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Structural Design Options for the New 34 Meter Beam Waveguide Antenna

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In addition to the successful network of 34-m High Efficiency antennas recently built by JPL, the Deep Space Network is embarking on the construction of a new 34-m high performance, research and development antenna with beam waveguide optics at the Venus site. The construction of this new antenna presents many engineering challenges in the areas of structural, mechanical, RF, and pointing system design. A set of functional and structural design requirements is outlined to guide analysts in the final configuration selection. Five design concepts are presented covering both the conventional center-fed beam optics as well as the nonconventional, by-pass beam configuration. The merits of each concept are discussed with an emphasis on obtaining a homologous design. The preliminary results of structural optimization efforts, currently in progress, are promising, indicating the feasibility of meeting, as a minimum, all X-band (8.4 GHz) requirements, with a goal towards meeting Ka-band (32 GHz) quality performance, at the present budget constraints.

I. Introduction

The planned construction of a new 34-meter diameter antenna with beam waveguide will enable the development of improved and flexible microwave optics, improved cryogenic equipment performance and maintenance, development of advanced transmitter and receiver and operations techniques, as well as the possibility of developing accurate antenna pointing hardware. It is also planned that the developed technology from this test bed antenna will be transferable to other antennas in the Network for increasing capabilities and performance improvement.

While this new high performance 34-meter antenna will closely resemble the present 34-m H. E. antennas in the Network, shown in Fig. 1, it presents many additional challenges in the areas of structural, mechanical, and microwave optics. For instance, the location of a beam waveguide near the center of the structure will necessitate the development of new elevation wheel-alidade configurations that accommodate the beam waveguide "tubes" without compromising structural performance.

In this article, the attention is focused on alternative structural design concepts and the merits of each with reference to the antenna functional requirements. Five design concepts emerged as candidates encompassing conventional, center-fed designs as well as nonconventional, by-pass designs. All concepts are presently undergoing extensive analysis and structure design optimization for performance evaluation prior to final decision making. Details of the concepts are given below.

II. Functional Requirements

From the structural-mechanical point of view the general functional requirements of the new antenna are tentatively scoped as follows:

1. (1) The antenna structure shall meet as a minimum all X-band (8.4 GHz) performance specifications under environmental loads; that is, it shall perform at least equal to the present 34-m High Efficiency antennas in the Network (Ref. 1). Subject to the funds available, the antenna design goal shall approach a Ka-band (32 GHz) quality performance.
2. (2) The antenna shall be an axisymmetric configuration with dual-shaped reflectors similar to the existing 34-m H. E. antennas.
3. (3) The antenna shall preferably be a center-fed beam waveguide (BWG) design with a built-in allowance for the addition of a by-pass BWG in the future.
4. (4) The antenna design shall be cost-effective in order to meet current Construction of Facility (COF) funding obligations.

In addition to the above general requirements, the specific design goals for the antenna structure are listed as follows:

(1) The gravity-loading path-length error (RMS) of the main reflector's backup structure shall be $\leqslant 0.38$ mm (0.015 inch). The Ka-band gravity RMS goal is 0.20 mm (0.008 inch).

(2) The wind loading path-length error (RMS) of the main reflector's backup structure shall be $\leqslant$ 0.48 mm (0.019 inch) at 48 kph (30 mph) steady wind. The Ka-band wind RMS goal is 0.18 mm (0.007 inch) at 32 kph (20 mph).

(3) The wind-pointing error of the structure shall be $\leqslant 13$ milli degrees (mdeg) at 48 kph (30 mph) steady wind. The Ka-band wind-pointing error goal for the structure is 3 mdeg at 32 kph (20 mph) wind.

(4) The antenna surface panels shall be manufactured with a surface error tolerance (RMS) $\leqslant$ 0.25 mm (0.010 inch). The Ka-band panel fabrication RMS goal is 0.13 mm (0.005 in.).

(5) The panel setting tolerance shall be at least equal to 0.25 mm (0.010 inch) with a goal of 0.13 mm (0.005 inch).

(6) The antenna structure shall survive steady wind loads up to 160 kph (100 mph) in the stow position.

(7) The antenna control system, servo drives, hardware and software shall, as a minimum, meet the X-band (8.4 GHz) overall operational pointing system precision of 7 mdeg, with a goal of 2 mdeg for meeting the Ka-band (32 GHz) requirements. Both pointing requirements represent about 10% of the halfpower beamwidth at the corresponding frequency.

In addition to the above key requirements, many other requirements must be satisfied for antenna foundations, fire protection, safety, supporting facilities, monitor and control, and operation functions.

III. Candidate Concepts

The following five elevation wheel concepts were selected for investigation:

Concept A: Center-fed with "spokeless" elevation wheel with a torus at the main reflector base.

Concept B: Center-fed with homologous[1] double octagon elevation wheel base and a hollow elevation bearing.

Concept C: Center-fed with a split (two) elevation wheel.

Concept D: By-pass mode with an octagon elevation wheel similar to the existing 34-m H. E. octagon.

Concept E: By-pass mode with a homologous, double octagon-based elevation wheel.

Concepts D and E above are possible alternatives to current preferable center-fed concepts A thru C.

Each concept is described with the accompanying Figs. 2-8 as follows:

A. Concept A

In this center-fed, "spokeless" elevation wheel concept, the main reflector rests at four points connected to a rectangular cross-section torus as shown in Figs. 2 and 3, whose circumference is divided into 24 sectors. The torus is supported at the two elevation bearings. To ensure homology and axisymmetry, each of the four main reflector-torus interface connections lies on a radial rib each making 45 degrees with the elevation axis. The single elevation bull gear and counterweight lie in the antenna plane of symmetry, orthogonal to the elevation axis.

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[1] The concept of a "homologous" antenna structure produces a structure that maintains, under varying gravity loadings, a perfect paraboloid surface (or a perfect shaped surface), although of different focal length, at all antenna tilts.

B. Concept B

In this center-fed hollow elevation bearing concept, shown in Figs. 4, 5 and 6, the main reflector is connected at eight points to the vertices of an octagon. Eight planar trusses join the octagonal base of an inverted pyramid which forms the elevation wheel. In this case, homology is achieved by locating the octagonal base in the plane of the elevation axis. The centerline of the BWG tube coincides with the elevation axis. In addition to housing the mirrors, the tube acts as a load-bearing element. The significant difference between this configuration and the 34-m H. E. antenna elevation is that the latter consists of only one plane at the octagon level while concept B possesses double octagon planes. Similar to the existing 34-m H. E. antenna elevation wheel, this concept has a single elevation bull gear with two eight-spoke inverted pyramids as well as counterweight located near vertex *A* of one inverted pyramid. The hollow bearing concept was also used in the 45-m antenna at Nobeyama, Japan (Ref. 2).

In order to minimize the distortion of the reflector's surface for gravity loading, the reflector combined with the basic elevation wheel structure must be axisymmetric about the central axis. Furthermore, the elevation wheel structure must be supported on two or more points on this axis and, in turn, the load must be transmitted by proper structural connections to the elevation bearings. This tipping structure combination must also be weight-balanced about the elevation axis (note that the tipping structure includes the main reflector, elevation wheel, subreflector, and its supports).

The cross-sectional areas of the structural members making up the tipping part of an antenna can then be designed by the JPL-IDEAS program to closely maintain an ideal surface. The computer program also allows focal length changes due to changes in the gravity loading components along the boresight axis (caused by rotation of the tipping structure).

The above structural design strategy, known as homology, has its best example in the Max Planck Institute's 100-meter Effelsberg antenna, near Bonn, Germany. This antenna uses a separate truss structure to carry the elevation gear and supports the reflector structure at two points on the reflector's truss structure. However, this concept of homology best addresses the gravity loading only but not wind loading. Application of the Effelsberg structure concept to the Deep Space Network (DSN) where low distortions under high wind velocities are necessary, results in excessive weight and thus a costly antenna.

The three high efficiency 34-m, X-band AZ/EL antennas now installed at the DSN stations have a partially homologous elevation wheel structure connecting the axisymmetric reflector to the elevation wheel. A compromised truss configuration was arranged in order to avoid interference with two diagonal supporting bars of the alidade.

The solution to this interference problem, in addition to satisfying completely the homologous requirements, is now available in concept B. To satisfy the homology requirements, the octagon of the elevation wheel must be in the same plane containing the elevation axis. When the octagon plane is horizontal, the vertical reactions at the elevation bearings are equal to the load at apex *A* of the inverted pyramid which connects the corners of the octagon. This pyramid apex is one of two supporting points on the symmetric axis of the tipping assembly. Also necessary for the homology requirement is that the center of the cross bars be connected to the corners of the octagon.

The important structural members are the bars connecting the octagon to the elevation axis. These bars should only transmit axial forces and not carry bending moments. Usually, a bar with two flexures or easily bendable sections at its ends satisfies the above requirements. In addition, the main reflector is supported by vertical and sloped bars between the octagon and the eight points at the base of the reflector structure. This type of truss results in tangential support between the reflector and the octagon.

C. Concept C

In this center-fed split elevation wheel concept, two elevation drives are needed instead of one as shown in Fig. 7. The split wheel concept has been employed in other BWG antennas, such as in the 64-m antenna at Usuda, Japan (Ref. 3). The counterweight location will be divided into two equal parts, one at each elevation bull gear. One of the advantages of this concept is in its geometry, similar to the present 64-m/70-m antennas in the network. The technology developed after the construction of a beam waveguide antenna with this concept C may be directly transferred to the 64-m/70-m network in the future at no elevation wheel modification cost. On the other hand, because concept C has a completely different elevation wheel-drive arrangement, it can be viewed as costly in retrofitting the present 34-m H. E. antennas having a single elevation bull gear.

D. Concept D

In this bypass BWG concept, shown in Fig. 8, eight radial ribs of the main reflector backup structure are connected to the octagonal base of an inverted pyramid which forms the elevation wheel identical to the 34-m H. E. antenna of Fig. 1. The octagonal base is offset from the plane of the elevation axis by approximately 60.96 cm (2 ft) to provide clearance between the reflector backup trusses and the alidade structure. The eight vertices do not provide a homologous support for the backup structure. Four out of the eight points are directly connected to the elevation bearings by structural steel plates, thus making them more rigid than the remaining points. These plates are necessary to enhance structural rigidity and achieve the required wind pointing accuracy. This concept was originally investigated because it requires the fewest structural modifications to the present 34-m H. E. antennas.

E. Concept E

In this by-pass mode concept, homology will be achieved in the same manner as described in concept B (of Figs. 4, 5 and 6) except that the beam path will be outside the area encompassing the two elevation bearings as in concept D (of Fig. 8). The elevation bearings will be designed, in this case, to be the same as the 34-m H. E. antenna. This concept has, similar to concept D, the disadvantage of a costly incorporation of center-fed beam optics (unlike any one of the three concepts A, B or C) if added in the future.

IV. Structural Analysis Methodology

In an effort to determine the structural configuration that best meets the performance requirements, several candidate tipping structures were conceived. Finite-element models were developed for each of the above five concepts, and their member sizes (decision variables) are optimized under environmental (gravity and wind) loads. The objective was to find the lowest weight and minimum RMS structure that meets gravity pathlength error, wind pathlength error, and wind pointing accuracy requirements.

For each model, the main reflector backup structure starts with a geometry that is similar to the 34-m H. E. antenna; the important difference among the models is the elevation wheel configuration. The preferable elevation wheel configurations satisfy two basic criteria: (1) allowing unobstructed access for a BWG to the vertex region of the main reflector; and (2) providing equal stiffness (i.e., more homologous) supports for the main reflector backup trusses.

Structural analysis and optimization is performed using the JPL-IDEAS program (Refs. 4-7). Using a Lagrange multiplier-optimality criterion formulation, the algorithm finds optional objective function minimizations, such as the lowest structure weight under various environmental loads, while satisfying structure compliance constraints imposed on the antenna surface accuracy or boresight pointing performance. The two significant environmental loadings considered are gravity and wind. Gravity load consists of all structural and nonstructural dead load. Steady wind load, which results from pressures applied to the antenna surface, is represented as resultant force vectors applied at the reflector backup structure nodes. The wind pressures, force and moment coefficients were derived from wind tunnel tests performed at Caltech[2] on representative scaled antenna models at several azimuth and elevation orientations.

Since the direction of the gravity loading vector relative to the structure varies over the elevation range of the reflector, the performance of the optimal design is rated at the antenna orientation(s) producing the worst gain loss. The gain loss is calculated from the Ruze equation, as proportional to the $(\mathrm{RMS})^2$ where RMS is the root mean square of the RF half-pathlength error of a paraboloid that best fits the deflected shape of the finite element grid points defining the antenna main reflector surface. The maximum gain loss occurs when the tipping structure is at either of the extreme elevation angles (0° or 90°). To mollify this effect, it is required that the RMS be zero (or minimum[3]) at a particular elevation angle, called the rigging angle, by forcing the reflector to be paraboloidal (or ideally "shaped") at this elevation angle. The rigging angle is determined from the IDEAS program by requiring equal RMS values at both zenith and horizon positions (Ref. 6), hence generating a single objective function to be minimized, instead of two.

Under wind loads, RF pathlength errors determined for the main reflector surface are adjusted to include error terms caused by shifts of the subreflector with respect to the position of the focal axis and nominal focal point of the best fit paraboloid. The equivalent adjustments are treated as additional, independent RMS pathlength errors. These offsets are not considered for gravity loading because the subreflector is automatically positioned to compensate for gravity deflections over the antenna elevation range.

Also, wind pointing error calculations include contributions from four components: (1) translation of best-fit paraboloid vertex, (2) rotation of best-fit paraboloid axes, (3) translation of the subreflector, and (4) rotation of the subreflector.

During optimization, a discrete set of values is chosen in the IDEAS program for sizing the design variables, which are

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[2] R. B. Blaylock, "Aerodynamic Coefficients for a model of a paraboloidal reflector Directional Antenna proposed for a JPL Advanced Antenna System." Internal memorandum CP-6, Jet Propulsion Laboratory (internal document), Pasadena, Calif., May 1964.

[3] The 64-m antenna at Usuda, Japan realizes lower surface RMS at zenith and horizon looks with nonzero RMS at the rigging angle in between 0° and 90°.

the cross-sectional areas of truss elements. Size selection was made from a handbook of square structural steel tubes to achieve a realistic design

V. Results to Date

The results of the structural analyses to date are preliminary and are presented for each concept as follows.

A. Concept A

The torus concept described in Section III is the result of several configuration studies aimed at producing an efficient structure. Some of the options tried in connecting the main-reflector base to the torus are illustrated in Fig. 9.

Unlike the 34-m H. E. antenna elevation wheel, the torus concept does not have bars (or spokes) to transmit loads to the elevation bearings. Instead, the torus transmits loads directly to the elevation bearing via ring action. An initial option, used in an existing BWG antenna, has the torus connected to each of the 24 radial ribs. This nonhomologous support configuration did not perform as expected. Furthermore, it was adversely affected by increasing counterweight loads. The addition of interior stiffeners, or "bootstraps" as in Fig. 9, provided some limited performance improvement. Connecting the counterweight directly to the "bootstraps" rather than the torus yielded substantial improvement in gravity RMS relative to the structure weight. The design progress was hampered by the existing nonhomologous supports. To achieve better homology, the number of torus main-reflector backup connections was reduced from forty-eight (two per main rib) to only four. This approach has produced a design with one-third the gravity RMS, and two-thirds the structure weight of the preceding one. The pathlength and pointing errors under steady-state wind loads, on the other hand, exceed the performance criteria.

B. Concept B

The results made to date in analyzing concept E are mostly applicable to concept B. In order to use the homologous-type elevation wheel, with a few changes from existing 34-m H. E. antennas, the interference with an alidade member must be eliminated. This can be accomplished by moving the interfering diagonal members in the plane of the elevation axis which provide lateral support to the elevation bearings. Instead of these diagonal members joining the base of the alidade at the azimuth/radial bearing, they were moved to the rear center of the structure at either the base or at a higher plane. Rearranging some other diagonal members of the alidade will be necessary to satisfy the function of the alidade.

A structural analysis was made using the JPL-IDEAS program and the existing 34-m H. E. antenna reflector computer model in combination with the homologous elevation wheel structure. Preliminary results indicated a gravity distortion (RMS) of the reflector of 0.10 mm (0.004 in.) for half pathlength at zenith or horizon position. When wind requirements are considered the design results in an increased weight and larger gravity distortions.

By increasing the height of the truss connecting the octagon to the reflector structure, adequate space is created to accommodate a large waveguide tube. Preliminary results showed that a 2.54 m (8.33 ft) round waveguide tube, as shown in Fig. 6, is possible.

Figure 6 shows also a square tube for the elevation axis shaft that does not violate homology conditions. Nodes *A* and *B* are the two points supporting the tipping assembly by a truss connection to the elevation bearings as required by homology. For supporting the tipping structure under the gravity loading component in the symmetric axis direction, node *A* is supported by rods *AC* and *AD* from the elevation axis bending-resistant shaft *CD*. This action requires that bars *CE* and *CF* only transmit axial forces and not bending.

For gravity loading support in the antisymmetirc direction, the two inverted cones from the octagon nodes to points *A* and *B* transfer the gravity loading forces to the elevation axis through bars *CE* and *CF*.

Increasing the distance between the octagon base and the elevation axis (as compared to the 34-m H. E. antenna reflector) to meet homology conditions has several unfavorable consequences that include the following:

(1) An increase in overturning moment on the alidade

(2) An elevation axis moment increase

(3) A yaw axis moment increase

A future change to a solid panel reflector surface would increase wind forces and moments. Improving the design for wind loading together with the cost impact are the subject of current investigations.

C. Concept C

The results of the split wheel concept are incomplete at the present time, but are expected to be close to either concepts A or B.

D. Concept D

The structural analysis of this concept has been completed, indicating that no substantial degradation of performance relative to the 34-m H. E. antennas will be expected.

VI. Summary

The construction of a new high performance research and development 34-m diameter antenna at JPL with beam waveguide optics presents many engineering challenges in the areas of structural, mechanical, RF, pointing and control system design. A set of functional and structure design requirements was outlined to guide analysts in the final configuration selection. Five design concepts were presented to include three conventional center-fed beam optics in addition to two nonconventional, bypass beam configurations. The merits of each concept were presented, with an emphasis on obtaining a homologous design. The status of the ongoing structural analysis and optimization effort for each concept was briefly discussed. Preliminary results are promising, indicating the feasibility of meeting, as a minimum, all X-band (8.4 GHz) requirements. Future work will include the selection of the final configuration to be built. The goal of satisfying a Ka-band (32 GHz) quality performance with the present budget constraints is also under investigation.

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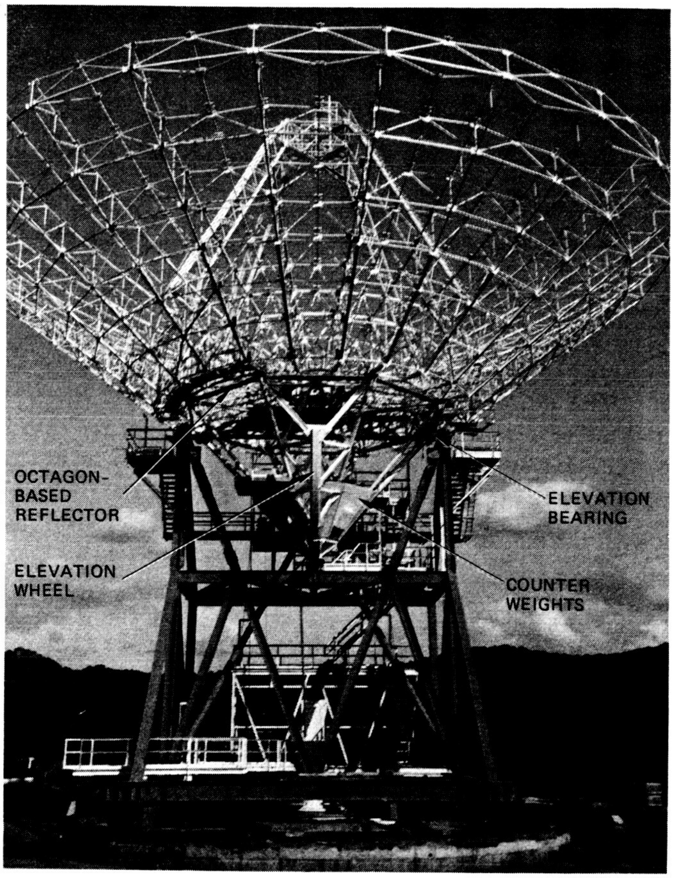


Fig. 1. The NASA/JPL 34-m H. E. antenna during construction

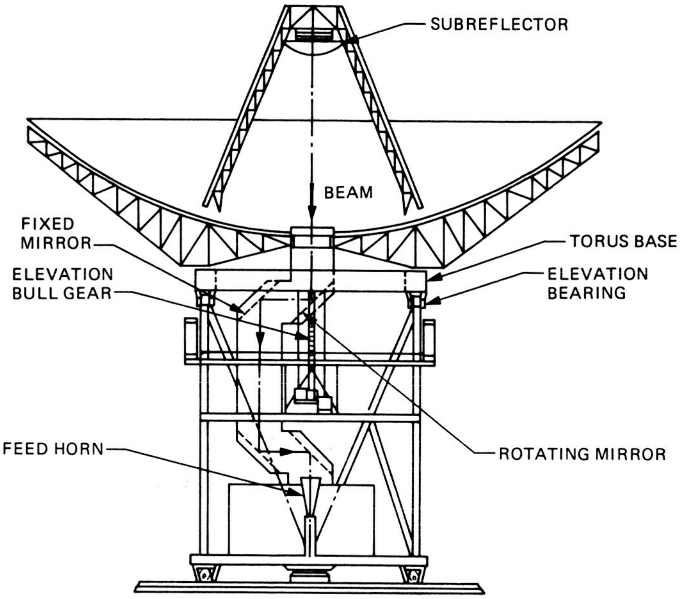
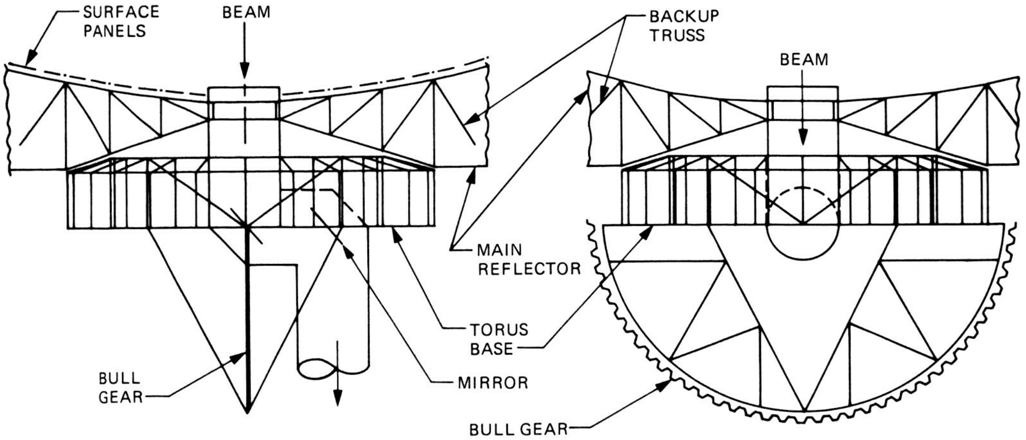


Fig. 2. A beam waveguide antenna layout with torus base, Concept A



SIDE VIEW, NORMAL TO ELEVATION AXIS

SIDE VIEW, PARALLEL TO ELEVATION AXIS

Fig. 3. Details of elevation wheel with torus base

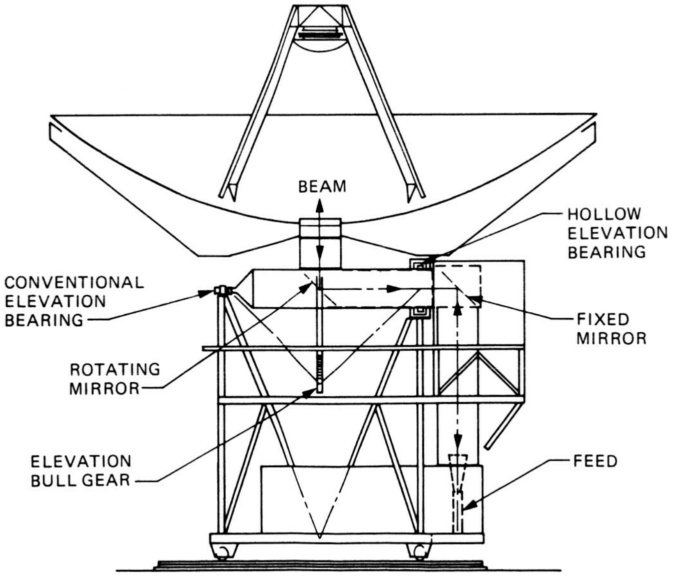


Fig. 4. A beam waveguide antenna layout with hollow elevation bearing tube, Concept B

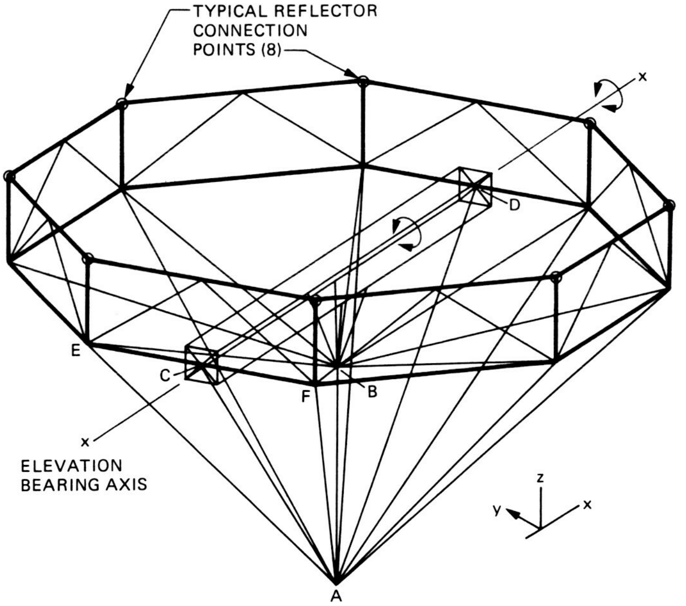


Fig. 5. Elevation wheel isometric view, Concept B

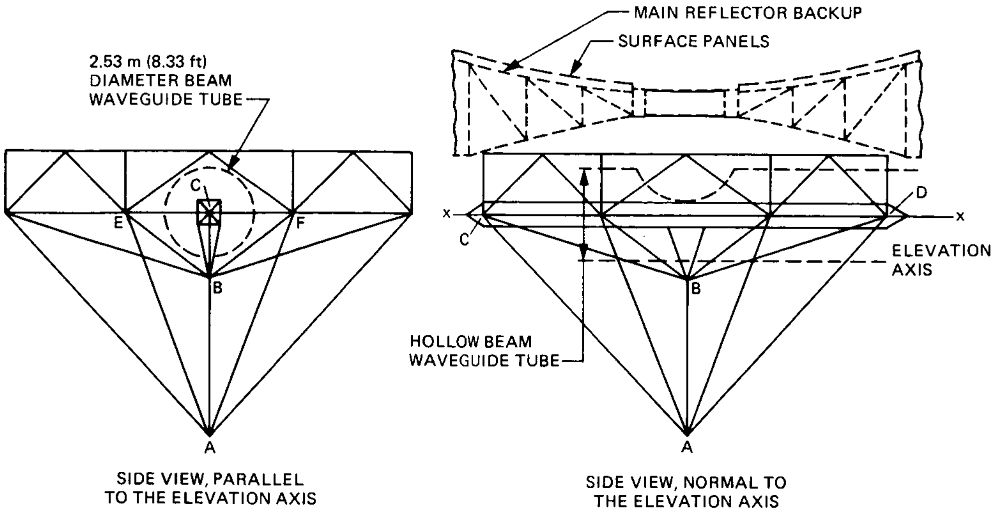


Fig. 6. Details of elevation wheel of Concept B

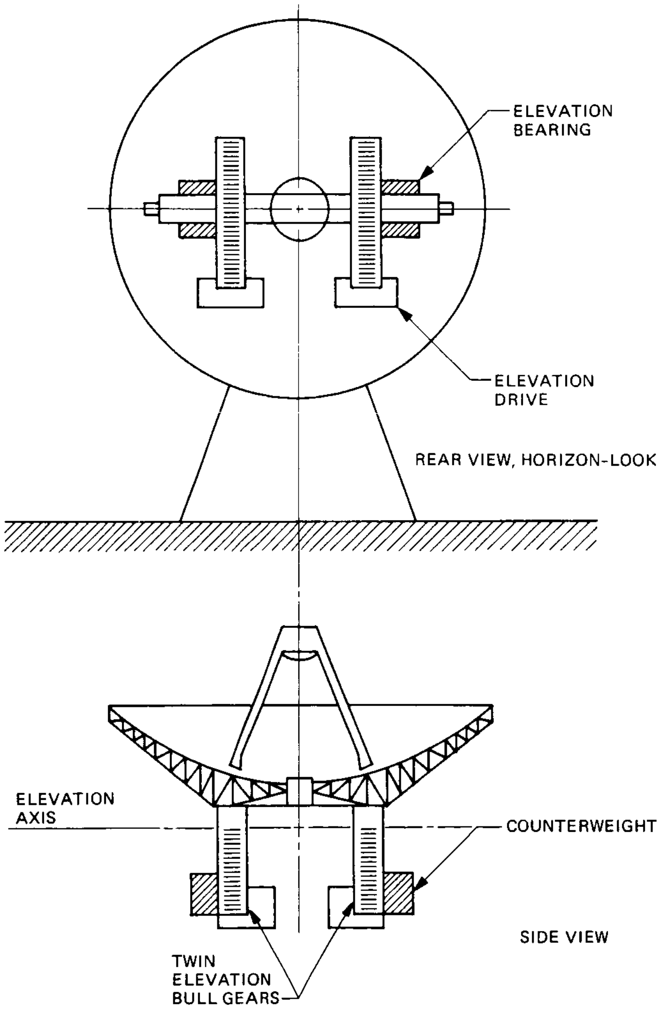


Fig. 7. A split elevation wheel concept, Concept C

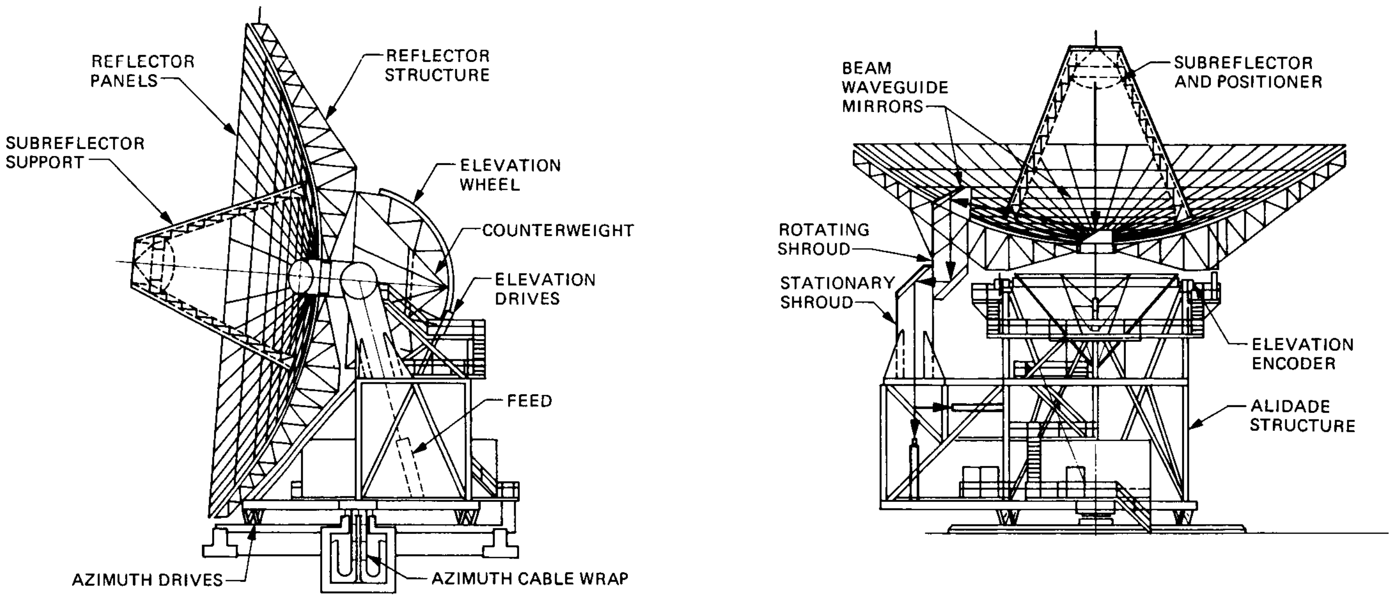


Fig. 8. A beam waveguide antenna with nonconventional, by-pass beam optics, Concept D

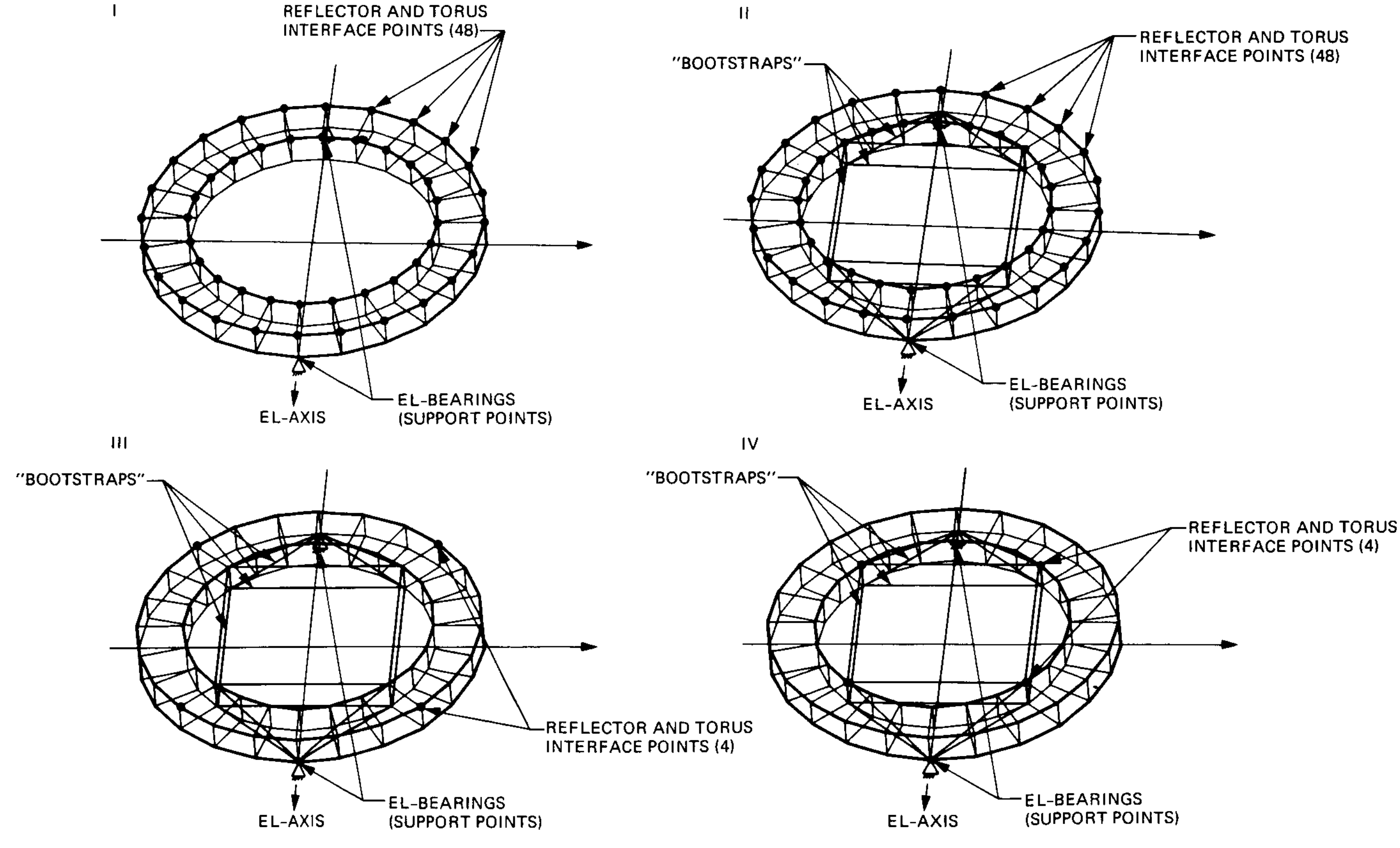


Fig. 9. Alternative main reflector-torus connectivity options