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ALIGNMENT DISPLACEMENTS OF THE SOLAR OPTICAL TELESCOPE PRIMARY MIRROR

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SUMMARY

Solar Optical Telescope (SOT) is a Space Shuttle payload which is at the present time (1978) being planned at Goddard Space Flight Center (GSFC). The selected alignment method for the telescope's primary mirror is such that the six inclined legs supporting the mirror are at the same time motorized alignment actuators, changing their own length according to the alignment requirement and command. This paper describes the alignment displacements, including circumvention of some apparent NASTRAN "limitations".

INTRODUCTION

According to Reference 1," the basic scientific justification for SOT is the need to achieve the very high spatial resolution required to determine the density, temperature, magnetic field, and non-thermal velocity field in a large number of solar features, on the scale of which the various physical processes of interest are occuring. These processes include changes in magnetic field strength, waves, single pulses, and systematic mass flows. To study them, it is necessary to resolve regions over which significant gradients occur in the local magnetic and velocity fields, as well as in the local densities and temperatures.

"The SOT is a '1-m telescope'. Its aperture is 125 cm diameter, which will give it a resolution of 0.1 arc sec at 5500 Å (72 km on the sun). It operates from 1100 Å into the infrared and so can observe solar phenomena from the photosphere up through the chromosphere and transition zone to the base of the corona. It will be possible to obtain long sequences of observations that will have uniformly high resolution over the field of view.

"The basic SOT is a large, high resolution space telescope system which will accomodate numerous experiment instruments."

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The SOT is one of the Spacelab payloads and its first launch, on the Space Shuttle, is tentatively scheduled for early 1983.

The Space Shuttle Orbiter with the SOT is shown in Figure 1, and the SOT alone is shown in Figure 2. As a Spacelab payload, the SOT remains attached to the Orbiter throughout the launch, flight, and landing. Typical mission would be of several days duration during which time solar observations are made. After return to earth, the SOT is refurbished and prepared for the next flight, typically with a different set of instruments.

The SOT consists of a 3.81 m diameter, 7.31 m long truss structure at the after end of which is mounted the primary mirror (Figure 2). The primary mirror assembly provides active alignment, including focusing, offsetting, rastering, image motion compensation, and sub-arc-second pointing, while the secondary (Gregorian) mirror is fixed (Figure 3). The estimated mass of the first flight SOT is approximately 3000 kg.

ALIGNMENT DISPLACEMENTS

The objective of this paper is to describe the use of NASTRAN for determining the alignment displacements of the SOT primary mirror.

The alignment system has been proposed by Dr. Richard B. Dunn of the Sacramento Peak Observatory in New Mexico. This displacement system is such that the 6 inclined legs supporting the primary mirror are at the same time motorized displacement actuators, changing their own length in response to alignment requirement and command. Figures 4, 5 and 6 show the geometric configuration of the actuator system and the NASTRAN model.

The command system for the displacements consists mainly of three alignment telescopes located around the primary mirror and an annular alignment mirror attached to the secondary mirror. The alignment command system is not part of this paper.

According to References 1 and 2, the following motions of the primary mirror are anticipated as required for alignment:

1. Rotation of the mirror about its focus (Figure 3 and grid point 15 in Figure 6). This motion will be used to offset, to correct the line-of-sight, to raster, and to provide the internal motion compensation. The expected range of this motion $\pm$ 0.5° which corresponds to a translation or decentering of the mirror of approximately $\pm$ 4cm.

2. Tilting of the mirror about its vertex (grid point 14 in Figures 5 and 6). This motion will be used to bring the conic foci of the primary and secondary mirrors (Figure 3) into coincidence. The expected range of this motion is $\pm$30 arc seconds which corresponds to a translation of the focus of approximately $\pm$ 0.65 mm.

3. Focusing, which is the translation of the mirror along the Z axis (Figure 6). The expected range of this motion is $\pm$1 cm.

4. Translations of the focus along the X and Y axes (Figures 4 and 6). The expected range of this motion is not known at the present time.

The specified tolerances are $\pm$ 38 microns "across the prime focal plane", as well as across all planes parallel to it, and $\pm$ 5 microns in focusing, motion No. 3 above. The "prime focal plane" is the X-Y plane at grid point 15.

The fundamental problem to be solved is a geometric one. That is, given the rotations and translations of the focus and the tilt of the vertex, determine the change in length of the actuators.

The displacement problem on hand is a complex and tedious geometric problem, unless it is modeled appropriately, and unless several "tricks" are used in order to permit the application of NASTRAN Rigid Format 1 for solution without resorting to the use of ALTERS.

First, in order to be able to rotate the mirror about the focus, a fictitious rigid element, the Mac Neal-Schwendler's RBE2 (Figure 6), has been introduced as part of the analytical model. The lines connecting the grid point 15 with the grid points 1 through 6, 13, and 14 are merely figurative representations of this element.

The element RBE2 and other features of the indicated analytical model (Figures 4, 5, and 6) make this an over-constrained rigid body problem with no "free point" to start inverting the matrices. This obstacle has been circumvented by the introduction of another fictitious elastic element into the system, CROD 8, between grid points 8 and 16, with the grid point 16 providing the free point (one degree of freedom on the GRID card). This element is theoretically connected to the actual structure at grid point 8. But in order to make it quite obvious that this fictitious element and free point can be entirely independent of the structure, another, alternate, element was placed arbitrarly somewhere in space. The second version of the solution for "Rotations and Translations" uses the fictitious element CBAR 9 (instead of CROD 8) located between fictitious grid points 100 and 101, away from, and unconnected to, the mirror and the fictitious element RBE2 7. The grid point 100 is constrained and the grid point 101 is free in all six degrees of freedom on its GRID card. The results were identical to those obtained with the element CROD 8.

The explanation for this phenomenon lies in the fact that NASTRAN needs at least one elastic element, no matter how fictitious, anywhere in space, with at least one "free point" to start inverting the matrices. One could compare it with priming a water pump.

Secondly, there are no loads, no forces, and no stresses involved in this problem, only displacements. But the element force recovery feature of NASTRAN has been utilized to determine the fundamental unknown: the change in length of the actuators (mirror's legs, Figure 5). This is an important parameter in the displacement system. In order to get these changes in length calculated directly and printed in the output, the original length of the actuators (336.1547 mm) has been substituted for the Young's modulus of elasticity on the material card (MAT1, Table 2). This is based on the following rearragement of the equation for elongation:

$$\delta = \frac{PL}{AE}$$

For A = 1.0 and E = L

$$\delta = \frac{PL}{L} = P$$

Consequently, the NASTRAN output under FORCES IN ROD ELEMENTS contains actually the changes in length of the actuators (in millimeters, Table 4).

After the above fictitious elements are introduced into the model, and the actuators' lengths substituted for the modulus of elasticity, the analyses become very simple.

The following basic analyses were performed:

1. Rotations about the focus and translations of the focus (grid point 15) along the three orthogonal axes using the fictitious element CROD 8.

2. The same as under 1. above using the fictitious element CBAR 9, instead of CROD 8 (Tables 1, 2, 3 and 4).

3. Tilting about the vertex (grid point 14) using the fictitious element CROD 8.

The following aspects are common to all three basic analyses:

1. Rigid Format 1 of the Mac Neal-Schwendler version of NASTRAN has been used. The reason for using this version instead of the NASA/ Cosmic Level 16 version was the fact that the Cosmic rigid elements CRIGD 1 and 2 each require two ALTER replacements while the Mac Neal-Schwendler rigid element RBE2 does not require any ALTER cards. Reportedly, the Cosmic limitation has been removed in the Level 17 version.

2. One-third of the mirror's circle (Figure 4) was covered in 5°-steps, from 0° to 120°, beginning at the + X axes, using two SUBCASES, rotation about the X axis and rotation about the Y axis, and then the combinations of the cosine and sine functions, respectively, of SUBCASE 1 and SUBCASE 2 as SUBCOMS (Table 1). In other words, the X axis is first rotated 5° about the Z axis and then the mirror is rotated about that new axis at the focus (by the selected unit of rotation of one arc second). The remaining two-thirds of the mirror's circle are repetitions of the covered one-third with some changes in sign.

3. The displacements are initiated by a combination of SPC and SPC1 constraints (Table 2).

4. The dimensions used are millimeters and radians, unless otherwise noted.

Examples of the output are shown in Tables 3 and 4.

A NASTRAN Rigid Format 1 limitation is that it will readily solve linear problems only. The problem on hand is geometrically non-linear, but NASTRAN can still be used for small displacements, depending on the required accuracy. Figure 7 presents geometric correction factors to be used with the NASTRAN output for the case of rotation about the focus, i. e. for the motion which produces the largest errors.

It was determined by inspection and comparison that the displacements as produced in the original output (Tables 3 and 4) do not exceed the indicated tolerances, therefore no corrections were required for any of the four basic motions.

A greater accuracy, had it been required, could have been achieved using NASTRAN Rigid Format 1. Assuming, for instance, that the given accuracy beyond a rotation angle of 10 minutes (of the focus, about the X axis, see Figure 4 and 6) is not satisfactory the correction could have been achieved in the following piece-wise linear manner:

1. On the basis of the original location of the grid points and the original length of the actuators, induce a 10-minutes-rotation. Add the increments to the original values.

2. The results of Step 1 provide the locations of the grid points and the lengths of the actuators after a 10-minutes-rotation. On that basis, induce another 10-minutes-rotation. Add the increments to results of Step 1.

3. The results of Step 2 provide the locations of the grid points and the lengths of the actuators for the second 10-minutes-rotation. On that basis induce another 10-minutes-rotation.

4. The addition of increments from steps 1, 2 and 3 offer the grid point displacements and actuator lengths for a 30-minutes-rotation.

   This process is illustrated in Figure 8.

   Table 5 lists the results of such a correction. By comparing the table in Figure 7 with Table 5, one may notice that the accurate correction in Figure 7 for the dimension "a" is 181.0 microns while the approximate correction in Table 5 is 120.7 mircons (Z coordinate). This correction process would be rather voluminous and tedious for the problem on hand because it would have to be repeated for each of the 26 SUBCASES and SUBCOMS of rotation about the focus. Depending on the required accuracy, more or less than three steps would have to be included, and possibly the process repeated for translations and tilt as well. Moreover, a separate MAT1 card would have to be used for each CROD, except the fictitious CROD 8. Without this correction process, one MAT1 card suffices (Table 1).

A correction program along these lines could be developed using NASTRAN.

CONCLUDING REMARKS

This problem and its solution illustrate the importance of proper modeling in the application of NASTRAN, which may mean the difference between a complex, tedious, and time-consuming job on one side and a simple and short job on the other without any sacrifice in accuracy.

It also points at the wide application possibilities of NASTRAN Rigid Format 1, without ALTERS, indicating that this Rigid Format can be used beyond statics, with no forces and stresses and elastic deformations.

REFERENCES

1. NASA/Goddard Space Flight Center/SSPP Office: Executive Summary Solar Optical Telescope Program Plan, May 1978.

2. Dunn, R. B., Sacramento Peak Observatory: Preliminary Design Analysis for the Solar Optical Telescope Main Mirror Actuator, August 1977. NASA CR 156701.

3. The Mac Neal-Schwendler Corporation: MSR-39 MSC/NASTRAN User's Manual, May 1976 (Revised January 1977).

4. NASA/Cosmic: The NASTRAN User's Manual (Level 16.0), March 1976. NASA SP-222 (03).

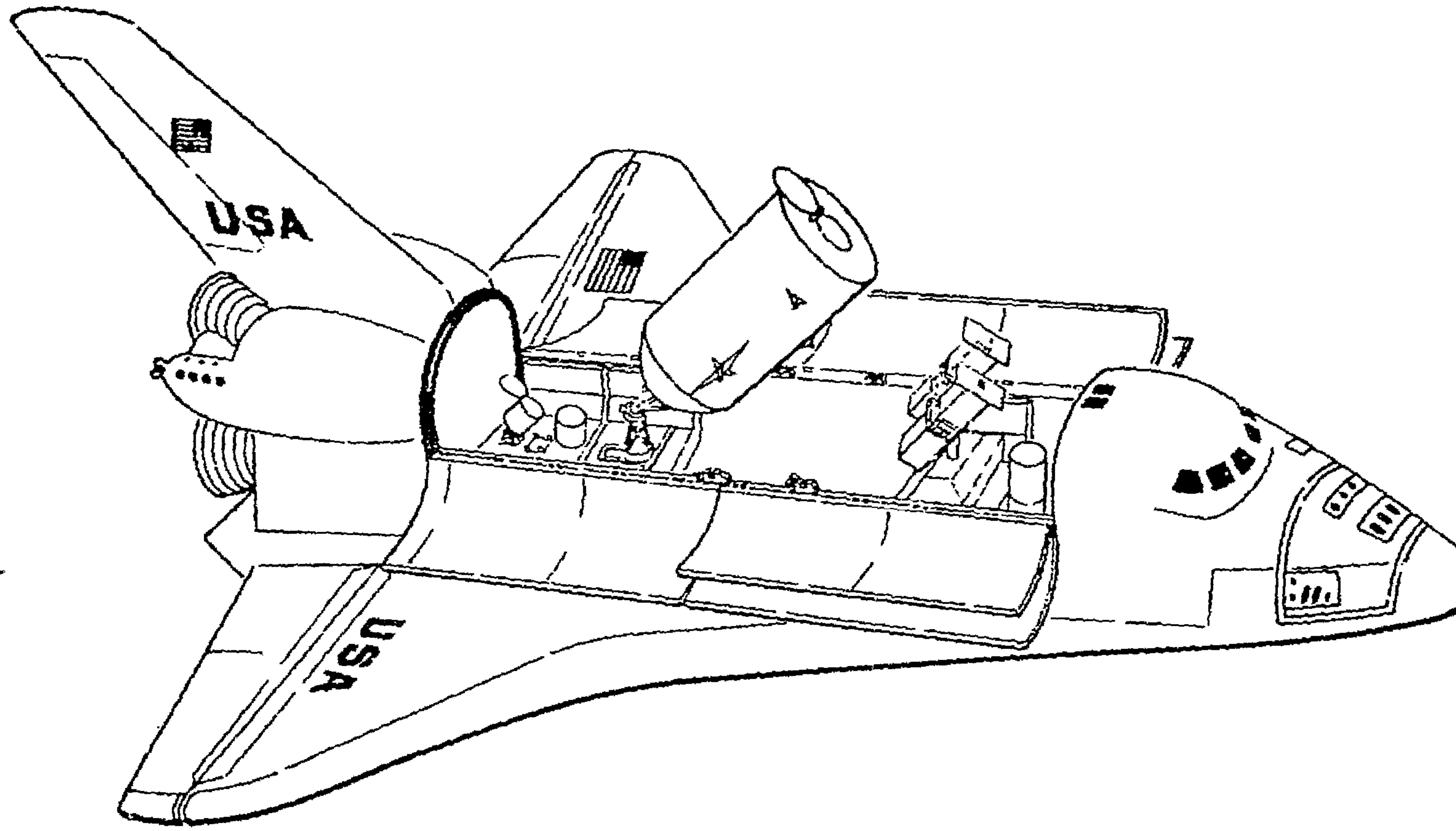


FIGURE 1: ORBITER WITH SOT

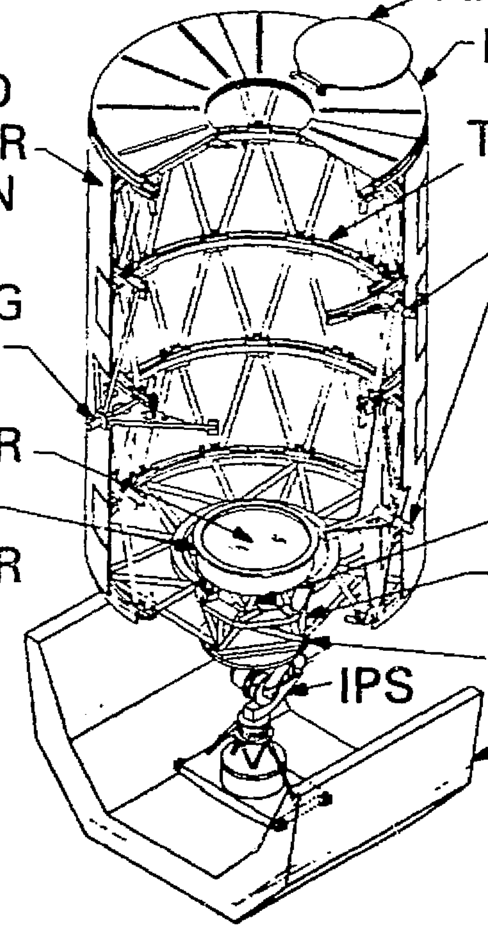


FIGURE 2: BASIC SOT

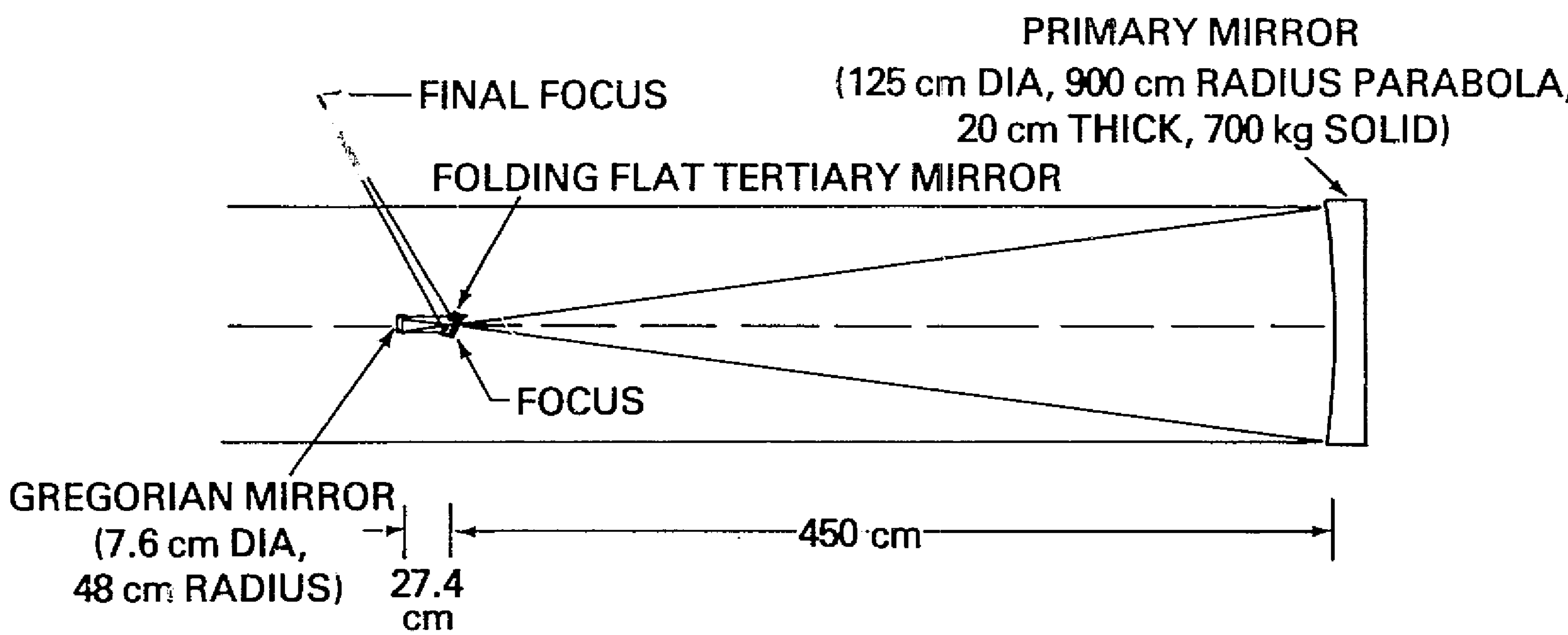


FIGURE 3: TELESCOPE CONFIGURATION

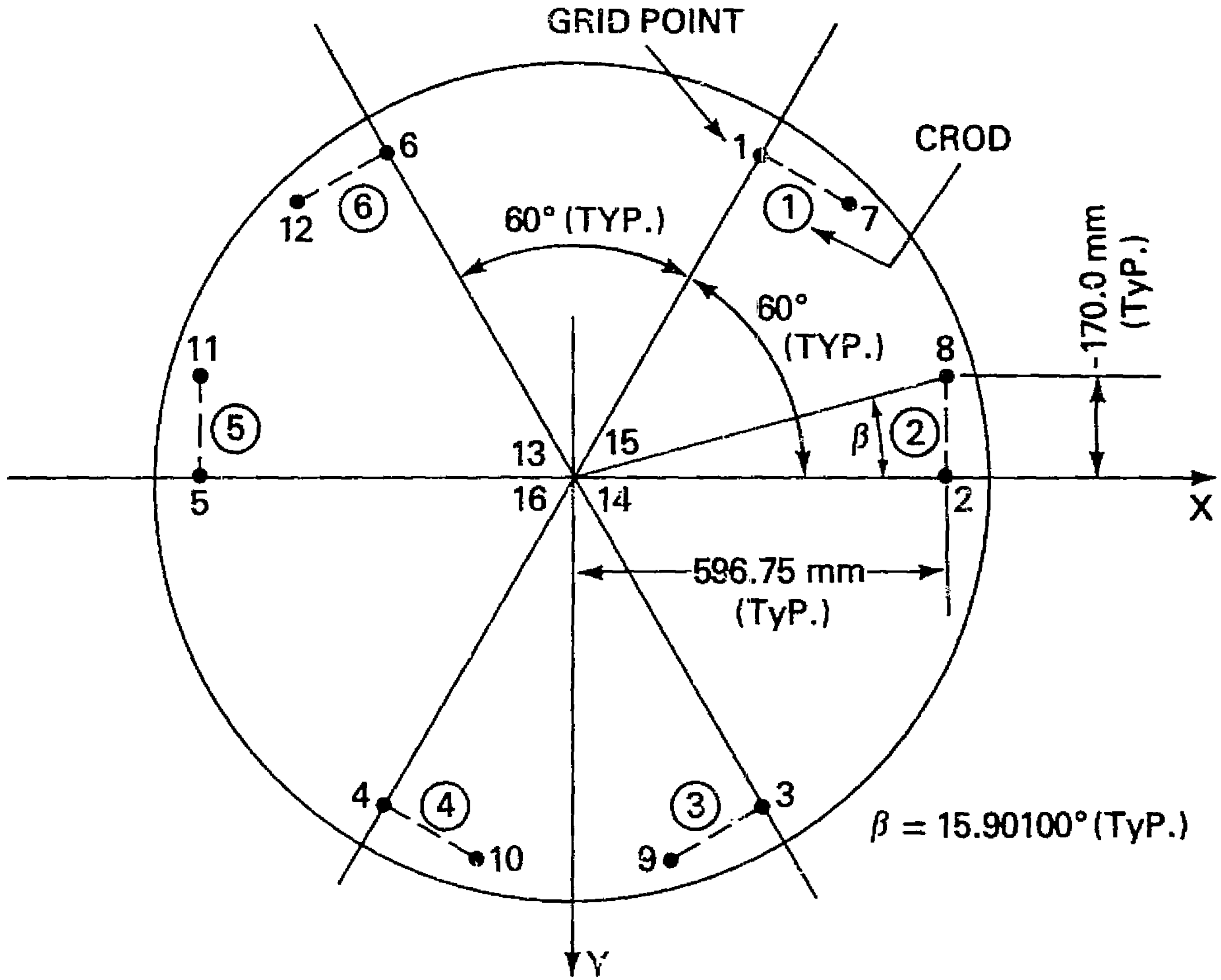


FIGURE 4: PLAN VIEW OF MIRROR & PARTIAL MODEL

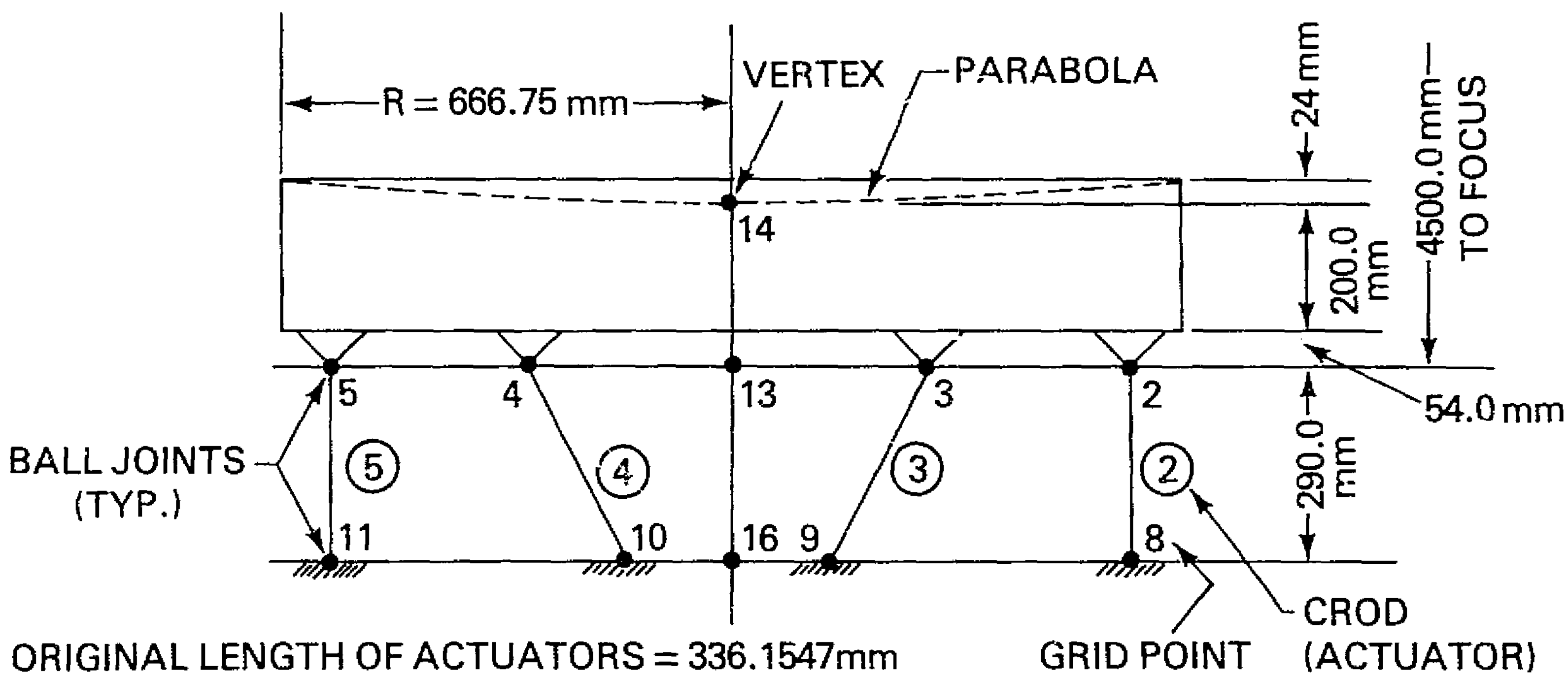


FIGURE 5: SIDE VIEW OF MIRROR & PARTIAL MODEL

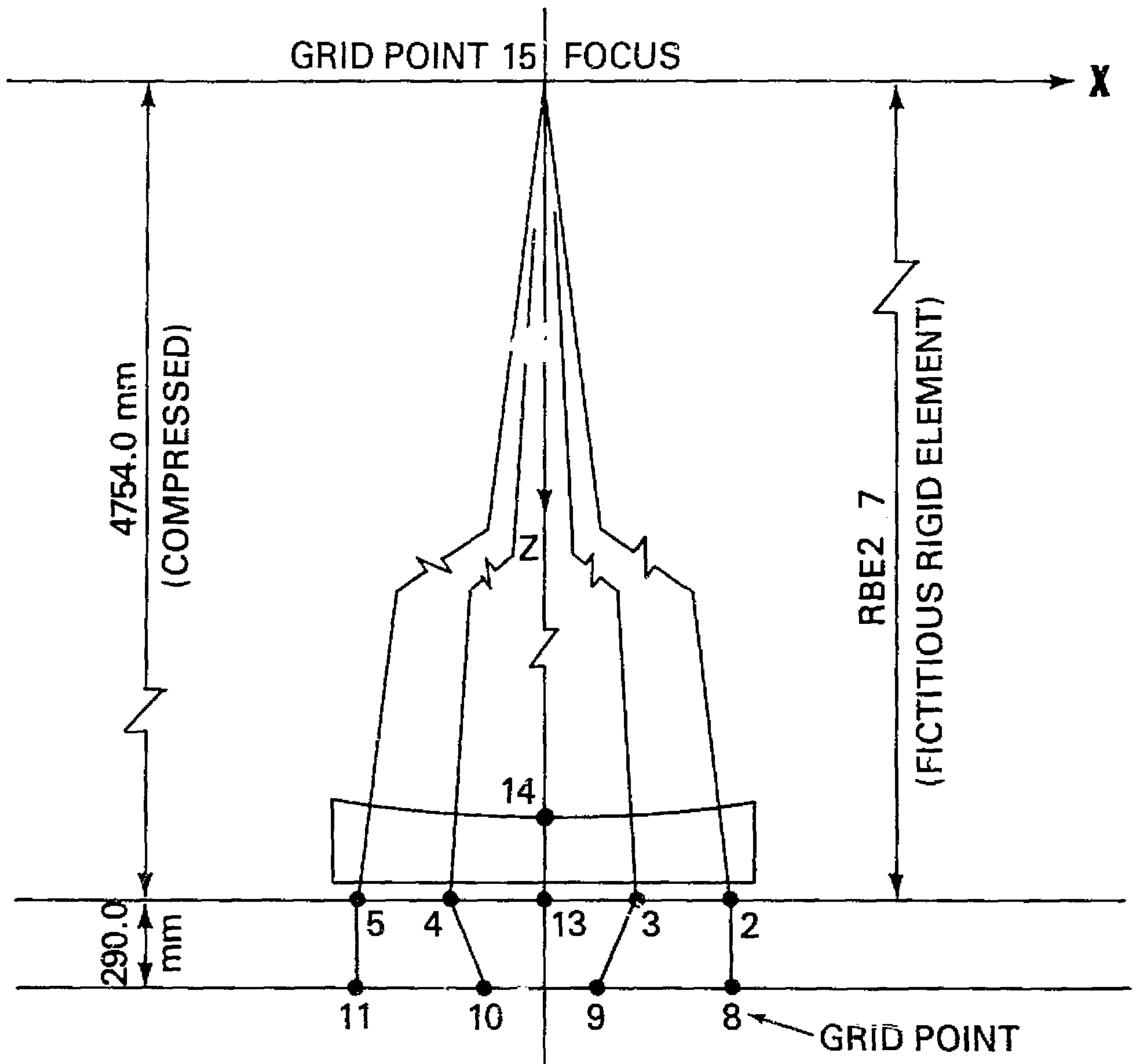
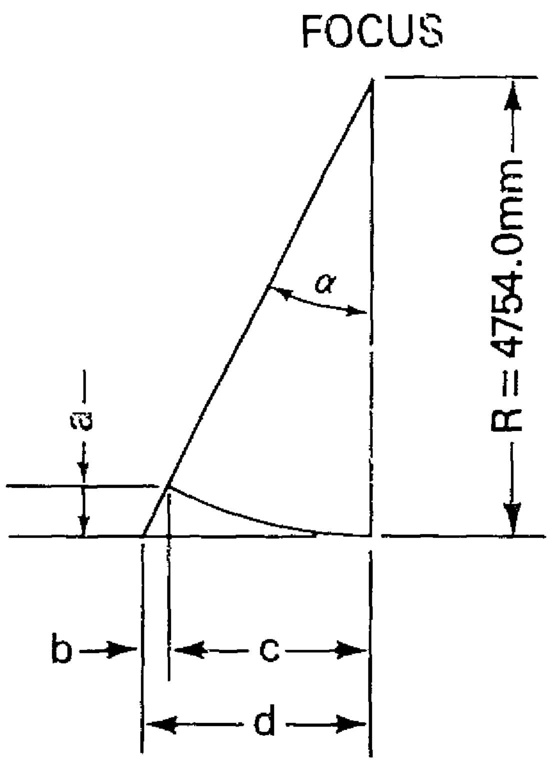


FIGURE 6: SIDE VIEW OF PARTIAL MODEL



α	a	b
	MICRONS	
1″	0.0001	0.0000
30″	0.0503	0.0000
1′	0.2011	0.0001
10′	20.1132	0.0585
20′	80.4526	0.4681
30′	181.0178	1.5797

$a = R(1\text{-}COS\ \alpha) = C\ TAN\ (\frac{\alpha}{2})$ $\quad d = R\ TAN\ \alpha$

$c = R\ SIN\ \alpha$ $\quad b = d - c = R\ (TAN\ \alpha - SIN\ \alpha)$

a = b = o IN NASTRAN OUTPUT, I.E. d = TRANSLATION VALUE FOR ROTATION α

FIGURE 7: ACCURATE CORRECTION SAMPLE

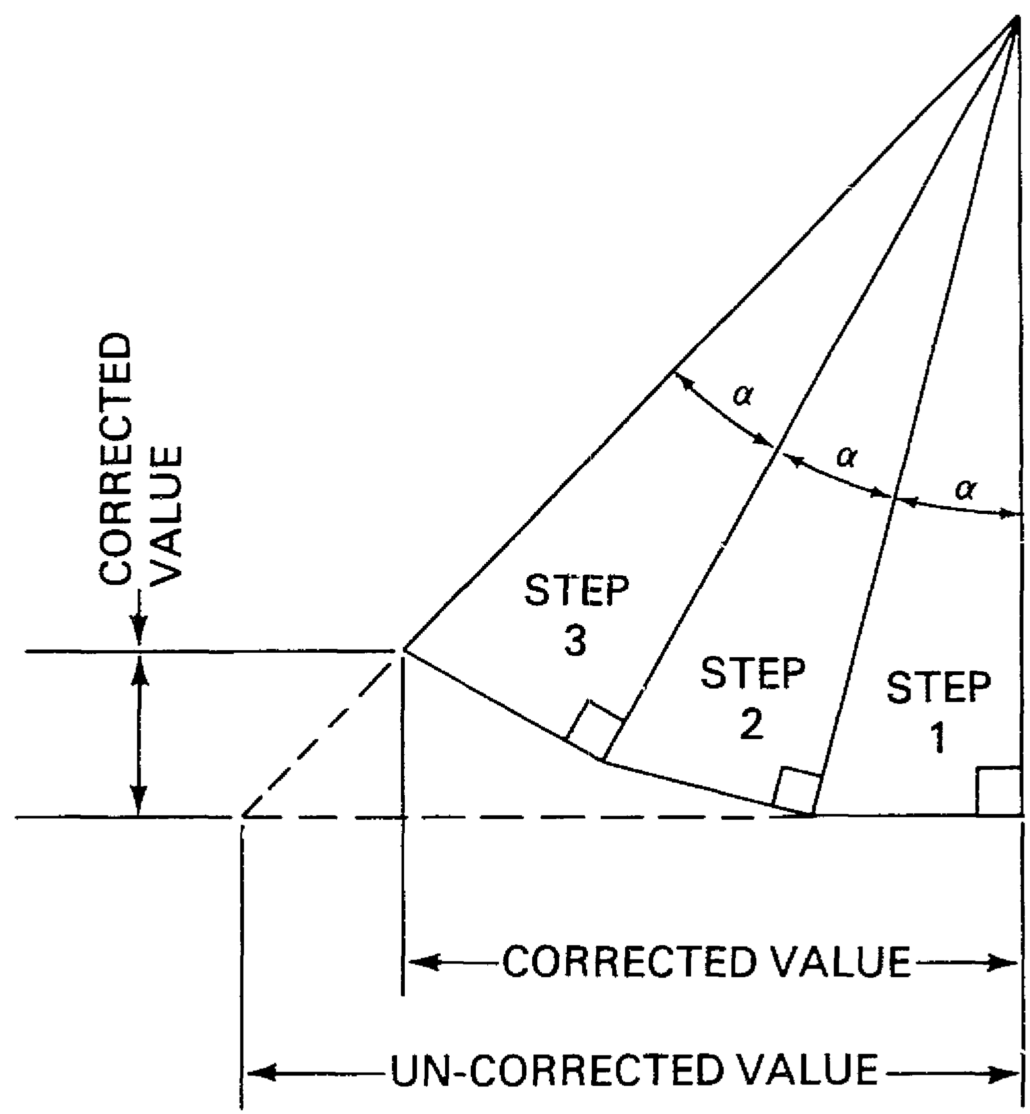


FIGURE 8: APPROXIMATE CORRECTION METHOD

TABLE 1:

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SOT PRIMARY MIRROR WITH FICTITIOUS G.P. 100 + 101
ROTATION + TRANSLATION DISPLACEMENTS

                    C A S E   C O N T R O L   D E C K   E C H O
CARD
COUNT
  1      TITLE = SOT PRIMARY MIRROR WITH FICTITIOUS G.P. 100 + 101
  2      SUBTITLE = ROTATION + TRANSLATION DISPLACEMENTS
  3      LINE = 70
  4      OUTPUT
  5         SET 1 = 1 THRU 6
  6         DISPLACEMENT = ALL
  7         ELFORCE = 1
  8         SUBCASE 1
  9           LABEL = 1 ARC SEC ROTATION ABOUT X AXIS
 10           SPC = 1
 11         SUBCASE 2
 12           LABEL = 1 ARC SEC ROTATION ABOUT Y AXIS
 13           SPC = 2
 14         SUBCOM 3
 15           LABEL = 1 ARC SEC ROTATION AT 5 ARC DEGREES FROM X AXIS
 16           SUBSEQ = 0.9961946981, 0.0871557427
 17         SUBCOM 4
 18           LABEL = 1 ARC SEC ROTATION AT 10 ARC DEGREES FROM X AXIS
 19           SUBSEQ = 0.984807753, 0.1736481777
 -.           . . . .  .

 83         SUBCOM 26
 84           LABEL = 1 ARC SEC ROTATION AT 120 ARC DEGREES FROM X AXIS
 85           SUBSEQ = -0.5, 0.8660254038
 86         SUBCASE 27
 87           LABEL = 1 ARC SEC ROTATION ABOUT Z AXIS
 88           SPC = 27
 89         SUBCASE 28
 90           LABEL = 1 MICRON TRANSLATION OF FOCUS IN X DIRECTION
 91           SPC = 28
 92         SUBCASE 29
 93           LABEL = 1 MICRON TRANSLATION OF FOCUS IN Y DIRECTION
 94           SPC = 29
 95         SUBCASE 30
 96           LABEL = 1 MICRON TRANSLATION OF FOCUS IN Z DIRECTION (FOCUSING)
 97           SPC = 30
 98      BEGIN BULK
```

TABLE 2:

SOT PRIMARY MIRROR WITH FICTITIOUS G.P. 100 + 101
ROTATION + TRANSLATION DISPLACEMENTS

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT	. 1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10 .
1-	CBAR	9	1	100	101	1.	0.0	1.	1	
2-	CROD	1	1	1	7					
3-	CROD	2	1	2	8					
4-	CROD	3	1	3	9					
5-	CROD	4	1	4	10					
6-	CROD	5	1	5	11					
7-	CROD	6	1	6	12					
8-	GRID	1		298.375	-516.801	4754.				
9-	GRID	2		596.75	0.0	4754.0				
10-	GRID	3		298.375	516.8007	4754.0				
11-	GRID	4		-298.375	516.8007	4754.0				
12-	GRID	5		-596.75	0.0	4754.0				
13-	GRID	6		-298.375	-516.801	4754.0				
14-	GRID	7		445.5993	-431.801	5044.		123456		
15-	GRID	8		596.75	-170.	5044.		123456		
16-	GRID	9		151.1507	601.8007	5044.		123456		
17-	GRID	10		-151.151	601.8007	5044.		123456		
18-	GRID	11		-596.75	-170.	5044.		123456		
19-	GRID	12		-445.599	-431.801	5044.		123456		
20-	GRID	13		0.0	0.0	4754.0				
21-	GRID	14		0.0	0.0	4500.0				
22-	GRID	15		0.0	0.0	0.0				
23-	GRID	100		0.0	0.0	10.		123456		
24-	GRID	101		10.	0.0	10.				
25-	MAT1	.	336.1547		.3					
26-	PBAR	1	1	1.	.083	.083	.141			
27-	PROD	1	1	1.0						
28-	RBE2	7	15	123456	1	2	3	4	5	+RB7
29-	+RB7	6	13	14						
30-	SPC	1	15	4	4.8481-6					
31-	SPC	2	15	5	4.8481-6					
32-	SPC	27	15	6	4.8481-6					
33-	SPC	28	15	1	1.0-3					
34-	SPC	29	15	2	1.0-3					
35-	SPC	30	15	3	1.0-3					
36-	SPC1	1	12356	15						
37-	SPC1	2	12346	15						
38-	SPC1	27	12345	15						
39-	SPC1	28	23	15						
40-	SPC1	29	13	15						
41-	SPC1	30	12	15						
	ENDDATA									

TABLE 3:

SOT PRIMARY MIRROR WITH FICTITIOUS G.P. 100 + 101
ROTATION + TRANSLATION DISPLACEMENTS

1 ARC SEC ROTATION ABOUT X AXIS

SUBCASE 1

D I S P L A C E M E N T   V E C T O R

POINT ID.	TYPE	T1	T2	T3	R1
1	G	0.0	-2.304786E-02	-2.505501E-03	4.848100E-06
2	G	0.0	-2.304785E-02	0.0	4.848100E-06
3	G	0.0	-2.304785E-02	2.505500E-03	4.848100E-06
4	G	0.0	-2.304785E-02	2.505500E-03	4.848100E-06
5	G	0.0	-2.304785E-02	0.0	4.848100E-06
6	G	0.0	-2.304785E-02	-2.505501E-03	4.848100E-06
7	G	0.0	0.0	0.0	0.0
8	G	0.0	0.0	0.0	0.0
9	G	0.0	0.0	0.0	0.0
10	G	0.0	0.0	0.0	0.0
11	G	0.0	0.0	0.0	0.0
12	G	0.0	0.0	0.0	0.0
13	G	0.0	-2.304785E-02	0.0	4.848100E-06
14	G	0.0	-2.181643E-02	0.0	4.848100E-06
15	G	0.0	0.0	0.0	4.848100E-06
100	G	0.0	0.0	0.0	0.0
101	G	0.0	0.0	0.0	0.0

ALL R2 AND R3 DISPLACEMENTS ARE ZERO.

TABLE 4:

SOT PRIMARY MIRROR WITH FICTITIOUS G.P. 100 + 101
ROTATION + TRANSLATION DISPLACEMENTS

1 ARC SEC ROTATION ABOUT X AXIS SUBCASE 1

F O R C E S I N R O D E L E M E N T S (C R O D)

ELEMENT ID.	AXIAL FORCE	ELEMENT ID.	AXIAL FORCE
1	7.989358E-03	2	-1.165550E-02
3	3.666280E-03	4	3.666283E-03
5	-1.165550E-02	6	7.989228E-03

TABLE 5: EFFECT OF APPROXIMATE CORRECTION ON ROTATION OF 30 MINUTES (IN 10-MIN-STEPS) ABOUT X AXIS AT FOCUS

ACTU-ATORS	CHANGE IN LENGTH (mm)		DIFFERENCE
	CORRECTED	UN-CORRECTED	(mm)
1 & 6	15.9327	14.3806	– 1.5521
2 & 5	– 19.5224	– 20.9800	– 1.4526
3 & 4	8.3499	6.5993	– 1.7506
GRID POINTS	CHANGE IN Y COORDINATE (mm)		
	CORRECTED	UN-CORRECTED	
1 & 6	– 41.4735	– 41.4861	– 0.0126
2 & 5	– 41.4866	– 41.4861	0.0005
3 & 4	– 41.4997	– 41.4861	0.0136
GRID POINTS	CHANGE IN Z COORDINATE (mm)		
	CORRECTED	UN-CORRECTED	
1 & 6	– 4.6306	– 4.5099	0.1207
2 & 5	– .1207	0.0	0.1207
3 & 4	4.3893	4.5099	0.1206

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