The Fabrication and Surface Tolerance Measurements of the JPL Clear Aperture Microwave Antenna

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Present ground station microwave antennas of the Deep Space Network are of the symmetric dual reflector (cassegrainian) type. An investigation is being made of alternative high-performance offset antenna designs which have a clear aperture (no reflector or structure blockage) with shaped reflector surfaces. A 1.5-m, 32-GHz clear aperture model was built for experimental studies. This article describes the unique processes of fabrication, surface measurement and alignment.

I. Introduction

Present microwave antennas in the NASA-owned Deep Space Network (DSN) are of the dual-reflector (cassegrainian) type. Recently an investigation has been made of alternative ground station antenna designs to increase the performance and enable efficient operation at 32 GHz. Significant advances in the synthesis microwave, analysis and performance optimization of several designs have been completed since 1978 (Ref. 1). Parallel studies on structural designs of antennas with symmetrical and asymmetrical reflectors were undertaken. The clear aperture (sometimes called offset) antenna design with dual-shaped reflectors emerged as a superior design. A 1.5-m clear aperture antenna model with shaped-reflector surfaces was selected as a proof-of-design for experimental verification. The predicted superior performance has a potential 2 to 3 dB increase in the gain to noise temperature ratio (G/T). This proof-of-design antenna was to be carefully tested at JPL both for mechanical stability and for the high-performance electrical (microwave) characteristics. The antenna synthesis and analysis has predicted a high aperture efficiency of 86%. It was necessary to obtain a highly accurate surface finish with minimum surface and alignment tolerance to permit accurate estimates of the electrical (microwave) loss at 32 GHz at the 0.5% level for surface error to wavelength ratio. This accuracy requirement corresponds to a mechanical setting accuracy at the 0.04-mm (0.0015-inch) level.

II. Surface Tolerances

The geometry specifications and the design details were developed in house to meet the needs of the high performance sought. The subreflector and feedhorn as shown in Figs. 1 and 2 were to be adjustable in X, Y, and Z axes plus a rotation for further mechanical alignment and microwave testing. The goal for the main reflector and subreflector surface tolerance was to be equal to 0.18 mm (0.007 in.) or better. The alignment error must be equal to 0.5 mm (0.020 in.) or better for optimum performance.

III. Fabrication Steps

After the documentation was completed a search was initiated to locate a vendor with the unique capability to machine the shaped surface of the reflectors to the specified tolerance. Among 20 firms contacted, Tempe Precision Aircraft Co. of Tempe, Arizona, was selected in June 1981, with a contract completion date of Feb. 1, 1982. The details of the computer coordinates for machining the reflectors were developed in house as described in the appendix. Details of the fabrication of the major components are as follows:

A. Main Reflector

This is designed to be 1.5 m in diameter. A 1524 × 1828.8 × 260-mm (5 ft × 6 ft × 10 in.) aluminum billet was blanchard ground and mounted on a three-axis, numerically controlled horizontal milling machine as shown in Fig. 3. The excess material was removed to form a unique "parabolic" shape. Since the machine was not large enough to machine the entire surface, the main reflector was rotated in 90 deg increments for machining. Each quadrant was machined in three steps. The first step was rough cut to remove excess material to within 2.8 mm (0.110 in.) of the finished surface. The second step was a cut to remove material to within 0.25 mm (0.010 in.) as shown in Fig. 4. The third cut produced a finished machined surface. The surface was spot-checked after each machining operation to verify the computer program results. After the surface was machined and the perimeter trimmed to the final envelope size, the reflector was removed and hand-finished to remove the tool marks. The main reflector surface was measured at 727 points at Tempe Precision Aircraft Co. as shown in Fig. 5 and verified at JPL machine shop as shown in Fig. 6. The root mean square (rms) error obtained from the two machines was 0.114 mm (0.0045 in.) as outlined in Table 1.

B. Subreflector

The subreflector, which is 0.4 m in diameter, was machined utilizing the same methods and equipment above. An rms error of 0.114 m (0.0045 in.) was obtained. The X-, Y-, and Z-axis adjustments were obtained utilizing three micrometer translation units with 50 mm travel.

IV. Field Alignment and Installation

The complete assembly was optically and mechanically aligned as shown in Fig. 7 utilizing an optical level (Wild, N-3), a theodolite (Wild T-2), two master precision levels, a series of inside micrometers and a precision fabricated template to maintain the theoretical geometry and to obtain the optimum signal reception. The three subassemblies were aligned within 0.25 mm (0.010 in.), verified and inspected as shown in Fig. 8. The assembly was transported to the test range and installed on an azimuth-elevation positioner located on the roof of the test building and the alignment was rechecked.

V. Results of Surface Measurements

An attempt was made to compute the rms value of the surface distortions in the Z-axis normal to the reflector surface. The surface distortions were measured in a local coordinate system and the reflector surface has a final shape close to a paraboloid. A FORTRAN computer program CAA-RMS, described in the appendix, was developed to transform the local coordinates into a global coordinate system. An rms best fitting program (half-path length error) was used to calculate the rms value of the reflector surface distortion. The rms values of the surface distortion of the main reflector e_1, were found to be 0.094 mm (0.0037 in.) without best fitting, and 0.0285 mm (0.001123 in.) with best fitting. The surface deviation of the subreflector e_2 (without best fitting), was found to be comparable 0.114 mm (0.0045 in.).

Since comparable machining techniques were used throughout, it is estimated that the fitted rms of the subreflector is approximately 0.028 mm (0.0011 in.). The net effective rms of both reflectors together, with best fitting, is thus approximately $\sqrt{e_1^2 + e_2^2}$ or 0.040 mm (0.0015 in.). This yields 0.5% for the ratio of surface error to wavelength at the 32-GHz microwave frequency, from the Ruze equation, and a gain limit frequency near 600 GHz. The 1.5-m clear aperture antenna model is currently undergoing electrical microwave tests that will be the subject of future TDA reports.

Acknowledgment

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Reference

1. Cha, A., "Design of a 1.5-m, 32-GHz, Clear Aperture Antenna," *TDA Progress Report 42-66*, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 1981, pp. 87-93.

Table 1. Results of surface measurements

Surface deviation, mm (in.)		
	Not best-fit	Best-fit
Main reflector	0.112 (0.0044)	0.028 (0.0011)
Sub-reflector	0.114 (0.0045)	0.028 ≅ (0.0011)
RSS	0.160 (0.0063)	0.038 ≅ (0.0015)

Half pathlength error, 0.0381 mm (0.0015 in.); surface tolerance loss ≅ 0.5% of wavelength (32 GHz); gain limit frequency ≅ 600 GHz.

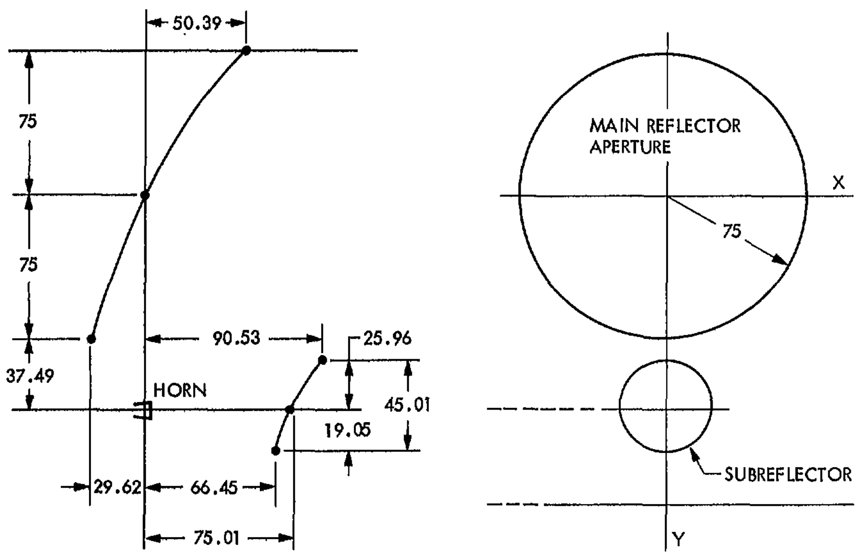

Fig. 1. Geometry of offset clear aperture dual reflector (in cm)

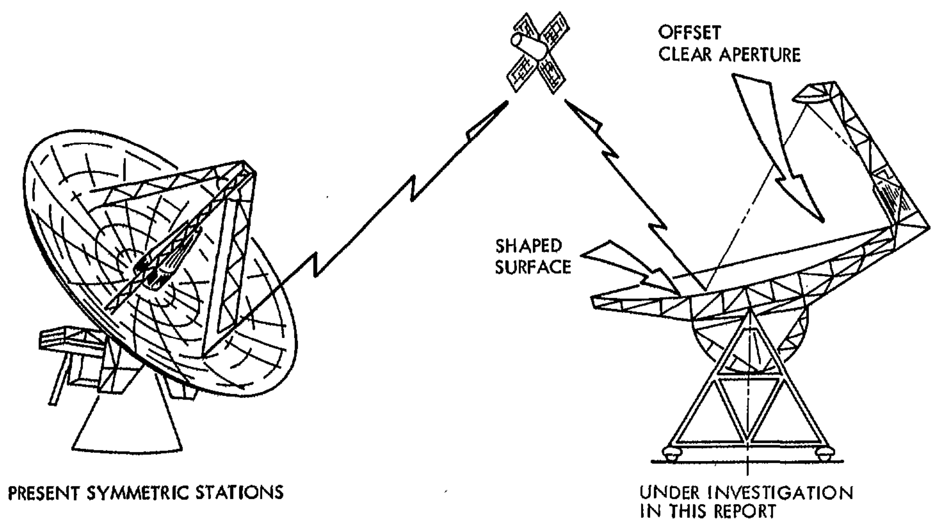

Fig. 2. Alternative reflector configurations for very low noise and high-gain ground stations

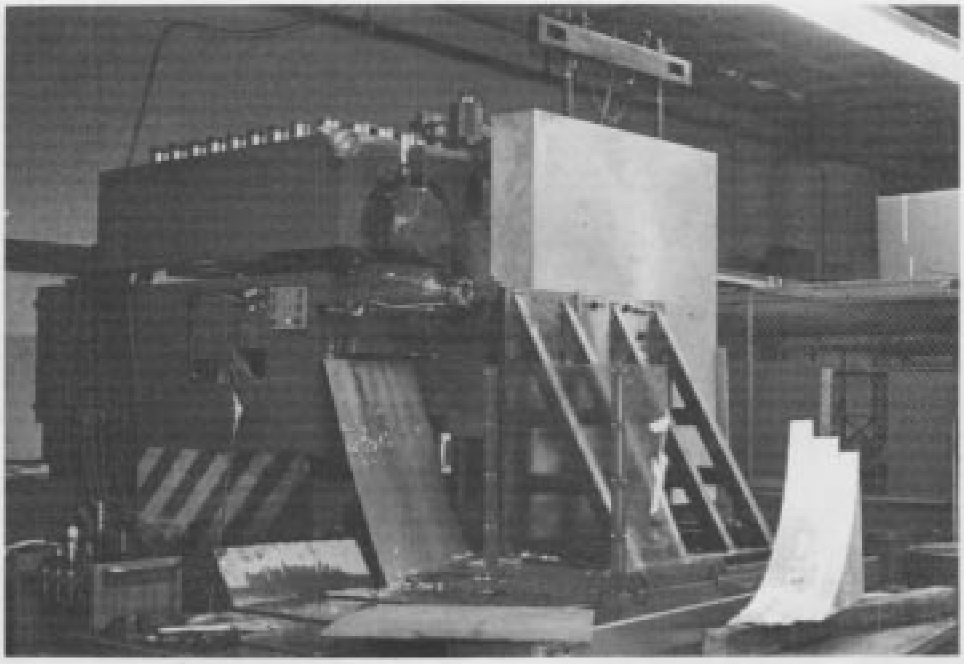

Fig. 3. Milling machine and tooling showing billet

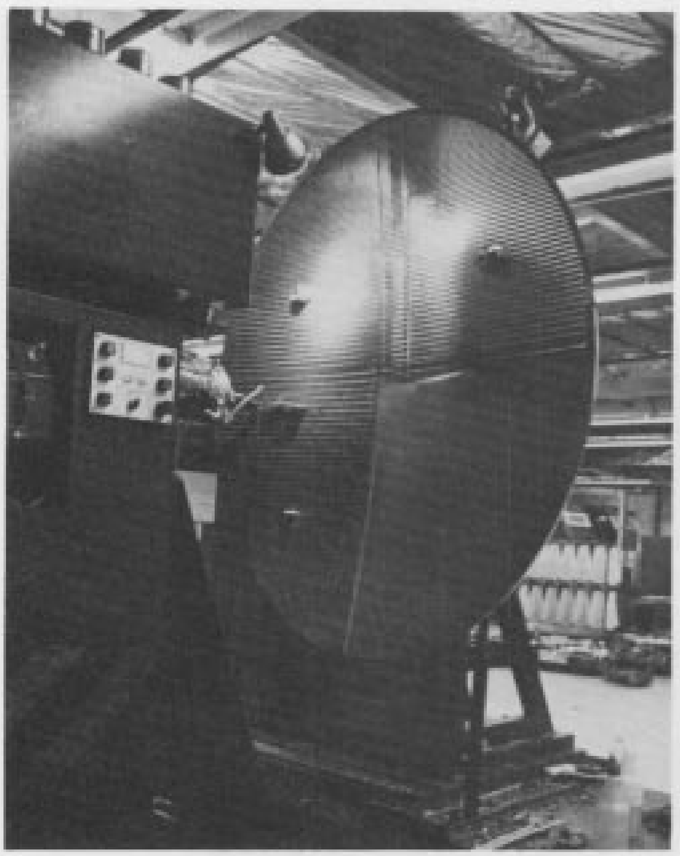

Fig. 4. First rough cut and one quadrant of second cut of main reflector

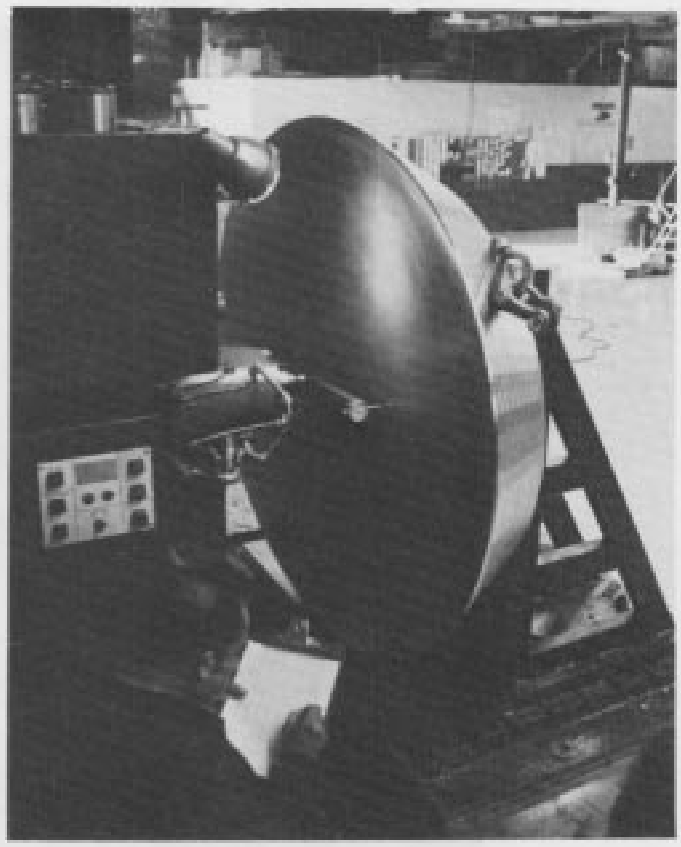

Fig. 5. Checking the rms of the completed reflector at Tempe Precision

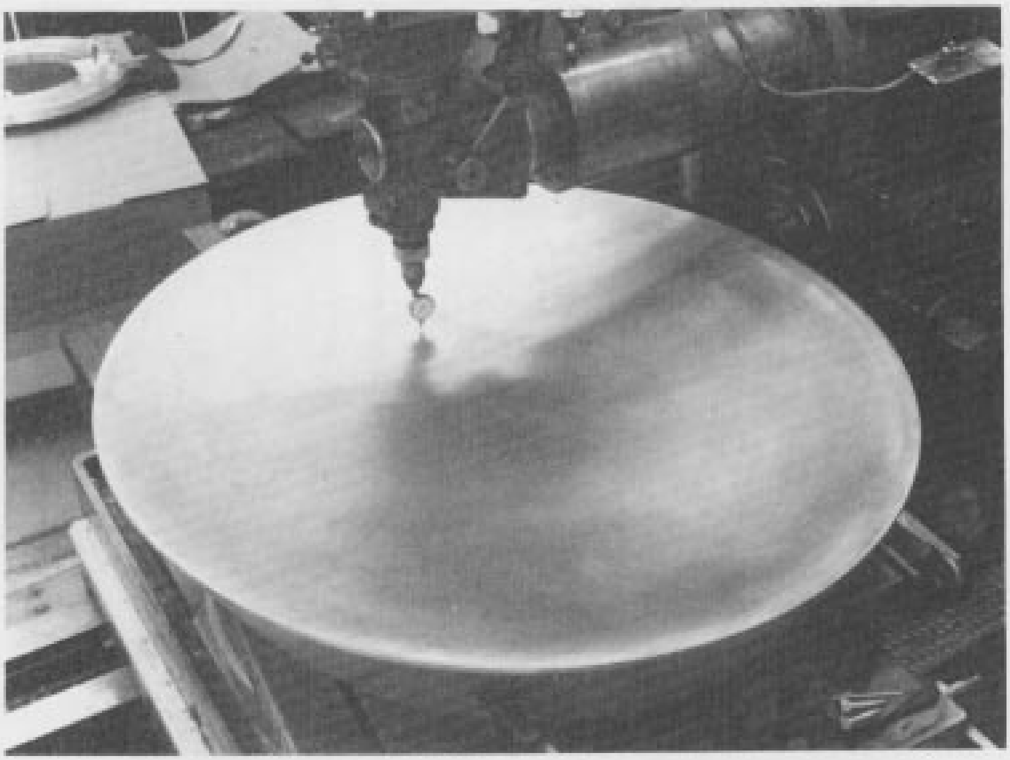

Fig. 6. Checking the rms of the reflector at JPL machine shop

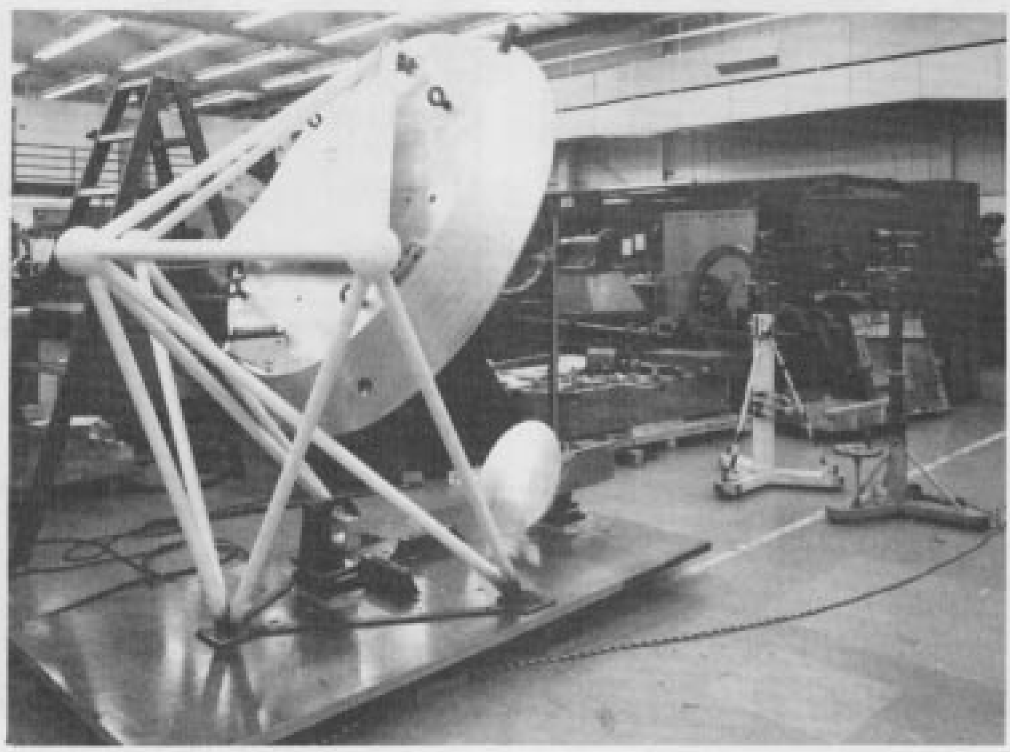

Fig. 7. Alignment equipment for the clear aperture antenna

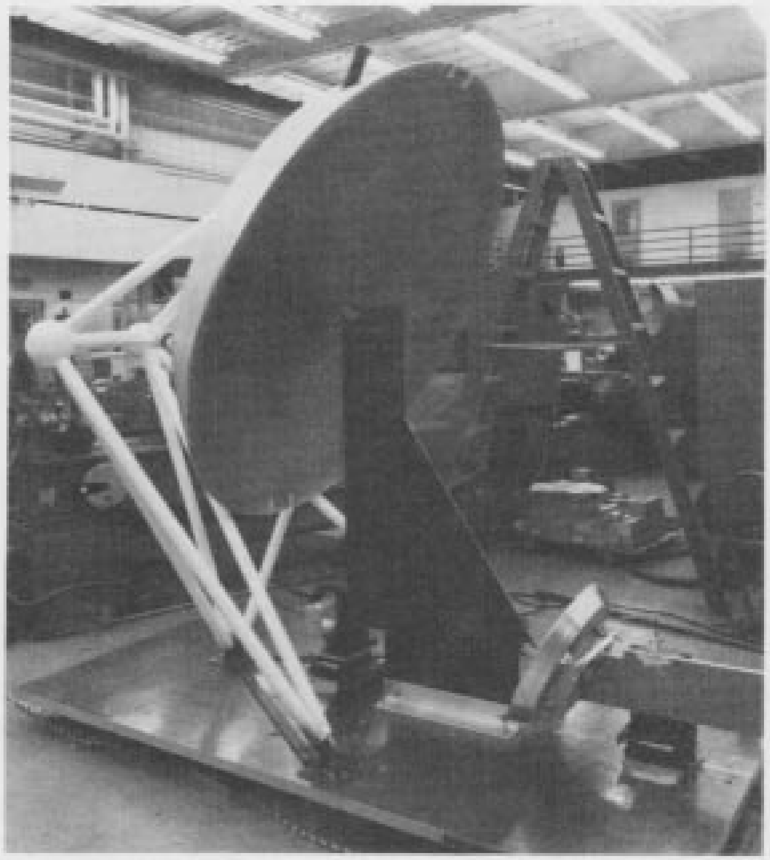

Fig. 8. Axis alignment of the clear aperture antenna

Appendix
Details of Computer Program CAA-RMS

The computer program CAA-RMS, written in FORTRAN, was developed to transform the measured surface distortions from a local-coordinate system into a global-coordinate system as shown in Fig. A-1. The output of this program as shown in Fig. A-2 is used as input to the JPL RMS-BEST-FITTING PROGRAM to calculate the best fitting rms value of the reflector surface distortion.

I. Surface Geometry Equations

The paraboloid is defined by

$$Z = \frac{X^2 + Y^2}{4F} = \frac{R^2}{4F} \tag{A-1}$$

where F = focal length

The slope is defined by

$$\frac{\Delta Z}{\Delta R} = \frac{R}{2F} = \frac{\sqrt{X^2 + Y^2}}{2F} \tag{A-2}$$

The normal vector at any point on the paraboloid is

$$N = (N_1, N_2, N_3) = \left(-\frac{2X}{C_1}, -\frac{2Y}{C_1}, \frac{4F}{C_1}\right) \tag{A-3}$$

where

$$C_1 = \sqrt{4X^2 + 4Y^2 + 16F^2}$$

The coordinate transformation from the local coordinate (x_1, y_1, z_1) to the global coordinate (X, Y, Z):

$$\left.\begin{aligned} X &= x_1 \\ Y &= Y_{off} + y_1 \cos\theta - z_1 \sin\theta \\ Z &= Z_{off} + y_1 \sin\theta + z_1 \cos\theta \end{aligned}\right\} \tag{A-4}$$

The measured distortion vector ΔZ has components U, V, W:

$$\left.\begin{aligned} U &= 0. \\ V &= \Delta Z \cdot \sin\theta \\ W &= \Delta Z \cdot \cos\theta \end{aligned}\right\} \tag{A-5}$$

The projection of the distortion vector on the normal has components:

$$\left.\begin{aligned} P_1 &= C_2 \cdot N_1 \\ P_2 &= C_2 \cdot N_2 \\ P_3 &= C_2 \cdot N_3 \end{aligned}\right\} \tag{A-6}$$

where

$$C_2 = U \cdot N_1 + V \cdot N_2 + W \cdot N_3$$

The length of the projected vector

$$PL = \sqrt{P_1^2 + P_2^2 + P_3^2} \tag{A-7}$$

When the normal is projected in dZ direction:

$$|dZ| = \frac{PL}{\cos(SLOPE)} = \frac{PL}{\cos\left(\sqrt{\frac{X^2 + Y^2}{2F}}\right)} \tag{A-8}$$

A listing of the program is given in Fig. A-3.

II. Sample Calculation

A. Input

Focal length of fitting paraboloid, F = 1342.39 mm (52.85 in.)

Offset of local coordinate system:

X_{off} = 0

Y_{off} = 1434.08 mm (56.46 in.)

Z_{off} = 383.03 mm (15.08 in.)

Angle between local and global systems:

θ = 28.073 deg

The surface distortions, ΔZ, measured in local coordinates, are read in (a total of 400)

B. Output

RMS values of the surface distortion:

0.094 mm (0.0037 in.) (without fitting)

0.0331 mm (0.001303 in.) (with best fitting)

The printout of this example is shown in Fig. A-4.

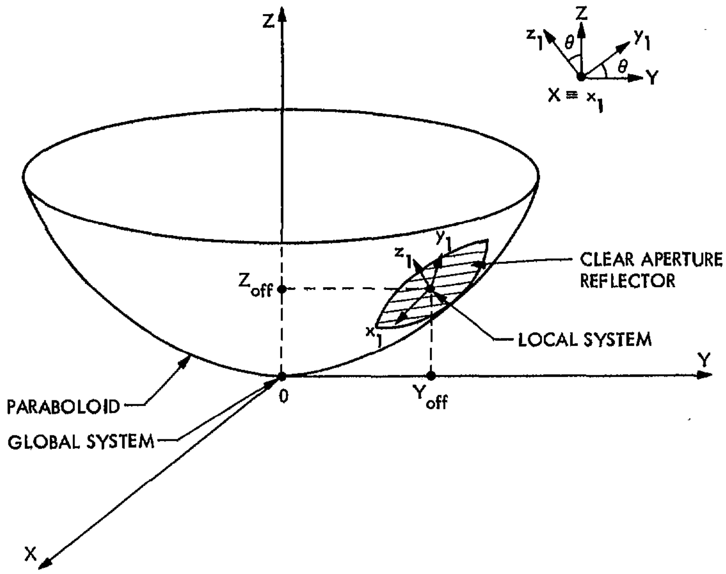

Fig. A-1. Local and global coordinates

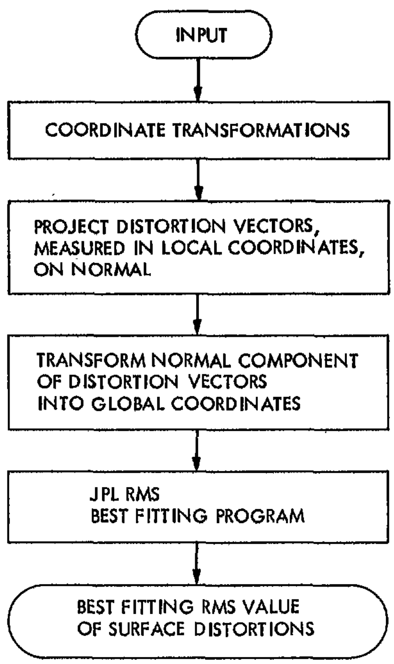

Fig. A-2. Flow chart of rms computer steps

```
48336*MKK(1).CAA-RMS
C       PROGRAM COMPUTES THE DELTA Z ERRORS OF CLEAR APERATURE REFLECTOR
C       WHICH HAS A SHAPED SURFACE CLOSE TO A PARABOLOID
C      THE OUTPUT FITS THE RMS BEST FITTING PROGRAM SO THAT A BEST
C       THE SURFACE WAS ACTUALLY MEASURED IN A LOCAL COORDINATE SYSTEM
C       ABOUT ITS X AXIS 28.073 DEGREES
C       OFFSET IN Y 56.46 INCHES FROM THE PARABOLOIDS' SYSTEM
C       OFFSET IN Z 15.08 INCHES FROM THE PARABOLOIDS' SYSTEM
C
C            CONSTANTS
C
      REAL N1,N2,N3
      AREA= 1.0
      F= 52.85             @ FOCAL LENGTH OF FITTING PARABOLOID
      YOFF= 56.46          @ Y OFFSET OF LOCAL COORDS SYSTEM
      ZOFF= 15.08          @ Z OFFSET OF LOCAL COORDS SYSTEM
      XROT= 28.073* 0.01745329252
      NP= 0
      DIMENSION ID(400), X1(400), Y1(400), Z1(400), ZERR(400)
      PRINT 4000
 4000 FORMAT ('   ID        X         Y         Z        ZZ   ZERR        V
     $    W      C2        P1        P2        P3        PL    TANG        DZ')
      PRINT 4100
 4100 FORMAT ('
     $               C1        N1        N2        N3        ',//)
C
C        READ IN DATA
C
      DO 50 I=1,400
      READ 1000, ID(I), X1(I), Y1(I), Z1(I), ZERR(I)
 1000 FORMAT ()
      IF (ID(I).EQ.0) GO TO 51
      NP=NP+ 1
      X= X1(I)
      Y= YOFF + Y1(I)* COS(XROT)- Z1(I)*SIN(XROT)
      ZZ= ZOFF + Z1(I)*COS(XROT) + Y1(I)* SIN(XROT)
      Z= (X*X+ Y*Y)/(4.*F)
C           N1,N2,N3 = COMPONENTS OF THE NORMAL TO PARABOLOID
      C1= SQRT(4.*X*X+ 4.*Y*Y+ 16.*F*F)
      N1= -2.0*X/C1
      N2= -2.*Y/C1
      N3= 4.*F/C1
C               U,V,W = COMPONENTS OF THE DISTORSION VECTOR
      U= 0.
      V= -ZERR(I)* SIN(XROT)
      W= ZERR(I)* COS(XROT)
C        PROJECT DISTORTION VECTOR ON NORMAL
      C2= U* N1+ V* N2+ W*N3
      P1= C2* N1
      P2= C2* N2
      P3= C2* N3
      PL= SQRT(P1*P1+ P2*P2+ P3*P3)
C                SLOPE OR TANGENT ANGLE TO PARABOLOID
      SLOPE= SQRT(X*X+ Y*Y)/(2.*F)
      SLOPE= ATAN(SLOPE)
      DZ= PL/ COS(SLOPE)
      TANG= SLOPE* 57.2957795131
C
      PRINT 2000,ID(I),X, Y, Z, ZZ, ZERR(I), V,W, C2, P1,P2,P3, PL,
     $  TANG, DZ
      PRINT 2100, C1, N1, N2, N3
 2100 FORMAT (69X,F8.2,3F8.4)
 2000 FORMAT (I5,4F9.4,F7.4,8F8.4,F9.4)
      WRITE (10,3000) X,Y,DZ,AREA,ID(I)
 3000 FORMAT (2F10.3,30X,F10.4,F10.2,I10)
   50 CONTINUE
   51 CONTINUE
      PRINT 5000, NP
 5000 FORMAT (1H0,'***** - ',I5,' - POINTS PROSESSED')
      STOP
      END

@PRT,S  MKK.CAA/LOCAL-DATA
```

Fig. A-3. CAA-RMS program listing

```
CLEAR APERATURE - A                                                    ORIGIN Y OFFSET =

   PUNCH = 0  OPTION = 0 BESTFIT= 0  SPLOSS = 0  NO OF POINTS = 135

   FOCAL LENGTH =   1.34239-M(    52.850-IN)

   CNST1 =   .00000   CNST2 =   .00000   CNST3 =   .00000

   YOFF =   .000   ZOFF =   .000   XROT =   .000

          INPUT DISTORTIONS OBTAINED ANALYTICALLY - OPTION  0

                     NORMAL ANALYSIS FOR INPUT DATA

 MINIMIZATION OF RMS WITH RESPECT TO THE DESIGN PARABOLOID

   RMS OF 1/2 LAMBDA WEIGHTED BY AREAS =     .09-MM         (  .0037-IN)

 MINIMIZATION OF RMS WITH RESPECT TO FOCAL LENGTH CHANGE

   RMS OF 1/2 LAMBDA WEIGHTED BY AREAS =     .03-MM         (  .001303-IN)

   NEW FOCAL LENGTH          =              1.34304-M    (    52.876-IN)

   DEVIATION OF THE MEAN - 1/2 LAMBDA =    -.00007762-MM

   X COORDINATE OF VERTEX =                 -.204-CM        (  -.080-IN)
   Y COORDINATE OF VERTEX =                  .486-CM        (   .191-IN)
   Z COORDINATE OF VERTEX =                  .042-CM        (   .017-IN)
   ROTATION ABOUT X AXIS  =                  .001452-RADIANS
   ROTATION ABOUT Y AXIS  =                  .000577-RADIANS

   ENGLISH UNITS USED FOR MEASUREMENTS AND CALCULATIONS

PLOTTING CONTROL CARD DATA - MG =     0  NV =    -1        .0000

@WRKPT  PRINT$
```

Fig. A-4. Sample results of CAA-RMS program