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A New Fabrication Method for Precision Antenna Reflectors for Space Flight and Ground Test

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Summary

Communications satellites are using increasingly higher frequencies that require increasingly precise antenna reflectors for use in space. Traditional industry fabrication methods for space antenna reflectors employ successive molding techniques using high- and low-temperature molds for reflector face sheets and then a final fit-up of the completed honeycomb sandwich panel antenna reflector to a master pattern. However, as new missions are planned at much higher frequencies, greater accuracies will be necessary than are achievable using these present methods. A new approach for the fabrication of ground-test solid-surface antenna reflectors is to build a rigid support structure with an easy-to-machine surface. This surface is subsequently machined to the desired reflector contour and coated with a radiofrequency (RF) reflective surface. This method was used to fabricate a 2.7-m-diameter ground-test antenna reflector to an accuracy of better than 0.013 mm (0.0005 in.) rms. A similar reflector for use on spacecraft would be constructed in a precise manner but with space-qualified materials. This report describes the design, analysis, and fabrication of the 2.7-m-diameter precision antenna reflector for antenna ground test and the extension of this technology to precision, space-based antenna reflectors.

Introduction

Since many commercial and NASA missions will require higher frequency communication bands, spacecraft antennas of increasing precision will be needed to minimize distortion of the antenna pattern received on the ground. For example, the 20/30-GHz band, which is just starting to be used commercially, will require reflector surface contour accuracies of less than the wavelength $\lambda/100$ at 30 GHz, or 0.1 mm (0.004 in.) rms. However, the 60-GHz band proposed for intersatellite link communications would require these tolerances to be halved. Radiometric research antennas for NASA's proposed "Mission to Planet Earth" atmospheric research spacecraft may operate at frequencies up to 183 GHz. This frequency range translates to reflector accuracies of 0.016 mm (0.00065 in.) rms if the $\lambda/100$ criteria is retained. Achieving these accuracies on reflectors several meters in diameter represents a significant technical challenge.

The requirements for ever-increasing accuracy for both ground-based and space-based antenna reflectors have necessitated a new and different approach to antenna design and manufacture. This report discusses (1) the traditional antenna reflector fabrication methods, (2) a new approach for designing precision antenna reflectors, (3) the results of fabricating two ground-based antenna reflectors using this new approach, and (4) extrapolation of the new approach to space-based antenna reflectors.

Space antenna reflectors are typically manufactured by fabricating low-temperature concave molds from a master convex pattern. High-temperature convex molds are made using the low-temperature molds, and the honeycomb sandwich panel face sheets are made on the high-temperature molds. The reflector assembly is also adhesively bonded on the high-temperature convex mold. The antenna shell is then fit to the original master pattern and attached to a stiff backup structure to complete the antenna reflector assembly. Until now, these methods have been satisfactory for the low-frequency reflectors currently in use. However, the cost of these reflectors has escalated, and the limits of accuracy achievable by using these methods appears to have been reached.

The objective of this effort is to use a new approach to design, analyze, and fabricate precision antenna reflectors for ground-test systems and for low-cost proof-of-feasibility models of space antenna systems. For ground-test antennas, the new approach is to design and build a rigid, dimensionally stable substructure with a machinable front face adhesively bonded to it. To date, a stainless steel, foam, and fiberglass composite 1.4-m-diameter ground-test antenna reflector has been built and radiofrequency (RF) tested, and a similarly constructed 2.7-m-diameter antenna test bed reflector has been fabricated and aluminized and will be RF tested in 1991.

Solid surface reflectors or deployable reflector segments for use on spacecraft can be fabricated by using a similar approach with lightweight space-qualified materials. For example, the rigid substructure and flat panels could be constructed with graphite/epoxy honeycomb sandwich panels or similar dimensionally stable materials. Machinable, low-density panels could be adhesively bonded to the flat panels. The low-density surface could then be machine finished and coated with a reflective surface. Such reflectors would be accurate, lightweight, and dimensionally stable.

The main advantage of this method of construction over conventional methods is the improved overall antenna performance achieved through the increased accuracy gained through machining. Also, since the final reflective surface is

machined, contours other than the usual parabolic figures of revolution can be fabricated if desired for particular missions where increased antenna scanning performance is required. Costs for limited quantities should also be lower because accurate, expensive low- and high-temperature molds will not be required.

Current Fabrication Methods

Ground-Based Antenna Reflectors

Ground-based antenna reflectors requiring great precision have also been fabricated by machining in the past. For example, a solid surface, 4-m- (157-in.-) diameter aluminum antenna reflector for a 20-GHz proof-of-concept program was made for NASA Lewis Research Center in 1983. It weighed 1270 kg (2800 lb) and had an accuracy of 0.013 mm (0.0005 in.) rms compared with the desired nonparabolic contour (ref. 1). However, this reflector was heavy, expensive, and had less than desirable thermal dimensional stability.

Another example of a machined reflector is the 10.4-m- (410-in.-) diameter telescope that was built for millimeter and submillimeter astronomy by the California Institute of Technology in the late 1970's. This reflector was fabricated by first building a very deep tubular steel truss structure to the approximate required shape. The truss structure was overlaid with aluminum plates to which thick aluminum honeycomb material was adhesively bonded. The honeycomb was then machined to the desired contour, and a thin, second face sheet was bonded to the honeycomb. The resulting reflector had an accuracy of 0.02 mm (0.001 in.) rms compared with the desired parabolic contour (ref. 2).

Ground-based antennas have also been fabricated by using the successive molding techniques described earlier but without a final fit-up to the original form. However, this method resulted in accuracies that do not quite approach those described in the previous two examples. Accuracy is lost at each replication during successive molding because both the molds and the final reflective surface distort during each step.

Space-Qualified Antenna Reflectors

Almost all space-qualified antenna reflectors have been fabricated by using successive molding techniques. For example, a 2.7-m- (107-in.-) diameter proof-of-concept antenna built under contract for NASA Lewis in 1984 was constructed by first fabricating a very accurate male plaster-of-Paris master mold. From the master parabolic form, a low-temperature female mold was made for the offset geometry. This low-temperature mold was used to form a high-temperature male mold, which, in turn, was used to mold the face sheet skins for the honeycomb sandwich panel reflective surface. The thin, doubly curved honeycomb sandwich panel shell was constructed by bonding the face sheets to the honeycomb core on this high-temperature mold. Then the resulting reflector had to be fitted to the original master surface in order to obtain the best approximation to the desired parabolic shape. Finally, the surface was locked in place by bonding it to a stiff, lightweight backup structure.

Although this design resulted in a very lightweight antenna reflector, the surface accuracy of 0.14 mm (0.0055 in.) rms when compared with a best-fit parabola was more than the 0.08 mm (0.003 in.) rms surface accuracy desired. In addition, had this been an antenna reflector for use in space, some surface accuracy might have been lost due to creep caused by thermal cycling in the orbital environment.

Currently, two space-qualified antenna reflectors are being fabricated for the Advanced Communications Technology Satellite Project Office at NASA Lewis by using a process that is similar to, but an improvement on, the one just described. Here, a female master pattern is first machined and then used to form a high-temperature male mold. The male mold is used to form the face sheets and the honeycomb antenna reflector shell assembly. The resulting reflector assembly is then attached directly to a stiff backup structure. The 2.2-m- (86.6-in.-) diameter offset geometry antenna reflector constructed using this advanced procedure has a 0.07-mm (0.0029-in.) rms figure of error compared with a best-fit parabola of revolution.

An Advanced Method For Ground-Based Precision Antenna Reflector Fabrication

Design and Fabrication Approach

The purpose of the precision fabrication program for the NASA Lewis reflectors was to fabricate more accurately contoured and less expensive antenna reflectors. For this new approach, different materials and fabrication techniques were used. To verify the new fabrication techniques, a half-size, 1.4-m- (53.4-in.-) diameter reflector was built first. The design goal for both the 1.4-m and the full-size 2.7-m (106.8-in.) reflectors was a surface contour accuracy of 0.025 mm (0.001 in.) rms.

The 1.4-m-diameter reflector was constructed and aluminized in NASA Lewis facilities to demonstrate that the fabrication and assembly techniques which would be used on the 2.7-m reflector were sound. However, the design of this half-size reflector was not verified by finite element analysis.

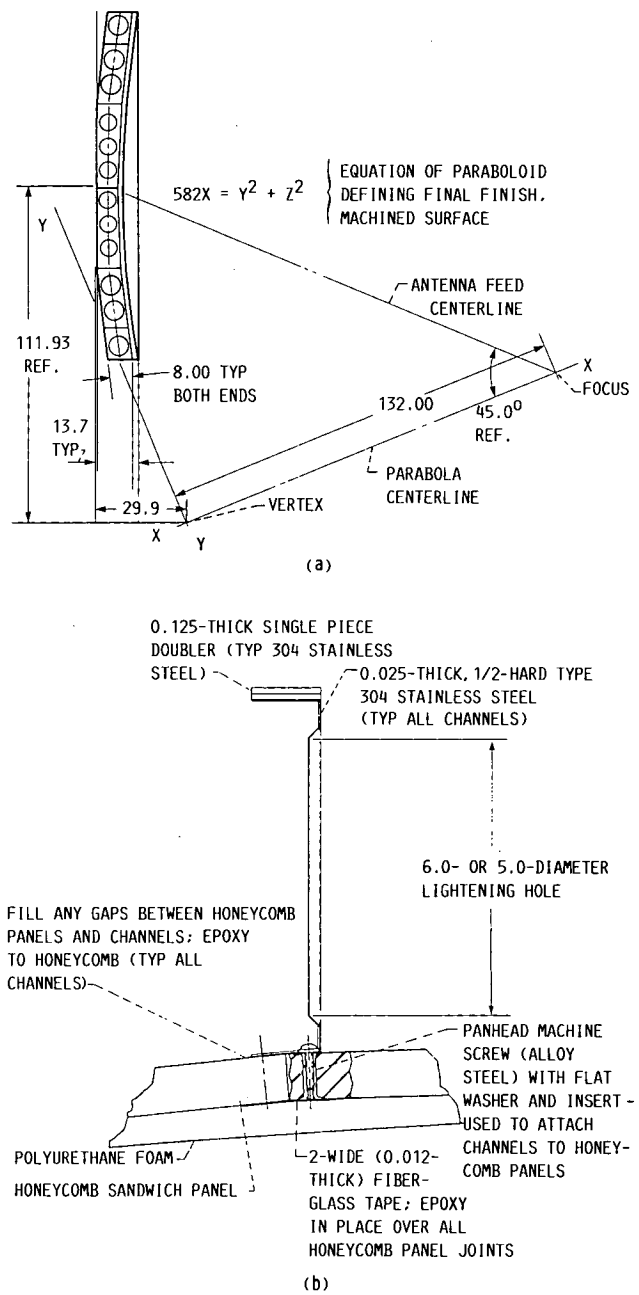
The basic reflector design approach was to provide a stiff supporting structure with an easily machinable front surface. This machinable surface was made of small, flat panels positioned to roughly approximate the contour of the desired reflector and then machined to the desired contour. Thus, the accuracy of the reflector would be determined by both the dimensional stability of the support structure and the accuracy of the machined surface.

Design

The full-size (2.7-m-diameter), offset-fed parabolic antenna reflector (figs. 1(a) and (b)) was designed to be built as a composite structure. The supporting structure of the reflector consists of thin gauge stainless steel structural channels upon which stainless steel honeycomb sandwich panels are mounted. Onto the honeycomb panels, machinable, flat panels of polyurethane foam are adhesively bonded. The supporting structure was configured to locate the machinable foam panels in approximately the final desired contour. After the rough reflector contour was machined into these panels, two plies of bidirectional fiberglass cloth were resin bonded to the polyurethane foam surface to create a strong front surface that would resist machining pressure. The fiberglass also sealed the foam to prevent it from outgassing when it was subjected to vacuum during the vapor deposition coating process. A thin layer of filled epoxy (gelcoat) was then applied to the fiberglass; this gelcoat layer provided the final surface to be machined. Cross sections of the composite structure described are shown in figure 2.

The fabrication drawings, as well as the analytical structural model which was used in the finite element analysis of the 2.7-m reflector, were generated on the three-dimensional computer-aided-design (CAD) system at NASA Lewis. First, the desired finished contour of the reflector was generated on CAD. Then, the flat machinable panels were laid out to best match the reflector contour. The panels were located such that the minimum thickness in any panel after final machining would be 0.635 cm (0.25 in.). Then, on CAD, the honeycomb panels were placed directly beneath the machinable panels. The maximum size of these panels was determined by calculations which gave the minimal deflection for a panel that was edge supported under a uniform 1g weight loading. After the panels were positioned, the channel structure was positioned to support resulting panel joints.

Type 304 stainless steel was chosen as the material for the structural channel and honeycomb panels because of its structural stiffness, dimensional stability, and good thermal distortion properties. A dense 321-kg/m^3 (20-lb/ft^3) polyurethane foam material was used for the panel because it could be easily machined. This type of foam is typically used to test computer numerically controlled (CNC) machining programs.



(a) Overall cross section of antenna reflector.
(b) Cross section of backup structure with flat panel attachments.

Figure 1.—Cross-sectional views of ground-based 2.7-m-diameter precision antenna reflector. (All dimensions in inches unless noted otherwise.)

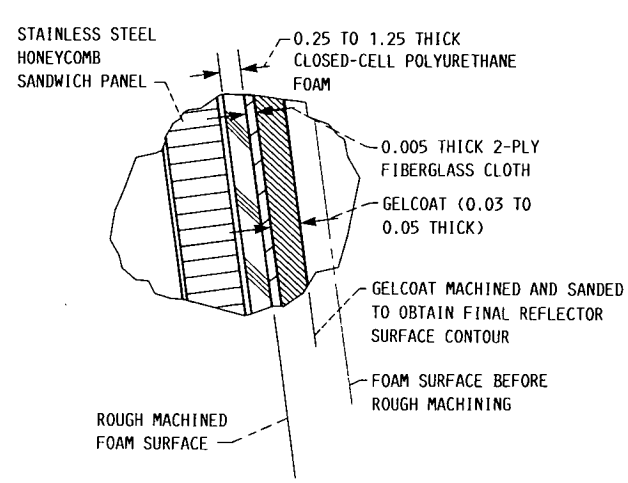


Figure 2.—Cross section of flat panel support structure of ground-based 2.7-m-diameter precision antenna reflector. (All dimensions in inches unless noted otherwise.)

Analysis

First, preliminary hand calculations were made to size the structural channel for the support structure and to determine the proper spacing of weight-reducing holes within the channel. A deflection analysis was performed to determine the maximum allowable dimensions for the edge-supported honeycomb sandwich panels.

With the results of the preliminary hand calculations used as a check, a finite element analysis, MSC/NASTRAN (MacNeal-Schwendler Corporation/NASA STRuctural ANalysis), was conducted on the design of the full-scale (2.7-m-diameter) reflector. The major components of the reflector were modeled in the following manner:

(1) Structural channel—BAR elements
(2) Honeycomb panel—eight-noded HEXA elements
(3) Contoured proofboard panel—eight-noded HEXA elements
(4) Fiberglass cloth layer—four-noded QUAD elements

The reflector, which uses offset antenna reflector geometry (fig. 1), is symmetric about its y-axis; therefore, only half of the reflector was modeled. The model was oriented as it will be mounted in the ground-based antenna system, and a 1g load was applied in the $-Y$-direction for the analysis.

As a result of the analysis, additional stiffeners were added to support the free edges of the reflector and to support the midsection of the larger honeycomb panels. These stiffeners were made of structural stainless steel tubing and were modeled as MSC/NASTRAN BAR elements.

The final analysis predicted that the maximum reflector deflection under the $-Y$-axis 1g loading was 0.001816 cm

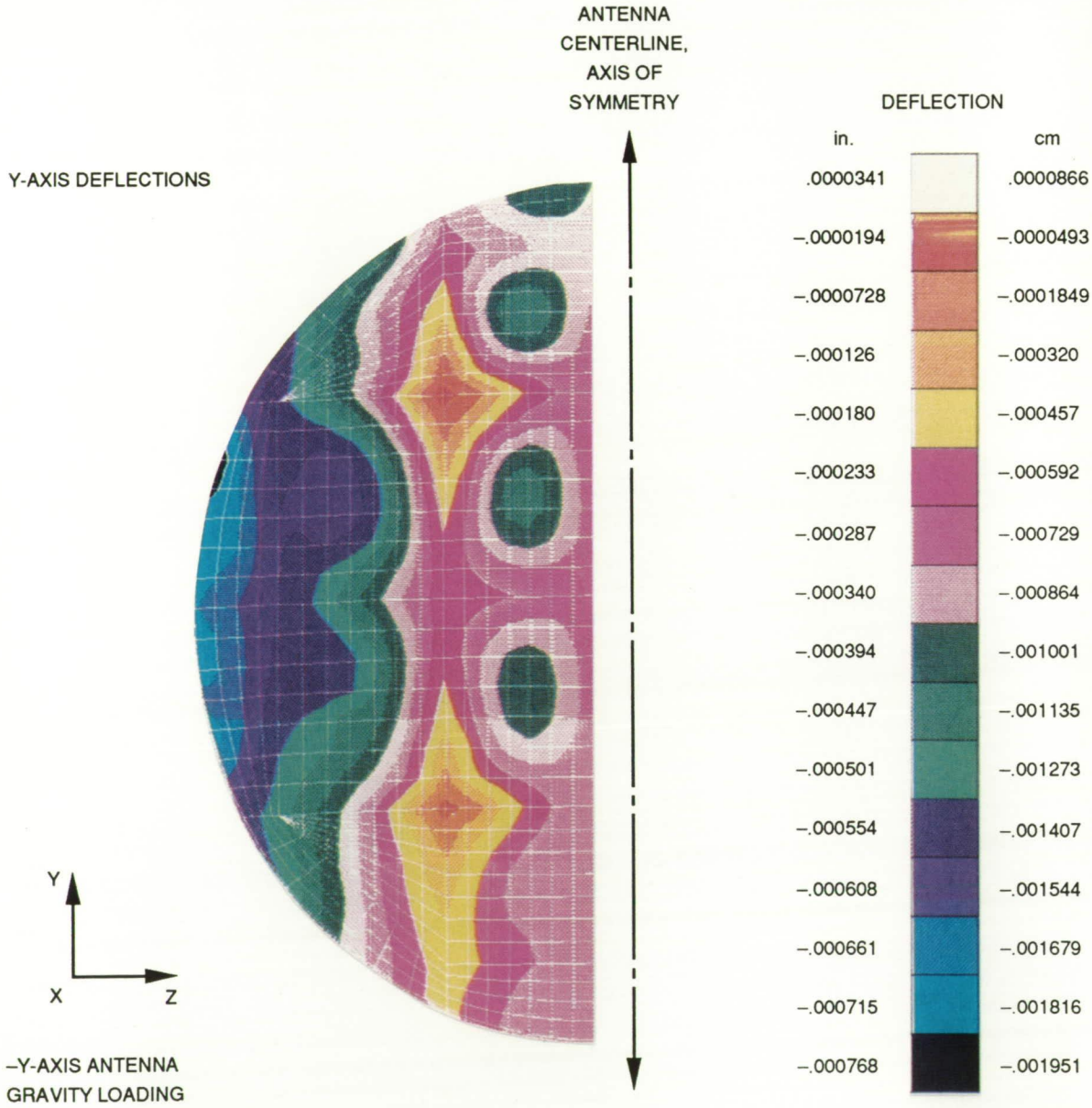


Figure 3.

(0.000715 in.) in the *Y*-axis at the outermost reflector free edge (fig. 3). The maximum deflection under 1g loading in the *X*-axis was 0.001417 cm (0.000558 in.) (fig. 4). The *X*-axis deflections are more critical than *Y*-axis deflections because errors in the *X*-axis more directly affect the phase of the near-field RF energy. Near-field phase errors result in large far-field antenna pattern errors.

Backup Structure Fabrication

The supporting structure for the 2.7-m reflector was fabricated in the NASA Lewis Metal Fabrication Shop. Structural channels were fabricated from 0.064-cm-(0.025-in.-) thick type 304 stainless steel sheet. The channels were laid out in a rectangular pattern to support the honeycomb sandwich panels, and the outer flanges of the channel were reinforced with doubler plates to add stiffness to the structure.

Rectangular, stainless steel honeycomb sandwich panels were laid onto the channels. The panels were constructed from 0.038-cm- (0.015-in.-) thick face sheets furnace brazed with AMS 4777 alloy to 2.46-cm- (0.970-in.-) thick, 0.953-cm- (0.375-in.-) hexagonal, 0.008-cm- (0.003-in.-) gauge honeycomb core material. The sheet stock for the honeycomb core was perforated such that each cell had a pressure relief hole for air to escape when the reflector was subjected to vacuum during the aluminum coating process. So that the sandwich panel flatness would be maintained to within ±0.038 cm (±0.015 in.), the panels were clamped between two graphite

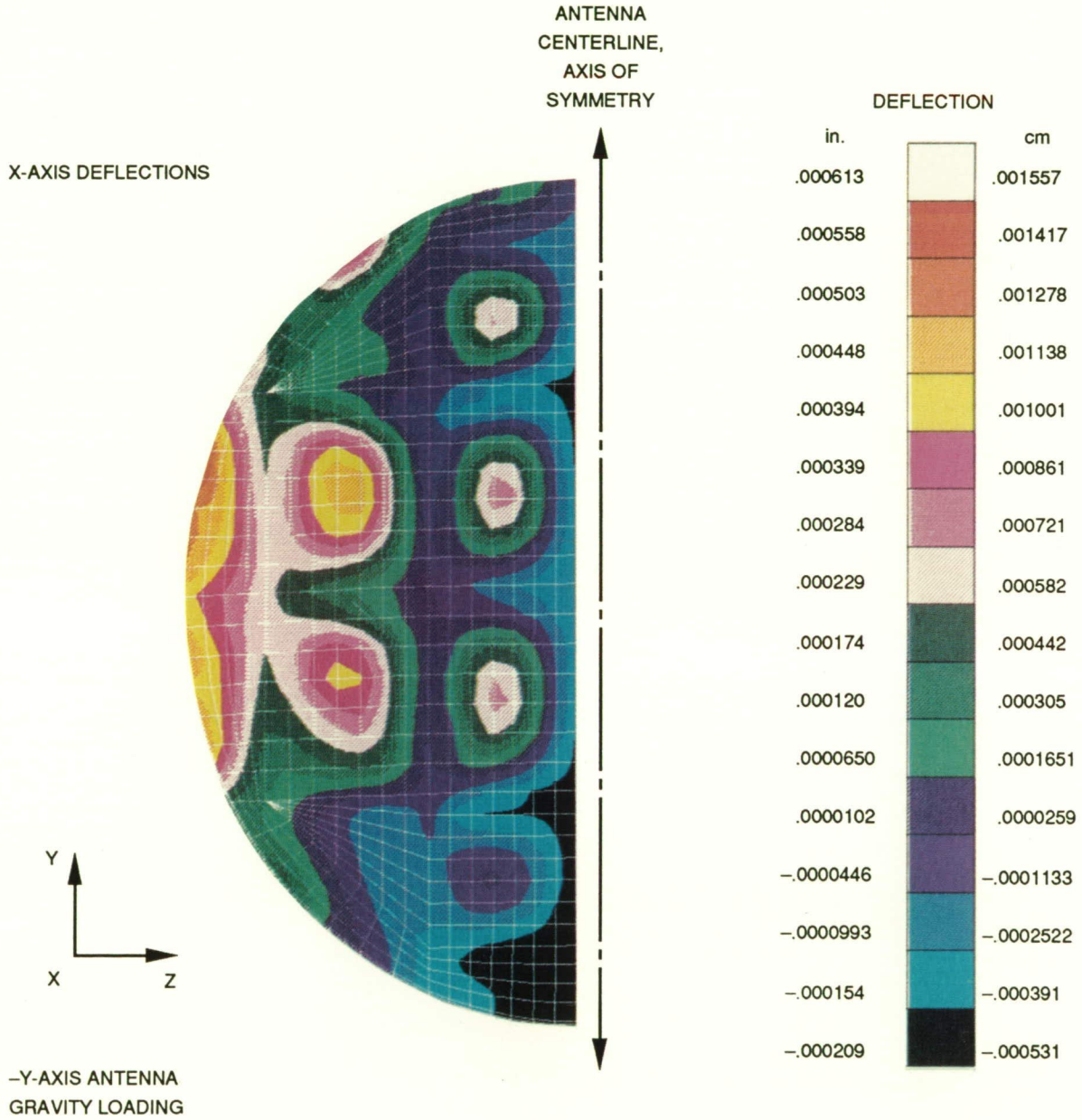


Figure 4

plates during the brazing process. The honeycomb sandwich panel was constructed entirely of type 304 stainless steel.

The honeycomb panels were attached to the structural channels by adhesive bonding and aircraft fasteners threaded into inserts mounted in the honeycomb panels. Then, the exposed joints of the honeycomb panels were reinforced with 5.1-cm- (2.0-in.-) wide, 0.030-cm- (0.012-in.-) thick, bidirectional fiberglass tape. Figure 5 shows the channel and honeycomb sandwich panel fabrication. Finally, polyurethane foam panels were cut to size and bonded onto the honeycomb panels with adhesives. At this stage, the reflector was ready for rough machining.

Machining

The rough machining, fiberglassing, gelcoating, and final machining on the 2.7-m reflector were completed under contract at the University of Arizona's Optical Sciences Laboratory. Reference 3 gives a detailed description of the complete machining operation including mounting the reflector; rough machining, fiberglassing, and gelcoating the surface; and final machining and measuring the reflector.

Both the rough machining and the finish machining were accomplished on the university's Large Optical Generator (LOG). The LOG (fig. 6) is a large, four-axis milling machine capable of machining items up to 8 m (26.2 ft) in diameter. It consists of two posts supporting a large crossbeam that holds a tool carriage and a rotating tool. A rotating table is centrally located under the beam. The tool carriage can be translated across half the length of the beam, and the rotating tool can be raised or lowered. The machine has demonstrated an accuracy of 0.00254 mm (0.0001 in.) when generating a smaller symmetrical figure of revolution.

To eliminate any potential reflector distortion when it was mounted to the machining table, the university proposed that the reflector be mounted with a three-point mount. A three-point support with a "whiffle tree" was designed and fabricated by the university to mount the reflector. This mount adapted the existing four-hole reflector mounting pattern to the three support points on the machine table by using a connecting beam with three ball joints to connect two of the points on the reflector to a single support point on the machine.

The reflector was originally designed to be machined with the reflective surface facing horizontally, which is close to the position of the reflector during operation (fig. 1). Because the LOG configuration required the reflector to be machined facing up, it became necessary to further reinforce the reflector-back supporting structure to avoid errors caused by gravitational deflections. These errors would not have become apparent until the reflector was oriented to its operating position.

Rough Machining

For the rough machining of the polyurethane foam (proofboard) surface on the LOG, a spherical cutter designed by Cornell University was used. This tool was initially built to machine the polyvinyl foam substrate on subreflectors for the Arecibo Observatory. The spherical cutter consists of 21 carbide-tipped bar cutters mounted in an aluminum holder in a double spiral pattern (fig. 7). As the cutting tool is rotated, the bar cutters define a spherical surface of 25.4-cm (10-in.) radius. The tool removes low-density material quite vigorously, and the tool path calculations for a spherical tool are quite straightforward. An initial cutting pass of about 0.38 cm (0.150 in.) removed all irregularities between the foam panels (fig. 8).

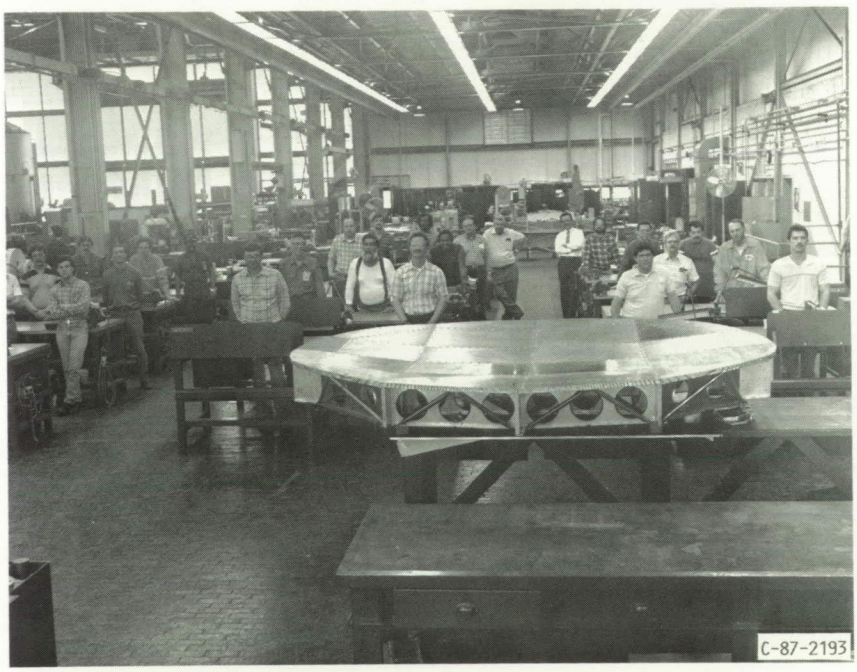


Figure 5.—Reflector panel and backup structure for 2.7-m-diameter antenna.

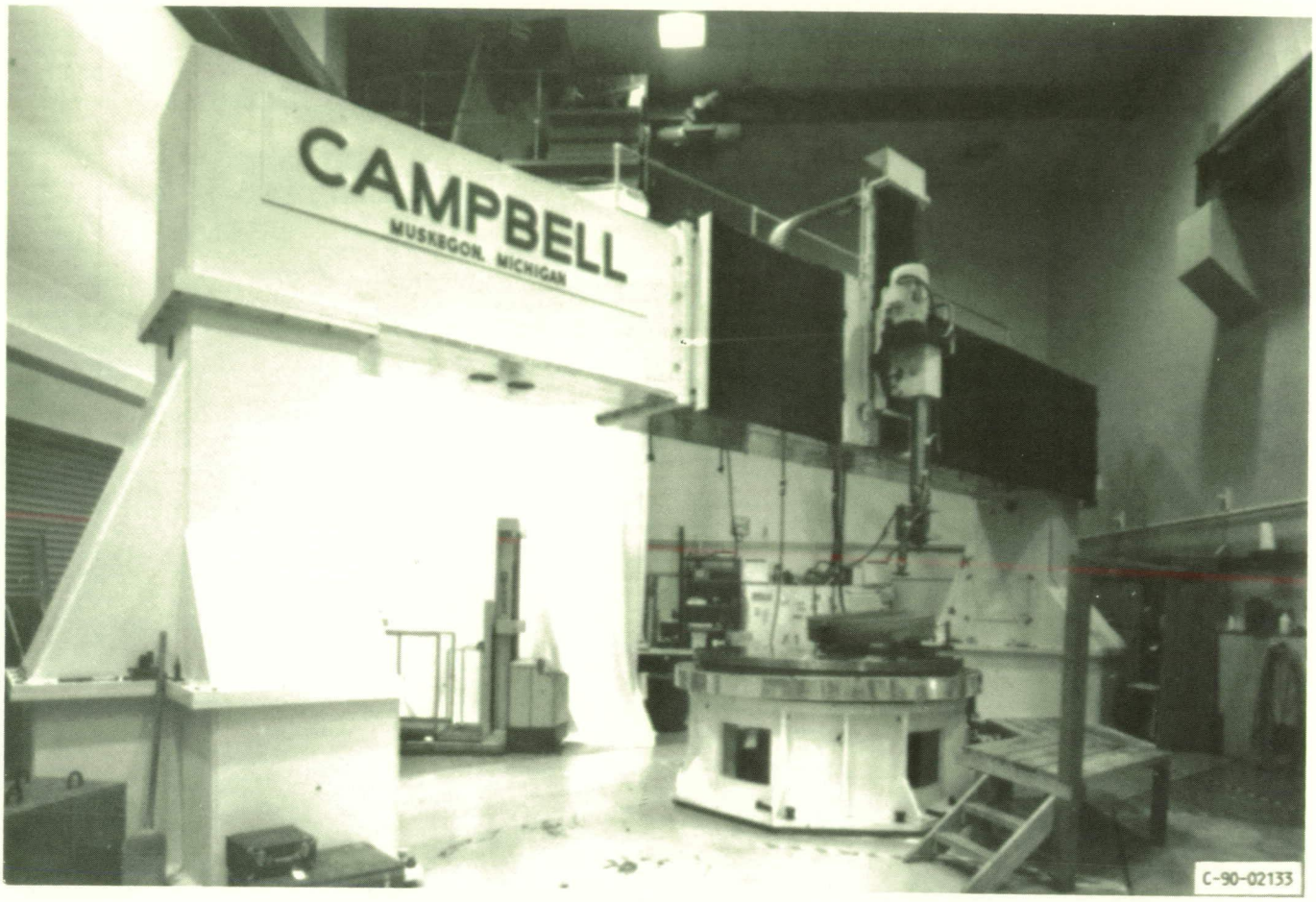


Figure 6.—Large optical generator (LOG).

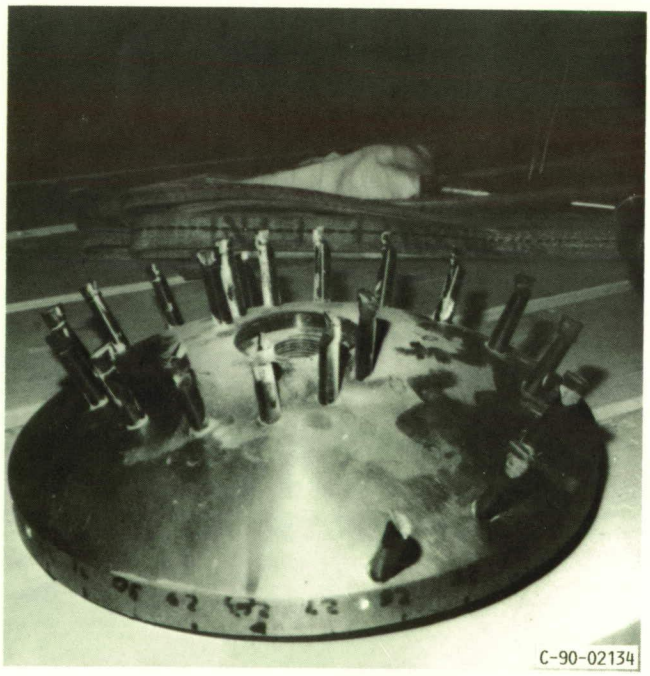


Figure 7.—Spherical cutting tool.

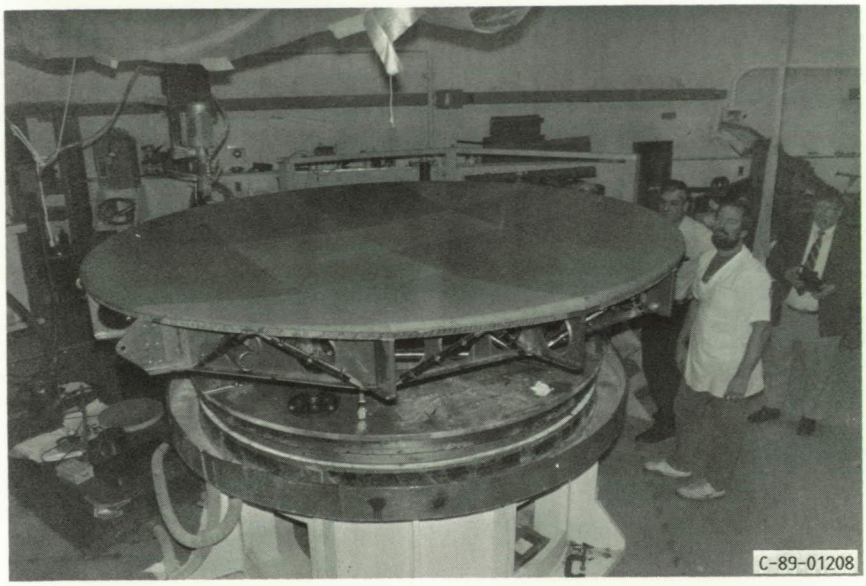


Figure 8.—Rough-machined 2.7-m-diameter antenna reflector.

After the rough machining, the panels were measured with an indicator having a 1-μm (0.000039-in.) resolution. These measurements and the radius of the ball tip were used to compile a generating table for the LOG. The difference between the cut surface and the generated table was calculated. The surface being measured was dominated by the scallop height left by the 25.4-cm- (10-in.-) radius cutting wheel. A 1.9-cm (0.75-in.) spiral machining pitch from the center of the reflector resulted in a scallop height of 0.018 cm (0.007 in.). The total peak-to-valley measurement at the surface was 0.05 cm (0.020 in.). This scallop was acceptable because the gelcoat layer was to have a minimum thickness of this amount.

Final Machining

After the polyurethane foam surface was rough machined, a fiberglass skin was applied. Two layers of 4-oz cloth were applied at a 45° bias angle. Epoxy with a slow hardener was applied and allowed to wet through to the foam surface. Then, a white epoxy surface coat was applied. This gelcoat was easily handled, was relatively odorless, and had a pot life of about 20 min at room temperature. Initial sample batches demonstrated that it cured to a very hard surface, yet was easily machinable with standard machine or hand tools. The surface finishes of the samples were very good. Specular reflections could be seen after hand finishing the surfaces with number 600 sandpaper, and better than a 2-μm (0.000079-in.) rms finishes were obtained.

A toroidal cutting tool (fig. 9) recommended by the university was used for the final machining. The tool, designed for rapid material removal of difficult-to-machine metals, has 11 ceramic cutting inserts, 2.5 cm (1 in.) in diameter, that resemble thick washers. These are mounted to a 20-cm- (8-in.-) diameter support. For this cutting application, rapid material removal was not needed. However, the tool geometry was needed in order to reduce scallop height and to make it easier to attain the desired finish. The advantages of a toroidal tool are—

(1) The tool has a constant cutter velocity on the part (as opposed to a spherical cutting tool).

(2) The effective tool cutting radius can be changed by varying the tilt angle. (This minimizes scallop tool marks.)

(3) The rounded inserts used are capable of producing very smooth finishes.

The primary disadvantage of a toroidal cutter is the difficulty of calculating and programming the tool path. With a spherical cutting tool (which was used in the rough machining), path calculation is straightforward. At the contact point with the machined surface, the surface normal intersects the tool's radius of curvature, and, as the spherical tool moves across the part,

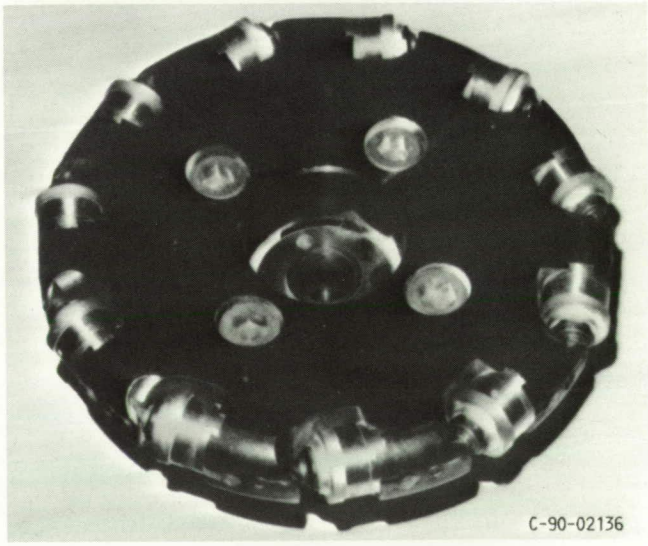


Figure 9.—Toroidal cutting tool.

this relationship always holds—making it easy to calculate the contact point with the cutting tool. It is also easy to visualize that what is actually being defined is the surface defined by the tool's center of curvature, which at any point is the spherical tool radius above and normal to the desired surface.

The path of the center of curvature of the tool is normally programmed into the memory of the LOG. However, with the toroidal tool the center of the tool constantly changes position relative to the cutting surface (fig. 10), complicating matters thoroughly. The basic problem is one of calculating the tangency point between a parabola of revolution and a toroid for any position or angle of these surfaces relative to one another. As the toroid moves across the surface, the contact point or point of tangency moves around the toroid (introducing both an error in radius and a spatial phase shift) and also around the insert washer cutters (introducing errors in radius and height). These corrections are very dependent on the tool angle, which is also difficult to measure accurately.

The center axis of the toroidal cutting tool was tilted about 2° from the vertical. This provided a very long, effective cutting radius, which was desirable to reduce tool scalloping. However, that long tool radius was constant only over a very limited area. By the time the edge of the part was reached, the effective radius, which was about 152 cm (60 in.) near the center, was only 20 cm (8 in.). This was unacceptable, for with the spiral pitch of nearly 1.9 cm (0.75 in.), the tool left a scallop of 0.023 cm (0.009 in.). Therefore, we decided to run three generating tables, with the starting azimuths offset by 120° on the reflector. In effect, the spiral pitch was reduced to 0.63 cm (0.25 in.). This was necessary because the memory space in the LOG controller limited the pitch of any one pass to 1.9 cm (0.75 in.). With the smaller effective pitch, the peak-to-valley scallop was reduced to 0.0025 cm (0.001 in.). The final reflector surface was hand sanded with number 600 paper as the reflector rotated.

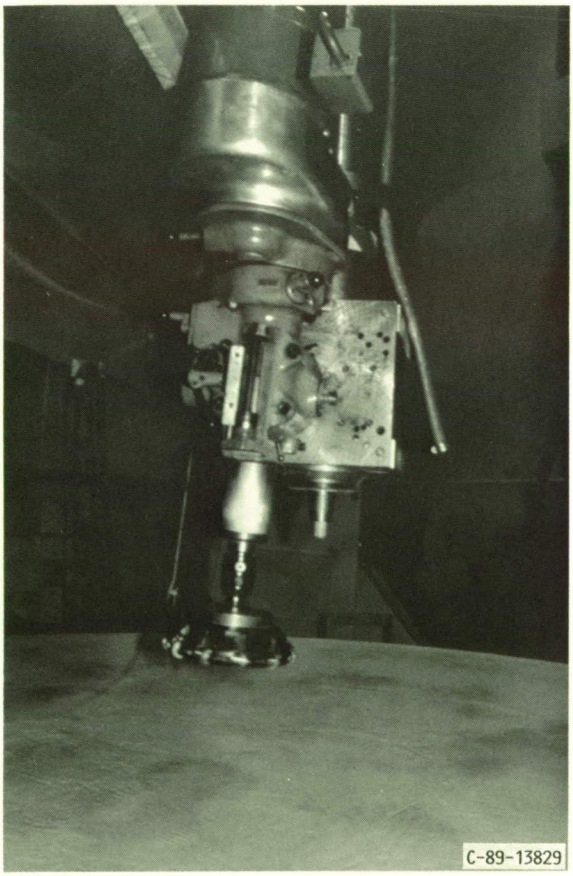


Figure 10.—Machining geometry of toroidal cutting tool.

Aluminization

A thin film of electrically conductive metal is required on the reflector front surface to reflect the RF energy during antenna operation. Aluminum is commonly used for this purpose. To determine the thickness of aluminum required to achieve adequate electrical conductance on the reflector surface, a series of tests were performed at NASA Lewis with test specimens manufactured from the reflector substrate material. Aluminum coating thicknesses ranging from 100 to 10 000 Å (3.94×10^{-7} to 3.94×10^{-5} in.) were applied to these specimens. The coated specimens were then inspected and tested for their RF reflectance. It was determined that a minimum of 1000 Å (3.94×10^{-6} in.) of type 1100 aluminum was required. No detrimental effects were noted when more than 1000 Å (3.94×10^{-6} in.) of aluminum was applied. Therefore, the coating specifications were set at 2000 ± 1000 Å ($7.87\times10^{-6}\pm3.94\times10^{-6}$ in.) of type 1100 aluminum.

The reflectors were aluminized using the vapor deposition manufacturing process. Vapor deposition involves vaporizing the metal to be deposited while both the metal and substrate are under vacuum. As it vaporizes, the gaseous metal deposits on the first surface it encounters. This deposition method allows extremely thin coatings to be deposited uniformly onto a smooth surface.

The 2.7-m reflector was aluminized under contract at Liberty Mirror Company, Brackenridge, Pennsylvania, because no NASA Lewis facility of adequate size was available. The contractor not only applied the aluminum, but also a 500-Å-thick coating of silicon dioxide to prevent the aluminum from oxidizing. The aluminization process was followed immediately by the application of the silicon dioxide while the hardware was still under vacuum. To calibrate the coating thickness, eight test specimens were placed around the perimeter of the reflector and were coated simultaneously with the reflector. These specimens were later inspected, and the film thicknesses were verified.

Design Approach for a Precision Space-Qualified Antenna Reflector

The same designs and fabrication techniques developed for building the ground-based antenna reflectors previously described would be used to design, analyze, and fabricate

precision antenna reflectors or segments of reflectors as proof-of-feasibility models for prospective space antenna systems. However, these designs would use lightweight, low coefficient of thermal expansion, space qualified materials, and the reflectors would be protected for use in the space environment. For example, machinable material such as the low-density, fibrous, sintered glass panels used as insulation on the space shuttle could be used as the machinable final antenna surface. To make the machined surface RF reflective, 1000 to 2000 Å of aluminum could be vacuum deposited on it. The machinable insulation panels could be adhesively bonded to underlying honeycomb sandwich panels made of near-zero coefficient of thermal expansion graphite/epoxy or graphite/polyetheretherketone (PEEK) quasi-isotropic sheets. PEEK is highly resistant to moisture absorption, subsequent dry-out, and ensuing distortion in the space environment. As before on the ground-based antenna reflectors, the honeycomb sandwich panels would be bonded to a stiff backup structure in order to maintain rigidity and dimensional stability.

Reflector Design

The stiff backup structure would be fabricated first. It could have rather loose dimensional tolerances because the final precision surface would be formed by machining. The backup structure would consist of crossmembers bonded together and supported by a master tool. The material for the backup structure could have the same near-zero coefficient of thermal expansion as the flat panel honeycomb sandwich panels but with added longitudinal flanges for additional stiffening. Reinforcing doublers or spiders would be used at the intersections of the crossmembers. (See figs. 11 and 12 for front, back, and cross-sectional views.)

The flat honeycomb sandwich panels would be made of graphite/epoxy or graphite/PEEK face sheets that have a near-zero coefficient of thermal expansion in the plane of the panels. The face sheets would be fabricated using plies of unidirectional graphite oriented at equal angles with respect to one another.

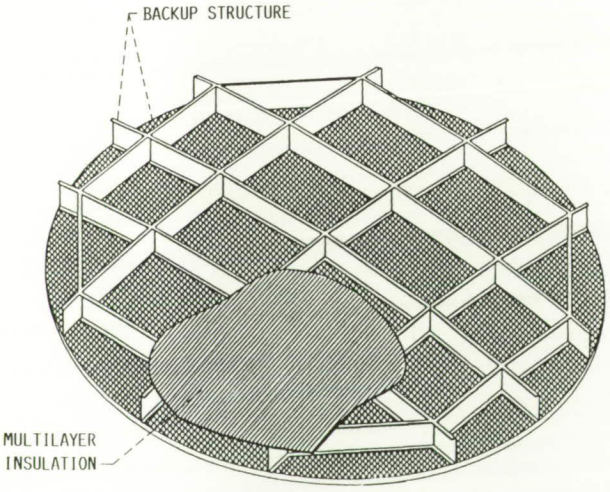


Figure 11.—Rear view of precision flight reflector.

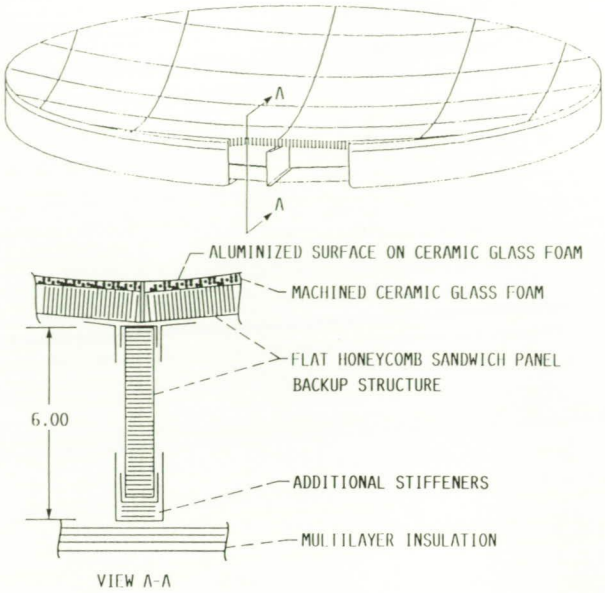


Figure 12.—Front view and cross section of precision flight reflector.

The flat honeycomb sandwich panels would be treated as a whole in regard to planar coefficient of thermal expansion. In other words, the face sheets, the adhesive layers, and the honeycomb core would all have their properties adjusted so that the entire sandwich panel assembly had a near-zero coefficient of thermal expansion in the planar isotropic direction.

To accomplish this, an egg-crate honeycomb core could be fabricated from the same material as the face sheets, and the mix of fibers in the face sheets could be adjusted to compensate for the expansion of the layers of adhesive. The machinable insulation panels would be bonded to the structural honeycomb sandwich panels before they were assembled to the stiff antenna reflector backup structure. Because the in-plane modulus of elasticity of the insulation panels is less than 670 MPa (100 ksi) and the coefficient of thermal expansion is less than 2.9×10^{-6} m/m/K (1.6×10^{-6} in./in./°F), the panel stiffness will have very little effect on the properties of the final composite panel. This is important because the thickness of the machinable insulation will vary from about 0.64 to 3.2 cm (0.25 to 1.25 in.) for a typical shallow curvature, offset parabolic geometry reflector.

The reflector would now be ready for machining, which should be done with the open concave face of the reflector pointing horizontally in order to avoid gravitational deflections. In addition, low-pressure tools would be required. The alternative would be to temporarily support the reflector horizontally on a very rigid, very stiff, and dimensionally stable fixture. Low-pressure, toroidal, ceramic-bit tools, which have been used to machine insulation panel samples with good results, would be recommended for this use. Application of vapor-deposited aluminum and a protective oxide coating to the machined surface would complete fabrication of the reflector.

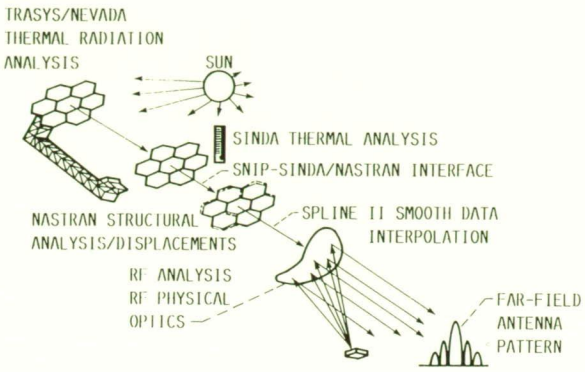


Figure 13.—Overall schematic of computer programs for analysis of thermally distorted antenna performance.

Thermal Distortion Analysis

Figure 13 shows an overall schematic of the computer programs necessary to perform a thermal distortion analysis (ref. 4). The first computer codes in the upper left corner of the figure are TRASYS (Thermal Radiation Analysis System) and NEVADA (Net Energy/Verification and Determination Analyzer). They are used to characterize the thermal environment of the spacecraft in orbit. First, the model geometry, surface properties, orbit, and spacecraft orientation must be defined. Then TRASYS and/or NEVADA generates the radiant heat interchange factors and the radiant heat inputs to each element of the model, and these become the input to the SINDA (Systems Improved Numerical Differencing Analyzer) thermal analyzer.

SINDA is a lumped-capacitance, finite-difference thermal analyzer. Each node in the SINDA model may be thought of as a point having thermal capacitance. All nodes are connected to other nodes by linear (i.e., thermal conductance) and nonlinear (i.e., radiation heat transfer) conductances.

At this point an interconnecting program is needed because both thermal and structural models of this antenna must be generated to predict the thermal distortions and stresses. Usually finite-difference thermal models are generated by a program such as SINDA to predict temperatures in the structure. Then finite element structural models are generated by programs such as MSC/NASTRAN (MacNeal-Schwendler Corporation/NASA STRuctural ANalysis) to predict thermal deformations and stresses in the structure.

The SINDA-NASTRAN Interfacing Program (SNIP) (ref. 5) is a FORTRAN computer code that is used to interconnect the thermal and structural models. It generates NASTRAN structural model thermal load cards when given SINDA (or similar thermal model) temperature results and thermal model geometric data. SNIP generates thermal load cards for NASTRAN plate, shell, bar, and beam elements.

MSC/NASTRAN is used to analyze antenna reflectors to predict their thermal deformation in the space environment. MSC/NASTRAN is a proprietary finite element structural analysis program of the MacNeal-Schwendler Corporation which is used widely in the aerospace industry, providing both static and dynamic analysis capabilities.

Solid antenna reflectors are modeled with NASTRAN plate and beam elements that exhibit bending behavior caused by temperature gradients through the element thickness. CADAM (Computer Aided Design and Manufacturing, CADAM, Inc.) is used to actually construct the models, while PATRAN (PDA Engineering, Inc.) is used to display the temperature and displacement data resulting from the analyses. The displacement data are used to predict the far-field performance of the antennas. However, the RF analysis program used for that prediction requires that the antenna reflector surface be mathematically described as a continuous surface. A spline program was needed to analyze the NASTRAN data set; however, no existing spline programs could fit a surface of the required smoothness to the NASTRAN data set.

A new interpolation method was needed because other spline programs used higher order polynomials for interpolation, and this resulted in high-order surface ripples in the distorted antenna reflector model. These ripples, in turn, resulted in errors principally in the far side lobes of the calculated far-field antenna pattern. The purpose of this new NASA-Lewis-developed interpolation method was to represent the surface with a lower order polynomial that was free of these high-order ripples and compatible with the RF analysis program.

The RF analysis program uses the physical optics method to calculate the far-field antenna power distribution pattern resulting from a given reflector configuration profile. It generates two-dimensional graphs of RF power directivity versus polar angle for azimuthal angles and produces a table of parameters characterizing the beam shape. This program can address more sophisticated Cassagrainian dual reflector antenna configurations.

This series of linked programs can be used to analyze the in-orbit RF performance of any new spacecraft antennas. Each antenna would require a new, individual mathematical model of its configuration for a thermal radiation analyzer such as TRASYS or NEVADA, the thermal analyzer SINDA, and the structural analyzer NASTRAN.

Results

Ground-Based 1.4-m Precision Antenna Reflector

After it was machined, the 1.4-m reflector was inspected in place on the NASA Lewis machine with a dial indicator. The surface measured within 0.041 mm (0.0016 in.) rms of the geometry desired. If the discrepancy was viewed as zero at the geometrical center of the reflector, then the reflector appeared to be curved in a concave direction from a true parabolic contour. The discrepancy was 0.10 mm (0.004 in.) at the upper outer edge, 0.09 mm (0.0035 in.) at the lower inner edge, and 0.06 mm (0.0025 in.) at the sides. The completed reflector weighed 41 kg (90 lb). Figure 14 shows

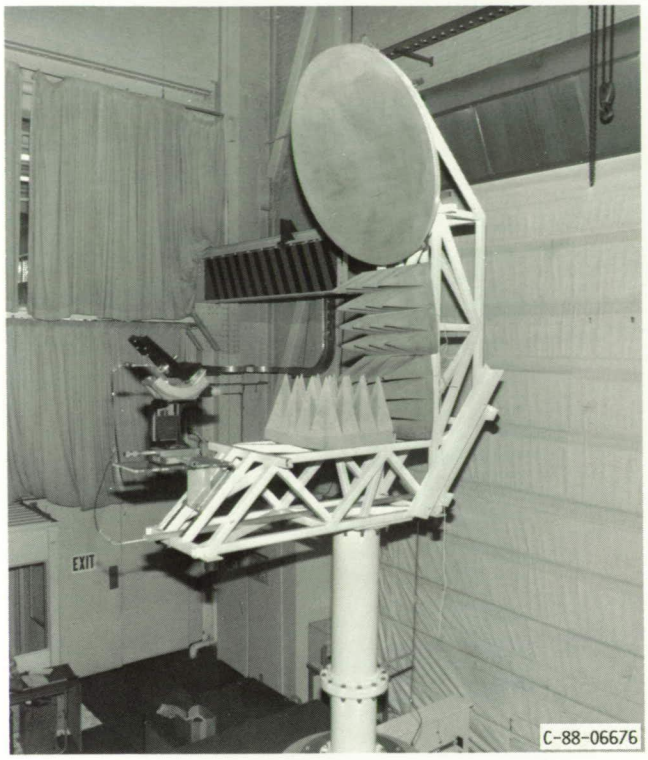


Figure 14.—Ground-based 1.4-m-diameter precision antenna.

the completed reflector mounted to its antenna support structure. To date, the antenna has been RF tested to 28 GHz at the National Institute of Standards and Technology (NIST) at Boulder, Colorado, and at the NASA Lewis Near-Field Antenna Test Facility.

Ground-Based 2.7-m Precision Antenna Reflector

Figures 15 and 16, respectively, show the aluminized, reflective front surface and the stainless steel backup structure of the 2.7-m ground-based antenna reflector. The completed reflector weighed 298 kg (657 lb) for an area density of 52 kg/m^2.

After the 2.7-m reflector was machined and sanded, it also was inspected in place on the milling machine (LOG). Initially, it had been planned to measure the part the same way it was generated. An indicator with a small spherical tip would have sampled every 5.1 cm (2 in.) of spiral length while spiraling out along a 5.1-cm (2-in.) pitch. In that way, the part would be sampled uniformly with area. The major drawback to this setup was the possibility of backlash errors as the horizontal drive oscillated to trace out the oval spiral. In addition, positional errors and time lags could have led to phase errors.

A new measurement program created at the University of Arizona employed measurement in consecutive concentric circles in order to contrast completely with the generating program. First, the indicator was set up in the geometric center of the reflector. Upon starting table rotation, the indicator moved out to the first measurement radius where all machine motions were stopped except for the table rotation. The table was used as the clock driver that programmed the computer to take a height measurement at the appropriate time. Each reading was added to the vertical encoder and compared with the theoretical value to give an error difference for each position on the ring. When measurements at a particular ring were finished, the machine used a full table rotation to move to the next measurement ring. In this way, there were no backlash errors, and, because the measurement program differed from the generating program, the metrology was decoupled from the generation metrology.

The predominant generating errors observed in the LOG measurements were setup errors. These were errors in tool radius, tilt, or initial position. Because each of these errors have a characteristic signature in a series of generating passes, they can be reduced. After several passes, the total figure error had been reduced to 0.036 mm (0.0014 in.) rms. The major error was in the astigmatic amplitude generated. This can be viewed as a rotational phase shift of the part.

If some freedom is allowed in mounting the final reflector to its antenna support structure, these remaining errors can be further minimized. If astigmatism remains in the final surface, and the surface figure produced has mainly an astigmatic error, then translating or rotating the part can bring the generated surface closer to the desired surface.

The data were fed into FRINGE, an optical metrology analysis program. FRINGE fits the error array to a high-order polynomial surface and determines the existing aberrations in the part. The final measurements in this case indicated a peak-to-valley error of 0.155 mm (0.0061 in.) or 0.039 mm (0.00154 in.) rms. They also indicated a component (noise) of 0.0087 mm (0.000342 in.) rms that the program could not fit. These errors underwent a transformation of coordinates to the original coordinate system aligned with the optical axis to analyze the effect of the reflector's motion relative to the optical axis. The predominant error was a focus error of 0.063 mm (0.0025 in.), which can be easily removed by focusing the reflector. Also present, however, was 0.027-mm (0.00108 in.) total astigmatism and 0.013 mm (0.00052 in.) of total coma. As mentioned in the preceding paragraph, aberrations can be modified by translation. Actually, translating the surface introduces additional aberrations, but if the sign is opposite of that present, the existing aberrations are reduced.

All errors were minimized by translating the reflector 1.98 mm (0.078-in.) in the Y-direction and -2.41 mm (-0.095 in.) in the X-direction (fig. 1). With the coordinate system aligned with the optical axis, the residual error was 0.006 mm (0.000244 in.), and the unfit error was 0.009 mm (0.000368 in.). Taking the root sum of squares, the total error of the part is then 0.011 mm (0.00044 in.).

The University of Arizona measurement data for the 2.7-m ground test antenna reflector were also processed at the Lewis Research Center using the Harris Corporation's NASTRAN Best-Fit Paraboloid program. There was excellent agreement

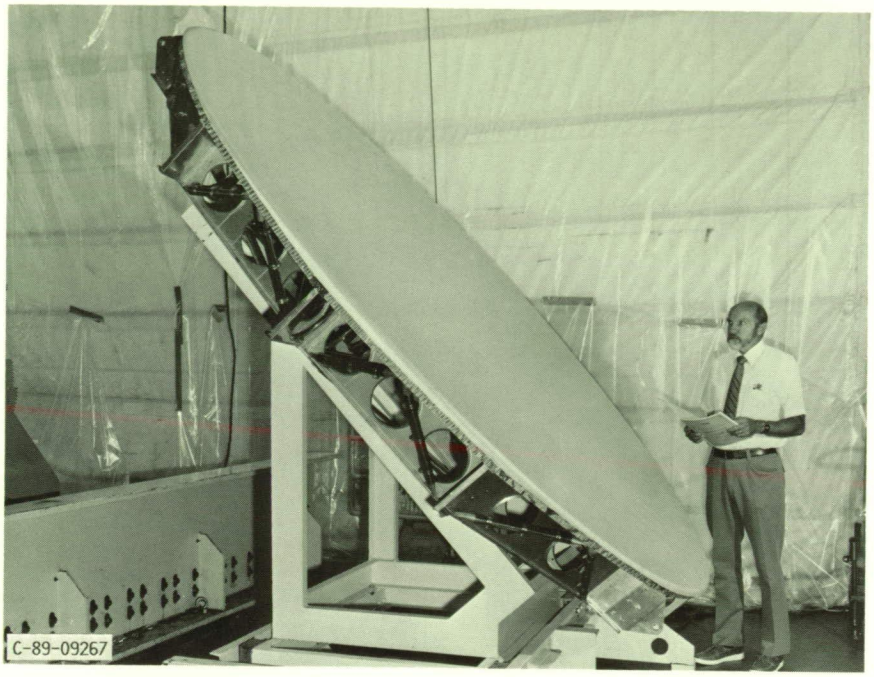


Figure 15.—Reflective face of ground-based 2.7-m-diameter antenna reflector.

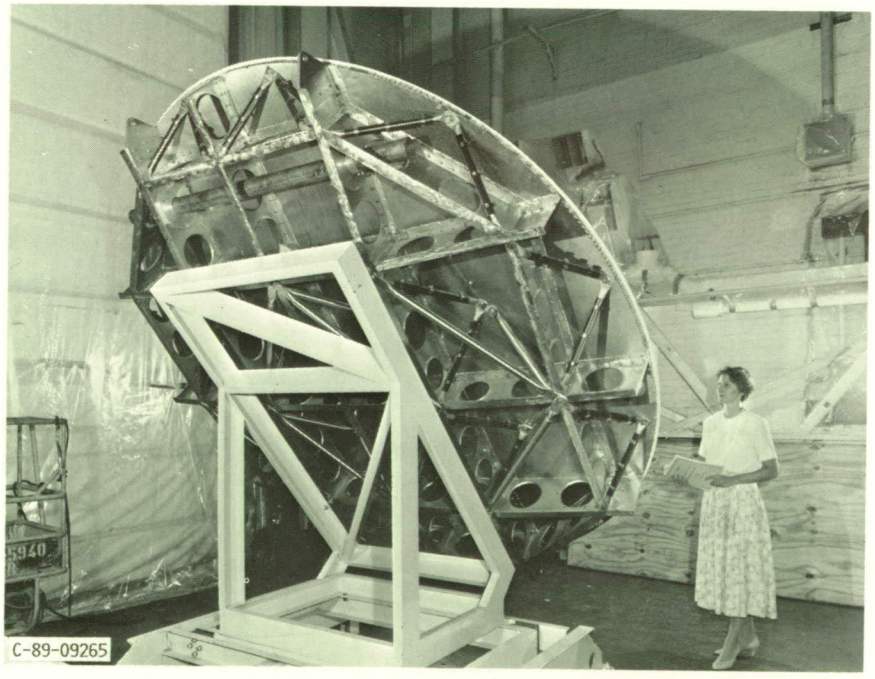


Figure 16.—Support structure of ground-based 2.7-m-diameter antenna reflector.

TABLE I.—REFLECTOR PANEL AREAL DENSITY COMPARISON

Program	Panel or reflector diameter		Accuracy required		Accuracy achieved		Areal density	
	m	ft	μm rms	in. rms	μm rms	in. rms	kg/m²	lb/ft²
ACTS reflector (transmit)	3.3	10.8	102	0.004	69	0.0027	3.45	0.71
ACTS reflector (receive)	2.2	7.2	102	.004	74	.0029	3.45	.71
Precision Antenna Reflector (PAR)	3.3	10.8	25	.001	[a]11	[a].00044	[b]5.2	[b]1.07
Large radiometer antenna reflector	2.5	8.2	16	.0006	----	----	[b]5.2	[b]1.07
Precision Segmented Reflector (PSR) (graphite/polymer) panel	2	6.6	3 to 4	.00011 to .00016	[c]1.5 to 2	[c].00006 to .00008	[c]6	[c]1.23

[a]For 2.7-m ground test antenna reflector.
[b]For 3.3-m PAR design.
[c]For 1-m panel.

between the results obtained by the University of Arizona's FRINGE program and the Harris program. When the reflector was translated −1.85 mm (−0.073 in.) in the *Y*-direction and −2.41 mm (−0.095 in.) in the *X*-direction, the calculated rms for the Harris program was 0.012 mm (0.00046 in.) in the *Z*-axis and 0.011 mm (0.00042 in.) perpendicular to the reflector.

Precision Space-Qualified Antenna Reflector Concept

Table I compares the anticipated results for the precision antenna reflector (PAR) concept with those of several other current and developmental antenna reflectors. For this table, the weight of the conceptual 3.3-m-diameter offset-fed antenna reflector described earlier was estimated, assuming that the reflector would be constructed of flat honeycomb sandwich panels with graphite/epoxy face sheets. The weight estimate includes a backup structure comprising the graphite/epoxy honeycomb sandwich panel ribs and all the connecting angle brackets and rib outer flange doublers.

The anticipated reflector surface accuracy was also estimated for the 3.3-m PAR concept. The accuracy achieved on the 2.7-m ground test antenna reflector was 0.011 mm (0.00044 in.) rms. A comparable accuracy should then be achievable on the conceptual 3.3-m reflector.

Table I compares the expected accuracy and the areal density (weight per unit area) of the conceptual 3.3-m PAR to the Advanced Communications Technology Satellite (ACTS) transmit and receive reflectors and to a very high precision research reflector, the Precision Segmented Reflector (PSR), intended for use in a near infrared telescope. Both the areal density and the expected accuracy of the PAR fall between these two types of reflectors. Thus, the PAR technology described earlier would fill a gap between the ACTS antenna reflectors recently fabricated and the PSR reflector segments being developed for the near-infrared telescope. Table I also shows how PAR technology might meet the requirements for antenna reflector segments on a proposed large radiometer antenna reflector intended for use on future weather satellites.

Space Antenna Reflector Thermal Distortion Analysis

A thermal distortion analysis of a 3.3-m offset-fed antenna reflector design has been completed. The results were reported in reference 4. The thermal model used in the analysis was for a spacecraft at geostationary orbit and included the effects of spacecraft shadowing. The antenna reflector model was similar to that previously described in size and shape. However, the materials used in this first design iteration differ greatly from those of the model currently under analysis and previously described. In the first design, the flat honeycomb sandwich panels were made of graphite/epoxy face sheets with an aluminum honeycomb core. The core material greatly affected the deflections caused by the orbital thermal loads. For the worst cold case, the calculated edge deflection was a fairly uniform −1.1 mm (−0.045 in.) in which the reflector curvature opened up, becoming less concave. When the reflector was partially shadowed, the edge deflection varied from −0.3 to −0.46 mm (−0.012 to −0.018 in.). Thus, a saddle shape would be superimposed on the geometry of the offset parabola. These deflections did not have a very deleterious effect on the far-field antenna patterns; however, the frequency used for the analysis was only 20 GHz.

Concluding Remarks

The objectives of this program have been met for precision ground-test antenna reflectors. A 1.4-m-diameter antenna reflector was fabricated as a pathfinder for the larger 2.7-m-

diameter reflector. The 1.4-m reflector was assembled in an antenna configuration, tested at 28 GHz at the National Institute of Standards and Technology, and used as a test antenna for calibrating the NASA Lewis Near-Field Antenna Test Facility. This reflector varied by 0.04 mm (0.0016 in.) rms from a "best-fit" offset parabola. The 2.7-m-diameter offset antenna reflector was also fabricated and aluminized. The accuracy for this reflector was 0.011 mm (0.00044 in.) rms compared with a "best-fit" offset parabola. The reflector is now ready to be mounted in the NASA Lewis Experimental Antenna System (EAS) for which it was designed.

A 3.3-m-diameter, lightweight, spacecraft version of the ground-test antenna reflector has been designed and analyzed. In addition, a second version has been designed, and analysis is currently underway. Furthermore, a simplified version of this model has been programmed to make it simpler to explore antenna RF performance as a function of varying the materials.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 3, 1990

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16. Abstract

Communications satellites are using increasingly higher frequencies that require increasingly precise antenna reflectors for use in space. Traditional industry fabrication methods for space antenna reflectors employ successive molding techniques using high- and low-temperature molds for reflector face sheets and then a final fit-up of the completed honeycomb sandwich panel antenna reflector to a master pattern. However, as new missions are planned at much higher frequencies, greater accuracies will be necessary than are achievable using these present methods. A new approach for the fabrication of ground-test solid-surface antenna reflectors is to build a rigid support structure with an easy-to-machine surface. This surface is subsequently machined to the desired reflector contour and coated with a radiofrequency-reflective surface. This method was used to fabricate a 2.7-m-diameter ground-test antenna reflector to an accuracy of better than 0.013 mm (0.0005 in.) rms. A similar reflector for use on spacecraft would be constructed in a similar manner but with space-qualified materials. This report describes the design, analysis, and fabrication of the 2.7-m-diameter precision antenna reflector for antenna ground test and the extension of this technology to precision, space-based antenna reflectors.

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