PHOTOGRAMMETRIC MEASUREMENT OF THE ARECIBO PRIMARY REFLECTOR SURFACE

Presented Paper
Coordinate Measurement Systems Committee Conference
Albuquerque, NM
August 13 – 17, 2001

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KEYWORDS: Arecibo, antenna, radio astronomy, photogrammetry, telescope

ABSTRACT

The largest single dish radio telescope in the world is located at the Arecibo Observatory in Puerto Rico. First operational in 1963, the observatory is today part of the National Astronomy and Ionosphere Center (NAIC). The NAIC, a research center operated by Cornell University in cooperation with the National Science Foundation, enables research in astronomy, planetary studies, and space and atmospheric sciences. The performance of the telescope depends to a great extent on the primary reflector surface. This spherical surface is composed of 38,788 perforated aluminium panels. Deviation of these panels from an ideal spherical surface is attributed to a variety of causes. These include ongoing soil motions and construction damage that occurred during the most recent upgrade, completed in 1997. Previous adjustment of this surface has been based upon theodolite measurements. As current surface error requirements could not be achieved in this manner, a photogrammetric approach has been adopted. This paper begins with a brief overview of the Arecibo radio telescope. The survey, analysis, and results to date of the photogrammetric measurement of the primary reflector surface are described, followed by an outline of future work.

Figure 1: Aerial view of the Arecibo radio telescope showing the large primary reflector, the suspended platform with Gregorian dome housing the secondary and tertiary reflectors, and the platform support towers. (*Photo by David Parker/Science Photo Library, courtesy of the NAIC - Arecibo Observatory, a facility of the NSF*)

1. INTRODUCTION

The largest single-dish radio telescope in the world is located at the Arecibo Observatory, approximately fifty miles southwest of San Juan, Puerto Rico (Figure 1). The primary reflector surface is spherical in shape, 1000 feet in diameter, and 161 feet deep. The surface of the dish covers 18 acres, the equivalent of approximately 26 U.S. football fields.

The performance of any radio telescope depends greatly on the degree to which the reflector surface conforms to its designed geometric shape. The spherical surface of the Arecibo primary reflector is composed of 38,788 perforated aluminum panels. Departure of the panels from an ideal surface has been attributed to a variety of causes including ongoing soil motions and construction damage that occurred during the most recent upgrade completed in 1997. Previous adjustment of this surface has been based upon theodolite measurements. As current surface error requirements could not be achieved in this manner, a photogrammetric approach has been adopted.

The measurement and alignment of antenna reflector surfaces is often accomplished via close-range photogrammetry. In fact, the first high accuracy industrial photogrammetric surveys were performed to quantify the surface of large antennas and radio telescopes. Furthermore, the requirement to measure such structures was instrumental in the development of systems based on the principles of analytical, monoscopic/convergent photogrammetry (Fraser, 1992). Early descriptions of photogrammetric antenna measurement can be found in Brown (1962) and Forrest (1966). The size and unique design of the Arecibo telescope make it a noteworthy photogrammetric application.

Photogrammetric surveys of the primary reflector surface were performed in the autumn of 2000; January, 2001; and again in May, 2001. In the following, the surveys, analysis, and results to date are described and future work is outlined. The paper begins however, with a brief history and description of the telescope itself.

Figure 2: Suspended platform with azimuth arm supporting the radome on the right and 96 foot line feed receiver on the left. The secondary and tertiary reflectors and horn feeds are housed within the radome.

2. THE ARECIBO RADIO TELESCOPE

2.1 History

The Arecibo Observatory was constructed from 1960 to 1963 by Cornell University under contract to the U.S. Air Force. It has been continuously operated by Cornell, initially for the Air Force and then for the National Science Foundation (NSF), which took over the facility from the Department of Defense in 1969. Since 1971, the observatory has been part of the National Astronomy and Ionosphere Center (NAIC). Research is conducted primarily in astronomy, planetary studies, and space and atmospheric sciences.

The near equatorial location of the telescope was chosen because it is ideal for both ionosphere and planetary studies. Additionally, the karst terrain in this area of Puerto Rico had many natural sinkholes that could be suitable for the construction of a spherical reflector.

2.2 Telescope Design

Parabolic antennas reflect incoming signals to a single focus. These antennas must be pointed directly at the signal source. As the primary reflector surface of the Arecibo antenna remains permanently fixed, different parts of the sky are examined by moving the receiver above it. Because the dish is spherical, signals are not reflected to the principal focus, but to points at various heights above the reflector surface. This is due to *spherical aberration*. As a result, line feed receivers were initially utilized to collect the signal.

The receivers are mounted on a rotating *azimuth arm*, which is in turn suspended from a large supporting platform approximately 500 feet above the reflector surface. The entire structure, weighing roughly 900 tons, is supported by 18 cables strung from three reinforced concrete towers placed around the dish with 120-degree separation. They are identified by their corresponding clock face positions, T4, T8, and T12. The tops of the towers are approximately 625 feet above the lowest point of the reflector surface. Each tower is back-guyed to ground anchors with seven 3.25 inch diameter steel bridge cables. The towers are seen in Figure 1. The 96-foot line feed receiver that remains in use today is seen in Figure 2 on the left side of the azimuth arm.

When the antenna was completed in 1963, the primary reflector surface was composed of wire mesh. Operating frequencies were below 600 MHz, limited primarily by this wire mesh surface. The current surface, composed of 38,788 perforated aluminum panels, was installed during the first major upgrade completed in 1974. Each panel is 3 x 6 feet and individually adjustable (Figure 3). The panels are supported by a grid of cables running north-south and east-west. These main cables are held in shape by approximately 2000 additional cables attached to concrete blocks on the ground below the reflector. These are referred to as tieback points (Figure 4).

Figure 3: Gregorian dome as seen from below through adjustable surface panels.

Figure 4: View underneath primary reflector showing tieback cables and blocks.

With the capability of adjusting the surface, the upper operating frequency increased to approximately 3 GHz. However, line feed receivers could not be constructed to specifications allowing operation at the highest usable frequencies. As a result, a second upgrade began in 1992. All but one line feed receiver were replaced by a Gregorian reflector system which would permit operation over the full frequency range afforded by the improved accuracy of the primary reflector, 8 GHz or higher. This system consists of specially shaped secondary and tertiary reflectors (Figure 5). These reflectors are housed within a 90-ton radome designed to protect them from adverse weather (Figure 2). The radome is suspended from the azimuth arm, 450 feet above the primary reflector surface. The new reflector combination brings the incoming radio waves to a single focal point maintained within a one-eighth inch circle (Steele, 1997). The line feed receivers (save one) were replaced by a variety of feed horns mounted on a rotating plate in such a way that they can be moved into the focus. Also part of the upgrade was the installation of a 50 foot high steel wire mesh ground screen around the dish, shielding the receiving system from radio noise radiated from the surrounding ground. The second upgrade was completed in 1997. More detailed descriptions of the Arecibo system design may be found in Kildal *et al*. (1991,1994).

3. PHOTOGRAMMETRIC MEASUREMENT

3.1 Surface Deformations

As mentioned above, the main cables are held in place by cables attached to concrete blocks on the ground under the primary reflector. Clearly, soil motions will have an effect on the reflector surface shape. Survey monitoring has indicated that soil motions have been significant, particularly in the southeast quadrant of the reflector. Part of the sinkhole had been filled in with dirt during construction and this area is less stable than the surrounding ground and more susceptible to motions produced by seismic tremors common to Puerto Rico.

The upgrade work itself caused some damage to the reflector surface. Panels were damaged by items dropped by construction personnel on the overhead platform. One large cable alone destroyed over 100 panels and some support cables when it was dropped from above (Goldsmith, 2001).

In a preliminary survey performed in the autumn of 2000, approximately 2000 retro-reflective targets were placed on the primary reflector surface, primarily at locations where tieback cables attach to the main cable support grid. The resulting unweighted rms surface error was approximately 15 mm. This was worse than what had been expected and an immediate adjustment of the tieback cables was undertaken. In January, 2001 the tieback points were resurveyed and the result showed an improvement in the rms surface error from 15 mm to approximately 5 mm. Early indications are that there has been a notable improvement in telescope performance after the adjustment of the tieback cables.

For optimum performance, the overall rms surface error should be less than 1/20 wavelength. At 10 GHz, this translates to 3 mm rms. It is believed that the panels themselves have an error of approximately 1 mm. The secondary and tertiary reflectors contribute smaller errors. Thus, the primary reflector surface adjustment error should ideally be below 2 mm rms. Photogrammetry was deemed to be the only practical means to achieve this level of accuracy (Goldsmith, 2001).

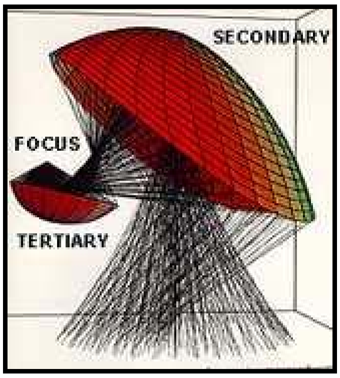

Figure 5: Radio waves are reflected through three surfaces before reaching the focus. (*Image courtesy of the NAIC - Arecibo Observatory, a facility of the NSF*)

3.2 Measurement System

The camera chosen for the measurement is the CRC-1, a large format, metric film camera manufactured by Geodetic Services, Inc. (GSI) of Melbourne, Florida. Designed specifically for close-range industrial photogrammetry, this camera is microprocessor controlled and uses standard aerial format film (23 x 23 cm). In combination with a 240 mm lens, the CRC-1 has an angular resolution of better than one arc second. A detailed description of the CRC-1 can be found in Brown (1984).

Digital cameras are clearly preferable for the majority of close-range industrial photogrammetric applications today. No film development and faster image measurement techniques means that results are available much faster and with less effort than with film cameras. However, for this application, the choice of a film camera over state-of-the-art digital cameras was made for several reasons. Firstly, available digital cameras have a considerably smaller imaging format. It is desirable that all or most of the targets be visible in each image. To achieve optimal accuracy with small or medium format cameras would require the acquisition of many more images than with a large format camera. Furthermore, the use of a small format camera with a shorter focal length lens would require that targets be so large as to be impractical and cost prohibitive. Using the CRC-1 and 240 mm lens, and with an average camera-object distance of 930 feet, three inch diameter retro-reflective targets were utilized.

Image measurement was performed on-site at Arecibo with the AutoSet-2, a sub-micron automatic monocomparator also manufactured by GSI (Brown, 1987). The AutoSet has a mensuration rate of better than two points per second.

3.3 Network Design

As is typically the case in industrial photogrammetry, the design of an appropriate imaging geometry was constrained by the limited availability of practical image stations in the immediate vicinity of the primary reflector surface. It was determined through simulation that shooting from the tops of the towers only would yield the desired triangulation accuracy of better than 0.5 mm. This corresponds to a mean proportional accuracy of approximately 1 part in 610,000. As the entire surface could not be seen in a single image, a total of six camera stations were utilized on towers T4 and T8. Three low stations cover the near field left, center,and right and three high stations cover the far field left, center, and right. Two pictures were taken from each station, one normal and one with a ninety degree roll to facilitate camera self-calibration. A total of 12 images each were captured from T4 and T8. The view from T12 is partially obscured by a catwalk that provides access from the ground to the suspended platform. Here, the imaging geometry for towers T4 and T8 was repeated on either side of the catwalk, giving 24 images for T12 and 48 images for the entire network.

3.4 Targeting and Image Capture

In the most recent survey completed in May of 2001, each of the 38,000 panels was targeted in addition to the 2000 tieback points for a total of approximately 40,000 points. Again, each of the targets was three inches in diameter.

Image capture from the towers is a difficult procedure. Personnel can reach the tower tops only by a series of ladders built into the side of the tower. Camera, strobe, tripod, and miscellaneous equipment are hoisted to the top by winch and a pulley attached to one of the platform support cables. Images are taken in the evening, immediately after the sun has dropped to a point where no direct sunlight falls on the reflector surface. Because of the time and work required, images are taken from only one tower per night. Weather permitting, all images will be captured in three consecutive nights. In the past, rain has made this impossible but during the latest measurement in May of 2001, the weather was cooperative.

3.5 Image Measurement and Reduction

Due to the large number of targets involved, plus time and personnel constraints, the measurement and reduction process became more than a matter of simply measuring all the pictures and performing a bundle adjustment. A large number of local workers had been hired and were standing by, waiting for data that they could then take into the field to perform the individual panel adjustments. It became necessary to devise a scheme that would get the field crew on the job as quickly as possible.

As the 2000 tieback points had been surveyed and adjusted in the Autumn 2000 survey, it was decided to make an initial measurement pass through all pictures for these points only. A bundle adjustment was performed for this data set and the triangulated coordinates of the tieback points would then serve to define the best-fit sphere of the primary reflector surface. The remaining 38,000 points on the reflector were divided into quadrants and each quadrant further subdivided into four patches of approximately 2400 points each.

One measurement pass through all 48 pictures was made for each 2400 point patch. After each patch has been measured, the points are triangulated using the exterior orientation and camera calibration parameters obtained from the tieback point bundle adjustment. The newly triangulated points are then measured to the ‘ideal’ spherical surface defined by the tieback points. The deviations of each panel from the ideal surface are converted into screw turns for field adjustment. In this way, the field crew could quickly begin on the physical panel adjustments for the first patch while the measurement and reduction of the remaining patches was ongoing. As the field crew requires approximately two weeks to complete adjustment of one patch it is relatively easy for the measurement and reduction personnel to stay ahead. At an approximate mensuration rate of two points per second, one patch in a single image can be measured in 20 minutes and 16 hours are required for all 48 images. The measurement of all points in all images would then take approximately 256 hours.

4. MEASUREMENT RESULTS

4.1 Tieback Bundle Adjustment

Ultimately, 47 of the 48 pictures taken were utilized and 1928 points were adjusted. The rms of the triangulation closure was 1.04 microns. The rms of the triangulated coordinate standard errors was 0.010, 0.011, and 0.012 inches in X, Y, and Z respectively. These correspond to mean proportional accuracies of 1 part in 1,250,000; 1 part in 1,111,111; and 1 part in 1,000,000 also in X, Y, and Z.

4.2 Dense Patch Triangulation

At the time of writing, eight patches have been measured and triangulated. These comprise all of the northeast and southeast quadrants (designated Quad 1 and Quad 2). The rms of the deviations from the best-fit surface of the triangulated points from the tieback bundle and each individual patch is shown in Table 1 below. The majority of the patches show an rms surface error between 5 and 6 mm. It is noteworthy that the patches lying furthest east show the largest deviations. This could possibly be attributed to the observation that the most significant soil motions occurred in the southeast quadrant of the reflector.

5. FUTURE WORK

Measurement and reduction of the northwest and southwest quadrants is ongoing at the time of writing as is the field adjustment of reflector panels. When all panels have been adjusted, the reflector will be surveyed again. It is likely that the survey/adjustment cycle will require several iterations. In the interim, antenna testing at higher frequencies will be performed to evaluate changes in telescope performance resulting from the adjustment of the primary reflector surface.

Table 1: RMS Deviations from Best-fit Sphere

Data Set	RMS of Deviations (*mm*)
Tieback points	1.29
Quad 1 Patch 1	5.76
Quad 1 Patch 2	5.43
Quad 1 Patch 3	5.89
Quad 1 Patch 4	6.67
Quad 2 Patch 1	4.54
Quad 2 Patch 2	5.16
Quad 2 Patch 3	4.98
Quad 2 Patch 4	8.38

6. CONCLUDING REMARKS

In the last decade, the availability of digital cameras and ongoing advances in automation of the photogrammetric process have dramatically improved the efficiency and economy of close-range photogrammetry for industry and engineering. For the majority of applications, this has rendered the use of film cameras obsolete. However, for unique applications such as the Arecibo primary reflector surface, film clearly still has a role to play.

As antenna technology advances, the need for more accurate measurement and alignment of reflector surfaces increases. Historically, photogrammetry has demonstrated the capability of satisfying the precision requirements for antenna measurement. As illustrated in this paper, it continues to do so.

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