Conceptual Studies for New Low-Cost 64-m Antennas

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Recent software developments expedite design investigations of proposed new 64-m antenna structures. The software consists of programs to generate structure model data and a design program that chooses preferential cross-sectional sizes of the structural members. Numerous new designs are summarized that can represent weight savings of from 25% to 50% with respect to the tipping weight of the existing Mars antenna. These designs provide a more favorable symmetrical support for the reflector backup and tend to provide superior surface accuracy for gravity, although not necessarily wind, loading on the antenna.

I. Introduction

The objective of the present study program is to examine cost reductions that may have become possible in the design of new 64-m antenna structures. The basis of comparison is the existing Mars (DSS 14) 64-m antenna, which is retained as a standard of reference for proposed new designs. The present article considers only the economies in the fabrication of the antenna-reflector backup and support structures. These are measured in terms of reduction of weight of the "tipping" structure, which consists of all the components that can rotate about the elevation axis. Any economies achieved through weight reduction of the tipping structure will perpetuate approximately proportionate economies in other components such as the alidade, pedestal, foundation, drives and bearings. Additional concurrent studies in progress consider cost reductions for these additional components through weight reduction of the tipping structure and also through new approaches to their individual configurations. Furthermore, since the present discussion considers only an exploratory examination of the backup structure weight reduction, examinations are continuing for promising additional improvements.

The original 64-m antenna structure was designed over 10 years ago, and at that time only limited software was available to analyze the expected performance using highly idealized analytical models. Since that time, the NASTRAN (Ref. 1) and the JPL-IDEAS (Ref. 2) computer programs have been developed with much greater problem size analysis capability so that less drastic analytical idealizations are necessary, which improves the accuracy of analyses. Furthermore, the IDEAS program has design capability to establish preferential member sizes (areas of rods or thicknesses of plates) in accordance with a performance objective for the design. Although the design process requires an iterative set of analysis-redesign cycles, these cycles are executed rapidly so that the present computer cost of design is comparable to former costs for computer analysis only. The historical process of analyzing a particular design, examining the results, subjective estimation of parameter changes that might produce design improvements, modifying the computer data, returning to the computer analysis program for verification, and then possible additional recycling of the process just described, was not only expensive in computer and manpower effort, it was also lengthy with respect to calendar time. The same process is now automated and can be performed within a time span measured by hours or days rather than weeks, permitting much greater depth of study for new designs and variation thereof.

A further extension of the opportunities to produce better designs occurs in newer methods of data preparation. Formerly, it was necessary to devote hundreds of manhours to fill out keypunch coding forms for the thousands of data cards needed to describe the structure and its loading. Today, the process is almost entirely automated, so that except for occasional special requirements, all of the necessary data cards are produced within a few minutes by special-purpose data generator programs. Consequently, the exploratory range for new designs can conveniently cover a much wider scope than heretofore.

II. Background

Two major conceptual innovations in the field of antenna structure design have occured since the completion of the successful Mars antenna structure in the middle 1960s. The first of these was the clarification of the conceptual idea of "homologous" deformation by Von Hoerner (Ref. 3), and the second was the antenna support configuration devised to emphasize homologous deformations that was adopted within the Bonn antenna (Ref. 4).

It has been well known for many years that the absolute magnitude of surface deformations is unimportant from a microwave efficiency standpoint in comparison to the deformations from any alternative paraboloid that best-fits the distorted surface. Specifically, Ruze (Ref. 5) gave a simplified equation from which the antenna surface efficiency and gain could be computed from the knowledge of the root mean square (rms) half-pathlength deviations of the reflecting surface from a best-fitting paraboloid. Utku and Barondess (Ref. 6) gave the equations from which the properties of the best-fitting paraboloid and rms pathlength deviation could be determined from the deflections of the structure. Von Hoerner's innovation was to propose that the properties of the structural members that supported the reflector surface could be chosen to promote the occurrence of relatively small rms deflections from the best-fit paraboloid, although the magnitudes of the absolute deflections could be relatively large. In principle, the concept of homologous deformation, whereby all of the deformations of the surface fall exactly upon a paraboloid, is conceivable in the case of gravity loading on antenna structures. That is, if we are concerned only with the deformations caused by the change in orientation of the gravity loading vector with respect to the antenna surface, the properties of the individual members of the structure can be chosen so that the deformed surface at every antenna elevation angle exactly fits an alternative paraboloid. In application, however, the homologous design is not achieved because of constraints upon the choices of member sizes for stress and buckling requirements, practical manufacturing considerations, and stiffness requirements for acceptable vibratory performance. Furthermore, when antennas are subjected to substantial wind loading, it is impossible to conceive of a design that can approach homology simultaneously for gravity loading and the host of variable distributions of wind loadings that can occur. Consequently, practical designs tend to be a compromise between homology for gravity loading and the maintaining of some minimum measure of absolute stiffness for vibratory and wind loading. The JPL-IDEAS design program can be used to provide compromise designs with respect to homology and the foregoing practical considerations.

The innovation in the Bonn antenna was to depart from the heretofore customary support of the antenna backup structure that often consisted of two hard points near the elevation axis and two softer points in the vicinity of the elevation wheel at about 90 deg from the elevation axis points. The Bonn support consists of members of equal stiffness to support a set of regularly spaced reflector backup radial rib trusses. The support members are generators of an inverted cone with the base attached to the radial trusses and a common junction at the apex. The apex point, which is below the elevation axis, is supported by an independent structure suspended from the elevation axis and is also driven in elevation by a conventional large elevation wheel with sector gear attached to its rim.

III. Configuration for New Antenna Studies

A. Backup Structure

The reflector backup consists of the conventional rib and hoop construction. There are 48 main rib trusses and 48 alternating intermediate ribs equally spaced within the 360-deg aperture. The rib trusses are braced by 11 circumferential hoop trusses. A schematic layout is shown in Fig. 1, where it also can be seen that the backup comprises replicate sectors of 15-deg modules. The main ribs are spaced at 7.5 deg within each module, and every other main rib has a cone generator bar to support it from below at ring 4. The intermediate ribs, which consist of a single top bar supported by the hoop trusses are omitted at ring numbers lower than ring 6, and the unsupported main ribs are omitted between rings 1 and 2. As shown in Figs. 1b and 1c, the hoop truss members occur in three categories: top, bottom, and diagonal bars. As shown in Fig. 1d, the rib members occur in four categories: top, bottom, diagonal, and post bars. Three additional categories of inter-rib bracing are: top surface diagonal bracing between adjacent rib tops, bottom surface diagonal bracing between adjacent rib bottoms, and inclined bracing from the top of one rib to the bottom of the next adjacent rib. Consequently, all members of the reflector backup structure can be classified within only 10 distinct category types. To emphasize manufacturing economy by means of replication, all members of the same category that occur at the same ring or within the same ring annulus are assembled into the same design variable group. Each member within a design group can be designed by the IDEAS program to have the same structural cross section. As an illustration, this particular antenna backup model, which has over 5000 individual bar members, requires less than 130 detailing variations to manufacture all of the bars.

The layout of ribs and hoops in Fig. 1 was arranged to provide a support at the four corners of each reflecting surface panel. The ring spacing and rib subdivisions were patterned to require surface panels of about the same size as used in the Mars antenna. The rib truss depths (Fig. 1d) are also similar to the Mars rib depths. A noticeable difference here, however, with respect to the Mars antenna is that the radial distance to rib truss panel points is the same for a given ring for all of the 96 rib trusses. The required type of symmetry that allows this repetition is destroyed within the Mars antenna because of an integral hub of reinforcing trusses that are arranged in a rectangular pattern. This reinforcing hub, which is used to support the backup, is, in general, skewed to the rib trusses. In the structure of Fig. 1, the function of the hub is replaced by the 24 cone generator support bars (bars A–S in Fig. 1d) and the central post (bar A–B). Because of the great emphasis on symmetry and repetition in this design, data generation is readily automated. Most of the data input required for subsequent design and analysis is generated within a special computer program in less than a minute of 1108 computer central processing unit (CPU) time. There are about 4000 data card images, which are computer produced on the basis of a relatively small number of input parameters that give key dimensions plus configuration and arrangement options. Another computer program automatically generates data to describe wind loading on the structure by interpolating from our existing wind tunnel pressure data.

B. Backup Structure Support

A diagram of the backup support is shown in Fig. 2. This supports the reflector backup ribs at the points marked "S" in the figure by means of the cone-generator bars that have a common apex at node 3 of the figure. The support carries the forces from the cone apex to the elevation bearing at node 4. The elevation bearing is supported by the alidade, for which redesign is not being investigated within this discussion. The apex of the cone is also supported in the longitudinal direction (parallel to the Y-axis) by a constraint that simulates the elevation drive pinion, as shown in Fig. 2b.

An independent structure, which is not shown on the figure, provides a separate support to bring the quadripod loads to the elevation axis. The quadripod structure is isolated from the reflector backup by its support to avoid load concentrations that would be incompatible with homology.

Before proceeding with the backup structure and support design, a preliminary design was performed for the support structure alone with simulated backup structure loadings. The purpose was to design the support to have sufficient stiffness for natural frequency requirements of the system. After this design was completed, some of the key supporting members were not allowed to change their properties when subsequently included with the entire structure. Had this exclusion not been made, designs to promote homology for the backup might have reduced the support stiffness excessively.

C. Computer Model

Symmetry of the antenna structure and gravity loading about the vertical plane perpendicular to the elevation axis (Y–Z plane, Fig. 1a) permits the analytical model to consist of only one-half of the structure. Consequently, only the structure contained between ribs 1 and 49 is needed for the computer model. The individual members contained on these two ribs are represented by bars that have half the cross-sectional areas of the actual members. In the case of wind loading, which is not necessarily symmetrical, this half-model can treat winds only directly into the face or back of the reflector, since these can be assumed to be symmetrical with respect to the model. However, since the structure is also symmetrical with respect to a plane containing its focal and elevation axes, the response to winds from side directions will be exactly the same as the response to face or back winds.

IV. Computer Design Execution

To illustrate how the computer design can progress, Fig. 3 shows a sample design history for the reflector backup structure. The objective in this case is to reduce the average rms deflection for gravity loading over the elevation angle range from 0 to 90 deg.

The horizontal scale at the bottom gives the design cycle number; the top horizontal scale gives the elapsed CPU time on an 1108 computer. The vertical side scale is a relative scale used for both structure weight and performance objective. At the starting cycle, the structural weight was greater than a specified maximum. The weight was reduced to specification at the first design cycle, but the objective became worse as a result of the weight reduction. In succeeding cycles, the weight was maintained as specified and the objective rms improved, so that at the last cycle, it is three times better than at the start.

The initial analysis and five succeeding design analysis cycles were completed by the IDEAS program in about 15.5 min of CPU time. A similar problem required about the same time for a single analysis cycle on the NASTRAN program. Depending upon the time of the week when the run is made, the computer charges vary from $30.00 at the off-hours weekend night rate to about $330.00 at the prime weekday rate.

The amount of improvement that occurs for a design process of several cycles, such as shown in Fig. 3, depends to a large extent on the starting point. If there is a good starting point, for which member properties have been well chosen to produce a reasonably good objective, the amount of improvement by reproportioning these members would be expected to be relatively small. If, on the other hand, the starting member sizes were chosen more arbitrarily so that they did not produce a reasonably effective objective, there are more opportunities for improvement and a greater reduction of the objective can be expected. The design in Fig. 3 started from an arbitrary point in which the member sizes were chosen by empirical rules built into the code of the data generating program; hence, the 300% improvement. By the end of the second cycle, the new member sizes derived by the program had improved substantially from the arbitrary starting sizes, and from then on, the rate of improvement was slower.

In this particular case, the gravity objective rms was considerably better than required for X-band operation. A subsequent design was performed for which a lower maximum structural weight was specified to permit a larger but still acceptable rms. Figure 4 shows the history of a design process resuming from the results of the lower-weight subsequent design that was just described. This illustrates an antenna backup structure design that is a compromise for the not necessarily compatible requirements for performance for wind and for gravity loading.

This is done in two stages. In the first stage, the objective loading is a particular case of wind loading that is assumed to be critical, and the design objective is to minimize the rms deflections for this wind loading with a maximum weight specified to be somewhat less than would eventually be accepted. The progress of the first stage takes place over the first four design cycles that are shown in the figure. Notice that the wind objective is reduced from about 7.5 units to about 5 units, while a weight specification of 3 units is maintained. However, in this design, the gravity response deteriorates appreciably.

During the next stage, which is covered by the last four cycles in the figure, gravity performance was the objective. The weight specification is increased to 3.6 units, and no member is allowed to decrease in size to guarantee that the wind objective previously achieved will not be degraded. The gravity objective is then effectively reduced, the wind objective improves slightly, and the specified weight is maintained through the last cycle. In the final design, the gravity and wind objective have both been improved to about two thirds of their initial values. In view of the initial point, which in itself was relatively effective, being the result of prior design improvements, the achieved improvement of about 33% is considered to be substantial.

V. Design Results

A. Basic Configuration

A number of design variations were explored for the structure described in Figs. 1 and 2. In each of the explorations, the variations were made for alternative objectives with respect to the choice of either gravity or wind loading as the design case, or selections from among preceding designs that were used as the starting points, or specified maximum total member weight, or relatively minor adjustments that related to groupings of members and establishment of initial minimum sizes. Each of these designs proceeded through four or five redesign cycles and produced restart member property cards to permit continuing designs that could resume from their best results. Four loading cases were used to establish minimum sizes required for stress integrity and to provide alternative choices of design objective for rms minimization:

(1) The gravity weight applied in the direction of the focal axis (Z-axis loading).

(2) The gravity weight applied in planes parallel to the aperture plane and acting perpendicular to the elevation axis (Y-axis loading).

(3) A survival wind load with the antenna at 90-deg elevation simulating a wind speed of 54 m/s (120 mph).

(4) A maximum operational wind load with the antenna at 60-deg elevation with wind from the rear and a wind speed of 34 m/s (77 mph).

The first two loading cases provide sufficient information to compute the gravity loading, and consequently the rms surface accuracy, at every elevation angle between the horizon and zenith. The second two wind loadings have been found to be the significant wind loading conditions for the Mars antenna.

In evaluating the performance of the new designs, the existing Mars antenna is used as a frame of reference for surface accuracy and tipping structure weight. Table 1 shows the Mars antenna data that are used for comparison.

As shown in Table 1b, the Mars antenna performs better with the wind from the front or rear than it does for the same wind loading applied from the side. This performance difference is the result of its unsymmetrical supporting configuration and does not have a preferential direction with respect to wind azimuth. Consequently, it seems reasonable to compare the performance of the new antenna designs with the average wind rms of the Mars antenna, which is also shown in this table.

Table 2 contains a summary of results for five new designs selected as the most promising from a much larger set of cases. These are listed in the order of their tipping weights, which were from 61% to 74% of the Mars antenna. All of these designs had considerably better performance with respect to gravity, but they did not always perform as well for the two wind loading cases. A composite rating factor is shown in the last three columns of the table, which gives a measure of design that takes weight and rms into account simultaneously. The factor is defined as the product of relative weight and relative rms. Factors less than unity are associated with designs that are more efficient than the Mars antenna; that is, designs with ratings less than unity would either weigh less for the same rms or would have a better rms for the same weight. In the particular case of wind loading, increasing the weight of the members by a common factor to bring the weight up to the weight of the Mars antenna would result in a design with an rms no more than the rating factor times the Mars antenna rms. Or equivalently, the antenna with additional reinforcing to have the same wind rms as the Mars would have a weight no more than its rating times the Mars antenna weight. In the case of gravity loading, where weight and rms response do not have a linear relationship but depend on the particular distribution of member properties, no such simple projections are possible.

In evaluating the relative performance merits of these alternative designs, it seems reasonable to consider the gravity performance to be more significant than the wind performance. The gravity loading is always present, while the joint occurrence of significant wind speeds and wind vector orientation relative to the antenna is statistical. Depending upon mission tracking requirements of the antenna system, it could be wasteful of material to reinforce the structure to maintain high performance for the occasional conditions of high wind speeds at unfavorable orientations. Either of design cases 64D-5 or 64E-5, which represent material savings of 39% and 35%, respectively, might be considered acceptable. Both of these designs are better for gravity performance than the Mars antenna, although the wind performance for the lighter of them is as much as 63% worse. Table 3 shows a comparison of weights of major components for these two antennas with the weights of the corresponding components of the Mars antenna (see Table 1).

B. Variations From the Basic Configuration

Several design variations from the basic configuration were explored to obtain guidance in establishing an eventual preferred configuration. The results of these are summarized below.

1. Reduced Number of Support Bars. As shown in Figs. 1 and 2, the alternate main ribs of the basic design are supported by a total of 24 cone support bars (marked A–S). As a variation, two out of every three of these bars were removed to investigate an opportunity to simplify fabrication and to increase clearances that would allow greater latitude in the alidade and support structure layouts. Removal of these bars tests the ability of the hoop trusses to distribute the loads in the circumferential direction from the unsupported ribs to the nearest supported ribs. In the basic design, there is only one unsupported main rib between supported ribs, while in the present variation, there are five unsupported ribs between any pair of supported ribs. With fewer supports, a small but noticeable deflection wave in the circumferential direction was found at radii near the radius of the support ring. However, progressing radially outwards towards the rim, this wave damps out rapidly because of the hoop truss action. The results of several trial designs show that for equivalent tipping structure weight, removal of the support bars provides no significant penalty of gravity rms but in some cases, increased the wind rms by from 15% to 50%. With additional design trials and the acceptance of some minor weight penalty, the wind rms undoubtedly could be brought closer to that obtainable with the basic number of supports.

2. Alternative Focal Length to Diameter Ratios. The focal length-to-diameter ratios (F/D) of the Mars antenna and the basic design are 0.423. Several other antennas in use have smaller ratios, which result in more sharply curved surfaces. A variation in F/D ratio was investigated to see if there is a structural advantage in using shorter focal lengths. The additional ratios investigated were $F/D = 0.33$ and $F/D = 0.25$. Figure 5 shows envelope sketches and dimensions for comparison. To provide for equitable design comparisons, envelope dimensions were established to provide the same alidade clearance at the breakpoint (change in slope of the bottom of the truss main rib) for all variations. The truss depth at the vertex was maintained exactly the same, and the maximum truss depths at the breakpoints were approximately the same. The smaller F/D ratios bring the vertex and focal point closer to the elevation axis, but the parabola rim is farther from the axis because of the increased curvature. Table 4 contains summary comparison results for two designs with these new F/D ratios and repeats the summary information for design 64D-5, which has a similar weight. From Table 4 we find no clear preference for either of the alternative F/D ratios. These and other designs not summarized in the table indicated slightly better gravity rms for the smaller F/D ratios and slightly worse wind rms.

3. Configuration Modifications. The support structure configuration of the basic design was chosen to be nearly compatible with the alidade structure of the Mars antenna. As a result of an examination of feasible configurations for new alidades, it was found that the vertex of the reflector could be brought closer to the elevation axis than it is shown to be in Fig. 1a. Specifically, a layout of a new alidade was developed to reduce the distance from the elevation axis to the bottom of the rib trusses at the vertex by about one half. This provides the advantage of bringing the structure closer to the elevation axis, reducing the counterweight, and reducing moments of inertia for driving about the elevation axis. It was also decided to reduce the number of structural members by doubling the spacing between main ribs, reducing their number by one half. With this new spacing, some of the surface panels are supported directly on the top hoop members with no supporting diagonal members to assist in carrying the load. This adds a small but acceptable amount of additional bending deflections at these points. The lower number of ribs also implies a total of only 12 rather than 24 cone support points. However, it was shown previously that as few as 8 support bars could be sufficient. A top view of the corresponding framing of the top surface of the half antenna model is shown in Fig. 6.

Preliminary results obtained so far for this model indicate promising opportunities for weight reductions. Therefore, studies of this modified configuration are continuing, and further refinements of the layout and design are being developed. Table 5 contains a comparative summary of two initial designs that have been developed. The first case represents the lowest weight that has been achieved in a design for a gravity rms objective. The gravity rms and low weight are promising, but the relatively high wind rms indicates that further reinforcement may be necessary for improvement. The second case in the table represents a heavier design but, nevertheless, is lighter than any of the basic configuration designs. This second case indicates that further development is also needed to improve its wind performance.

VI. Summary

Conceptual studies of new 64-m antenna reflector backup and support structures are performed efficiently using new special-purpose software to generate, analyze, and design the structures. New designs are assembled and processed rapidly and economically in investigations of design improvements to be achieved through parameter and configuration variations.

Design studies performed for a basic model of a new antenna result in tipping weights with respect to the elevation axis of from 61% to 74% of the corresponding weight for the existing Mars antenna. In addition to these weight savings, the emphasis in the new designs upon modular repetition of structural component members will produce additional economies in manufacture. The new designs have better accuracy and RF performance for gravity loading than the Mars antenna, although their accuracy for wind loadings tend not to be as good in view of their lighter weights. Nevertheless, because gravity loading is always present and significant wind loading is only occasionally present, the importance of performance for gravity loading predominates over the importance of wind loading performance.

A special study to investigate reducing the focal length-to-diameter ratio of the reflector, which would produce more sharply curved surfaces, indicates no major advantages in the structure design. It was found that shorter focal lengths are a little better for gravity loading and a little worse for wind loading.

Initial investigations found a promising modification of the basic configuration design that provides additional weight reductions resulting in weights in the neighborhood of half of the Mars antenna weight. The modification has about half the ribs of the basic configuration, which would further simplify fabrication. It would require, however, a different alidade configuration from the basic model. The basic model, on the other hand, is more closely compatible with the Mars alidade. Design studies are currently continuing for further refinement of this newest design.

References

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Table 1. Mars 64-m comparison data

a. Components

Item	Mass, kg	Weight, kips
Reflector backup	315	695
Elevation wheel, reflector support and counterweight	751	1655
Quadripod and subreflector	25	55
Feed cone	27	60
Surface panels	26	58
Total tipping structure	1144	2523

b. Surface accuracy

	rms distortion	
	mm	in
Gravity, maximum	0.51	0.020
Survival wind, 90-deg elevation		
From front	4.54	0.179
From side	9.09	0.358
Average	6.82	0.269
Operational wind, 60-deg elevation		
From rear	1.93	0.076
From side	3.86	0.152
Average	2.90	0.114

Table 2. Summary of five new alternate designs

Run number	Tipping weight relative to Mars	Surface rms relative to Mars			Composite rating		
		Worst gravity	Survival wind	Operational wind	Worst gravity	Survival wind	Operational wind
64 D-5	0.61	0.55	1.32	1.63	0.34	0.81	0.99
64 E-5	0.65	0.83	0.97	1.19	0.54	0.63	0.77
64 D-1	0.67	0.40	1.35	1.66	0.27	0.91	1.11
64 F-2	0.71	0.64	0.89	1.09	0.45	0.61	0.77
64 F-5	0.74	0.40	0.86	1.05	0.29	0.63	0.78

Table 3. Component weight comparisons with respect to Mars antenna

Item	Run number	
	64 D-5	64 E-5
Reflector backup	0.50	0.57
Elevation wheel, reflector support and counterweight	0.61	0.64
Quadripod and subreflector	1.12	1.12
Feed cone	1.00	1.00
Surface panels	1.00	1.00
Total tipping structure	0.61	0.65

Table 4. **Summary of designs for alternative *F/D* ratios**

Run number	F/D	Tipping weight relative to Mars	Surface rms relative to Mars			Composite rating		
			Worst gravity	Survival wind	Operational wind	Worst gravity	Survival wind	Operational wind
64 D-5	0.423	0.61	0.55	1.32	1.63	0.34	0.81	0.99
33 B-4	0.333	0.62	0.37	1.43	1.74	0.23	0.89	1.08
25 B-4	0.250	0.62	0.55	1.42	1.72	0.34	0.88	1.07

Table 5. **Sample design summaries for modified configuration**

Run number	Tipping weight relative to Mars	Surface rms relative to Mars			Composite rating		
		Worst gravity	Survival wind	Operational wind	Worst gravity	Survival wind	Operational wind
02-5	0.44	0.95	2.42	3.79	0.42	1.06	1.67
02-1	0.58	0.49	1.42	2.18	0.28	0.82	1.26

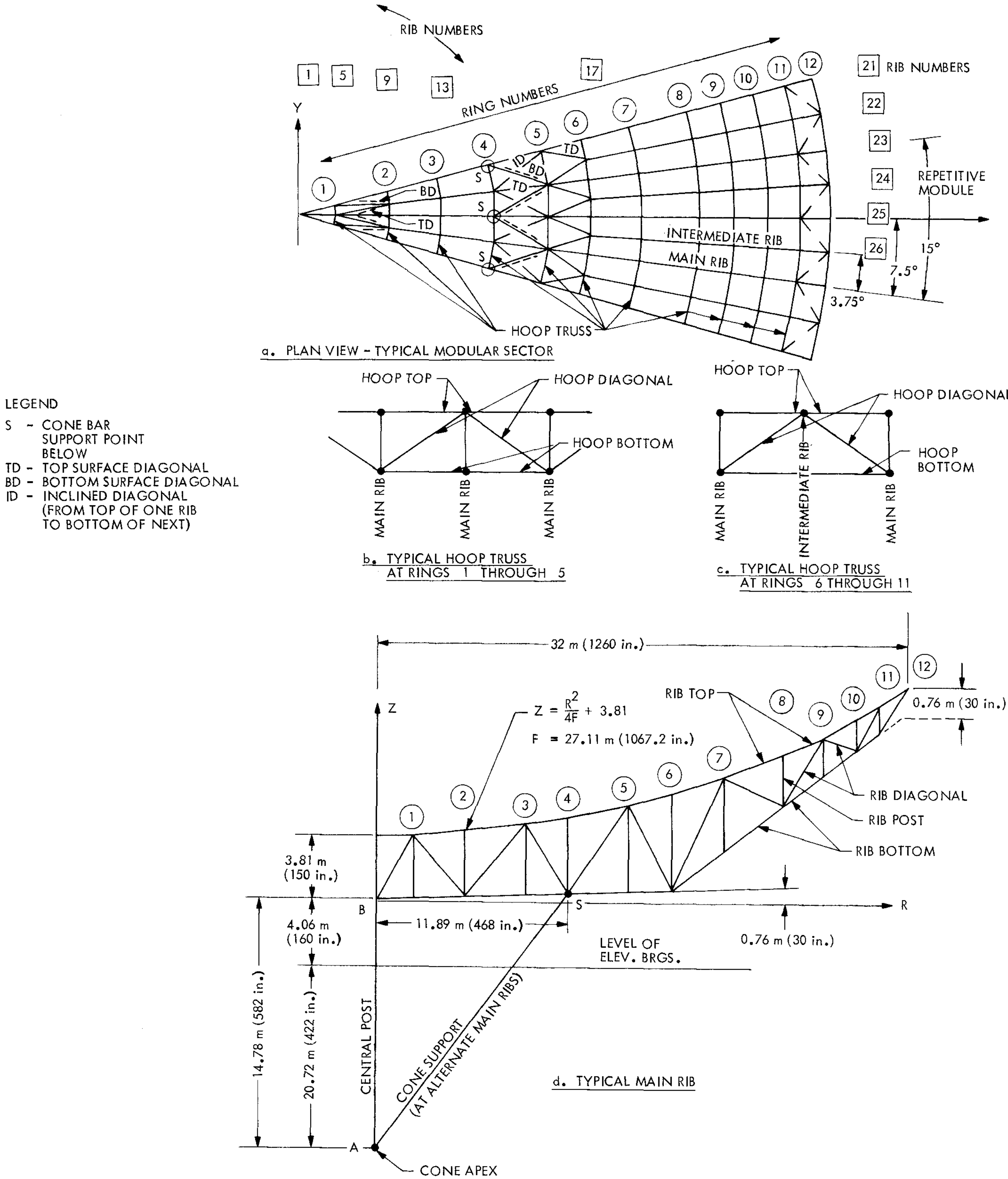

Fig. 1. Backup structure framing members

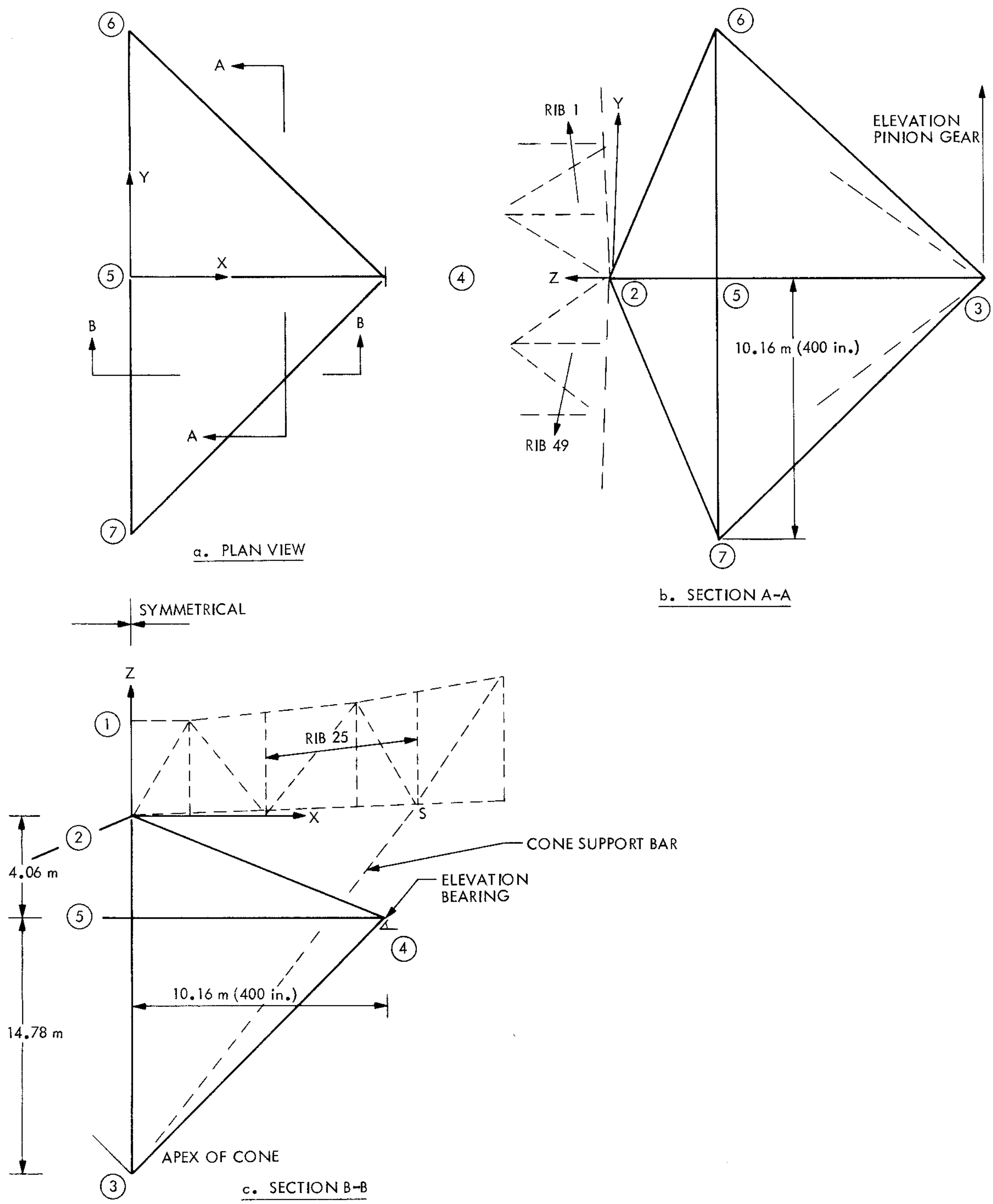

Fig. 2. Support structure for backup

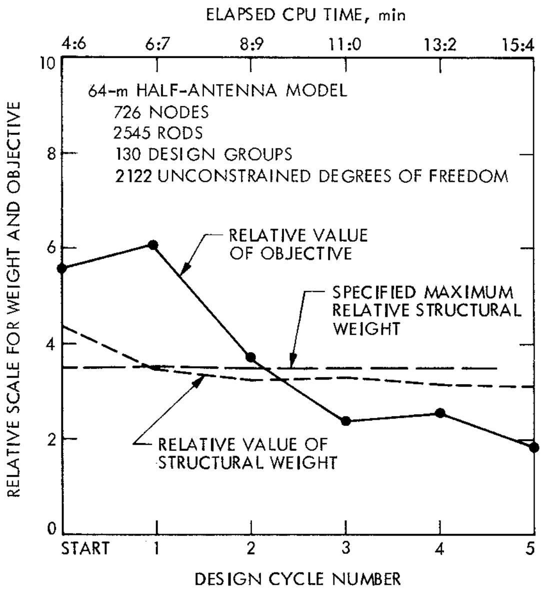

Fig. 3. Design history for 64-m antenna structure

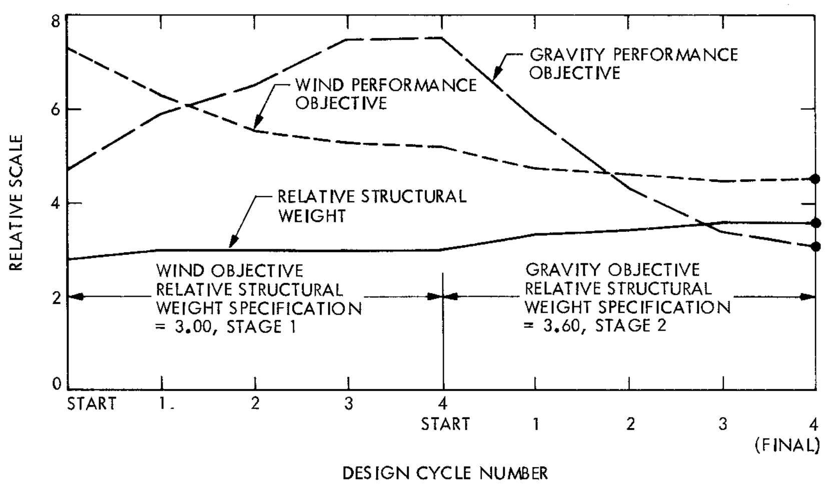

Fig. 4. Wind/gravity design history

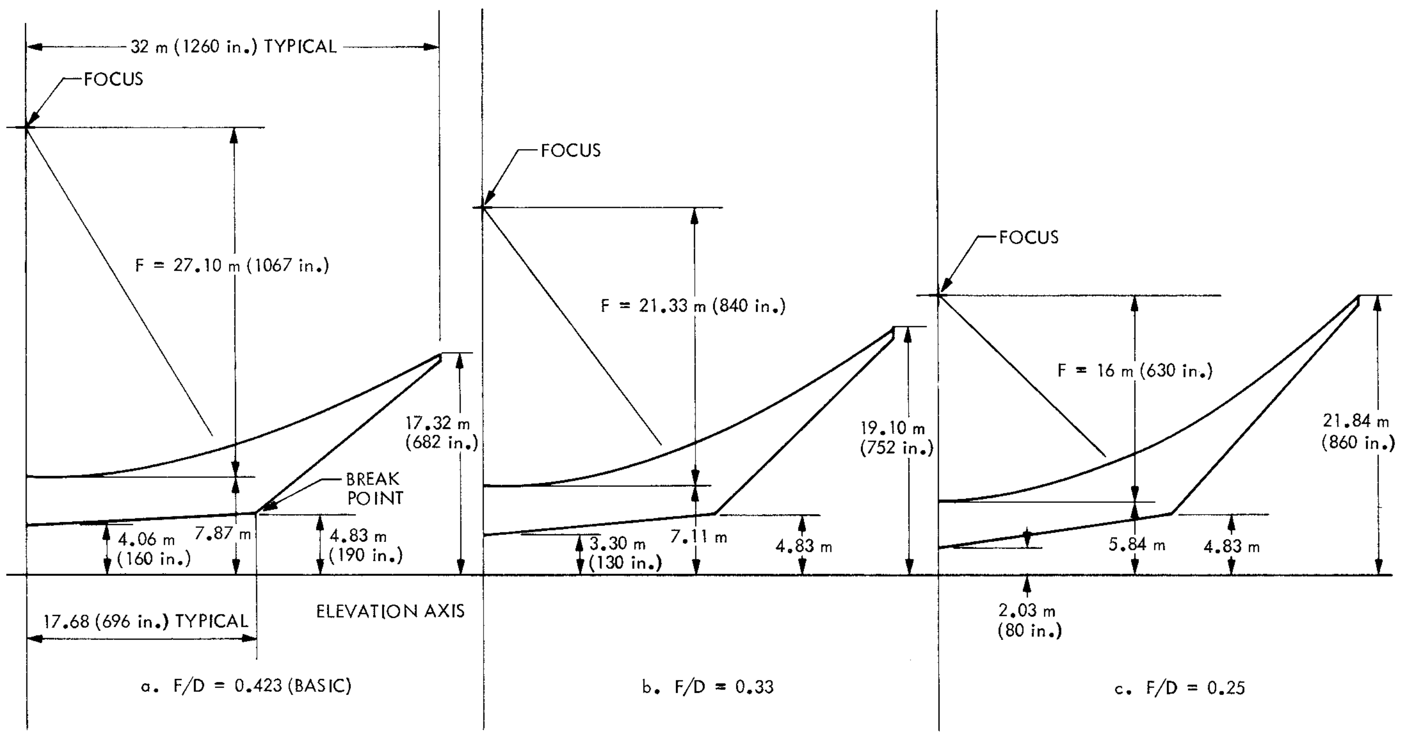

Fig. 5. Envelope dimensions for focal length-to-diameter variations

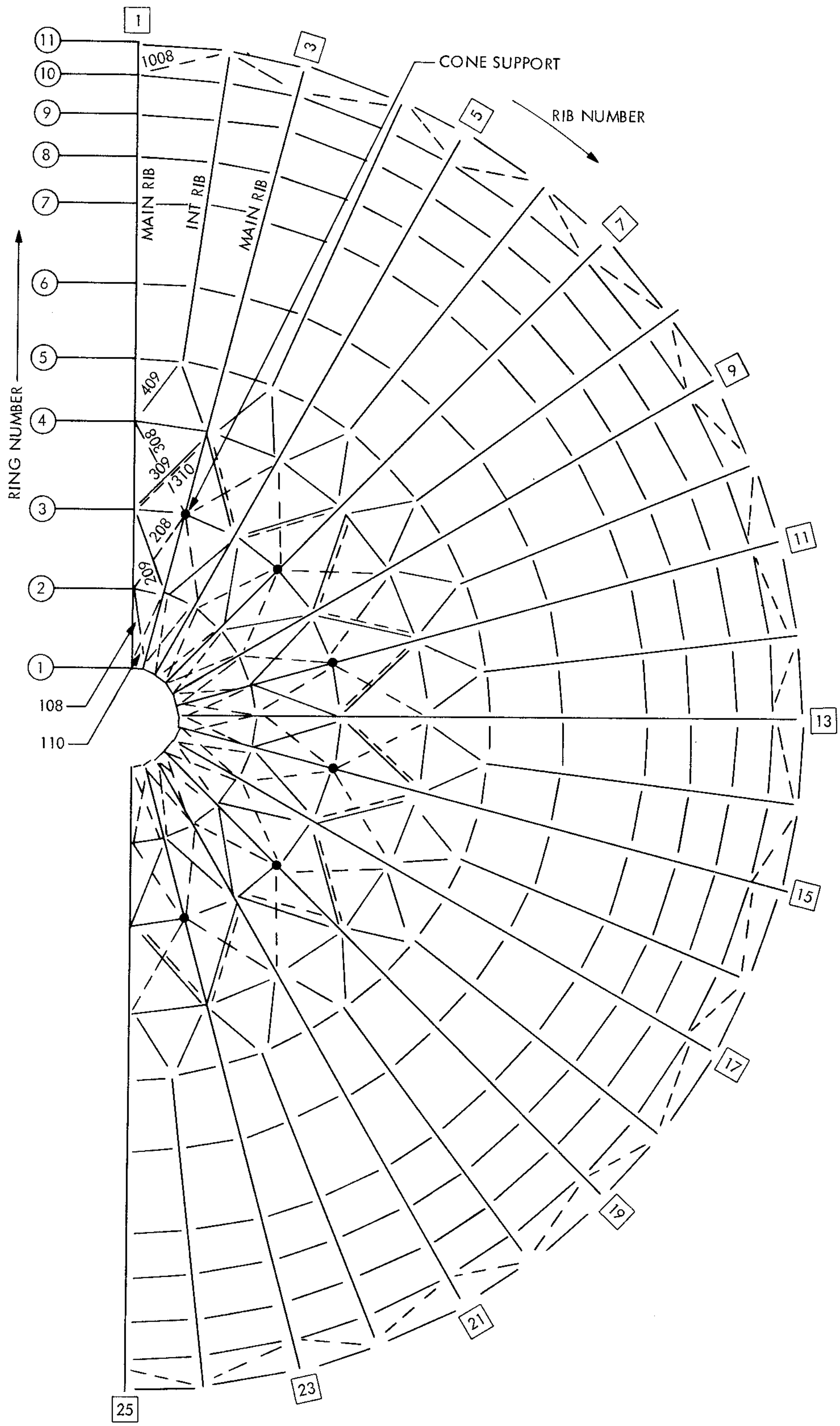

Fig. 6. Modified configuration top surface framing