

FEASIBILITY OF MICROWAVE HOLOGRAPHY FOR IMAGING THE
SEA SURFACE

22

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This paper considers the possibility of imaging the sea surface in three dimensions by means of microwave holography from a low-flying aircraft. This is a solution looking for a problem; perhaps it is applicable to oceanography or to the calibration of satellite-borne instruments. Others have attempted another means of imaging in three dimensions, namely stereo photography, but with only limited success. This paper is in two parts, the first of which is a brief feasibility study. The second part briefly reviews some computer experiments (published elsewhere) in which we have demonstrated the feasibility of computing three-dimensional images of objects from raw holographic data that have been recorded on magnetic tape. These experiments used synthetic data.

Let us begin by reviewing a well known two-dimensional imaging technique as a useful basis of comparison, namely side-looking radar. As shown in Figure 1, the resolution in the range direction to the side of the aircraft is achieved by range gate in the ordinary radar fashion. In the angular direction the resolution is achieved by using a long antenna aperture in the fore-and-aft direction. The scheme is necessarily side-looking because the range and angular resolution contours will fail to intersect at appropriate angles for a resolution grid in any other direction.

For high resolution the aperture length must be a great many times longer than the wavelength of the radar. The length may be either the physical length of a very long antenna, or the length may be synthesized by the forward movement of the aircraft. The latter requires that the phase of the return signal be recorded so that a data reduction procedure can add the signals in the same phase relationship as a long physical antenna. In

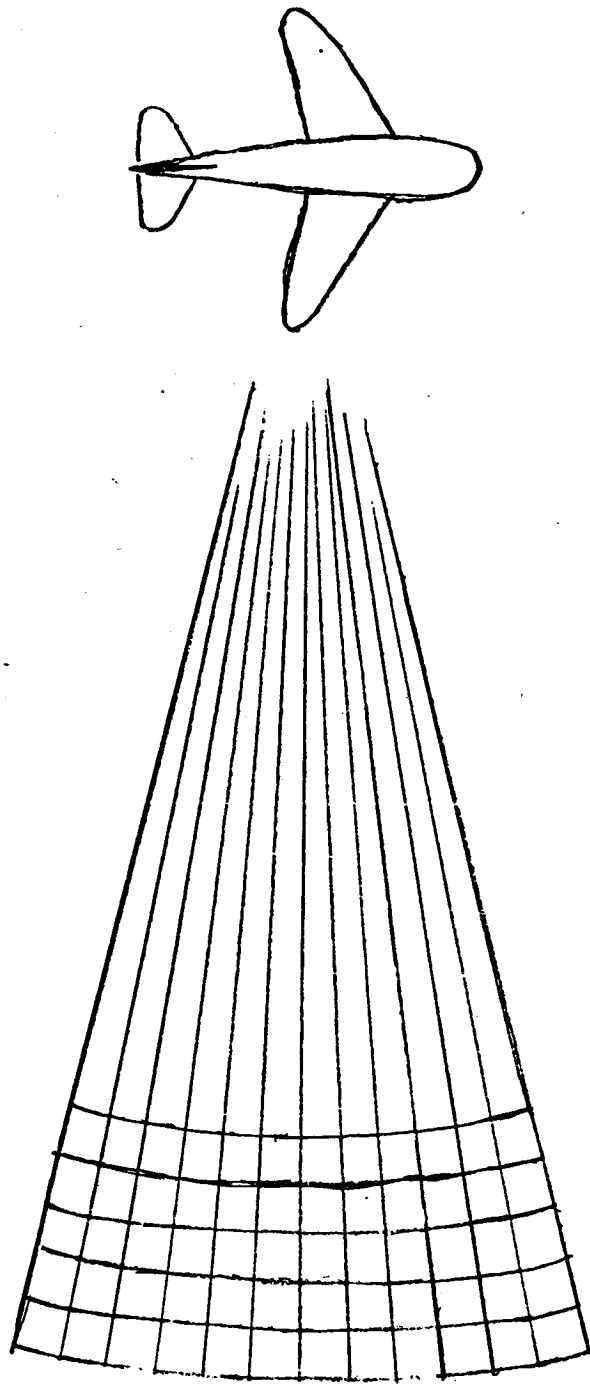


Fig. 1. Side-Looking Radar

the synthetic case, the radar beam illuminates a much wider area than the angular resolution to be achieved after data reduction. The number of resolution cells within the beam width, 12 in Figure 1, is equal to the number of signals added during aperture synthesis.

To the side-looking radar system compare the down-looking holographic system shown in Figure 2. A real lateral receiver aperture is formed by an array of simple receiving antennas beneath the aircraft. Almost certainly they would all fit in one row beneath either the fuselage or a wing, but the figure shows them staggered and situated on both the wing and fuselage to emphasize that computer data processing can introduce corrections that permit such arrangements when desired. The forward movement of the aircraft synthesizes the aperture in the fore-and-aft direction. This dimension may be only half as long as the lateral real aperture owing to the translation of the transmitter as well as the receiver. The signal from each element of the receiving array is stored on a separate track of a multi-track tape recorder. The number of elements in array determines the number of resolution cells across the swath in the final image.

Figure 3 shows typical major lobes in the antenna patterns of the receiving array, the 7 thin antenna lobes, and a single wide lobe of the transmitter illuminating the swath. If the receiving antennas were dense, e.g. dipoles spaced a half wavelength apart, or paraboloidal reflectors that are almost touching, then the receiving pattern would have only a single major lobe instead of 7 as shown. A sparse array would give the multiple grating lobes as indicated in the figure, but these lead to no spurious signals providing that the transmitting antenna pattern is narrow enough to illuminate only one of these as shown in the figure. This provision translates into a physical requirement that the transmitting aperture be at least as large as the spacing of the receiving elements.

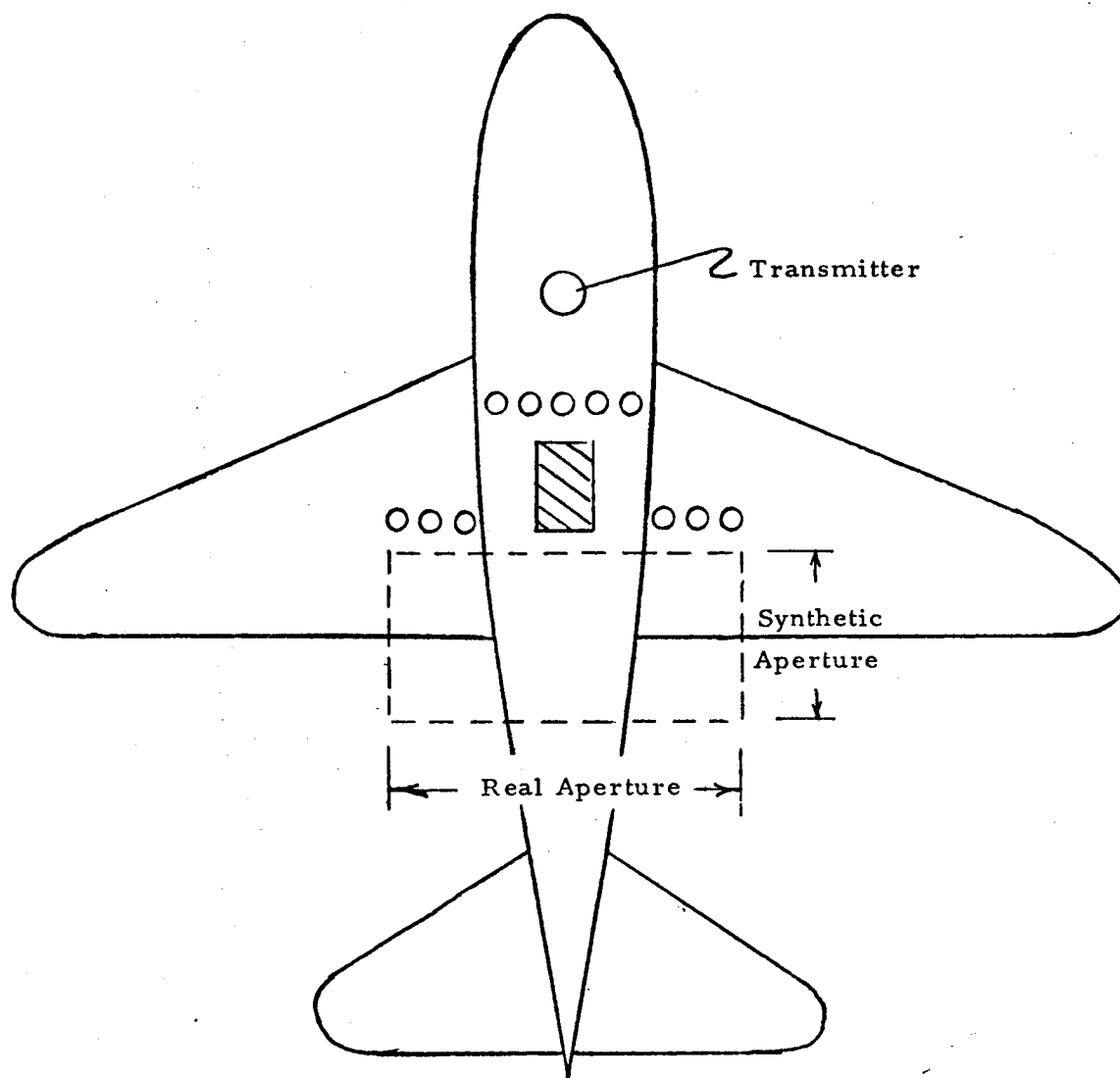


Fig. 2. Down-Looking Holographic Radar

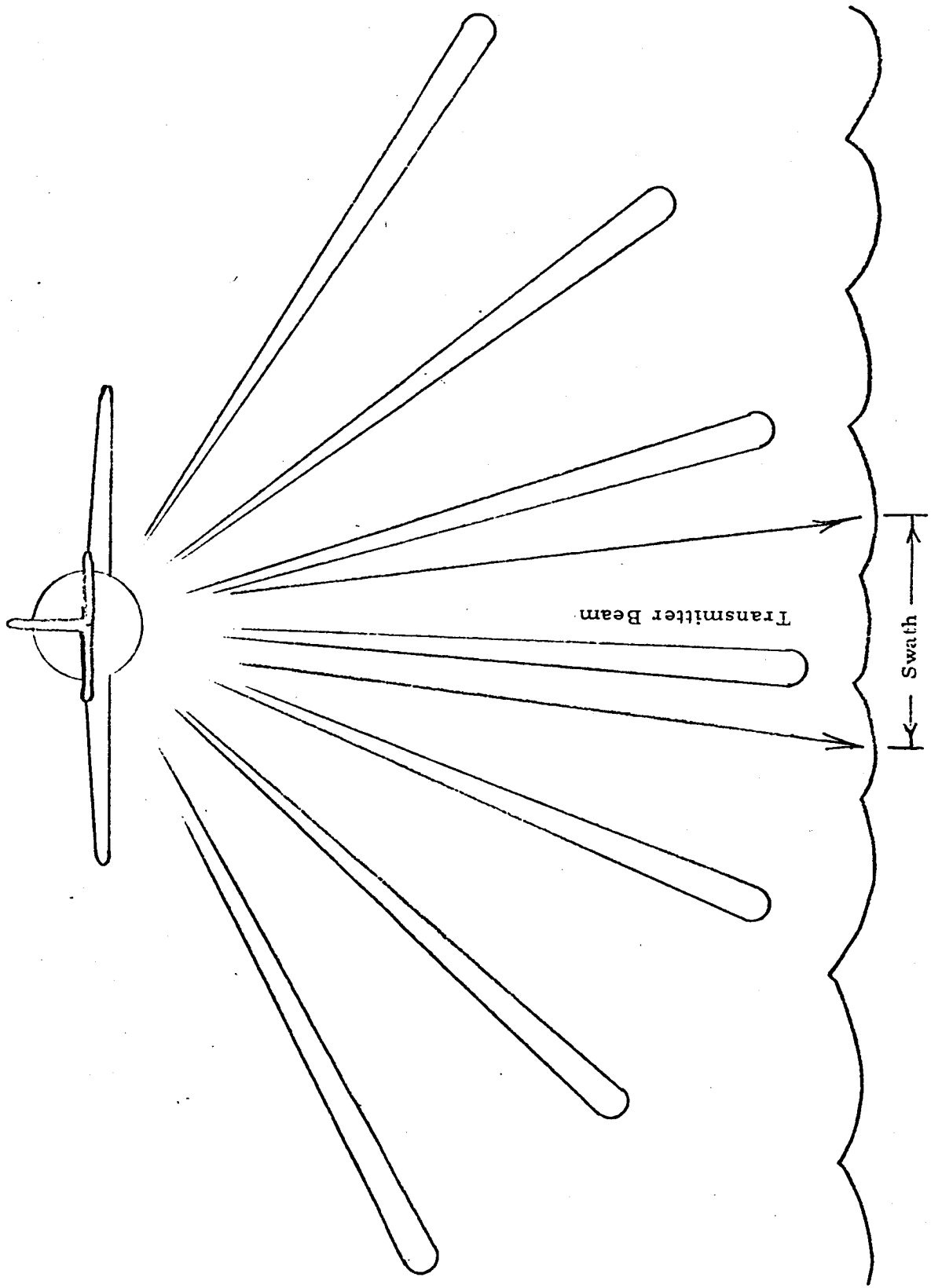


Fig. 3. Antenna Patterns

For the ocean application let us compare the systems just described on the basis of the amount of aperture that may be synthesized for high resolution. An expression derived below is valid for any synthetic aperture in either side-or down-looking systems. The linear resolutions on the water's surface is given by

$$\epsilon = \lambda r / (2L_s), \quad (1)$$

where λ is the radar wavelength, r is range to the target (which might be called altitude h in the down-looking case), and L_s is the length of the synthetic aperture. Note that λ/L is ordinary angular resolution of an aperture, the factor of $1/2$ applies to synthetic aperture since the transmitter as well as the receiver is in motion and phase shifts are thereby doubled, and r is the lever arm that gives linear resolution. The maximum length that may be synthesized is

$$L_s = Vt$$

where V is the velocity of the aircraft and t is the time during which the target holds still to sufficient accuracy. This time is

$$t = \lambda / (4\pi) / u,$$

where u is the random component of the movement of the sea surface projected along the line-of-sight. (A steady movement of a frozen sea surface is indistinguishable from a correction to the aircraft velocity. Such correction must be found by trial and error anyhow.) The above equations combine to give

$$\epsilon = 2\pi r (u/V) \quad (2)$$

which curiously is independent of the microwave frequency. For high resolution (small ϵ) both r and u should be small, as they are in the down-looking case, r because the vertical distance represents minimum range, and u because the minimum projection of the random movements of the sea is along a vertical line-of-sight.

Both r and u are difficult to estimate well. Consider first a down-looking system. The range r depends on how low the pilot is willing to fly, which in turn depends on weather and the pilot's daring. Let us say r ranges from 50 to 200 feet. The surface velocity component u does not fall readily out of the theoretical models for sea states, but a value near 0.5 knots seems reasonable in moderate seas. As an example let us assume

$$\begin{aligned} r &= 100 \text{ ft} = h \\ u &= 0.5 \text{ knots} \\ V &= 200 \text{ knots, and find} \\ \epsilon &= 19 \text{ inches.} \end{aligned}$$

Recall that this is horizontal resolution; vertical resolution will be that of the radar range gate. Thus sea states 1 and 2 will not be resolved, but a down-looking synthetic system will give an image of the larger structure in moderate to high seas, providing the radar is the nano-second type that generates sufficiently short pulses.

Clearly the resolution on the order of 20" is needed, so synthetic aperture side-looking radar is not applicable to the problem of imaging the sea. A side-looking system with a real aperture L_r is not unreasonable however. To estimate its size, let us assume some values compatible with the previous estimates, namely

$$\begin{aligned} \lambda &= 1 \text{ inch} \\ r &= 200 \text{ feet (slant height when } h=100 \text{ feet)} \\ \epsilon &= 20 \text{ inches, and find} \\ L_r &= 10 \text{ feet.} \end{aligned}$$

These and some other comparisons between the two systems are shown in the table on the following page. In this table note the rather self-explanatory items that are not discussed here in the text, such as optical storage of bulk data, shadowing, etc.

To complete the brief feasibility study of microwave holography, let us estimate the data bandwidth that results from the previous assumptions. The bandwidth will depend on the fidelity demanded of the recording, the coding of the signals, and other electronic factors, but for a rough estimate let us allow 10 cycles for each information bit in the hologram, or 20 cycles for each resolution cell, since the information capacity of the image is less than or about equal to the information capacity of the hologram. Thus the bandwidth is determined by the speed of the aircraft and the size of the linear resolution cell. Let N_v stand for the number of vertical resolution cells or range increments. If $N_v = 5$ we find:

$$\begin{aligned} B &\approx 20 N_v V / \epsilon \text{ per channel} \\ &\approx 20 \text{ kHz per channel,} \end{aligned}$$

where the previous assumptions were used again. This modest bandwidth applies to each recording channel, and the number of channels equals the number of resolution cells across the width of a swath. (Of course, if desired, channels could be multiplexed in some fashion and the results recorded with megahertz bandwidths.)

	SIDE-LOOKING RADAR	DOWN-LOOKING HOLOGRAPHIC RADAR
ADVANTAGES	<ul style="list-style-type: none"> *Wide swath *Optical storage of bulk data *Operational technique 	<ul style="list-style-type: none"> *Three-dimensional images *No shadowing *Strong signal from smooth surfaces
DISADVANTAGES	<ul style="list-style-type: none"> *Only two-dimensional *Shadowing *Real aperture required with horizontal target motion 	<ul style="list-style-type: none"> *Narrow swath *Limited data for computer processing *Little tolerance for vertical motion
MOST OBVIOUS APPLICATION	Mapping	Detailed inspection of a statistical sample

This concludes the discussion of feasibility. The proof that pulse holographic images may be computed with reasonable speed is published elsewhere [W. Wells, Acoustical Holography, Vol. 2, p.87, ed. Metherell & Larmore, Plenum Press, N. Y., 1970; D. M. Milder and W. Wells, IBM J. Res. & Dev., Vol. 14, p. 492 (Sept. 70)]. A sizable frame, say 50 x 50 may be computed in less than a minute on a moderate speed computer.

Several of the published images are reproduced here for convenience. In two dimensions the images of very small triangles were computed. Figures 4, 5, and 6 show a specular triangle; Figure 7 a diffuse one. These figures are analogous to a microscope view that shows the fine detail caused by edge diffraction. The contours connect points of equal image intensity. The theoretical resolution is indicated on the figures. The blooming effect at the right angle in Figure 4 is an anomaly which occurs when both legs of the triangles are parallel to the edges of the aperture and the receiver is in the direct glare of the specular reflection. The effect goes away when the triangle is rotated about the line of sight. Figure 5, or tilted very slightly, Figure 6. Figure 7 shows a diffusely reflecting triangle; often the fine structure of ocean waves will make them diffuse reflectors. The blotches of high and low intensity in this image are completely analogous to those seen when laser light illuminates a diffuse reflector. They are characteristic of coherent illumination.

Finally Figure 8 shows range slices through a three-dimensional radar image. At $R=16.5$ a plane greek letter Π comes into focus; its true shape is indicated by straight lines, the image by the contours. Similarly at $R=17.5$ a θ comes into focus.

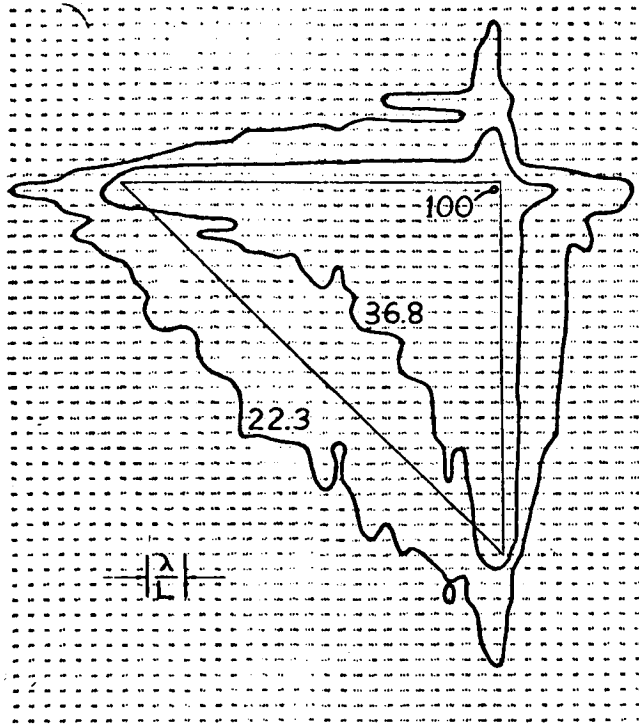
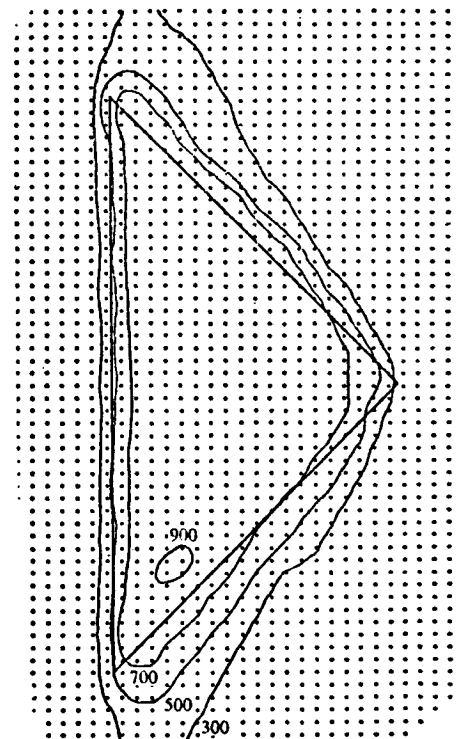


Figure 4
 Specular Glare, Sides Parallel
 to Aperture Sides

Figure 5
 Specular Glare, Rotated



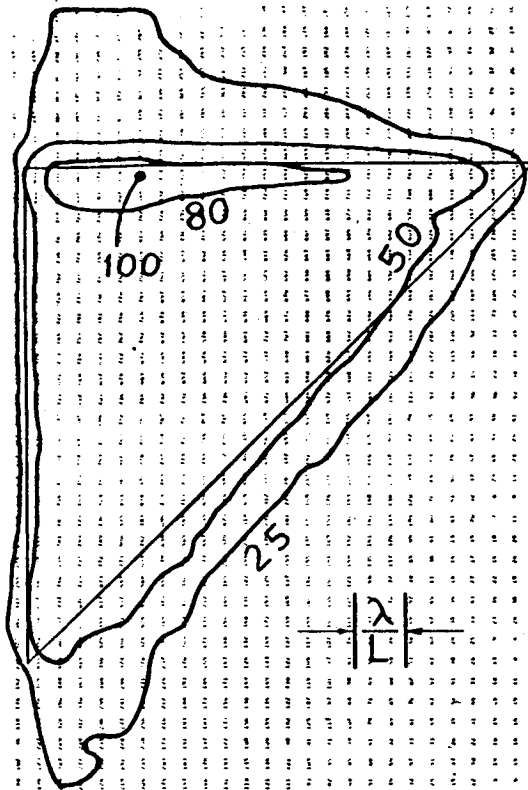
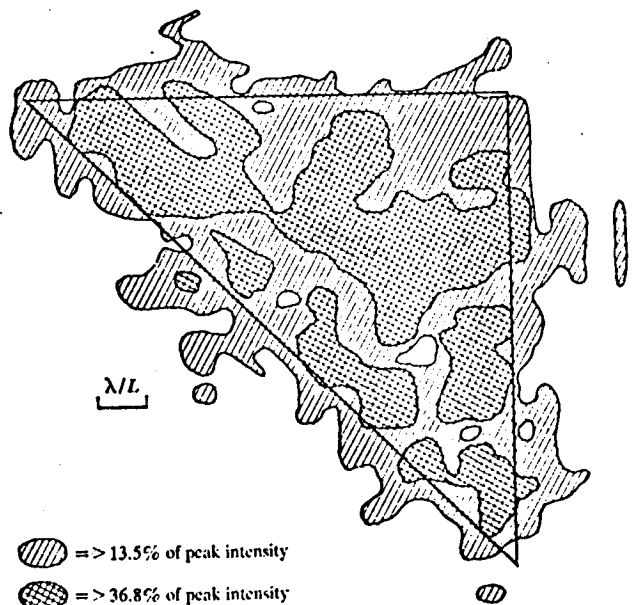


Figure 6
Tilted Off Specular

Figure 7
Diffuse Reflector



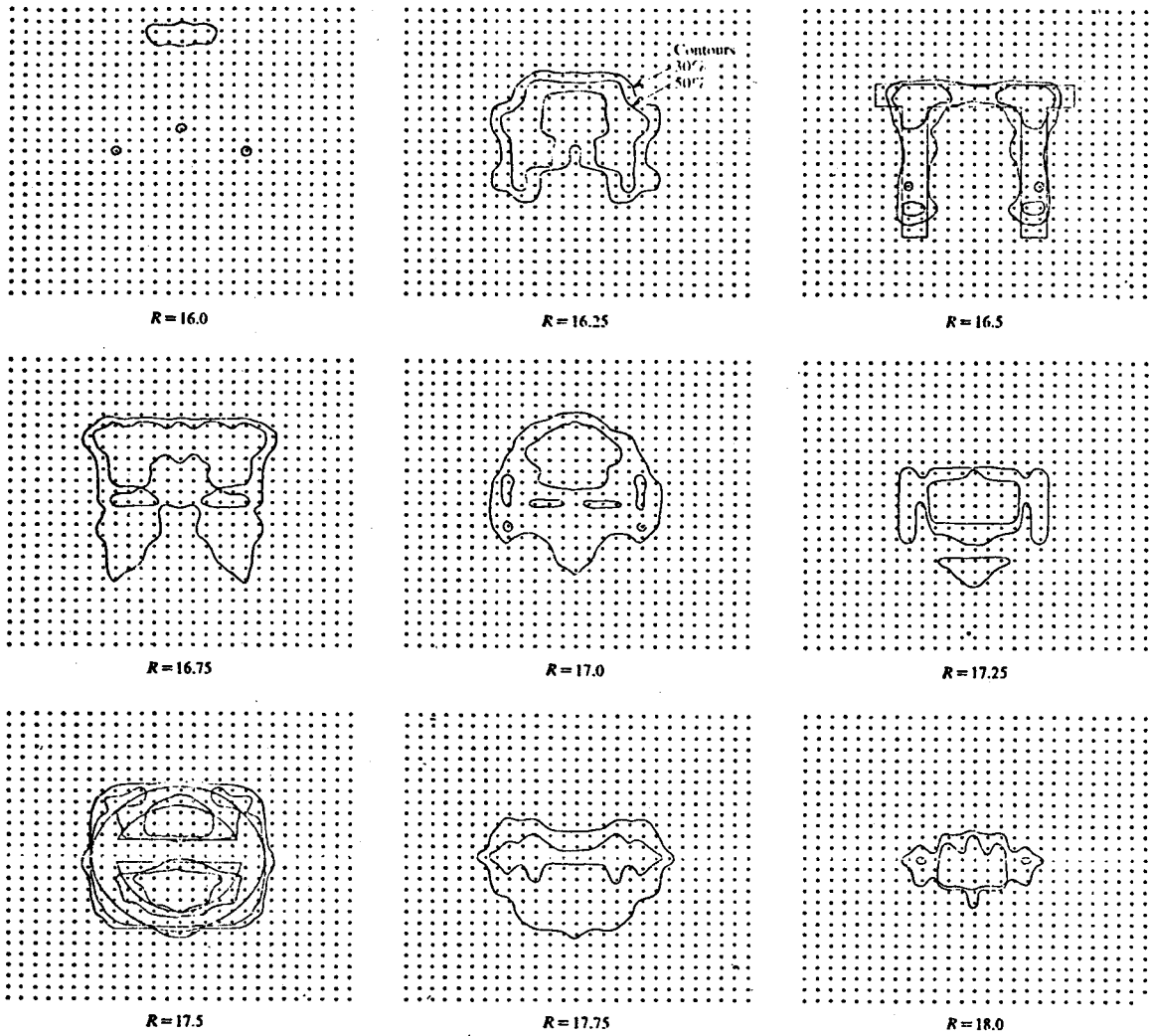


Fig. 8. Greek Letters Π and Θ Come into Focus at Ranges 16.5 and 17.5