

CONTROL SYSTEMS LABORATORY

OPTICAL SIMULATION OF RADAR RESOLUTION

Report R-111

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ABSTRACT

It is difficult and expensive to evaluate with radar equipment the resolution required in order that a given target be detectable. In an effort to obtain this information more cheaply and easily, an optical simulator has been constructed in which the very high resolution in an optical aerial photograph has been degraded by known amounts. Portions of typical degraded photographs are included, as are the conclusions drawn from them. It is hoped that these will assist in the choice of the design parameters of future radar equipment.

I. Introduction

The ability of a radar operator to detect various ground targets on the radar display is determined primarily by the resolution of the equipment, though other factors, especially contrast, are of considerable importance. In recent years, radar resolution has improved considerably. The simple means of obtaining improvement have been rather thoroughly exploited, so that further advances will be bought at higher and higher costs. In order to avoid striving for unnecessarily good resolution, it is highly desirable that accurate data be available, which will give the radar resolution required to achieve the target detectability for which a given equipment is being designed. To obtain information of this sort from measurements on many radar sets is difficult and expensive. As an alternative, radar photographs may be simulated by degrading the resolution of optical photographs. Because this is an indirect approach, the significance of the results may be questioned. Differences in contrasts and other factors may make any numerical conclusions inaccurate, perhaps by a factor of two. Nevertheless, since the general conclusions should be correct and the numerical results approximately correct, studies of this sort should be of considerable value. Budenbom and Herriott¹ have degraded optical photographs for this

¹ B.T.L. Special Report No. 27635 (Secret)

purpose by moving the print a controlled amount during exposure, so that a point on the original is transformed into a short line. Repeating the process at right angles, the short line becomes a rectangle. This rectangle, then, is the minimum resolvable area of their simulated radar photograph.

In the present study we have repeated and extended the previous work. Our method allows us to reproduce rather accurately the intensity distribution across this minimum resolvable area, including the side lobe structure, rather than having a rectangle which cuts off abruptly at its edges.

II Procedure

A. Optical System

The method adopted for degrading the resolution of the original aerial photograph is such that a point on the original can be transformed into any desired intensity distribution on the final film, provided that an appropriate mask can be made. In order to understand this, consider first the cone of rays converging to form the image of a point source of light (Fig. 1). At a distance x from the image, the cross section of this cone is a circle of diameter $d = D \frac{x}{V}$, where D is the lens diameter and V is the image distance; i.e. it is a reduced "image" of the lens itself. If, for example, a mask with an aperture in the form of a triangle were placed next to the lens, this circle would also become a triangle. Furthermore, as a mask, one

can use a photographic film whose transmission at any point corresponds to the lobe structure of the radiation pattern from an antenna. The light distribution across d then has this same form. This mask is two dimensional of course, so that both range and azimuth patterns can be reproduced.

If the object is a photograph illuminated from the rear, it will be reproduced at d , with each point on the original being transformed into an intensity distribution corresponding to whatever range and azimuth pattern has been chosen.

If a given mask is used, the "patch size" on the degraded photograph is proportional to the distance x by which the image is defocused, so that photographs with a number of different patch sizes may be obtained with a single mask. However, these photographs will all be of different sizes. In order to keep them all on the same scale (1:1 magnification), the object distance must also be varied, so that a modified equation for d results:

$$d = D \left(2 - \frac{u}{f} \right), \text{ where } f \text{ is the focal length}$$

of the lens and u is the object distance.

This theory assumes simple geometrical optics and thus neglects the wave character of light. The defocused image at d is really a Fresnel diffraction pattern. Under some conditions the "image" of a line shows doubling caused by the Fresnel diffraction peaks. This effect cannot be eliminated, but it can be reduced to the point where it is not noticed. Note that in the above equation either D

or u can be varied to obtain a desired d . For a given d , there exists a pair of values, D and u , such that diffraction effects are a minimum. The equations giving this minimum are too complicated to solve by ordinary procedures. However, it is not difficult experimentally to choose values of D and u so that the diffraction does not cause objectionable effects, provided that the two dimensions of the patch are not too different.

B. The Masks

The simplest mask to construct consists merely of four sheets of thin metal taped to a support. These sheets can be placed so as to define a rectangular hole of any desired dimensions. The patch defined by such a mask has sharp edges as in Budenbom's case. Radar sets, however, do not produce this sort of response. The more or less square pulse generated by the transmitter is stretched out and rounded by all subsequent processing, so that in the final display it has the general shape of a Gaussian distribution. In the azimuth direction, there is a rounded main lobe with weaker side lobes on either side. This pattern for a simple untapered antenna (two-way) is of the familiar form, $\sin^2 \theta / \theta^2$. This also is the form of the light intensity distribution in the Fraunhofer diffraction pattern of a single slit. To produce a mask which simulates the radar antenna pattern then, it is merely necessary to photograph this diffraction pattern, being careful to minimize photographic distortion, and then to enlarge this photograph to appropriate dimensions.

In general, radar antennae are designed to have other patterns, usually the effort being to reduce the side lobes with the attendant broadening of the main lobe. These changes may be approximated by distorting the diffraction mask. A variety of techniques may be used. For example, side lobes can be eliminated simply by masking them off or, the side lobes can be intensified easily by making a weak negative of the diffraction pattern with only the main lobe showing and then superimposing this on the diffraction pattern. A correspondingly longer exposure time is required in making the degraded photographs so that the relative exposure for side lobes is increased.

For the mask for the range dimension we have used the same diffraction pattern with the side lobes masked off. This has the right general shape and should be a sufficiently good approximation for most radar sets.

Since this work has been completed, new methods of making masks of arbitrary density distributions in either coordinate or with circular symmetry have been developed².

C. The Photographic Mosaic

The degraded photograph obtained by this method could be made to match a radar photograph accurately if the transmittance

² Myers, John J., Optical Simulation of Antenna Images, Report No. R-109, Control Systems Laboratory, University of Illinois, Urbana, Illinois.

at any point on the original film were proportional to the radiation reflected to the radar by the corresponding point on the ground (assuming that the nonlinearities in the two systems are the same). However, the following important differences exist:

1. Microwave and optical reflectivities differ, so that various targets do not have the same relative intensities. A metal bridge, for example, would appear the same to the radar whether painted black or white.
2. Shadowing differs, since radar targets are illuminated by the radar itself, so that long shadows are thrown. Whereas, optical survey photographs are usually made vertically downwards, with a high sun for illumination, so that shadowing is small.
3. Limited dynamic range affects the two processes differently. In the radar, the complete return from the antenna pattern is combined linearly in the antenna before the signal is limited in the receiver or video amplifier. The return from a strong target may be perhaps 10^4 times as strong as that from its neighbors, so that its side lobes overwhelm the other returns. An identical effect occurs in the photography, but the side lobes involved this time are the minute diffraction rings introduced by the original camera lens, not the artificial side lobes introduced by this simulator. If the original photograph used in the simulator is a paper print, reflectance variations

of only about 10:1 are obtainable. A transparency on film is better, with a range of up to perhaps 300:1 being possible. This produces limiting in the simulator before side lobes are added, which means that very strong targets do not exist on the photograph to force through their side lobes. We partially compensate for this by making the side lobes on our masks much stronger than they would ever be from a radar antenna.

In order to maintain as large a dynamic range as possible we used, for our mosaic, positive transparencies of aerial photographs made from the original negatives and not from prints. From these we made negatives on stripping film. These negatives were stripped and assembled on a large sheet of plate glass. This was diffusely illuminated from the rear and rephotographed onto the 4" x 5" film which we used as our original. (There are rather large variations in background density in this mosaic. However, because of the time and expense required, it was not remade.) On our original the transmittance varied by a factor of about 100:1, much less than the variation of the original scene, but better than the 10:1 we had with an earlier mosaic made from paper prints.

In a radar photograph, the patch size in the azimuth direction is proportional to range, whereas our optical photographs have a patch which is independent of range. This difference does no harm; actually it makes it easier for us to interpret our

photographs.

The mosaic covers an area approximately 16 x 20 miles in St. Louis and vicinity.

D. The Photographs

We made photographs with patch dimensions chosen to give answers to the following questions:

1. With a square patch (i.e., equal range and azimuth resolutions) how small must the patch be for specific targets to be recognized? To answer this question, patches from 50 feet square to 1600 feet square were used. In Figure 2 a portion of the mosaic, including Lambert Field, is shown, degraded in this manner.

2. How is the above result affected by the addition of side lobes to the azimuth dimension of the patch? For this, 10 o/o and 30 o/o side lobes were added for patches from 50 feet square to 800 feet square, where a 10 o/o side lobe means that the transmission of the mask at the center of the first side lobe is 10 o/o of what it is at the center of the main lobe. Because of limiting in the photographic film as discussed above, the effect of 10 o/o side lobes here is less than it would be in an actual radar. Figure 3 illustrates the effect of these side lobes.

3. How is the target detectability affected if the patch is not square? For the answer, patch sizes of 400 x 400 feet and 200 x 800 feet were compared in Figure 4.

4. Assuming azimuth resolution cannot be improved, at what point does improving range resolution cease to pay? For this test, a series with an 800 foot azimuth dimension, and with 1600, 800, 400 and 200 foot range dimensions were compared in Figure 5.

For convenience, patch size was measured between the first zeros on either side of the main lobe.

III Results and Conclusions

Evaluation of a series of photographs such as these is difficult because of the personal judgments involved. For our first attempt we chose ten objects in known locations, including airports, bridges, and point, line, and area targets. These were rated by three observers on a 0 to 4 basis as follows:

- 4 - Target sharp and easily identified.
- 3 - Target somewhat fuzzy but still easily identified.
- 2 - Target detail lost but target still identifiable.
- 1 - Target can be picked out, but not without knowing its exact location.
- 0 - Target lost.

The judgments concerning any one target were too variable to be statistically significant. However, an average for all ten

targets (i.e., an average of 30 judgments) gave a significant "average target detectability," which is plotted on a semilog scale in Figure 6. From this test we can draw several qualitative conclusions:

1. Strong side lobes are necessary to make a clearly defined degradation by this technique, again because of limiting before, rather than after, the summing of the total signal return.

2. An airport can be picked out even though the width of the patch is twice as great as the width of the runway.

3. A square patch is decidedly superior to a rectangular patch of the same area.

4. With one patch dimension fixed, target detectability improves as the other dimension is decreased, down to the point where the second dimension is half the first. Beyond that point there is little if any gain; perhaps there is even a loss.

5. The fact that the target detectability falls off exponentially with patch size in Figure 6 is probably an accidental result of our method of rating the photographs.

Reconnaissance photographs would normally be used to detect targets of military significance. In an effort to obtain the sort of assessment which the photographs would have in a military situation we asked a group of air force trainees from nearby Chanute Air Force Base to try to find significant targets on the various photographs. A total of 433 men participated. The men, in groups of about twenty, were shown three slides each, first a poor

one, second a fair one and third the undistorted control. They were asked merely to find all bridges and airports. We then tried to correlate the success which the men had in identifying these targets with the patch size. Unfortunately there was so much variation among the men and the groups that the results are of little significance.

Several causes for this failure became evident. For the benefit of possible future experimenters in this area it is worthwhile discussing these. In spite of our best sales talk, the men were poorly motivated. Perhaps they resented being taken from their regular classes and being forced to take a test whose significance they did not properly understand. A higher caliber of men is needed for a satisfactory test. The room used was not good. It was satisfactory in the morning, but it became much too warm and also too light when the afternoon sun hit the windows. Also some of the men who did not have good eyesight were unable to properly view the screen. In an attempt to assure uniformity, the tests were timed, five minutes being allowed for each slide. This was so long that the men became bored with the first fuzzy slide. On the other hand, with slides which require careful study of fine detail five minutes is not long enough³.

³ J. Myers (C.S.L. Report R-109) had similar difficulties. He minimized their effects by designing a simplified experiment. Slides were viewed by one competent observer at a time using a magnifying glass in surroundings which were as nearly ideal as possible.

In an effort to avoid the mistakes of this test a second one was arranged. This time a group of about 25 trained photo and radar reconnaissance observers were given a similar set three transparencies on which they were asked to locate the same targets. They worked individually and they were allowed all the time they desired. However, an entirely unexpected difficulty arose. St. Louis is an excellent area for photo reconnaissance. These men had just been using photographs of that area for training purposes, and so they recognized the photographs instantly. Most of them tried to give unbiased evaluations. These are worth a short discussion. A large airport like Lambert Field can be recognized all the time if the patch size is 800 ft. on a side or less, but is lost completely with a 1600 ft. patch. Small airports are usually missed in a test of this sort, even when they are clearly visible to a person who knows their locations. A photograph of such an area contains a wealth of information which is too large even for such excellent observers as these to examine in sufficient detail. Bridges make more significant test objects because they are located within a small area, namely across an easily recognizable river. Results for a group of six prominent bridges have been added to Figure 6 (the curve marked Lockbourne). They are presented only for square patches up to 400 ft., the ordinate being the average number of bridges detected. This curve approximately superposes on the earlier ones obtained at C.S.L., and hence tends

to verify the earlier conclusions.

This experiment was undertaken because we had devised a method which we thought would produce rather accurately some of the effects of poor resolution. We did not carefully consider the methods to be used for the evaluation until the photographs had all been obtained. It is now abundantly clear that the difficult step is the evaluation. In further work in this area the experiment should be designed around the evaluation technique to be used, not around the physical method to be used in producing the photographs. That is to say, the evaluation should be allowed 80 o/o of the effort, not 20 o/o as was done in this experiment.

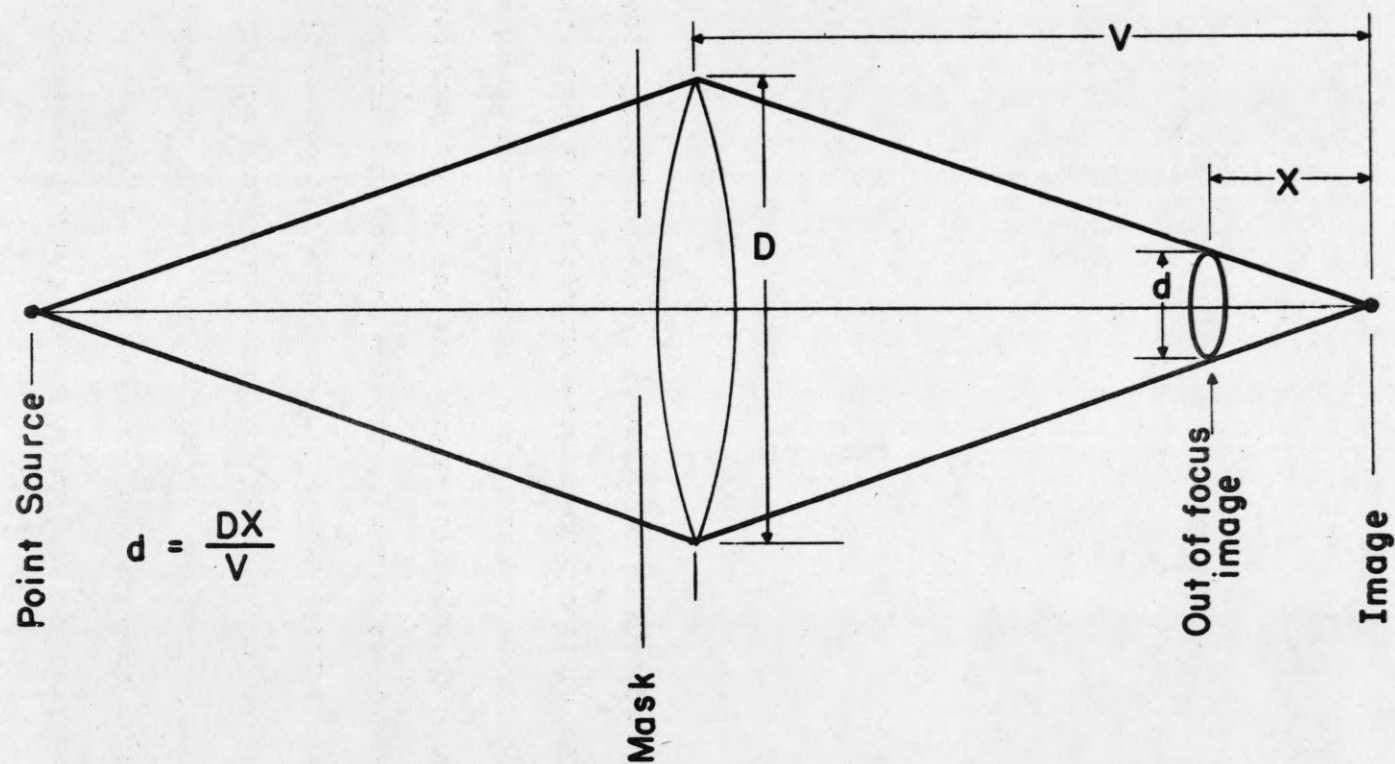
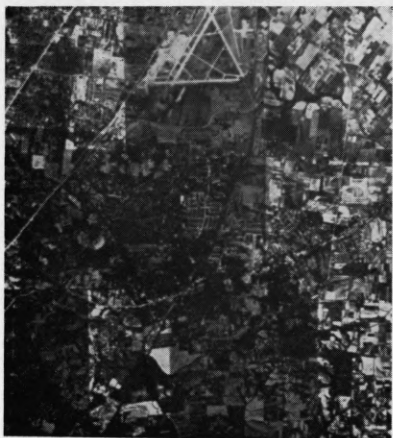


FIGURE 1: RAY DIAGRAM



50 FEET



100 FEET



200 FEET



400 FEET



800 FEET



1600 FEET

FIGURE 2
PHOTOGRAPHS WITH VARIABLE SQUARE PATCH
NO SIDE LOBES



0% SIDE LOBES



10% SIDE LOBES



30% SIDE LOBES

FIGURE 3
PHOTOGRAPHS WITH VARIABLE SIDE LOBES
400-FOOT-SQUARE PATCH



200 x 800 FEET



400 x 400 FEET

FIGURE 4
PHOTOGRAPHS WITH VARIABLE ASPECT RATIO
NO SIDE LOBES



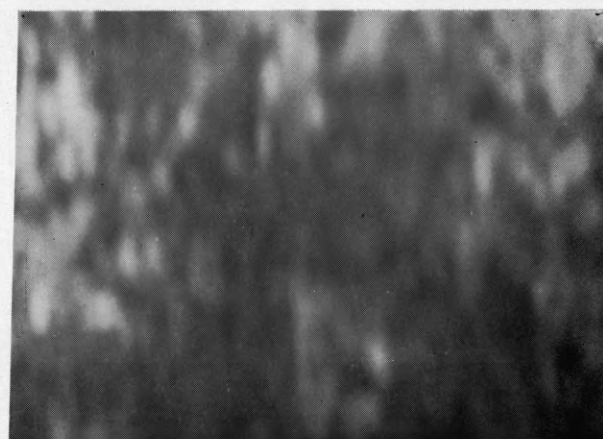
200 x 800 FEET



400 x 800 FEET



800 x 800 FEET



1600 x 800 FEET

FIGURE 5
PHOTOGRAPHS WITH VARIABLE RANGE RESOLUTION
NO SIDE LOBES

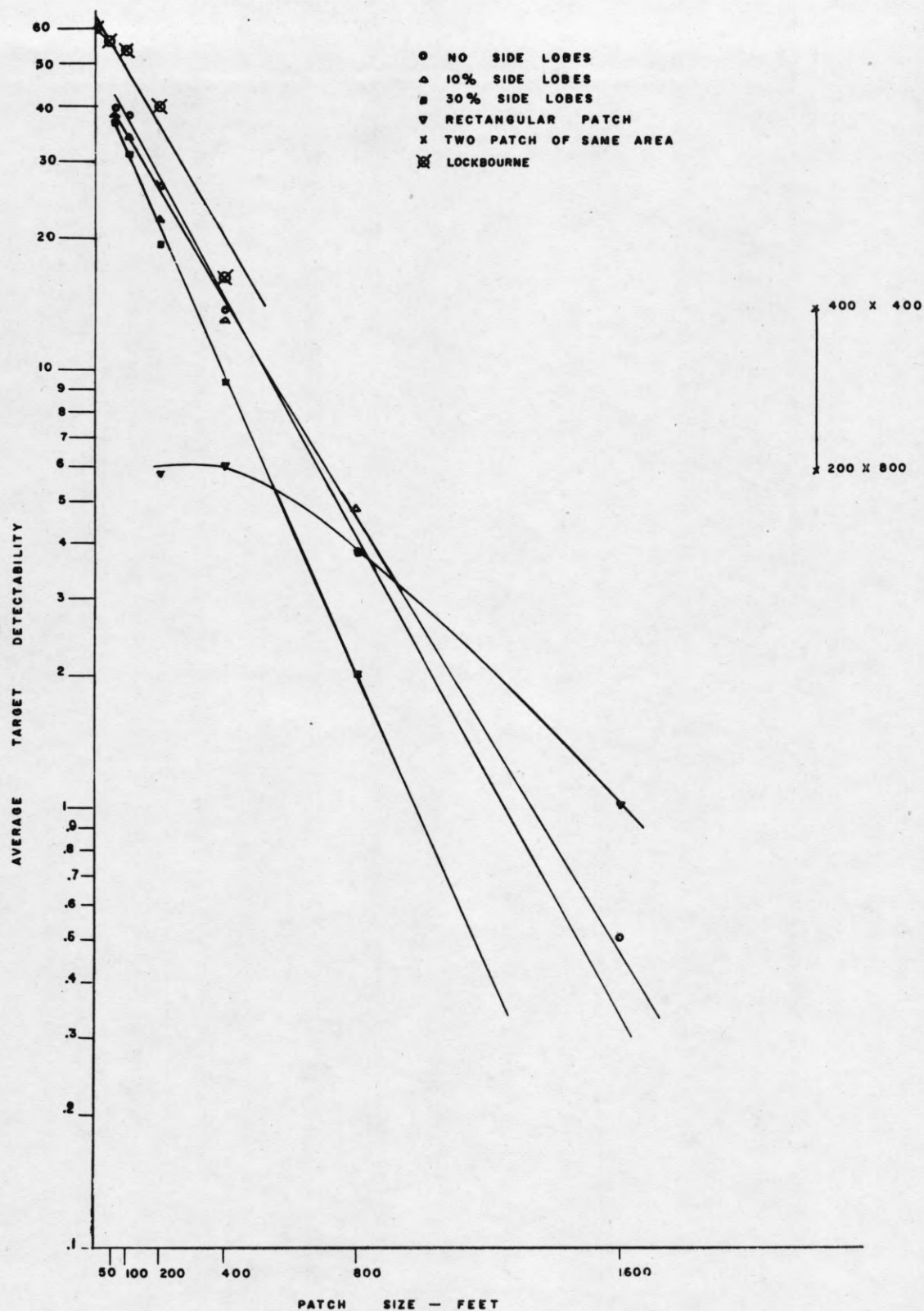


FIGURE 6: AVERAGE TARGET DETECTABILITY

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