Comparison of Imaging Geometry for Radar and Camera Photographs[*]

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ABSTRACT: *It is well known that radar images of objects have different geometries from the images produced by optical systems such as the human eye or cameras. A study was performed to determine the nature of the radar imaging process. Synthetic radar images of a number of simple shapes were constructed by graphical techniques and by photographing models in an optical device which simulates the radar geometry. The results are supported by observations of image detail on actual radar photographs.*

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THE development in recent years of high-resolution side-looking radar has resulted in radar photographs of startling quality and information content. A good quality high-resolution radar photograph is in many ways comparable to a conventional aerial photograph. To exploit these achievements GAC (under contract to the Corps of Engineers GIMRADA contract DA-44-009-ENG-4462) conducted an extensive program to determine the problems involved in extracting mapping detail from high-resolution side-looking radar photography. As part of this program, an analysis was made of those imaging geometry characteristics which affected the identification of radar returns.

Despite its superficial similarity in appearance, the geometry of a radar photograph is markedly different from that of a conventional optical photograph. An aerial photograph is, of course, a perspective view of the ground. Thus the distance of an image from the center of the photograph depends on the angle made by the optical axis of the camera and the object on the ground. In addition, that angle will remain constant regardless of the orientation of the camera about its optical axis.

The human eye operates in a similar fashion, so that if an optical photograph is focused on the retina, an image is formed with the same geometrical relationships as when the eye looks at the terrain itself. Consequently, the photographic process enables the observer to examine at his leisure a geometrically exact, visual replica of the terrain. Unfortunately, this is not true for side-looking pulse-ranging radar-images in *either* the x or y reference directions. They have one type of location geometry along the flight path, the azimuth or x-direction, and another at right angles to it, the range or y-direction, neither of them being the same as that for a camera. Figure 1A shows the points, a, b, and c at different elevations above a base line parallel to the aircraft ground track. For convenience $ab=bc$ or S. Thus, if the aircraft travels at a constant speed, the time it takes the side-looking radar-beam to move from a to b is the same as it requires to move from b to c. Therefore, the equivalent scale distances equal to

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[*] Presented at the 28th Annual Meeting of the Society, The Shoreham Hotel, Washington, D. C., March 14–17, 1962.

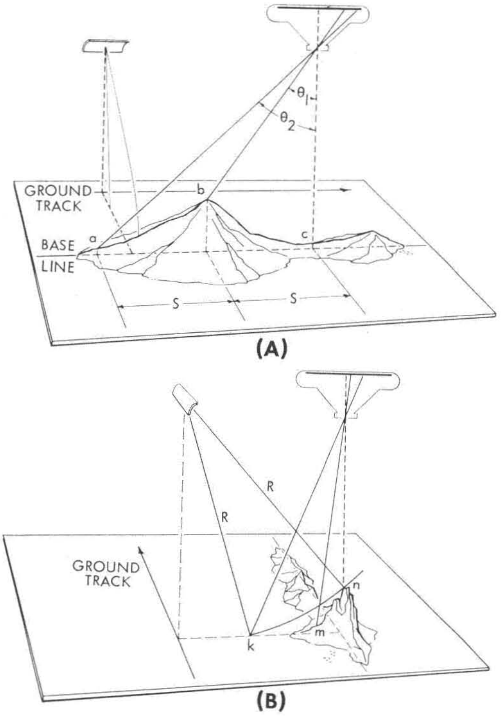


FIG. 1. Radar and Camera Geometry (A) parallel to ground track and (B) in range direction.

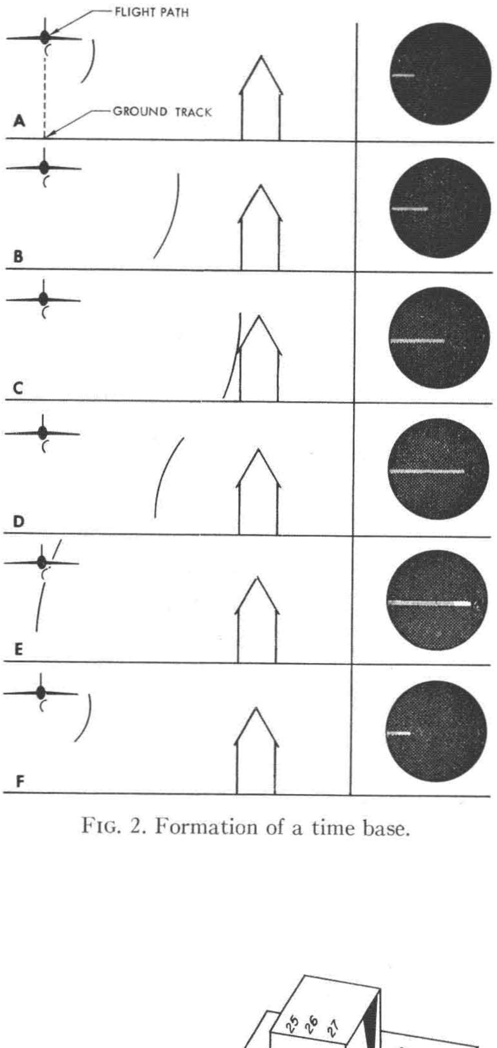


FIG. 2. Formation of a time base.

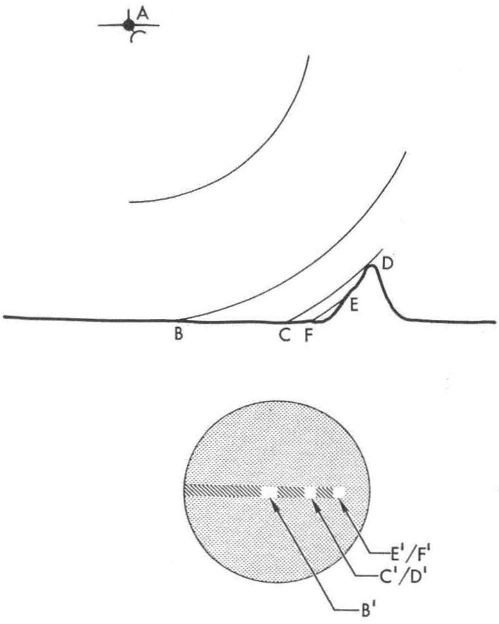


FIG. 3. Range determination.

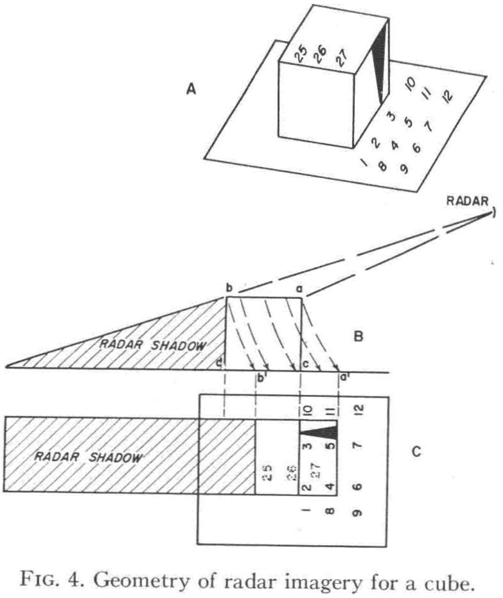
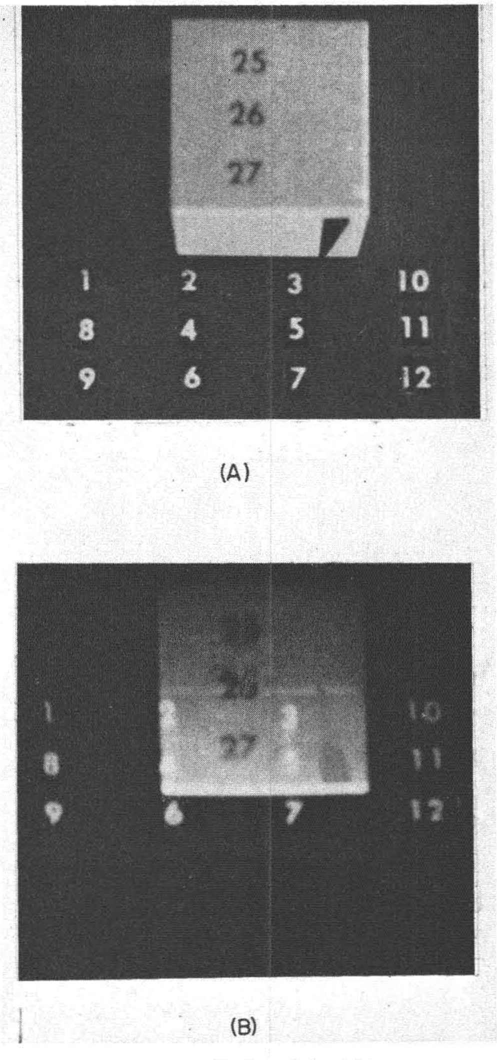


FIG. 4. Geometry of radar imagery for a cube.

ab and *bc* on the radar-image will be the same. On the other hand, a camera with its optical axis passing vertically through *c* will separate the points by a distance dependent on the tangents of their viewing angles, θ_1 and θ_2. Thus either the camera or the eye would show the image of *b* considerably closer to *a* than to *c*. Generally image discrepancies on radar photographs in the flight-path direction do not cause major interpretation errors, except when other distortions are introduced by navigation or film-speed errors.

Of course, a continuous-strip oblique camera, utilizing the radar's flight path would maintain the azimuthal distance relationships of *a*, *b*, and *c*. Their range relationship, however, would differ from that of the radar photograph.

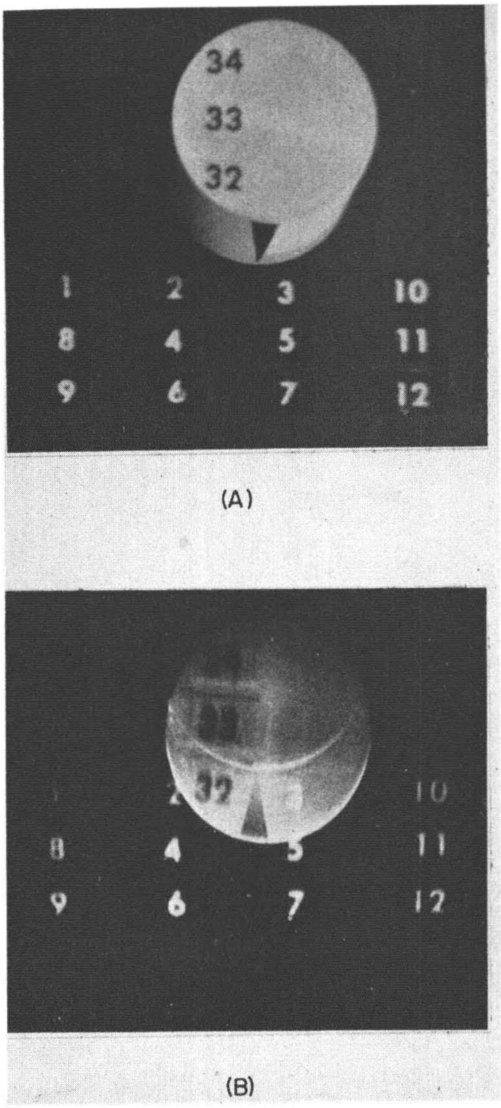
The distortions produced on the radar photograph in the range direction are much more serious. Since radar is a range measuring system, an image will be recorded in direct relationship to the time required for a pulse of microwave energy to be transmitted, impinge upon an object, and be reflected back to the antenna. Figure 1B shows three points lying in the plane of the radar fan beam. The separation of *k*, *m*, and *n* on the radar image is proportional to their distances from the aircraft. Points *k* and *n* are equidistant from the



(A)

(B)

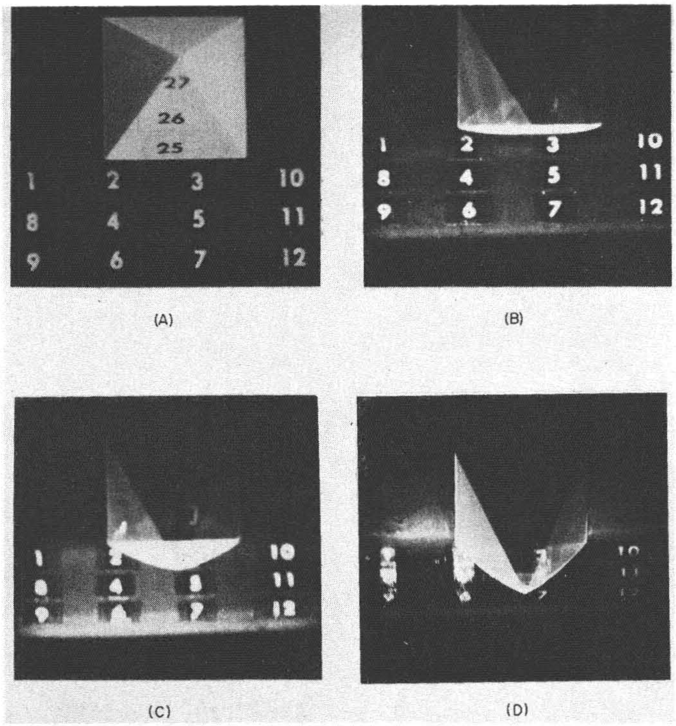
FIG. 5. Cube as displayed by (A) camera and (B) radar simulator.



(A)

(B)

FIG. 6. Cylinder as displayed by (A) camera and (B) radar simulator.



(A) (B)

(C) (D)

FIG. 7. Pyramid as displayed by (A) camera and (B), (C), and (D) radar simulator.

aircraft and will be displayed at the same point on the cathode-ray tube; while *m*, which has a greater slant range, or distance from the antenna than the two, will appear to have a greater range. No such interchange of positions will be produced by the camera; the location of the three points on the film will be determined by the tangents of their respective viewing angles. Obviously, the radar discrepancy in this case is most pronounced when steep slopes are viewed.

If the time-range relationship is to be used, a time-measuring device must be available. The cathode-ray tube (often called a "scope" or "crt") is commonly used to perform this critical function, since a spot representing the transmitted pulse can be swept across its screen at a known rate to form a time base, as shown in Figure 2. At instant *A*, the radar-pulse leaves the aircraft; and a spot representing the radar-pulse simultaneously begins to move across the *crt* screen. At instant *B*, the pulse is traveling toward the object; and the spot is still moving across the screen. The pulse strikes the object at instant *C*, and at instant *D* the reflected energy is returning to the radar receiver. At instant *E*, the reflected energy has returned to the receiver; and there is an increase in intensity of the spot on the right side of the *crt*. At instant *F*, another pulse is transmitted from the aircraft to start another sweep.

It can be seen that objects closer in time will be displayed at nearer ranges. Features located on the same time-reference (that is, at any position on the spherical wavefront generated by the transmitted pulse at any given time), but not necessarily at the same ground distance from the antenna, will be displayed at the same position, or range, on the radar photograph.

Both of these precepts are demonstrated in Figure 3. A pulse of microwave energy is transmitted by the antenna, *A*. The first object detected by this pulse is at *B*, which is eventually recorded on the *crt* at B'. The transmitted pulse continues to *C* and *D*, which are illuminated simultaneously. The reflections from these latter two points are received at the antenna at the same time, and therefore are displayed on the *crt* at the same position, C'/D'. Once beyond *C* and *D*, the microwave energy illuminates *E* and *F*. Since these points are detected later than *C* and *D*, they are recorded further in range on the *crt*, at E'/F' actually appearing beyond the image of peak, *D*, on the radar photograph.

This effect was studied in detail on a number of simple geometric shapes, a cube, cylinder, pyramid, cone and sphere. In these studies, it is assumed that radar-resolution is small compared to the dimensions of the object, and that the objects are small compared to their distance from the aircraft.

Since radar, like a camera, presents a two-dimensional view, all parts of the model above an arbitrary datum plane are displaced. It has been shown, however, that because of its range-measuring properties, radar-displacement is toward the ground track of the aircraft, direct opposition to the camera condition.

By means of descriptive geometry the amount of displacement was determined for various parts of each of the shapes studied. A model of each was mounted on a base plate. A pattern of numbers was placed on the plate and the models to detect any displacement. In addition, a black triangle was drawn on the cube and the cylinder, with the apex of the triangle at the base of the model. Figure 4A is an oblique view of a cube used in this study. Figure 4B shows the side view of the model. As shown before, all objects which are at the same slant range from the aircraft will be displayed at the same point on the *crt*. Here, point *a*, the upper leading edge of the cube is recorded at the same position as *a'*, *b* is moved to *b'*. Intermediate positions are similarly displaced. The result of this effect is that part of the base plate *ca'*, the vertical face of the cube *ca*, and a portion of the top of the cube will be superimposed and displayed as overlapping images in the area *ca'*. The area behind point *b* will not be illuminated by the radar-beam and will be shown as a radar shadow area. Figure 4C is a drawing of how a radar photograph of a cube will look. Notice the inversion of the triangle. This indicates that the top of the cube has been displaced forward and down, while the base *dc* remains at its original position. The trailing lower edge of the cube, *d*, is lost in the radar shadow, however, and is never seen. Similar studies were made for the other shapes with comparable results.

To confirm our graphical results, the objects were scanned by an optical-mechanical radar simulator. The simulator will not be described in detail. Suffice it to say that the device, developed by GACA, reproduces the exact geometry of side-looking radar by means of a collimated light source, a rotatable object plane, and a stationary camera. However, the intensity illumination from the various parts of the model is not necessarily accurate.

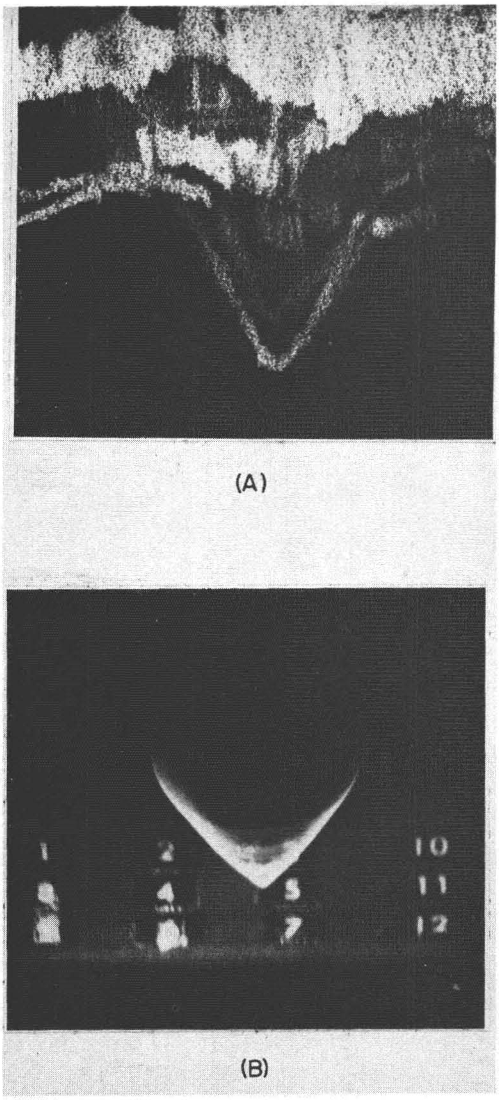


FIG. 8(A). Artist's rendition of radar photograph of conical mountain and (B) Simulated radar photograph of cone.

Figure 5 shows both (*A*) a conventional photograph and (*B*) a simulated radar photograph of a cube. The conventional photograph is readily recognizable, following established and well-known laws of vision and optics. Now examine the simulated radar photograph, part (*B*) and compare it to the graphic display of Figure 4. The top leading edge of the cube has been pulled forward to where it touches numbers 6 and 7. Number 26 has been displaced forward and down to the lower leading edge of the cube, just above points 2 and 3. The black triangle shows that the

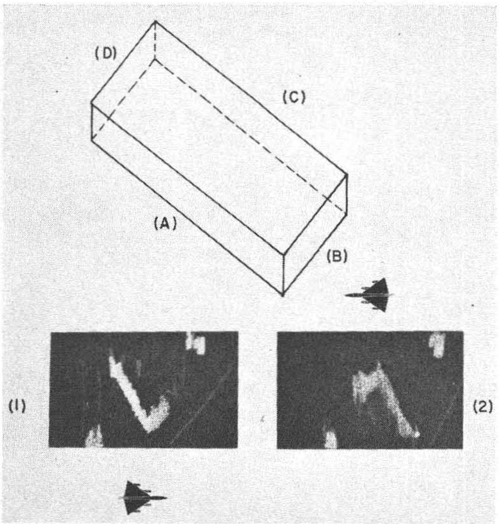


FIG. 9. Artist's rendition of apparent shape of rectangular buildings.

front of the cube has been pulled forward and down to the base. The base of the triangle is displaced almost as far as the line 6, 7, while its apex remains fixed.

The results obtained for the other shapes were similar, if allowance is made for the variations in shape. For instance Figure 6 shows (*A*) the optical and (*B*) the simulated radar photograph of a cylinder. Notice the triangle again has been displaced forward and down. The top edge has been displaced forward to point 5. The inner bright line is the base of the cylinder.

Figure 7 shows (*A*) the optical photograph and (*B*), (*C*), and (*D*) simulated radar photos of a pyramid. In (*B*) the radar-beam is nearly perpendicular to the face of the pyramid. The angle of incidence increases in (*C*) and (*D*) resulting in greater displacement. As can be predicted, the geometry of a cone is very similar to that of a pyramid.

In addition to being based on theory and backed by controlled experiments, the results that have been described were observed on numerous operational radar photographs. Because of security regulations examples of actual radar photographs cannot be shown, but figures which approximate them have been prepared. Figure 8 shows (*A*) an artist's rendition of a radar photograph of a steep, somewhat conical mountain and (*B*) the simulated radar photograph of a cone. From the reference to the simulated photograph, an

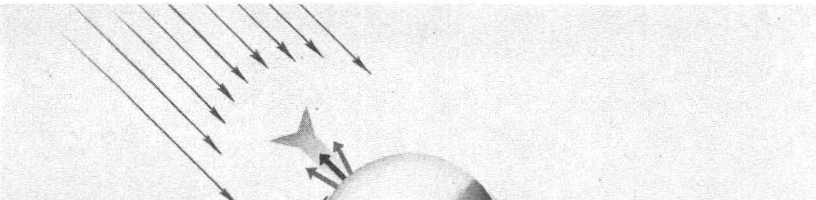


FIG. 10. Sphere as displayed by combined diffuse and specular reflection.

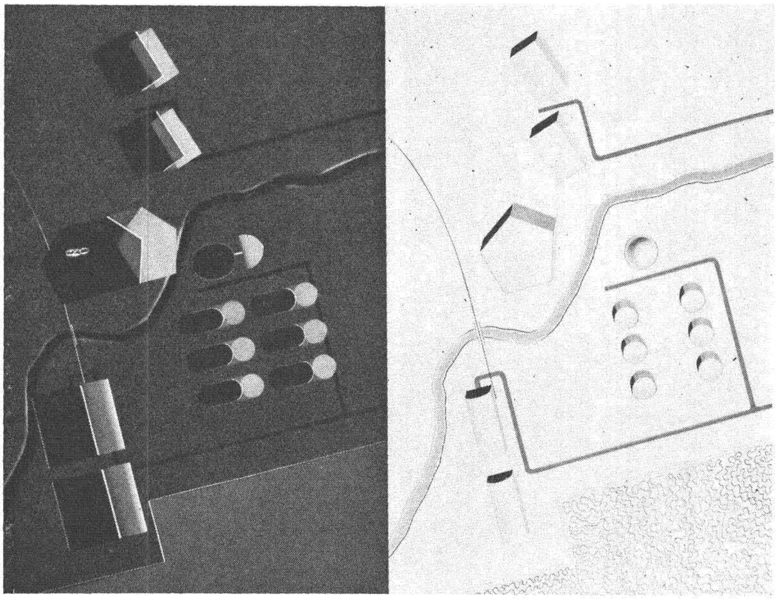


FIG. 11. Artist's conception of radar photograph.

approximate position can be obtained for the true position of the base of the mountain.

The identification of radar-images is further complicated because the recorded reflections may be either diffuse or specular (i.e. mirrorlike, where the angle of incidence equals the angle of reflection). In Figure 9 the L-shaped returns in the artist's rendition of radar photographs (1) and (2) represent returns from a building whose actual shape is shown in the sketch. For photograph (1) the radar illuminated sides (*A*) and (*B*), but the radiated energy was reflected specularly off the roof. In photograph (2), the radar was on the opposite side of the building and sides (*C*) and (*D*) were illuminated. Again, no reflected energy was recorded from the roof. The result, in both cases, is that the roof is a no-return area and the two reflecting sides combine to present the L-shaped return.

Figure 10 demonstrates the formation of the image of a sphere when both these effects are present. The bright dot and straight line are due to specular reflection, while the medium intensity semi-circle is due to diffuse reflection. The shadow is present in either case. This represents the maximum return that can be expected from a structure of this shape. Probably less return will normally be present.

Figure 11 is an artist's conception of a group of typical structures and their pre-predicted radar signatures. The logic of each of the simulated radar-images can be defended on the basis of previous discussions.

The identification of radar-imagery is complicated. Many additional problems such as aspect-angle, reflection characteristics of surface materials, system-sensitivity and resolution combine to confound and confuse the interpreter. In addition, as the resolution of the radar system improves, its image geometry problems will become greater because smaller and smaller elements will become resolvable. Undoubtedly the interpreter of the future will be aware of this and realize why a sidewalk apparently is connected to a sky light, or that a tank has its treads wrapped around its turret. These and similar situations will, in time, be as routine as the identification problems now encountered on conventional aerial photography and solved by competent interpreters.

A wealth of information is present in high-resolution radar photography. When detail extraction techniques are better understood, the image interpreter will have another tool in his kit; one that defies clouds and darkness in his continuous search for information.