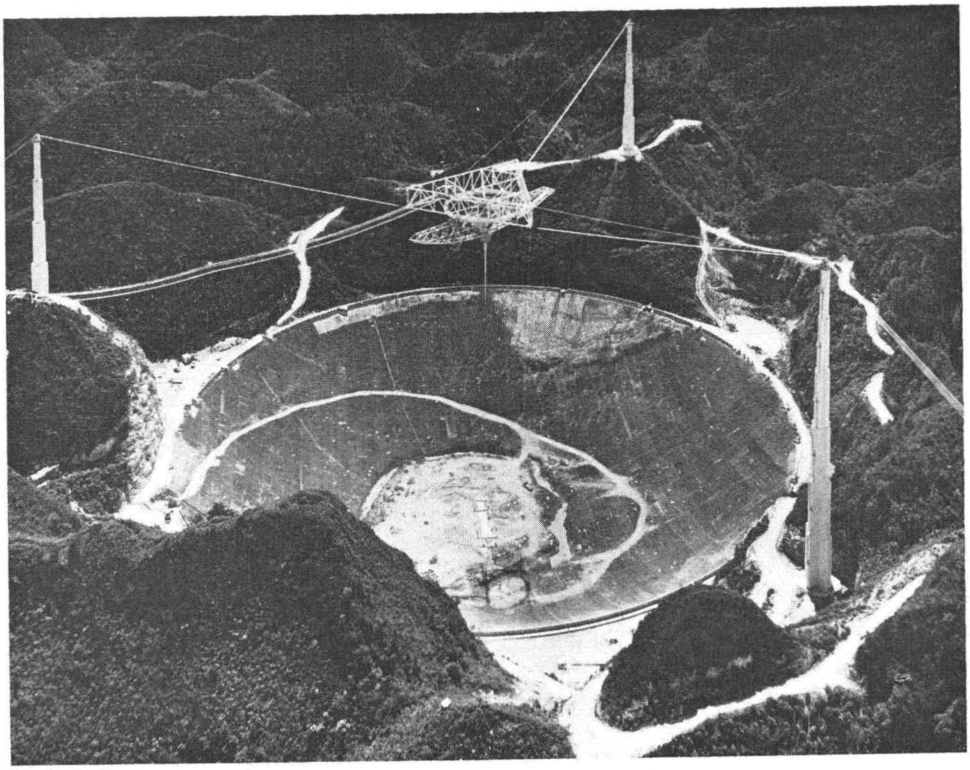

FIG. 1. Antenna of the Arecibo Ionospheric Observatory.

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Radio Reflector Calibration

The world's largest "dish" is calibrated photogrammetrically, applying the techniques of analytic aerotriangulation.

(*Abstract on next page*)

INTRODUCTION

THE 1000-FOOT REFLECTOR of the world's largest radar-radio telescope is being periodically calibrated by analytical photogrammetric methods. The telescope, the principal instrument of the Arecibo Ionospheric Observatory,† is located in a natural limestone sink in northwest Puerto Rico. Unlike most radio telescopes, the Arecibo antenna consists of a fixed spherical-cap reflector and a line feed suspended 435 feet above the reflector and movable in elevation and azimuth. The beam may be directed at any target in a 40 degree cone centered overhead. The support structure for the feed is suspended over the reflector center by three sets of cables, visible in Figure 1. Several other guy cables pass from the support structure down to anchors near the reflector rim. The reflector surface is composed of half-inch opening steel wire mesh at a mean height of

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twenty feet above terrain. The specified reflector tolerance was originally a standard deviation of ±30 mm. from the theoretical spherical surface at 60°F. The mesh is supported by a system of suspended cables in such a manner that some parts of the reflector surface remain fixed with temperature change while other parts rise and fall more than 1 mm./°F. Therefore, it is desirable to measure all sample points of the reflector surface in the shortest possible time—a requirement ideally suited to the use of photogrammetric methods.

feed arm gives a stereopair of photographs covering more than one half of the reflector surface.

As the feed arm can be rotated through 540° about the center of the feed support structure, the same stereopair can be obtained by placing a camera at only one end of the feed arm and rotating the arm 180° between the first and second exposures of the pair.

In order to cover reflector areas near the rim, it is necessary to aim the camera as shown in Figure 2 instead of toward the re-

ABSTRACT: *The 1,000-foot aperture fixed spherical reflector of the Arecibo Ionospheric Observatory antenna is being periodically calibrated by analytical photogrammetric methods. Twelve photos of the reflector surface are taken from a rotating platform 500 feet above the reflector using a six-inch focal length aerial film camera. A total of 633 signalized reflector targets and 33 ground control points are photographed; about 250 reflector targets and 15 ground control points appear in each photograph.*

The analytical solution is performed simultaneously for all twelve photographs using a modification of Duane Brown's methods. Surface deviations of the reflector are determined with a standard error of ±12 mm. A procedural change being planned will result in a decrease in the standard error of determination to an estimated ±6.7 mm.

PHOTOGRAPHIC PROCEDURE

A U. S. Air Force KC-1B film aerial mapping camera was loaned to the Observatory for the calibration photography. This camera has a nine-inch square format and a six-inch focal length. The camera manufacturer indicates a systematic radial distortion curve within ±10 microns and a film platen flat to ±5 microns. Polyester-base film is used to minimize random film shrinkage.

The locations of the camera stations presented a practical problem: the shortest possible time interval between exposures is desirable to minimize temperature differences. The use of a helicopter was ruled out because of the hazard of flying near the support structure cable systems. Any camera locations on the rugged terrain surrounding the reflector would require excessive time between exposures to transport the equipment.

Fortunately the feed arm, a part of the feed support structure, furnishes an adequate camera location. The feed arm is the long narrow truss structure with curved lower surface in Figure 1. It is located just below the triangular main support platform. A KC-1B camera aimed downward at the reflector center from each end of the 300-foot long

flector center. One stereopair covers about one-third of the reflector in this configuration.

To assure that all reflector targets appear in at least one stereopair, six pairs as in Figure 2 are necessary with the feed arm rotated 60° between pairs. All points on the reflector surface appear on from two to all twelve photographs, with a mean value of five photographs for any point. The mean object distance for each stereopair is about 500

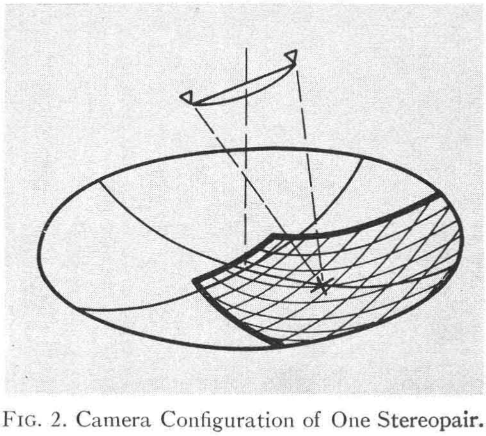

FIG. 2. Camera Configuration of One Stereopair.

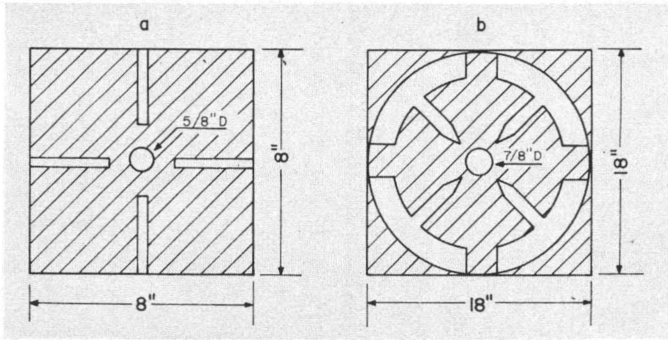

FIG. 3. Reflector and Ground Control Targets.

ft., so that the base-height ratio of the photography is 0.6.

Other preparations were made for the calibration of the reflector after the establishment of the photographic procedure. The reflector surface is represented by 633 eight-inch square aluminum targets (Figure 3a). These reflector targets are painted flat black and flat white and are wired to the reflector mesh. They are positioned in a rectilinear grid pattern of rows and columns 35 ft. apart.

To control the photogrammetric work, 33 reference point positions were surveyed on the ground beneath the mesh and at the rim. These control points are signalized as shown in Figure 3b. From 14 to 17 evenly distributed ground control point images appear on each photograph.

Analytical Solution

The versatile methods of analytical rather than instrumental photogrammetry were a clear choice for this work both to provide the most efficient use of the data and to give the strongest solution. Rental of a Mann 422C monocular comparator was arranged with the L. C. Smith College of Engineering, Syracuse University. The Control Data 3200 computer of the Observatory is used for the data reduction.

A modification of the methods of Hellmut Schmid[1] and Duane Brown[2] was developed for the mathematical model. All twelve photographs are considered simultaneously. For each exposure the usual six orientation parameters are determined. Additional seventh and eighth parameters for each exposure are carried as direct unknowns. The seventh unknown is the systematic scale difference between x and y photographic coordinates; this gives a much stronger solution than possible from merely measuring shrinkage marks on the negative. The eighth unknown parameter is the axis skew or the nonperpendicularity of the x and y photo coordinate axes. The axis skew is not necessarily caused only by the comparator. Talts[3] has shown that when using polyester-base film a significant improvement in the residuals can be made with a correction for axis skew.

In addition to the 8 times 12 or 96 exposure unknowns there are three ground coordinate unknowns X, Y, Z for each of the 633 reflector targets, or a total of about 2,000 unknown values. The 633 reflector targets and the 33 ground control points each appear on five photos. Each photographic image has an error equation for the x and for the y residual. Thus, there are a total of $666 \times 5 \times 2 = 6{,}660$ error equations for the 2,000 unknowns, an overdetermination of 3.3. During the solution, however, this problem can be reduced to little more than the accumulation and inversion of a 96 by 96 matrix.[2]

The solution is iterative. The input data require approximations for all unknowns including the X, Y, Z coordinates of the reflector targets. Very close approximations are obtained for the orientation unknowns by performing an independent spatial resection for each exposure using ground control point photo and ground coordinates. Then, approximations for the reflector target coordinates are obtained by spatial intersection from separate pairs of resected exposures.

If the input data are prepared in this way only two iterations are normally required for the twelve-photo solution. The solution is terminated when after an iteration the sum of the squares of the residuals fails to decrease significantly from the preceding iteration.

The following types of output data are available after the solution:

1. The 96 exposure parameters.
2. For each reflector target:

a. The coordinates X, Y, Z,
b. The standard errors in determining the X, Y, and Z values,
c. The reflector deviation from the theoretical surface,
d. The standard error in determining this deviation.

3. The total number of equations and unknowns, blunders or measurements not considered in the solution, the standard error of unit weight on the photograph, the mean and standard reflector deviation errors, and the mean error in determining the reflector deviations.
4. The x and y photo coordinates of each target image with the final residuals v_x and v_y.

The fourth type of output data proved to be extremely valuable in detecting systematic errors not solved directly in the solution. After the first twelve-photo solution the standard error of unit weight was ±0.011 mm. The 6,600 residuals were then studied. Based on this analysis, the systematic radial distortion curve was adjusted slightly and the photo coordinates of the perspective center given by the manufacturer were found to be correct. More important was the discovery of a highly significant correlation between the residuals v_x, v_y and the photo coordinates x, y. Although this effect was labeled as comparator error, the exact causes of the relationship were not isolated in the camera-film-comparator system. However, the effect was easily eliminated by calculating x and y coordinate correction tables.

Armed with this new information, a second twelve-photo solution was performed resulting in a standard error of unit weight of ±0.0085 mm. An analysis of the residuals from the second solution resulted in slight adjustments to the radial distortion curve and comparator coordinate correction tables. The twelve-photo solution was repeated a third time incorporating the slight adjustments in the coordinate corrections. The standard error of unit weight then was ±0.0079 mm. After this third solution no systematic errors were found in the residuals that would significantly affect the reflector calibration. A test for objective de-centering error as described by Brown[4] was made with negative results; doubtless, the de-centering was absorbed in the other corrections.

The final mean standard error in determining the deviation of a single reflector target was ±12 mm., or 1/25,000 of the reflector aperture.

Improving Present Determination Accuracy

A new reflector accuracy standard has recently been adopted. The reflector surface is now being adjusted to meet this new goal: a standard error reflector deviation of ±10 mm. from the theoretical surface at 60°F. The calibration method must be revised for this new accuracy. The procedure is generally the same, except that the photographs will be taken from a platform hanging 160 ft. below the present position at one end of the feed arm. Sixteen exposures instead of twelve will be made by the intrepid photographer from this precarious perch. With this new scheme the anticipated final standard error in determining a single reflector target deviation is ±6 mm. or 1/51,000 of the reflector aperture.

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2. Brown, D. "A Solution to the General Problem of Multiple Station Analytical Stereotriangulation," RCA Data Reduction Technical Report No. 43, 1958.
3. Talts, J. "Various Transformation for Correction of Error Caused by Film Distortion" *Särtryck ur Svensk Lantmäteritidskrift*, No. 3, 1964, and presented at X Congress International Society of Photogrammetry, Lisbon, September, 1964.
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Announcement of New Publication

Spot Diagrams for the Prediction of Lens Performance From Design Data, by Orestes N. Stavroudis and Lloyd E. Sutton, National Bureau of Standards Monograph 93; September 7, 1965; 96 pages; 75 cents. (Order from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402, or from local U. S. Department of Commerce Field Offices.)

The ability to predict the performance of a lens from its design parameters, prior to its fabrication, can save time and expense for both the manufacturer and the user. The National Bureau of Standards has developed a system for analyzing optical designs, using spot diagrams, which has been applied to over twenty designs for aerial camera lenses. Monograph 93 provides a detailed description of methods used to calculate, produce and interpret spot diagrams, plus a compendium of spot diagram analyses done at NBS.