New Short-Time Alignment Technique for 70-Meter Antenna Surface Panels

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With severely limited field modification time for upgrading the 64-m antenna to 70-m diameter, a new shorter time method for aligning the surface panels of the main reflector was needed. For each target on the surface panel, both distance (or range) and elevation angle measurements are made. A new technique for setting the surface panels at zenith look has been devised. This article describes the software required to convert the computed target distortions obtained from the JPL-IDEAS structural analysis computer program (defining the gravity load change from a 45-deg elevation angle to zenith look) into the theodolite reading at zenith look. The technique results in a perfectly shaped reflector at the 45-deg rigging elevation angle, with acceptable surface error tolerance.

I. Introduction

The normal procedures used to set the surface panels of the main reflector are as follows:

(1) Assemble the surface panels at zenith look with the mounting screws near the midpoints of their adjustment ranges with the edges of the surface panels aligned. A drill tape, holding drill bushings located at predetermined fixed arc distances (measured from the vertex of the paraboloid surface), is positioned on the surface panels. The mounting holes for the targets (for theodolite readings) are drilled as located by the bushings. The tape is laid on the surface radially and is moved circumferentially to cover all target positions.

(2) The elevation angular positions of the targets are read by the theodolite, with the antenna tilted at the rigging angle (usually 45-deg elevation). The theodolite bearings are preloaded to suit the 45-deg tilt prior to taking angle measurements. The difference between the actual angle read and the ideal angle (computed from the ideal reflector surface equation) is converted into a target translation (either up or down), which in turn is then converted into the number of turns needed for the mounting screws.

(3) The reflector is rotated to zenith look to correct the target's position by turning the surface panel mounting screws, accessible through holes in the surface panels.

The new panel setting method uses an advanced elevation-angle-measuring theodolite (Kern Model E2) attached to a distance or ranging device (Kern Model DM 503). Optical mirrors (prisms) are used as targets mounted on the surface panel corners. By this new combination of target angle and range (measured from the center) plus the computed distortion angle of the target (due to the change in gravity loading caused by the rotation of the reflector structure from the 45-deg rigging elevation angle to zenith look), the surface panels will be set directly at zenith look. In this case, the theodolite bearing preloading will not be required.

The theodolite zenith angle and the range measurements (using the ranging device) are simultaneously read and then fed into a portable microcomputer so that the target position corrections can be computed instantly and printed out.

The new setting method eliminates several time-consuming processes, including the use of the drill tape to locate the targets and instead, using semiautomated target range readout. Also, corrections to the adjustment screw of a target can immediately follow a reading by the theodolite. The description and calibration of the new angle/range measuring instruments will be given in a separate future reporting by others. In this article, only the algorithms used in the computer software are described.

II. Target Identification

The primary objective of the 70-m antenna surface panel setting alignment procedure is to obtain the newly shaped surface profile and geometry, as shown in Fig. 1 of JPL drawing No. 9486339 (see footnote 1) at the 45-deg elevation rigging angle. Because this shaped surface is axis-symmetric, only a radial profile is needed to completely describe the surface. A table of radial distances and heights, as measured from, and above, the vertex of the replaced 64-m surface, is also shown in the drawing. Figure 1 of this article gives the typical height dimensions of the theodolite and each optical target (prism or corner cube).

The targets are located on the individual surface panels (as shown in JPL drawing No. 9487694; JPL internal document). Figure 2 shows the target numbering scheme. The circumferential rows are numbered sequentially, starting from the reflector center up to row 21 (the outermost row). However, to account for the targets that were intentionally moved to miss hatches, etc., row numbers 22 through 25 are used as shown in Fig. 2. The radial columns are numbered clockwise from top to bottom. A target is numbered as the sum of the 100X column number plus the row number.

The first and fourth quadrant targets shown in Fig. 2 conform closely to the locations of the work points of the half-structural finite element model with the Y-Z plane of symmetry. The target numbers in the second and third quadrants are given negative signs. The distortion vectors of the targets in the second and third quadrants have only sign changes in their X components relative to the first and fourth quadrant distortion-vectors of the corresponding mirror-image targets. When the theodolite reads or points to a target, the inputs of range, elevation angle, and azimuth angle in subroutine (TNODE) define the target number.

III. Obtaining the Undistorted, Shaped Surface Profile

When the surface panels are initially assembled on the reflector, the targets on the panels are arranged in rows or circles, with the radial distances measured from the centerline of the theodolite (as shown in Fig. 1) to within ±1 cm (0.4 in.) of nominal, using measuring tapes or other ranging devices.

A table giving nominal radial distances of each target, including radial distances of plus and minus 2.54 cm (1 in.) and 5.08 cm (2 in.) for each row of targets, was generated. This table was then used to compute respective heights vs range, defining the undistorted, shaped surface profile by interpolation, using the slightly modified software described in JPL internal document D-1843 (see footnote 1). By geometry, the range, elevation angle, and slope, as defined by Fig. 1, were also computed (in run-stream-ST-MGLBCHK/70M) for each radial distance.

Because the new ranging theodolite is most precise with the azimuth axis vertical, the setting of the surface panels will be restricted to the zenith look of the reflector. As will be described later, the distortion component at each target will be reduced to an equivalent change (Δ) in the ideal elevation angle of the theodolite-to-target line. The change (Δ) is added to the elevation angle that defines the undistorted shaped profile. The result is that target-setting measurements and corrections can be done directly with the antenna at the zenith-look altitude.

The 70-m antenna shaped-surface profile was designed by JPL to generate a uniform radiation pattern on the main reflector and satisfying other microwave requirements. A Physical Optics (PO) analysis[2] was performed to generate the shaped-surface contour that closely follows the existing 64-m antenna paraboloid. The focal length for the 64-m antenna is 27.109 m (1067.294 in.), and the final design focal length of the best-

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[1] A. G. Cha, and W. A. Imbriale, *Computer Programs for the Synthesis and Interpolation of 70M Antenna Reflector Surface*, JPL Report D-1843, internal document, Jet Propulsion Laboratory, Pasadena, Calif., November 1984.

[2] A. G. Cha, *Physical Optics Analysis of NASA/JPL Deep Space Network 70M Antennas*, JPL Report D-1853, internal document, Jet Propulsion Laboratory, Pasadena, Calif., November 1984.

fit paraboloid to the new shaped profile of the 70-m antenna is 27.237 m (1072.329 in.).

IV. Gravity Loading Distortion Analysis

The gravity loading components of the reflector structure at zenith look (shown in Fig. 3) are computed as changes from the gravity loading at the 45-deg rigging elevation angle. From the structural analysis program (IDEAS, Ref. 1), the distortion vector obtained at zenith look will equal the sum of: (a) the unit (1.0 g) gravity loading (off/on) distortion vector in the direction $+z$ multiplied by -0.293, plus (b) the unit (1.0 g) gravity loading (off/on) distortion vector in the direction $+y$ multiplied by +0.707.

With a negligible loss in accuracy, the Z coordinates of the top chords of the reflector structure were assumed to be on a close-fit paraboloid to the shaped profile. Thus, the paraboloid RMS (root mean square) best-fit program (described in Ref. 2) with its many computing options, can be advantageously used.

The two outputs (file 81) of the IDEAS program (with the JRMFIL option) are for the unit $+Z$ gravity-loading distortion vectors assigned to the top nodes of the reflector structure, followed by the unit $+Y$ gravity loading distortion vectors. The format of the IDEAS output is compatible with the RMS program input requirements consisting of the coordinates of the grid nodes, the three-component distortion vectors, (u, v, w) the area weighting factors (A) and the identifying number of the grid nodes.

A special run-stream (ST-RMS-ZENLK/70MA-HALF) adds the $+Z$ and $+Y$ gravity loadings, as proportioned by the above gravity vector changes (outlined in Fig. 3), and outputs the summed zenith-look distortion vector (in file 80). At the same time, a constrained best-fit paraboloid was fitted to these distortion vectors (at the zenith look), forming a paraboloid having a 27.229 m (1072.0 in.) focal length. A 1/2 contour map of the best-fit paraboloid is shown in Fig. 4.

The vertex of the best-fit paraboloid, for a gravity loading in the $+Y$ lateral direction, has typically shifted in the $-Y$ direction by -17.752 cm (-6.969 in.) with a rotation of the Z axis about the X axis of -0.003881 radians. The RMS program computes the surface normal errors at each grid node of the best-fit-paraboloid. The resulting contour level lines for the right half are plotted in Fig. 4.

The above best-fit results obtained by the RMS program are of interest also for predicting the performance loss of the 70-m antenna due to the distortions of the reflector structure from the ideal shape. However, in this article the constrained best-fit paraboloid is assumed to be the baseline shape to which the (target) distortion vectors are added to define the distorted shape.

By conforming or constraining the axis of the best-fit paraboloid to coincide with the axis of the measuring theodolite of the undistorted, shaped profile (by translation, rotation and focal length change), the resultant target distortion vectors can be converted to a distortion angle (ideally, to be read by the theodolite), as shown in Fig. 5.

The distortion data at zenith look are first sequenced (by run-stream ST-SEQ-RMS/70MA) to provide grid node numbers for the midpoint adjustment screws for panel rows No. 4 and 5 and the targets moved to clear hatches and other openings, as shown in Fig. 2. Two inner nodes for columns No. 3, 7, 11, 15, etc. are deleted to match the targets actually used on the surface panels. Next, the sequenced distortion data at zenith look is best-fit with the RMS program, with constraints described above (by run-stream ST-EL90545/FFITT-70-A).

The results from this constrained best-fit are plotted in Fig. 6 for only the YZ plane. The coordinate system for this constrained best-fit paraboloid is shown by the rotated baseline marked with 0.001066 radians rotation. In the Z direction, the normal distortion vectors are plotted vs the radial distances from the center for the YZ plane (for the change from the 45-deg elevation angle to zenith look) and the result after the best-fit procedure.

V. Panel Midpoint Data Interpolation

Distortion data for the midpoints of panel rows No. 4 and 5 and the targets relocated to miss hatches and other openings were not output by the IDEAS program because no finite-number grid numbers existed for these nodes. The normal distortion vectors for these adjustment targets were generated by straight-line interpolation from the distortions of the targets on the same column on adjacent rows. (Run-stream ST-GEN-INTM/70M-DIST computes and writes the interpolated distortion vectors in file 8).

VI. Surface Panels Installation

The assembly of the reflector structure at zenith look to match the engineering drawing specifications and to the axis-symmetric configuration presents no special problems. Some additional compensation for gravity-induced bending deflections may be required as more truss members are added radially during field assembly.

If the surface panels along the YZ plane of symmetry are installed to compensate for the "as computed" gravity displacement, the top edge of the uppermost panels must be set about 46 mm (1.80 in.) below the nominal surface, and the bottom edge set about +37 mm (1.47 in.) above the nominal surface, as shown in Fig. 6. However, surface panel supports for this wide range of adjustments will be impractical for the present simple design scheme of the adjustment device.

The adjustment ranges can be decreased if the rotational components of the gravity displacements are removed and compensated by a small change in the elevation angle. This is accomplished by the best-fit described above, and with the alignment of the theodolite axis with the constrained-fit paraboloid axis. As shown in Fig. 6, the negative normal setting value reduced to about 4.0 mm (0.2 in.) and 7.0 mm (0.3 in.) for the positive-signed offsets along the *YZ* plane. The normal setting values for the first and fourth quadrant are shown in the contour map of Fig. 7.

The actual setting position (or theodolite angle) of a target will be the sum of the angle for the undistorted, shaped profile plus the equivalent angle for the distortion as described above with the axis of the reflector at 89.939 deg (90.000–0.061) elevation angle.

VII. Theodolite Computer Software

The theodolite readings (elevation and azimuth angle plus range data to be stored and processed in the computer) will be entered automatically at the same time by a pushbutton switch on the theodolite. The software sequence of steps is as follows:

First, after run-stream (ST-THEOX/70A) is activated, a table of range, elevation angle, and slope of the targets (70M-RANGE/TABLE) located on the undistorted shaped profile will be read in. Second, the gravity distortion data (EL90545-FFIT/70MA-SIM-FDR + INTM-ANGD1/70MA) for the zenith-look altitude are read in as normal distortion vectors for all target nodes. Third, the previous day's accumulated target readings are read into the computer core (from file 11). Finally, new target readings of zenith angle, range, and azimuth angle to a new target are read in by the theodolite. From the elevation angle (converted from the zenith angle theodolite reading), range and azimuth angle, subroutine TNODE decodes the node number (column × 100 + row).

When the measured range is input to the program THEOX/70M the elevation angle (ELG) for a target on the undistorted shaped profile (Fig. 7) is determined for this range by interpolating the range table (70M-RANGE/TABLE) generated by run-stream ST-MGLBCHK/70M, as previously discussed.

The distortion vector, in its normalized form (FER in Fig. 7) is converted to an equivalent theodolite elevation angle (ERELA in Fig. 7) which, when added to angle ELG, should result in the correct setting elevation angle of ELGR. The program THEOX/70M, for each reading input from the theodolite, will give the following outputs: (1) the elevation angle for a target on the undistorted shaped profile for the input range reading, (2) the difference between the input elevation angle and the above computed angle, (3) the target number, and (4) the distortion angle, linear error, and number of corrective turns of the adjustment screw.

After one day's target reading, the program will list a summary of the nodes read and their setting values, followed by a listing of 50 nodes without any theodolite input data. An overall RMS of the normal errors will be output, followed by the RMS values per each row of targets. File 11 will be overwritten with all new input data, including the corrected reading.

VIII. Quadripod and Subreflector Alignment

If the quadripod is assembled to align with the same theodolite used to set the surface panels, and to its datum targets, the quadripod will be erected with a built-in compensation of 0.061 deg for the resulting deflection from zenith to the 45-deg rigging angle. However, it will be necessary to add more compensation than 0.061 deg for gravity displacements indicated by the displacement numbers shown in Fig. 6.

The datum targets on the main reflector, used at zenith look by the panel's target setting theodolite, will not be normal to the reflector axis at the 45-deg rigging elevation angle where the final setting of the subreflector will be necessary. Another set of datum targets can be installed for use at 45 deg elevation.

IX. Results of Algorithms Verification

A check on the overall accuracy of the algorithms used was made by first generating (from the run-stream ST-MGLBCHK/70M) a series of simulated theodolite readings of: (1) zenith angle, (2) range, and (3) azimuth angle (TEST-DATA/70M-PERFECT) for the targets located on the undistorted, shaped profile at radial distance of the 70-m targets (file 9). To reduce the number of data points, targets at every odd numbered column and row for only the first and fourth quadrants were selected to compare with results from the distortion data.

The simulated theodolite reading of each target on the undistorted, shaped profile was generated. These readings should produce correction angle or normal length equal to the computed normal distortion vector, as described in section IV.

These simulated theodolite readings were input to the basic theodolite/computer operating program (THEOX/70M-ABS) by run-stream (ST-THEOX/TEST-70MA), incorporating the distortion vectors from an initial IDEAS analysis (designated as 70MA in this article). For each theodolite reading on the undistorted, shaped profile, the computed normal error is in agreement with the normal error computed by the run-stream (ST-RMS-ZENLK/70MA-HALF, described in section IV). The overall normal RMS distortion was 2.89 mm (0.114 in.), which also is in agreement with the normal RMS error of 2.88 (0.1135 in.) of ST-RMS-ZENLK/70A-HALF, where the RMS error was computed for the odd-numbered columns and rows of targets.

To check the generation of the undistorted, shaped profile described in section III, a series of even-numbered radial distances was input to the run-stream (ST-MGLBCHK/70M-CHECK). The resulting height calculations verified the values in Table 1 (JPL drawing No. 9486339, Sheet 3 of 3; JPL internal document) to four decimal places.

X. Summary

With a limited time for antenna construction, a new scheme was required for setting the surface panels, using a ranging and angle-measuring theodolite connected to a computer, with the reflector positioned at zenith look.

The software used in the computer is described in this article. To comply with the polar coordinate system of the theodolite, the dimensions of the undistorted, shaped profile of the reflector were converted to range and elevation-angle values. By constrained best-fit, the computed distortion vector (by the IDEAS program) with the RMS program adjustments for the surface panel supports were minimized and added to the shaped-profile dimensions.

With the computer-operated theodolite, theodolite-target field readings were converted in real time into point corrections. The latter are converted into the number of turns needed for the adjustment screws holding the surface panels.

References

1. Levy, R., "Optimization of Antenna Structure Design," *Eighth Conference on Electronic Computation*, pp. 114–129, ASCE, Houston, Tex., February 1983.
2. Katow, M S., and Schmele, L. W., "Antenna Structures: Evaluation Techniques of Reflector Distortions," *Space Programs Summary 37–40*, Jet Propulsion Laboratory, Pasadena, Calif., Vol. IV, September 1968, pp. 176–184.

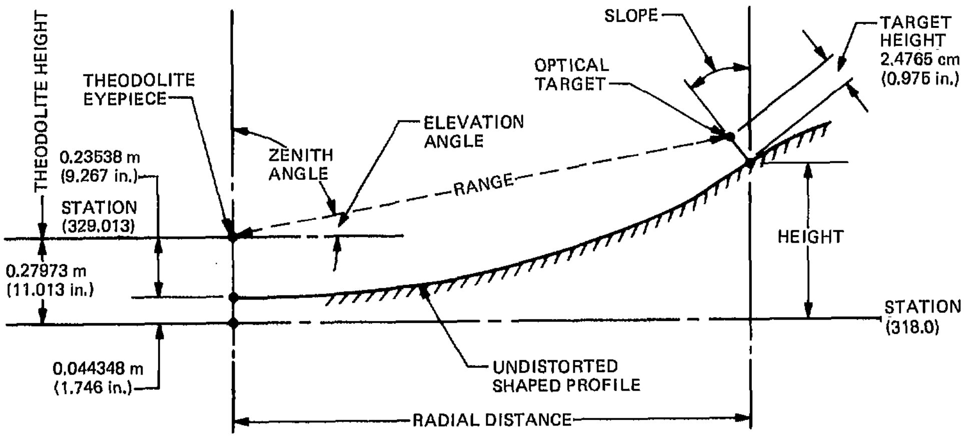


Fig. 1. Shaped main reflector profile

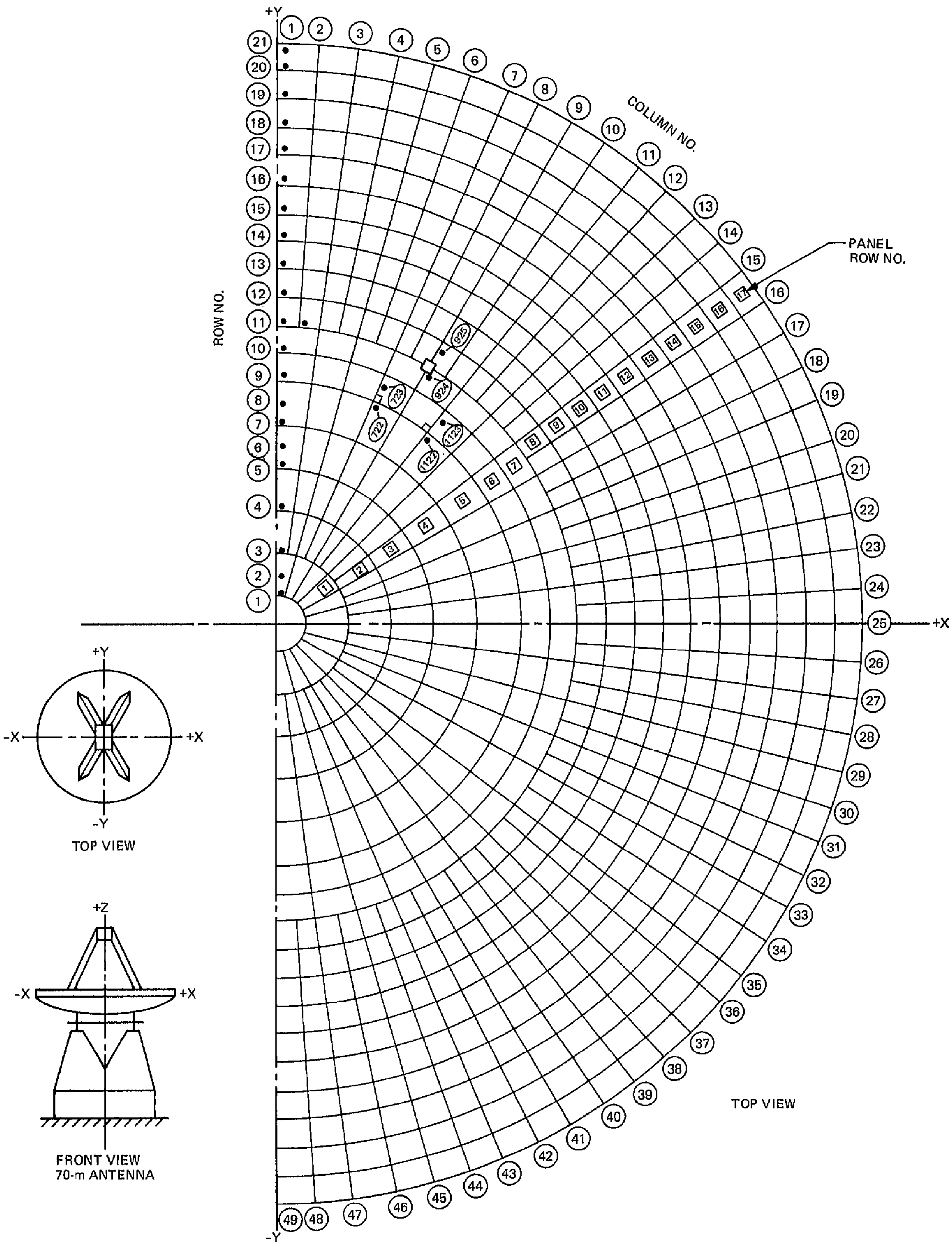


Fig. 2. Target-numbering scheme

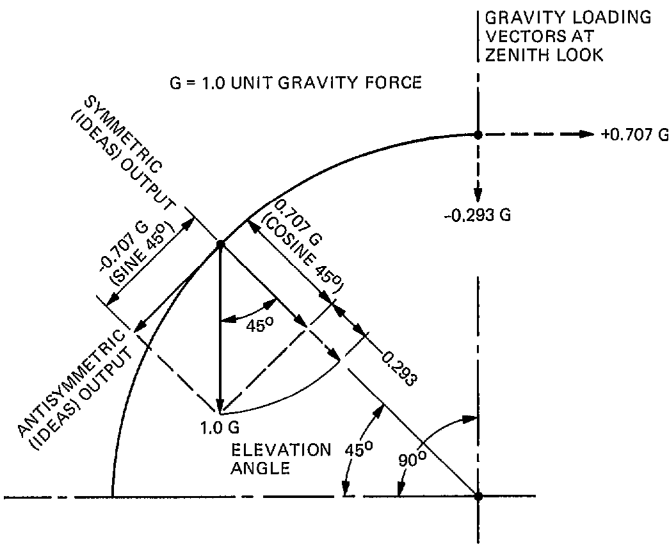


Fig. 3. 70-m gravity loading components for surface panels rigged at 45-deg elevation

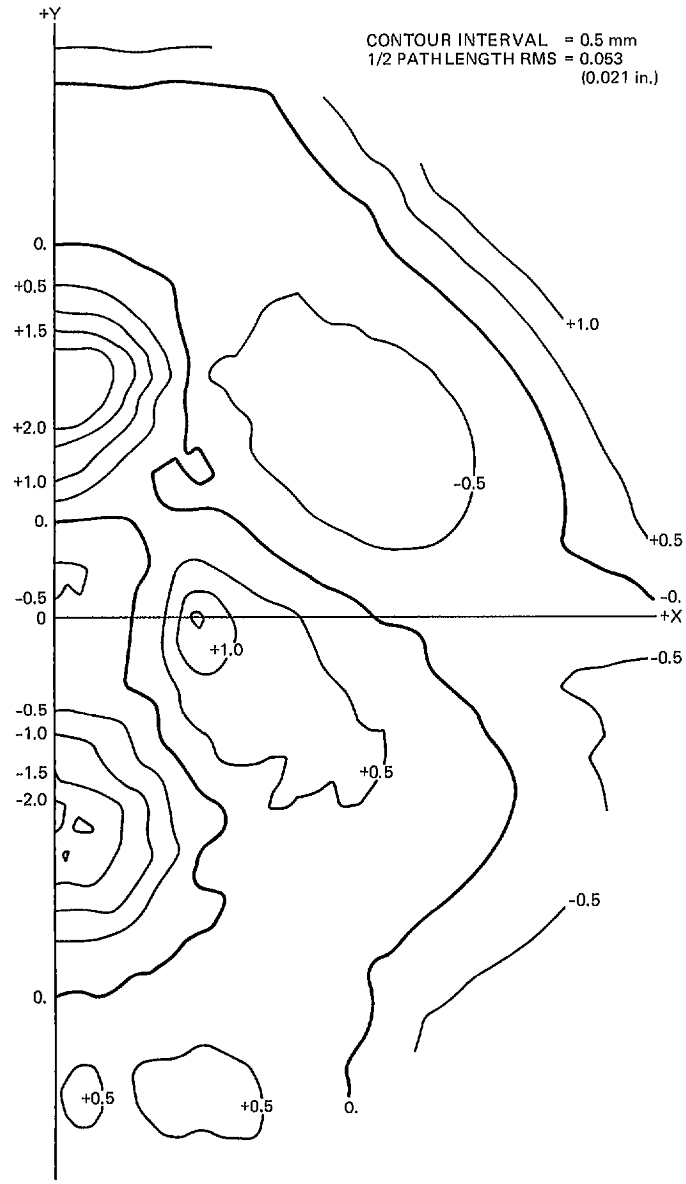
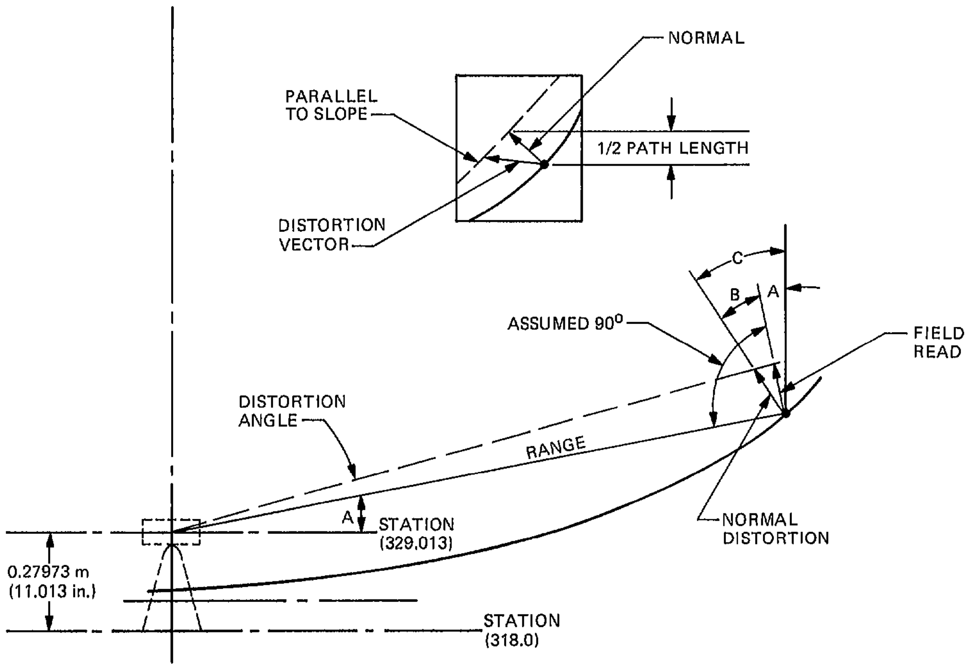


Fig. 4. 70-m reflector structure best-fit distortion at EL-90 with panels set at 45 EL



A = THEODOLITE ELEVATION ANGLE

B = C - A

C = SLOPE OR TANGENT ANGLE TO PARABOLOID

$$\text{DISTORTION ANGLE} = \frac{\text{NORMAL} \times \cos(B)}{\text{RANGE}} \text{ rad}$$

Fig. 5. Distortion angle geometry

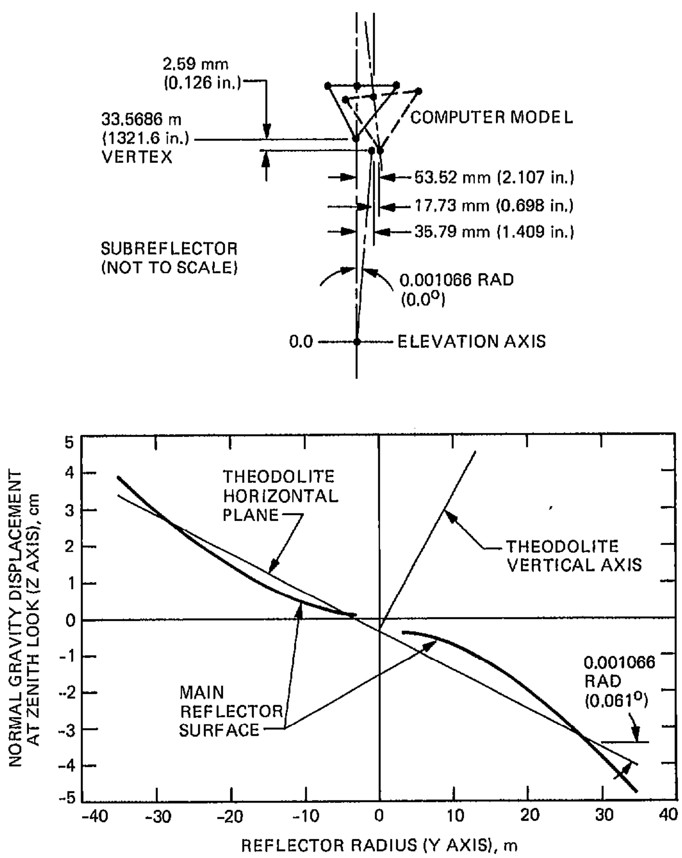


Fig. 6. Gravity loading displacements at zenith look: YZ plane

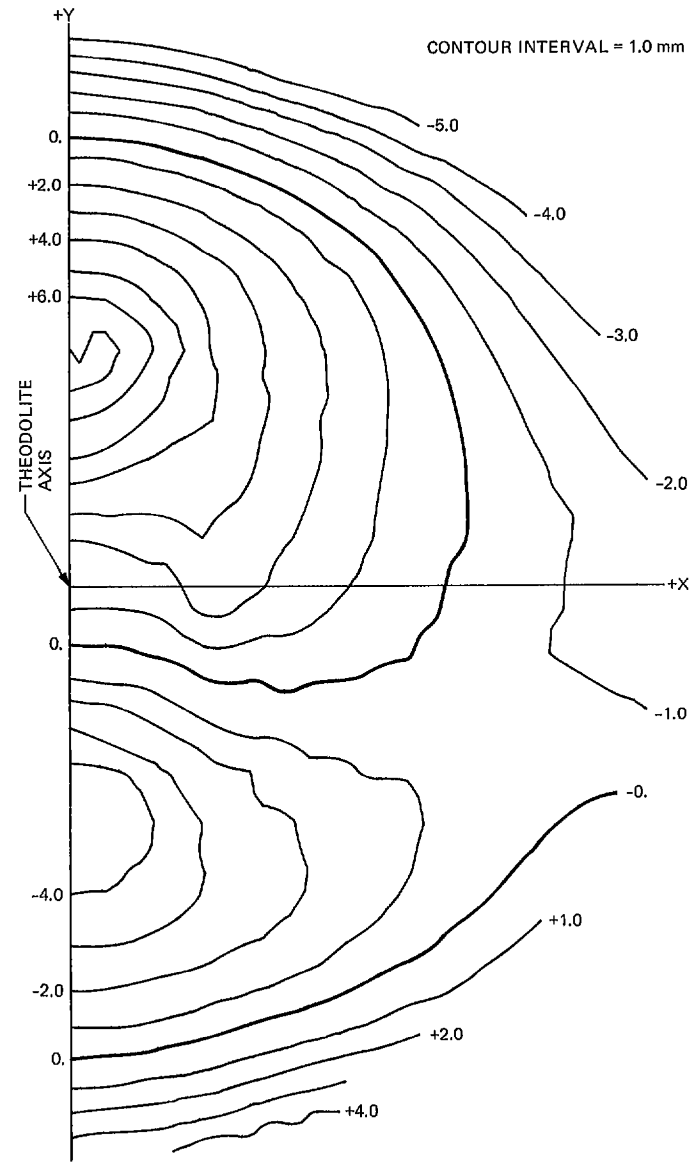
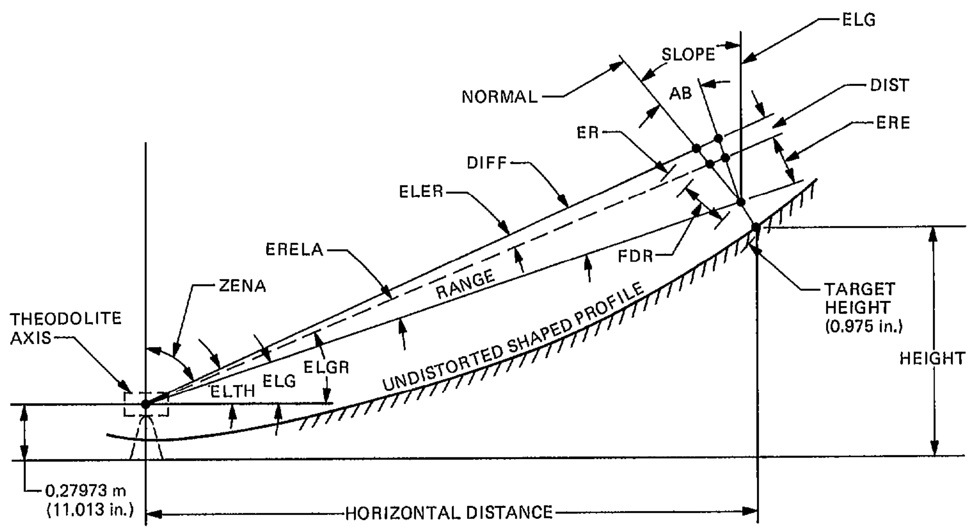


Fig. 7. Distortion contour map referred to the theodolite axis



ZENA	MEASURED ZENITH ANGLE (Grad)
ELG	ELEVATION ANGLE TO TARGET ON UNDISTORTED SHAPED PROFILE (Grad)
ELTH	MEASURED ELEVATION ANGLE (Grad)
ERELA	ANGULAR DISTORTION VECTOR (Grad)
ELER	ANGULAR POSITION ERROR OF THE TARGET (Grad)
SLOPE	SLOPE ON UNDISTORTED SHAPED PROFILE (deg)
FDR	NORMAL DISTORTION VECTOR
ER	CORRECTION - CONVERTED TO NO. OF TURNS OF PANEL ADJUSTMENT SCREW (20 THREADS/in.) PANEL ADJUSTMENT SCREWS ARE NORMAL TO SURFACE
ERE	LINEAR DISTORTION VECTOR NORMAL TO LINE OF SIGHT
DIST	TARGET POSITION ERROR NORMAL TO LINE OF SIGHT
DIFF	ELTH - ELG (Grad)
ELGR	CORRECT TARGET SETTING ANGLE (Grad)

Fig. 8. Corrective algorithm notations