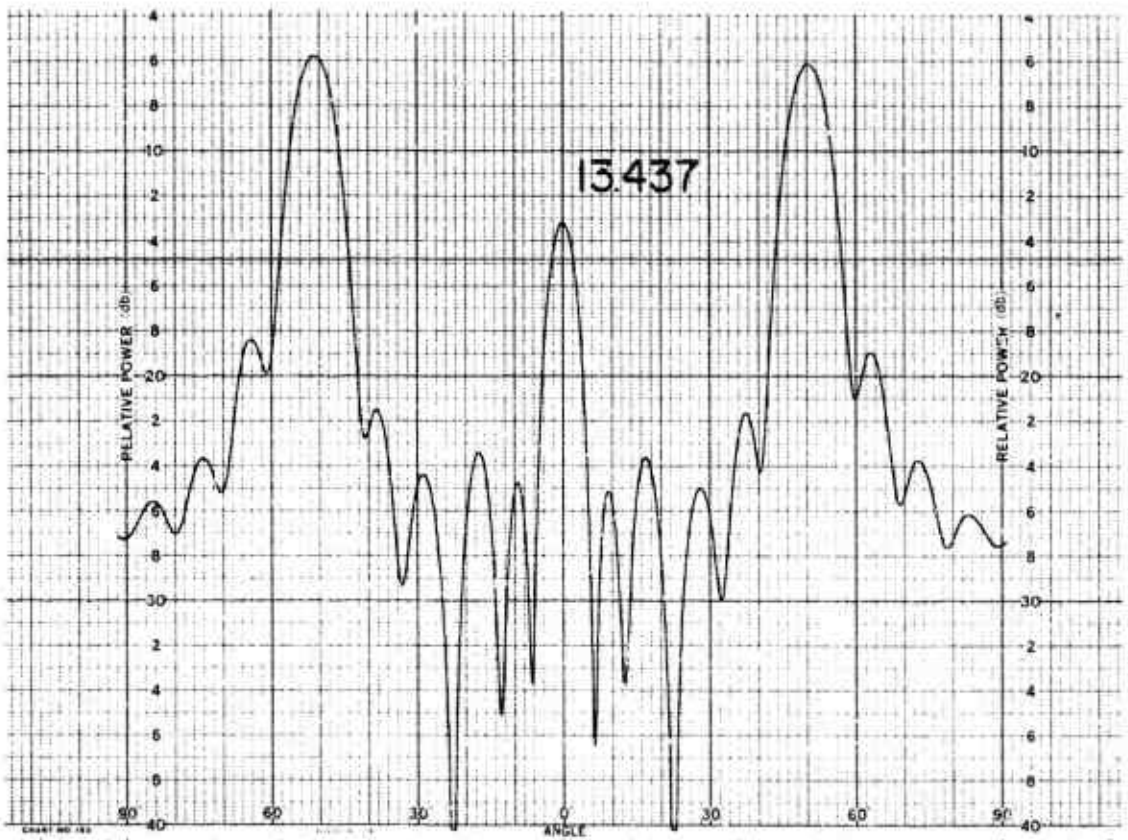
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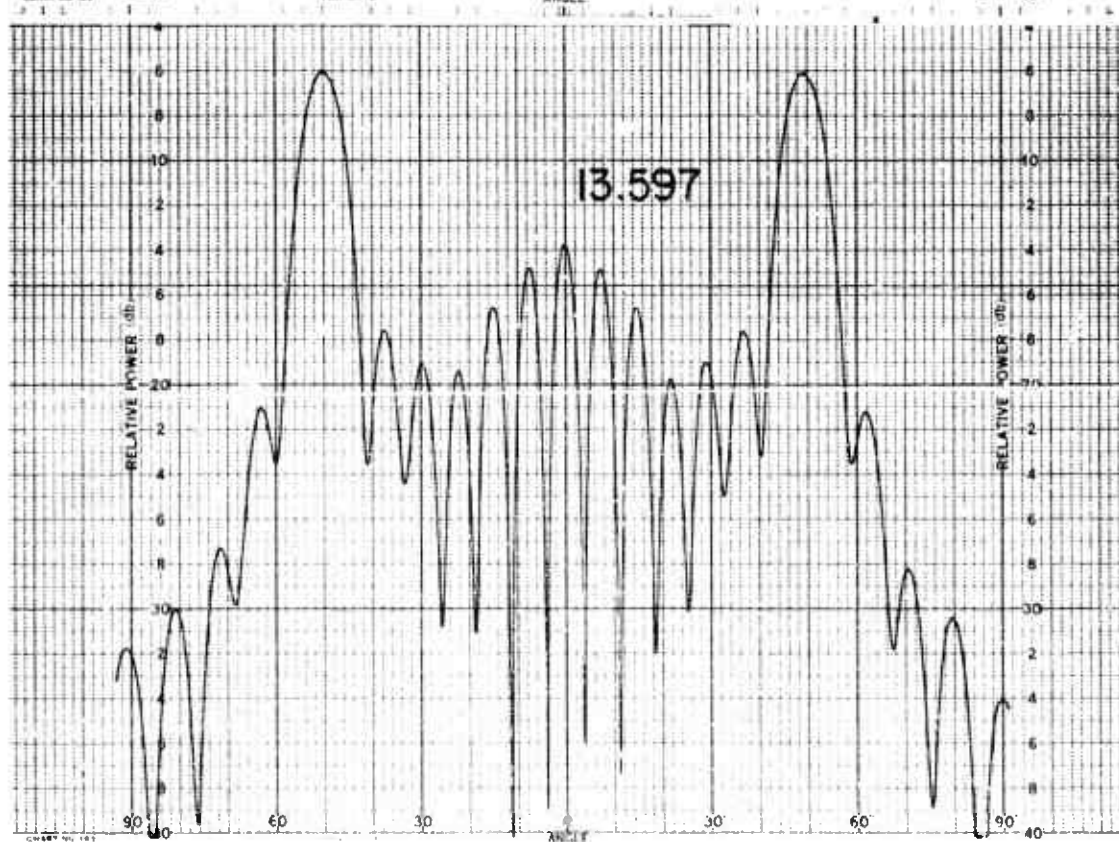
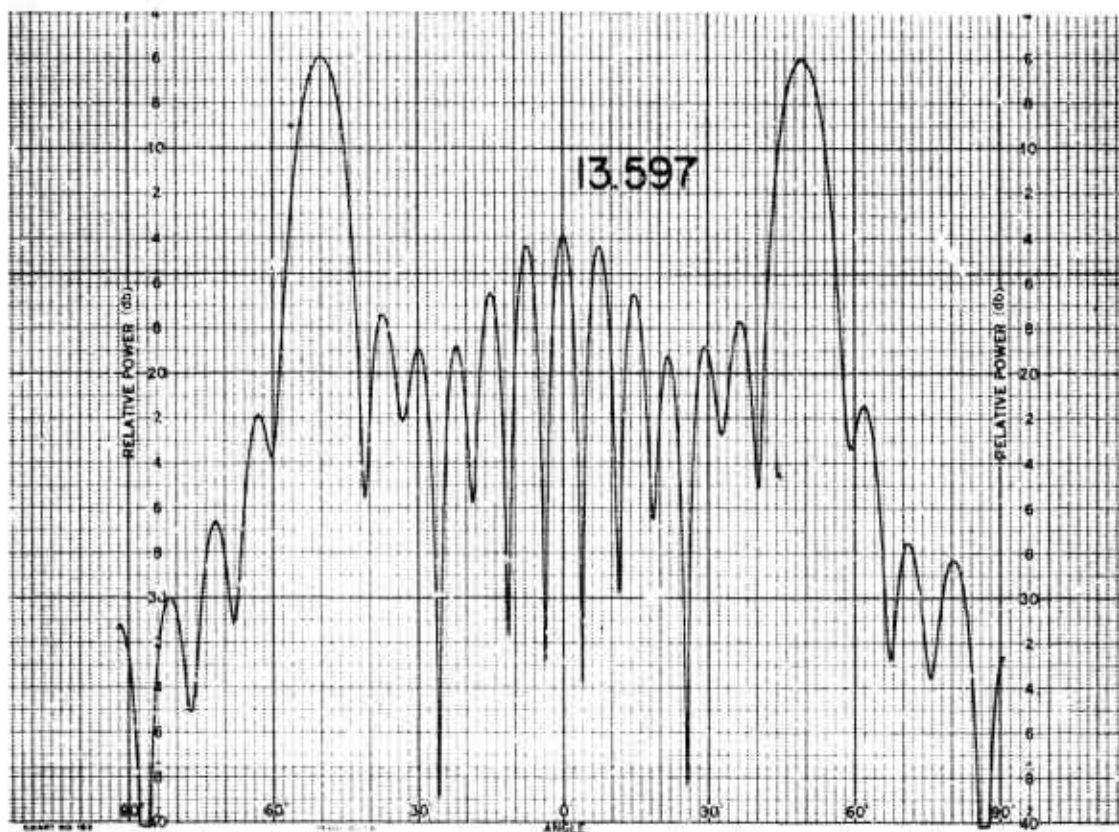
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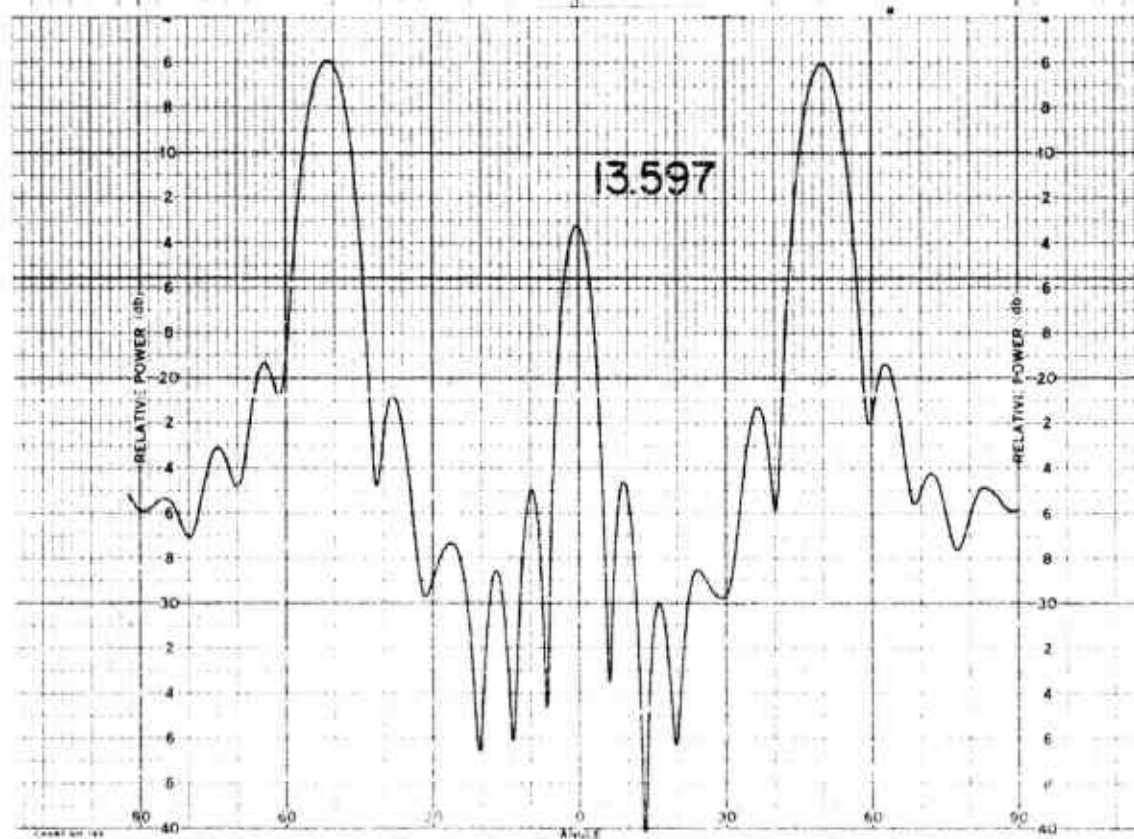
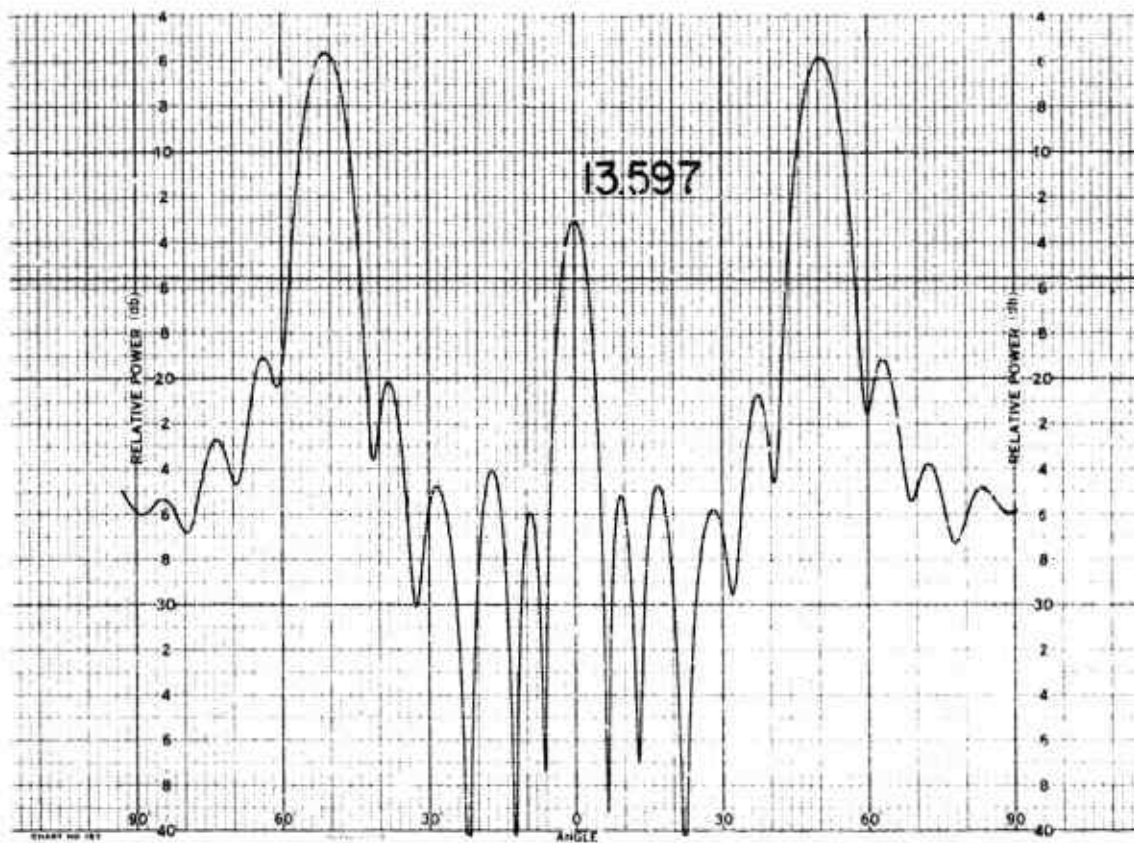
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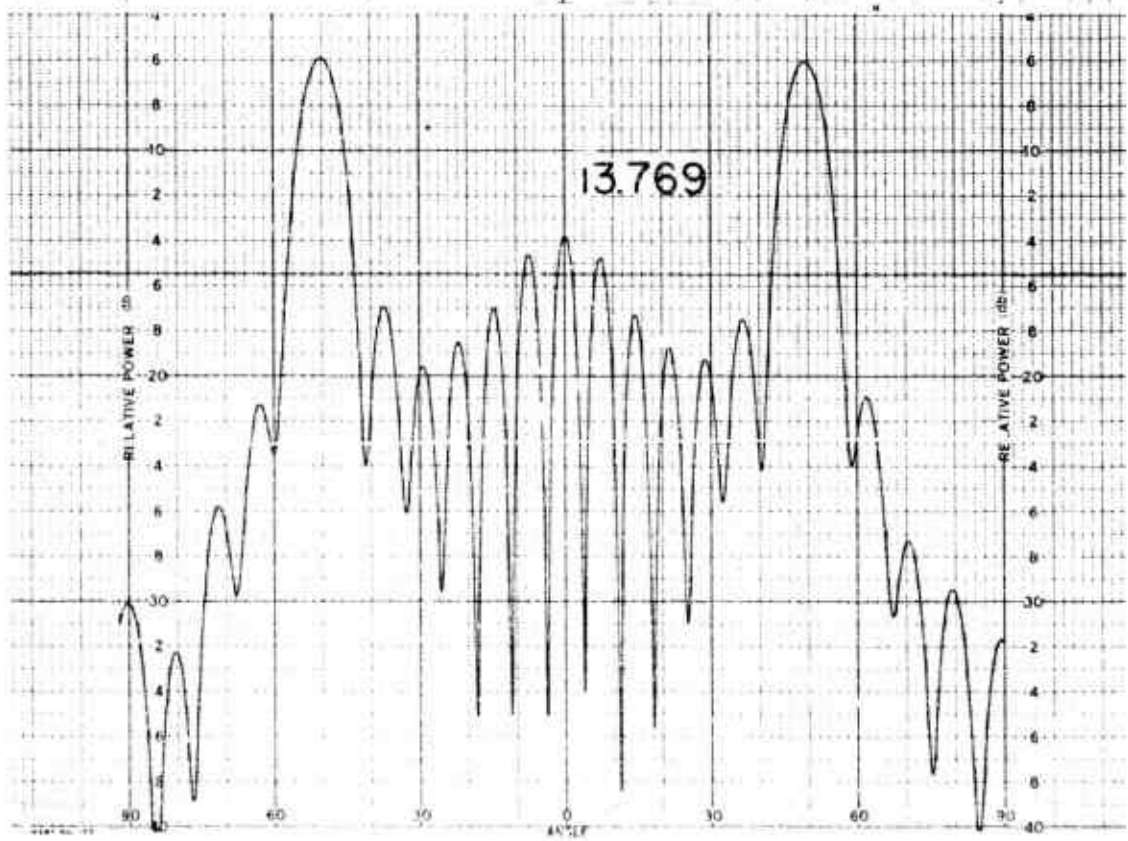
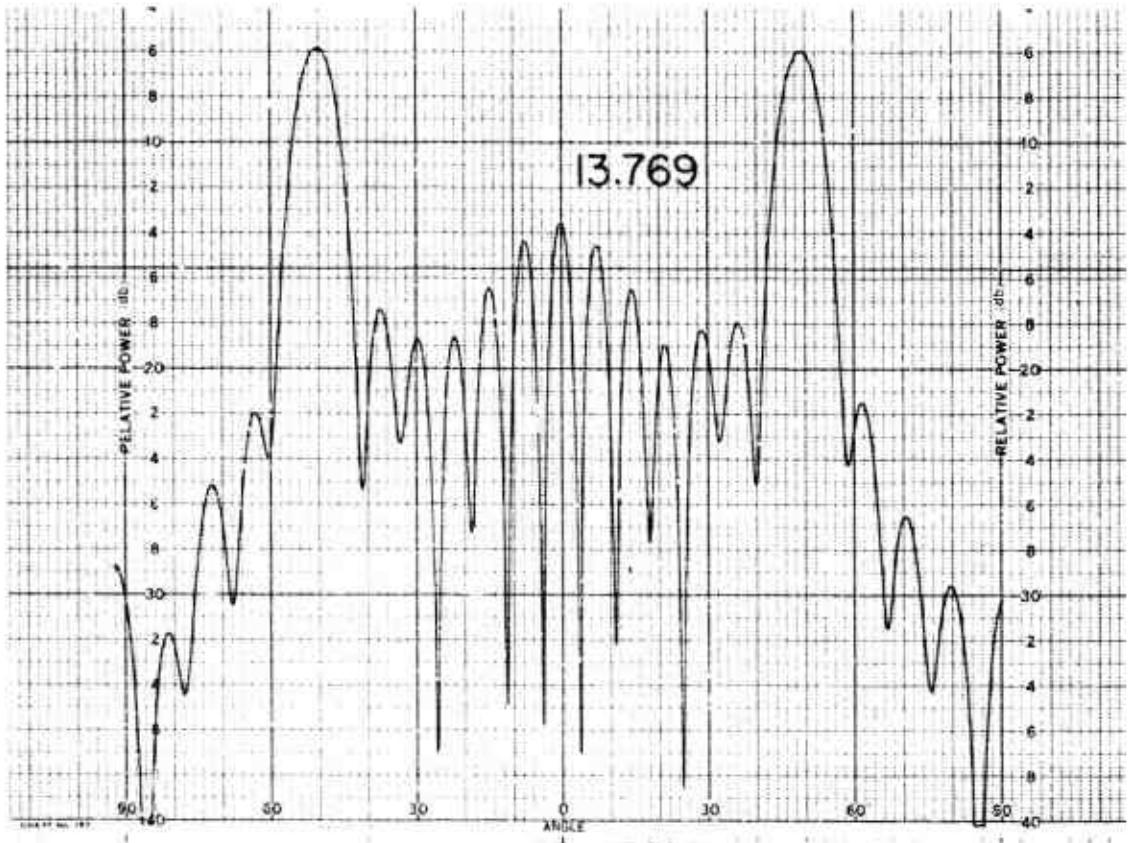
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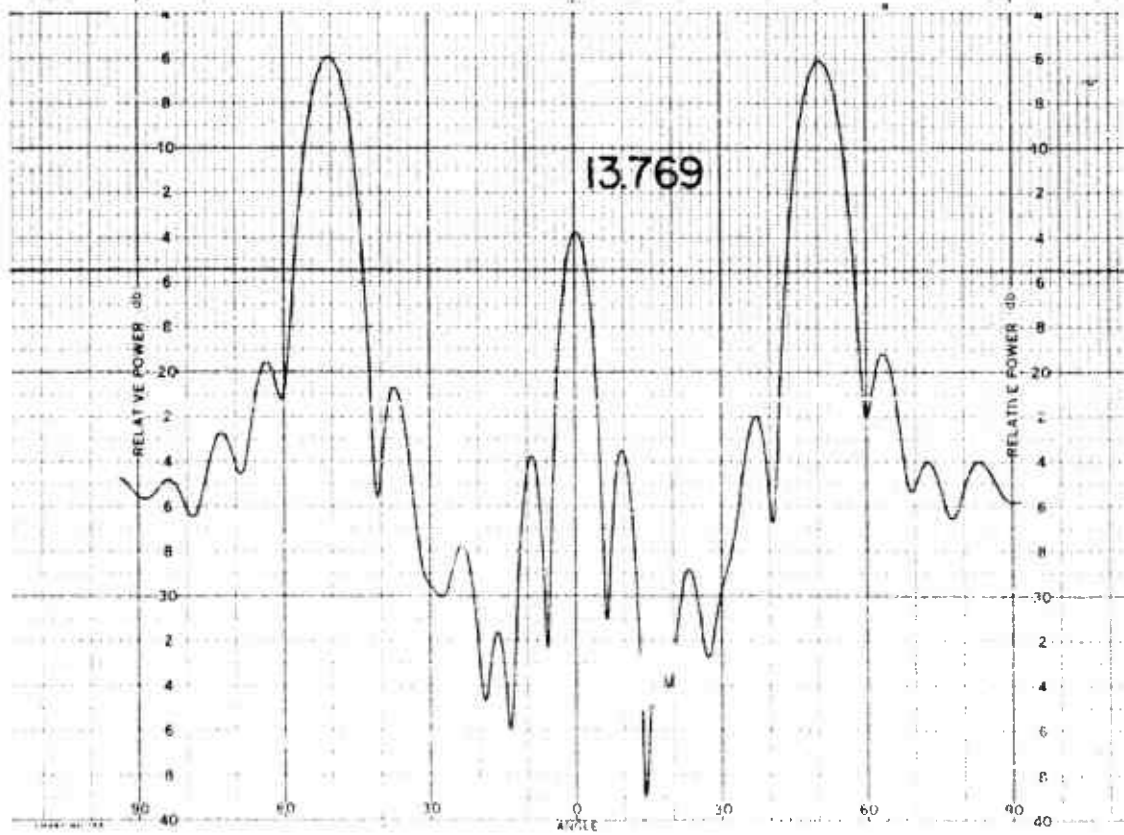
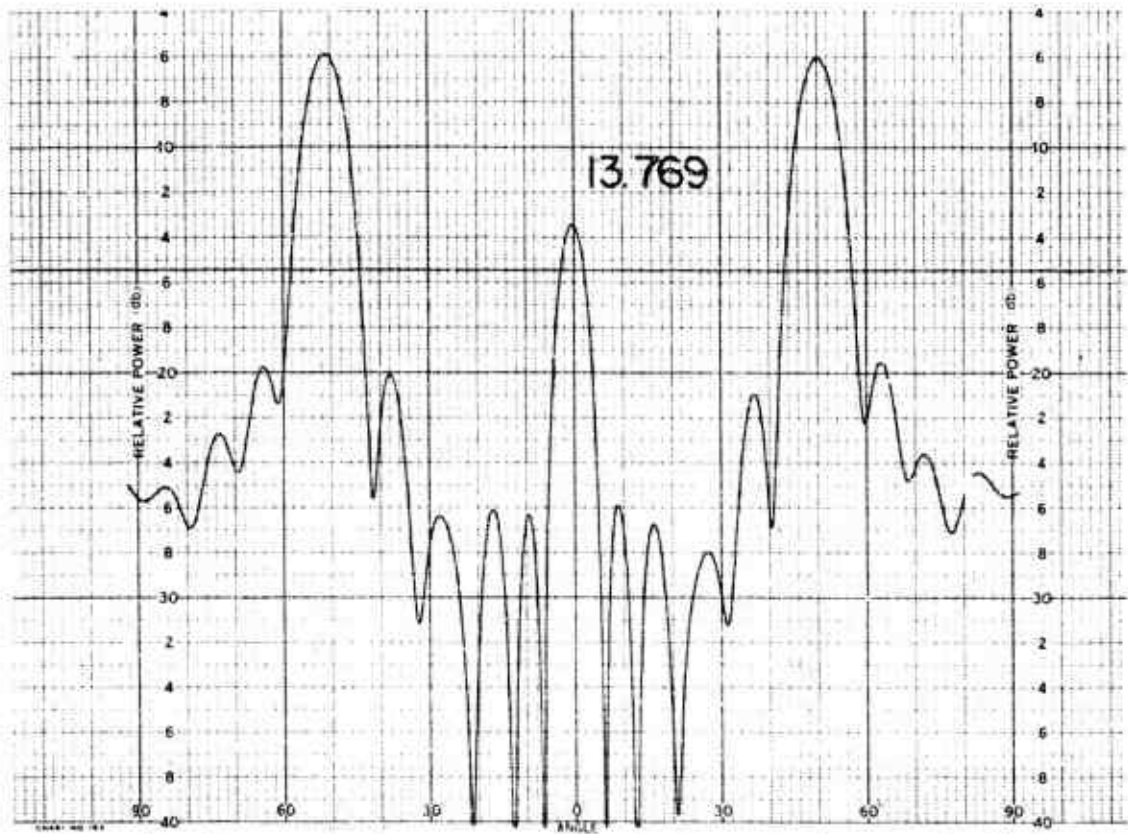
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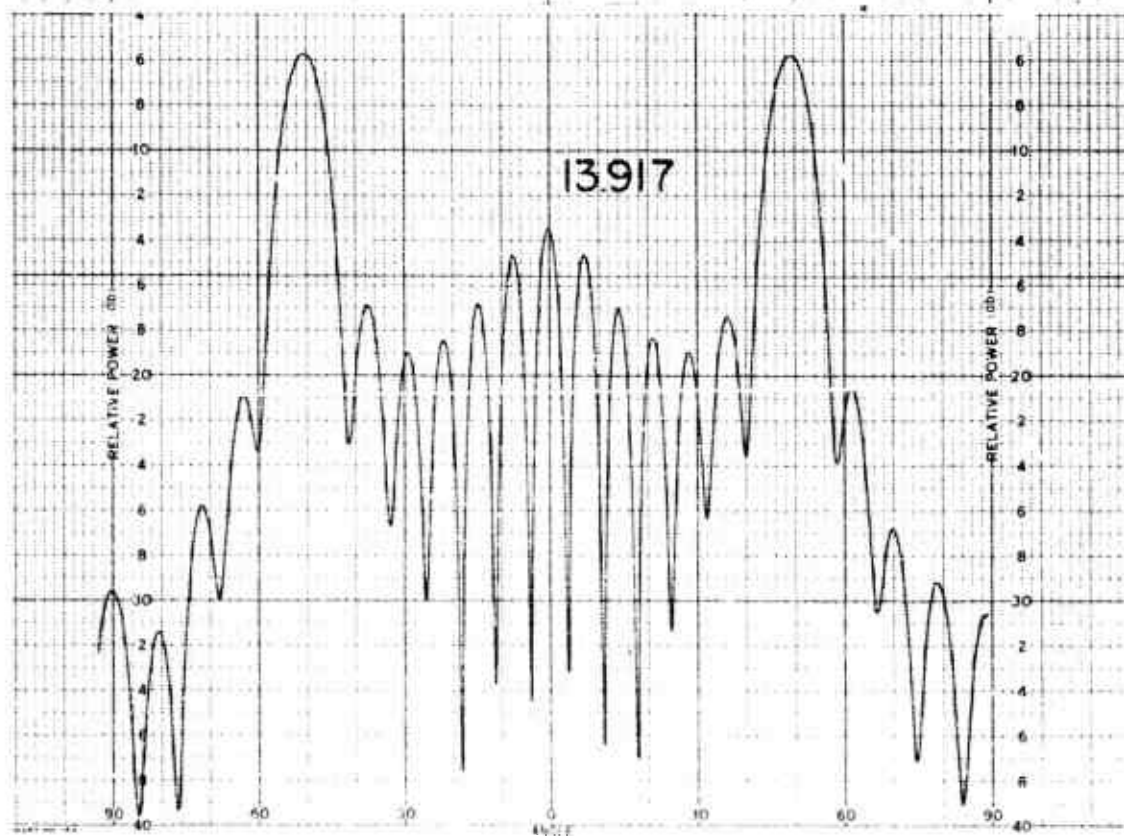
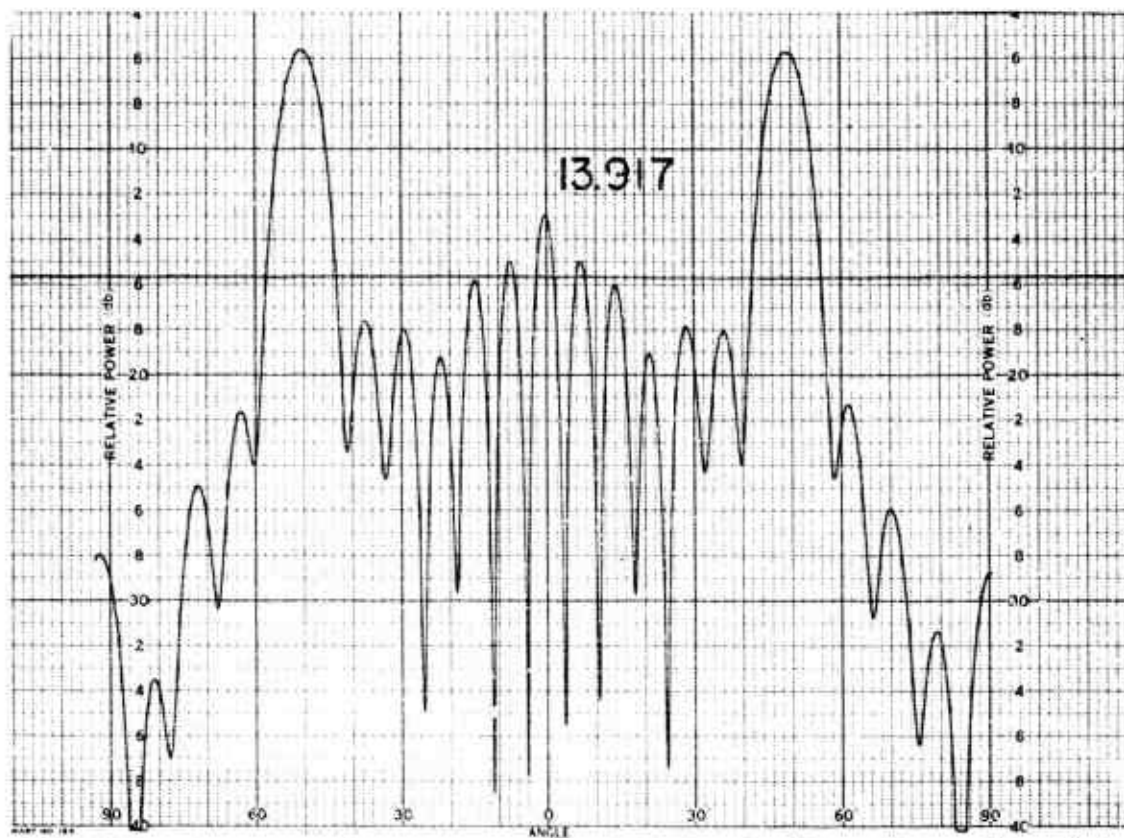
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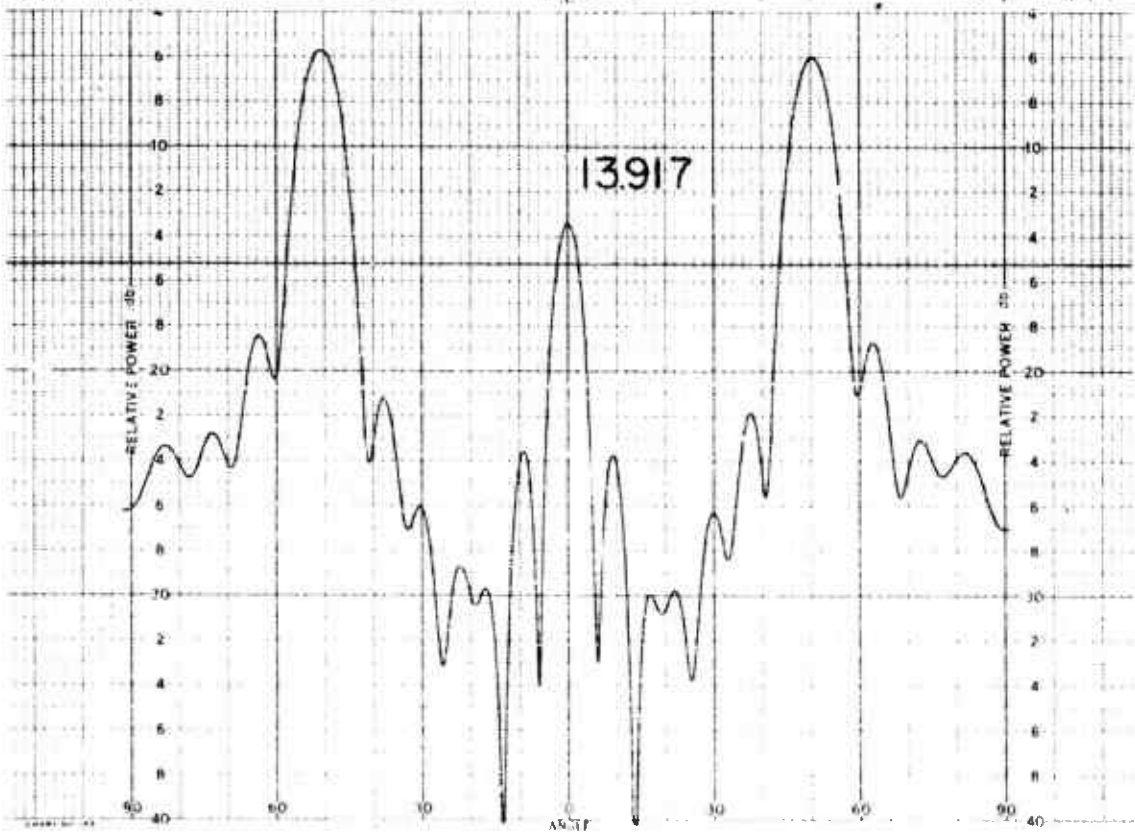
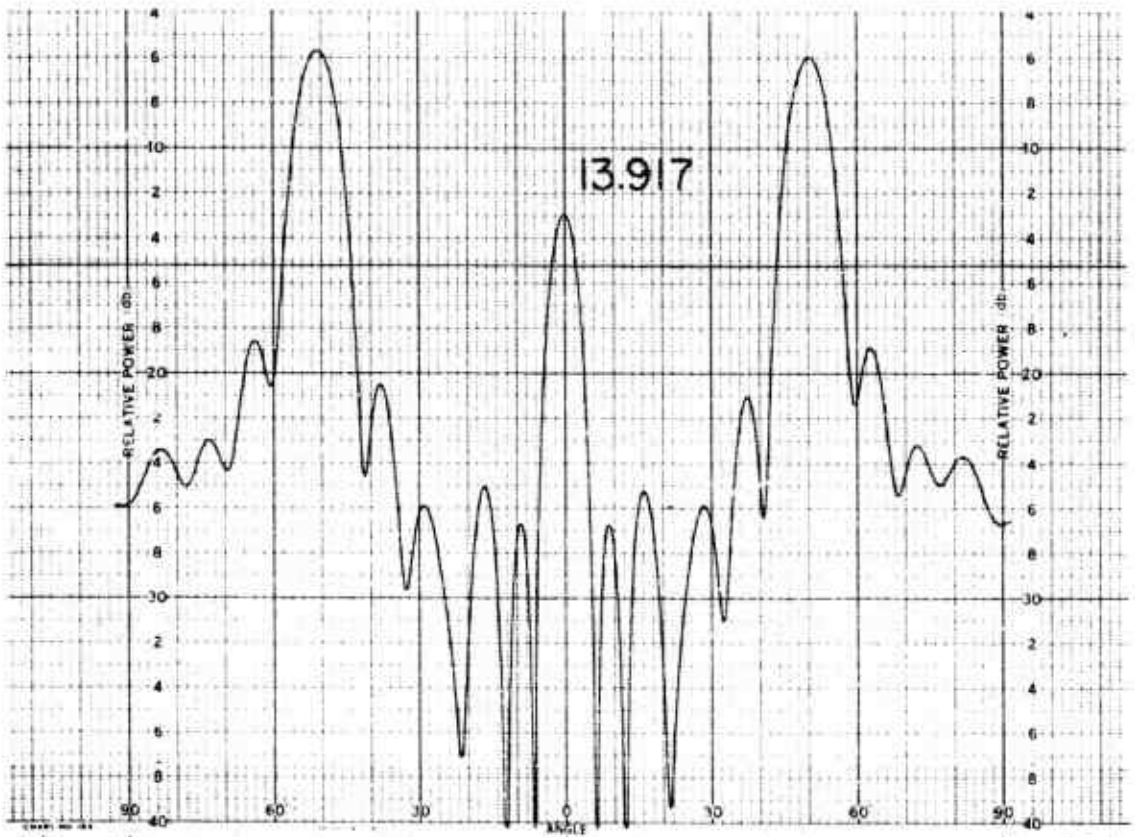
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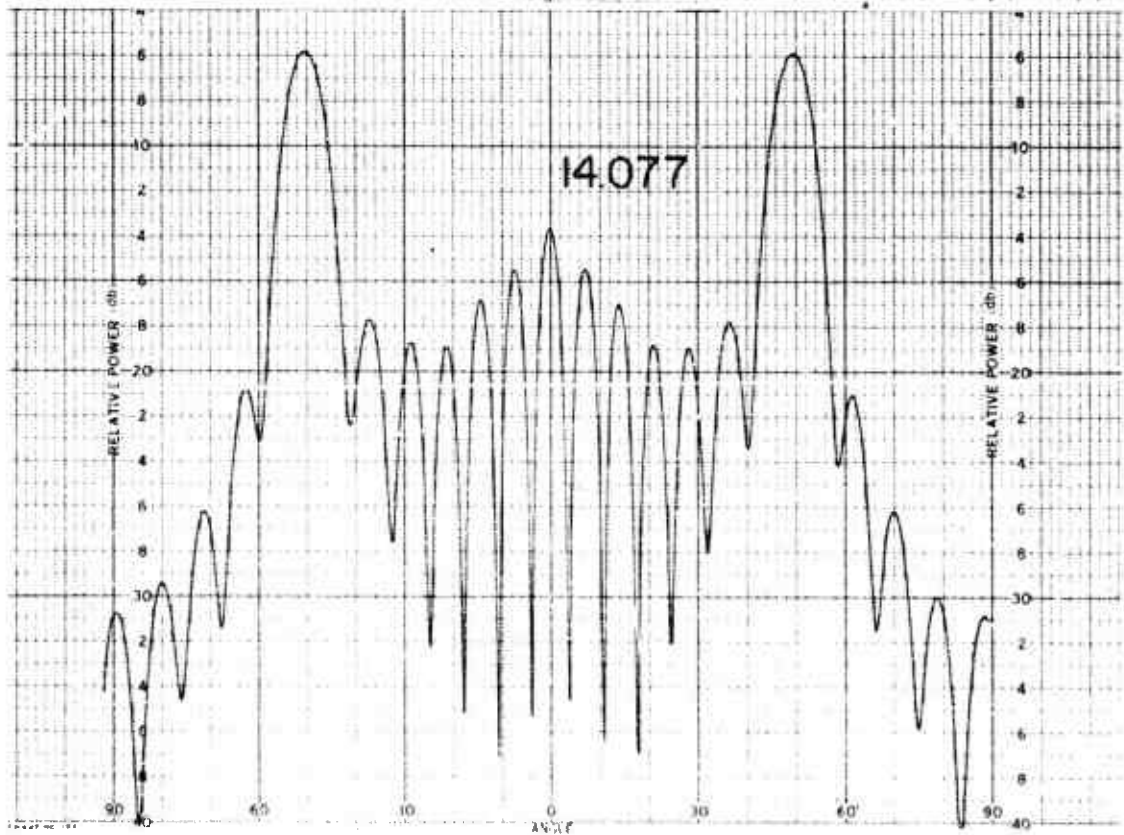
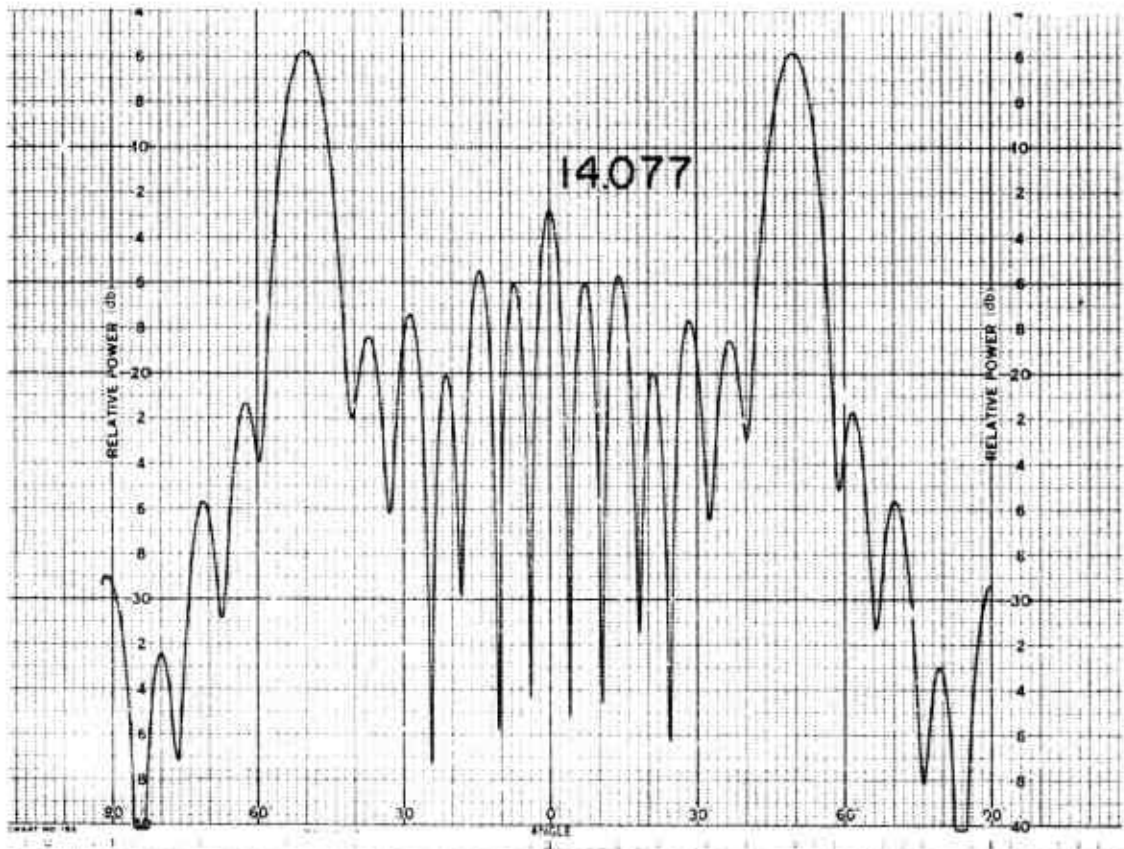
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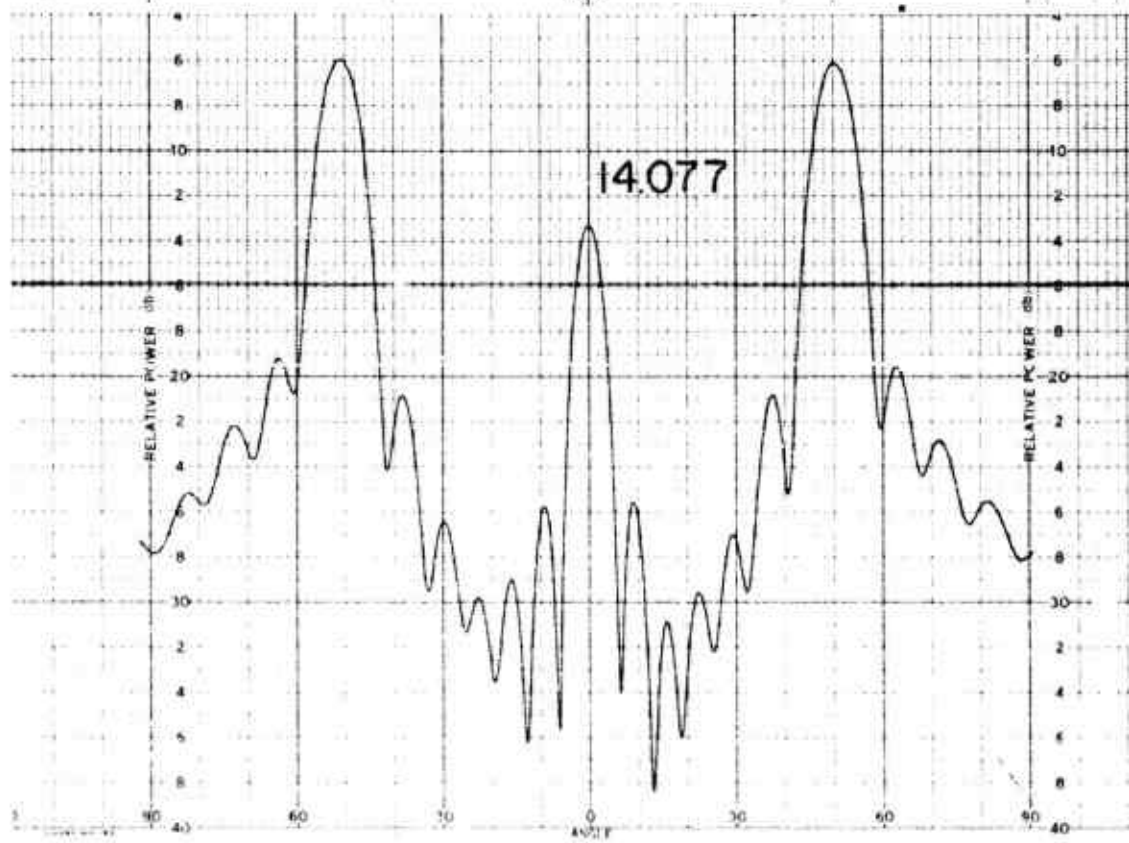
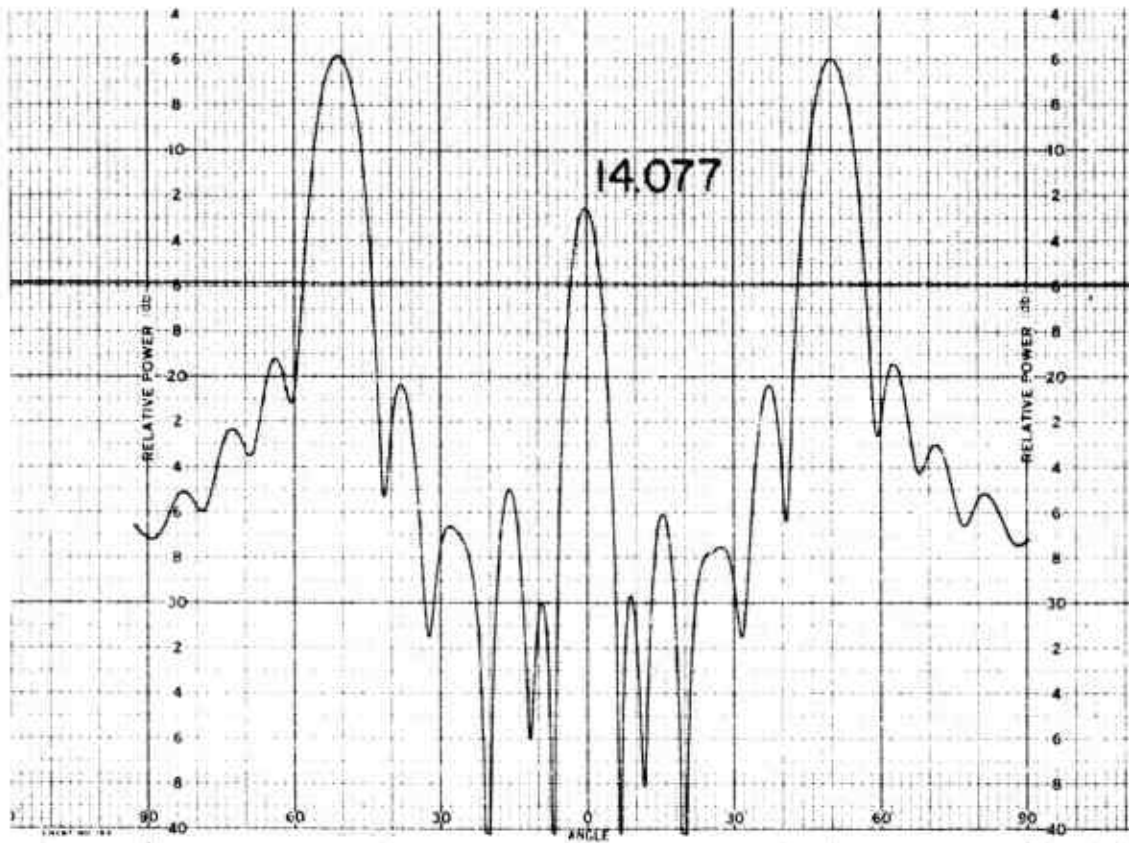
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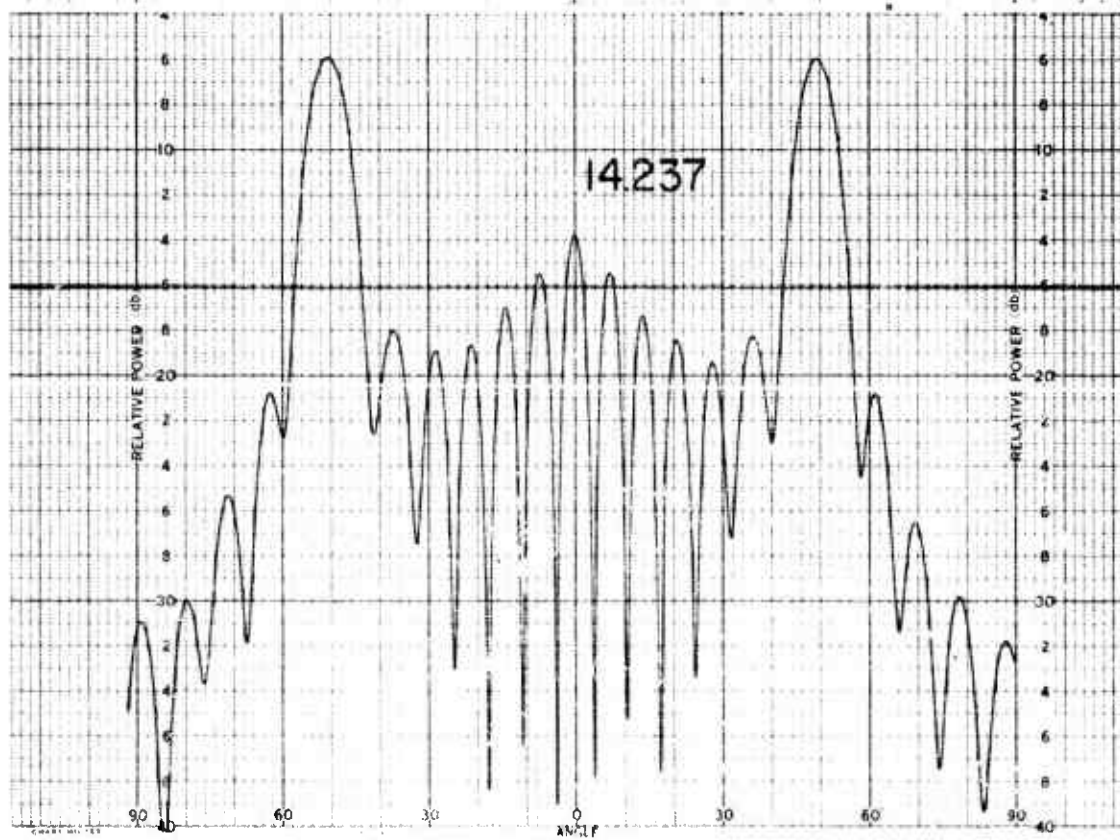
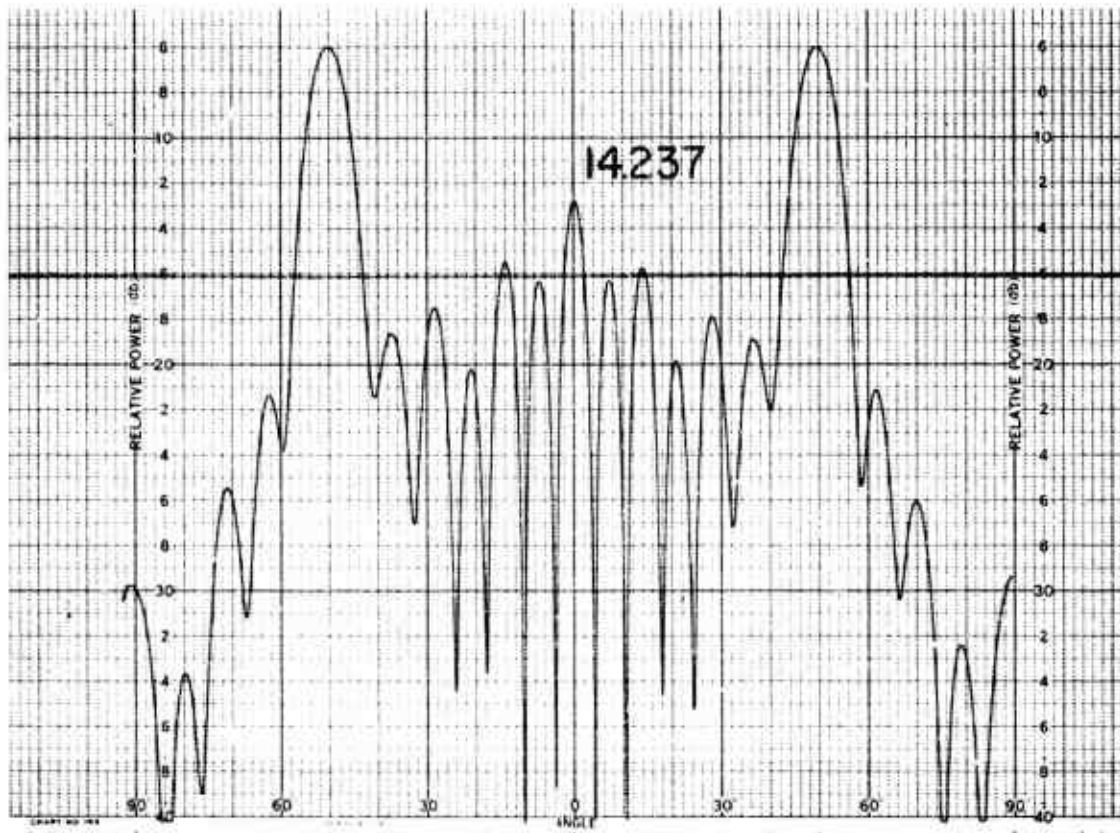
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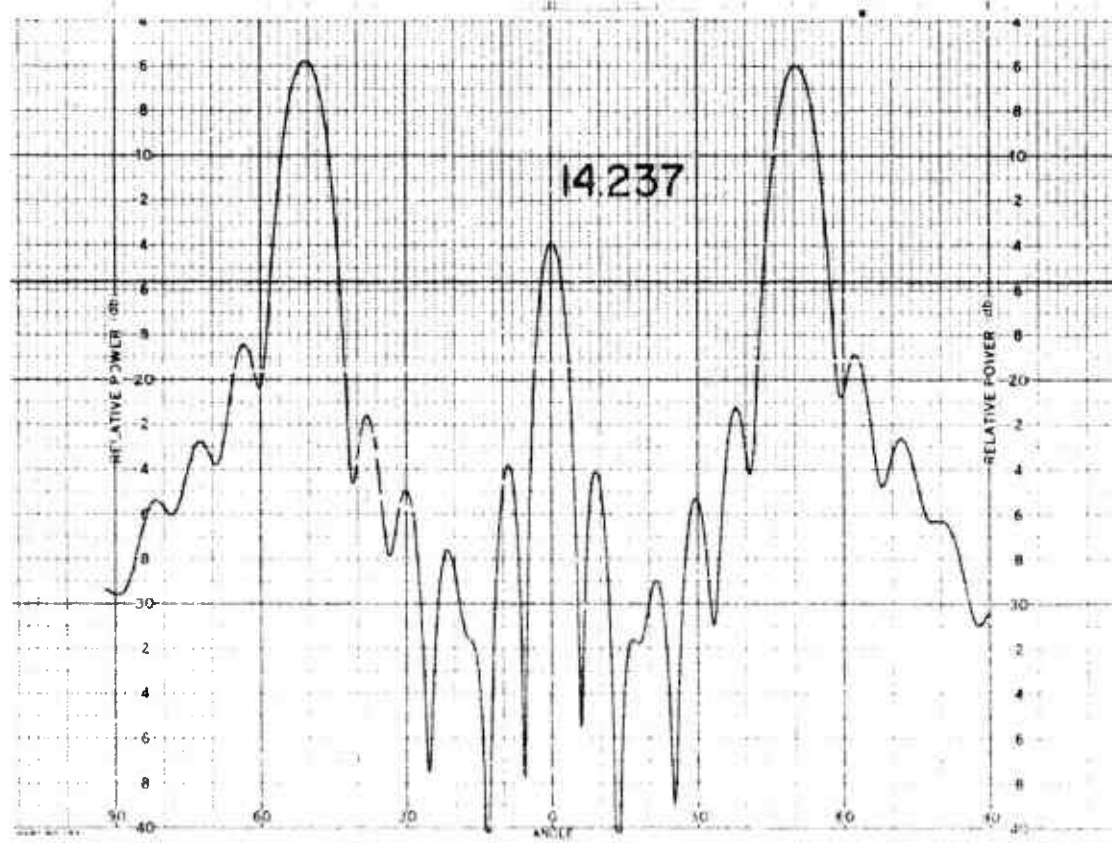
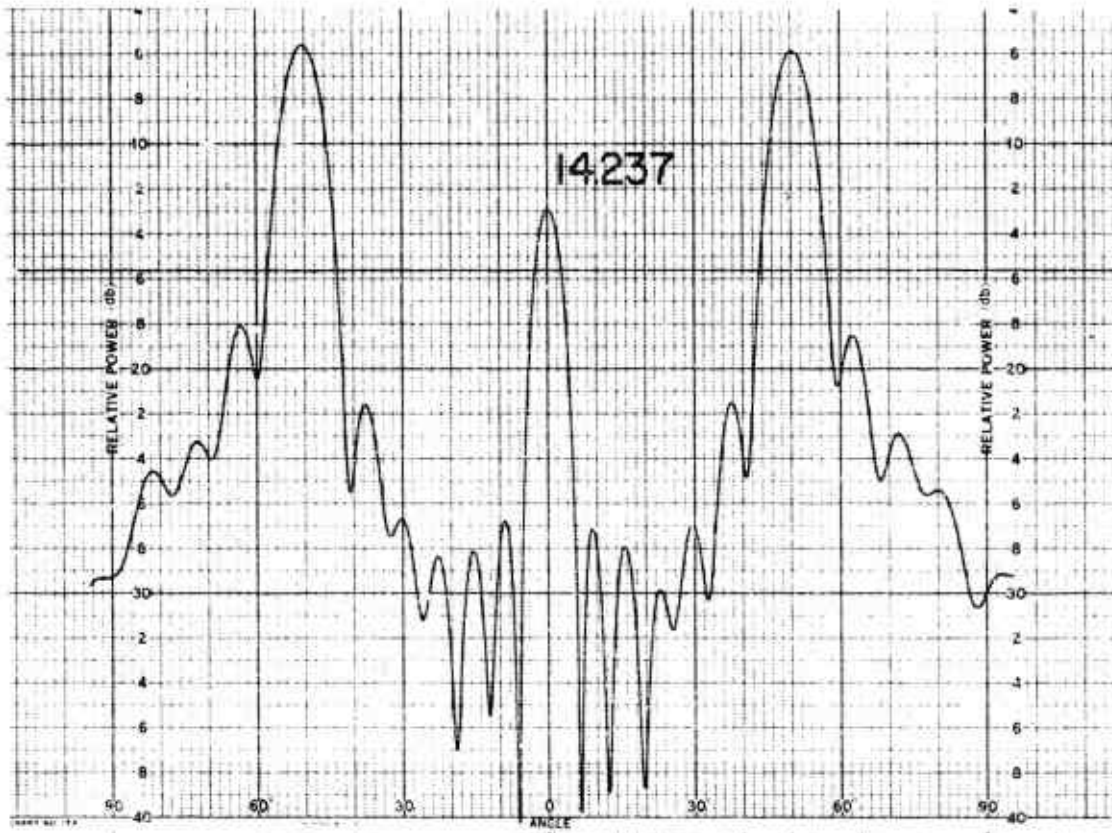
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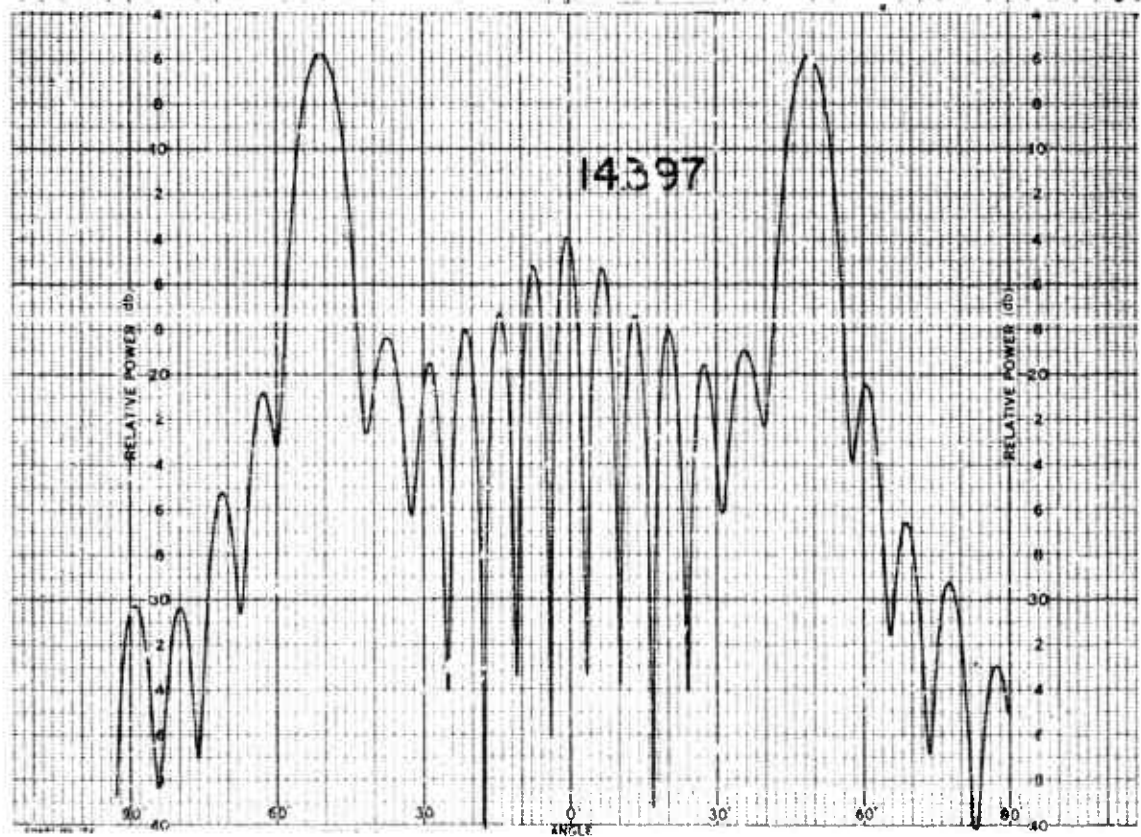
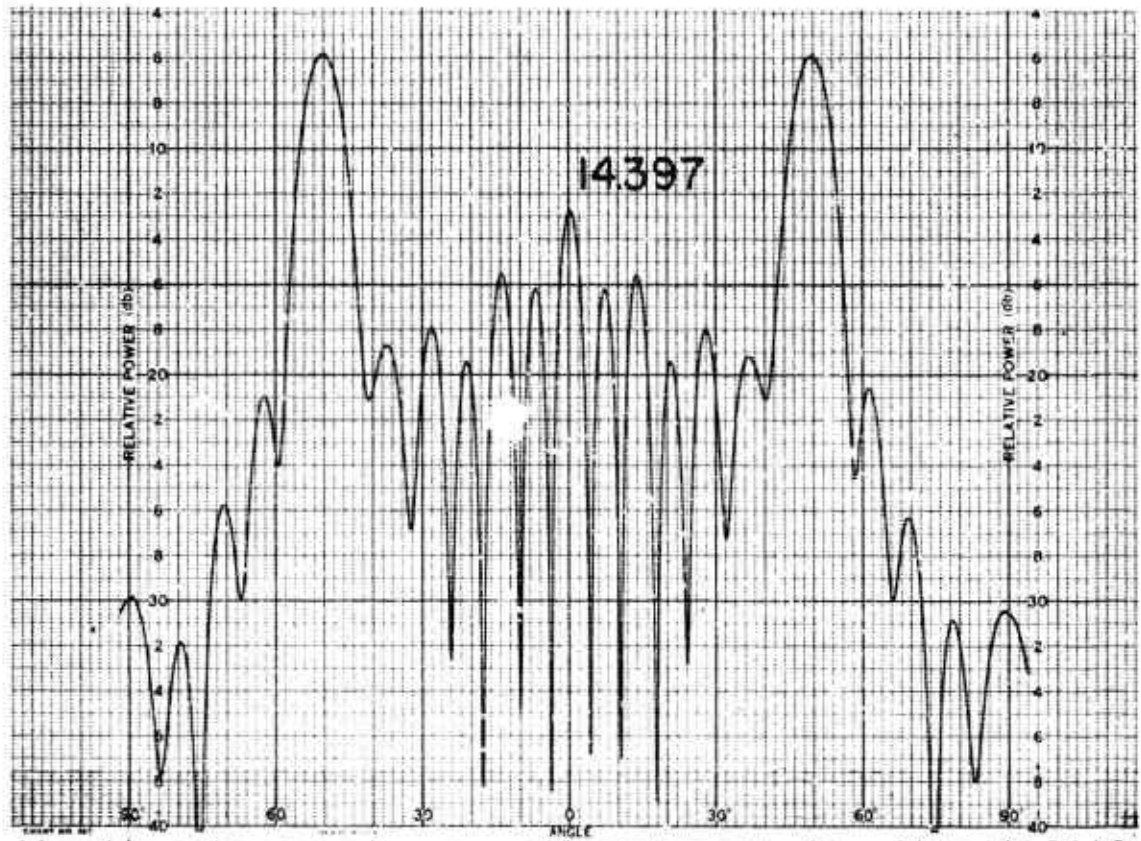
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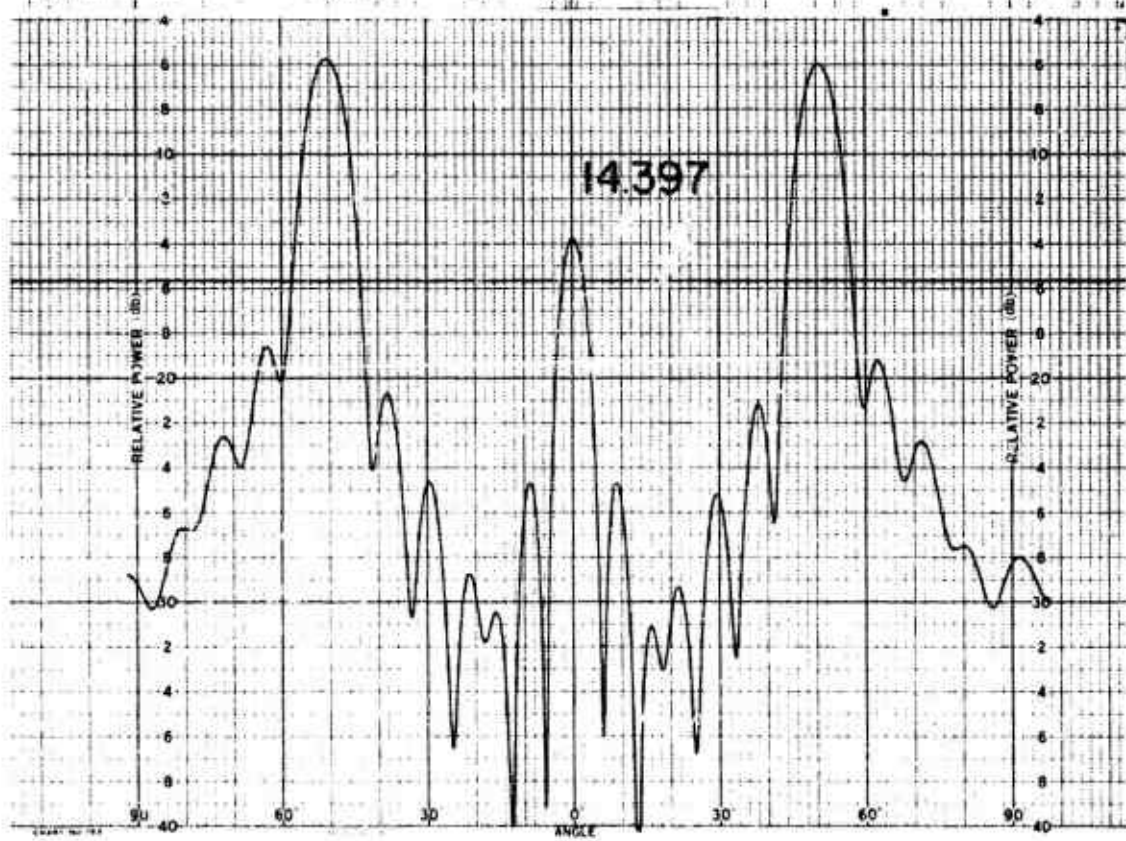
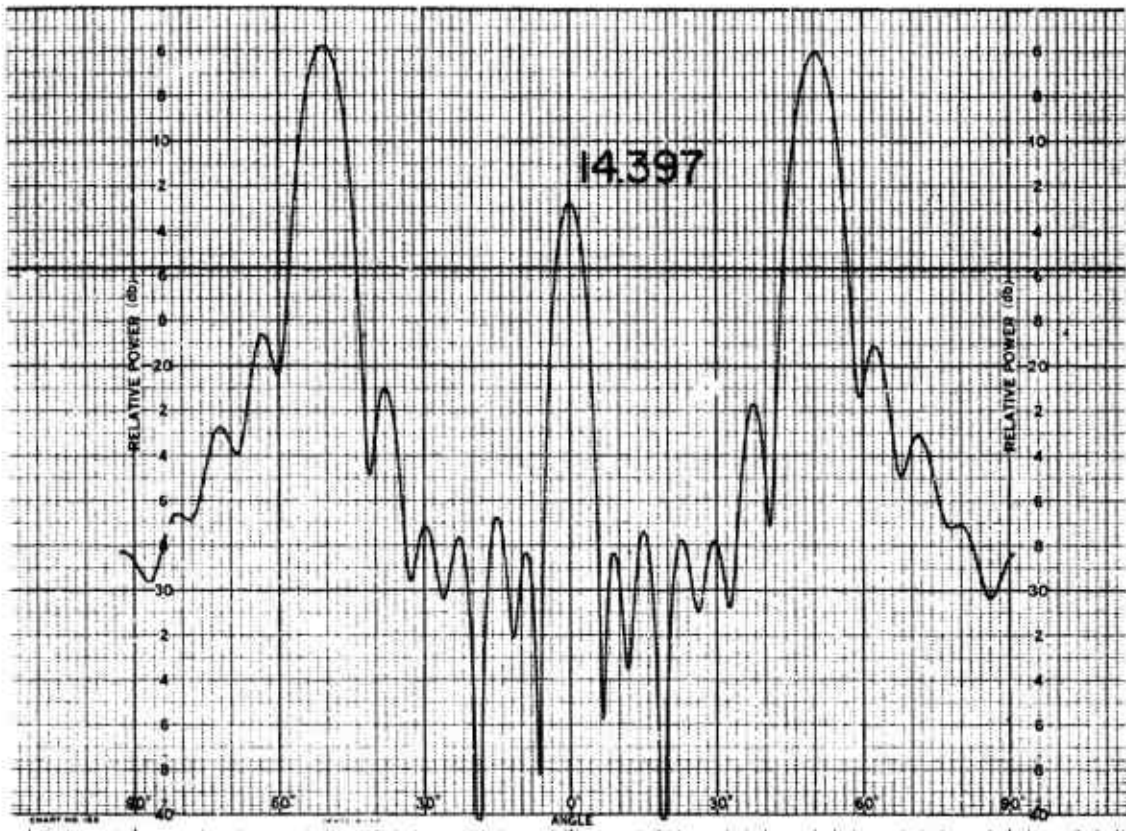
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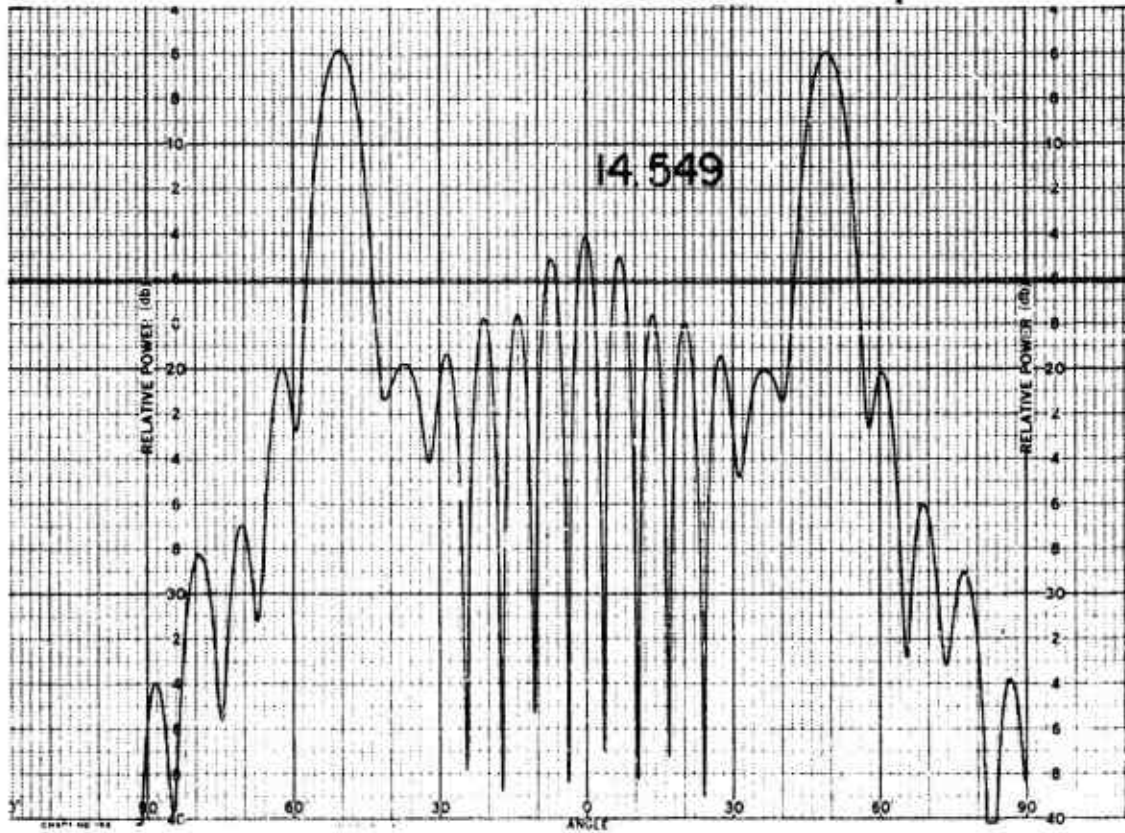
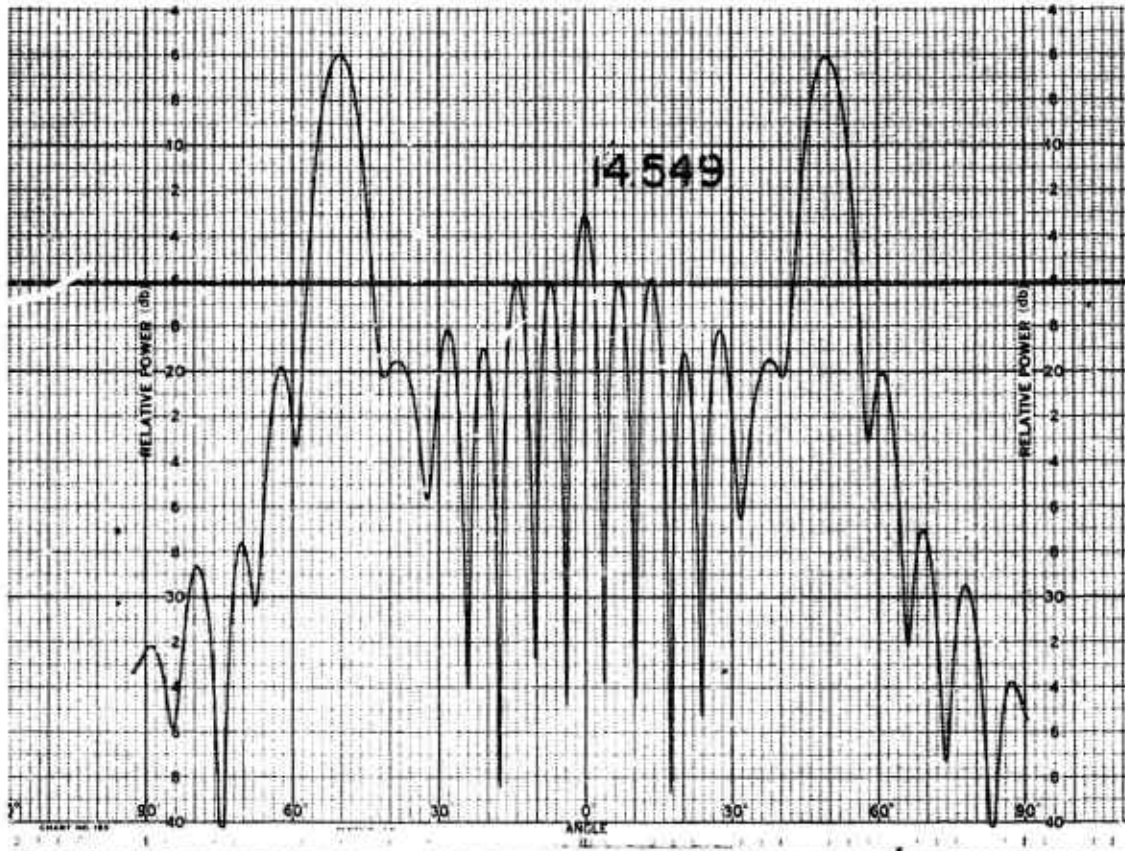
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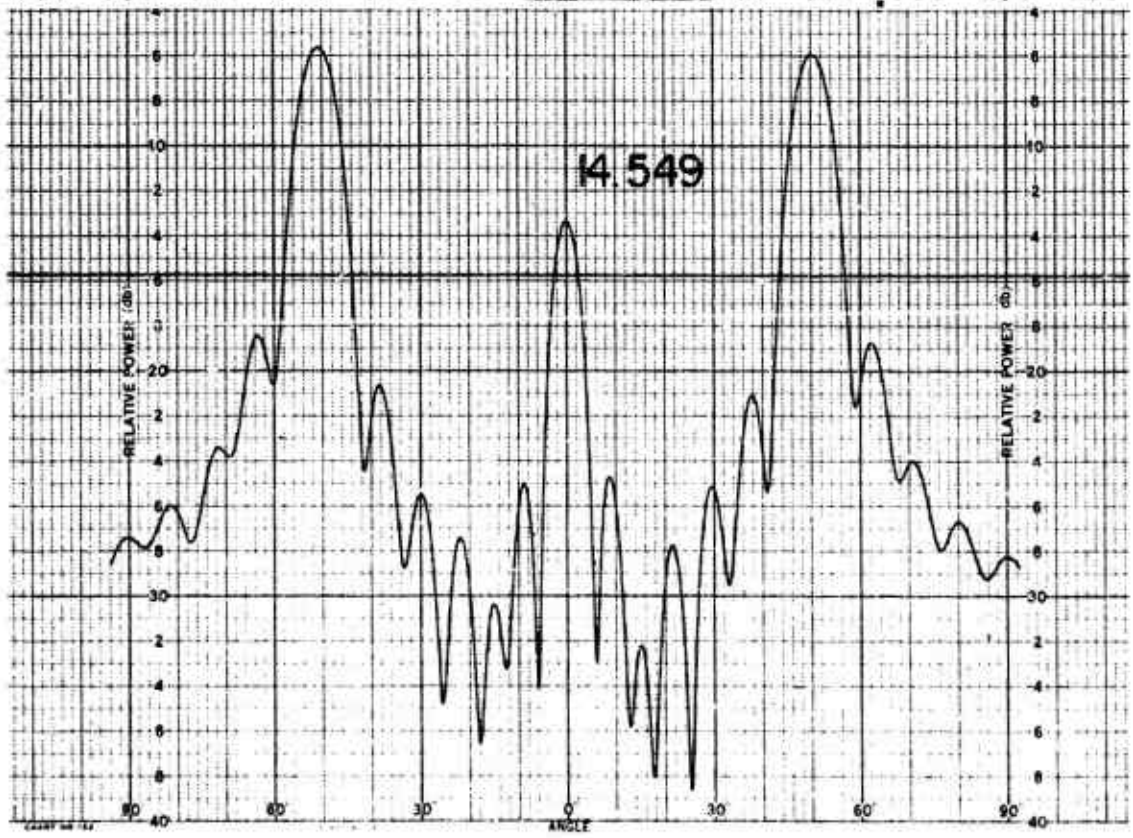
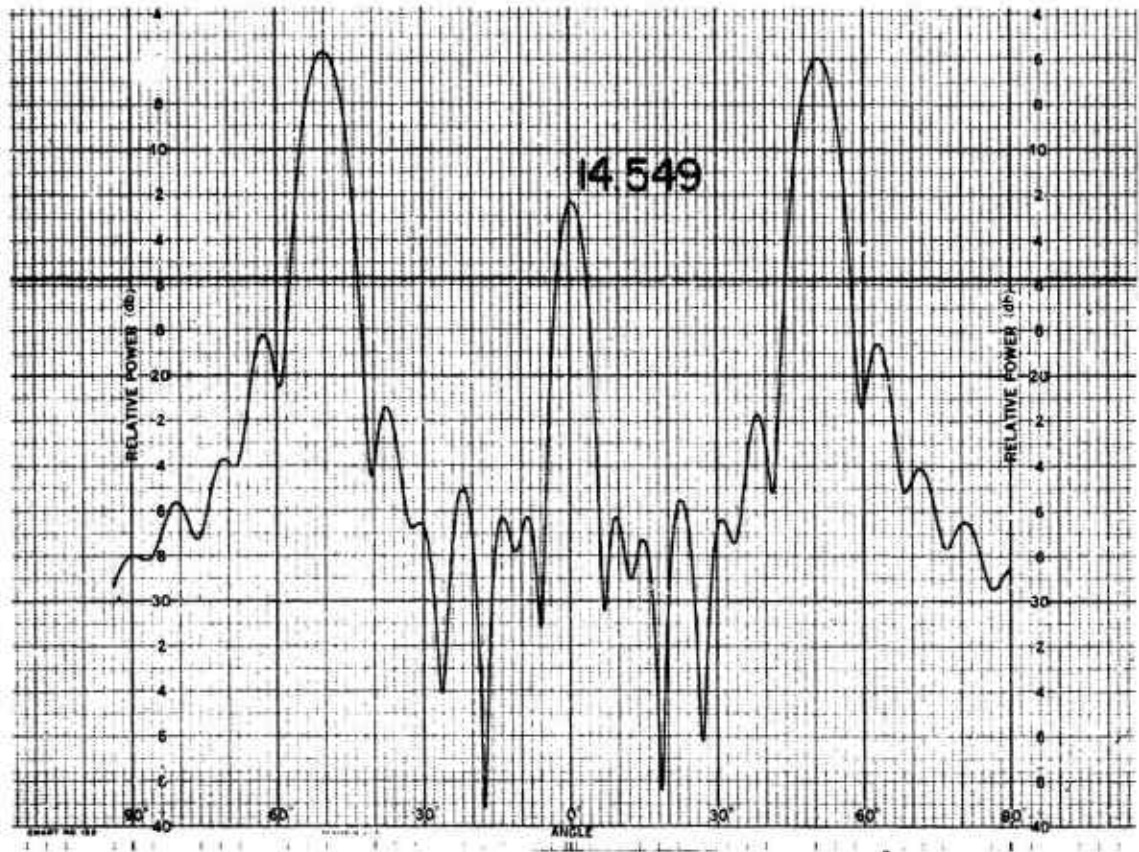
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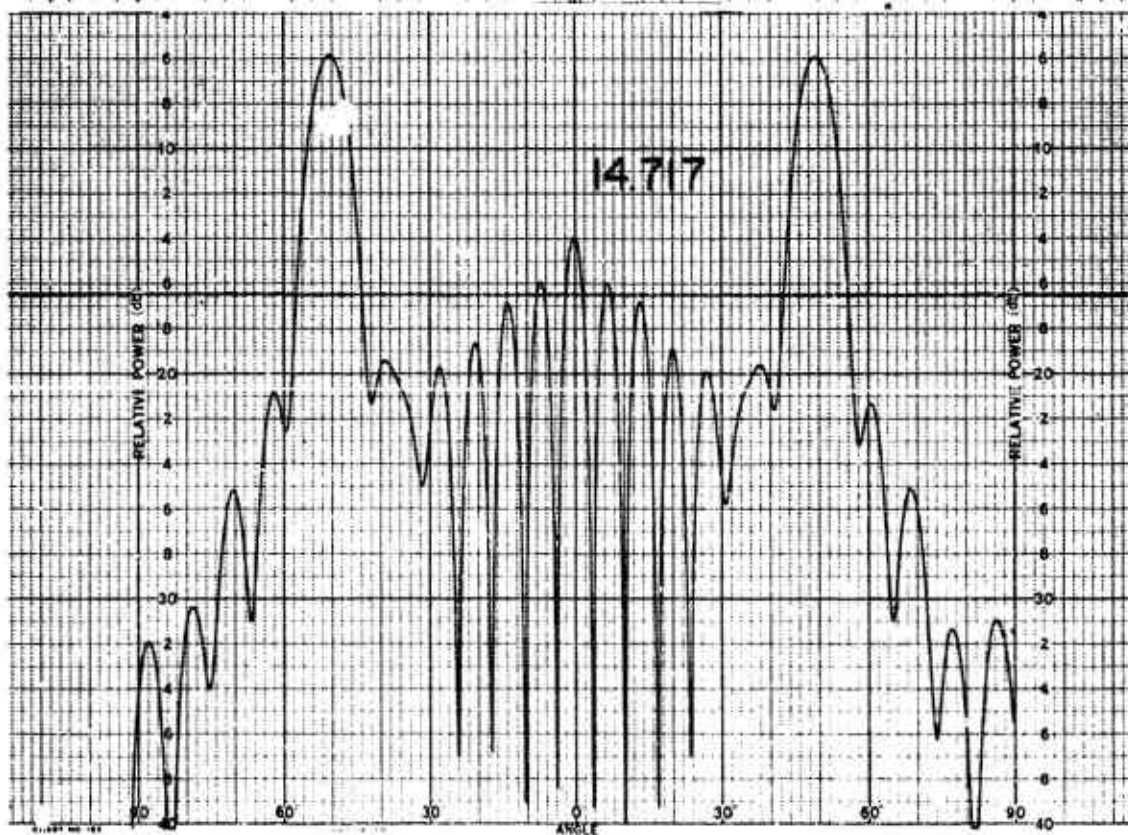
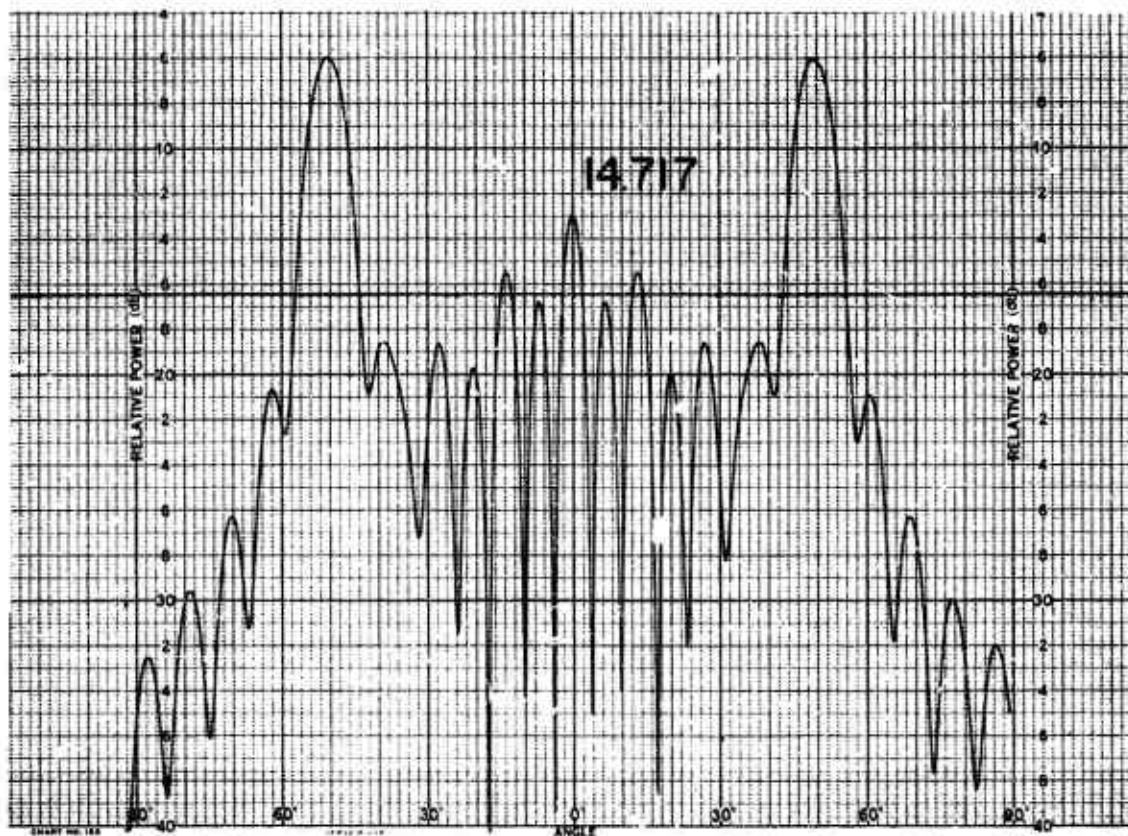


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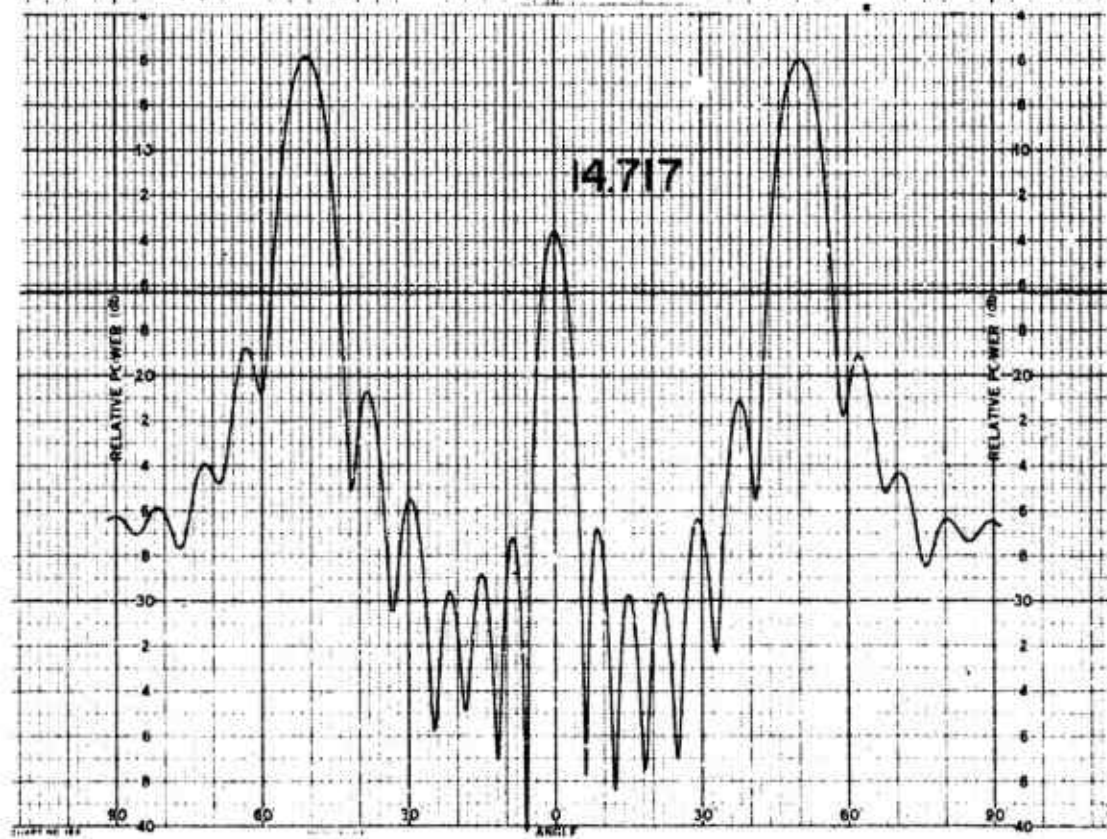
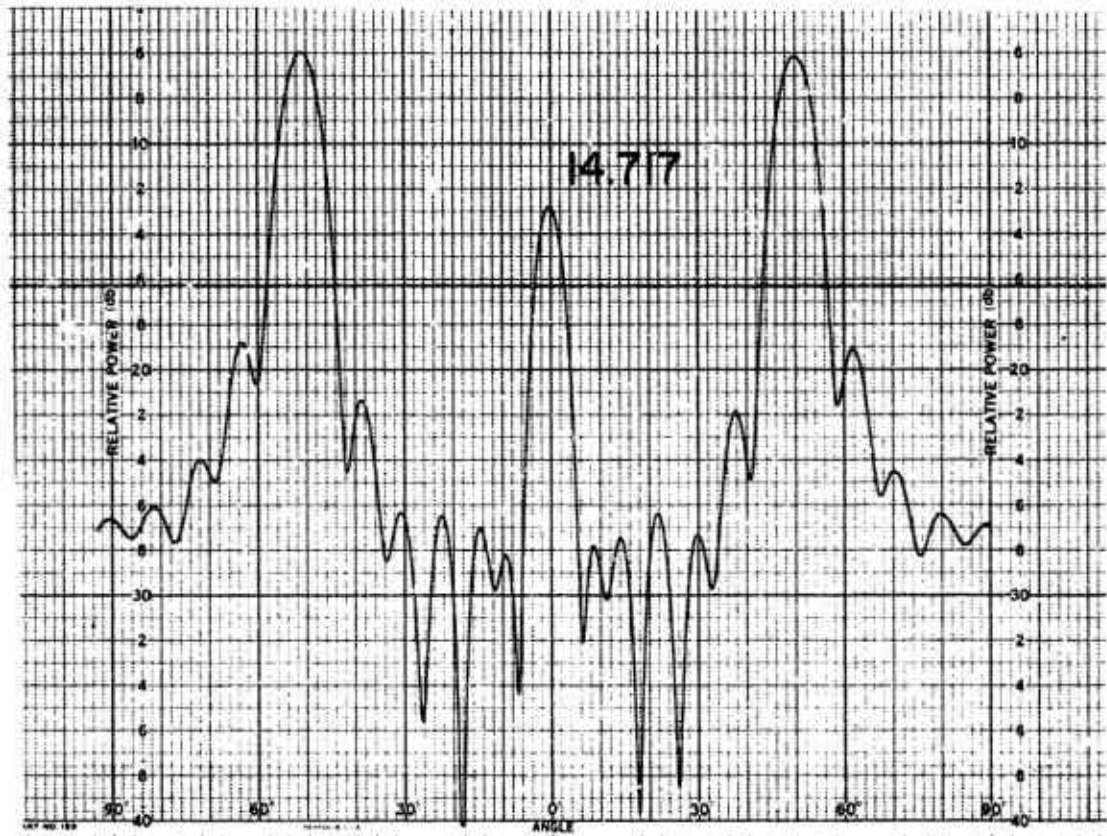


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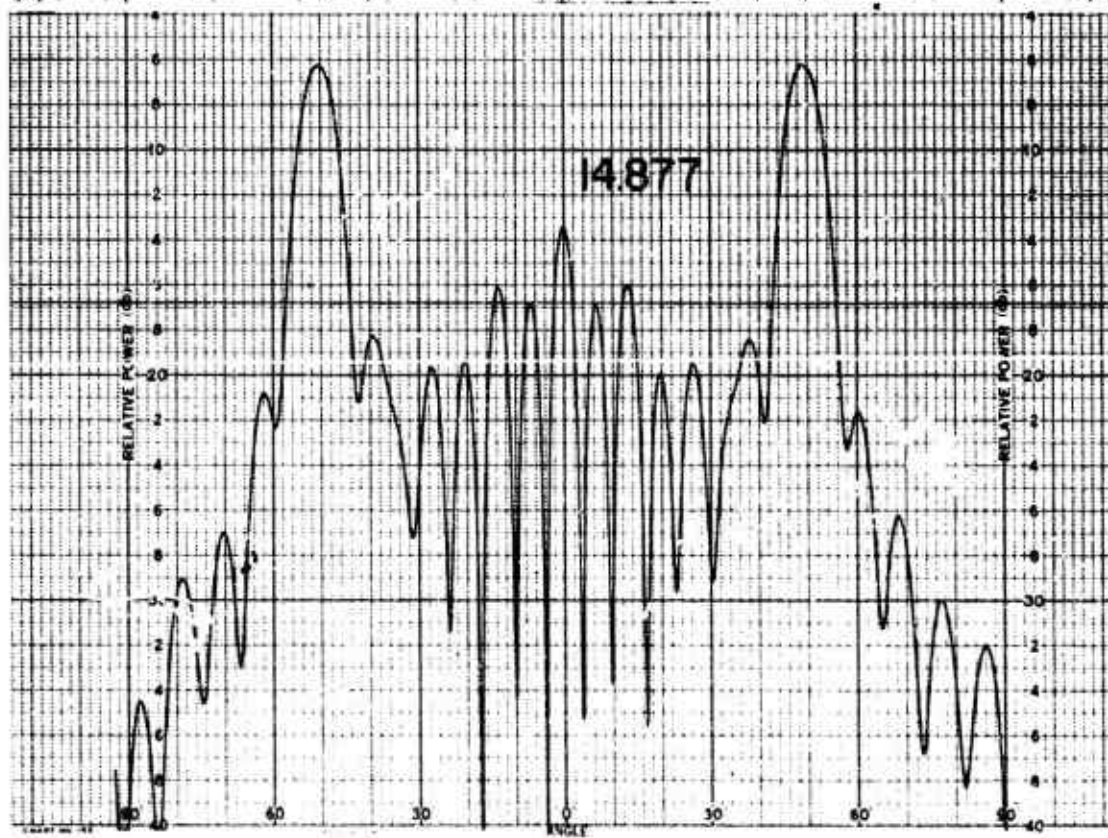
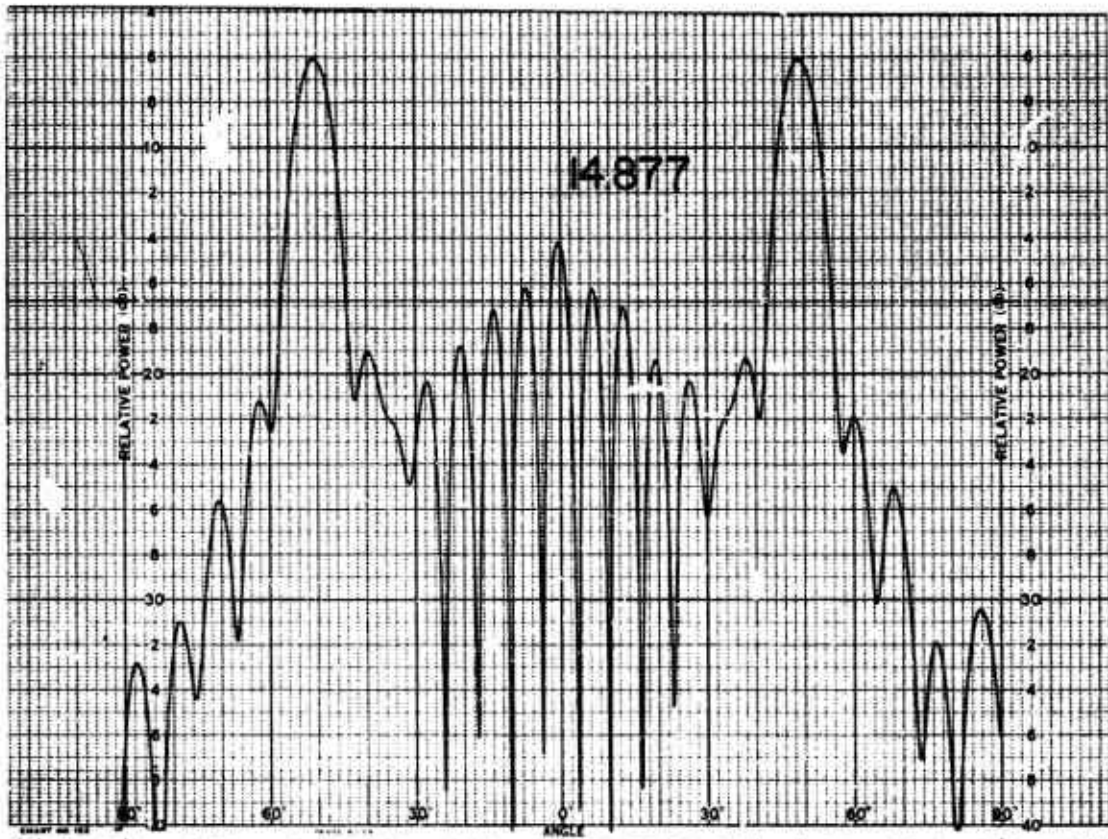




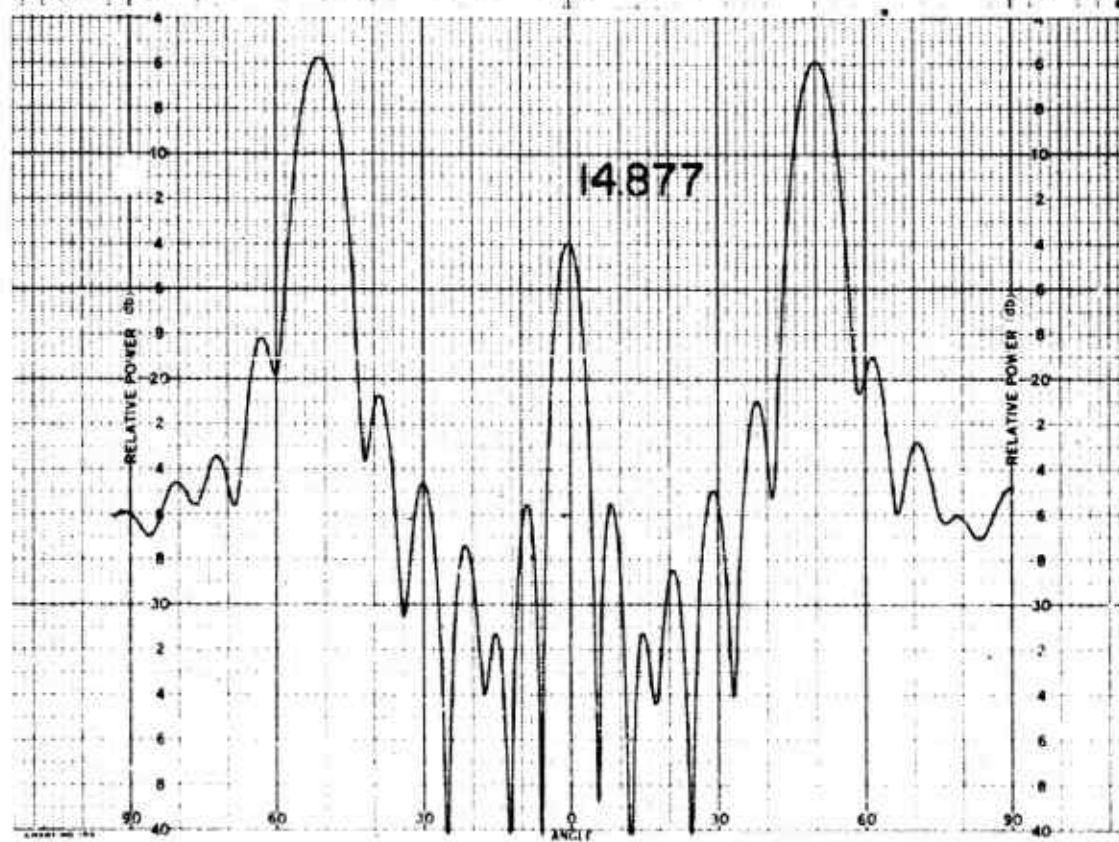
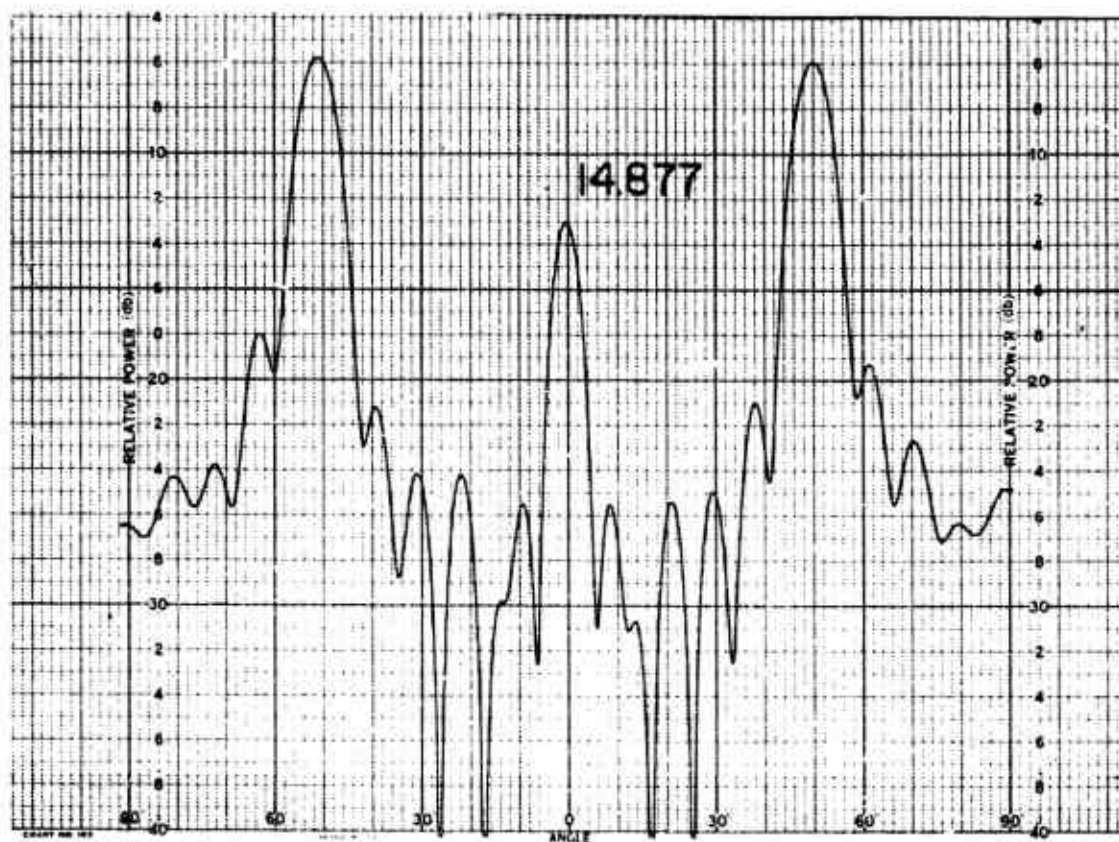
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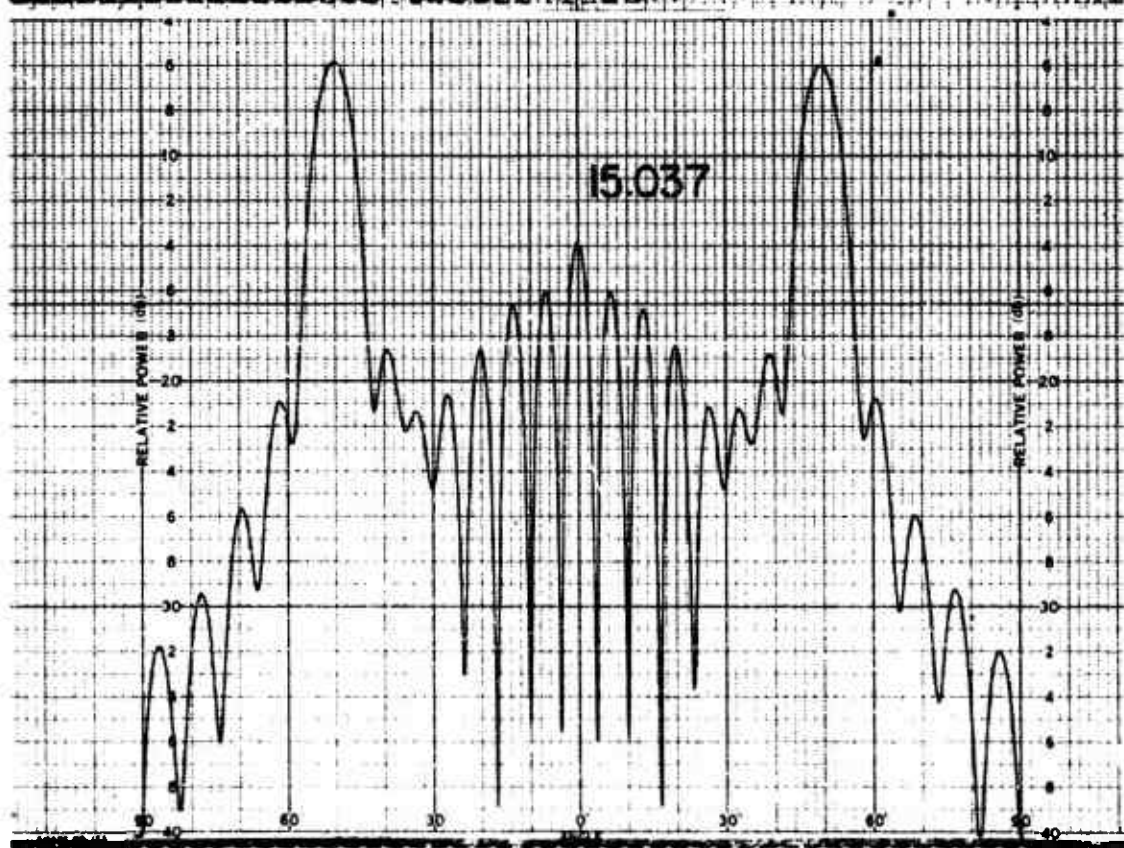
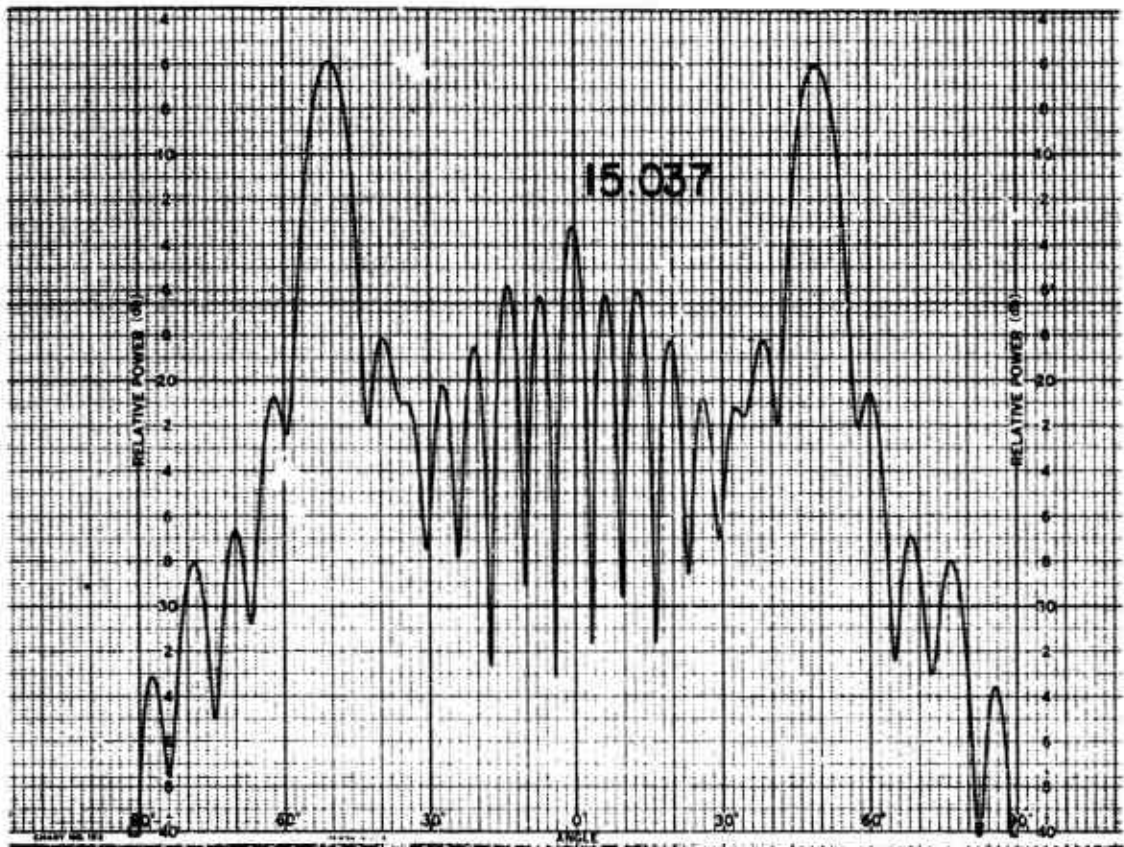
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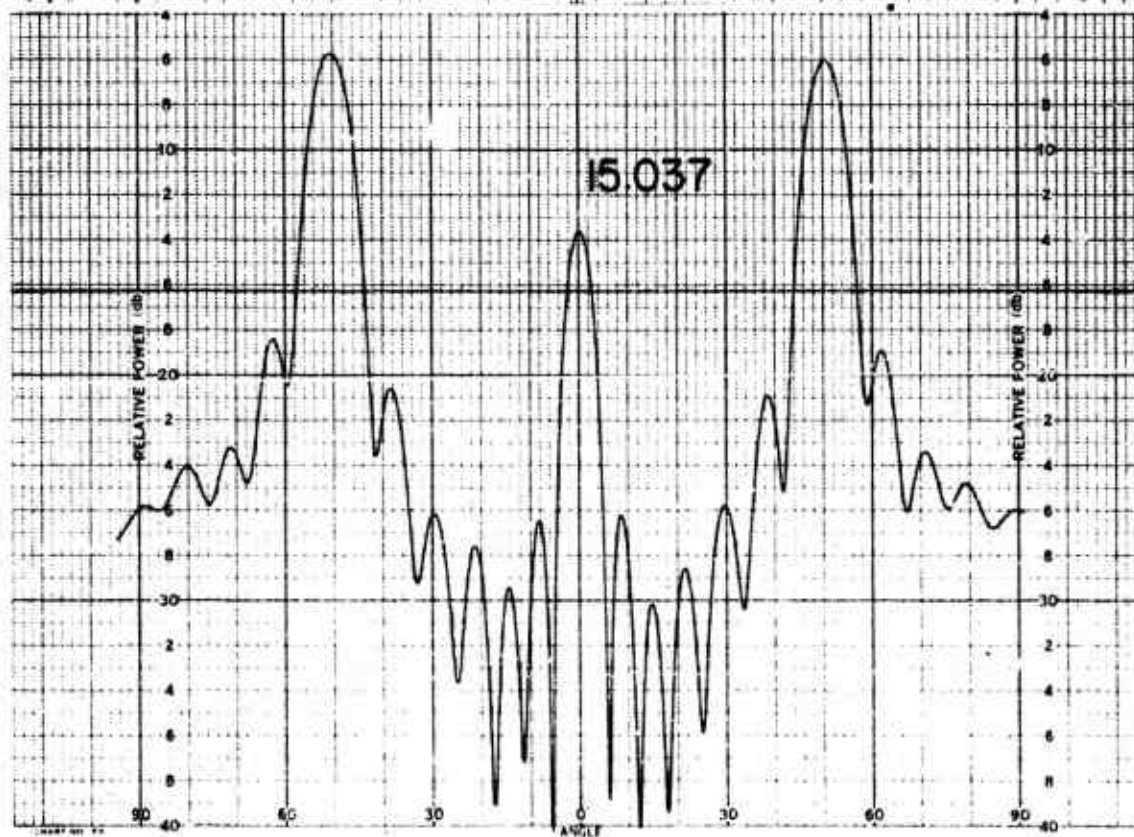
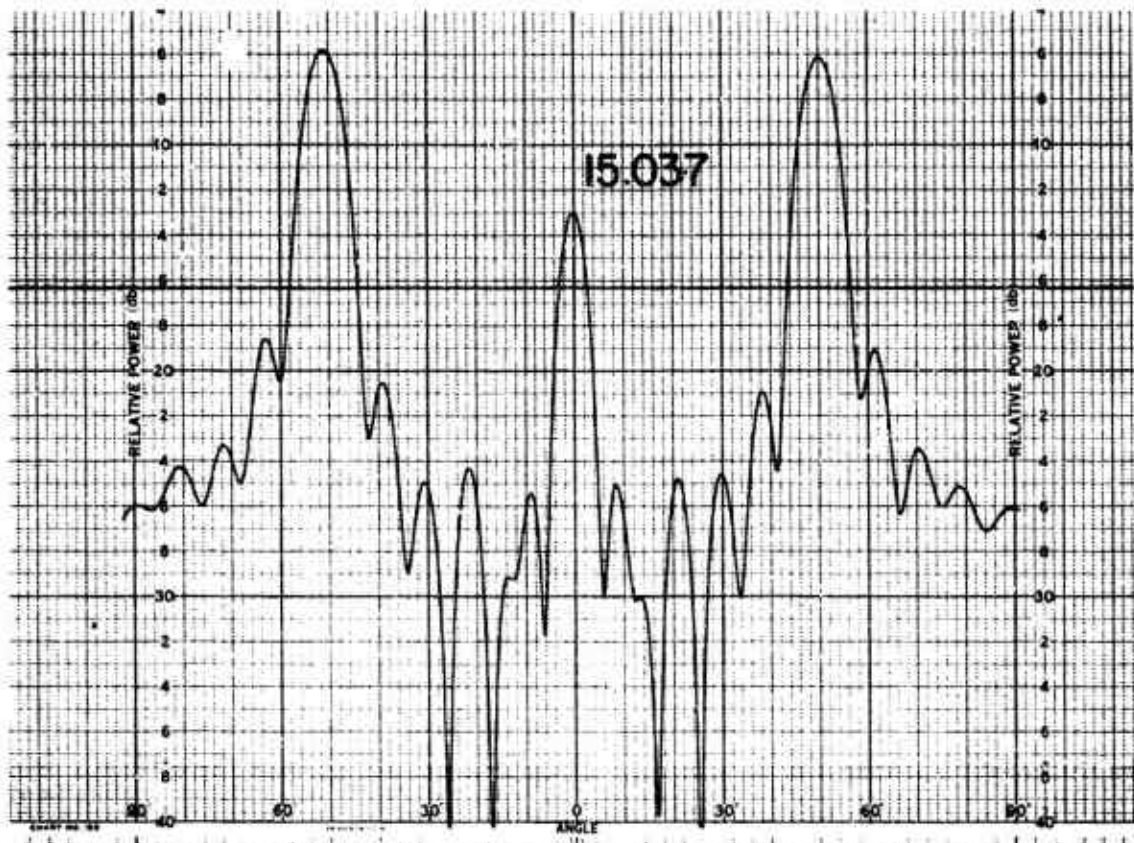
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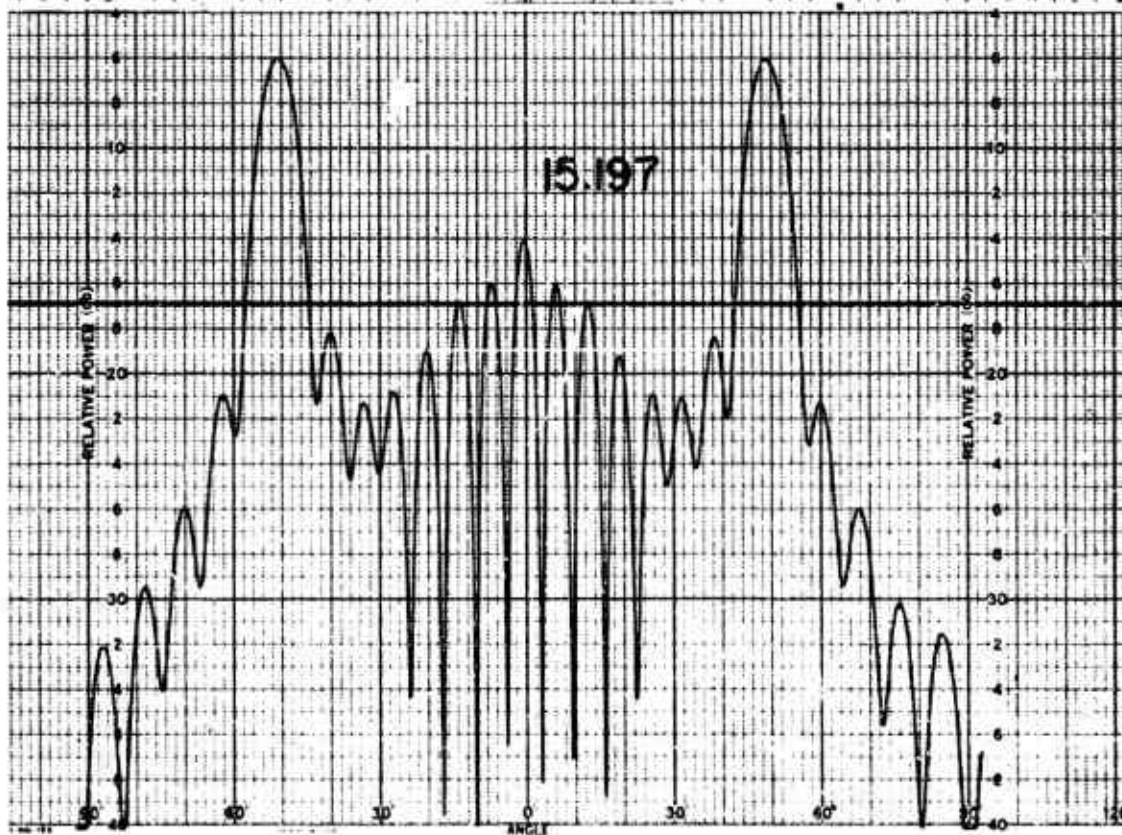
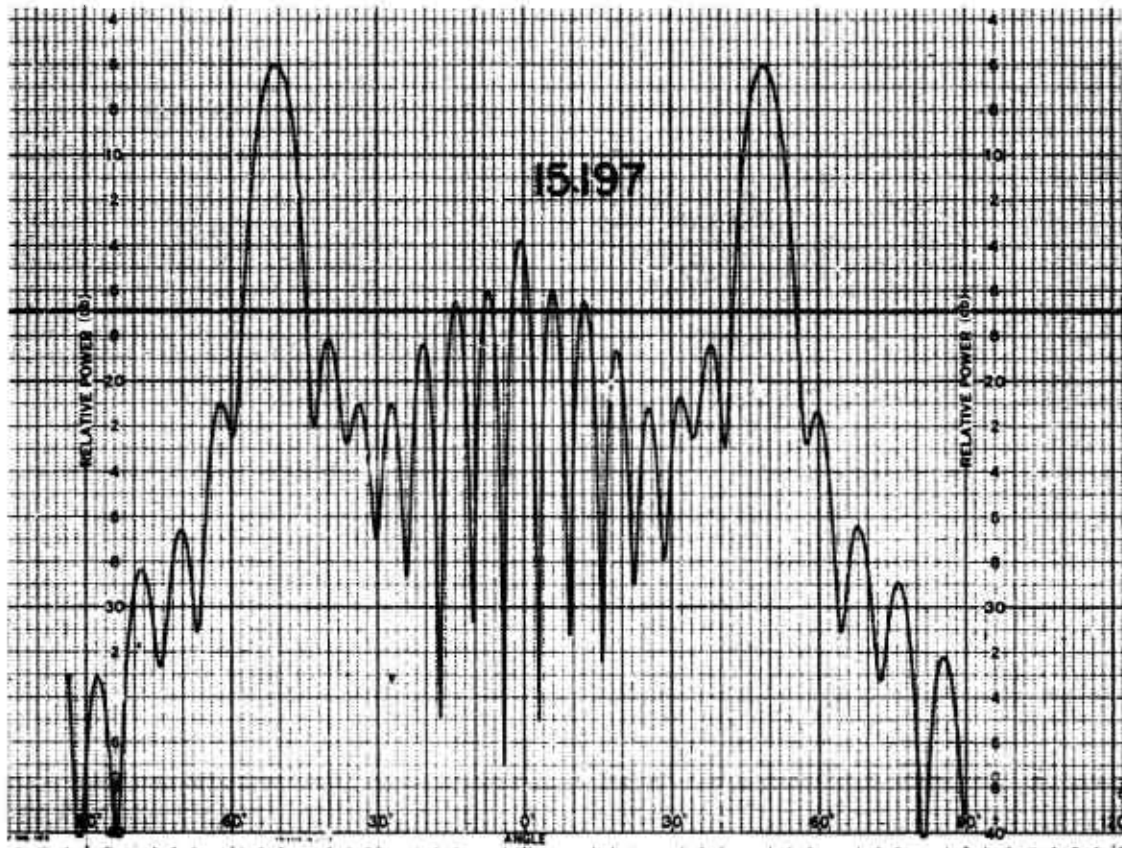


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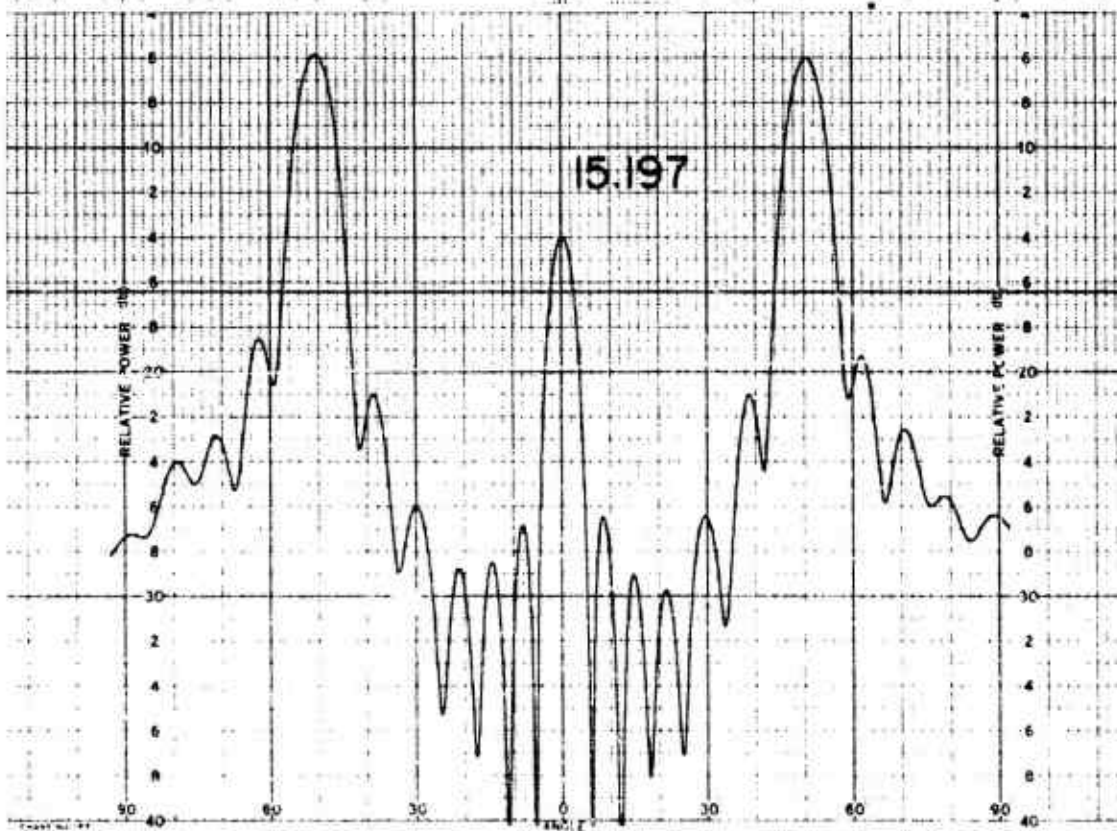
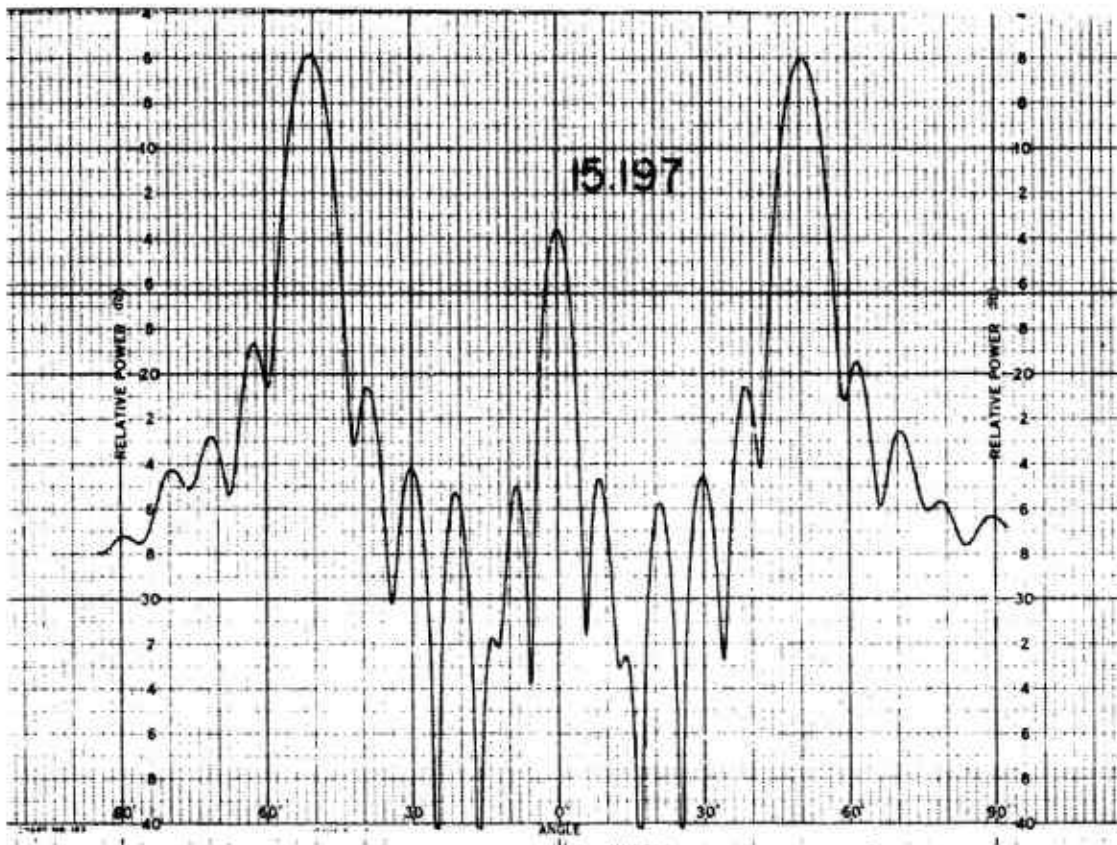


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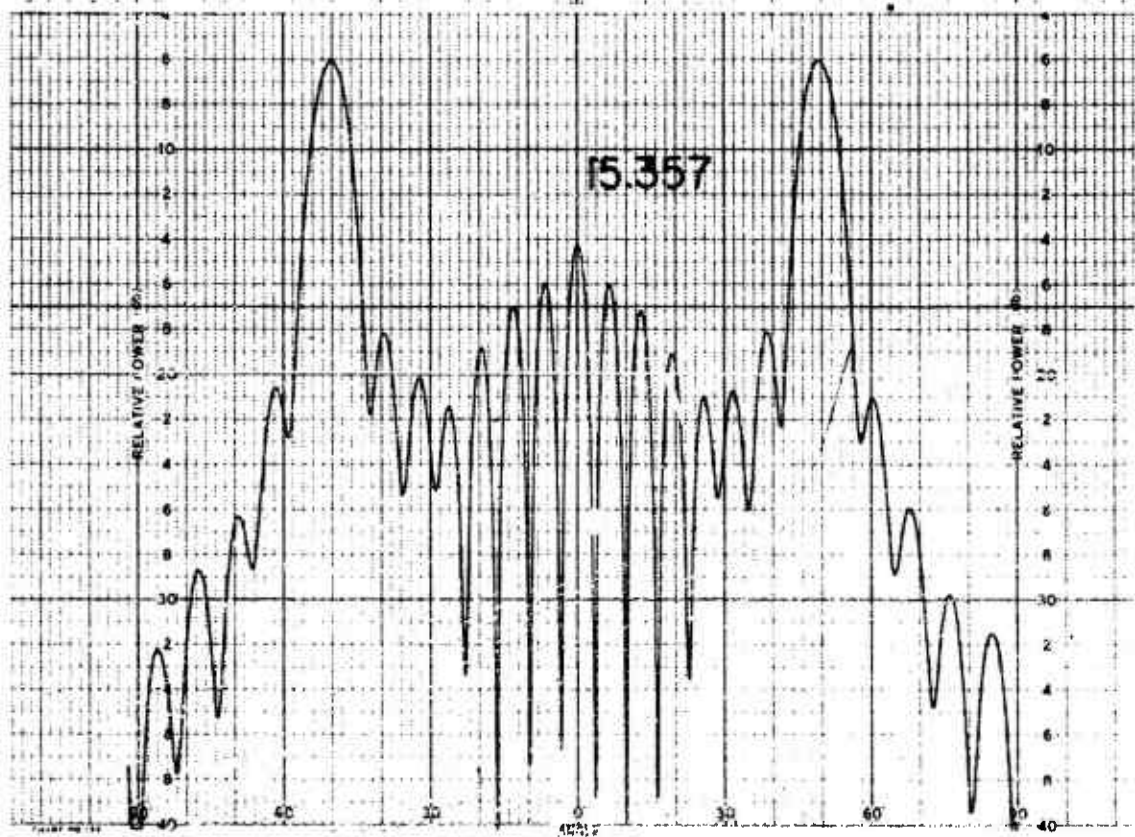
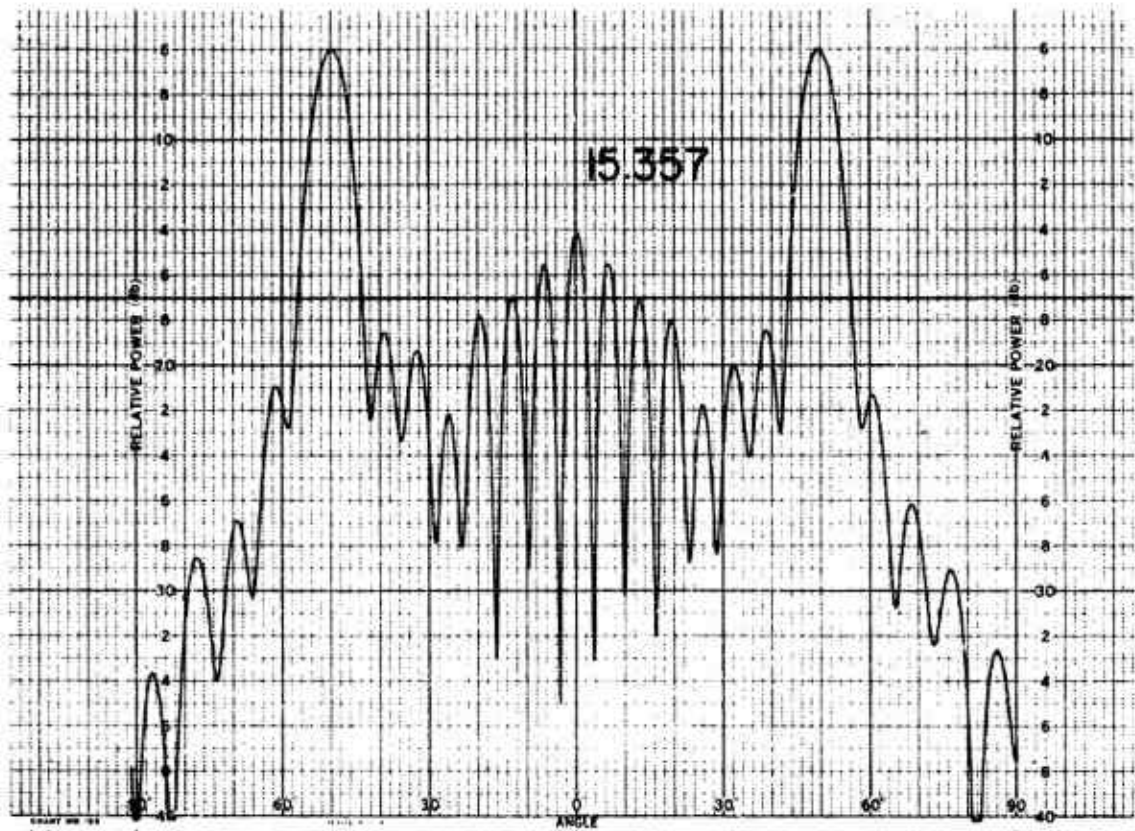




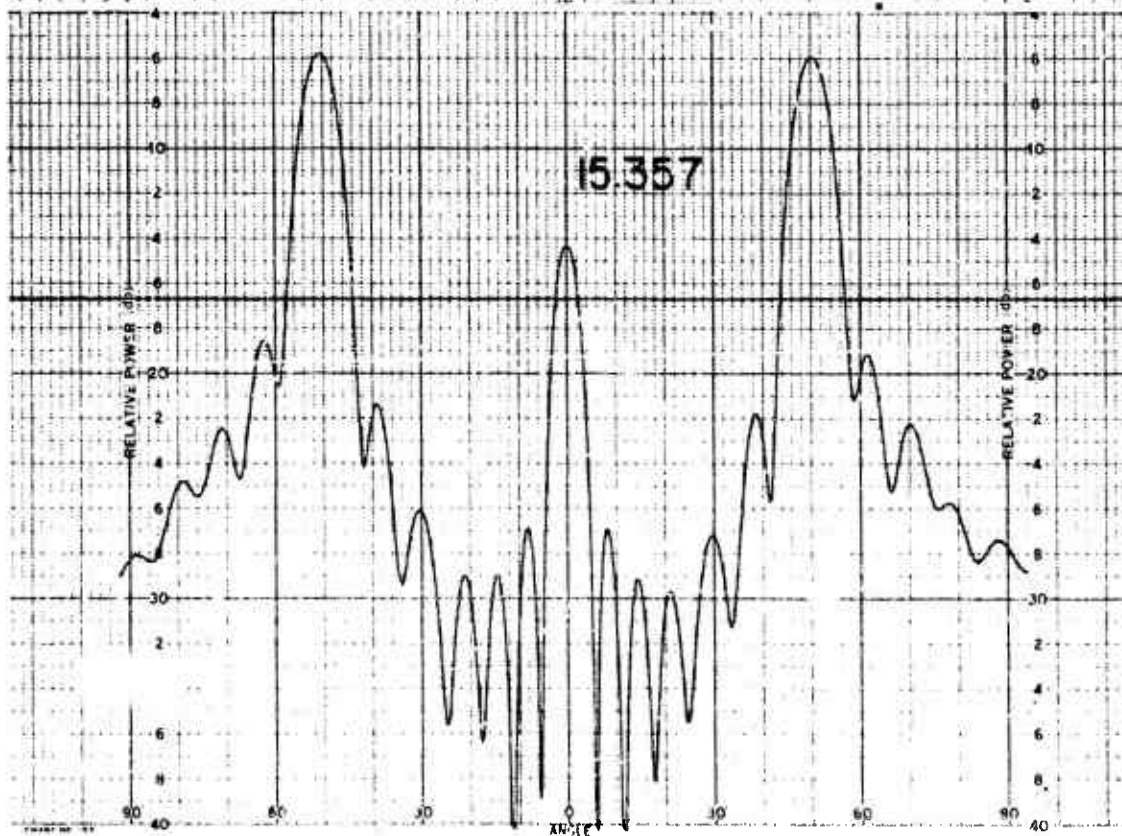
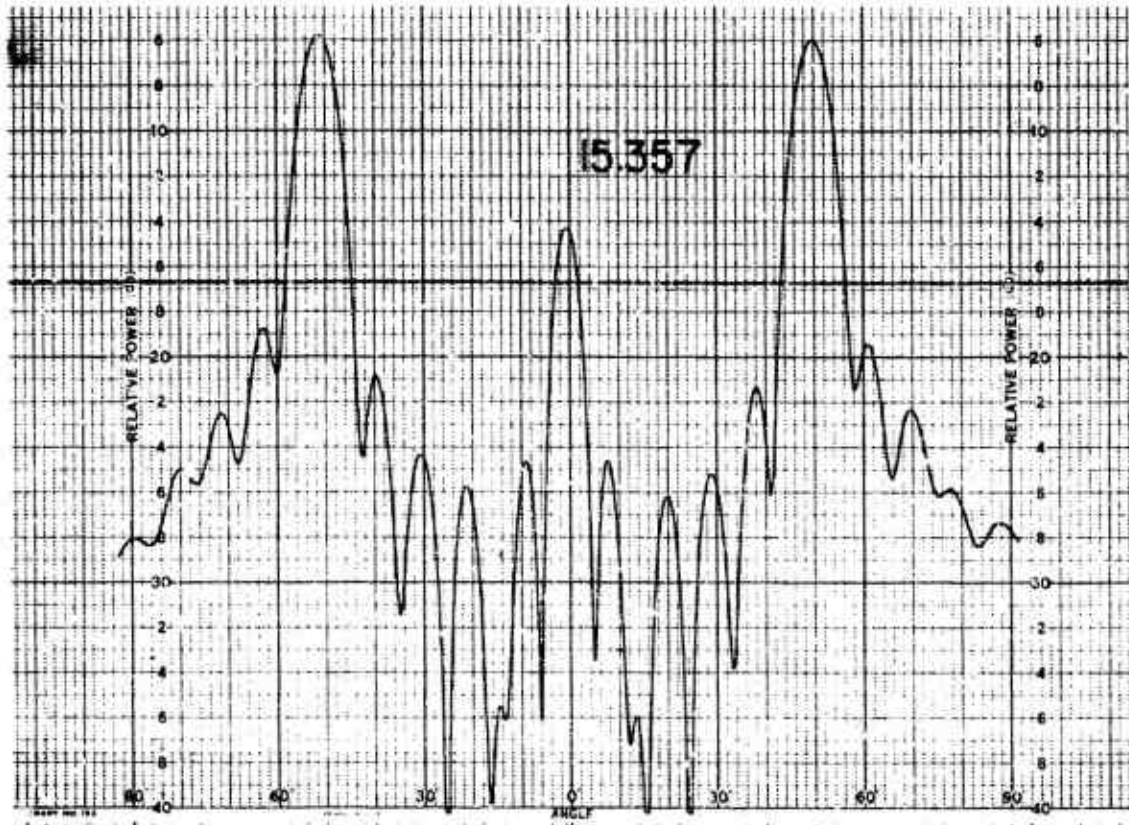
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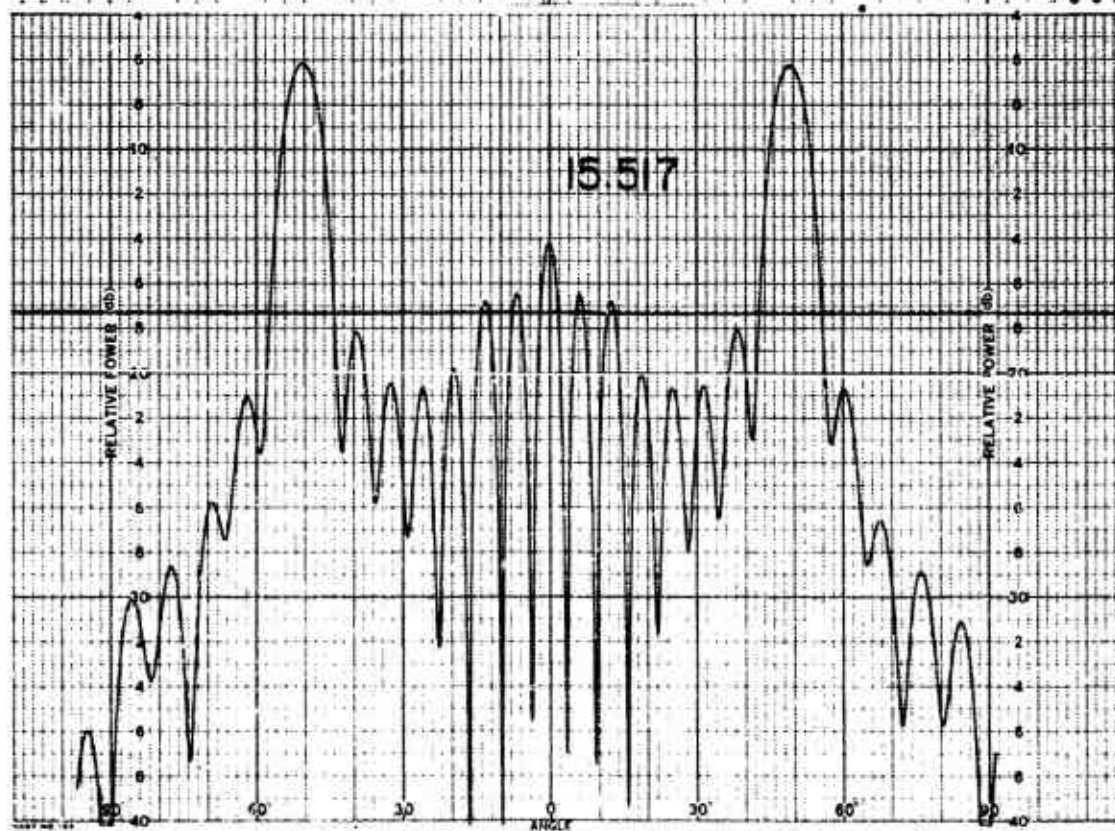
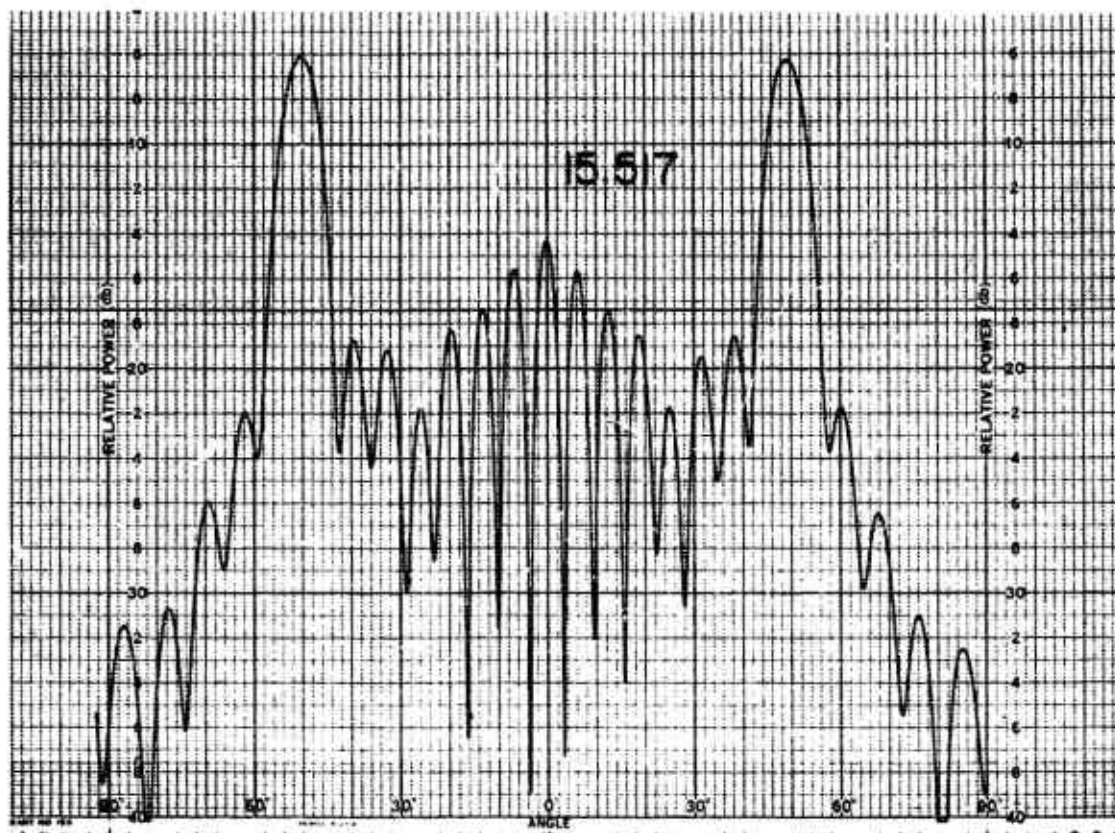
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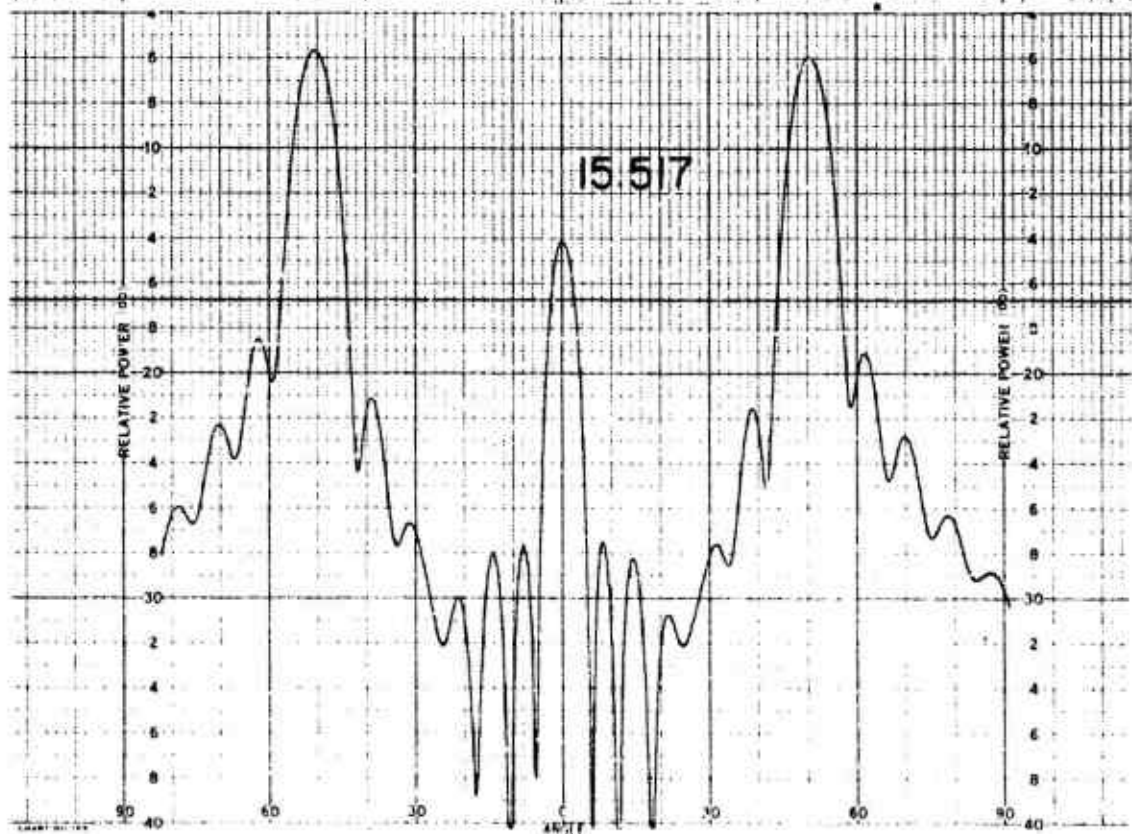
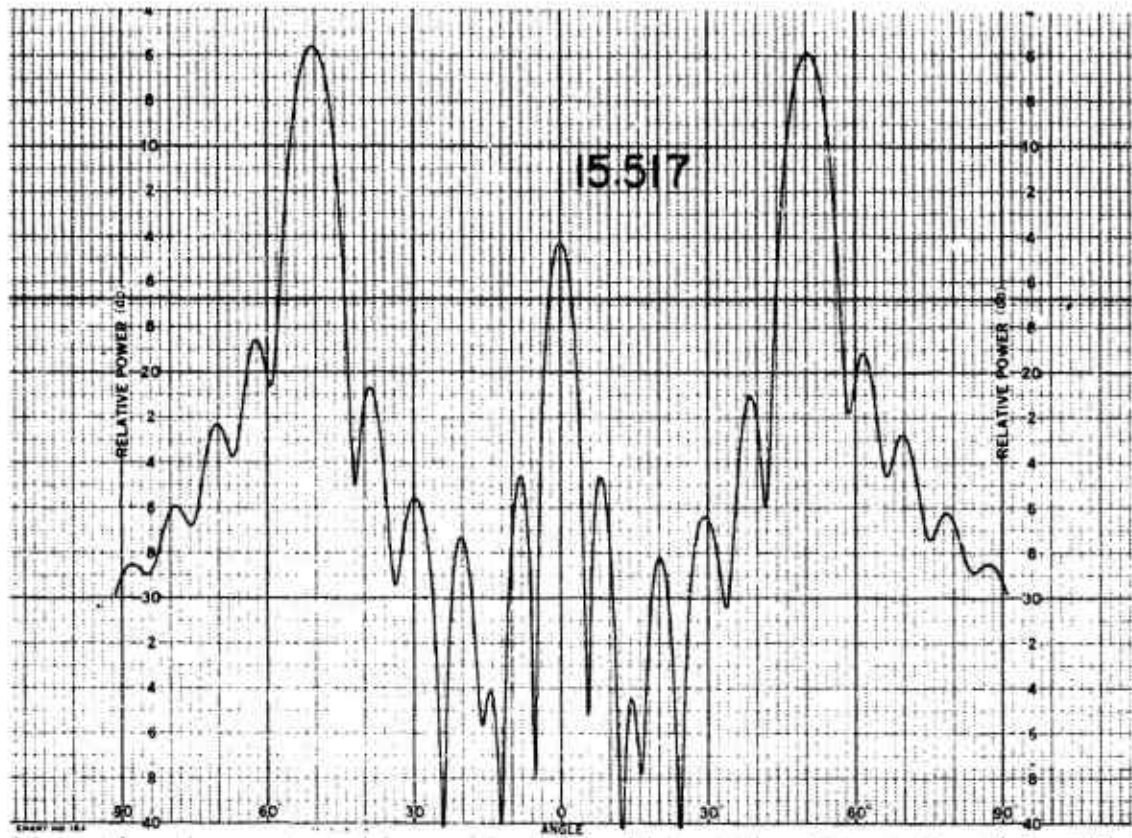
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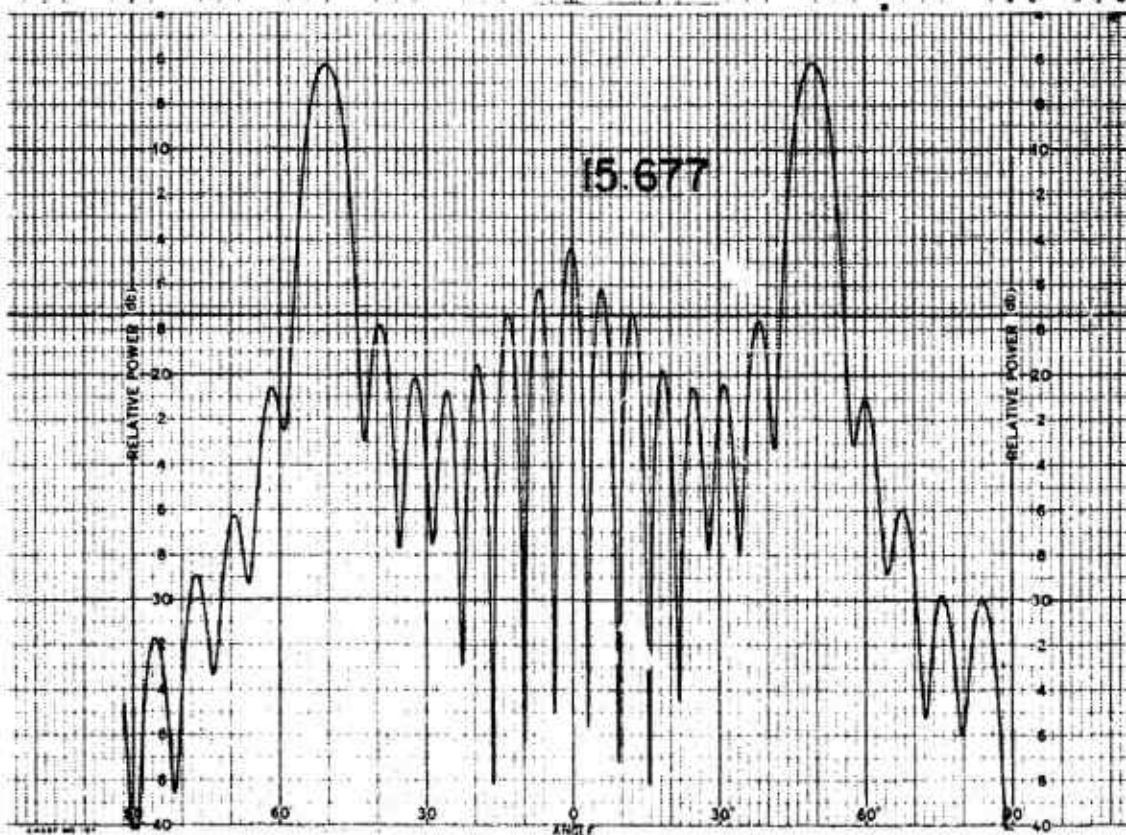
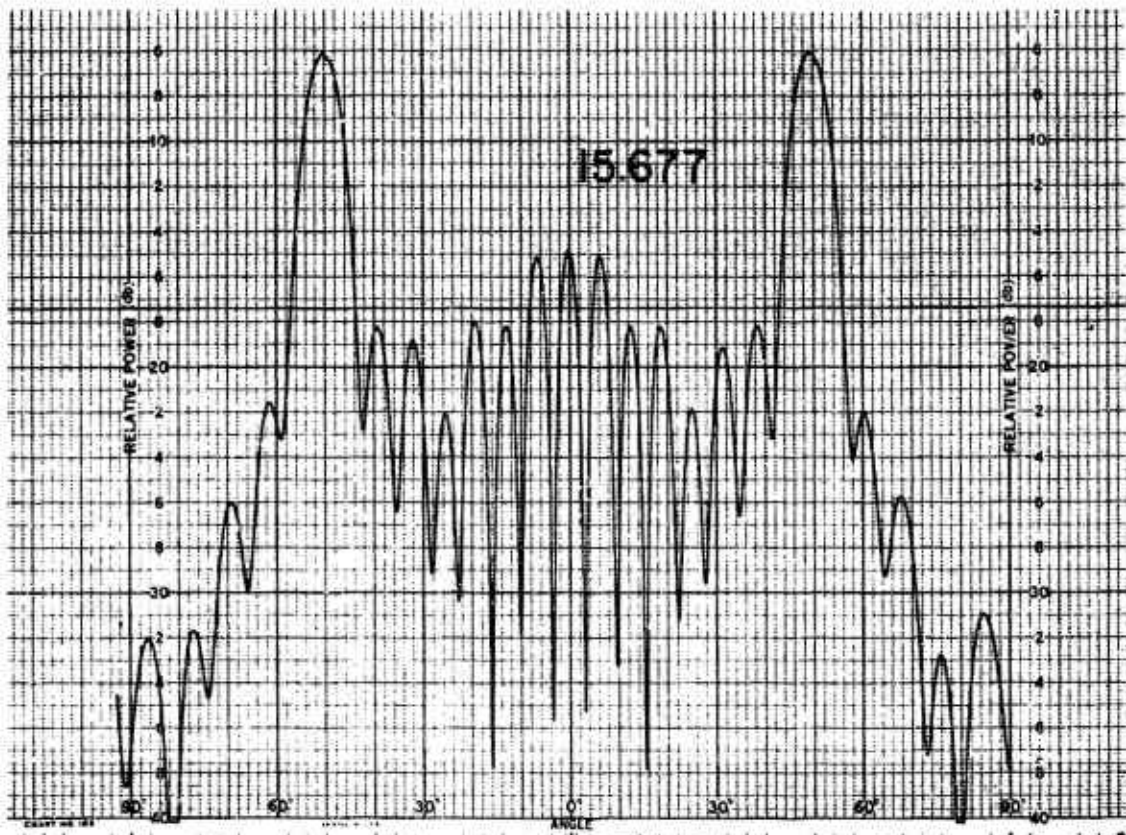
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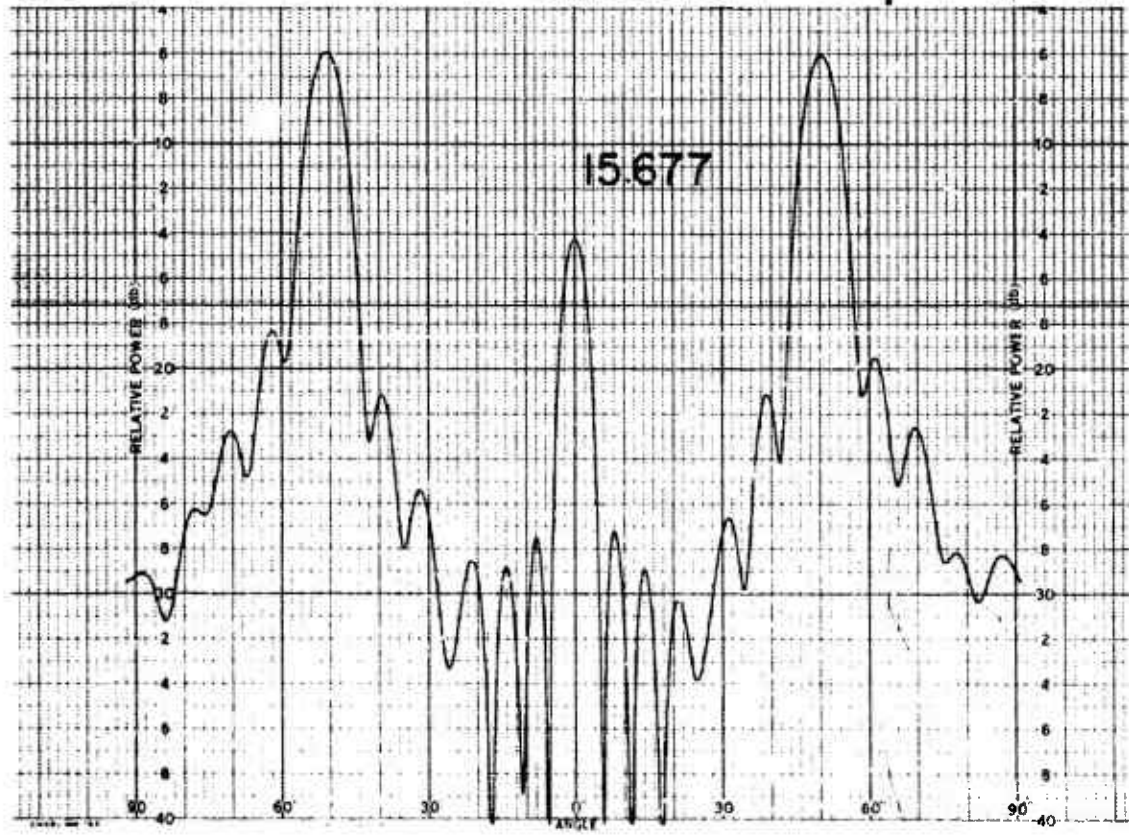
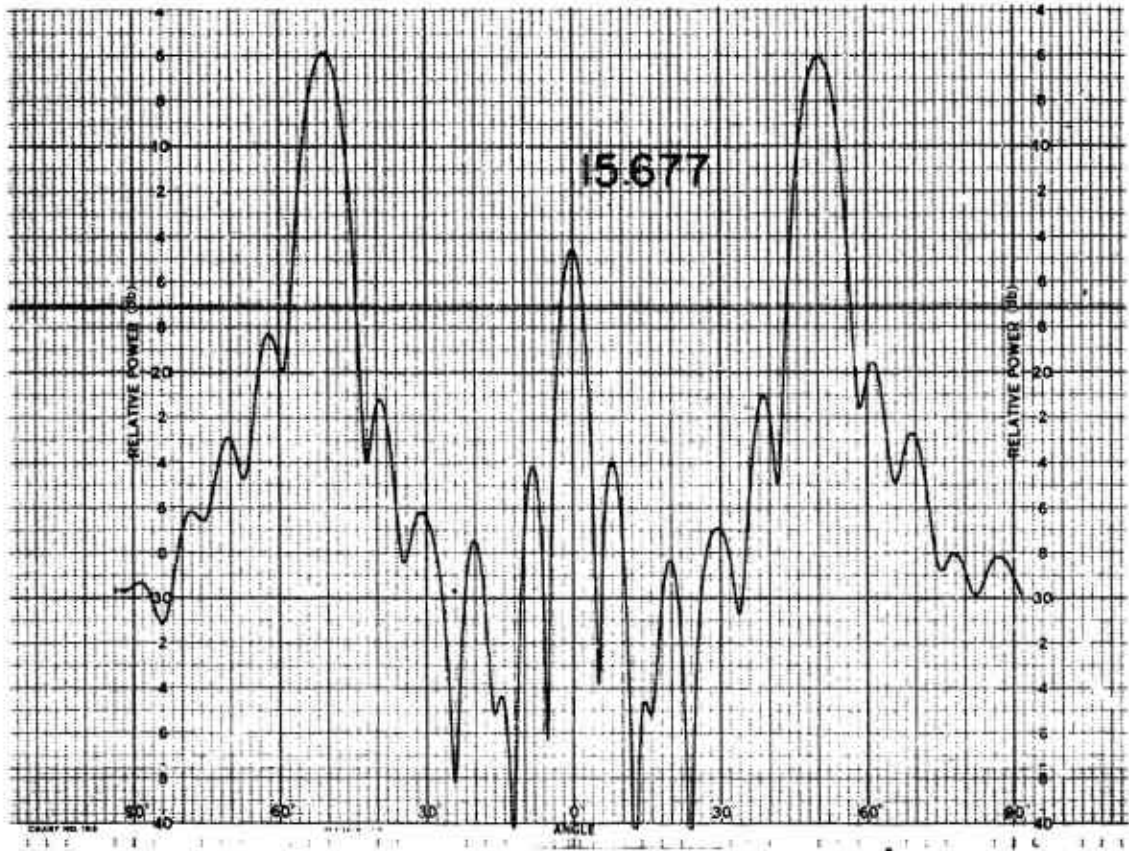
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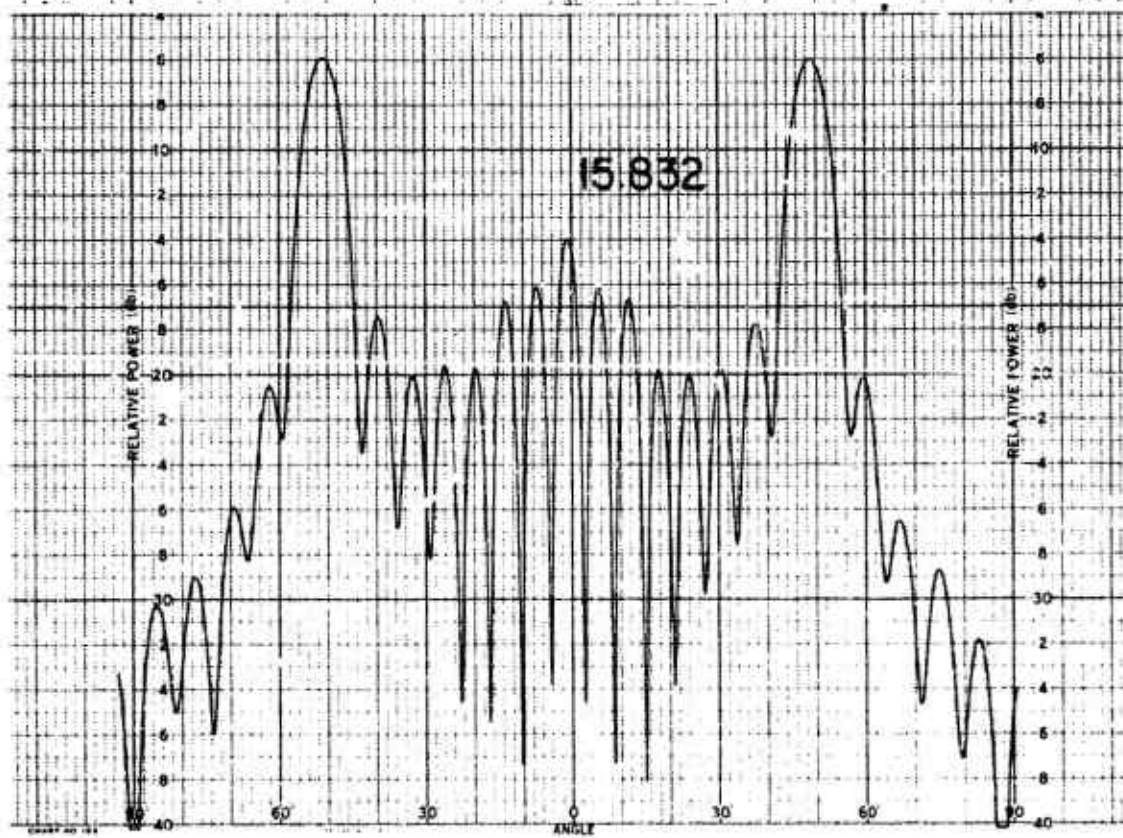
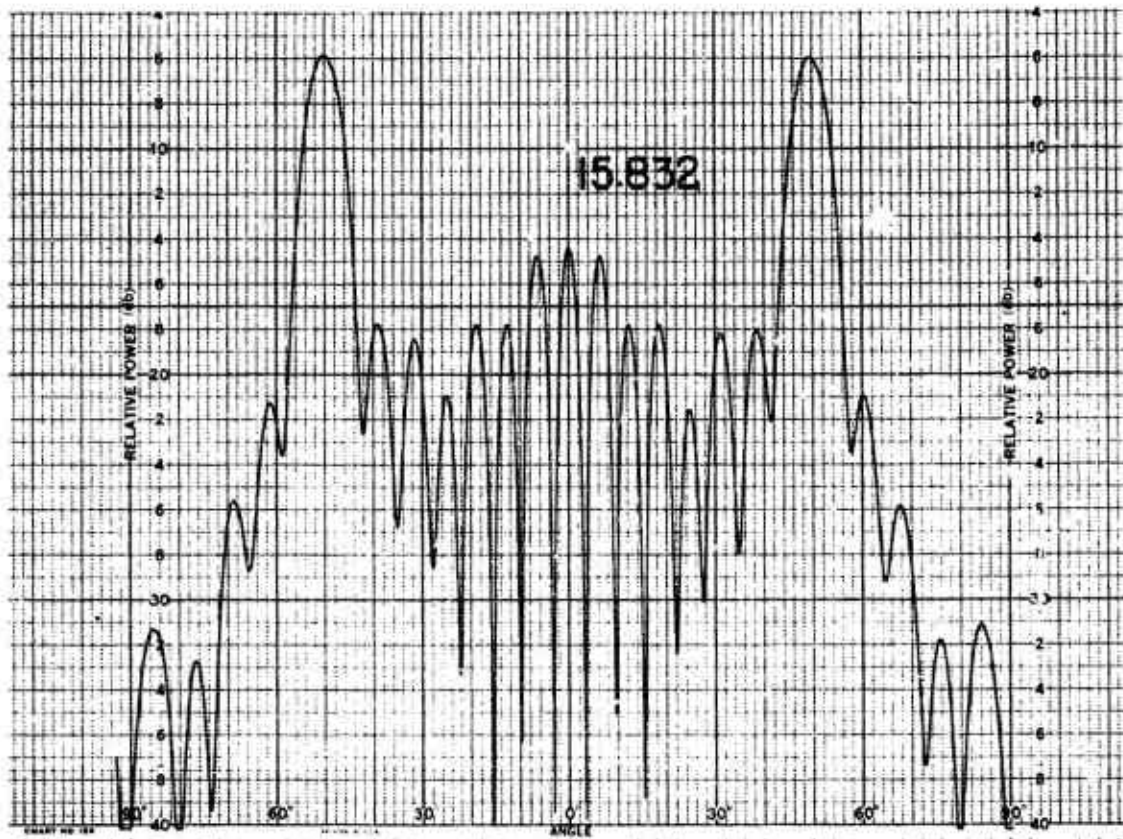
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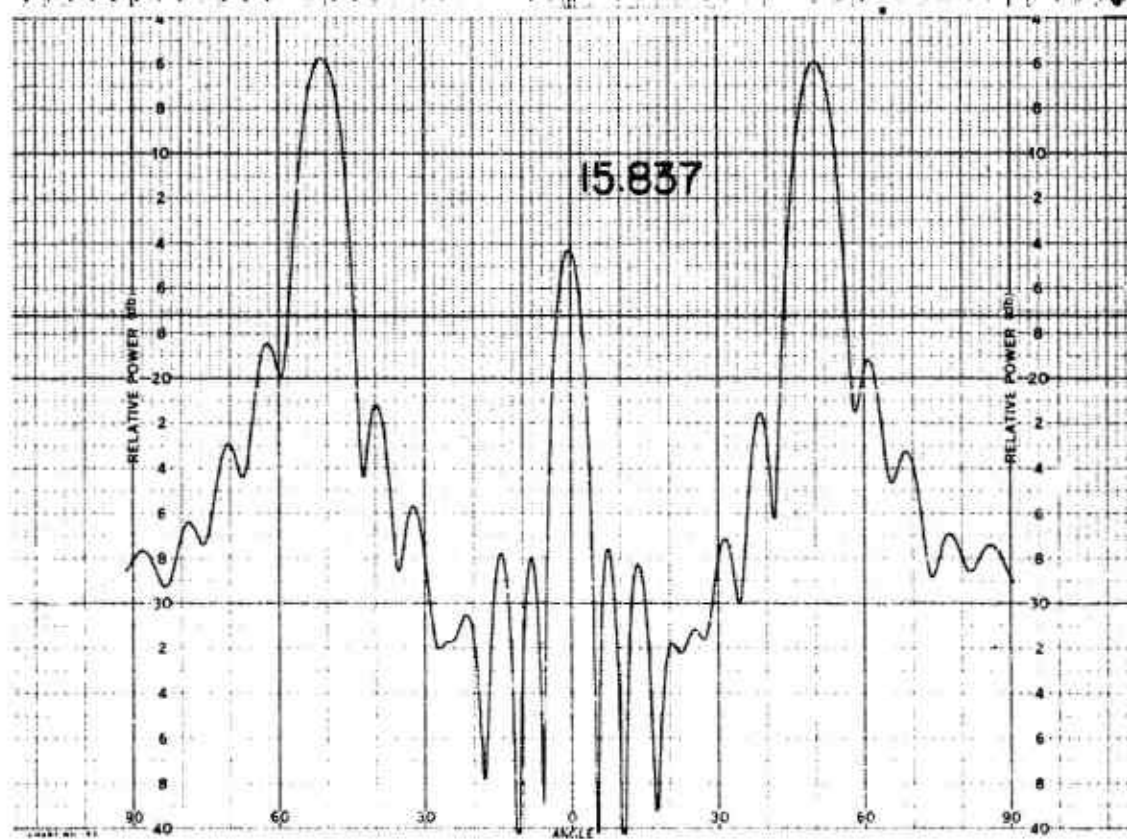
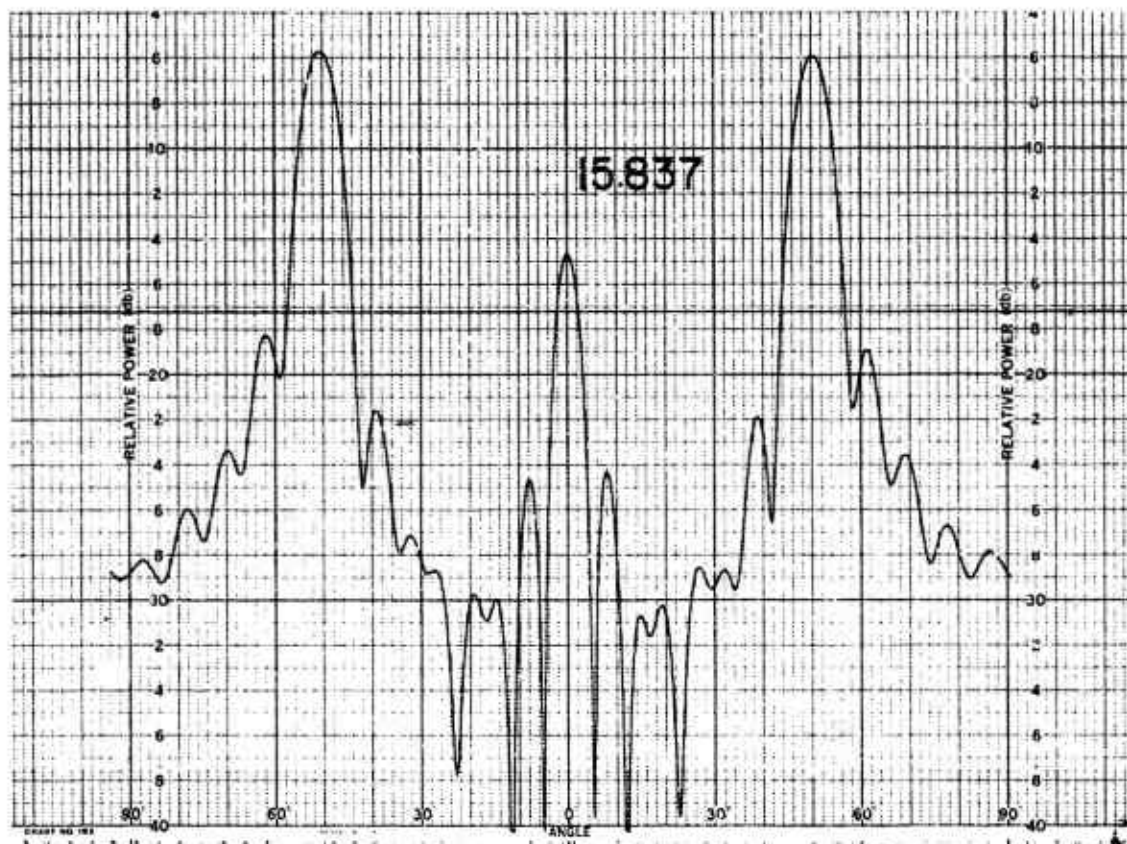


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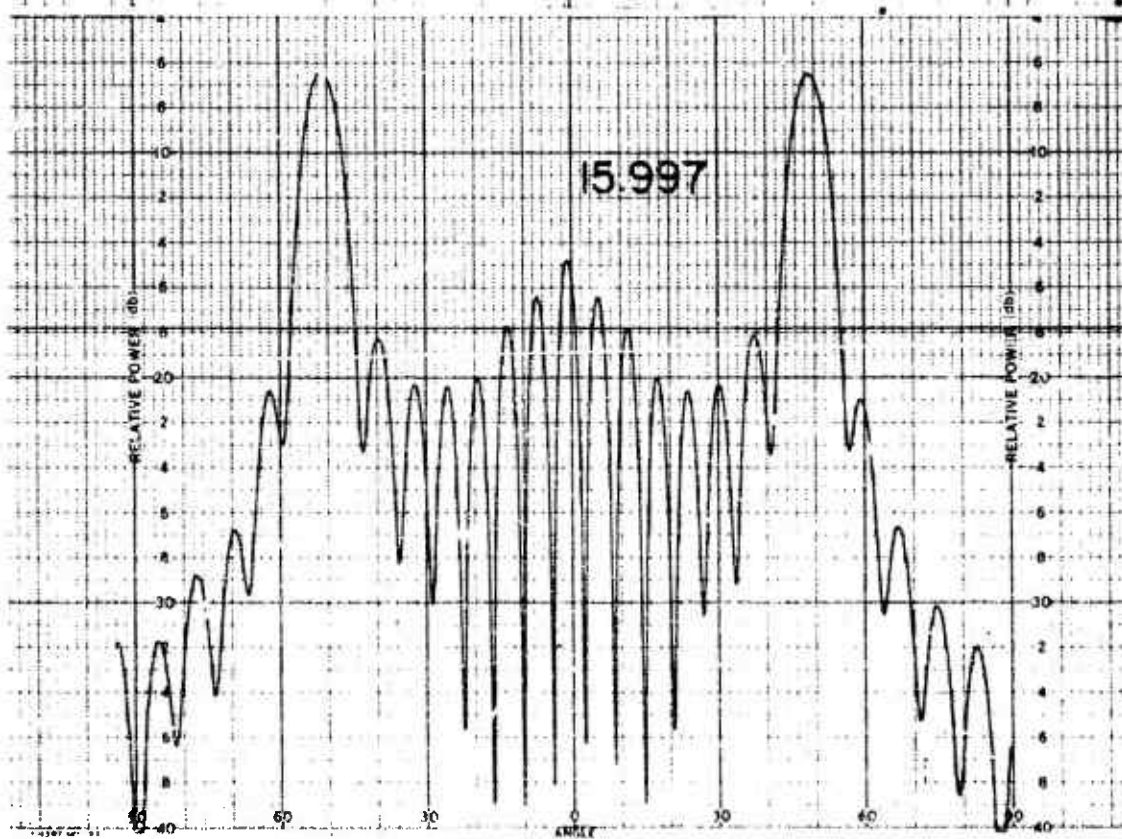
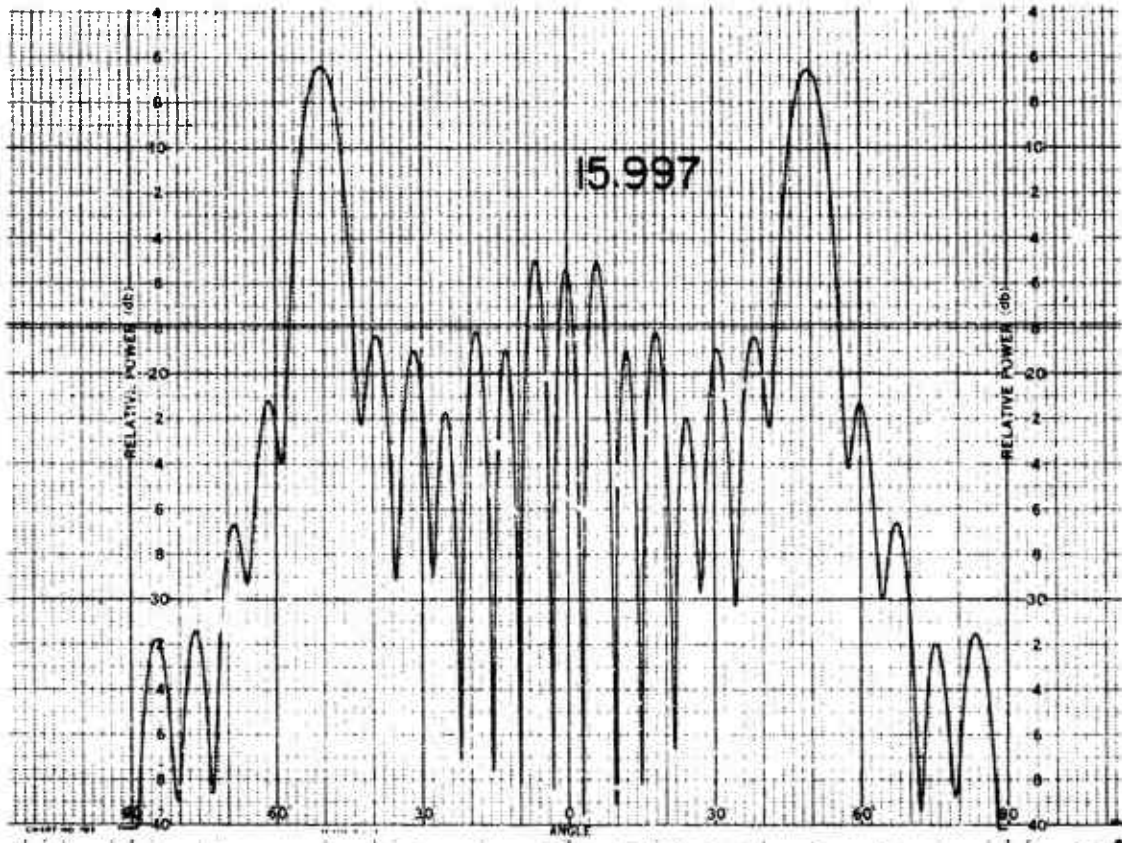


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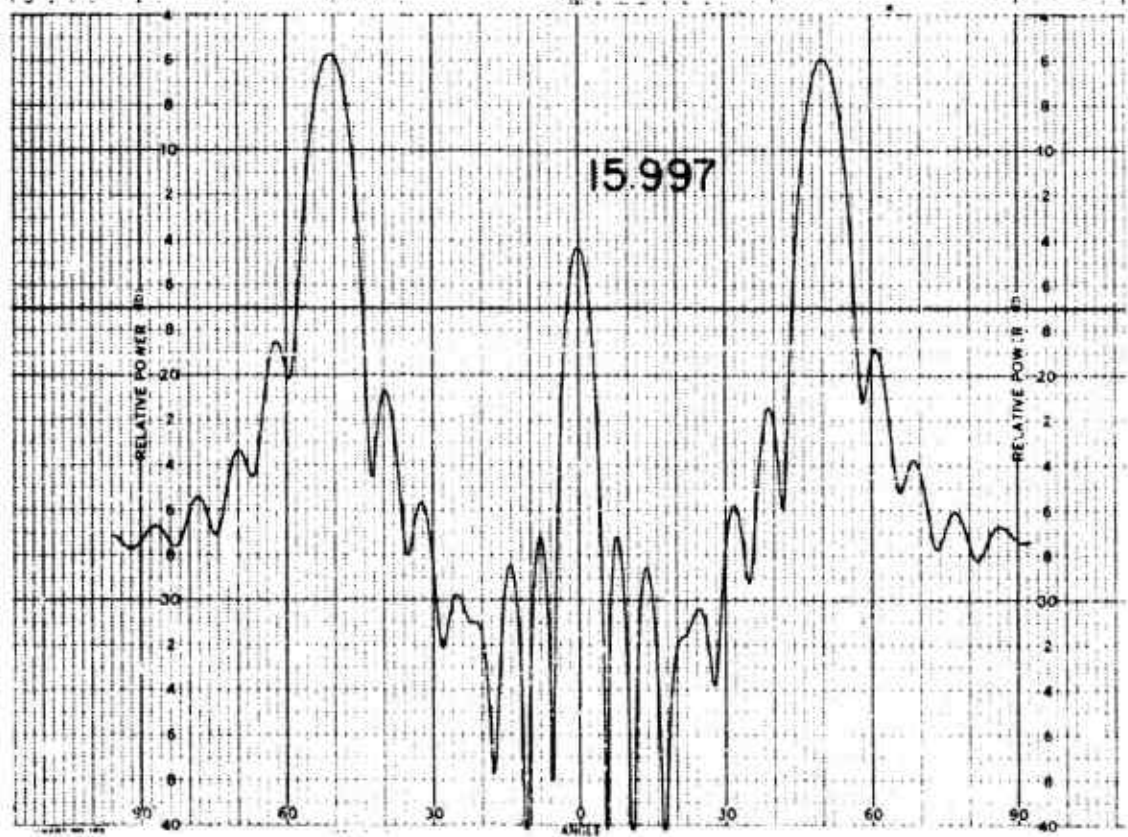
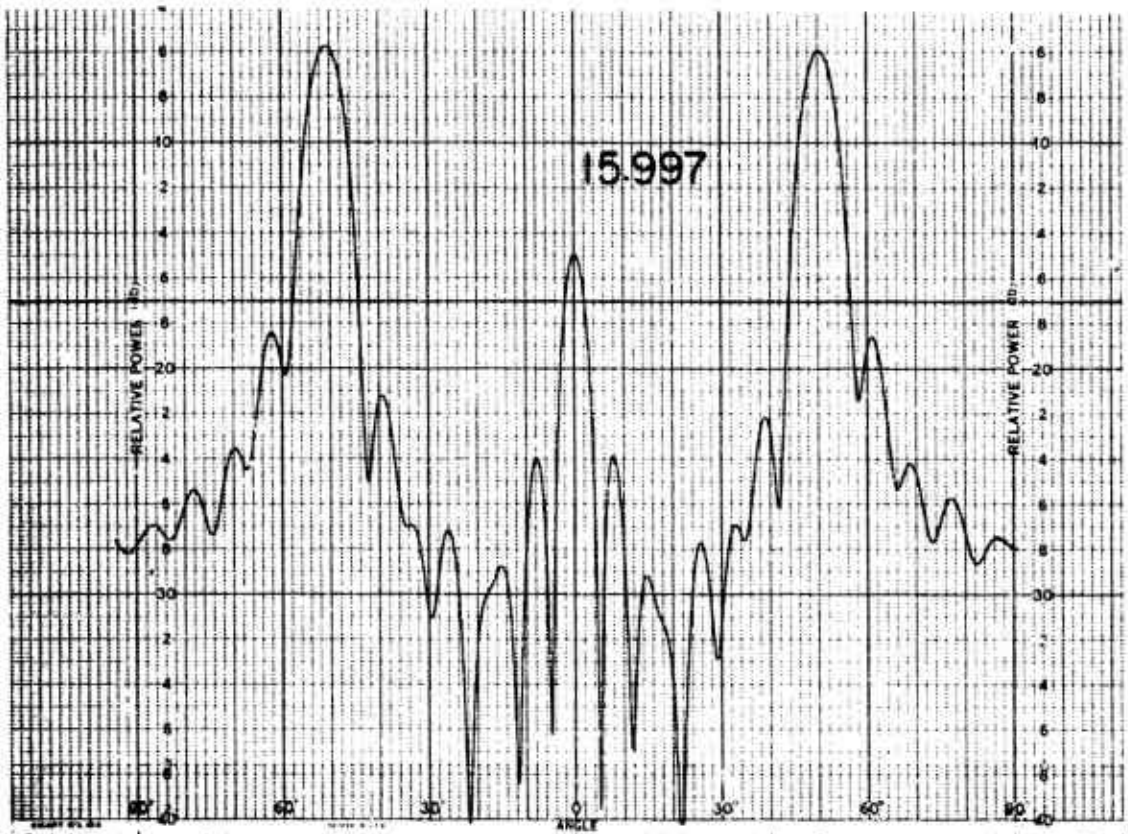


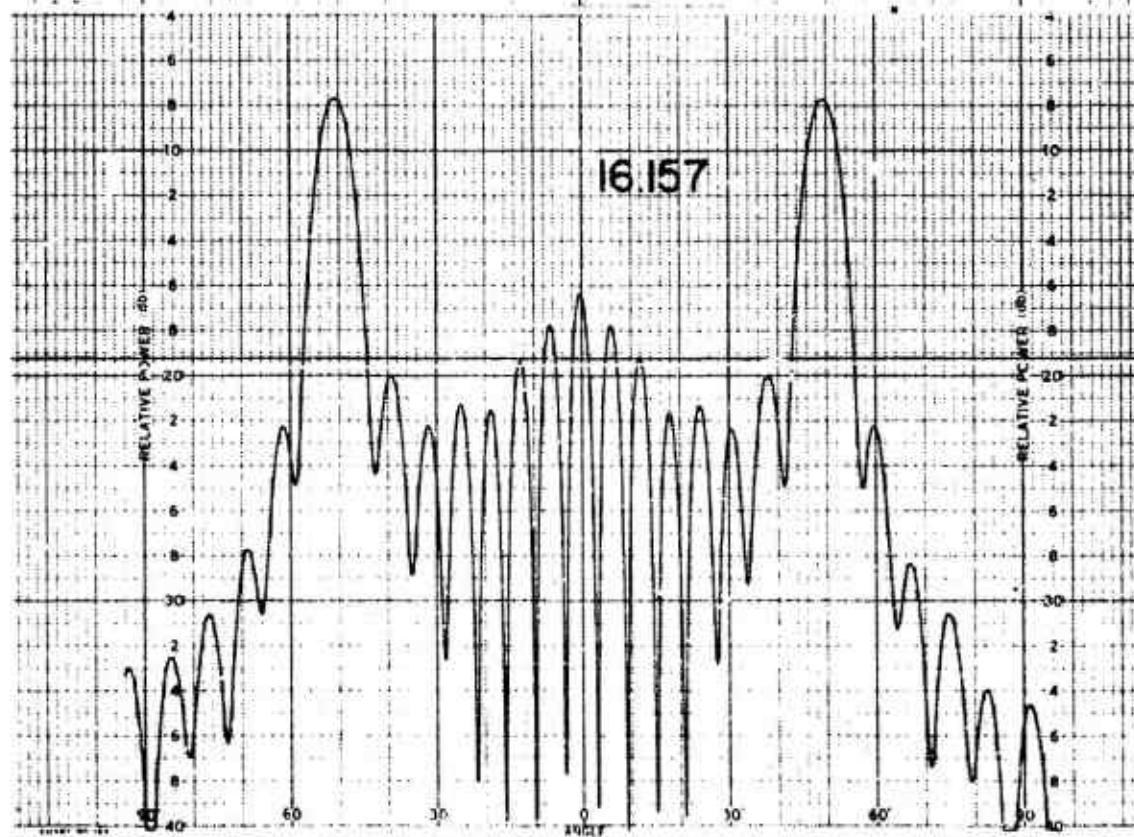
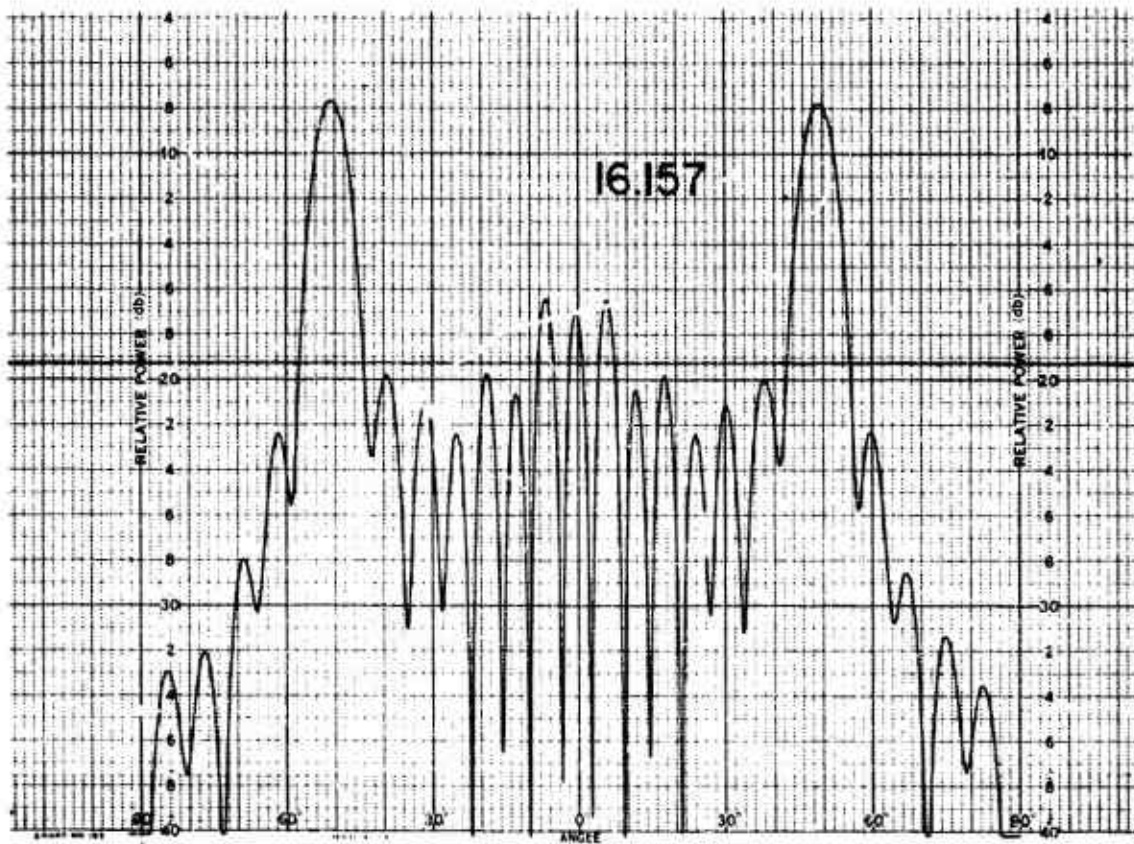


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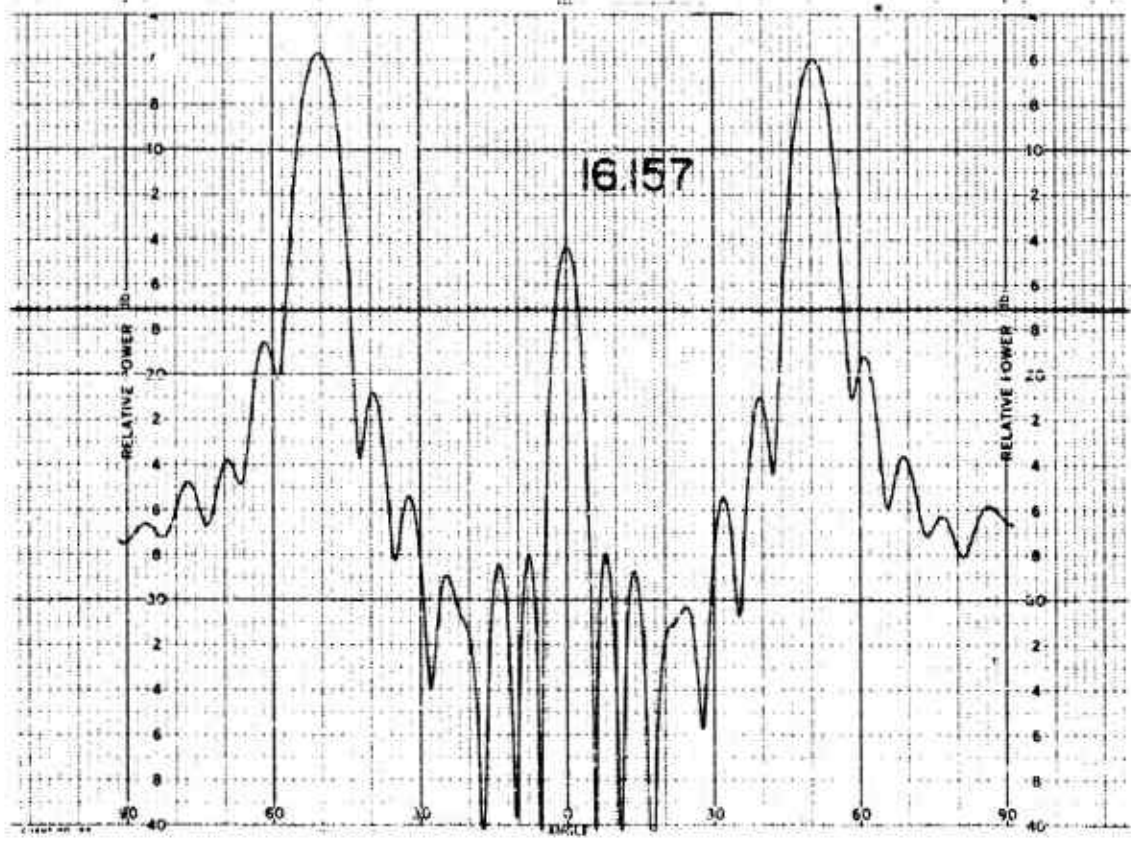
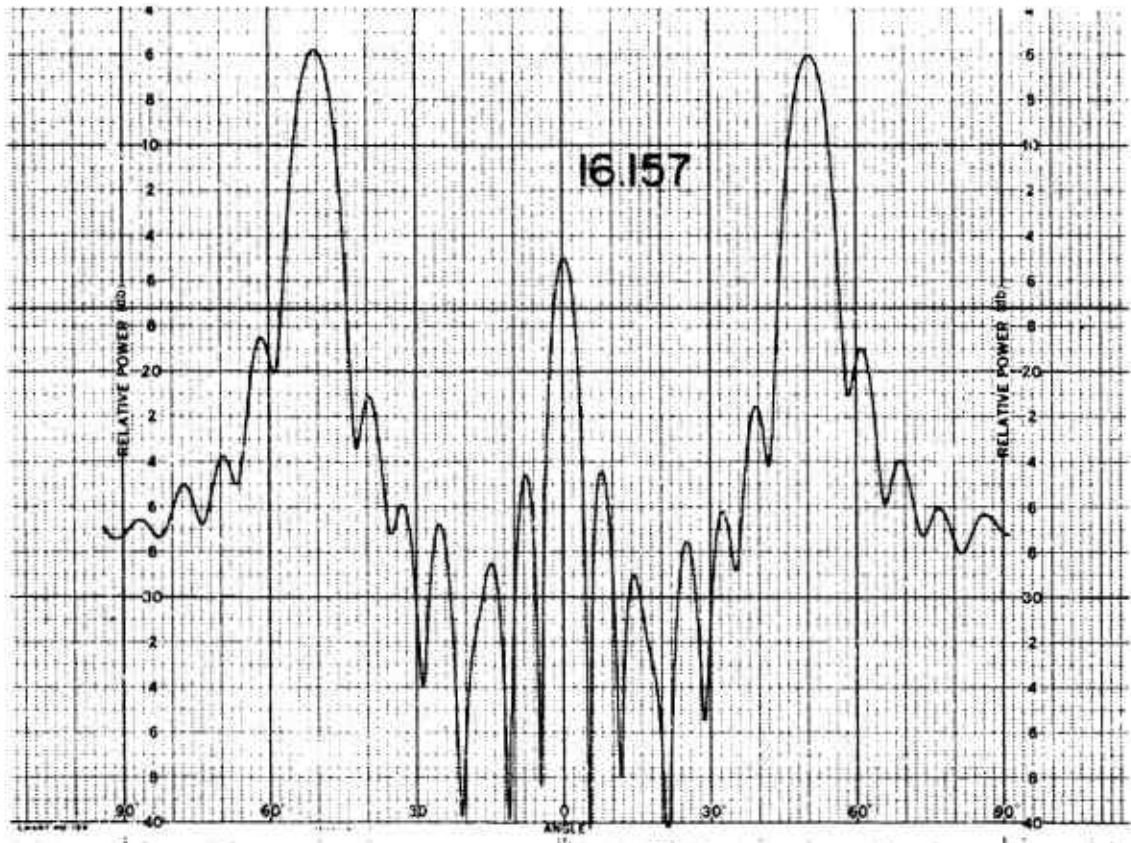


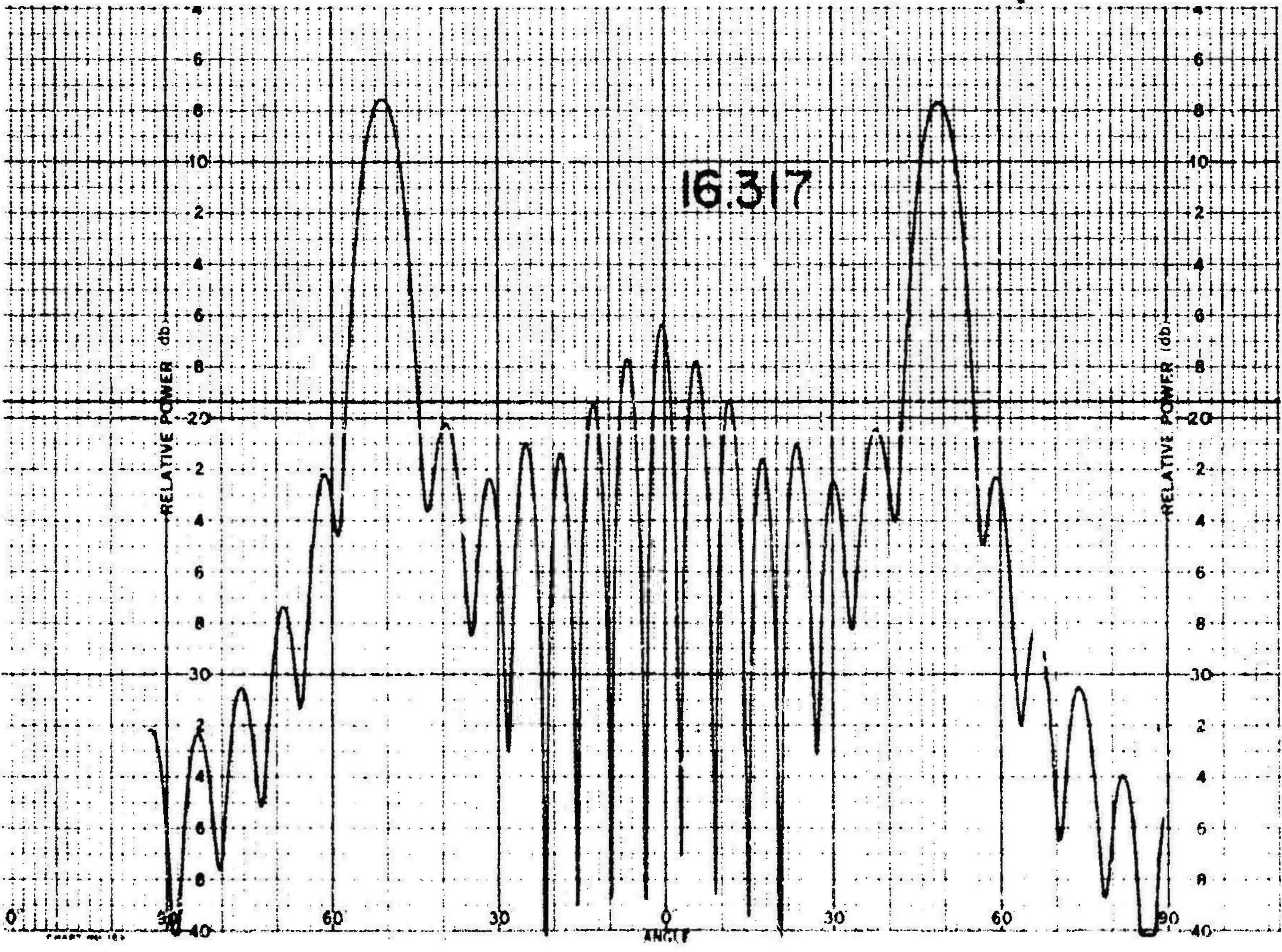
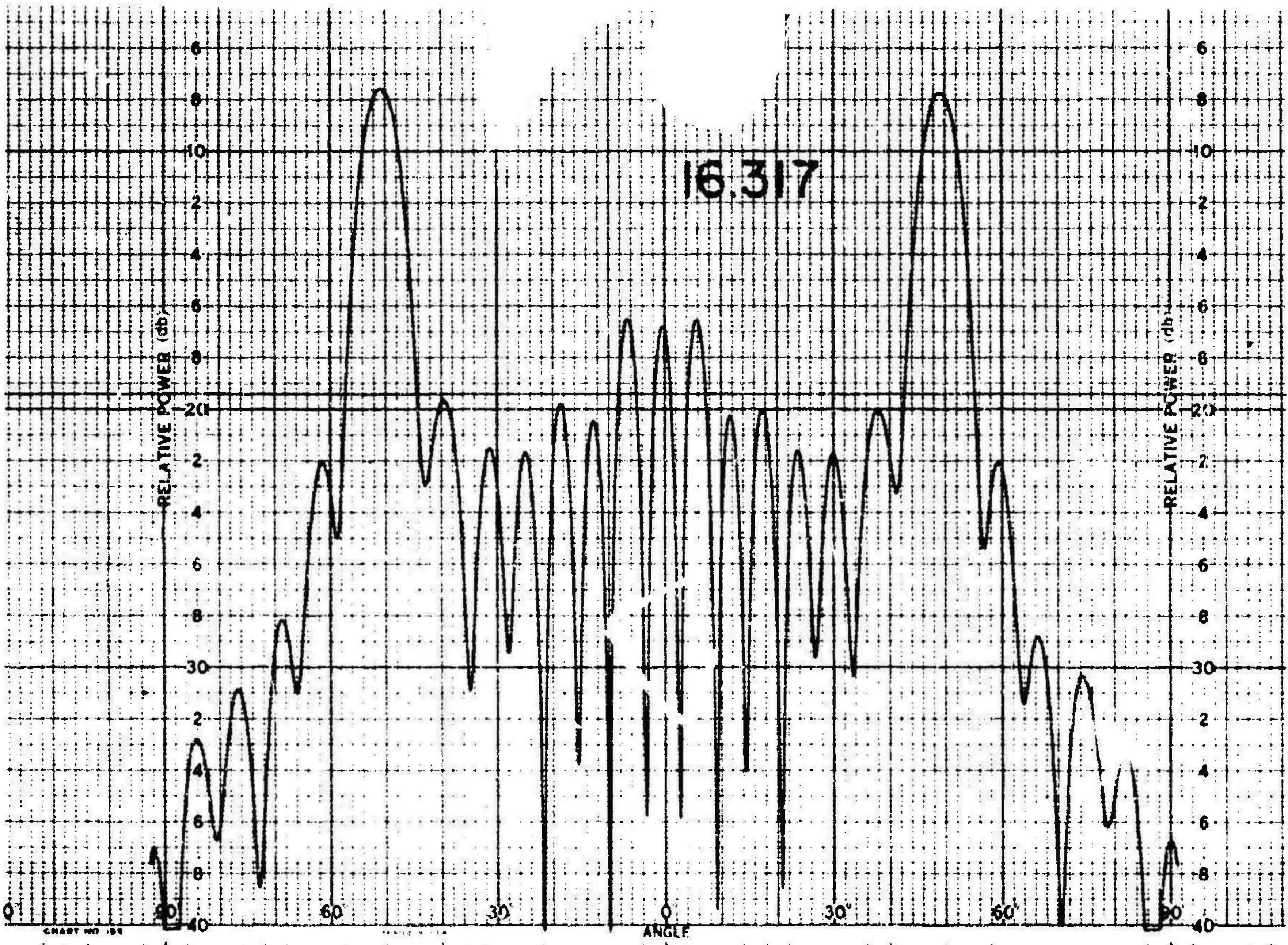
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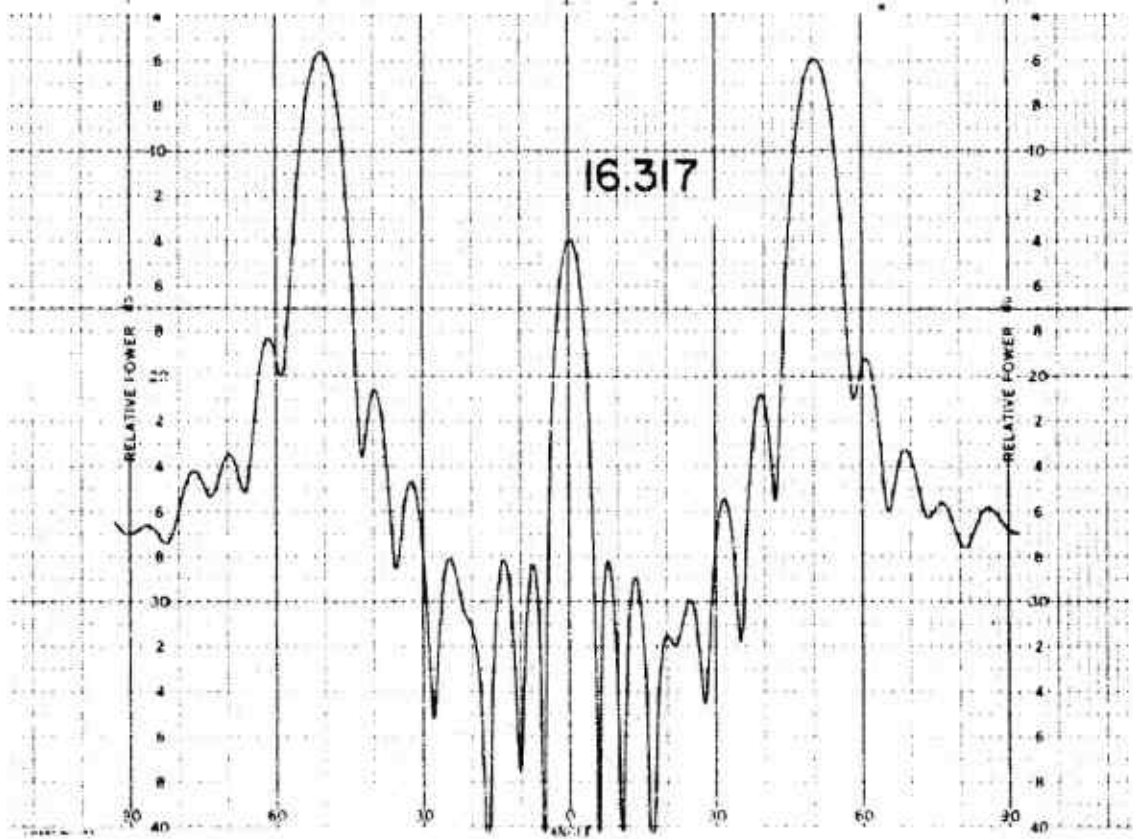
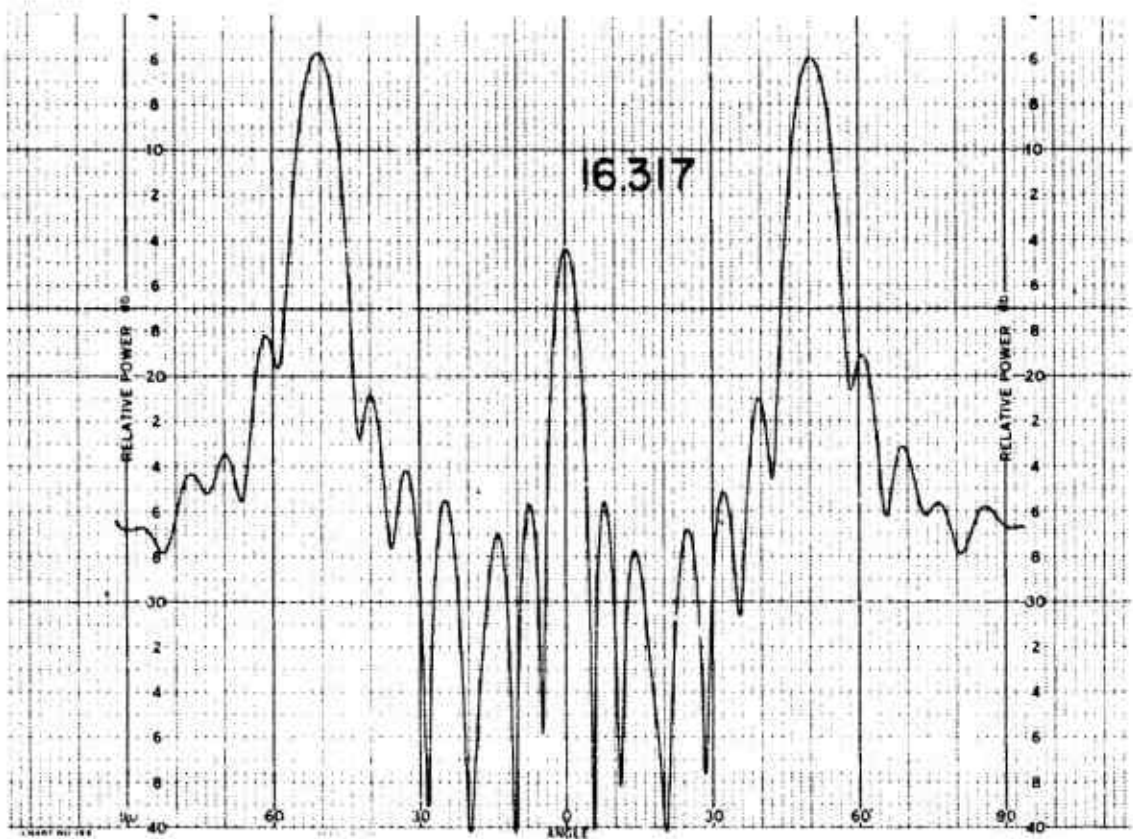


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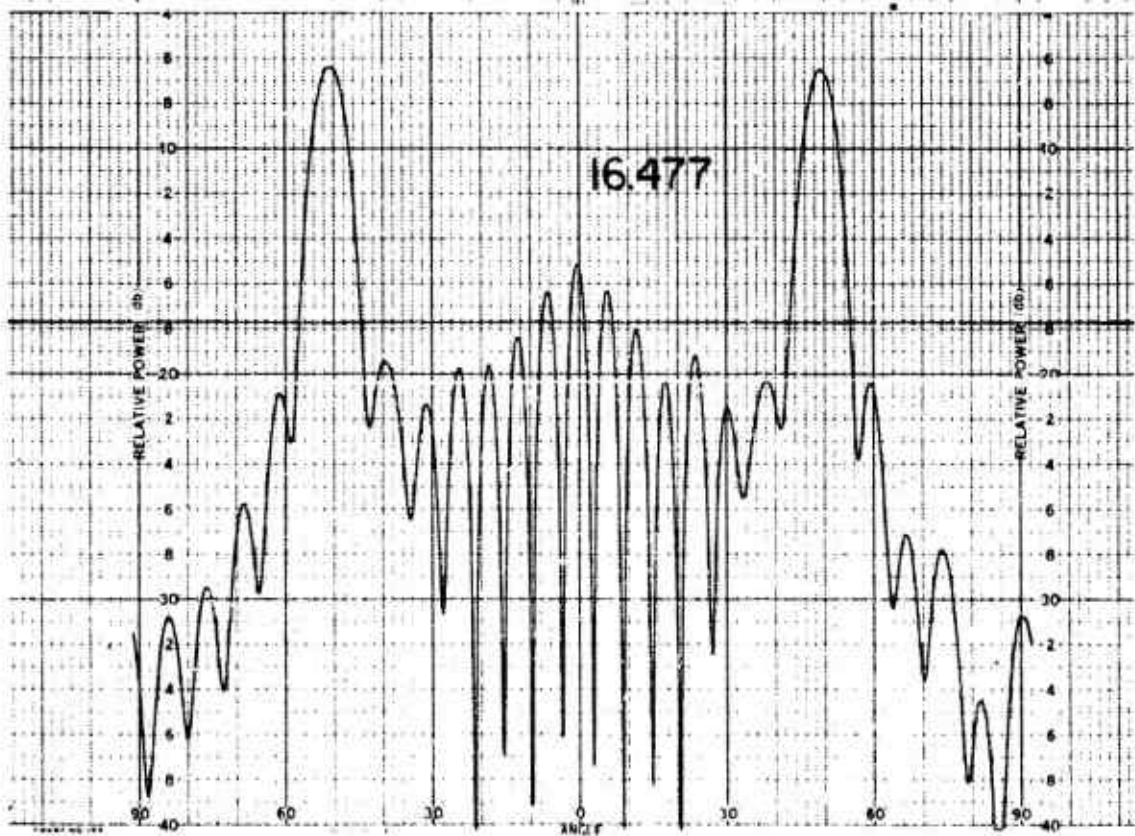
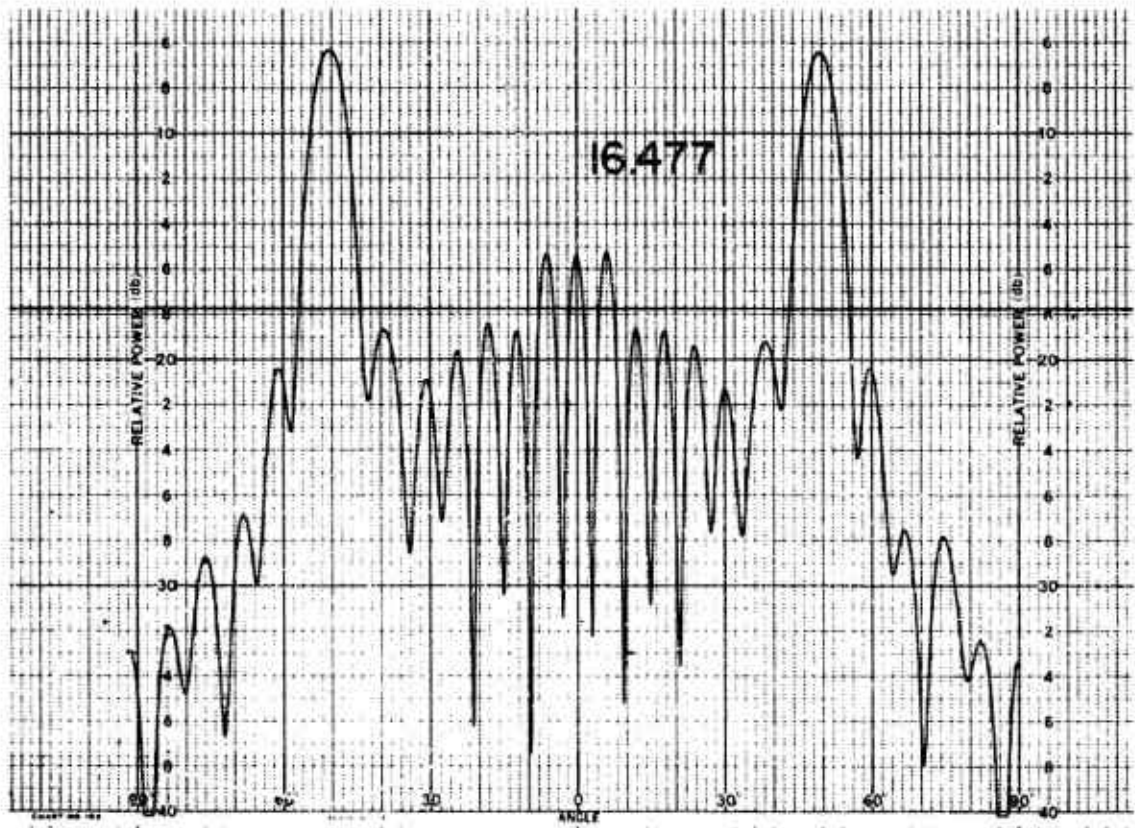


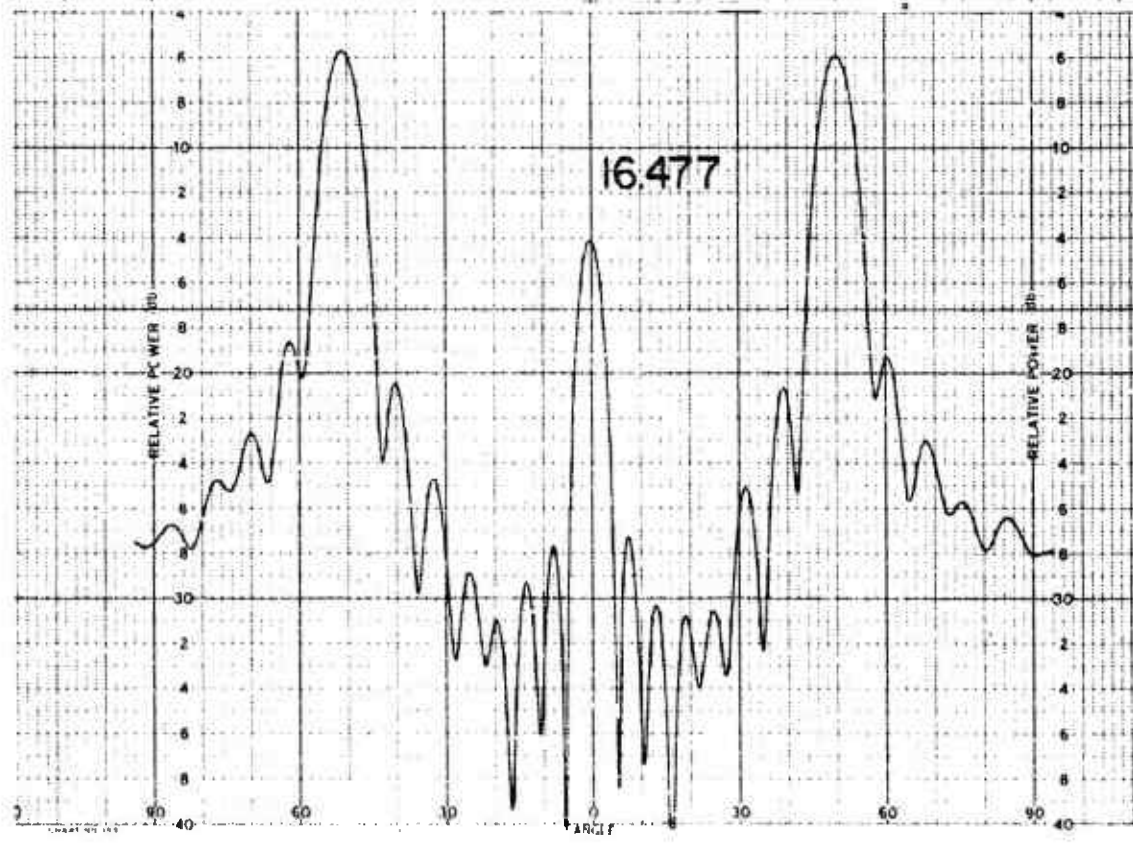
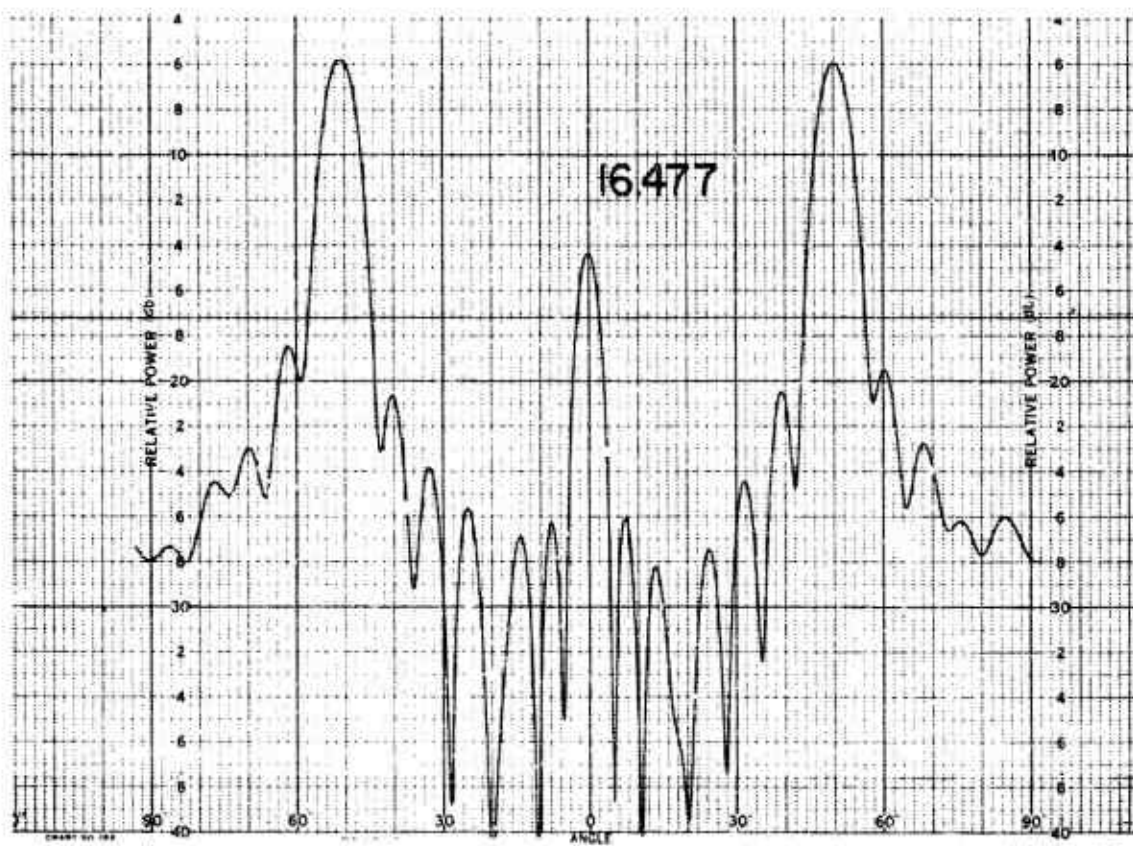


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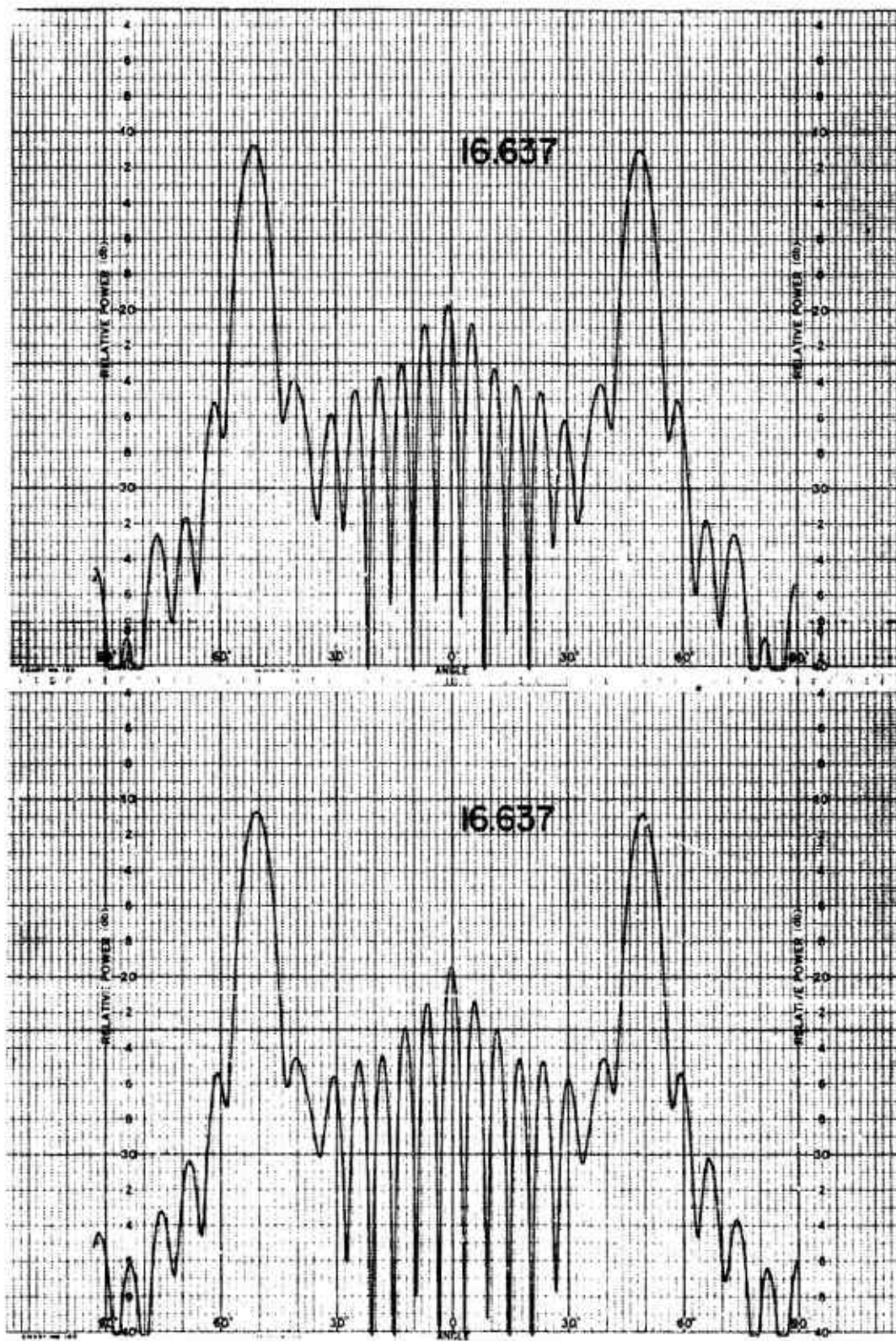


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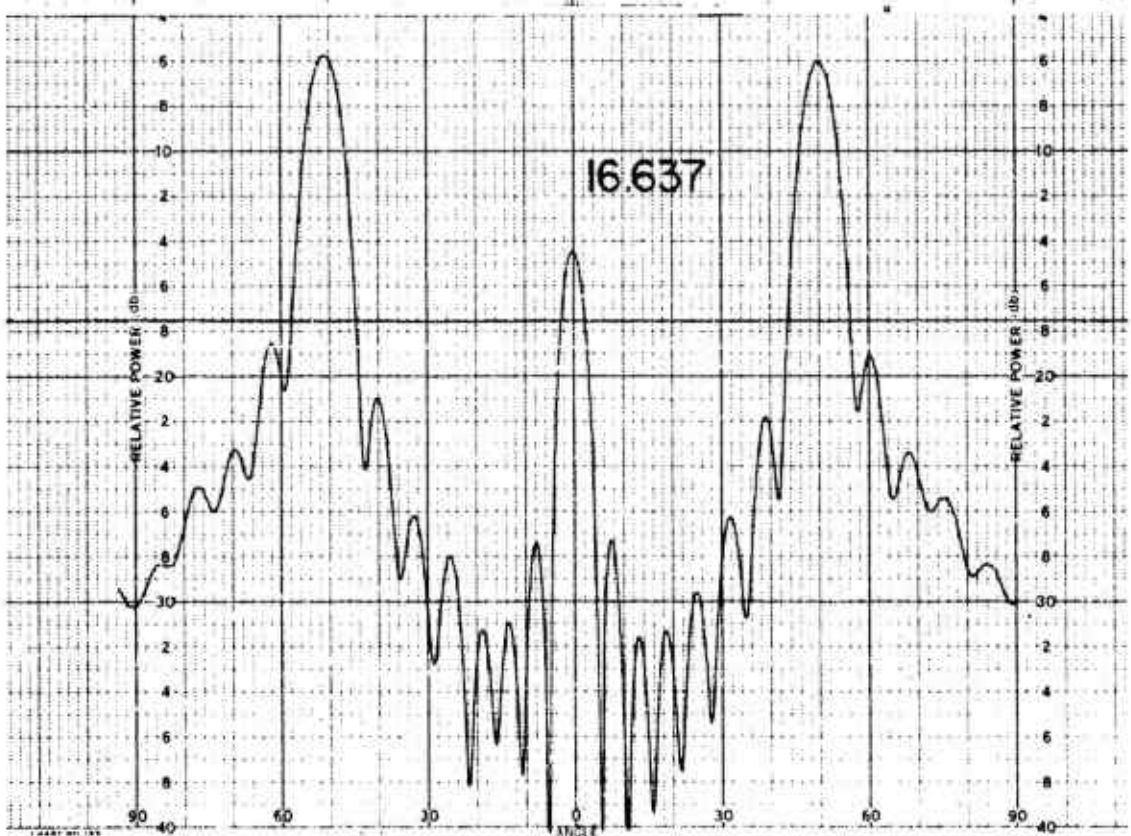
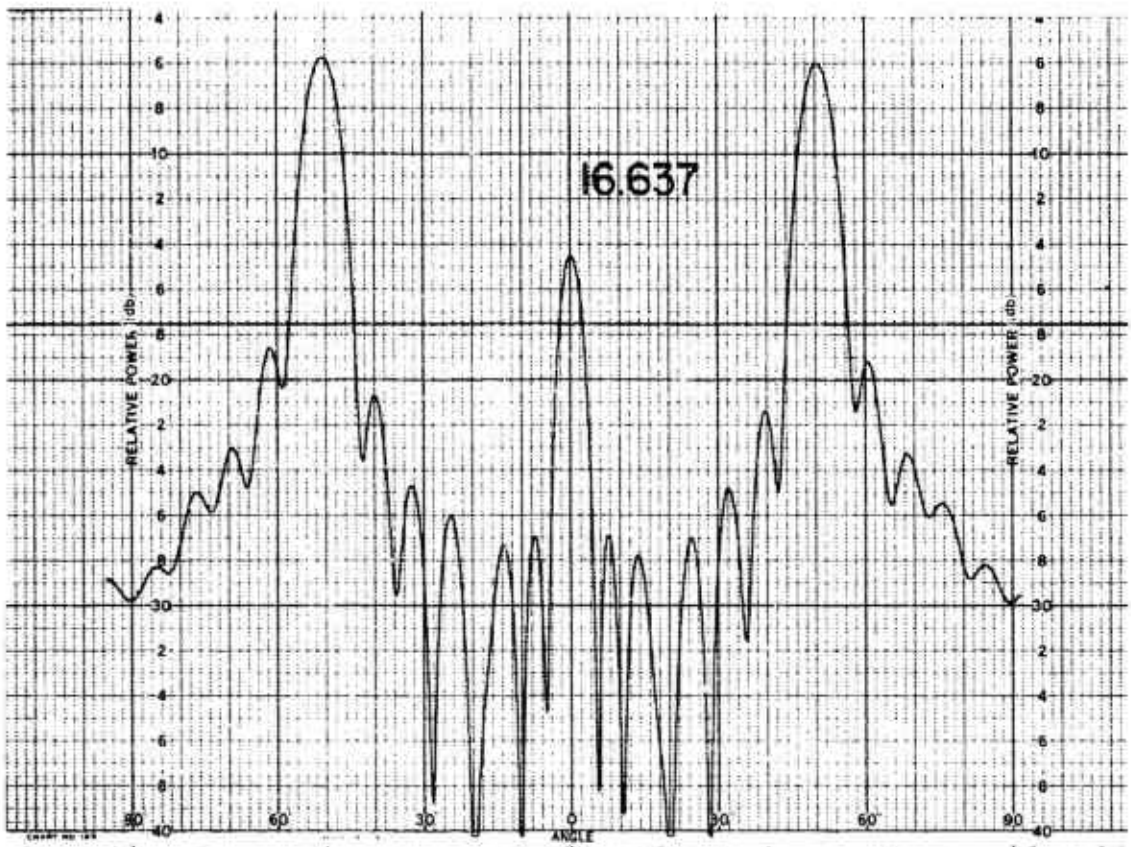


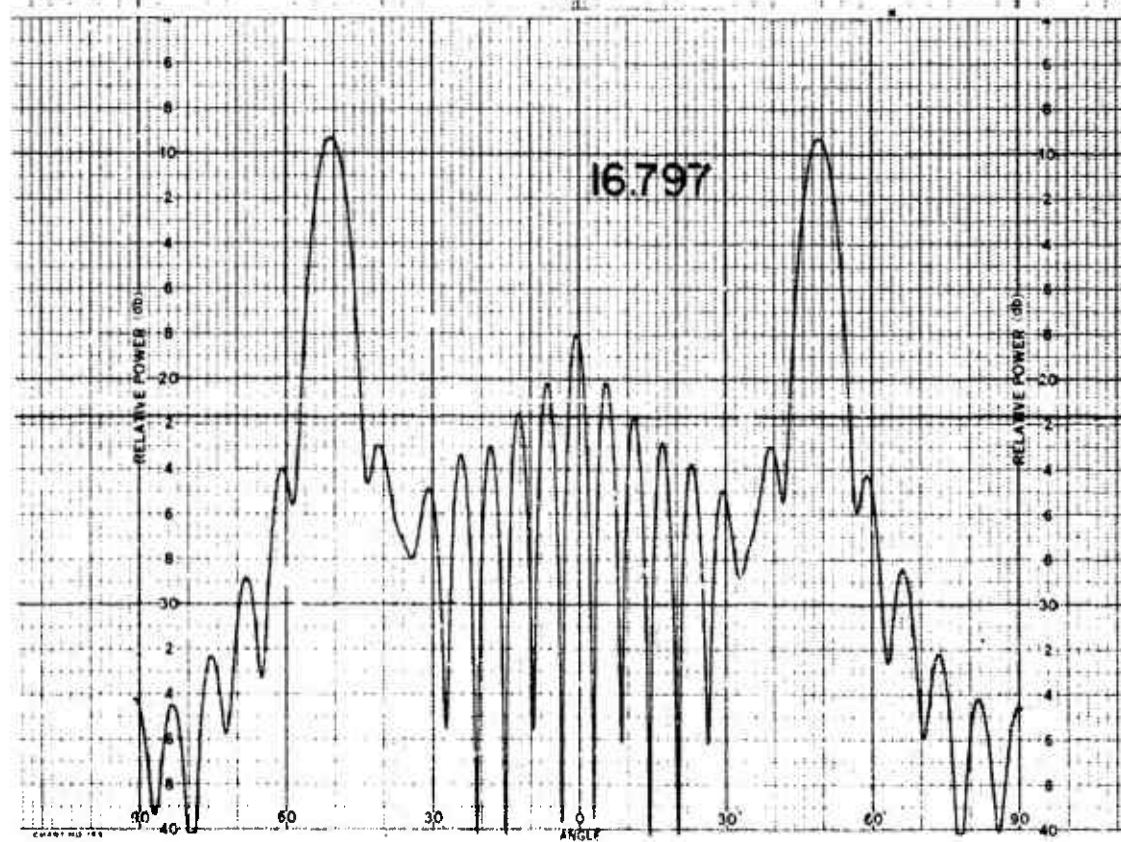
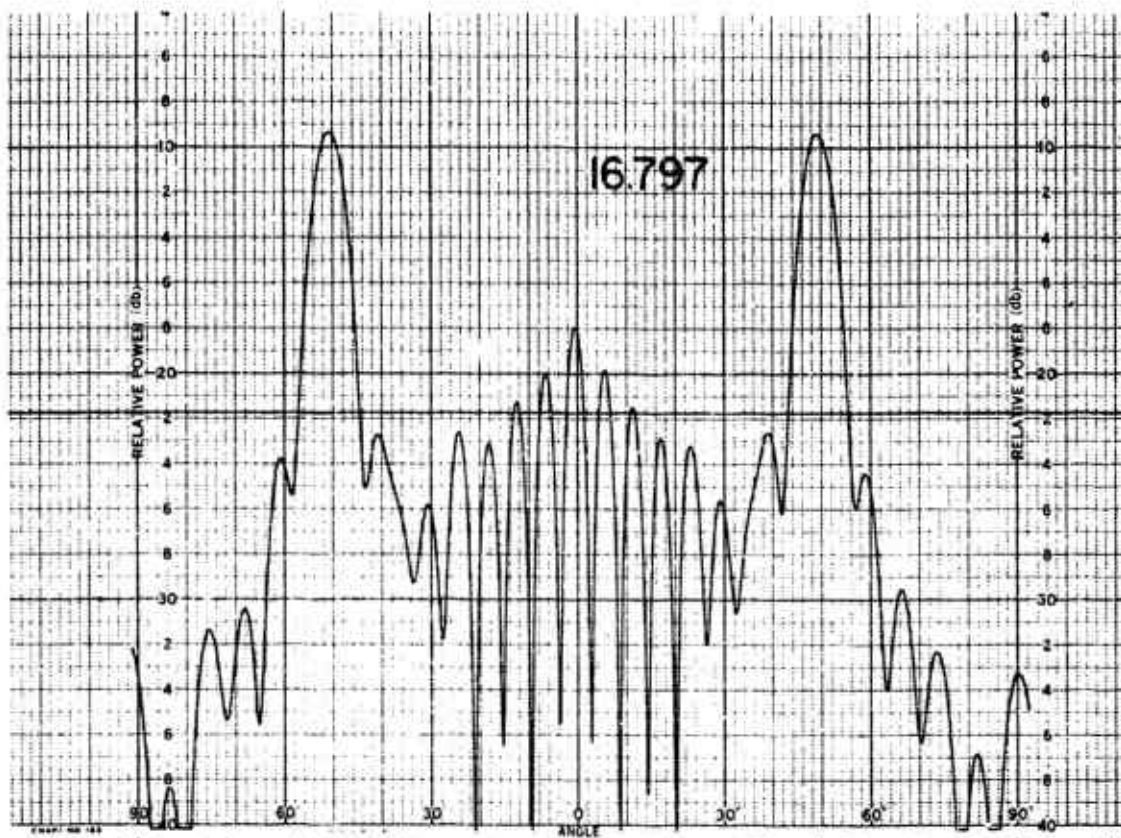


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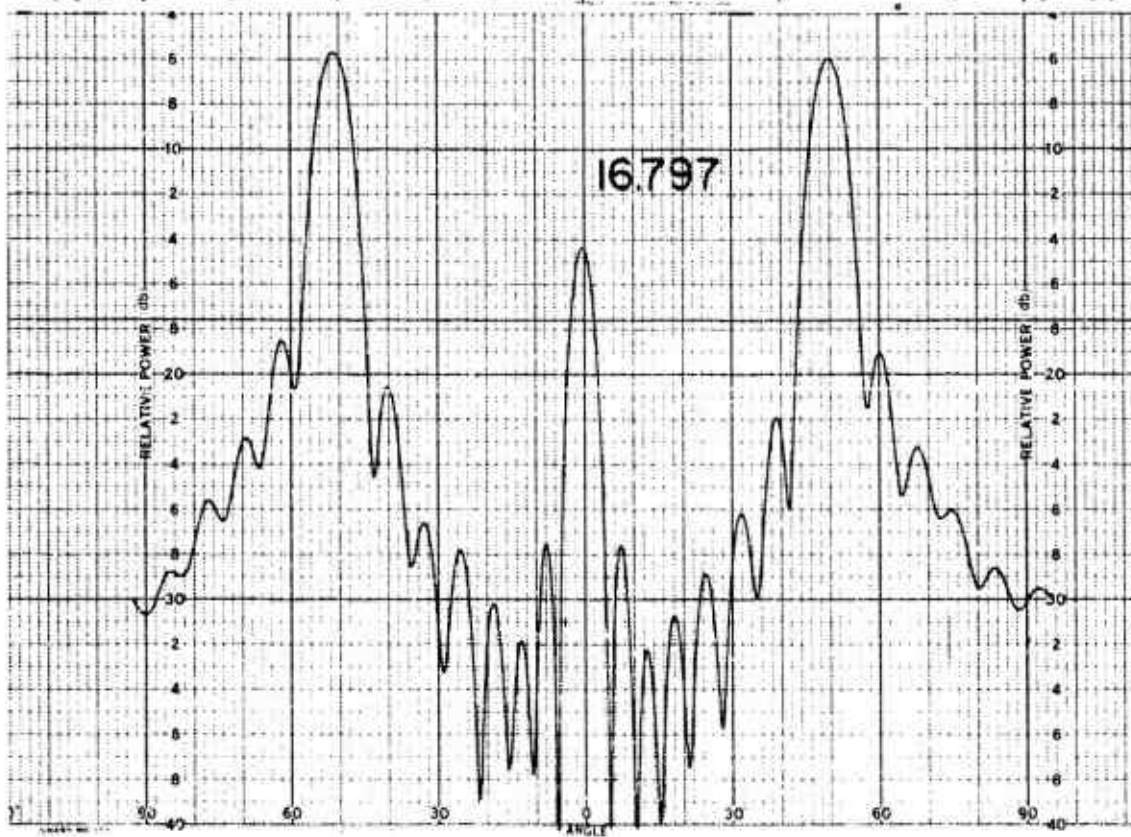
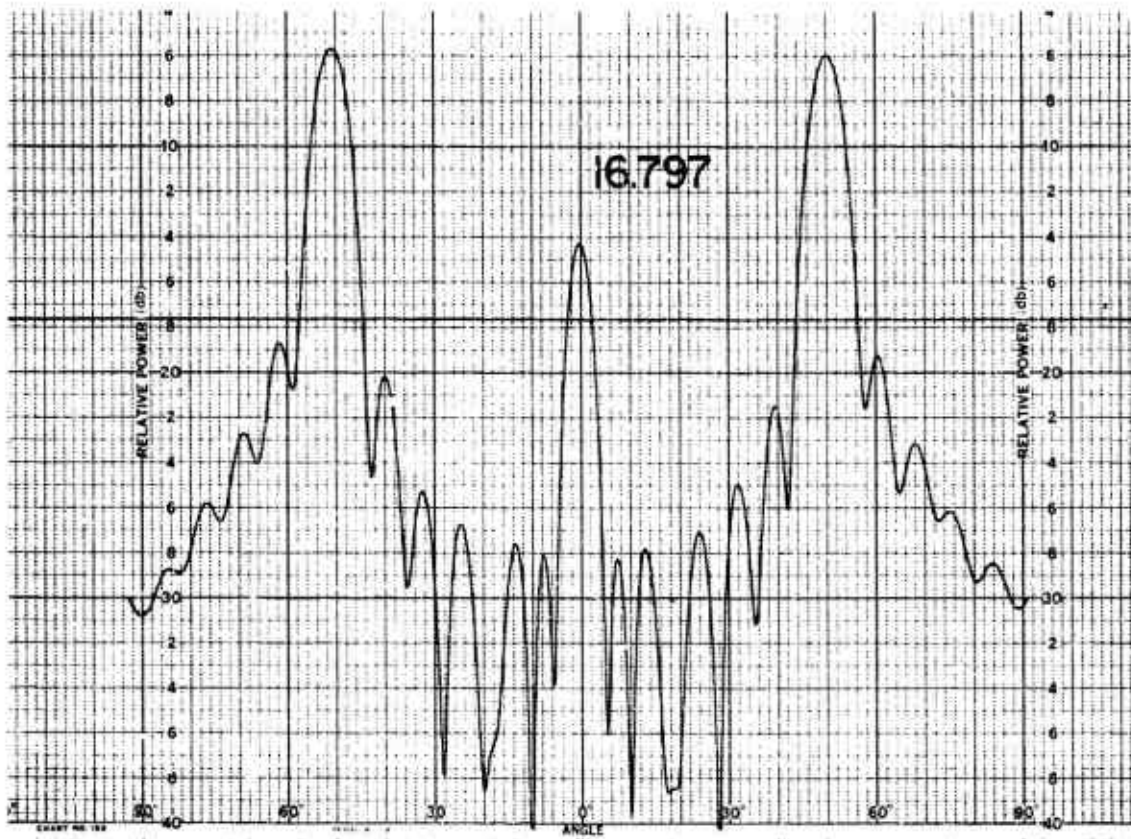


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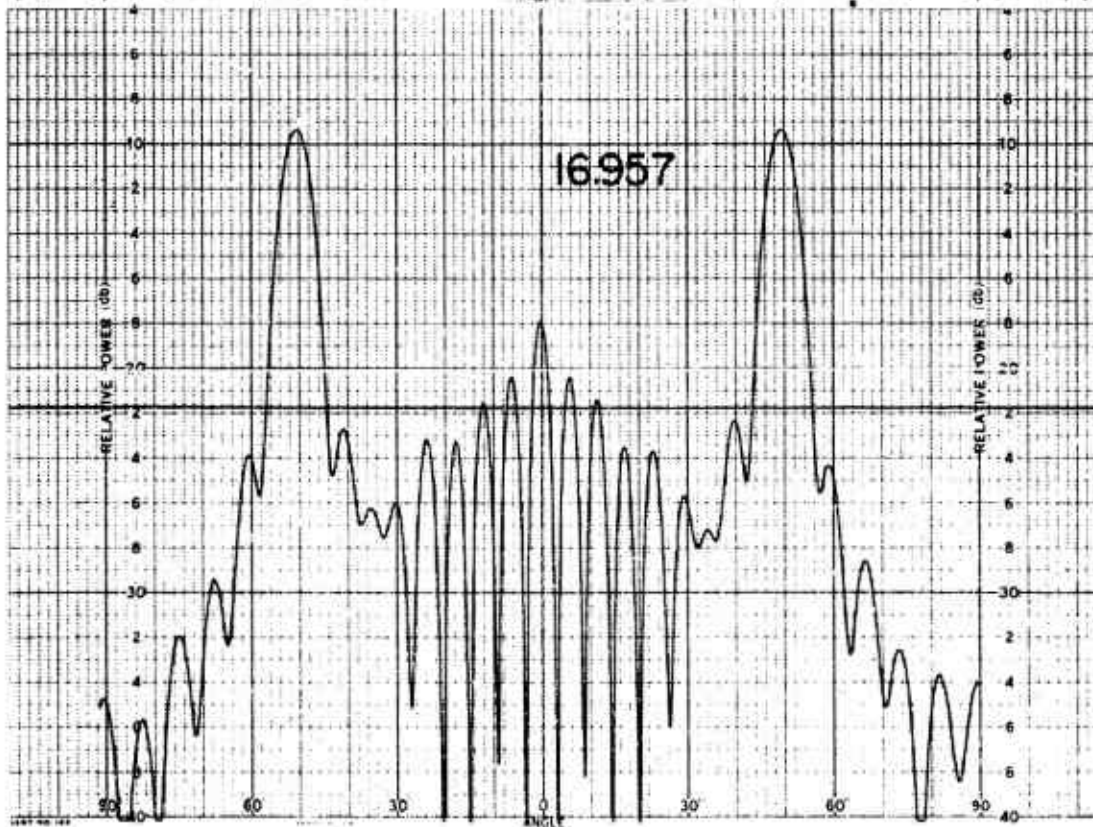
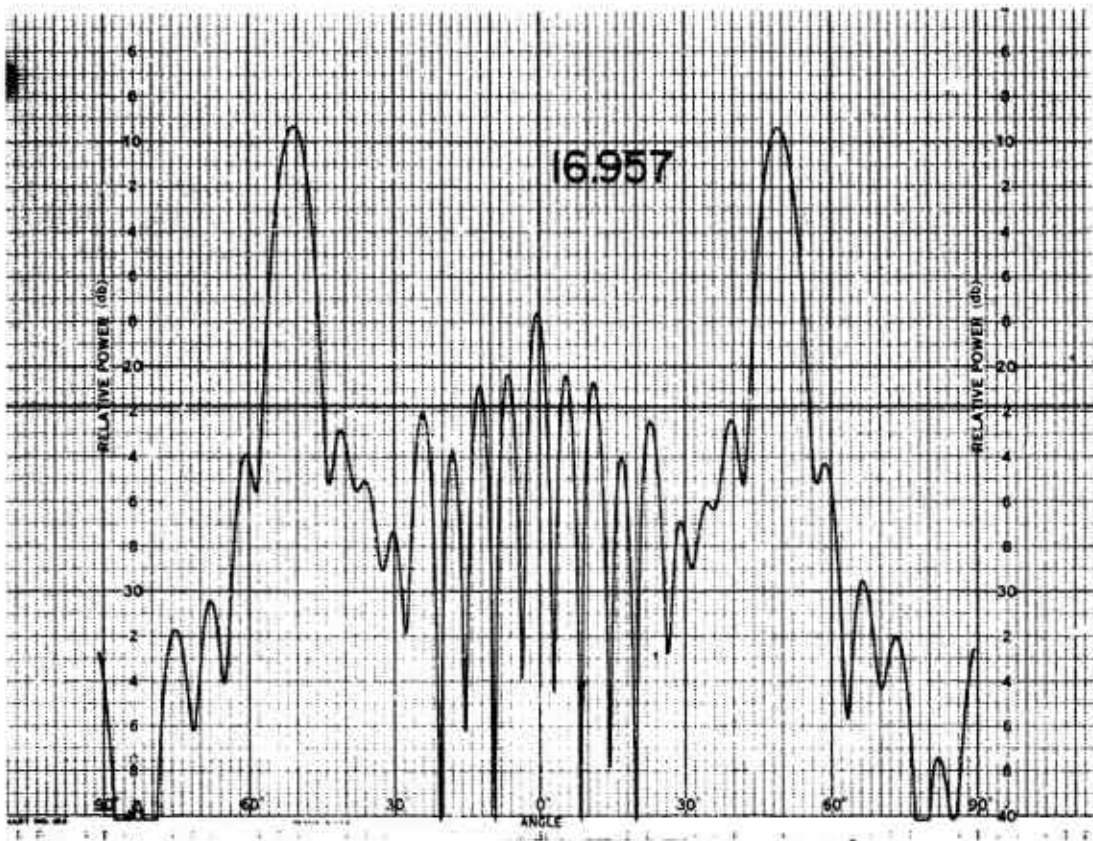




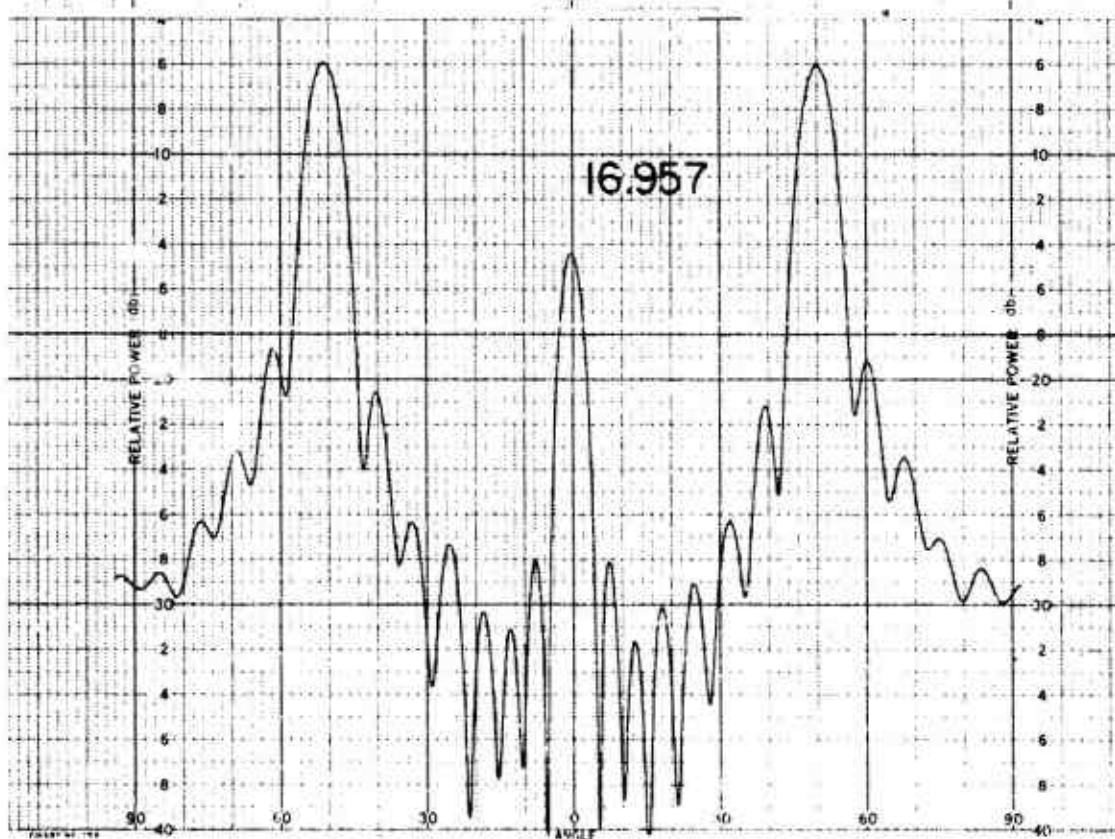
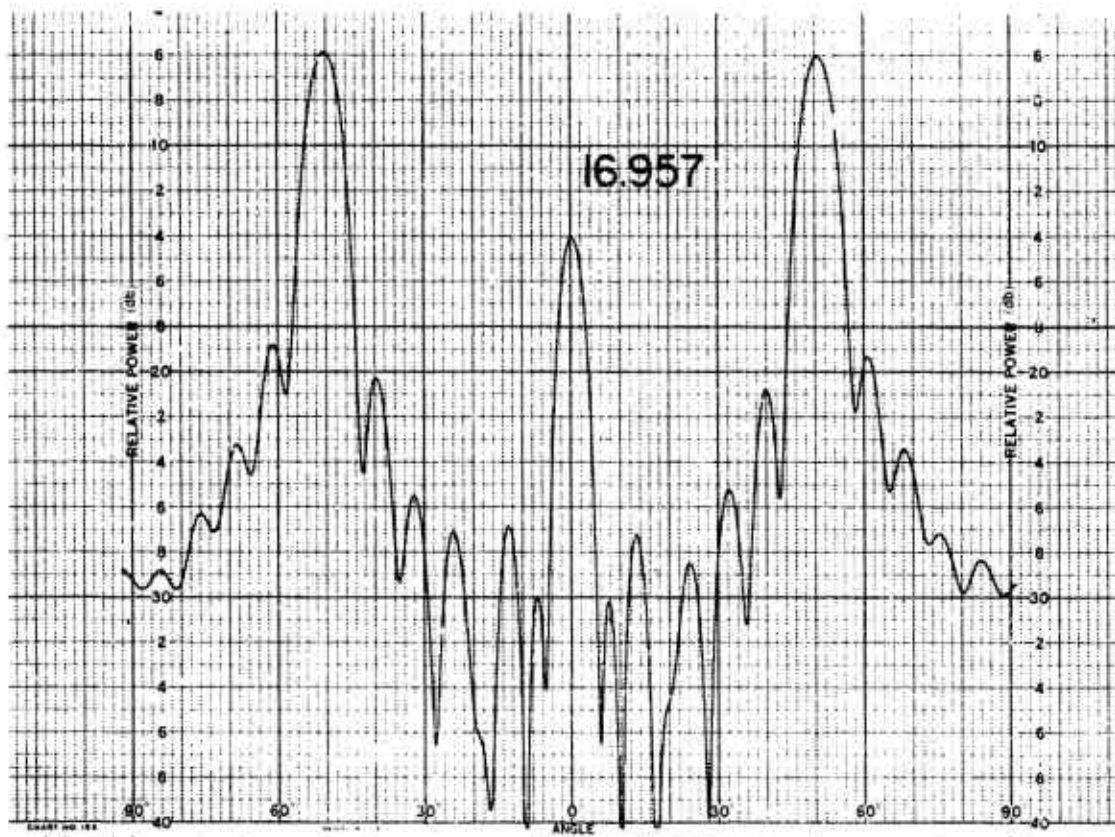
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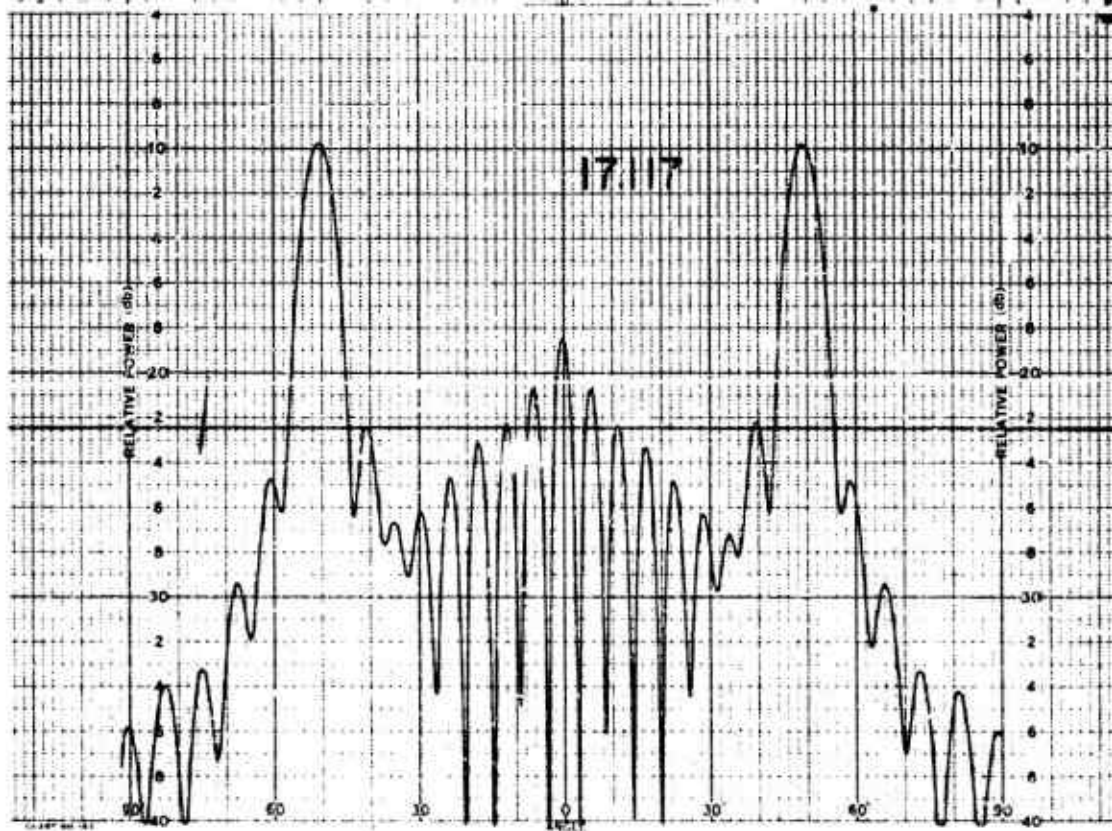
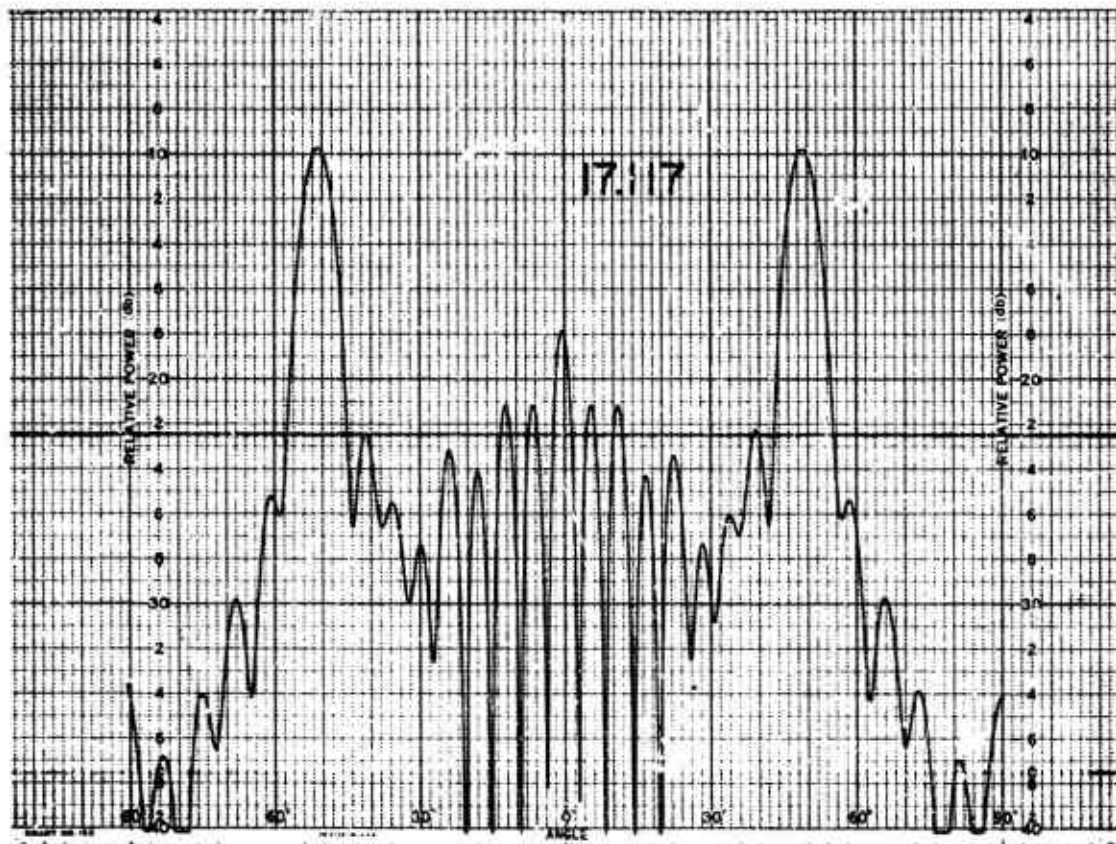
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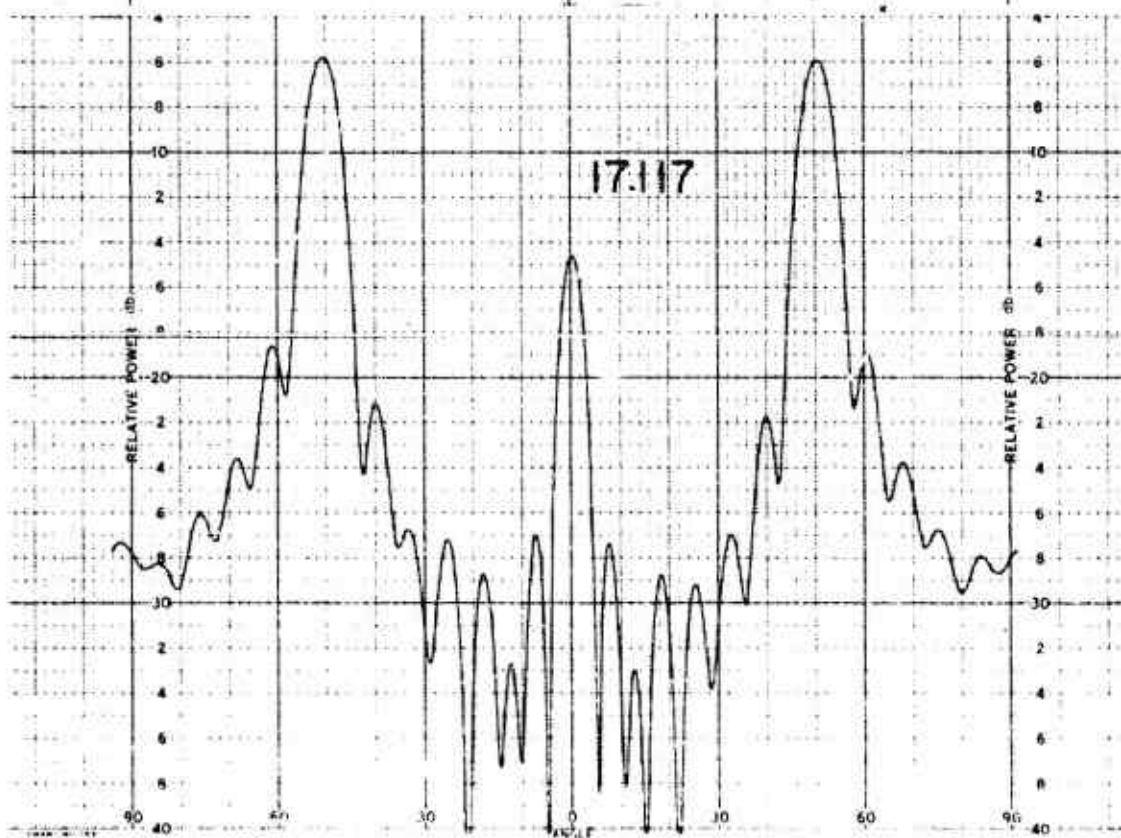
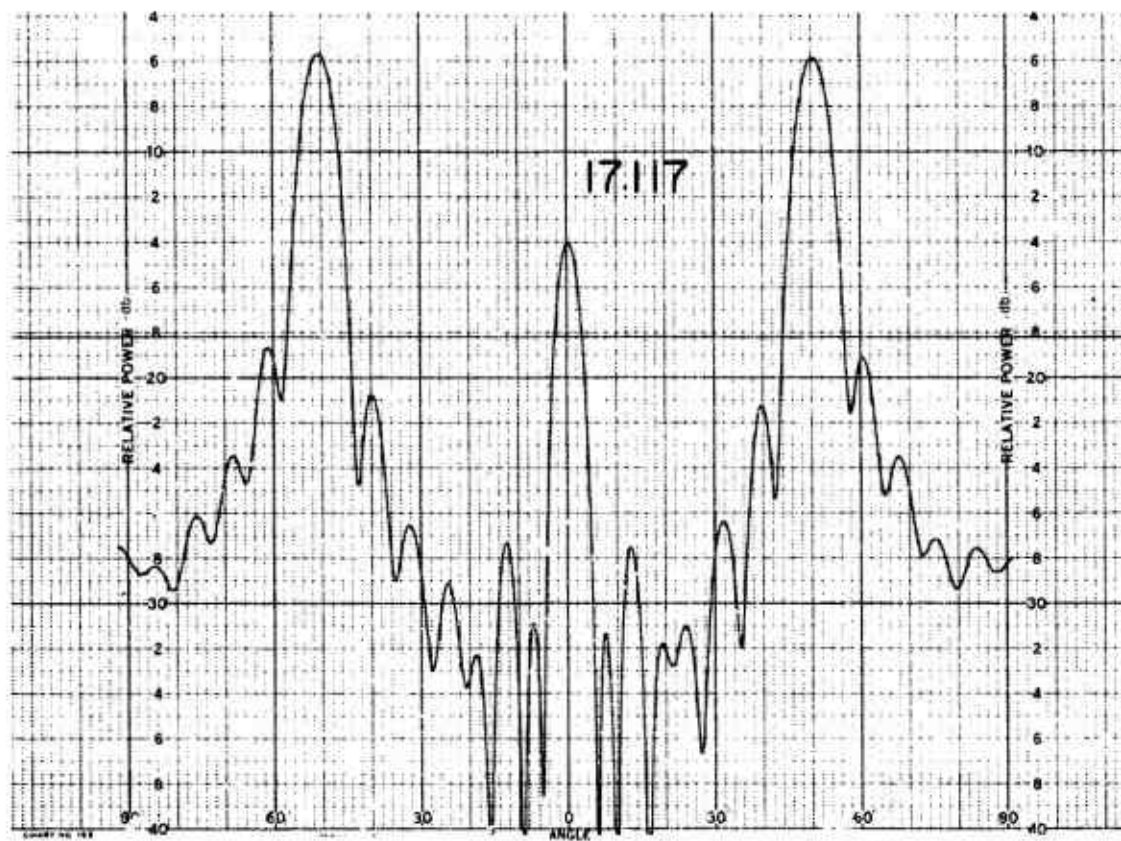
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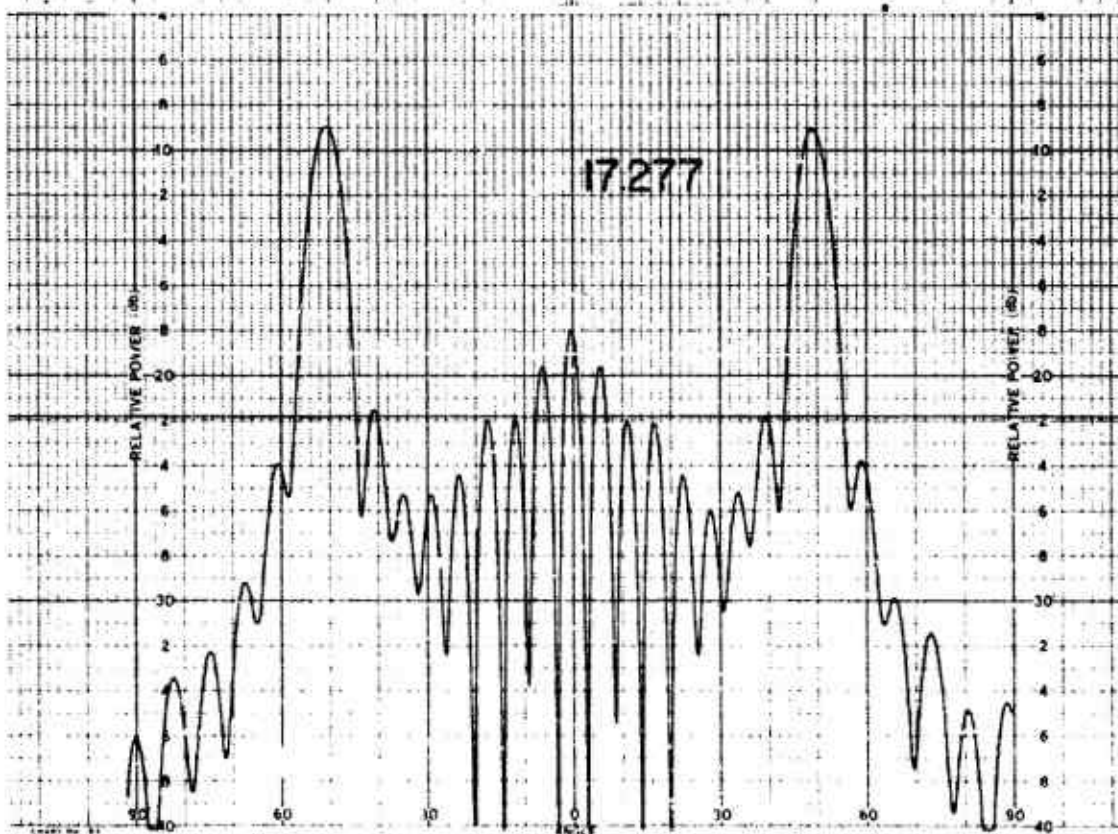
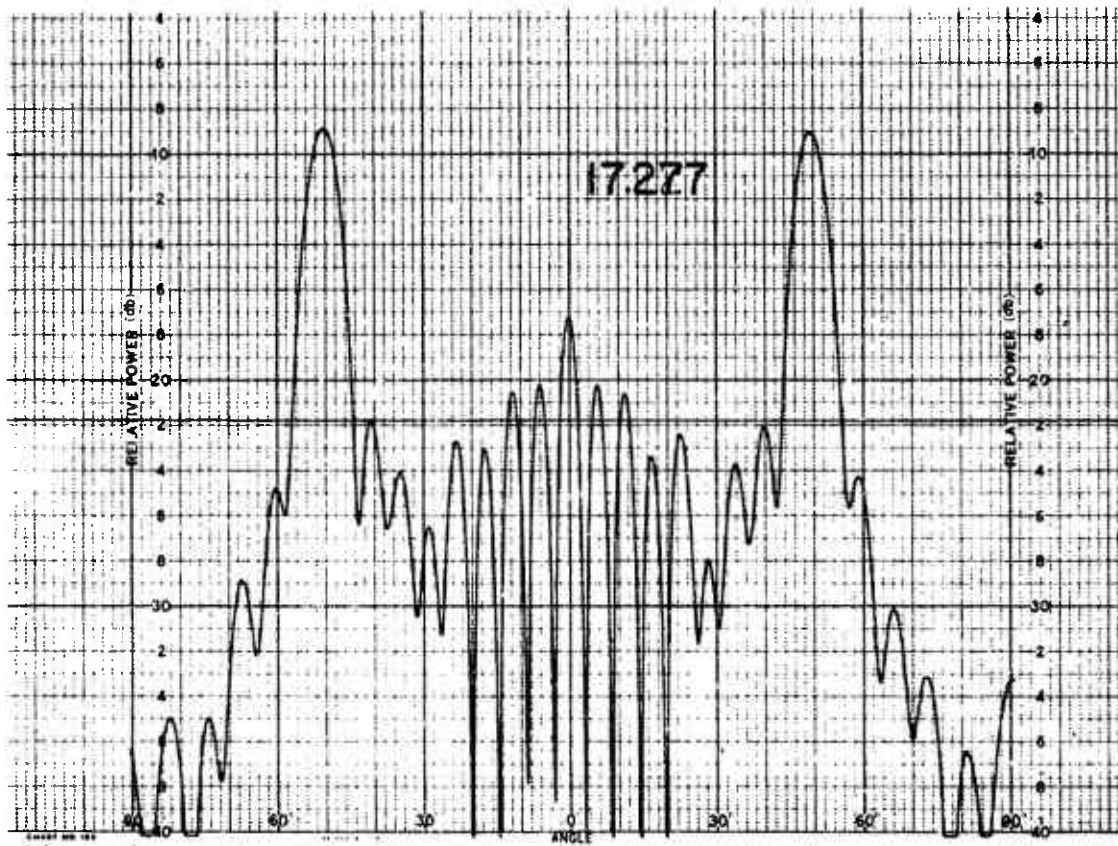
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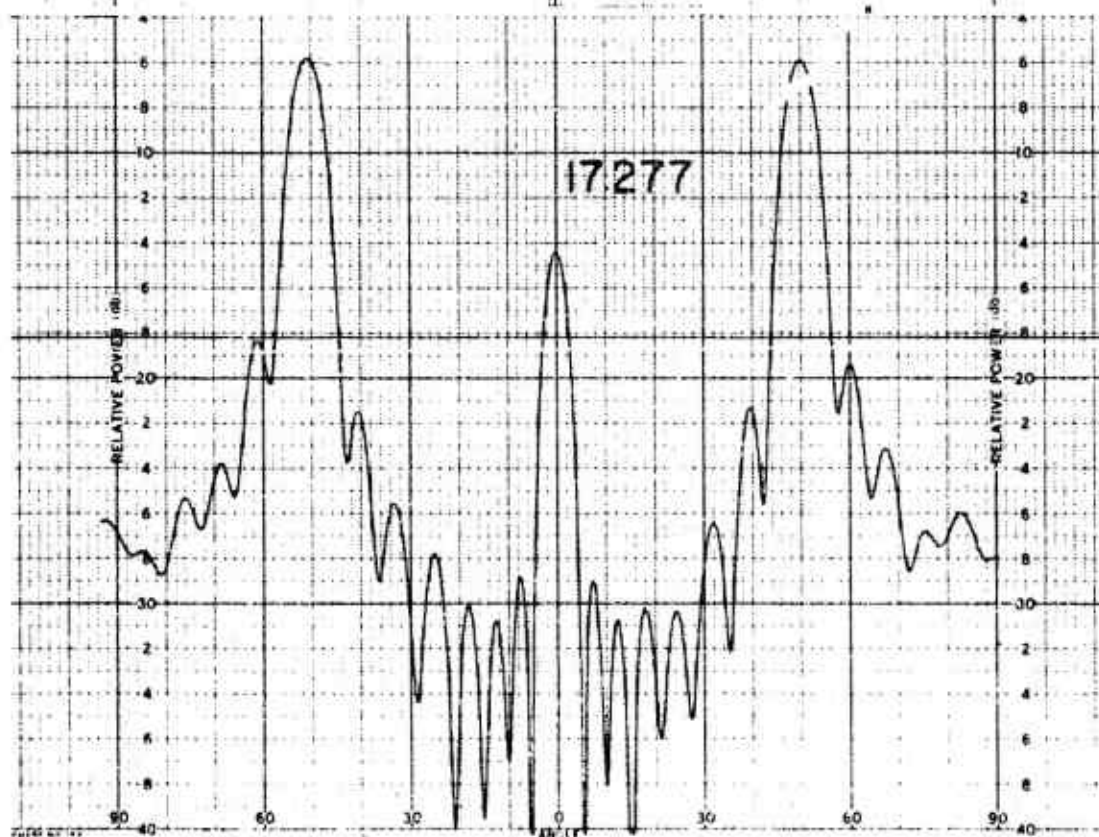
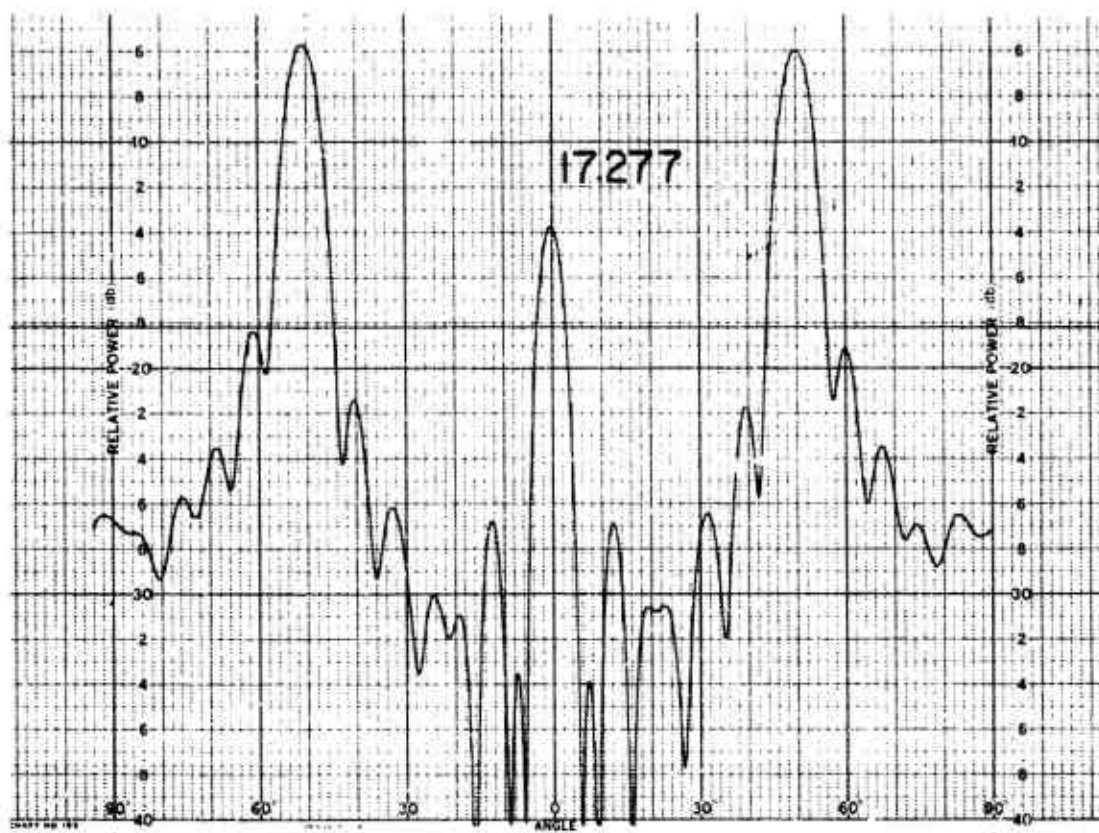
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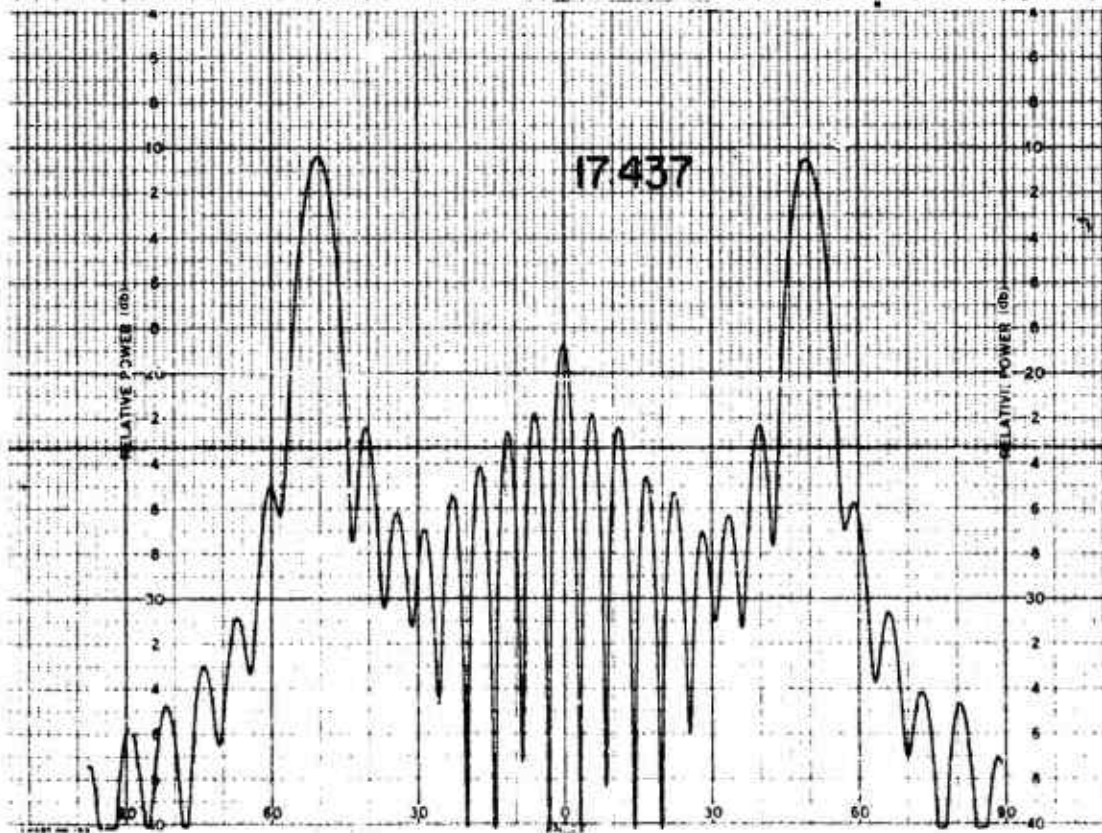
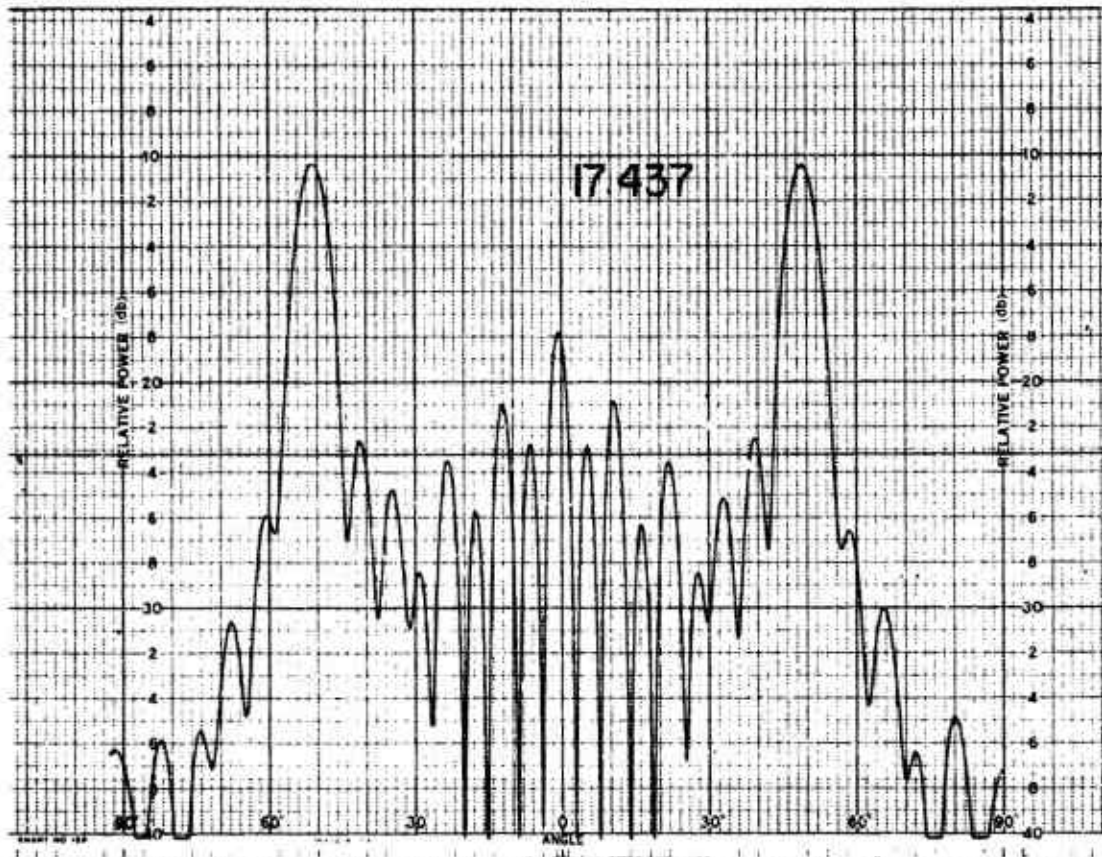
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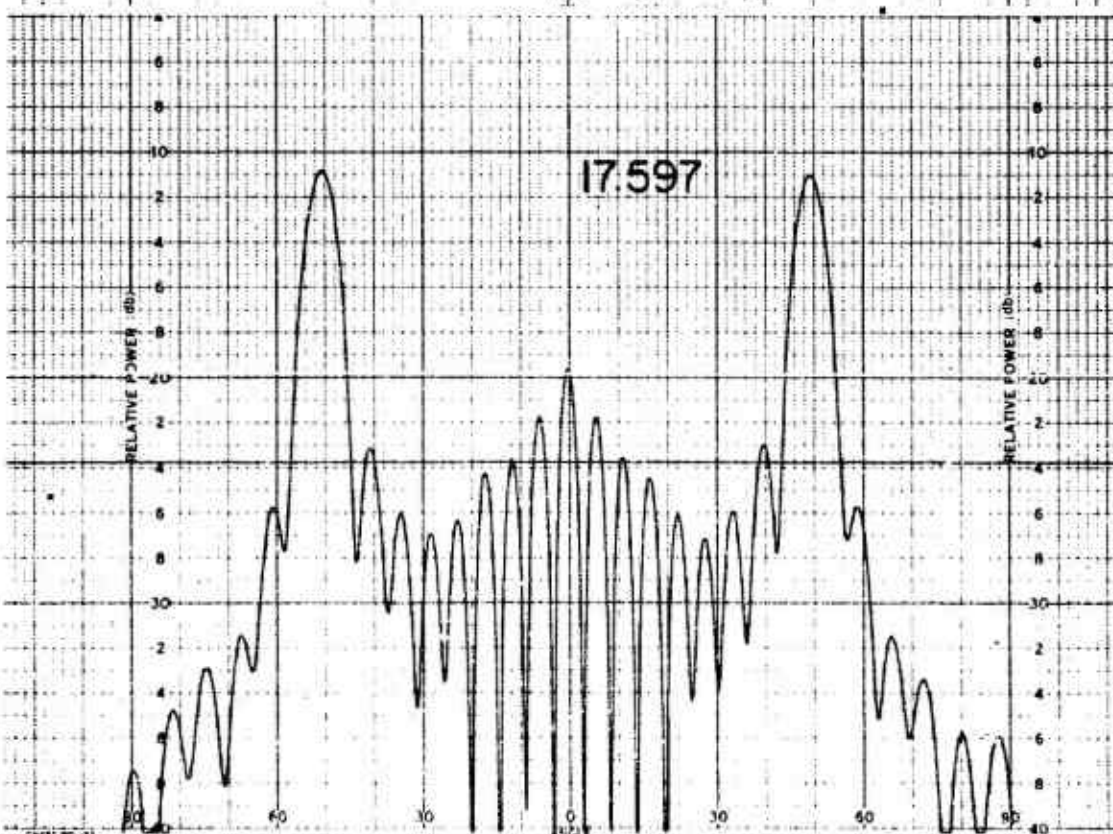
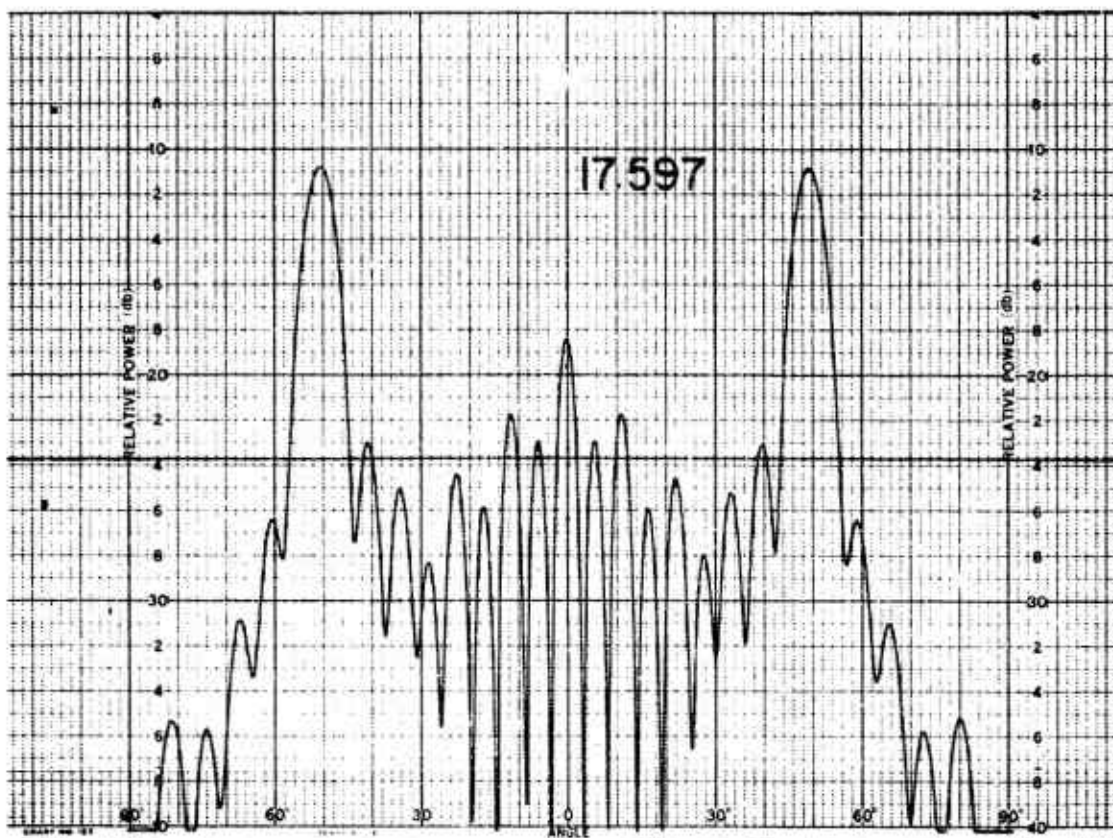


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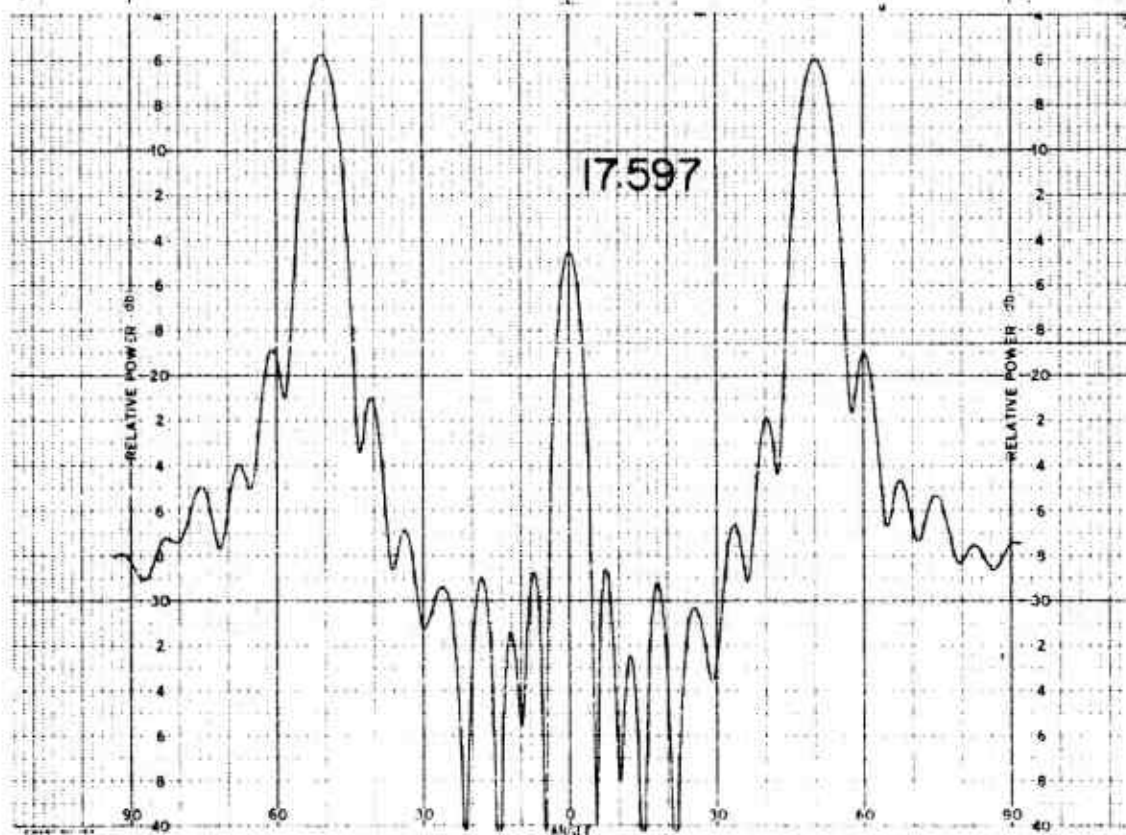
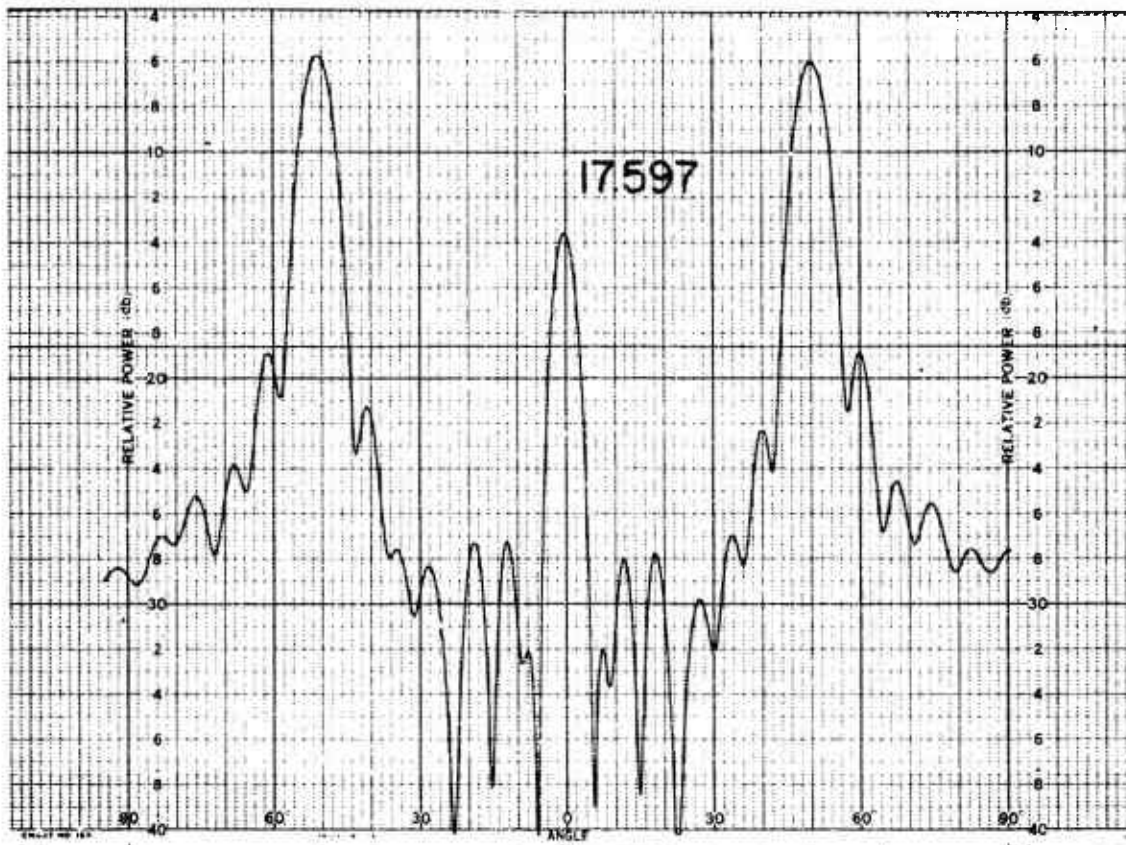




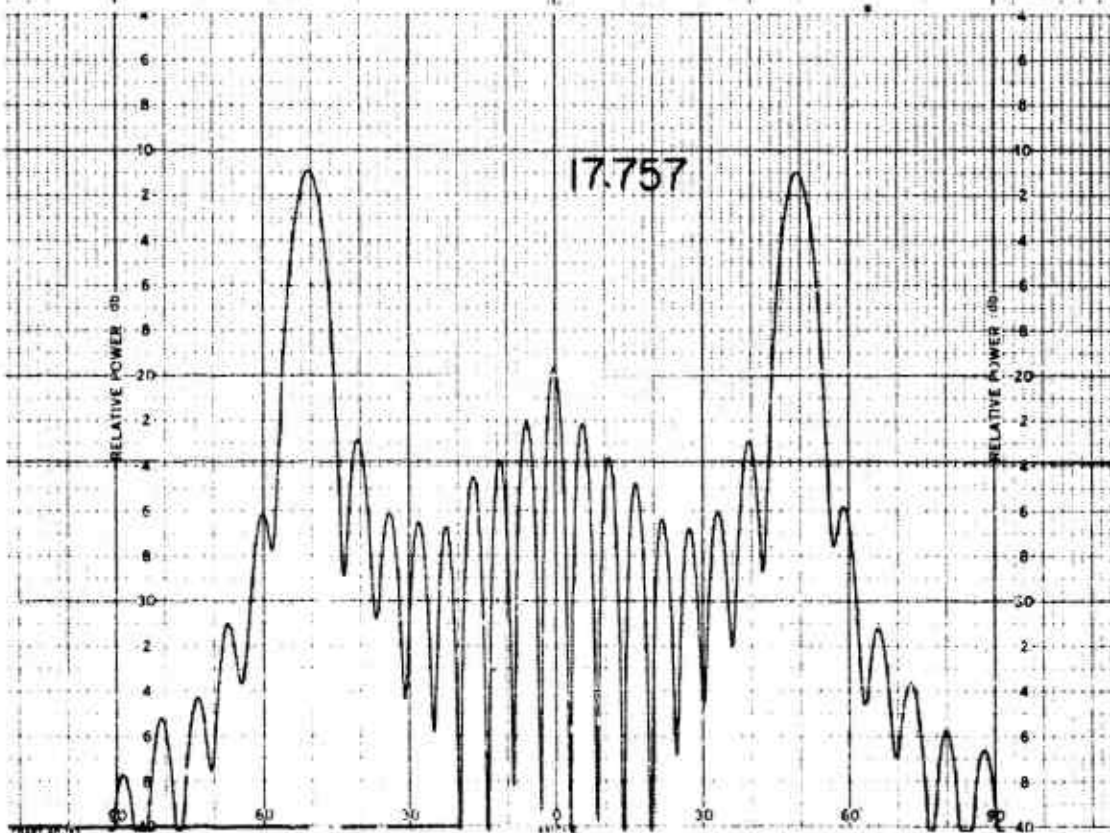
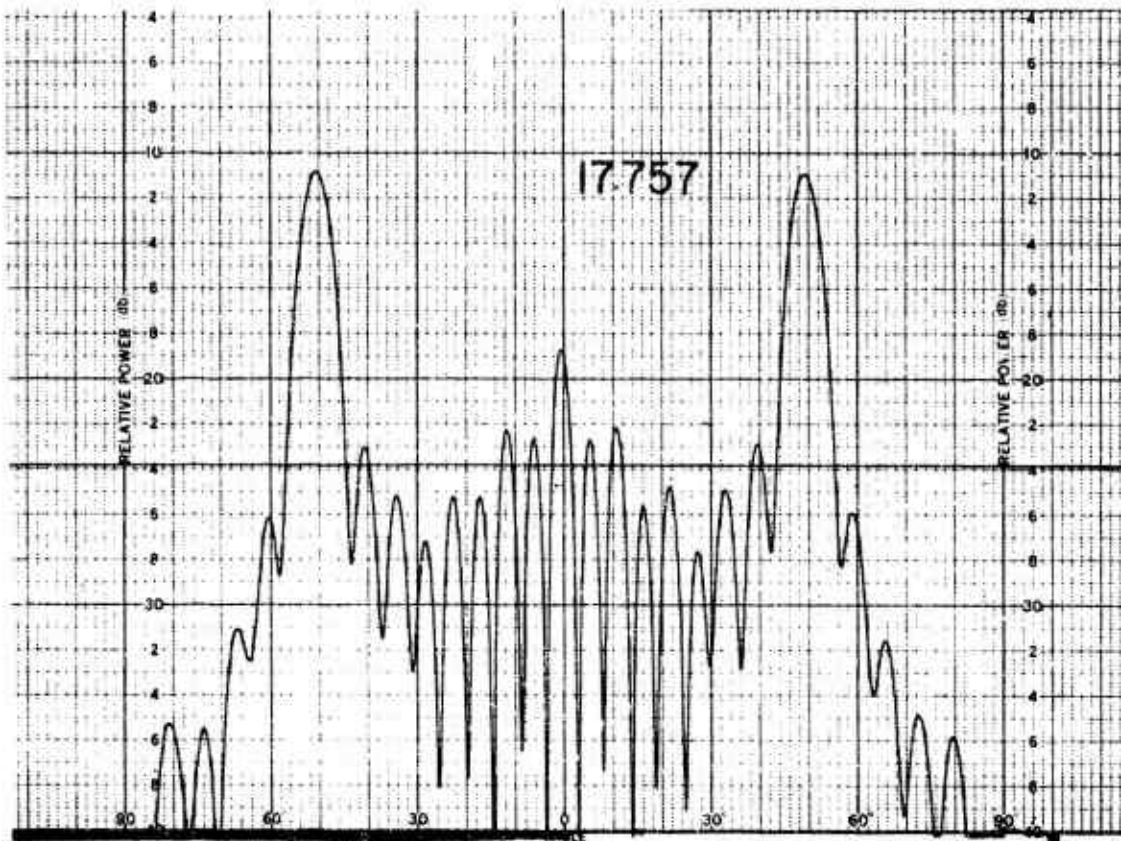
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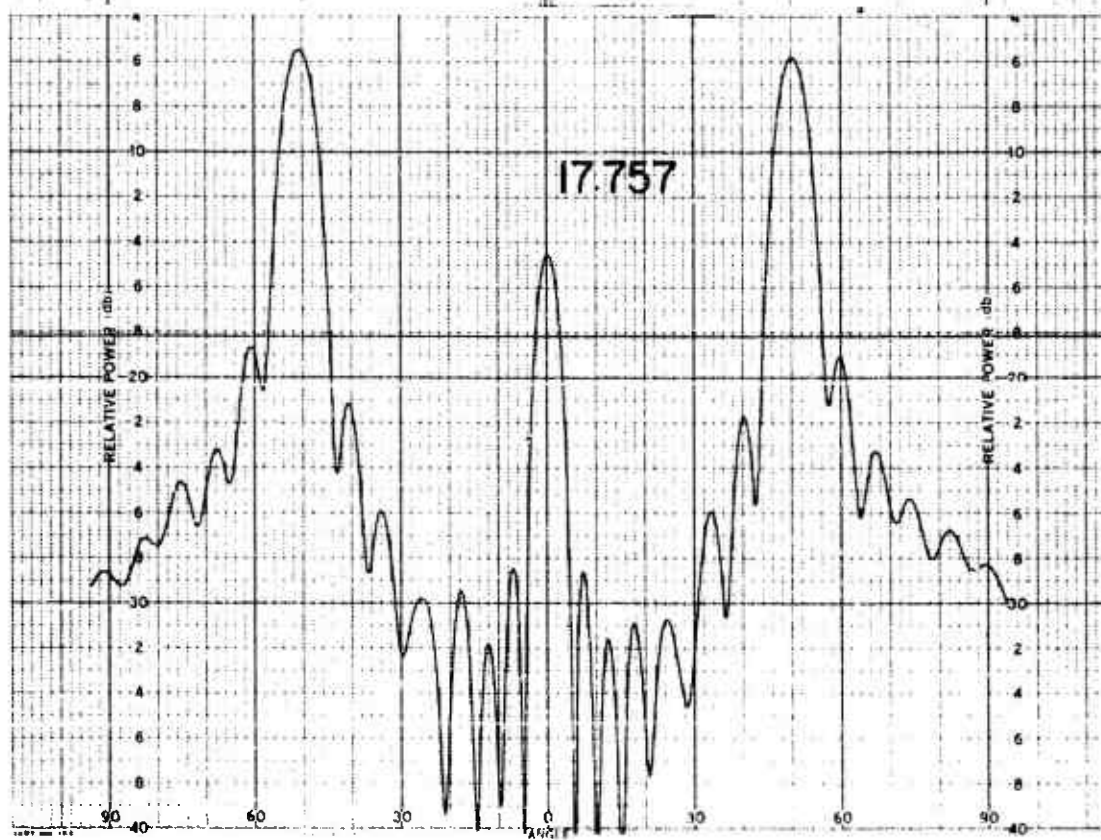
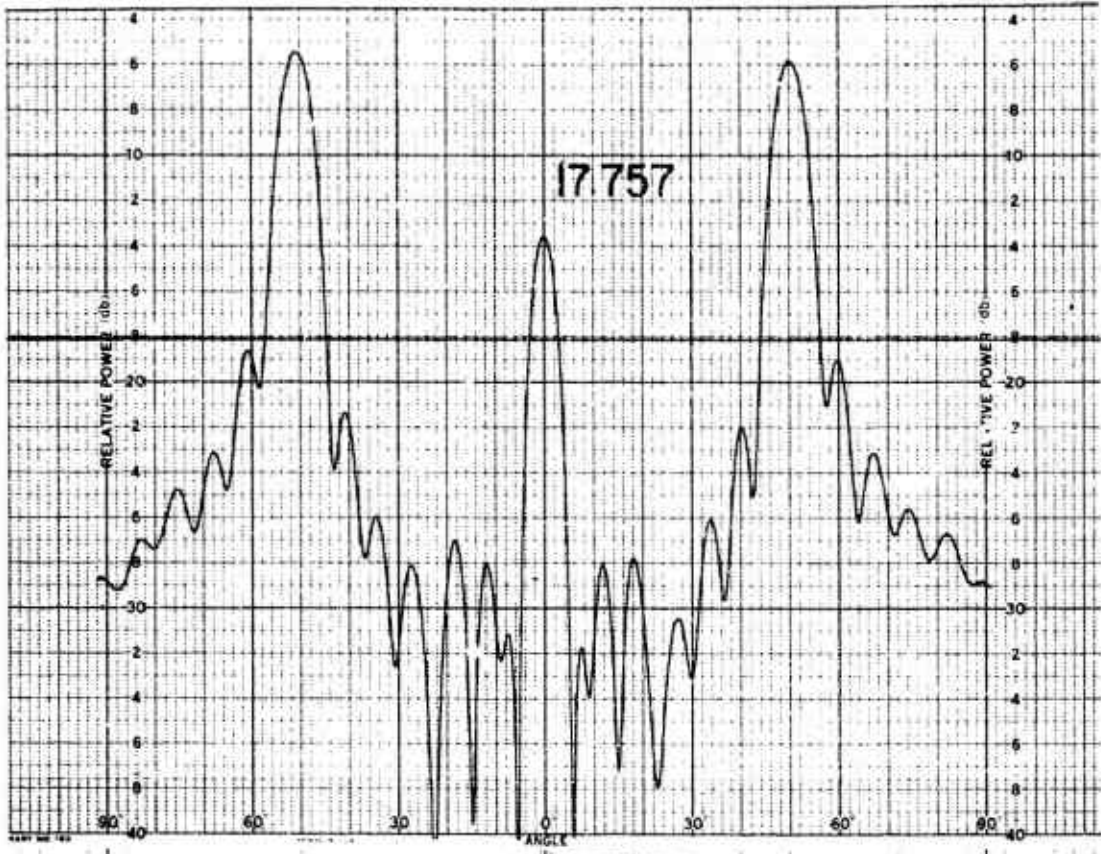


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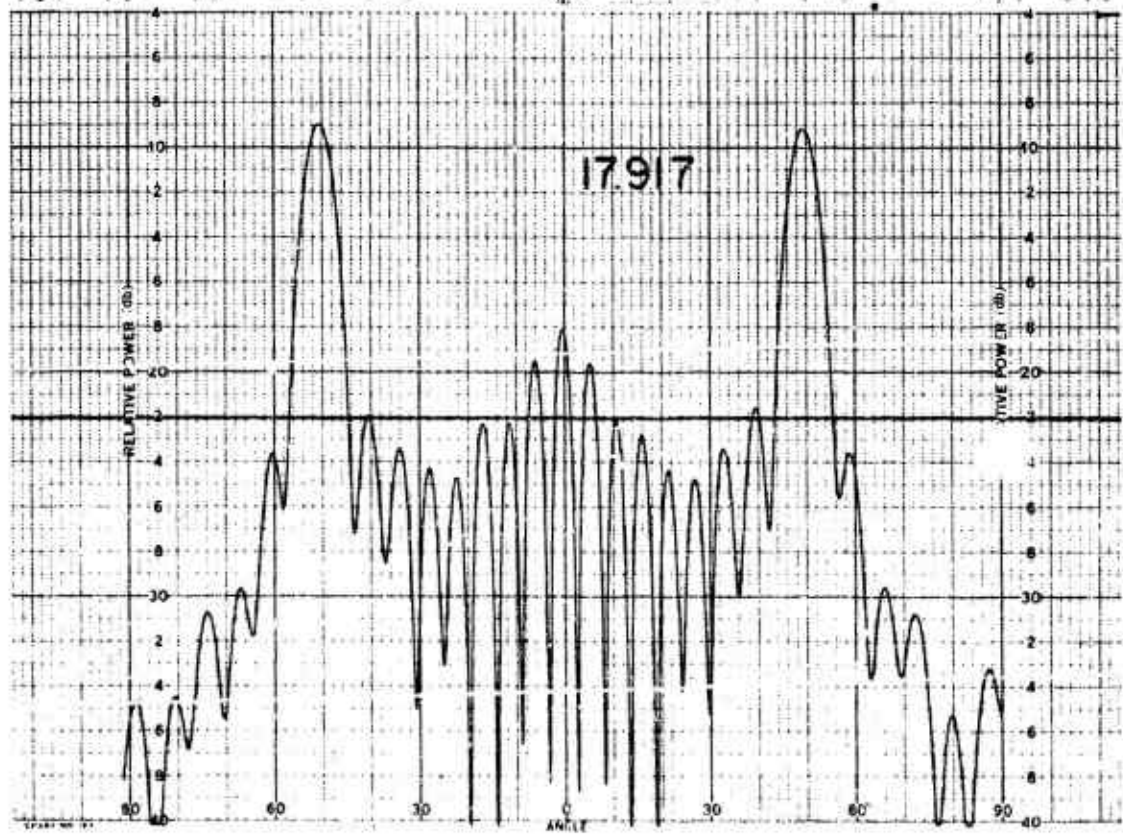
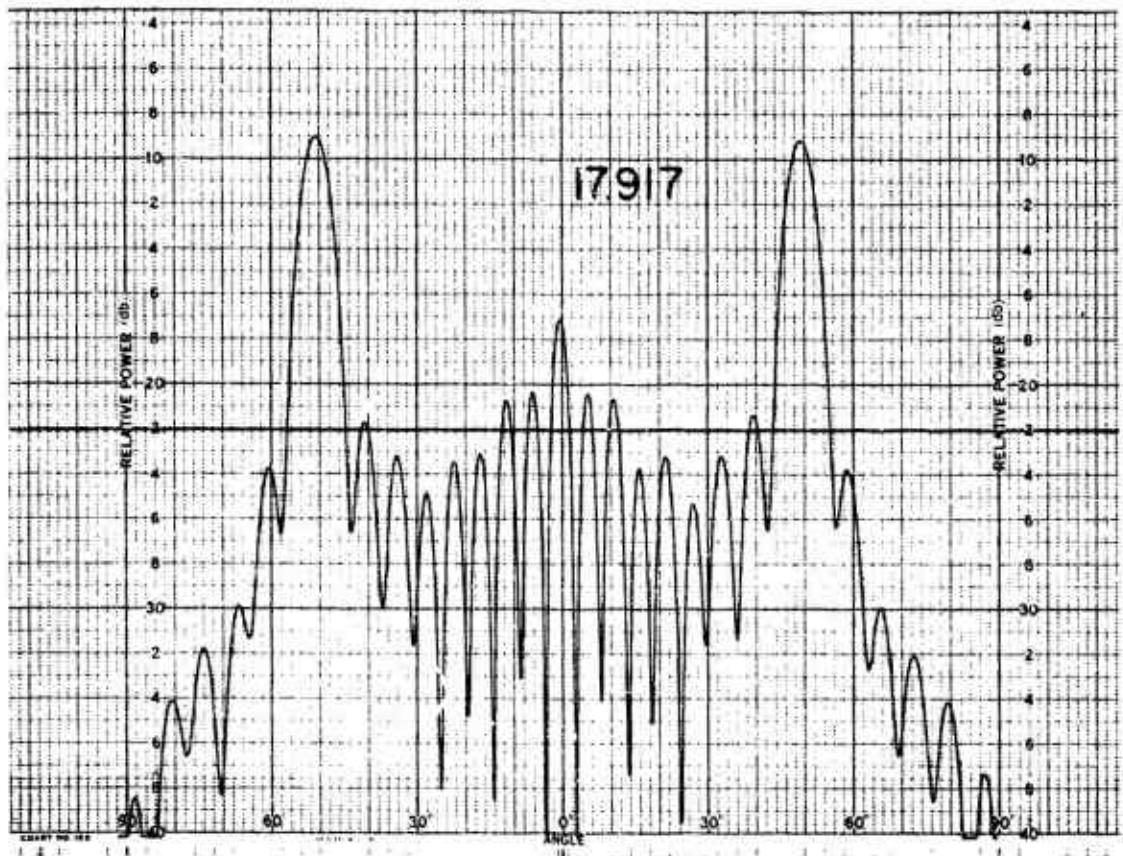


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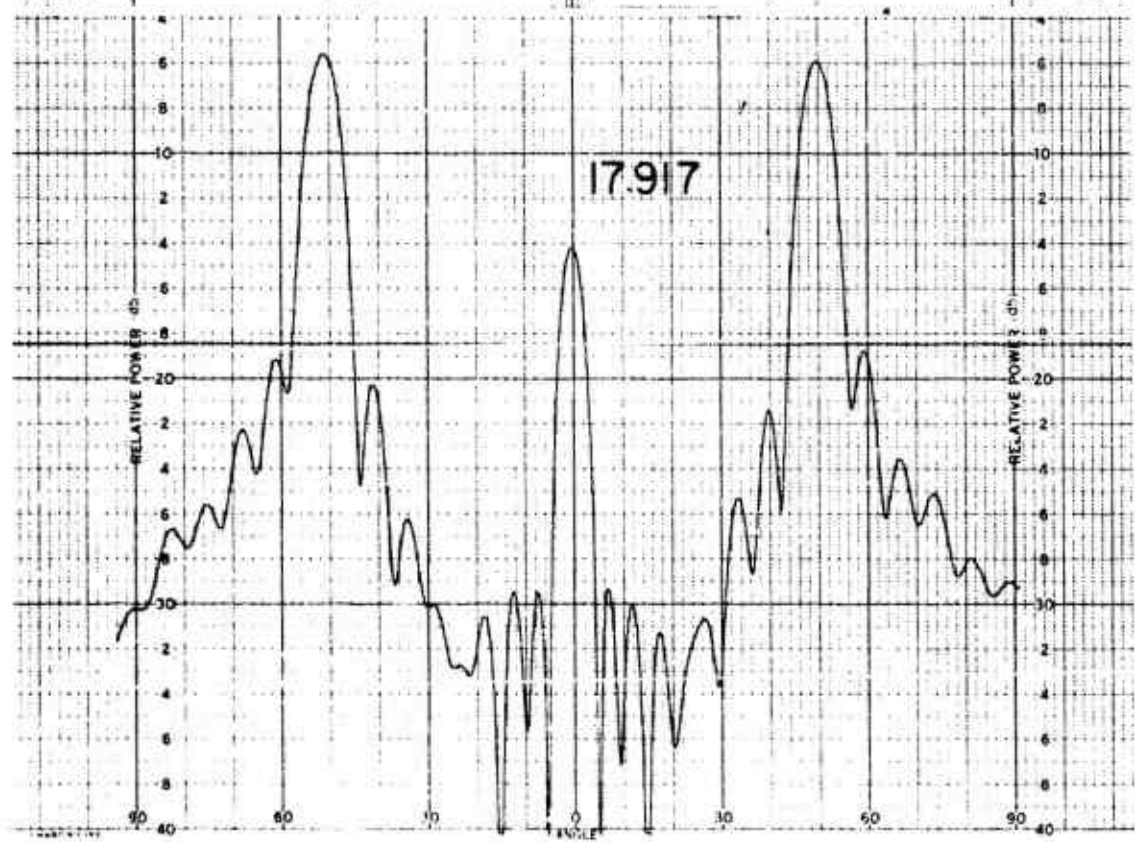
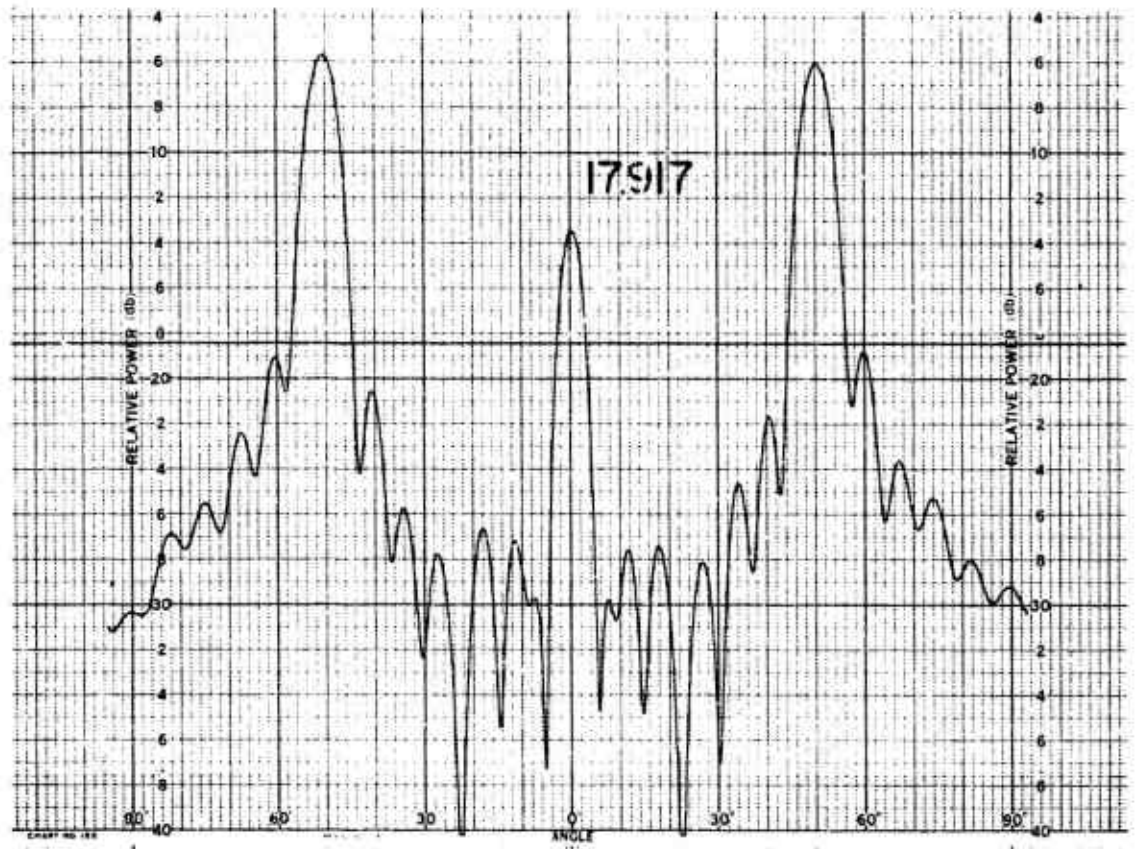




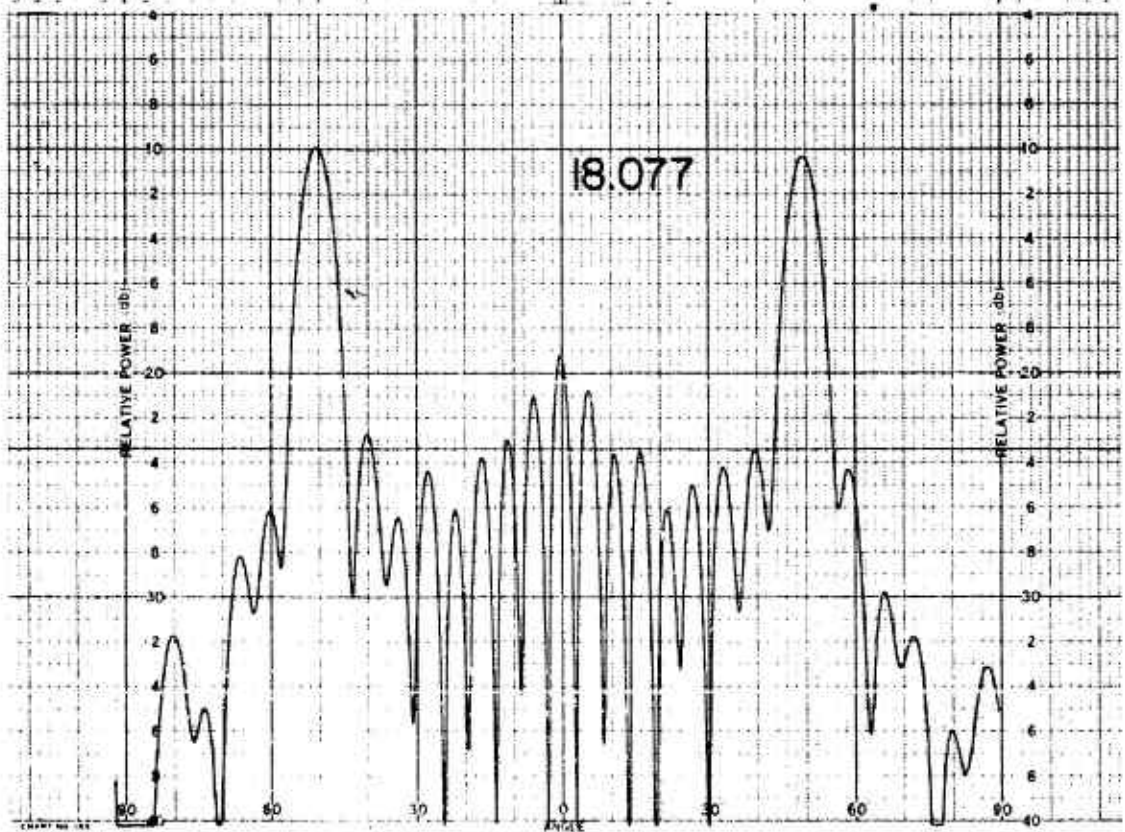
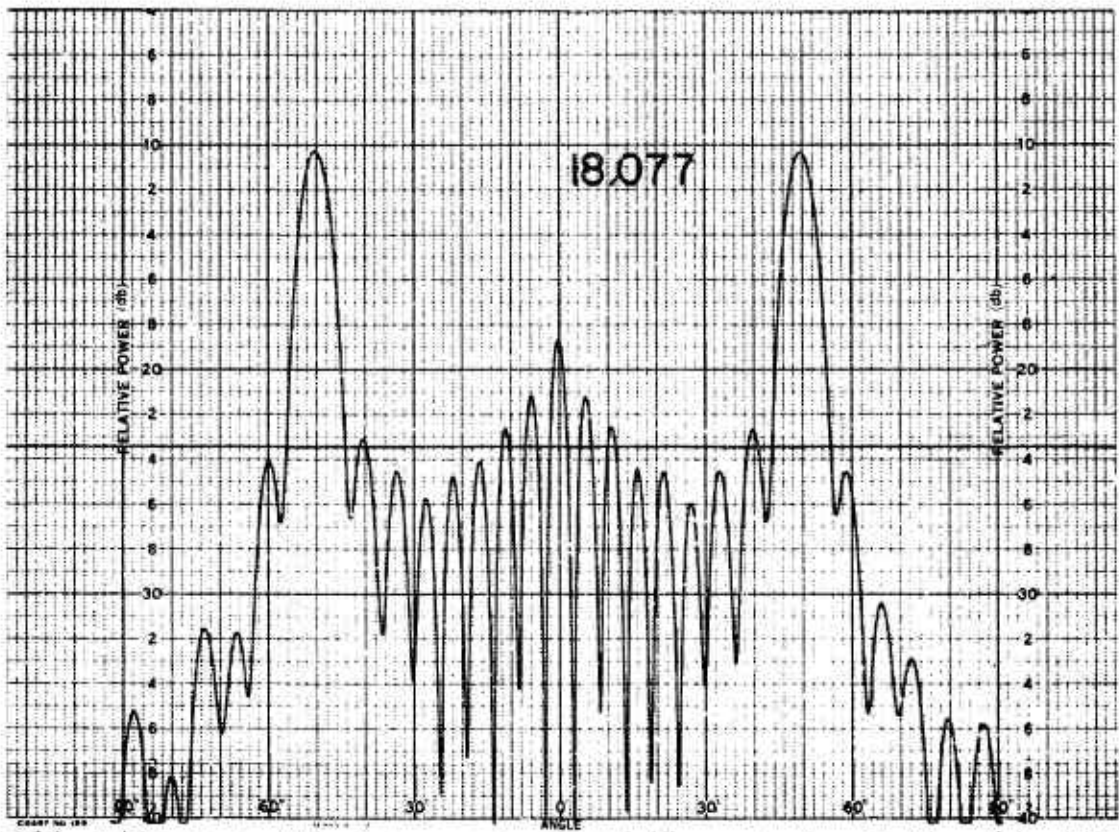
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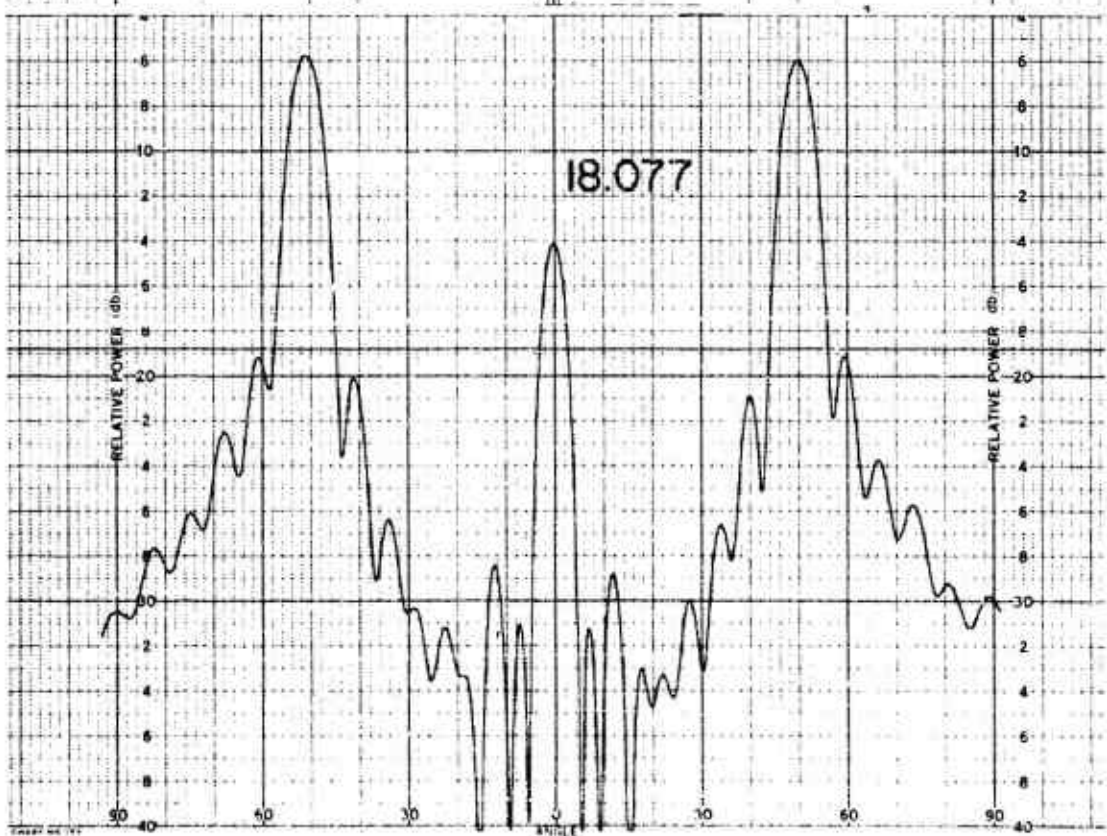
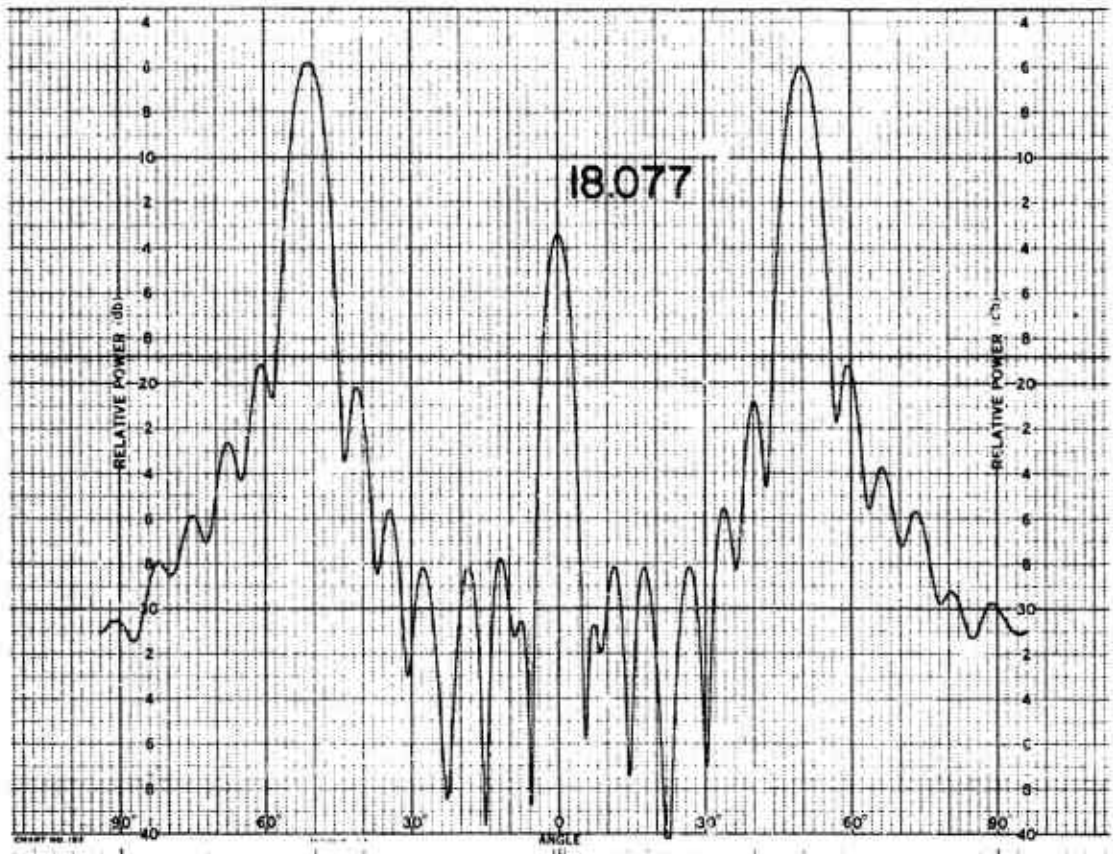
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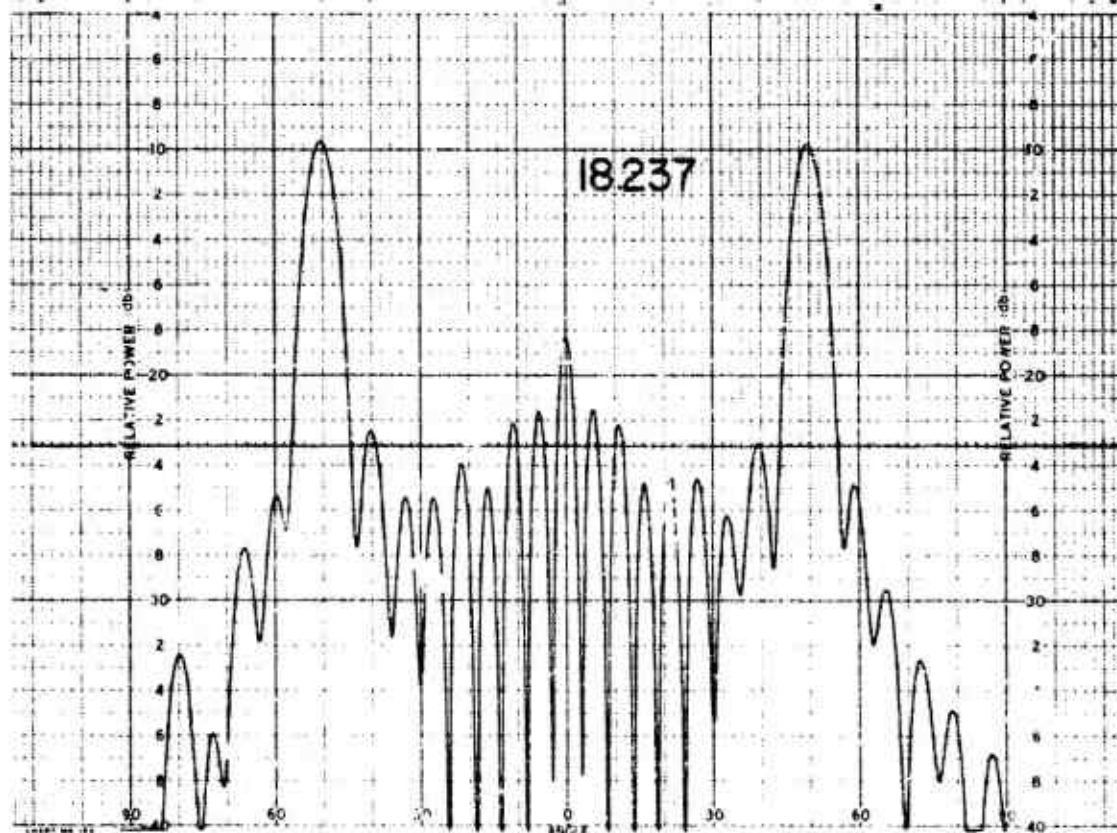
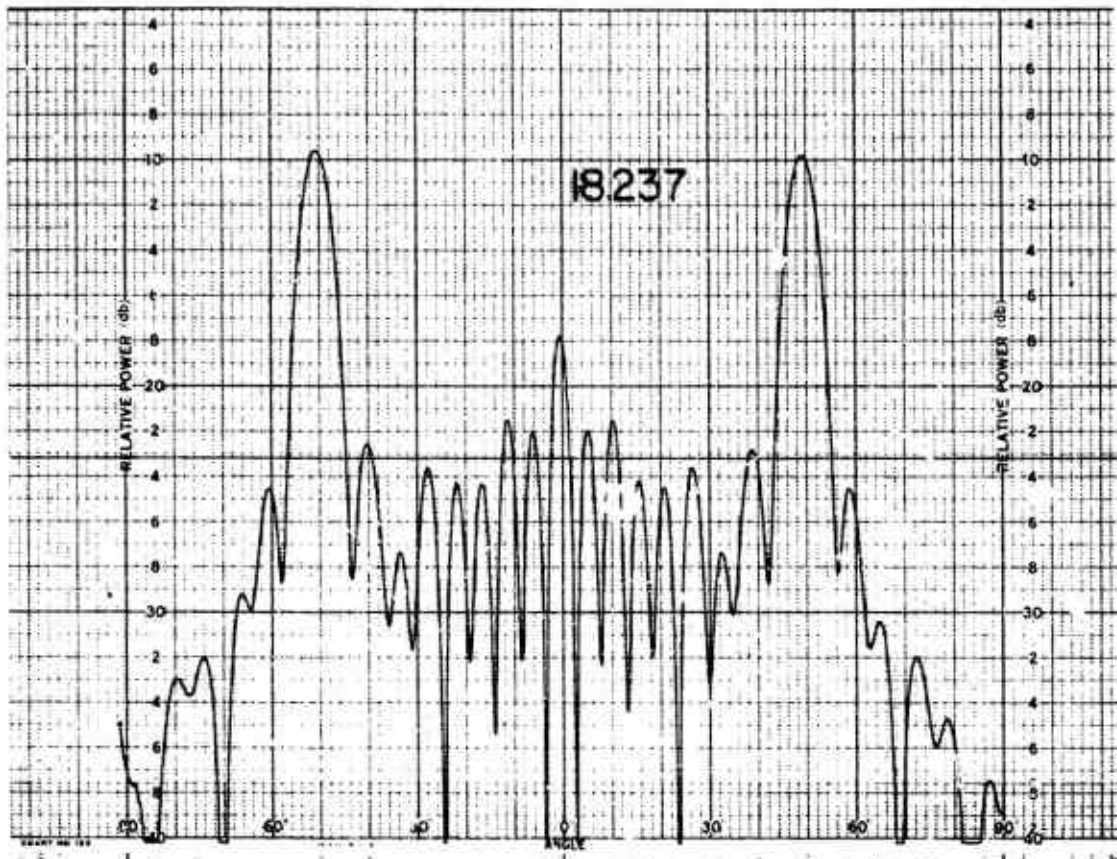
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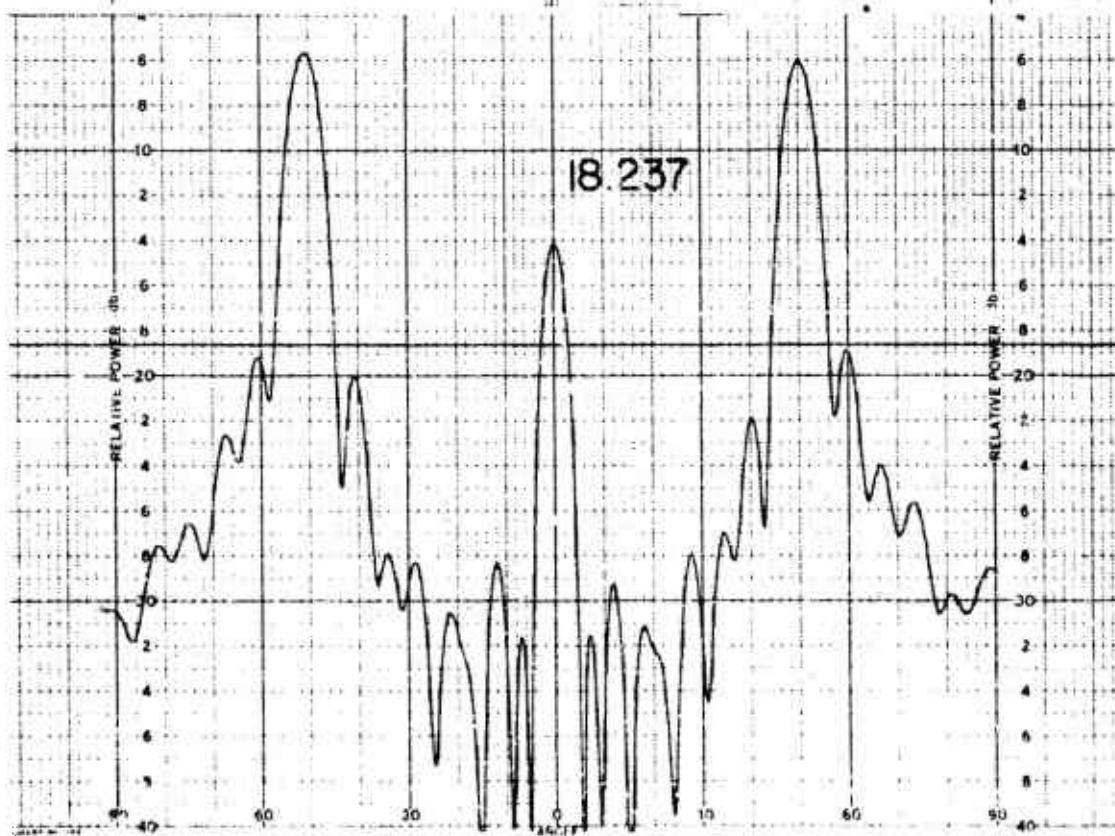
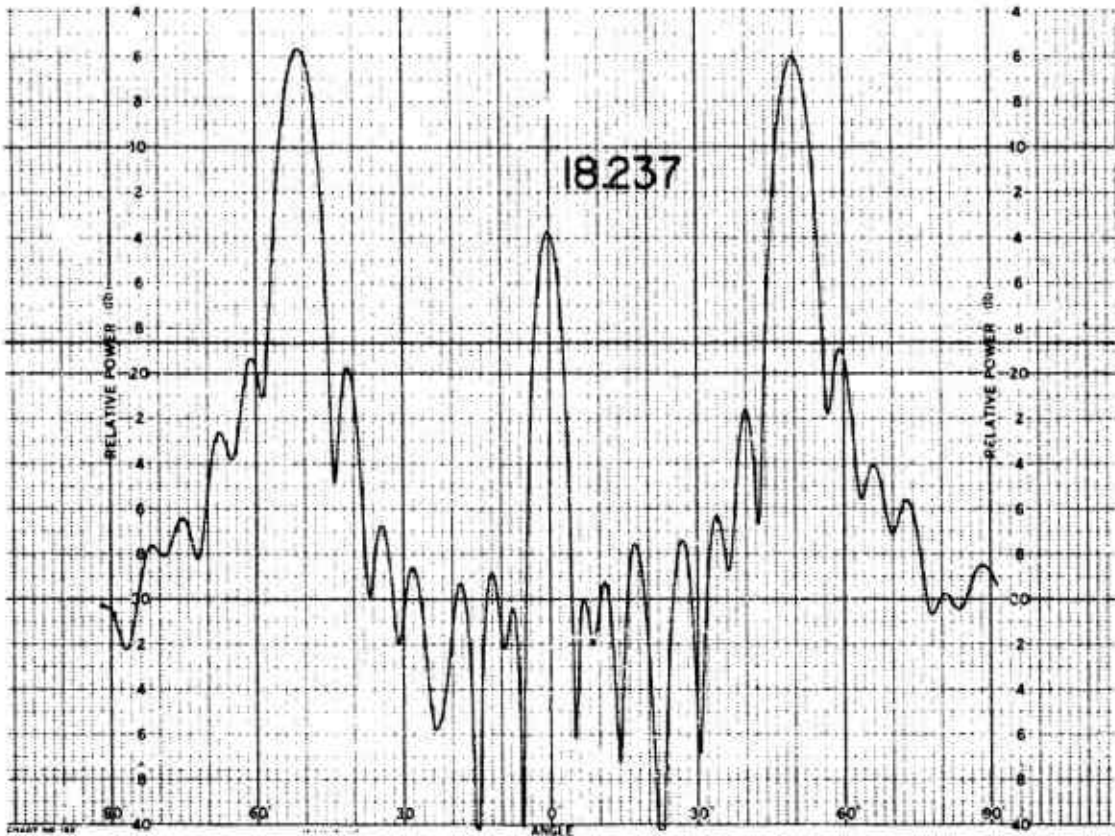
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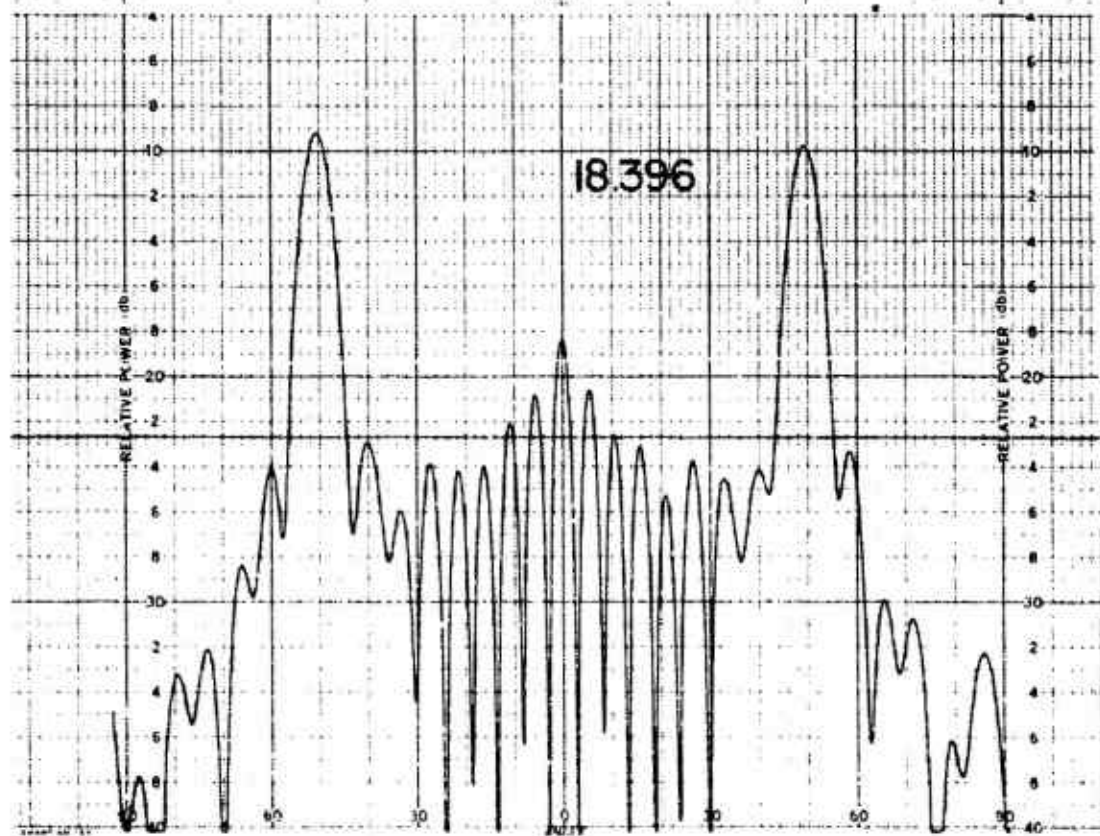
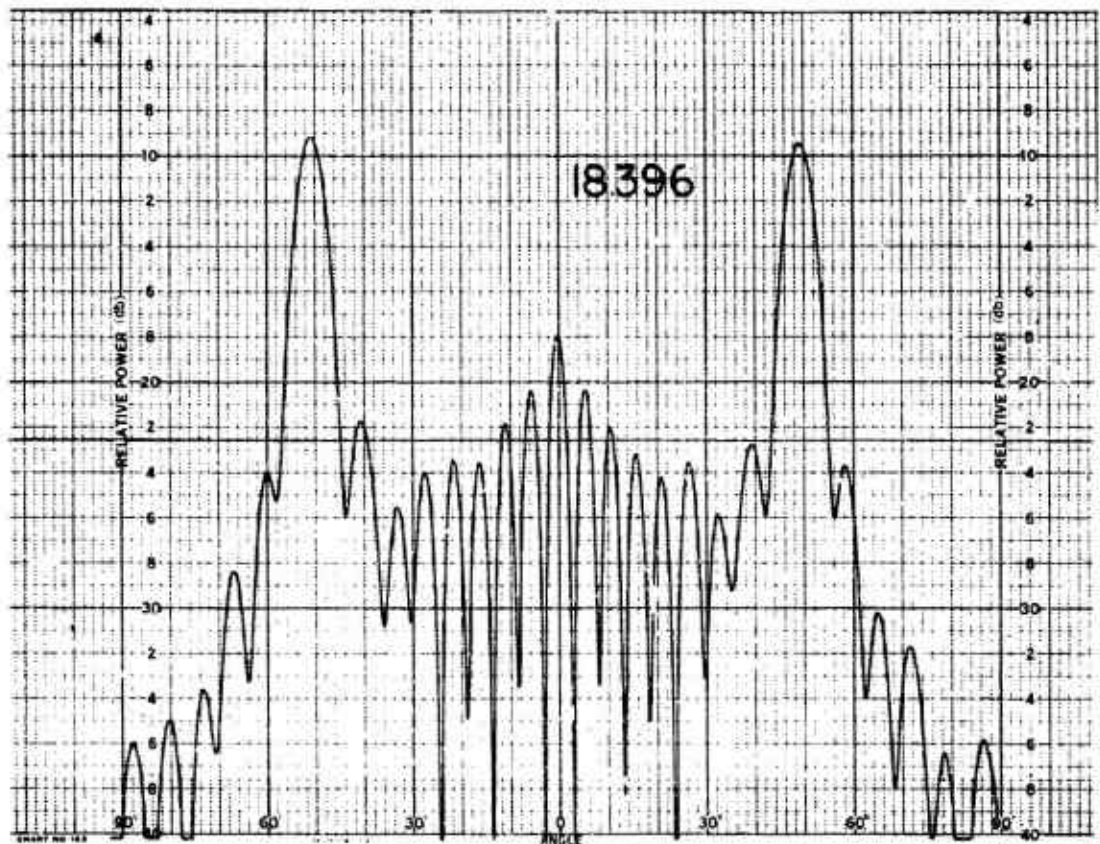
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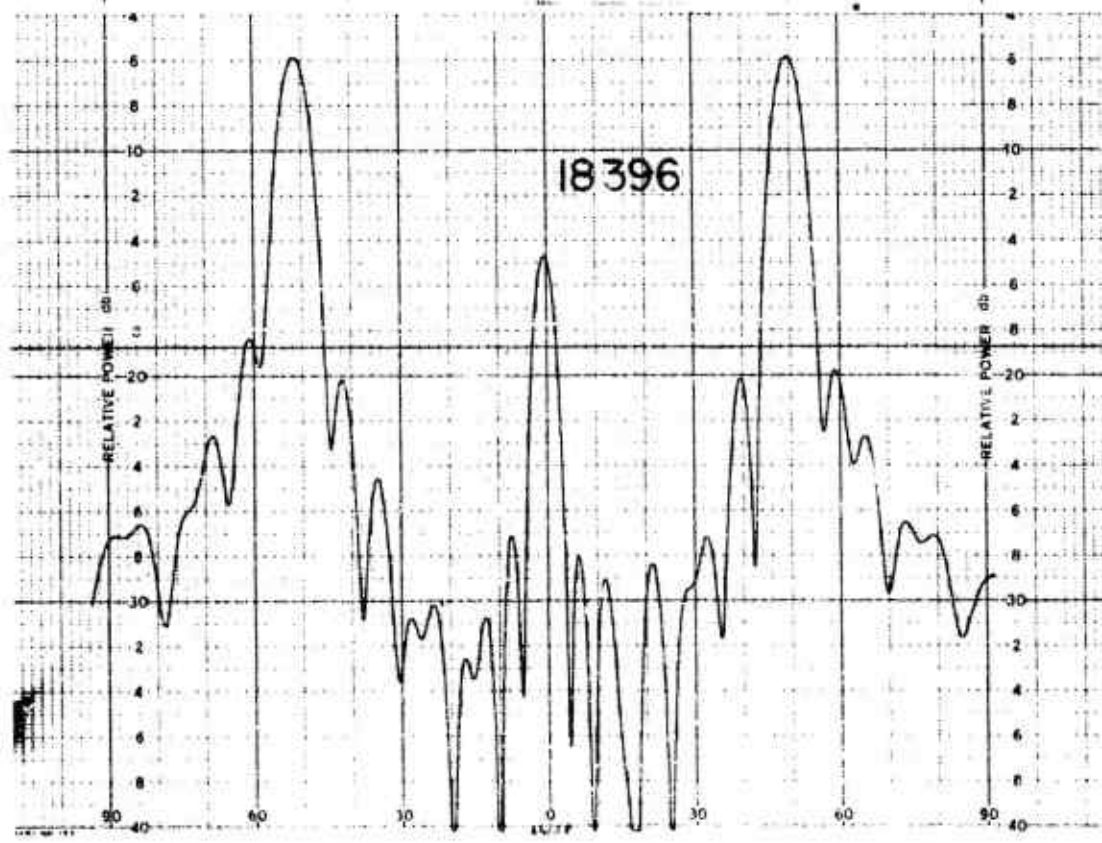
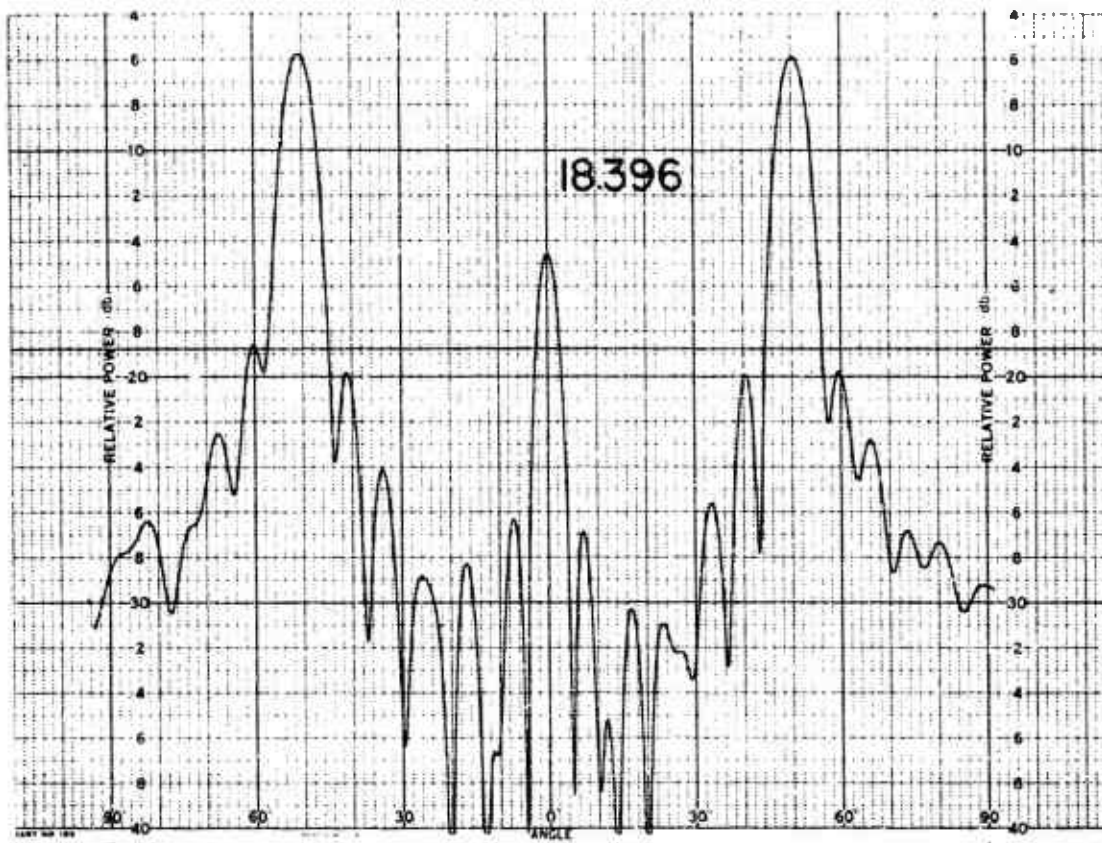
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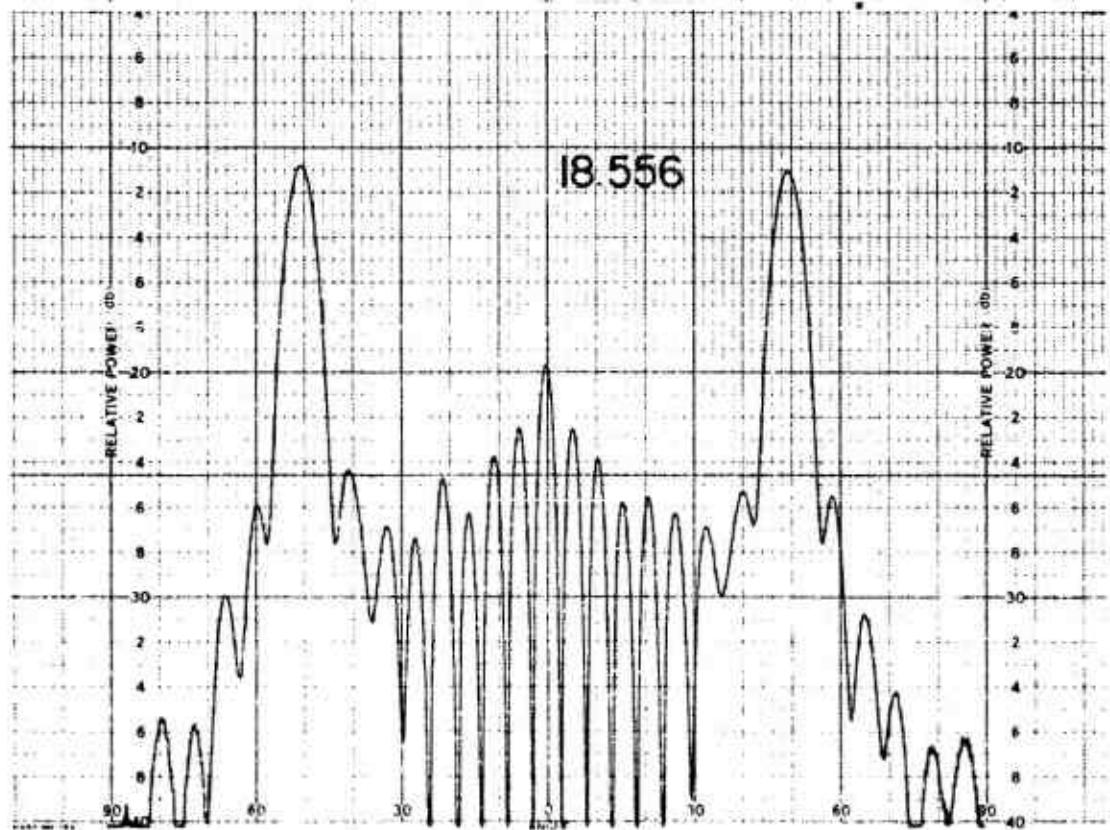
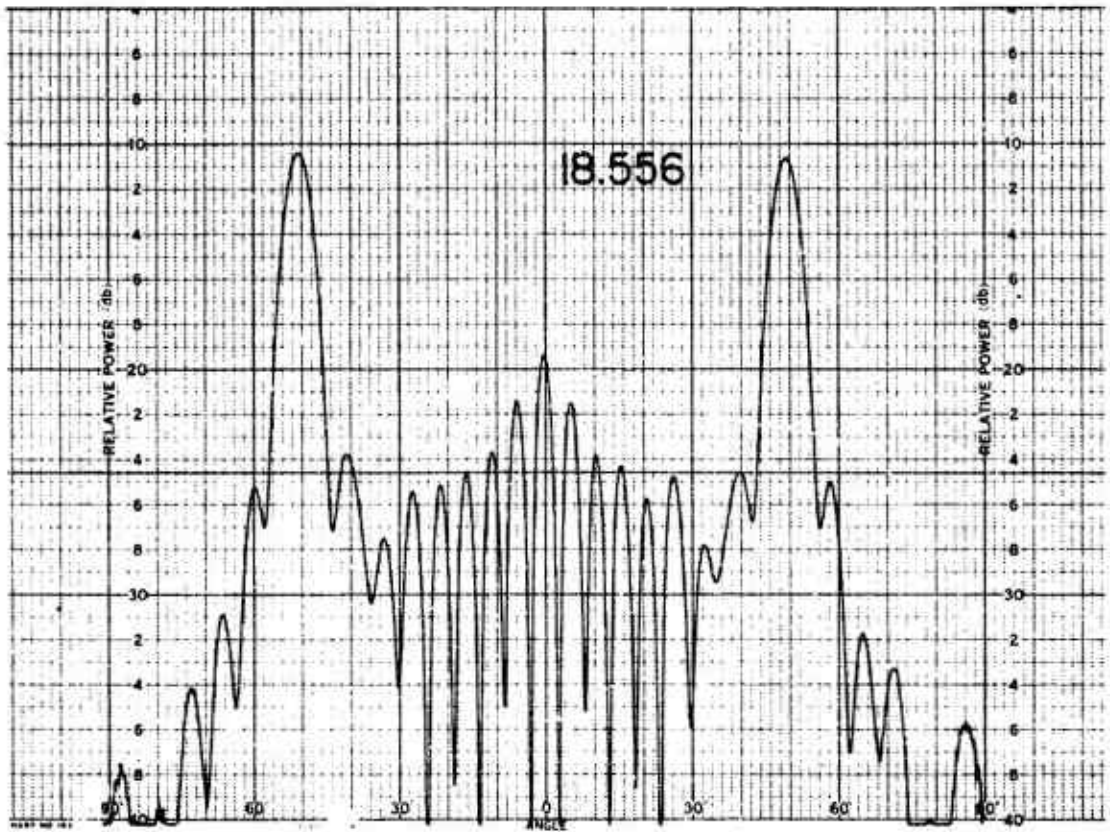
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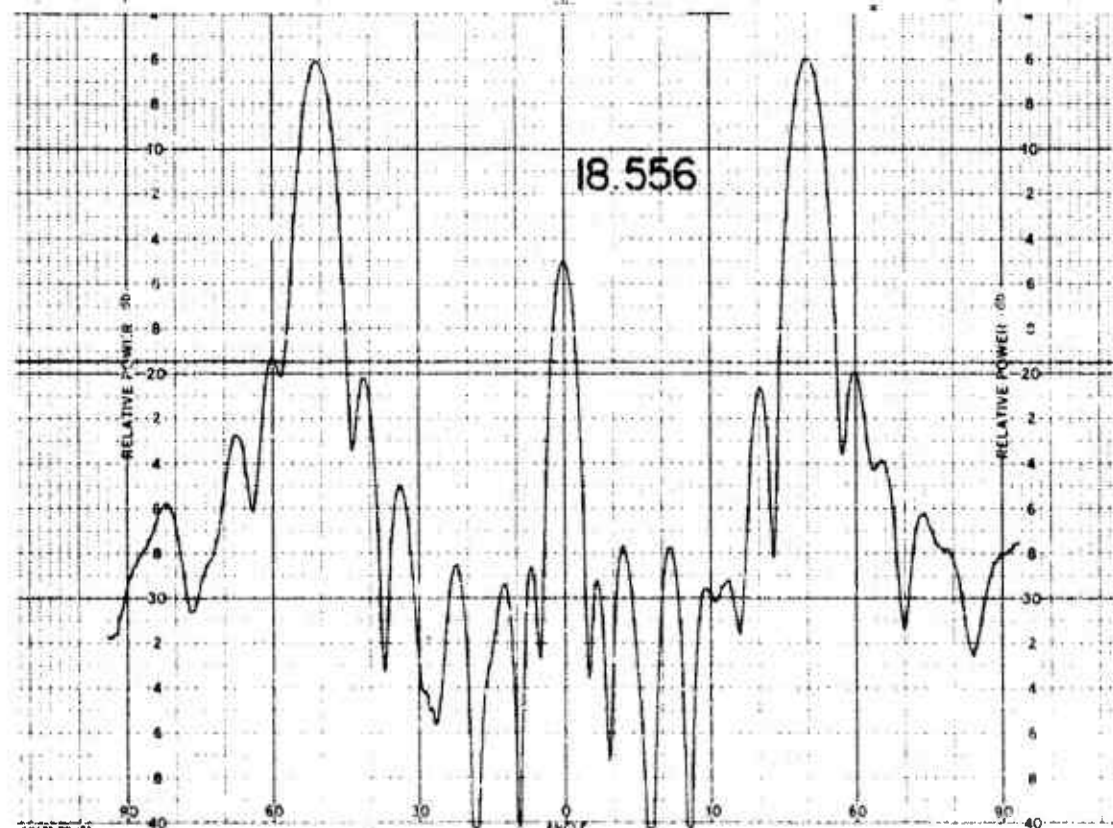
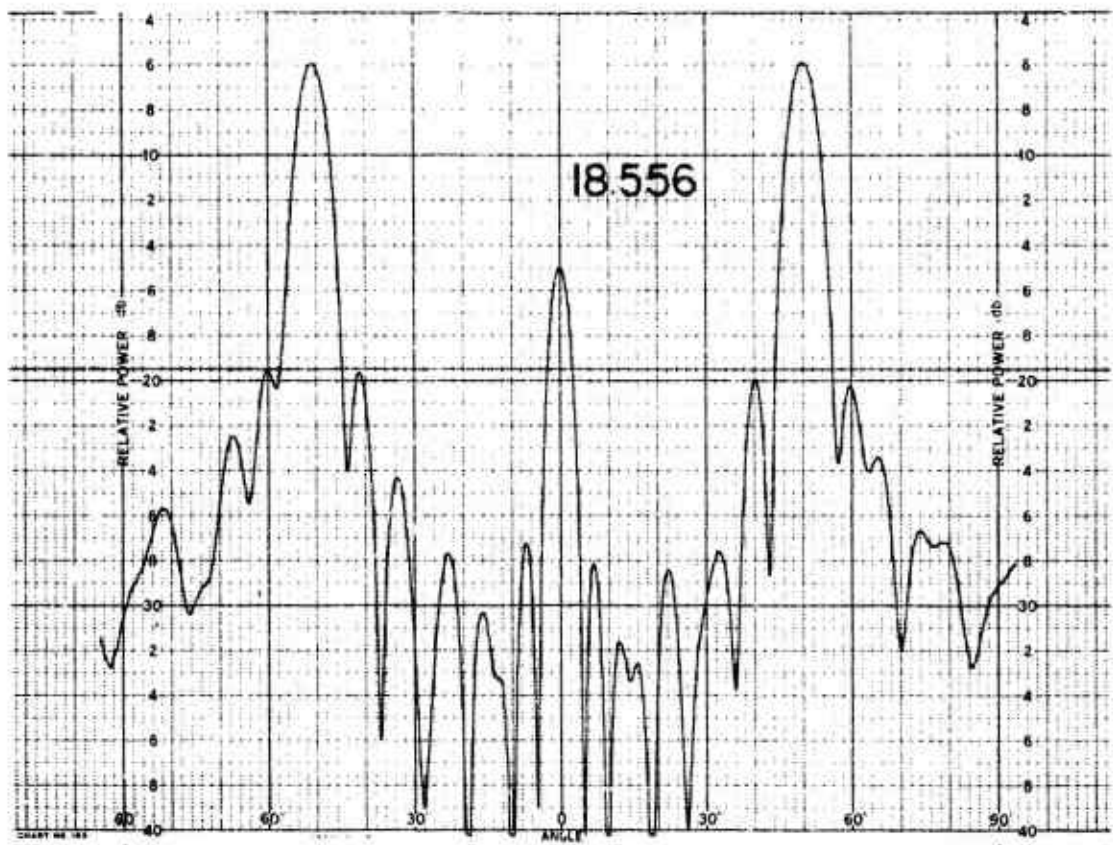
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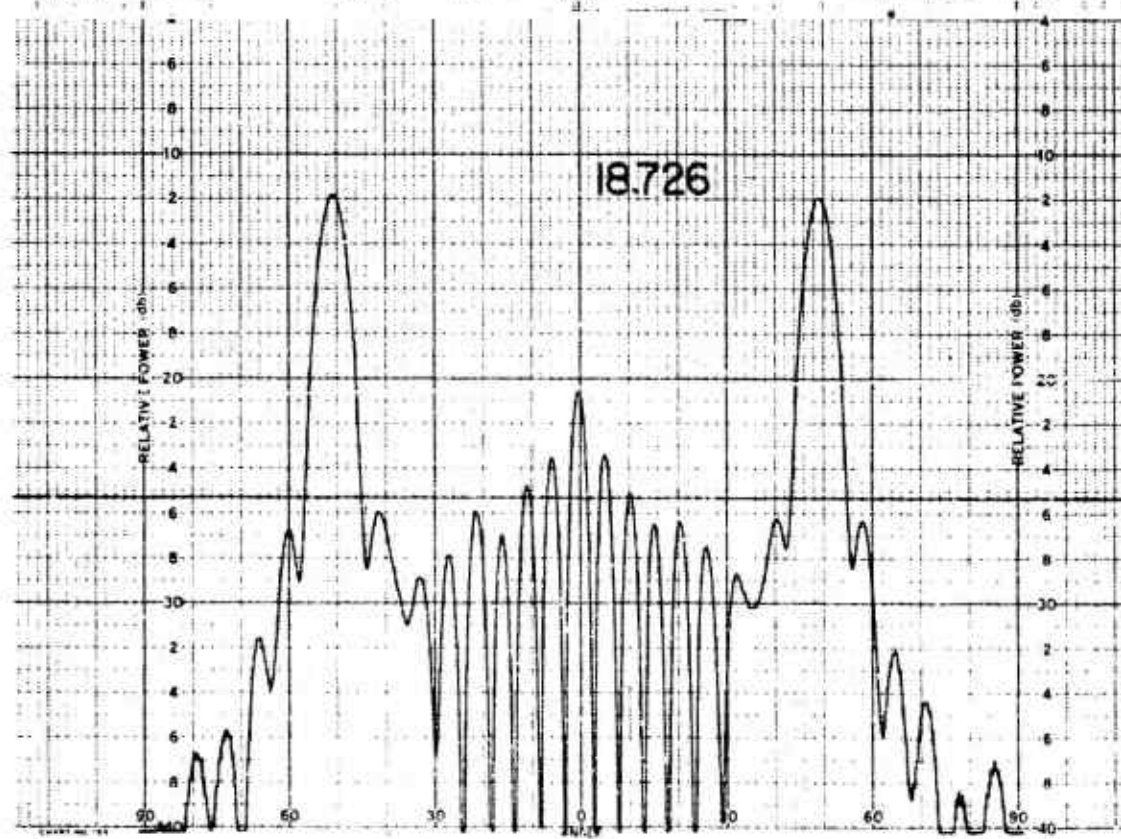
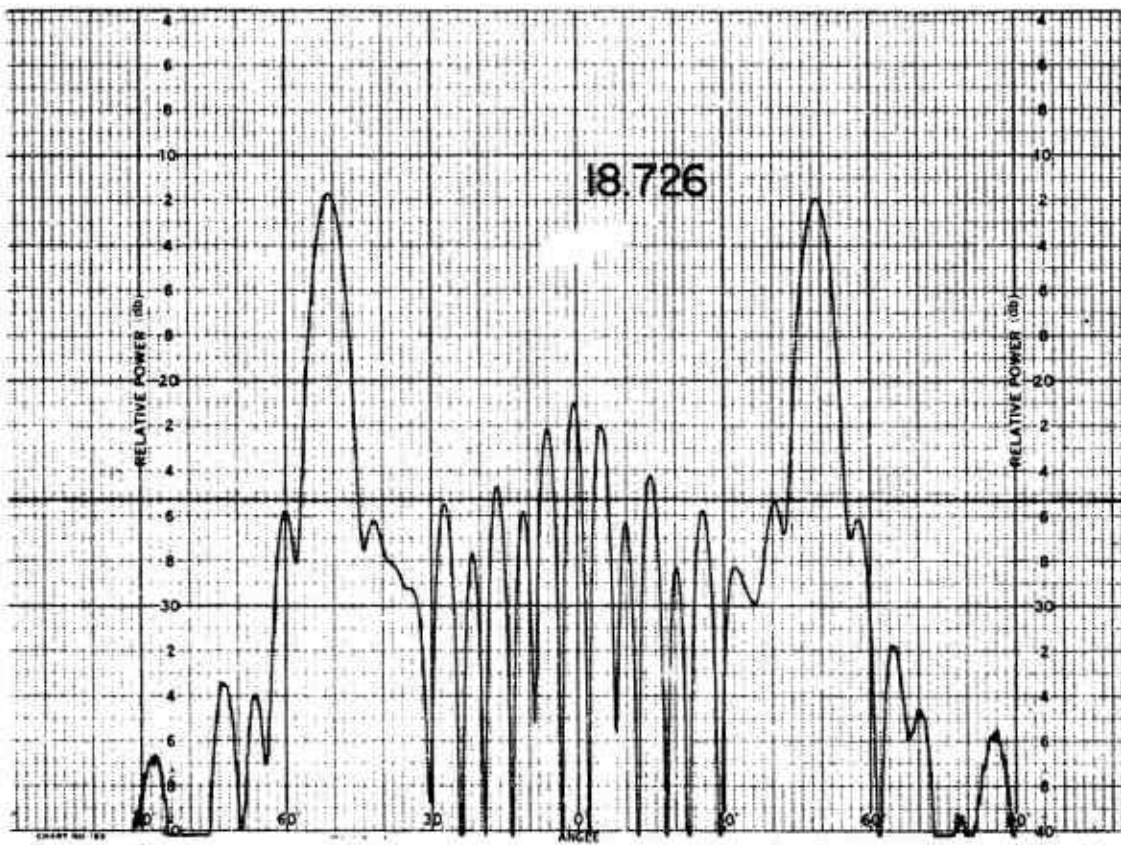
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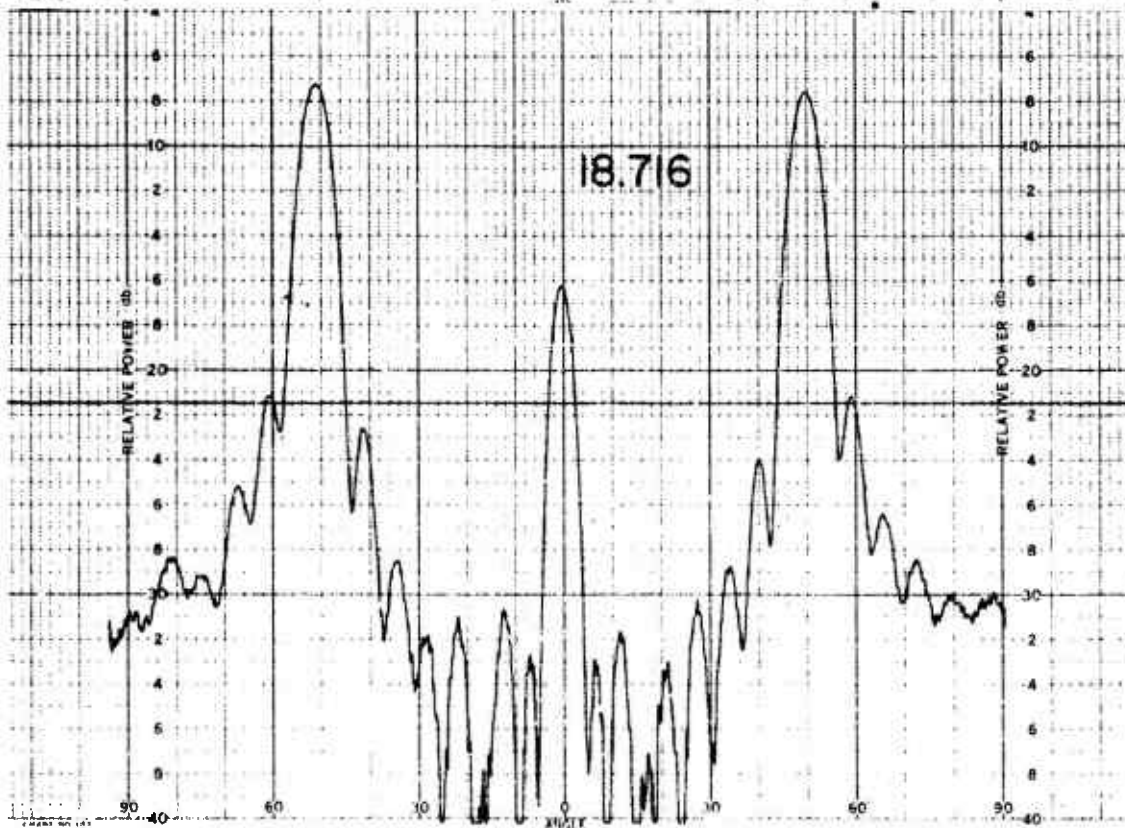
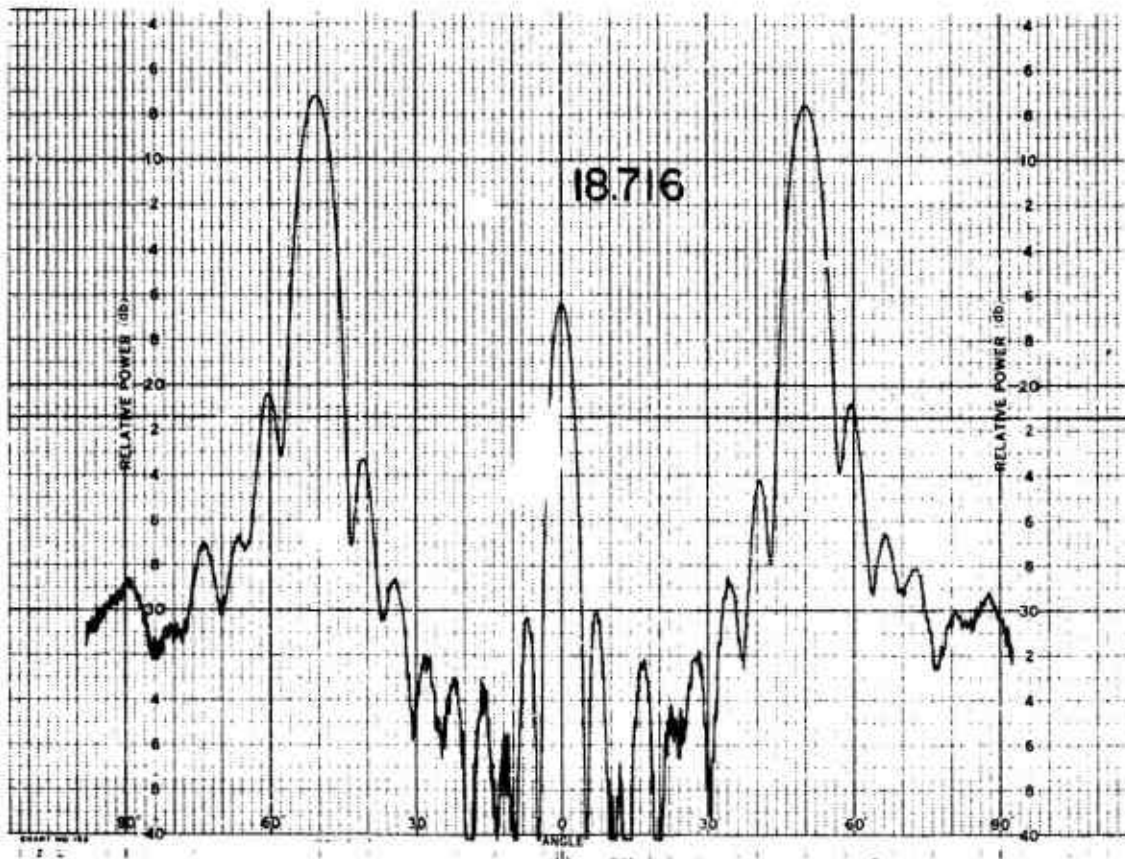
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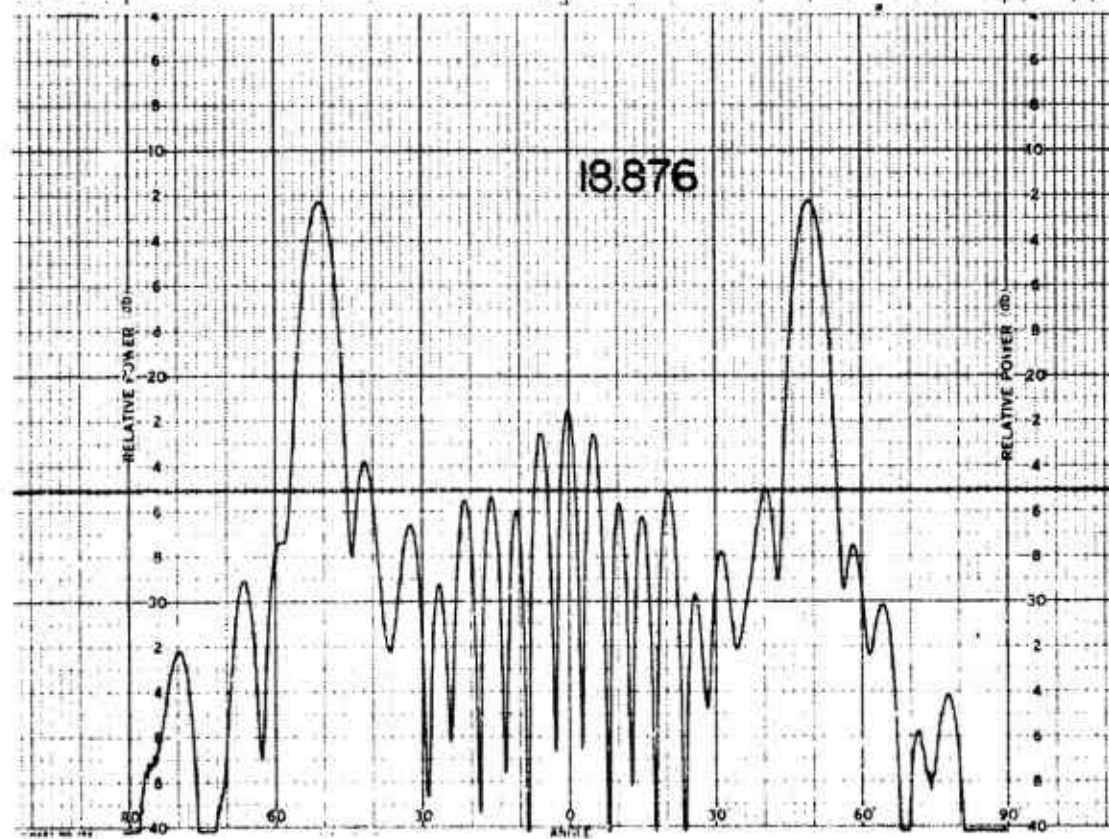
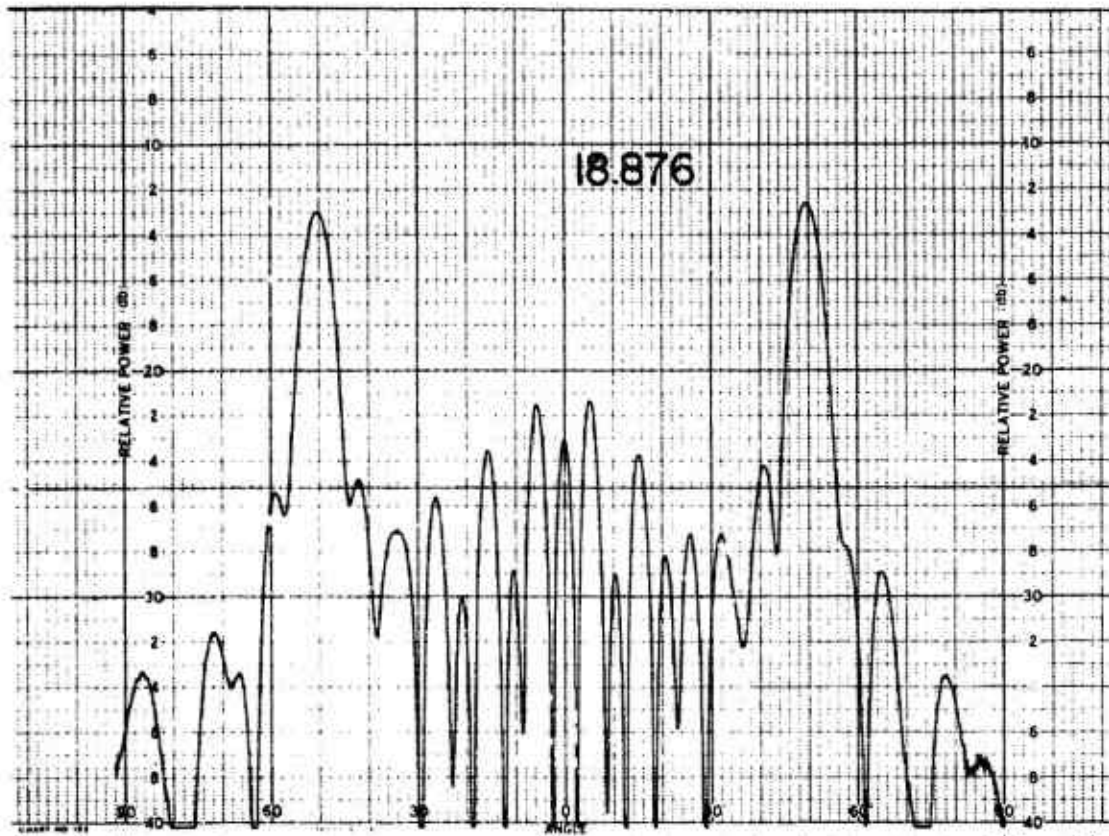
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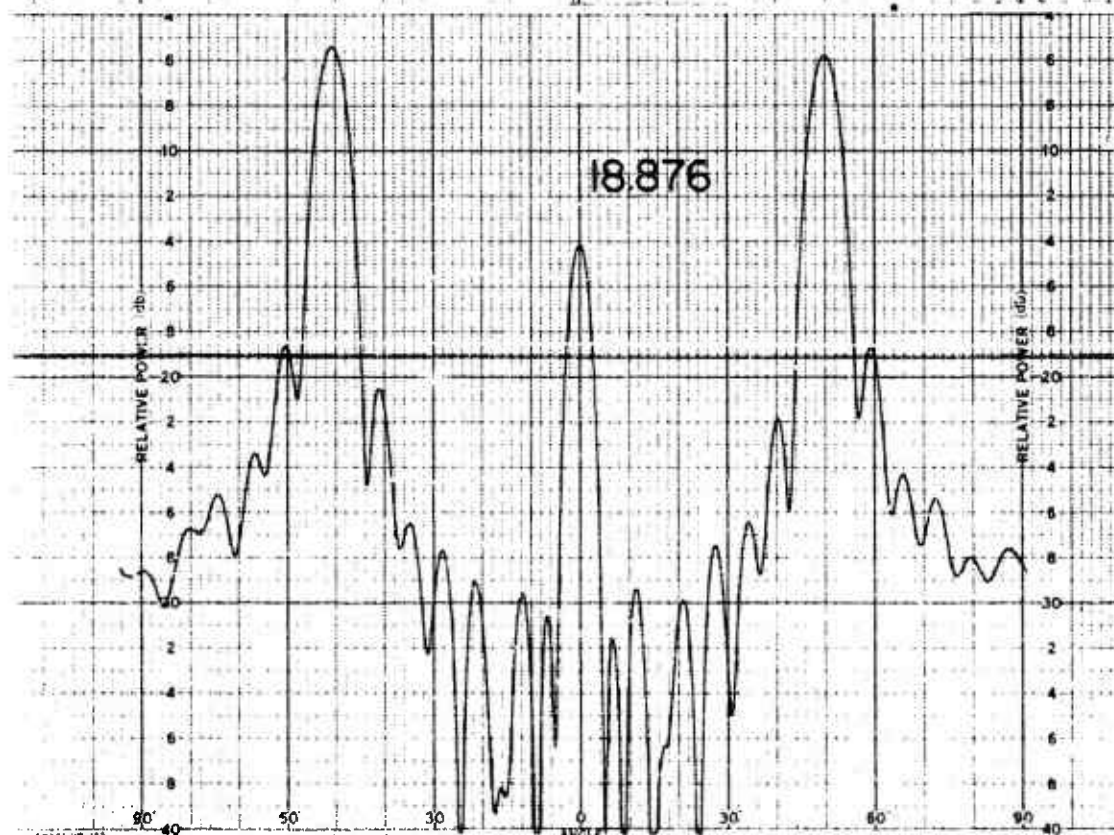
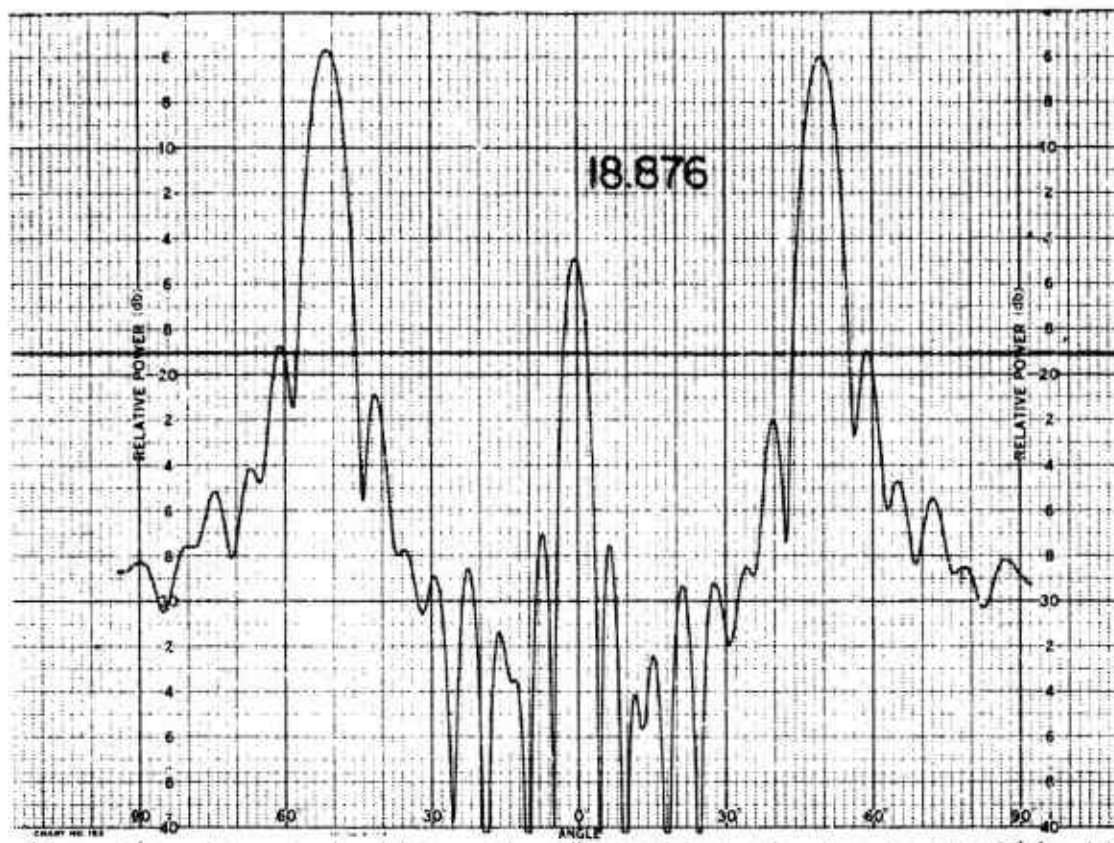
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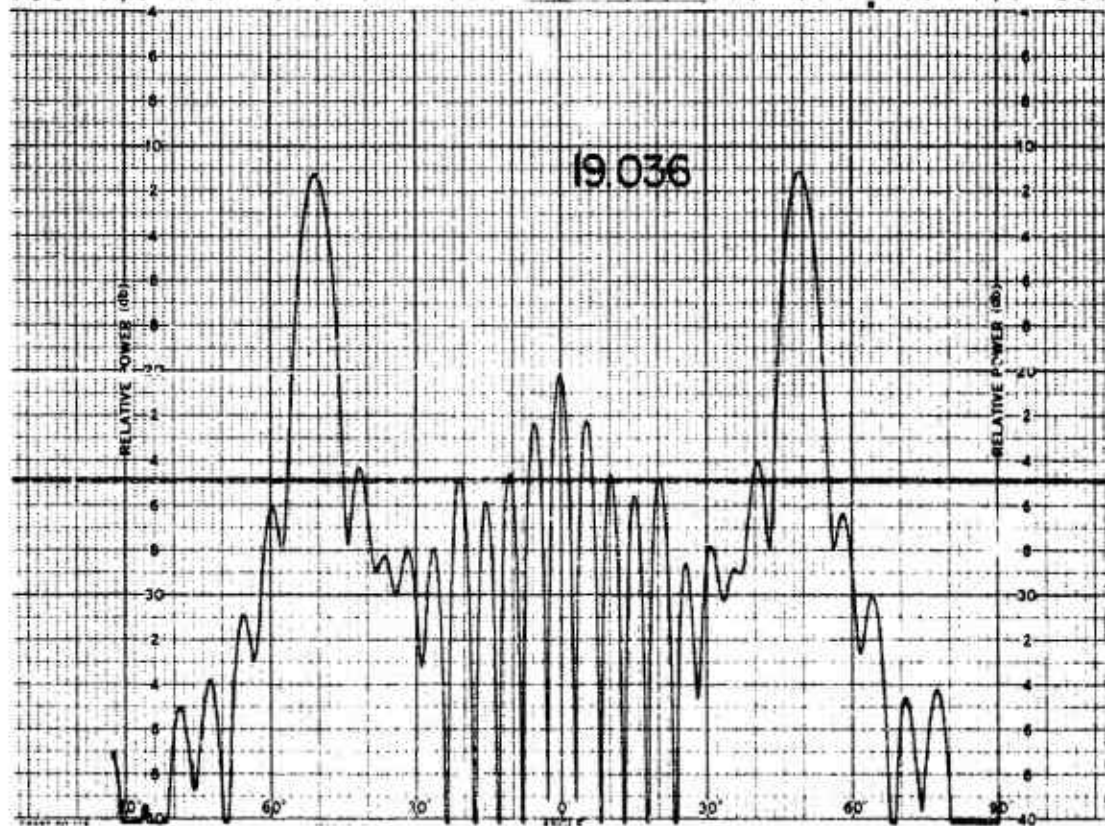
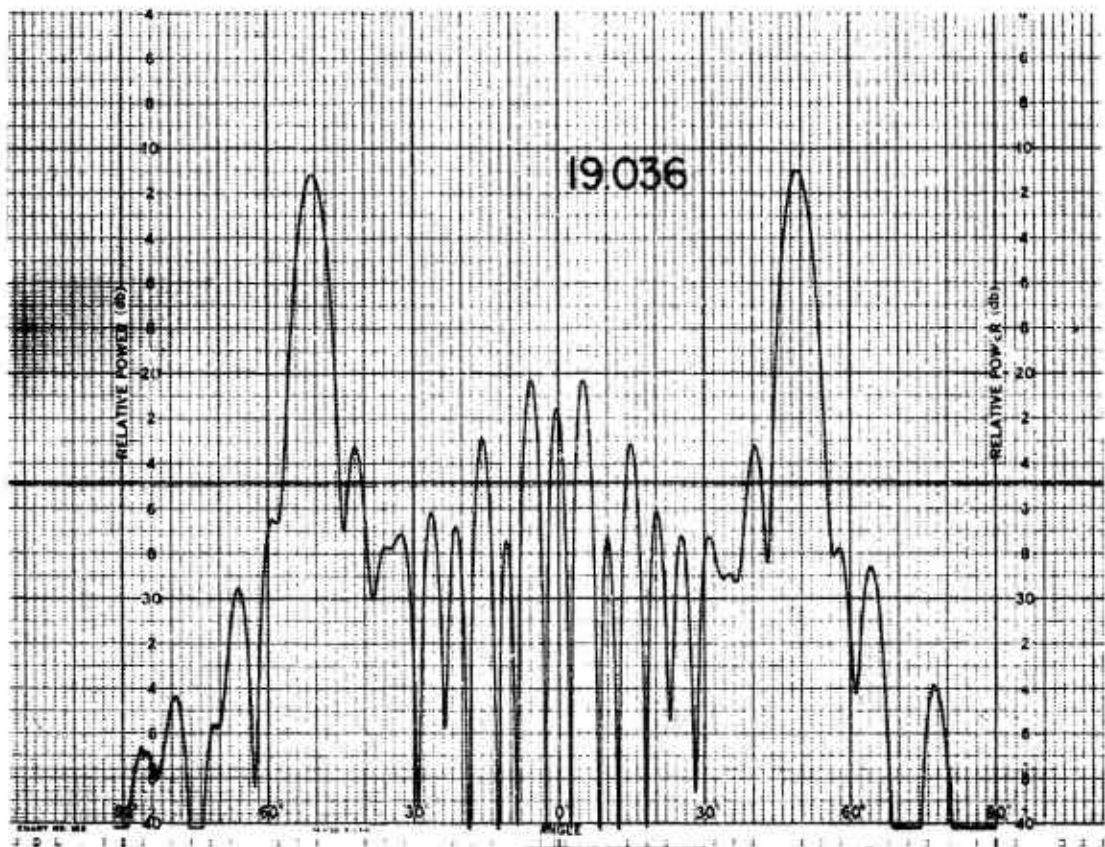
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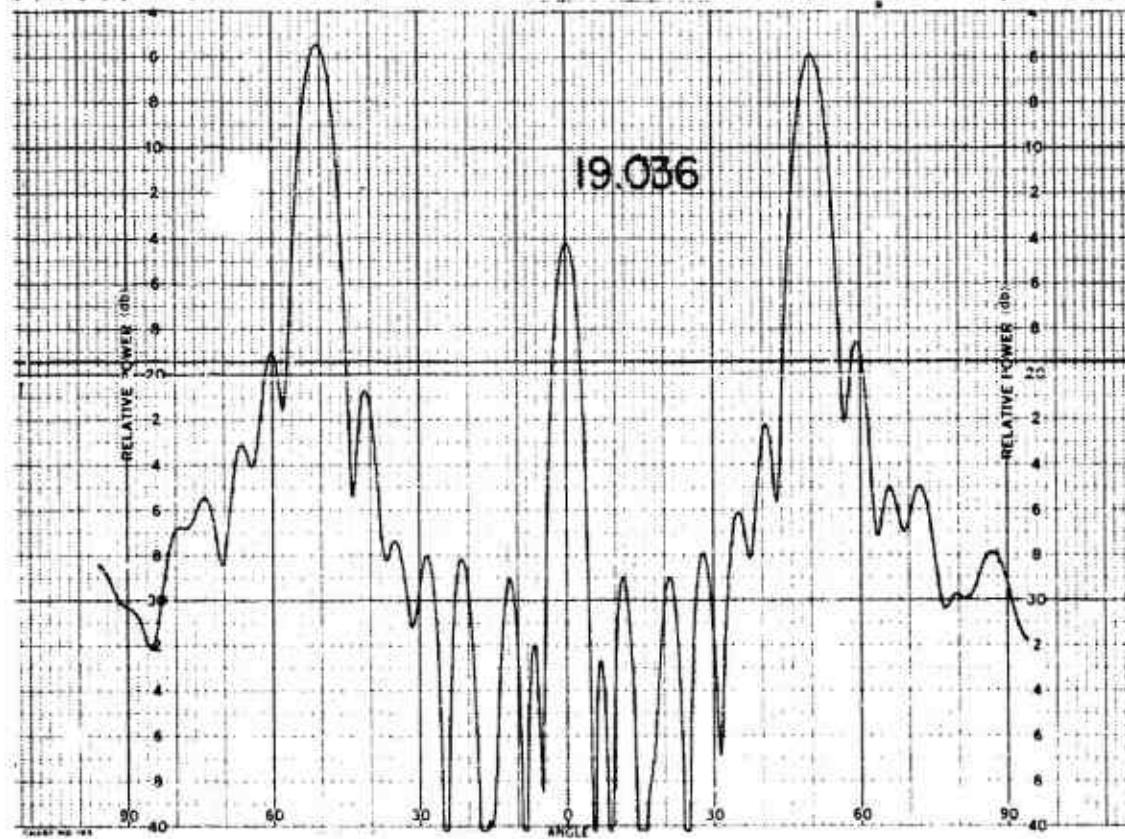
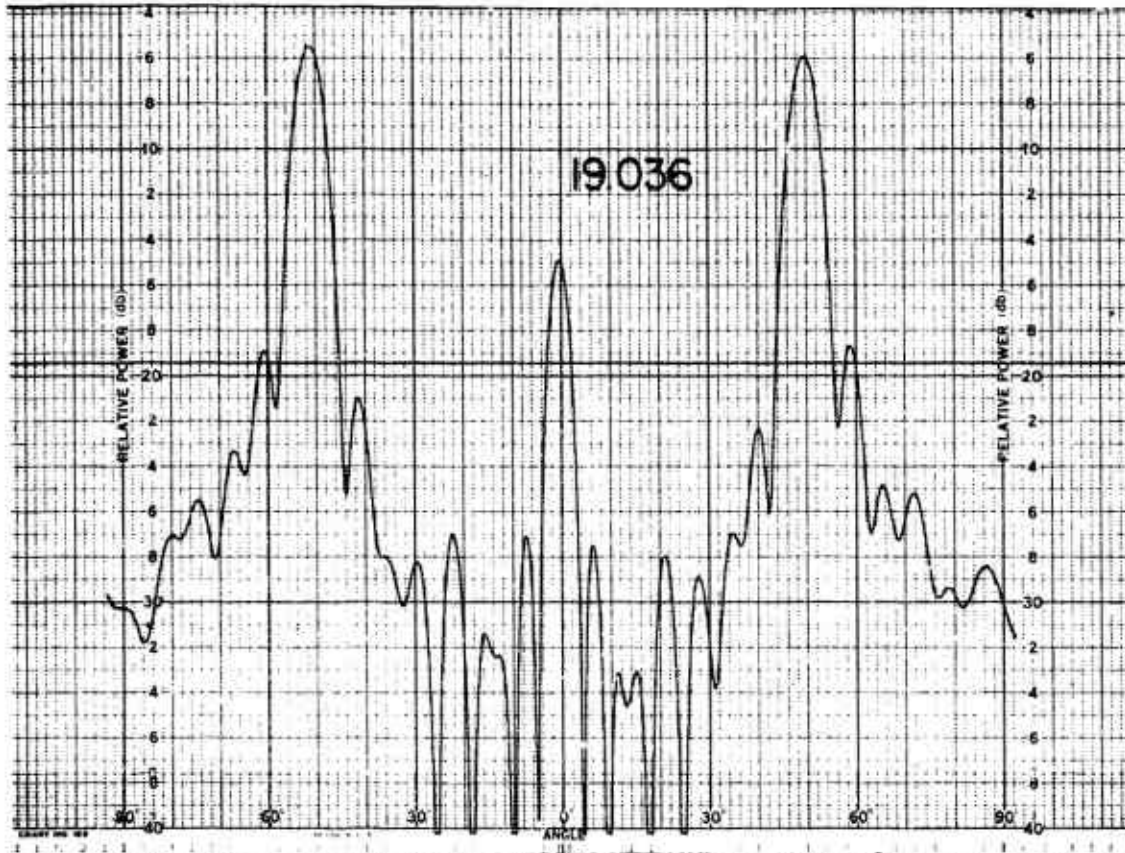
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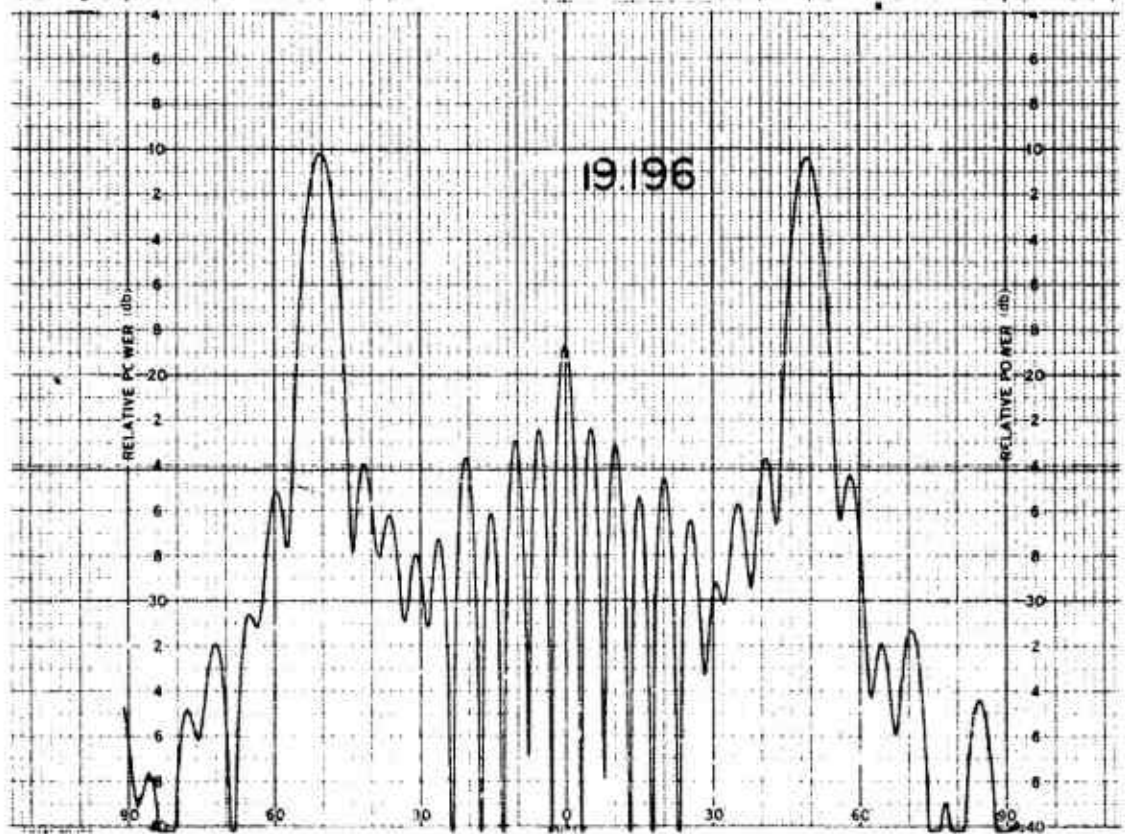
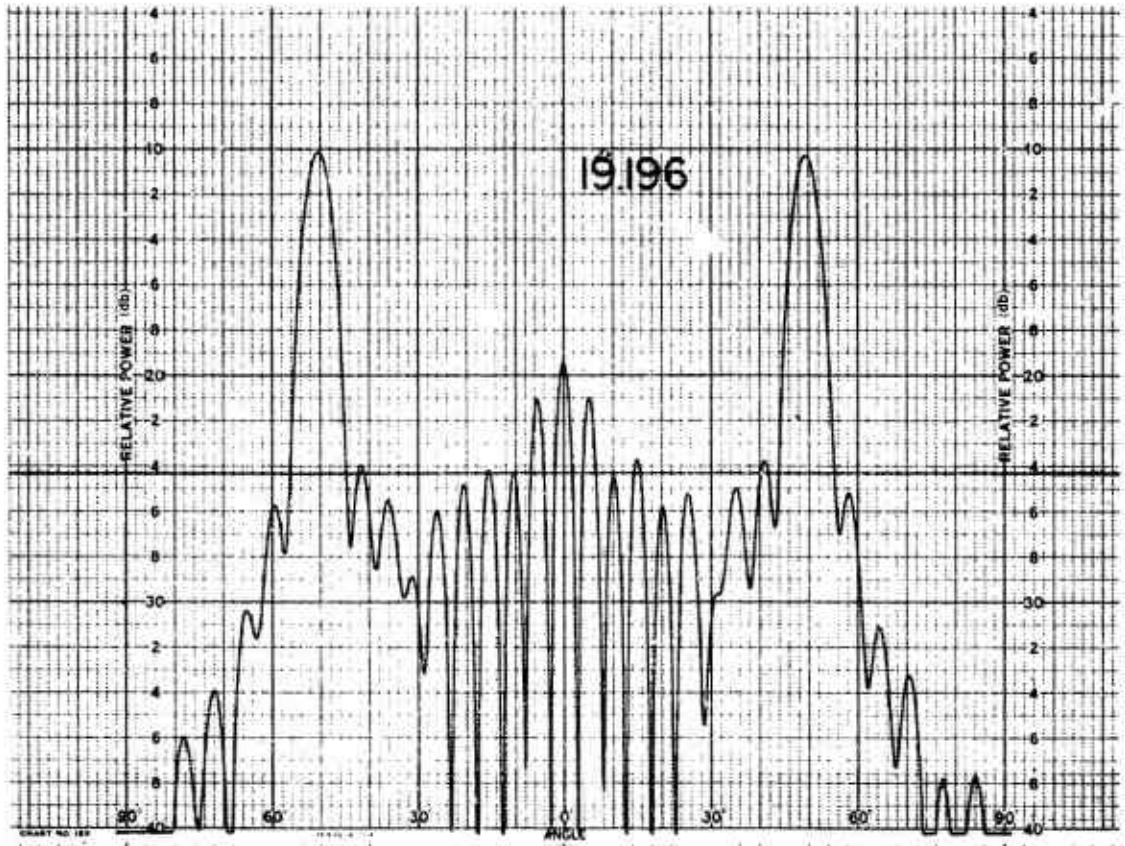
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