Microwave Antenna Measurement

Clive S. Fraser
Geodetic Services, Inc., Melbourne, FL 32901

ABSTRACT: The application of analytical photogrammetry to the measurement of microwave antenna reflectors is discussed. Recent developments in close-range photogrammetric systems, notably large-format cameras and automatic comparators, have greatly enhanced both the accuracy and economy of antenna mensuration. Accuracy aspects are discussed and advantages of the photogrammetric approach are highlighted. Five recently conducted antenna measurement projects are reviewed.

INTRODUCTION

THE RADIO PERFORMANCE of a parabolic microwave antenna is very dependent on the degree of conformance of the dish's receiving surface to its geometric design specifications. Surface errors can adversely affect gain. Modern high resolution antennas are being designed for improved gain at increasingly higher frequencies and, thus, surface accuracy specifications are becoming ever more stringent.

As surface accuracy requirements increase, so there is a need to address the problem of measuring the surface of the reflector to an accuracy sufficient to either demonstrate conformance with specifications or provide the data required to enable the surface to be adjusted to an acceptably precise figure. The surface accuracy criterion for large antennas designed to operate at high frequencies can approach 1 part in 500,000 of the dish's diameter, and measurement to such tolerance requires specialized techniques.

One method for the mensuration of antennas, both large and small, which is attracting wide usage is analytical photogrammetry. This technology was developed by Geodetic Services, Inc. (GSI), and over the last two decades it has been employed in several hundred calibration measurements of parabolic antennas ranging in size from 1 m up to 100 m in diameter (e.g., Brown, 1980; Brown, 1981). The status of GSI's technology around 1970 was reviewed by Kenefick (1971) (at that time GSI was a division of DBA Systems, Inc.). The present paper, which is a condensed version of the report by Fraser (1986), describes a number of parallel advances leading to dramatic improvements. Other recent applications of photogrammetry to the measurement of antennas are described by El Hakim (1984) and Oldfield (1984).

Traditionally, the photogrammetric system for antenna measurement employed by GSI comprised a large-format plate camera; a manually-operated precision monocomparator, and a mini-computer based data reduction sub-system, at the heart of which was a self-calibrating bundle adjustment program. In recent years, however, significant technological advancements have taken place in this system. Notable among these developments are a microprocessor-controlled large-format film camera which is optimized for use with retrotargetting technology (Brown, 1984), an automatic video-scanning monocomparator of sub-micrometre accuracy (Brown, 1986), and a personal-computer-based network design and data reduction system. It is not the purpose of this paper to detail these developments, but more to describe, through reference to a number of antenna measurements recently undertaken by GSI, the profound impact they have had on measurement accuracy and economy. For a full account of the developments in GSI's system for industrial photogrammetry the reader is referred to Fraser and Brown (1986).

In the following sections, accuracy aspects of antenna mensuration by photogrammetry are discussed and five recently conducted measurements are reviewed. Initially, however, it is useful to recall some of the advantages photogrammetry exhibits over alternative techniques for antenna calibration.

ADVANTAGES OF PHOTOGRAMMETRY

Considering the new developments in photogrammetry, this method for antenna mensuration is now arguably unequaled in versatility and accuracy. In addition to high precision — accuracies routinely in excess of 1 part in 250,000 of the reflector diameter, with 1 part in 500,000 within the state of the art — a few of the advantages photogrammetry displays over alternative optical and mechanical calibration techniques are as follows:

- The antenna can be measured in any orientation, in either a static or dynamic mode. Most conventional optical-mechanical methods require that the dish be mounted in a fixed orientation (usually with the axis in a vertical orientation).
- Any size aperture can be measured. Indeed, as will be detailed in a latter section, it is possible to measure the surface conformity of both the main and sub-reflectors (in the same coordinate system) on a large antenna in a single calibration survey. Moreover, photogrammetry can be used to measure any

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reflector surface, be it plane, paraboloidal, hyperbolic, or some other shape.

- Photogrammetry requires a minimum of antenna downtime. On-site data acquisition time comprises the period in which the photography is taken; and this can range from a few tens of minutes to a few hours, but does not involve the days of downtime experienced with alternative techniques. Influences, such as shape change due to diurnal thermal stresses, have a minimal impact because the data are gathered in such a short period of time.
- No special environmental conditions are required for the photogrammetric measurement. Indeed, this technique is applicable for tests involving the measurement of environmental effects on surface shape (measurements have been carried out in solar vacuum chambers, for example).
- The measurement need not be confined to points on the reflector surface. The coordinates of additional points of interest on say the feed, sub-reflector, or quadripod apex can also be triangulated.
- By virtue of the automatic monocomparator, photogrammetry is a highly automated procedure the accuracy of which is no longer dependent on human skill. Moreover, the measurement accuracy on a dish is relatively homogeneous over the entire reflector surface (no degradation is experienced in progressing from the vertex to the rim), and accuracy estimates are computed for every individual triangulated target point.
- The photogrammetric mensuration process involves the collection of a data set with considerable observational over-determination. This fact gives rise to an extremely reliable triangulation solution for target points on the antenna, and it affords a high degree of quality control (through the provision of extensive internal self-checking).

ACCURACY ASPECTS

The accuracy of photogrammetric triangulation is influenced by a number of factors (see, e.g., Brown (1980), Torlegård, (1981), Fraser (1984)). Perhaps most important among these for antenna networks are imaging scale, the accuracy of image point measurement, and imaging geometry. This presupposes, of course, that a high-precision photogrammetric camera and appropriate data reduction scheme (the self-calibrating bundle adjustment) are employed.

With regard to imaging scale, the guiding rule is a simple one: the antenna should be imaged at the largest practicable scale. Large format cameras such as the CRC-1 from GSI (Brown, 1984) are essentially mandatory if optimal accuracy is required without the imposed constraint of imaging an excessive number of photographs, which is the course of action often required for large antennas when small and medium format close-range cameras are employed. As regards photo measurement, the AutoSet video-scanning monocomparator developed by GSI (Brown, 1986) displays an RMS *xy* film reading accuracy of about 0.4 μm. This fact alone enables antenna measurements to be carried out from three to ten times more accurately (as indicated by the computed standard errors of *XYZ* object point coordinates) than would be the case if image mensuration was carried out on a conventional photogrammetric comparator or analytical plotter. In addition, the automatic comparator measurement rate of about one point per second is some five times faster than human setting.

It is intuitively apparent that the accuracy and reliability of the photogrammetric triangulation process will be greatly influenced by the number and geometry of intersecting rays. The impact of the number and geometry of camera stations on photogrammetric network precision can be illustrated through reference to Figures 1 and 2. Shown in Figure 1 is a camera station configuration appropriate to the measurement of an antenna reflector of diameter *D* from convergent photography taken by a large format (23- by 23-cm) camera of 240-mm focal length. For the example given, all exposure stations are located at a distance of 1.3 diameters (1.3*D*) from the vertex and all cameras are pointed towards it. The stations are symmetrically disposed with respect to the reflector axis, and lie on the perimeter of the circle shown. The angle θ is referred to as the angle of convergence.

Shown in Figure 2 are the effects on accuracy of (a) varying the angle of convergence from 40 to 110 degrees, and (b) varying the number of equally spaced photographs around the circle from 2 to 12. A unique pair of coordinate standard error curves, which depend upon the magnitude of the convergence angle, are shown for each given number of camera stations. In generating these accuracy curves, an image coordinate measurement accuracy of 1.5 μm has been used. For image coordiniate digitization on GSI's AUTOSET automatic film reader, such a level of measurement precision is very conservative. Each proportional accuracy (standard error di-

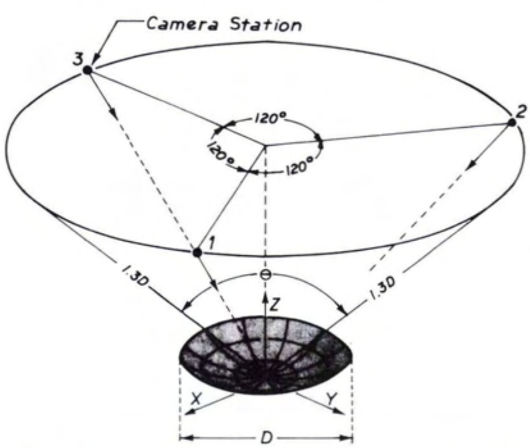

FIG. 1. Illustration of a symmetric three-station photogrammetric network for antenna measurement. Camera has a focal length of 240 mm and a format of 23 by 23 cm.

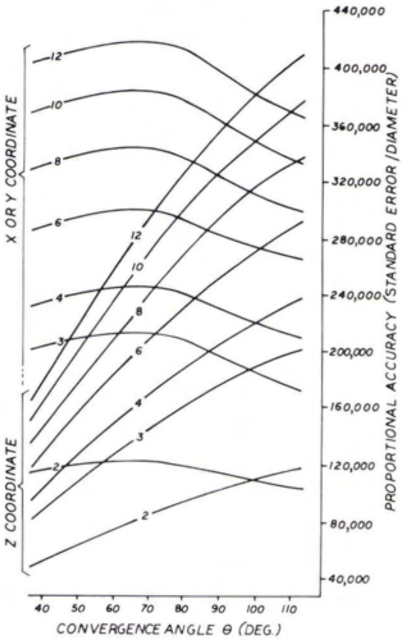

FIG. 2. Average proportional accuracies of photogrammetric triangulation to be expected from generalization of Figure 1 to various numbers of stations and various angles of convergence. RMS accuracies of plate coordinates are assumed to be 1.5μm.

vided by diameter *D*) value represents an RMS estimate for points (100 or more) spread throughout the reflector surface area. These RMS values have been obtained from the covariance matrix of *XYZ* object point coordinates generated in a free-network bundle adjustment in which inner-constraints were imposed on all object points (see Fraser (1982, 1984) for a further account of the free-network approach). It is interesting to note that the so-called 'limiting standard errors,' which are obtained by assuming that the projective and self-calibration parameters are free of error (i.e., standard error of zero), are for all practical purposes the same as the free-network estimates. This level of agreement may, however, only apply to networks with a 'strong' imaging geometry.

Coordinate standard errors are relatively homogeneous over the entire reflector surface. This is primarily due to the relatively narrow field of view of the camera, which results in all points exhibiting near enough to the same intersection geometry. Although the point-to-point precision remains reasonably constant, there is a significant variation between accuracies in the *XY* plane and the *Z* direction. For low convergence angles the standard errors in *Z* are appreciably poorer than in *X* and *Y*. This descrepancy in precision is purely a function of the geometry of ray intersections. As the convergence angle increases, so the accuracy in the *Z* component improves. At a convergence angle of about 100°, standard errors in *X*, *Y*, and *Z* become essentially equal to one another.

The accuracies of triangulation obtained for points on the antenna increase approximately in proportion to the square root of the number of photographs. For example, the exposure of two photos at each of the stations in Figure 1 would enhance the accuracy by a factor of 1.4 as compared to the case of a single photo at each of the three camera stations. As can be seen from Figure 2, accuracies can normally be expected to improve at a somewhat faster rate when additional camera stations are employed because of the improvement in triangulation geometry.

For surface calibration surveys, accuracies in *Z* are typically of more importance than accuracies in *X* and *Y*. This would suggest the adoption of a large angle of convergence, θ; for example, in the range of 100° to 110°. However, at large angles of convergence, perspective foreshortening of the photographic targets can increase to the point where image mensuration is affected. Accordingly, a θ range of 60° to 90° is generally adopted for the measurement of parabolic antennas. As an example of the use of Figure 2, consider the case where an accuracy in *Z* of *D*/200,000 is desired and a convergence angle θ of 80° is adopted. From the figure it can be seen that a minimum of six photographs would be necessary. With this geometry the corresponding accuracies in *X* and *Y* approach *D*/300,000.

For preliminary planning purposes, a general insight into the level of accuracy anticipated in a photogrammetric measurement of an antenna can be gained from Figure 2. It must be remembered, though, that the accuracy curves have been defined in a fairly narrow context; namely, they relate to the symmetrical configuration of camera stations shown in Figure 1 and to a camera of 240-mm focal length. Obviously, circumstances may dictate that a photogrammetric network for an antenna measurement have both an imaging geometry different from that shown in Figure 1 and a camera of focal length differing significantly from 240 mm. Indeed, of the five measurements discussed later in this paper, only two utilized a geometry similar to the symmetrical distribution shown in Figure 1, although all but one employed the CRC-1 camera with a lens of 240-mm focal length. A wide range of alternative set-ups to the one shown in Figure 1 are possible. As far as design accuracies are concerned, the important consideration is that for a postulated situation one can always execute a computer simulation of the photogrammetric triangulation in order to predict associated *XYZ* coordinate accuracies. A number of iterations of this process can lead to a nearly optimal experimental design within the specified framework of constraints. Indeed, it is normal practice at GSI to subject any new project to such a process of optimization unless it happens to conform closely to a previously executed project.

RECENT APPLICATIONS

LARGE PARABOLIC ANTENNA

DSS-15 is a large cassegrain antenna situated at a NASA tracking station in the California desert near Goldstone. In mid-1985 a photogrammetric calibration survey of this antenna, which is shown in Figure 3, was undertaken for the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. Surface conformity measurements of both the primary, quasi-paraboloid, 34-m diameter reflector (m-ref) and the secondary, quasi-hyperboloid, 3.6m diameter reflector (s-ref) were required at two antenna orientations for each reflector. The m-ref was initially measured in the 45° elevation orientation, and then in the 'horizontal' (6° elevation angle), whereas the s-ref was photographed in the vertical and 'horizontal' orientations.

One very noteworthy feature of the DSS-15 calibration survey, which made it unique in comparison to other large antenna measurements recently conducted by GSI, was that the 1000 or so retrotargets on the m-ref surface and the 250 retrotargets on the s-ref were measured in a common coordinate system. Thus, the photogrammetric measurement went beyond the usual scope of independent determination of m-ref and s-ref surface conformity. The subreflector's position and orientation with respect to the vertex and axis of the m-ref were also measured, and it was possible to determine the offset and angular relationships between s-ref and m-ref coordinate axes. When viewed in the context of alternative reflector surface mensuration techniques such as microwave holography and direct optical systems, the measurement of the s-ref in the same reference coordinate system of the m-ref presents a problem which is most often not solvable in a practical manner. The photogrammetric approach, however, is extremely versatile and can be adapted to a wide range of operational requirements.

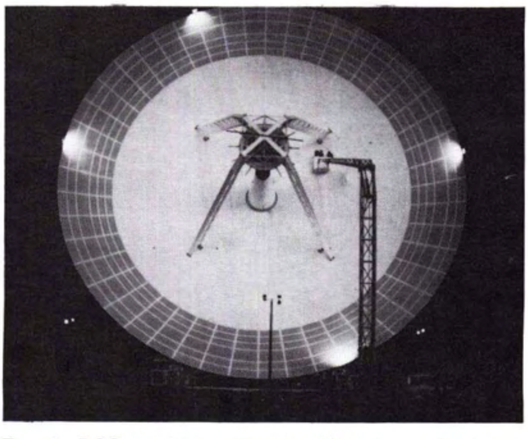

FIG. 3. DSS-15 34-m antenna. Also shown is cherry-picker used to position the camera at each exposure station.

Four separate photogrammetric networks were designed for the DSS-15 survey. In the two m-ref measurements, photography was secured with the CRC-1, with 240-mm lens, over an imaging distance of close to 50 m (imaging scale of approximately 1:200). For the antenna in the 'horizontal' position, nine camera stations were occupied so as to provide the convergent imaging configuration shown in Figure 4. A cherrypicker (Figure 3) was used to raise the camera and operator to the required elevation at three positions, and the lateral convergent geometry was obtained by rotating the antenna in azimuth through two rotations of approximately 35°. For the measurements at a 45° elevation angle, cherrypicker height limitations necessitated the adoption of a less than optimum imaging configuration comprising ten camera station positions. Nevertheless, the network exhibited sufficent geometric strength to yield point positioning accuracies which were well within the specified tolerances.

In Figure 3 a dozen stand-off brackets of a metre or so in length can be seen positioned about the quadripod apex, around the circumference of the s-ref. At the end of each of these brackets a back-to-back retrotarget was positioned in such a way that the point would be imaged in both the photography taken of the m-ref and that taken for the s-ref networks. It was through these 'tie' points that the s-ref and m-ref *XYZ* point coordinates could be determined in a common reference system.

The procedure involved in securing the photography of the s-ref is illustrated in Figure 3. With the antenna in the 'horizontal,' position the cherry-

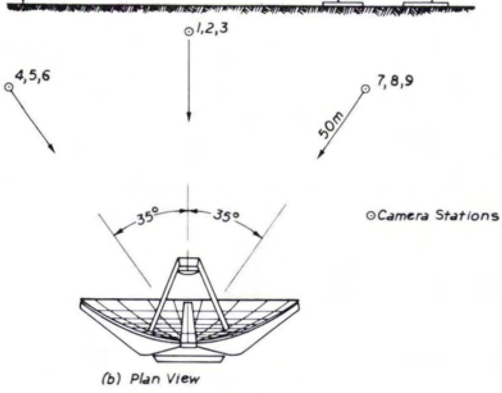

FIG. 4. Network geometry comprising nine camera stations for DSS-15 measurement.

picker was used to position the camera at each of six stations close to the m-ref surface. The six stations fell nominally on the circle containing the quadripod legs, thus giving rise to an imaging distance of approximately 10 m (average imaging scale of 1:40). For the vertical antenna orientation, the camera operator simply walked to the desired position on the m-ref surface, lay on his back with the camera hand-held on his chest, and took the photography of the s-ref which stood some 10 m above him. Six stations were again occupied.

Absolute scale was established in the measurement by means of known distances between retrotargets on a precision 30-m MINVAR survey baseline tape which was suspended under tension across the face of the m-ref. No other object space control was employed.

Photography was scheduled for a six-hour period from about midnight to dawn on a night when the antenna had no tracking commitments. The photogrammetric measurement did not necessitate any additional antenna downtime.

In order to exploit the fully automatic image coordinate measurement feature of the AutoSet monocomparator, approximate *XYZ* coordinates of target points are required. These coordinates are determined in a preliminary photogrammetric triangulation of a subset of the photographs. In the case where all targets are imaged on each photograph, two images only need be measured. The initial film reading procedure involves the semi-automatic mode of AutoSet in which the operator brings each target into the measuring window with the aid of the digitizing pad control unit. From the 19 photographs forming the two m-ref networks, three were measured in this manner, and the remaining 16 were read in the fully automatic mode. To read the 1000 or so targets on each of the initial three photographs, a time of about 90 minutes was required. After the computation of approximate *XYZ* coordinates of all target points, the fully automatic measurement took only 40 minutes for each of the remaining photographs. A similar procedure was followed for the s-ref. Three exposures were initially read semi-automatically, each measurement taking about 25 minutes, with the remaining nine photographs being measured automatically in just under 10 minutes per photo. The total film reading time amounted to 18 hours. A conservative estimate for the time required to measure the frames manually on an analytical stereocompiler, with double settings on each target, is 100 hours, some five times longer than the time expended on AutoSet.

The self-calibrating bundle adjustment approach was employed for the data reduction of the four networks. Accuracies achieved surpassed the design criterion of 0.25 mm (one-sigma value) in each photogrammetric triangulation. For the m-ref network at the 6° elevation, mean coordinate standard errors of 0.13 mm in *X* and *Y*, and 0.22 mm in *Z* were obtained. The mean positional standard error of 0.17 mm corresponded to a proportional accuracy of 1 part in 200,000. The measurement at the 45° position yielded a mean standard error of 0.19 mm, or 1 part in 180,000. Not surprisingly, given the much larger imaging scale involved, the two s-ref networks yielded considerably higher levels of point precision. In each case a standard error value of 0.04 mm was obtained.

For an independent check of the photogrammetric measurement results, JPL personnel placed four shimmed targets on the m-ref surface. The thicknesses of these spacers was then determined photogrammetrically by computing the 'height' difference between each shimmed target and the m-ref surface at that point. Thus, eight independent measurements of thickness were obtained, providing a mean value for each of the four shims. On comparing the true versus measured thickness, JPL determined the RMS error of the measurements to be 0.15 mm, with the range being from 0.02 mm to 0.30 mm. These results confirmed the accuracy of the photogrammetric calibration procedure.

Following photogrammetric triangulation, the three-dimensional coordinates were subjected to a best-fit paraboloid analysis, and a contour map of surface departures was compiled. In the case of DSS-15, it was also possible to quantify the changes in shape of the m-ref and s-ref surfaces between the different elevation settings of the antenna. The variations in alignment and relative position of the s-ref with respect to the m-ref were also determined.

For tracking in the microwave X-Band range, a reflector surface accuracy of about 0.25 mm is required. The tracking of higher frequencies, however, necessitates an even more stringent tolerance on surface conformity. In the case of the 22 GHz range, an appropriate surface accuracy level is about 0.13 mm, or 1 part in 260,000 of the DSS-15 diameter. Consider now the necessary upgrading of the photogrammetric network for the 'horizontal' position that would be required to yield this level of accuracy. As it turns out, one practical option would be to retain the basic configuration of nine camera stations shown in Figure 4, and expose two photos at each station. This simple doubling-up of photographic coverage would yield a design mean standard error of 0.12 mm, or 1 part in 280,000. In terms of manhours expended, the cost of achieving this increased level of accuracy would be modest: virtually no extra time required in data acquisition, an increase of a few hours in data reduction, and only six extra hours of film reading on AutoSet.

Antenna Panels

Each of the individual panel sub-assemblies making up the surface of a large antenna reflector also needs to be manufactured to tight surface tolerances. Prior to being fitted in position on the antenna, the surface conformity of the panel must also be verified. Traditionally, this task has been carried out by contact measurement using templates—a tedious and time consuming procedure. More recently, photogrammetry (e.g., El Hakim, 1984) and digital theodolites have been employed. Here, the example of a photogrammetric inspection measurement of a 2.1-m by 2.7-m panel from the DSS-15 antenna is discussed.

The photogrammetric network design for the measurement called for the positioning of four camera stations. These were nominally situated along extensions of the two panel diagonals some 3 m out from the center at a height of 3 m above the reflector surface. Two photographs per station were taken using the CRC-1 with 240-mm lens. A sample photograph of the array of 200-odd target points, which was exposed at station number 3, is shown in Figure 5. The final accuracy obtained was well within the client's specification of 0.03 mm. In fact, the mean positional standard error was 0.014 mm, or 1 part in 240,000.

Each of the eight photos was read on AutoSet in less than 15 minutes. Indeed, the time for mensuration and data reduction totalled 2-½ hours. When combined with the one hour required to take, process, and dry the photography, the total panel measurement time amounted to about 3-½ manhours. Mention was made earlier that digital theodolite systems have been employed for the inspection of panels. It is noteworthy that, in the measuring task discussed, the one-man photogrammetric operation yielded results of significantly higher accuracy and reliability than those feasible with a real-time digital theodolite system employing two operators over roughly the same measuring time. Of course, it is possible to achieve similar levels of accuracy by adding additional theodolites to the real-time system, or utilizing more theodolite stations and post-processing the data through a photogrammetric bundle adjustment approach. Both options, however, impact very unfavorably on the economy of the measuring process.

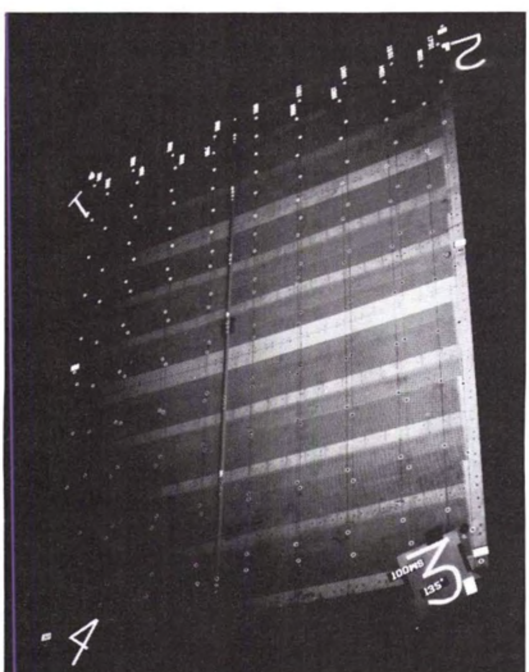

FIG. 5. Microwave antenna panel.

SMALL SPACE DEPLOYABLE ANTENNA

Figure 6 shows an offset cassegrain antenna of 2.9-m diameter mounted in a NASA radio frequency (RF) testing facility. The antenna assembly forms part of the Advanced Communications Technology Satellite. For such an antenna, surface shape requirements are very stringent, and in this case the reflector was designed to maintain a shape that was within 0.08 mm while being subjected to significant thermal loading and acceleration. In order to verify that the reflector conformed adequately to design, a photogrammetric 'mapping' of the dish was carried out.

The design accuracy specification for the measurement called for a mean standard error of *XYZ* coordinates of 0.025 mm. With the aid of GSI's interactive design simulator, a 12-photo network was planned. Six camera stations were to be positioned so as to provide a strongly convergent imaging geometry. Two photographs were to be taken at each, with there being a nominal 180° camera roll between the successive exposures. It should be noted that a six-photo network (i.e., only one photo per

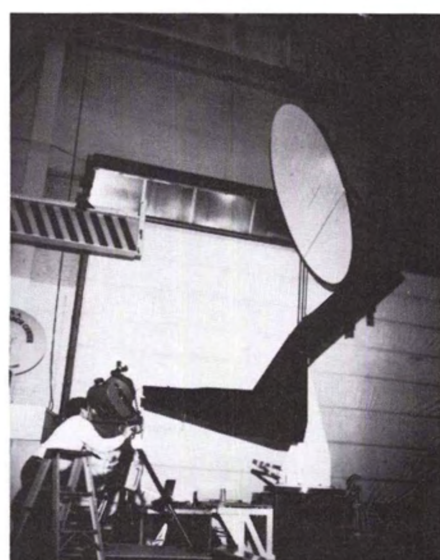

FIG. 6. Photographing the 2.9-m space deployable antenna (photo courtesy of NASA-Lewis Research Center).

station) could have yielded the required accuracy, but because this project was one of the first on which the AutoSet monocomparator was employed, the level of precision was increased to aid in a general evaluation of system performance.

Some 680 retrotargets were positioned in a 10-cm grid pattern on the reflector surface, and an additional 250 closely spaced targets formed a cross at the center of the dish. The CRC-1 camera with 240-mm lens was used for the photography, which was taken at a scale of about 1:20. By virtue of the targets being in a grid pattern, the automatic line following mode of AutoSet could be employed in the film reading process. Normally, with double settings on a manually operated photogrammetric comparator, it would take a GSI technician about four hours to manually read 960 image points. The same task on AutoSet required about 45 minutes when line following was used, and just under 35 minutes when the fully automatic mode was selected.

In the self-calibrating bundle adjustment of the 12-photo network, an RMS value of 1.1μm was obtained for the residuals of image coordinates. This level of misclosure was a little higher than anticipated and may be attributable in part to short period deformations of the reflector; a thermally induced movement of only 0.005 mm is sufficient to account for an image residual of 0.25 μm at the adopted photographic scale. One of the often quoted merits of photogrammetry is the fact that the method displays a very high internal reliability as a result of incorporating considerable observational redundancy. For this antenna measurement the least-squares bundle adjustment exhibited 18,600 degrees of freedom. The computed mean standard error for the *XYZ* coordinates was 0.008 mm, or 1 part in 370,000, and no point displayed a positional standard error exceeding 0.012 mm (1 part in 250,000).

Antenna Mold

Figure 7 shows a 1.8-m by 4-m mold which is used for forming composite antennas for shipboard use. The surface conformity of the final antenna to its design shape is, naturally, a function of the surface accuracy of the mold. Photogrammetry provides an ideal tool for the surface calibration of such molds. In the case of the mold shown in Figure 7, it was required that the surface be measured to an accuracy of 0.025 mm, or about 1 part in 175,000 of the diagonal dimension.

To meet the accuracy criterion specified, GSI designed a photogrammetric network comprising ten camera stations, as shown in Figure 8. Basically, the camera stations were symmetrically disposed at 45° intervals around the mold, at radial distances (in the horizontal) of approximately 4.3 m. The measurement of a mold generally requires more camera stations than the measurement of the formed antenna. This is because the mold's convex chape invariably presents foreshortening problems, and additional photographs are required to ensure that all targets are imaged with a sufficiently strong geometry. To overcome image foreshortening due to convex surface curvature, two further camera stations were added, some 3-m out along the positive and negative *X*-axes. With the exception of the two outer most exposure positions along the *X*-axis, which were at a height of 2.5 m above the center of the mold surface, all camera stations were at heights of close to 4.2 m.

A CRC-1 camera with 240-mm lens was employed for the photography, and a total of 953 retrotargets were imaged, nine of these being on a scale tape which lay adjacent to the mold. All photos were measured on the AutoSet monocomparator. Following the initial reading of four negatives in semi-automatic mode with automatic line-following, all remaining photos were digitized in fully automatic mode, the time required for each being just over 30 minutes. In the subsequent data reduction, RMS standard error values obtained in the three coordinate axes were 0.012 mm, 0.010 mm, and 0.013 mm for X, Y, and Z, respectively. The resulting mean

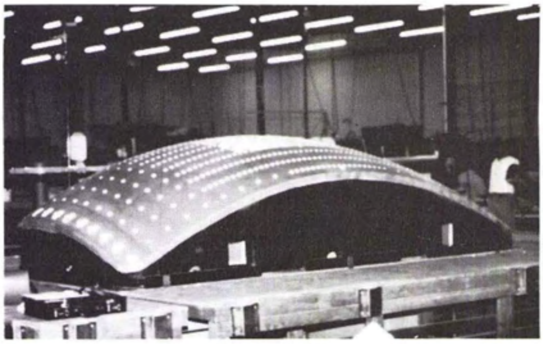

FIG. 7. 1.8- by 4-m antenna mold.

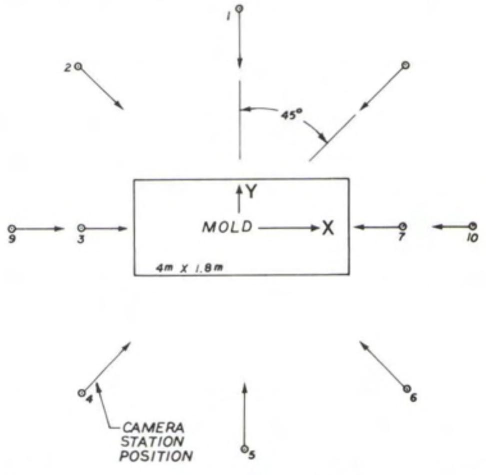

FIG 8. Camera station configuration for mold measurement.

positional standard error of 0.012 mm was represented a proportional accuracy of better than 1 part in 360,000.

In addition to measuring the mold, GSI has also completed calibration surveys of a number of the antennas formed on it. In one instance the opportunity arose for checking the photogrammetrically determined antenna surface profiles against those measured on a large coordinate measuring machine, the accuracy of which was about 0.025 mm. A high degree of agreement was found in the data from the two independent measuring techniques. Overall, an RMS discrepancy value of just over 0.025 mm was obtained from a sample of several hundred points. This level of difference was consistent with the one-sigma photogrammetric positioning accuracy of 0.02 mm.

Space Deployable Hoop-Column Antenna

In Figure 9 is shown an artist's rendition of a large hoop-column antenna deployed on the space shuttle. The technology for this antenna is at present being developed by NASA. As part of the developmental process, a 15-m deployable model has been built. This model is shown in Figure 10. The reflector surface of the model is formed by 24 fabrication sections of gold-plated molybdenum mesh which are sewn together. This mesh is supported by a rigid hoop about the antenna rim, and by supporting cords from the central column, both above and below the reflector. The upper cords, which are of a quartz filament material, simply support the hoop whereas the lower cords are used to shape the antenna surface. The 'ribs' shown in Figure 10 are not rigid members but a truss assembly with a "wedding veil" material which is provided to avoid tangling problems with the supporting cords during deployment. The antenna is an extremely light-weight structure; the mesh surface of approximately 175 m² weighs only some 4 kg.

Fig. 9. Artist's rendition of a large hoop-column antenna deployed on the space shuttle (photo courtesy of NASA-Langley Research Center).

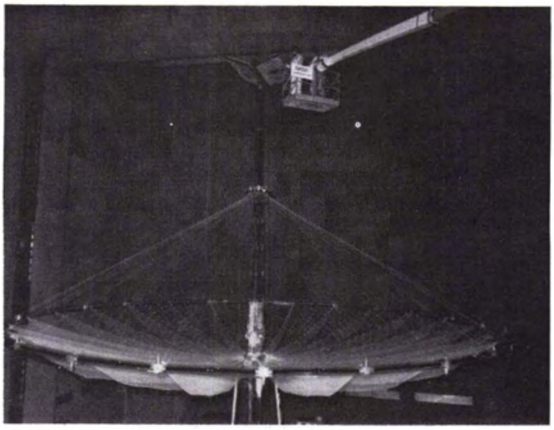

Fig. 10. A 15-m diameter model of the hoop-column antenna (photo courtesy of NASA-Langley Research Center).

To provide surface measurements for verification of conformance to design during both deployment and RF testing, photogrammetry was employed. In all, six photogrammetric measurements of the antenna were carried out by the NASA Langley Research Center, utilizing the STARS industrial photogrammetric system from GSI. The goals of the photogrammetric surveys were (a) to determine the RF surface to an accuracy of 0.18 mm (1 part in 83,000), (b) to provide scaling and orientation data on the reflector and support structures, and (c) to develop a very fast turn-around capability for the measurement results so as to minimize costly downtime in the RF testing facility.

In order to achieve the measurement accuracy of 0.18 mm, a photogrammetric network of eight camera stations was established. The antenna was photographed with the CRC-1 camera with 120-mm lens from vantage points about 6.5 m above the hoop, the stations being spaced at approximately 45° intervals around the rim. A total of 3300 photogrammetric retrotargets were positioned on the surface and support structure, as well as on the floor below the antenna. In the six photogrammetric surveys conducted, however, not all target points were observed; some 1000 points were included in the first two measurements, and this number was increased to 2000 in the remaining four networks.

Immediately following the photographic data acquisition phase, the negatives were dispatched to GSI's facility in Florida where they were measured on the AutoSet comparator. The utilization of AutoSet was necessary in light of the goal to achieve a fast turnaround capability (NASA's photogrammetric system contained only a manually operated monocomparator at that time). In fully automatic mode the reading time on AutoSet of 2000 points on a photograph was about 85 minutes; a total of 13 hours was required to measure each of the last four networks. Digitized image coordinates were transferred to the Langley Research Center over a telephone data line for subsequent photogrammetric triangulation.

Original simulations of the antenna measurement indicated that photogrammetric accuracies of close to 0.12 mm could be expected to be obtained for the triangulated *XYZ* coordinates. The resulting accuracy estimates were, however, somewhat poorer than this, the mean standard error being of the order of 0.17 mm (1 part in 88,000). The answer to why design precision was not achieved lay in the fact that the antenna was non-rigid during the time in which the photography was taken. The lightweight structure exhibited torsional motion in the presence of indoor air currents, and after oscillating appeared to settle back to a slightly different shape. The resulting surface distortion was primarily tangential (constant *Z*) and had little effect on the RF surface. The effect on the level of closure in the photogrammetric triangulation, however, was quite noticable. Routine application of AutoSet in combination with the CRC-1 typically yields RMS triangulation residuals of 0.5 to 1.5 μm, whereas in the hoop-column antenna measurements closures of 3.5 to 4.5 μm were obtained.

Following photogrammetric triangulation for each independent network, *XYZ* coordinates were transformed into the reference system of the design coordinates. This provided an independent basis for assessment of the RF quality of the surface. In addition, the coordinate data served as input for a structural finite element analysis, which was performed by NASA to facilitate optimum surface 'fine tuning' of the reflector shape. Due to the tremendous time savings afforded by AutoSet, the photogrammetric triangulation and subsequent finite element analysis could be carried out and completed concurrently with other necessary preparations for testing in the RF test laboratory. Thus, costly RF facility downtime was eliminated and all test objectives were met on schedule.

CONCLUDING REMARKS

Recent technological advances in close-range photogrammetry have had considerable impact on the accuracy and economy of antenna mensuration. The five measurement projects reviewed illustrate that accuracies surpassing 1 part in 250,000 of the antenna diameter are now routinely obtainable. Moreover, with the development of the AutoSet automatic comparator, the photogrammetric measurement can now be carried out both more rapidly and at considerable cost savings as compared to the conventional manual approach. From the discussion of antenna mensuration accuracy, it has been shown that object point positioning accuracies of 1 part in 500,000 are now within the state of the art.

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