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RECENT ADVANCES IN STRUCTURAL TECHNOLOGY FOR LARGE DEPLOYABLE AND ERECTABLE SPACECRAFT

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ABSTRACT

Ultra-low mass deployable and erectable truss structure designs for spacecraft are identified using computerized structural sizing techniques. Extremely slender strut proportions are shown to characterize minimum mass spacecraft which are designed for Shuttle transport to orbit. Analytical results are presented which demonstrate discrete element effects using a recently developed buckling theory for periodic lattice type structures. An analysis of fabrication imperfection effects on the surface accuracy of four different antenna reflector structures is summarized. This study shows the tetrahedral truss to have the greatest potential of the structures examined for application to accurate or large reflectors. A deployable module which can be efficiently transported is identified and shown to have significant potential for application to future antenna requirements. Recent investigations of erectable structure assembly are reviewed. Initial experiments simulating astronaut assembly by extra-vehicular activity (EVA) show that a pair of astronauts can achieve assembly times of 2-5 min/strut. Studies indicate that an automated assembler can achieve times of less than 1 min/strut on an around-the-clock basis.

KEYWORDS

spacecraft, truss, platform, antenna, module, deployable, erectable, buckling

INTRODUCTION

It is anticipated that future space missions will involve spacecraft which are extremely large compared to those in use today. Potential missions being considered require spacecraft ranging in size from state-of-the-art antennas to futuristic, kilometer size solar power satellites. The aerospace community faces a major challenge to devise ways to accomplish these missions. Extremely high mission complexity and resultant cost dictates that concepts be developed which permit mission accomplishment in the most efficient manner. This will require that spacecraft mass transported to orbit be reduced to a minimum. Spacecraft must be designed for efficient packaging in Shuttle for transport to orbit. Mission requirements affecting spacecraft structural design must be examined in conjunction with

Shuttle constraints to insure that the most desirable spacecraft concept is identified.

Previous studies identified trusses as a candidate low-mass structural class which meets the requirements of many future missions. These studies encompassed trusses which were either deployed (unfolded on-orbit), erected (assembled on-orbit), space fabricated (manufactured and assembled on-orbit), or made functional by a combination of these methods. It is desirable to understand the application limits of each concept to permit selection of the simplest technique that meets mission requirements. The purpose of this paper is to present selected results from (1) recent LaRC sizing studies which identify efficient structural proportions and application limits of deployable and erectable structure concepts, (2) supporting analytical developments which are applicable to reticulated structure design in general, and (3) spacecraft assembly studies for both modular and erectable concepts.

STRUCTURAL SIZING STUDIES

Efficient structural proportions for a range of spacecraft sizes were recently determined by Heard (1980), where non-linear mathematical programming techniques were used to minimize the mass per unit area of spacecraft deployable and erectable structure. A wide range of mission requirements and constraints were parametrically investigated to determine structural dimensions of minimum-mass designs that satisfied specified conditions. Such studies are necessary to understand the relationship among the large number of design requirements, constraints and sizing variables involved and to identify practical limitations of both deployable and erectable structures for large spacecraft.

Spacecraft Geometry

A tetrahedral truss platform is selected for study due to its low mass and high stiffness characteristics (Mikulas, 1977 and Bush, 1978). This platform, shown in Fig. 1(a), has a hexagonal planform. The face and core struts can be dissimilar if required by the sizing process; however, all struts are made of graphite epoxy material with a longitudinal modulus of 117 GPa. Both deployable and erectable truss platforms (Fig. 1b, c) are sized for transport to orbit via Space Shuttle. Transporting either platform type with Shuttle imposes unique constraints on the structural sizing process through the way each concept packages in the Shuttle cargo bay.

Deployable truss packaging. The deployable platform is considered to be constructed of cylindrical struts as shown in Fig. 1(b). The platform is considered to have inward folding face struts; therefore, the face struts can never be longer than the core struts. The core struts have an upper limit on length, which is taken to be 18 m (slightly less than the Shuttle cargo bay length). A hexagonal-shaped tetrahedral platform folds into a hexagonal-shaped package with the arrangement shown in Fig. 1(b). The cross-sectional area of this package is a function of the strut diameters. The Shuttle flights required to transport this package is approximated as either the ratio of (1) the folded spacecraft cross-sectional area to the Shuttle cargo bay cross-sectional area or (2) the total spacecraft mass to the Shuttle lift capability (29,480 kg). A minimum estimate of the Shuttle flights required to transport a given platform to orbit is given by the higher of the two ratios. The problem of joining segments of a deployable truss when multiple Shuttle flights are required is not addressed in this study.

Erectable truss packaging. The erectable truss platform is constructed of tapered, nestable struts which are packaged in Shuttle in stacks of strut halves, as shown in Fig. 1(c). The stacks of strut-halves may not exceed 18 m in length which is the length of the Shuttle cargo bay. A square packing array is considered for the cross-sectional arrangement of the stacks. Maximum diameters of the face and core struts determine the cross-sectional area required for stowage of the erectable spacecraft structure. The number of Shuttle flights required for the erectable components are calculated in the same manner as for the deployable spacecraft structure.

Spacecraft fundamental frequency. The effect of the spacecraft design fundamental bending frequency, f_d, on spacecraft structural mass per unit area and number of Shuttle flights is shown in Fig. 2 for both deployable and erectable spacecraft with spans of 400 m and 800 m. These calculations were made assuming a simply supported strut fundamental bending frequency, $f_s \geq 10\ f_d$, and a distributed non-structural mass, $m_p = 0.1\ kg/m^2$, representative of a low mass reflector surface. Strut and platform vibration frequencies were calculated in this study considering strut loads to be zero.

The structural mass per unit area is shown in Fig. 2(a). Deployable (dashed lines) and erectable (solid lines) platforms are shown to have essentially equivalent masses at lower values of design frequency (on the order of reflector mesh mesh surfaces) because of minimum gage and minimum strut diameter limits. Mass per unit area is shown to increase rapidly for higher values of design frequency. The increased structural mass necessary to meet higher stiffness requirements is accentuated by platform size, as seen by comparing the 800 m platform results with those of the 400 m platform.

The strong influence of platform design frequency on the number of Shuttle flights required to transport the various spacecraft to orbit is shown in Fig. 2(b). For lower values of design frequency, the Shuttle flights required by deployable and erectable spacecraft are equivalent, as shown by the nearly horizontal portions of the curves. Shuttle flights in this region are governed by mass considerations, and not the geometry or packaged size of the structures, which are different for each type of spacecraft. At higher values of design frequency, the deployable structure strut dimensions are sufficiently large that package size dominates the Shuttle payload and the curves become nearly vertical. The Shuttle flights required by erectable spacecraft exhibit a more gradual increase, being controlled by the minimum mass requirements. Thus, for a given size spacecraft, erectable structure using nestable struts permits use of a stiffer structure than possible with deployable spacecraft without incurring increased Shuttle flights. Different design requirements do not alter this result; but only change the frequency at which the deployable limit occurs.

Strut fundamental frequency. It is desirable that coupling not occur between the vibration modes of the struts and the overall spacecraft. One design approach employed to reduce the possibility of this occurring is to size the structure such that the fundamental frequencies of the struts and spacecraft are widely separated. The effects of imposing this design condition on spacecraft mass per unit area and Shuttle flight requirements are shown in Fig. 3 for a spacecraft design frequency $f_d = 0.1$ Hz. A range of strut fundamental design frequencies, f_s, is considered so that the frequency ratio, f_s/f_d, varies between 2 and 10. Results are shown for erectable and deployable platforms for both 400 m and 800 m spans. The mass per unit area requirements (Fig. 3a) at a strut frequency factor of 10 is approximately 3-4 times greater than at a ratio of 2. The Shuttle flights (Fig. 3b) required by the 400 m platforms are not adversely affected by the frequency ratio over the range investigated. However, an abrupt increase in Shuttle flights occurs for the 800 m deployable platform above a frequency ratio of 5. Such a practical limit of this parameter exists for other large size deployable platforms or smaller platforms with more severe design requirements. The existence of a "critical" strut design frequency, above which a deployable spacecraft becomes impractical to transport with Shuttle, indicates a need to identify the maximum required value of this parameter, relative to the spacecraft frequency.

Strut design load. The design of a low-mass truss structure can be adversely affected by loads which the structure must support. The frequency results shown in Fig. 2 and 3 also included the application of a gravity control moment to the spacecraft. Strut loads induced by this gravity gradient control moment were found to be insignificant. However, other loads resulting from docking, maneuvering, or assembly loads for erectable platforms could be significant. The effect of a constant strut design load is shown in Fig. 4. Shuttle flights (Fig. 4b) required for the erectable platforms are relatively unaffected over the load range considered because the payloads remain mass controlled. The influence of strut design load on the Shuttle flights required for the 400 m deployable platform is significant, increasing from one-half flight, for essentially zero design load, to approximately four flights for a design load of 400 N. The increased strut cross-section required for the higher loads causes a packaging penalty which is reflected in the Shuttle flights required for the 400 m deployable platform. The 800 m deployable platform Shuttle flight requirements indicate that the larger strut cross-sections required to satisfy frequency constraints are sufficient to carry strut loads up to approximately 100 N. Above this value, strut cross-section increases significantly to carry the load, as shown by the increased Shuttle flight requirements. Truss mass per unit area (Fig. 4a) is shown to increase at a much lower rate than Shuttle flight requirements.

Strut slenderness. The structural proportions which characterize minimum mass truss designs are extremely important, particularly for deployable trusses. Conventional truss structures typically employ struts having slenderness ratios (defined as the ratio of strut length to radius of gyration) less than 200-300. The computerized sizing procedure employed to minimize the spacecraft structural mass per unit area produced truss designs having struts with slenderness ratios between 600 and 4000 which still satisfied all imposed constraints and requirements.

The benefits of slender strut construction are illustrated in Fig. 5, where the Shuttle flights required for various size spacecraft are given as a function of the slenderness ratio which optimizes truss mass per unit area. For the calculations shown in Fig. 5 the distributed non-structural mass (m_p) was assumed to be equal to .1 kg/m^2 and the struts were constrained to have a fundamental frequency which was greater than or equal to 10 times the spacecraft fundamental design frequency. The curves for each spacecraft size in Fig. 5 are the loci of minimum mass designs and encompass an approximate range of spacecraft design frequencies from .04 Hz to .28 Hz. For a given size spacecraft, as slenderness ratio increases (and frequency decreases) the Shuttle flights required to transport that spacecraft decrease rapidly. Each curve exhibits an abrupt change at an approximate slenderness ratio value of 1600. At slenderness ratios less than this value, Shuttle flights of deployable tetrahedral trusses are volume controlled; above this value they are mass controlled for the design requirements considered in the study.

The potential benefit of reducing the number of Shuttle flights required to orbit a large deployable spacecraft (e.g. antenna or collector surface) is sufficiently attractive to warrant a thorough investigation of slender strut construction of large truss structures.

ANALYTICAL DEVELOPMENTS

Sizing studies, such as those previously discussed, direct future developments in spacecraft design toward periodic, truss type structures. The size and proportions of antennas, platforms, and booms currently envisioned are unprecedented. Structural analysis of such periodic configurations will require special techniques to adequately and efficiently consider high degree of freedom systems. Analytical innovations, such as the Finite Element Transfer Matrix technique used by McDaniels (1980) to determine the frequency response of rotationally periodic structures, are needed to reduce computational time. Ultra-low mass truss-type structures are also very discrete in nature. Stiffness averaging (or smearing) techniques which may be satisfactory for overall structural behavior are inadequate to describe structural response which is localized (involving two or three bays). Assurance of structural integrity will require extremely accurate analyses since it may be very difficult, if not impossible, to proof test some of the larger components on earth. Recent developments which improve our ability to more accurately analyze large periodic truss type structures are discussed in following sections.

Structural Accuracy Analysis

The use of a structurally efficient configuration for an antenna structure may be negated if the chosen configuration cannot be economically fabricated to the accuracy required by its electromagnetic function. Hedgepeth (1980) studied four antenna structural configurations to determine the relationship between their surface error characteristics and random fabrication imperfections. Typical results from this study are summarized in Fig. 6 where the root mean square surface displacement, δ_{rms}, is related to the standard deviation of the member length error, σ_ε, over a range of focal length to apperture diameter, F/D, values. The study results shown in Fig. 6 reveal that the lowest error configuration is the tetrahedral truss. Thus, from a fabrication accuracy viewpoint, the tetrahedral truss has the potential for application to antenna reflectors which are more accurate or larger, than do the other configurations examined.

Buckling Theory

Anderson (1980) recently developed a new, accurate theory which accounts for the discrete buckling behavior of a class of periodic, lattice structures. The theory is applicable to structures having each internal node (strut or element intersection) connected to surrounding nodes in identical geometrical fashion by beam-columns. The structural stiffness matrix of each member is based on an exact solution of the beam-column equation under axial load, therefore, it is unnecessary to introduce intermediate nodes to achieve accurate results as with more conventional techniques. Because of the periodic nature of the structure, the response is also assumed to be periodic. This assumption is used to express motions of neighboring nodes in terms of the 6 degrees of freedom of a typical node. Buckling solutions are obtained by setting the resulting 6 x 6 determinant of the assembled global stiffness matrix equal to zero. Application of this theory to two structural configurations is discussed in subsequent sections.

Three longeron truss column. The three longeron truss column was shown in optimum design studies by Mikulas (1978) to be a highly efficient structural configuration for long, lightly loaded, boom applications. These studies were based on the commonly used approach of equating the Euler buckling load of individual longeron members (struts) to the overall column buckling load. An exact analysis of a three longeron truss column using the theory of Anderson (1980) is presented in Fig. 7. The critical buckling load of the column, P, normalized by the Euler buckling capability, P_E, of the three longerons one bay in length, is shown in Fig. 7 as a function of the buckle half-wavelength, λ, normalized by a bay length of the column, ℓ. The area of the diagonal members was chosen to be small (5%) relative to the longerons in order to show a case where the diagonal bracing is not fully effective in supporting the longerons. The column will buckle at the lowest possible load, having an integer number of half-waves, into either of three possible mode shapes which are dependent on the column length. In Fig. 7, short columns (1 or 2 bays) are shown to involve longeron buckling between nodes. Intermediate column (3-17 bays) buckling involves nodal movement and occurs 30% below the short column load. Long columns (>17 bays) exhibit Euler buckling which is reduced by transverse shear deformations.

<u>Isogrid cylinder</u>. The isogrid cylinder was also shown by Mikulas (1978) to be a highly efficient structural column for lightly loaded application. This configuration is very attractive for overcoming practical minimum wall thickness constraints encountered in solid wall cylinder designs, or as an alternative configuration when minimum tube sizes in built-up trusses are active design constraints. Figure 8 shows the critical buckling load, P, normalized by the buckling load of of a cylinder with equivalent, smeared wall stiffness, P_{EQ}, as a function of the element slenderness ratio (length/radius of gyration). Two grid orientations are examined; (0°, ± 60°) elements and (± 30°, 90°) elements. In each case, circumferential and helical members are examined both as straight (solid lines) and curved elements (dashed lines). The (± 30°, 90°) configuration is shown to exhibit the highest buckling load, for straight elements, over most of the element slenderness range examined. When curved element construction (which is more realistic for composite material construction) is considered the buckling load prediction for the (± 30°, 90°) configuration is reduced the greatest amount from smeared theory results. All configurations are shown to exhibit large reductions from the smeared theory predictions as the elements become more discrete, or slender.

Missing Member Effects

It is extremely desirable that large spacecraft exhibit a high tolerance to damage and still be capable of mission accomplishment. Postulating that individual truss elements or struts may fail or be damaged in some way could overload adjacent struts. The use of estimated "stress concentration factors" from conventional plate theory are shown by Walz (1979) to be highly conservative. Some results from this study are shown in Fig. 9 for the equilateral triangle face of a tetrahedral truss subjected to various inplane loads. It is shown that load concentration factors calculated from a discrete analysis are over a factor of 2 less than is estimated by conventional plate theory. Such conservatism in load as shown previously can cause significant mass and Shuttle flight increases.

Faceted Reflector Design

Many proposed missions involve the construction and use of very large reflectors for electromagnetic application which usually are doubly curved surfaces. When the doubly curved surface is approximated using curved gores of open mesh, as is the usual case for deployable antennas, saddeling or unwanted curvature results from the biaxial tension field used to stretch the mesh. Out-of-plane mesh curvature problems (but not necessarily wrinkling) are eliminated when flat panels are stretched. Agrawal (1980) examined the approximation of doubly curved surfaces with flat facets of various geometries. Figure 10 shows a generalized preliminary design curve for sizing triangular facets with sides of length L to meet curved surface accuracy requirements, δ_{rms}, for a given reflector application, F/D. Since it is envisioned that facets would be stretched between truss nodes, this type of analysis is useful for incorporation into a computerized structural sizing code. Optimum spacecraft designs can be obtained which simultaneously meet structural and electromagnetic requirements. An exact geometric analysis for doubly curved lattice structures by Nayfeh (1980) provides refined design information for fabrication of space trusses and reflectors.

SPACECRAFT ASSEMBLY INVESTIGATIONS

For those applications where deployable spacecraft complete with functional equipment and systems cannot be efficiently transported or reliably deployed, alternative approaches must be considered. Three different methods currently under investigation for such applications, each requiring on-orbit equipment assembly, are discussed in subsequent sections.

Deployable Spacecraft Modules

Functional requirements conceiveably can result in a spacecraft size exceeding that which can either be earth fabricated and tested or reliably deployed in space as a single unit into a functional state. One concept which retains many desirable features of deployable trusses is the repeating truss element, or hexagonal module, depicted in Fig. 11. This module can be fabricated on earth to the required accuracy, complete with functional surface and experimentally verified. It is folded into a compact configuration, with all strut elements parallel, for stowage in a Shuttle cargo bay cannister. On orbit each module is extracted, deployed, and passed to an assembly site where it is attached to other modules to form a complete antenna. Potentially, if required by efficient design, each module can be constructed to expand to a diameter and/or depth which is approximately twice the Shuttle cargo bay length. Ribble (1980) reports a design study for this deployable module, including conceptual assembly scenarios which include astronaut extra-vehicular activity (EVA) and Shuttle attached or free-flying assembly fixtures. This study details initial joint hardware designs as well as parametric performance estimates, shown in Fig. 12, of antenna reflectors constructed from these modules. Antenna accuracy (frequency) is shown in Fig. 12 to increase with apperture diameter, when constant size faceted modules are used to assemble the larger reflectors.

Erectable Spacecraft-Astronaut Assembly

Erectable spacecraft, characterized by nestable struts, offer an attractive alternative for those missions requiring stiffer structure than can be transported as deployable truss segments and/or modules (see Heard, 1980). However, erectable spacecraft must be assembled on orbit--an operation which appears formidable when first considered. Many perceived missions require spacecraft of 100 to 300 m span. While large by present spacecraft standards, such structures can involve hundreds--not thousands--of structural components placing them potentially within the capability of astronaut assembly. Since man's capability for assembling structural components in a weightless, pressure suited environment is virtually unexplored, a series of tests was undertaken at the NASA Marshall Space Flight Center Neutral Buoyancy Facility (NBF). These initial experiments (Loughead, 1980) investigated the capability of two pressure suited astronauts to assemble a six-strut tetrahedral cell shown in Fig. 13, using various strut lengths, joint hardware, and assembly procedures. The average, unassisted assembly times for various pairs of subjects using 5 m struts is also shown in Fig. 13. The bounding lines around the data indicate the general learning curve trend. As more tests were conducted, experience was gained and the assembly times decreased, appearing to approach approximately five min/strut for the unassisted assembly tests shown. Other tests simulating assisted EVA assembly yielded times of approximately two min/strut, illustrating the usefulness of assembly aids for improving astronaut efficiency in performing weightless assembly tasks. The NBF tests thus far provide needed qualitative information on specific task performance by pressure suited astronauts. Future experiments must investigate ways to enhance and maintain astronaut productivity over longer periods of time than studied previously.

Erectable Spacecraft-Automated Assembly

Some proposed missions require erectable spacecraft sufficiently large or complex (in a system sense) that astronaut capability is more efficiently used performing tasks other than structural assembly. For such spacecraft, it would be desirable to automate the assembly process as much as possible. A versatile concept detailed in Fig. 14(a) has emerged from studies (Jacquemin, 1980) and is artistically depicted in Fig. 14(b) in a Shuttle attached mode assembling a linear structure. As perceived, this assembler is also capable of operating in a free-flying mode. Conceptually, the machine is an assemblage of simple mechanisms which perform specific sequential operations to construct repetitive truss structures, either linear beams or area platforms, using nestable struts.

The assembler consists of two pairs of swing arms, each pair connected by a tie-rod and a gimballed four-sided main frame. Cannisters, containing nested half-struts and/or nodal joints are attached to the arm and frame members. In the free-flying platform assembly mode, the machine operates by alternately swinging the upper and lower arms to walk from node-to-node (hardpoints) along the platform edge inserting struts and nodes which are dispensed from the cannisters as it progresses. Strut halves are snapped together as the machine steps, using a strut assembly mechanism which is shown in the figure. Whether or not the assembler operates as a free flyer or remains Shuttle attached must be determined from assembly dynamics and control studies.

Studies indicate that such an automated machine is capable of assembly rates of less than one min/strut and can operate around the clock, requiring astronaut involvement only for surveilance, maintenance and servicing. The capability of this automated assembly concept machine to perform installation of other spacecraft systems along with the structure assembly process is currently being examined to further incrase its versatility and utility.

Assembly Assessment

A preliminary perspective of assembly capability may be drawn from the studies to date. The on-orbit assembly time required to construct platforms of 100 m to 1000 m span, using 20 m nestable struts is shown in Fig. 15 for various assembly rates. The simulated EVA assembly rates are derived using Neutral Buoyancy Facility data for one pair of astronauts, and assuming that these rates are applicable for 8 hrs/day, not necessarily performed all in one shift or by the same people. The automated machine assembly rates are derived using the theoretical timelines and assuming 24 hr/day operation.

It is shown in Fig. 15 that within the five-day on-orbit operational limit of

Space Shuttle, approximately a 200 m span platform could be assembled by astronauts. It is also shown that a much larger platform, on the order of 400-500 m span, could be erected with the automated assembler in the same five-day period. Conversely, the machine is also applicable to more rapid construction of smaller platforms or beams to reduce astronaut structural assembly tasks, or free them for systems installation and checkout duties.

Viewing the results shown in Fig. 15 in a qualitative, rather than quantitative sense, indicates that both man and machine can make significant contributions, either independently or together, toward assembling spacecraft on-orbit. The level of involvement using either method is an issue which requires much future study, and even then will probably be decided on a case-by-case basis.

CONCLUDING REMARKS

Ultra-low mass designs of large deployable and erectable tetrahedral truss platforms which meet a variety of practical requirements and constraints are identified using computerized structural sizing (mathematical programming) techniques. These designs are characterized by structural mass per unit area which is equivalent to that of mesh reflector surfaces. Platform fundamental frequency, which is a measure of overal structural stiffness, is shown to be a strong design driver, indicating a need to determine the minimum acceptable value of this parameter which will permit mission accomplishment.

Strut proportions characterizing minimum mass designs of deployable and erectable trusses are found to be much more slender than struts conventionally used for earthbound structural applications. The advantages of minimum-mass slender strut construction, illustrated herein, warrant a thorough investigation to determine the feasibility of fabricating spacecraft in this manner.

For platforms with minimum stiffness requirements, optimum deployable and erectable structures were found to require approximately the same number of Shuttle flights for transporting to orbit. Higher platform stiffness requirements or more severe design constraints, however, results in increased strut diameters which significantly increase the Shuttle flights required by deployable structures and limits their usefulness. Erectable platforms were found not to be limited in this manner because of the more efficient packaging of nestable struts, thereby offering an alternative for platforms with stiffness requirements that cannot be efficiently met by deployable structure.

In general, strut stiffness requirements were found to impact deployable structures more severely than erectable structures primarily due to the resultant increase in Shuttle flights required. The severe effect on structural proportions of maintaining high strut frequency relative to platform frequency indicates a need to determine the minimum value of this parameter required to prevent vibrational coupling between strut and platform.

A new, versatile, and accurate buckling analysis for periodic structures with discrete members is summarized which requires the eigenvalues of only a 6 x 6 determinant to effect solutions. Studies comparing the sensitivity of various spacecraft structure concepts to fabrication imperfections show truss-type construction to have the greatest potential for application to antenna reflector structure requiring high surface accuracy. Concepts for assembling spacecraft on-orbit from modules or elements are discussed and a deployable module which has wide application potential is identified. Initial experiments show that astronaut assembly of erectable struts may be a viable and efficient means of building some types of spacecraft on orbit. Conceptual studies of automating the nestable column assembly process show a promising assembler configuration which is versatile and efficient.

Studies of deployable and erectable spacecraft to-date have identified a variety of potential solutions to the challenge of building the ultra-large spacecraft required by future missions. Ongoing and future investigations will supply the technical information needed to select a given concept for a particular mission.

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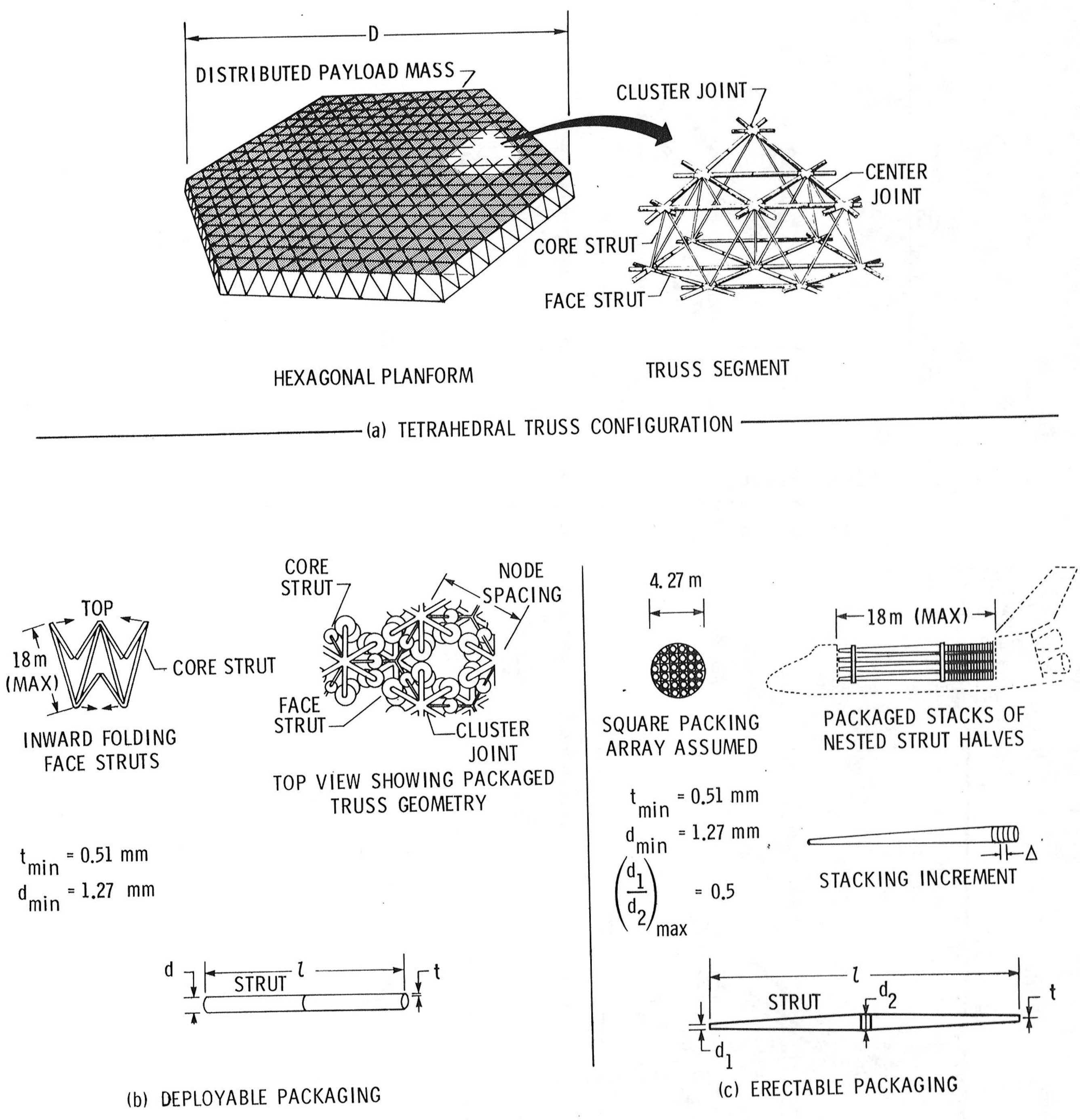


Fig. 1. Tetrahedral truss nomenclature and packaging geometry.

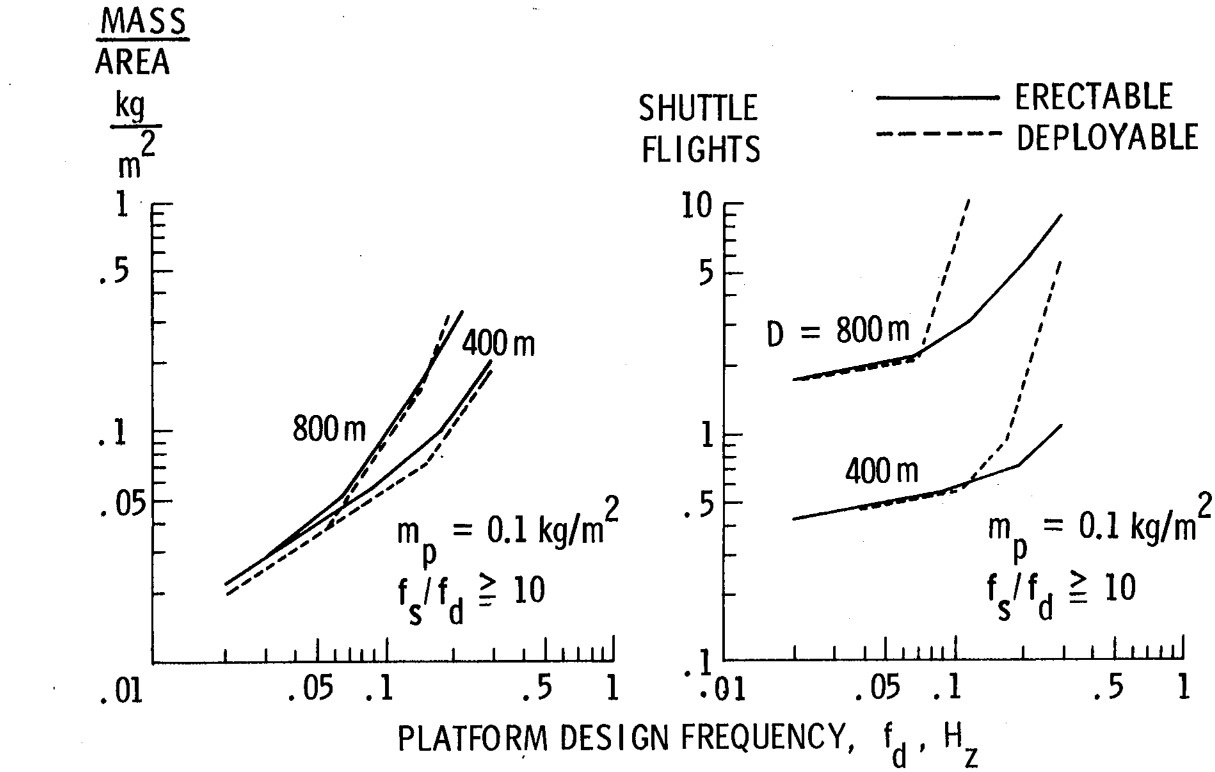


Fig. 2. Comparison of deployable and erectable platform structural mass per unit area and Shuttle flight requirements as a function of platform design frequency.

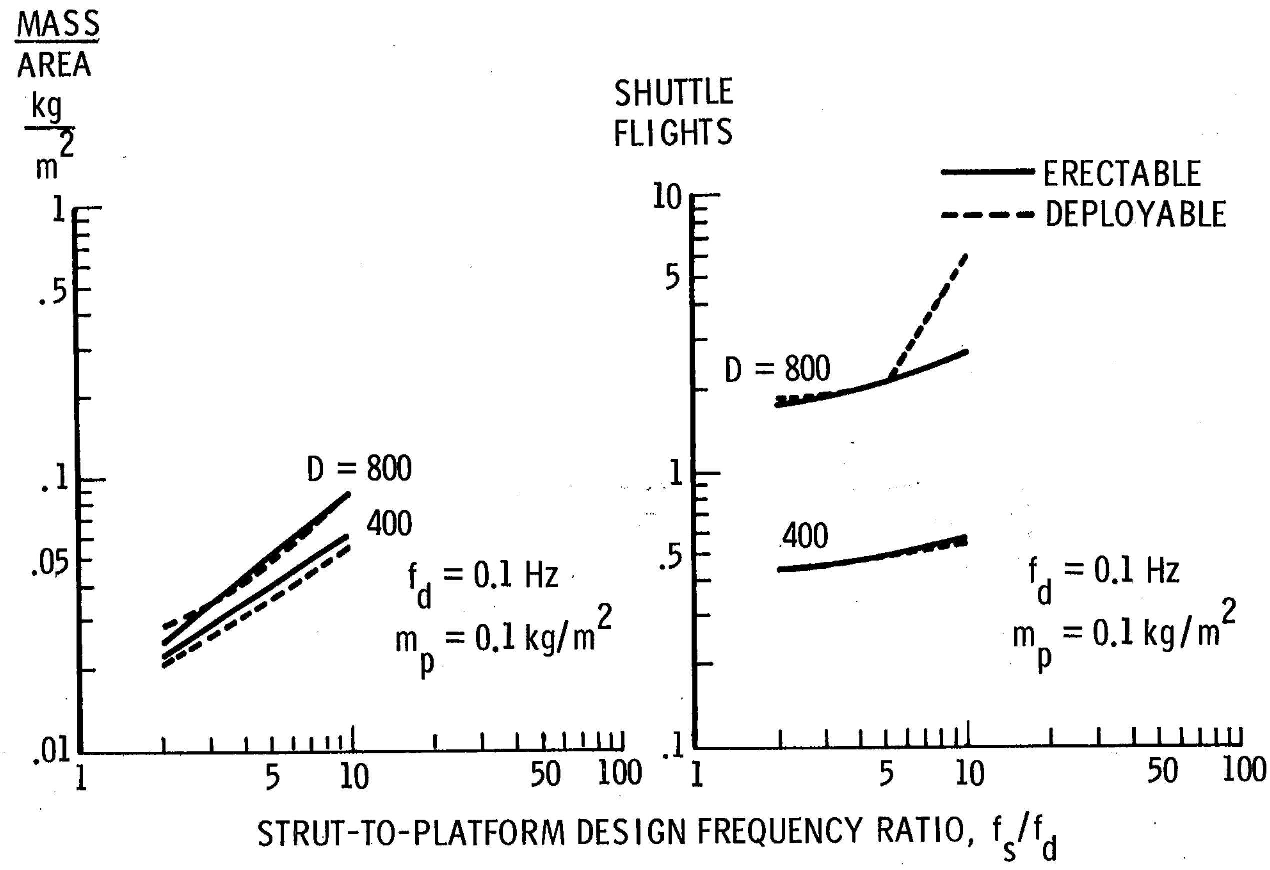


Fig. 3. Effect of strut-to-platform design frequency ratio on platform mass per unit area and Shuttle flight requirements.

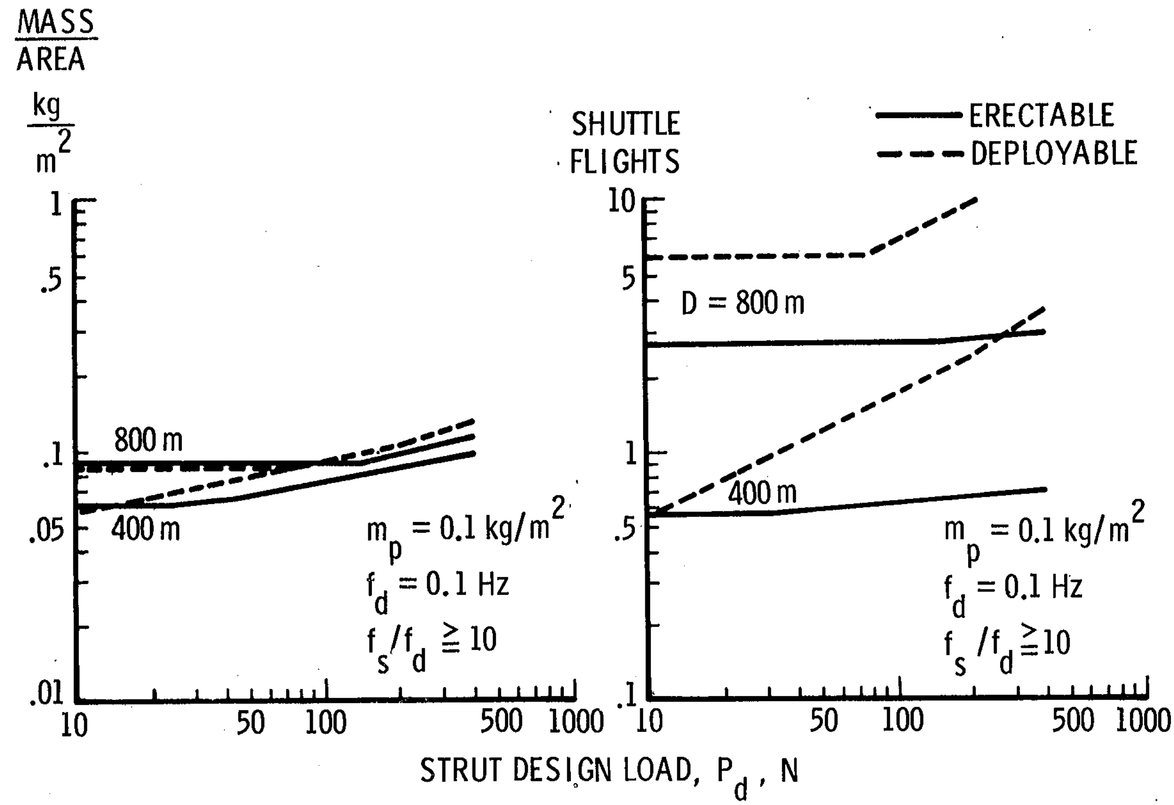


Fig. 4. Effect of strut design load on platform structural mass per unit area and Shuttle flight requirements.

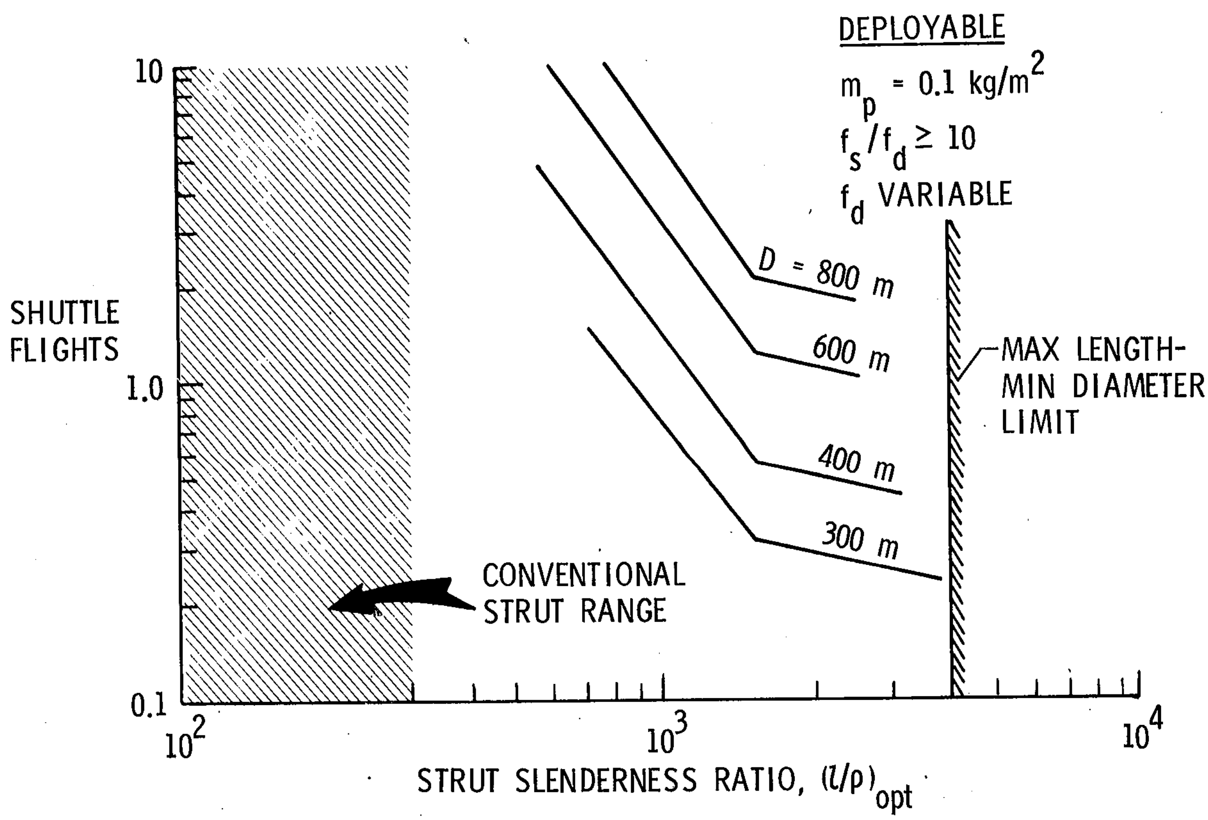


Fig. 5. Shuttle flight requirements for spacecraft with struts of optimum slenderness.

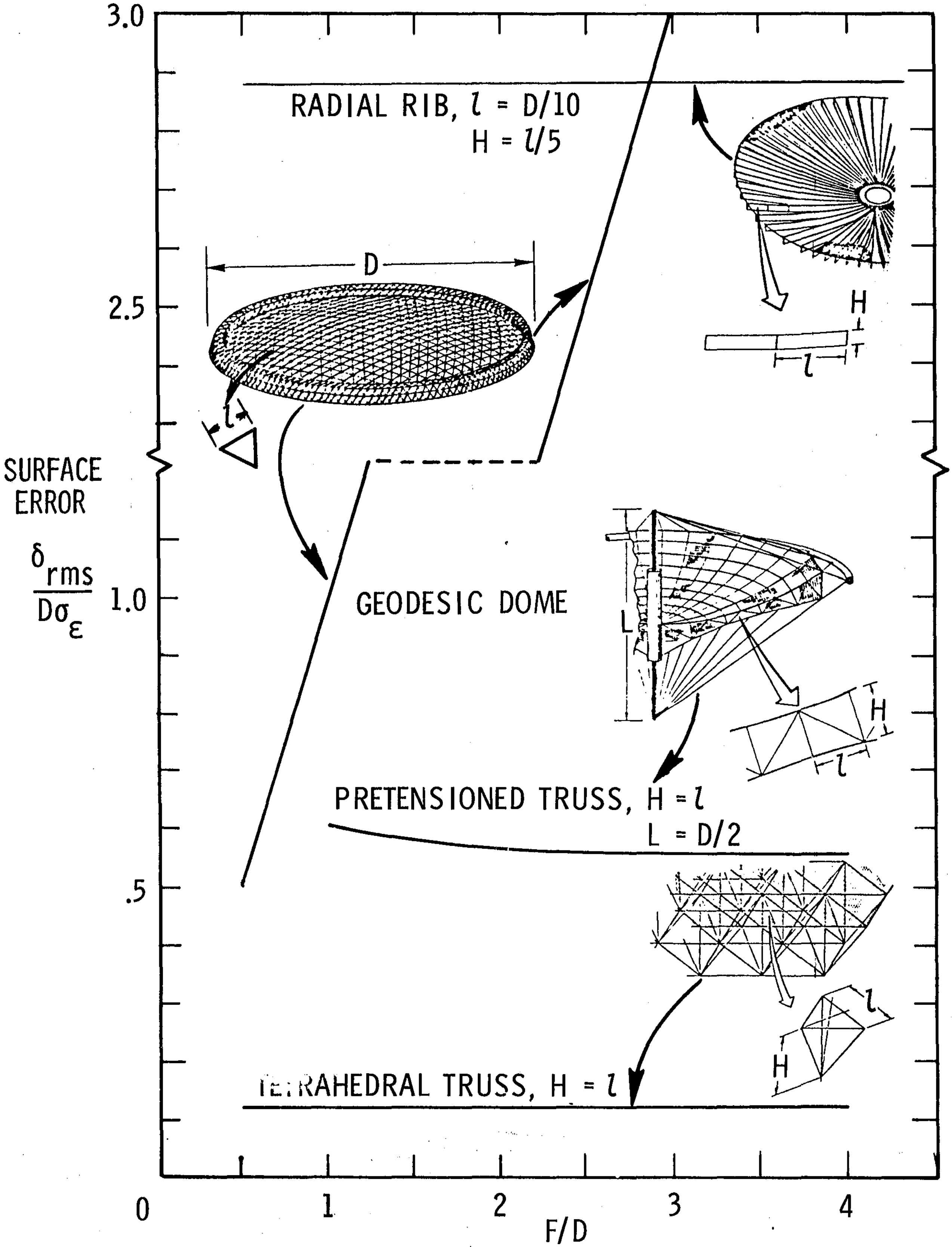


Fig. 6. Surface accuracy of various structural configurations.

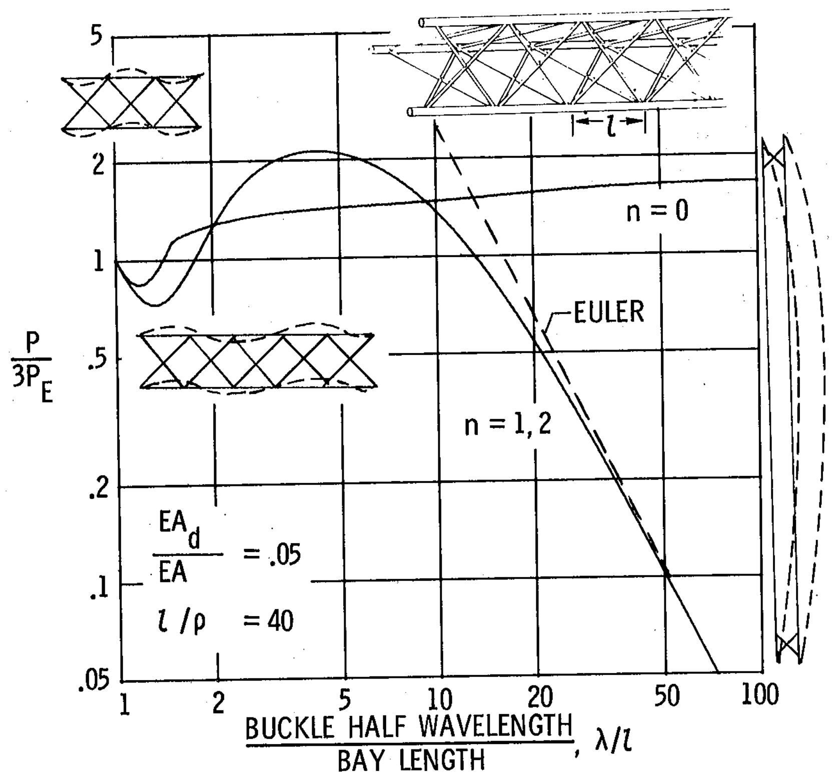


Fig. 7. Buckling analysis of three longeron truss column.

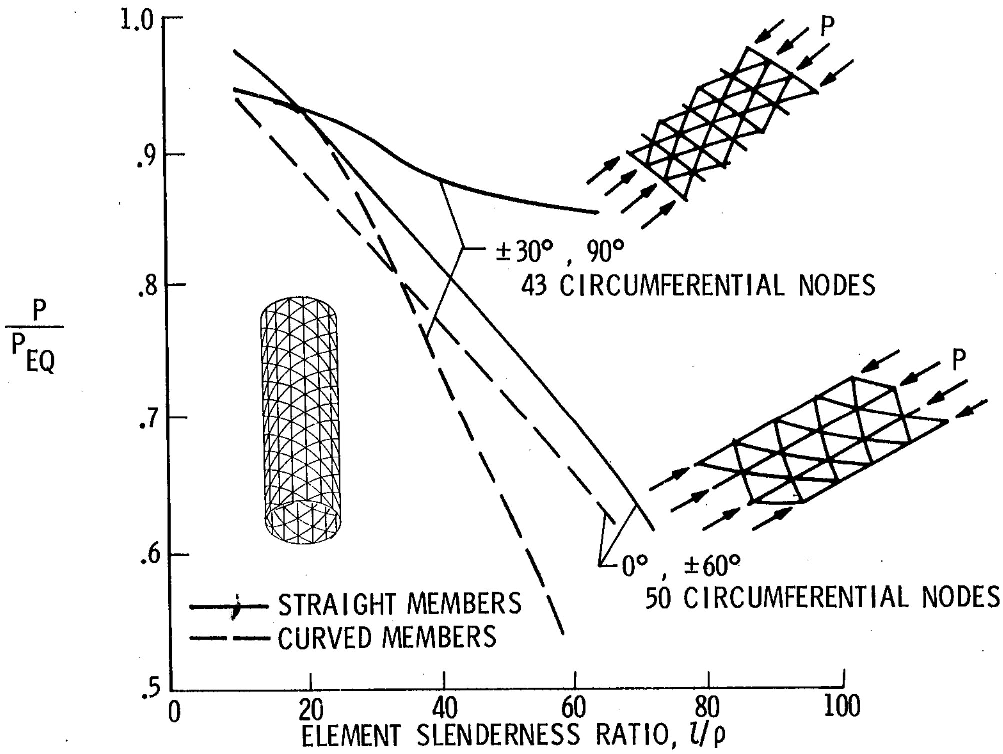
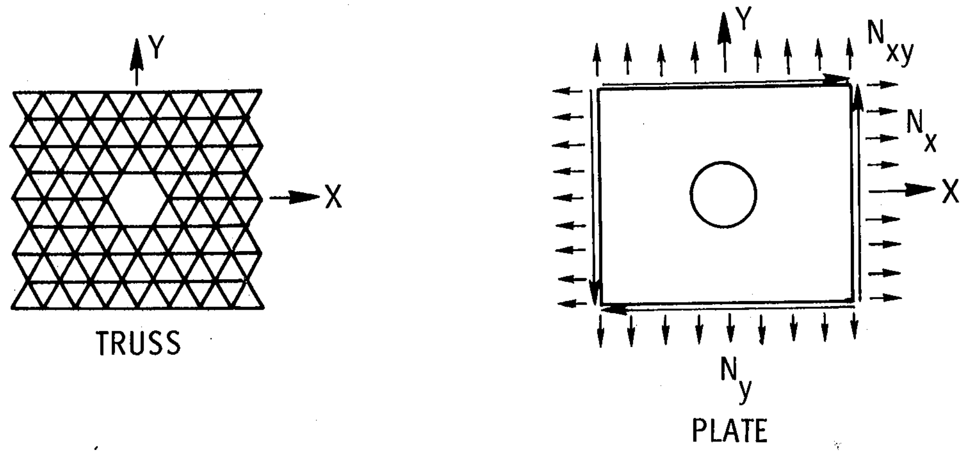


Fig. 8. Buckling analysis of isogrid cylinders with different member orientations.



	TRUSS	PLATE
LOADING	LOAD CONCENTRATION FACTOR	STRESS CONCENTRATION FACTOR
N_x	1.30	3.00
N_y	1.48	3.00
N_{xy}	1.56	4.00

Fig. 9. Load concentration factors for truss face with missing members.

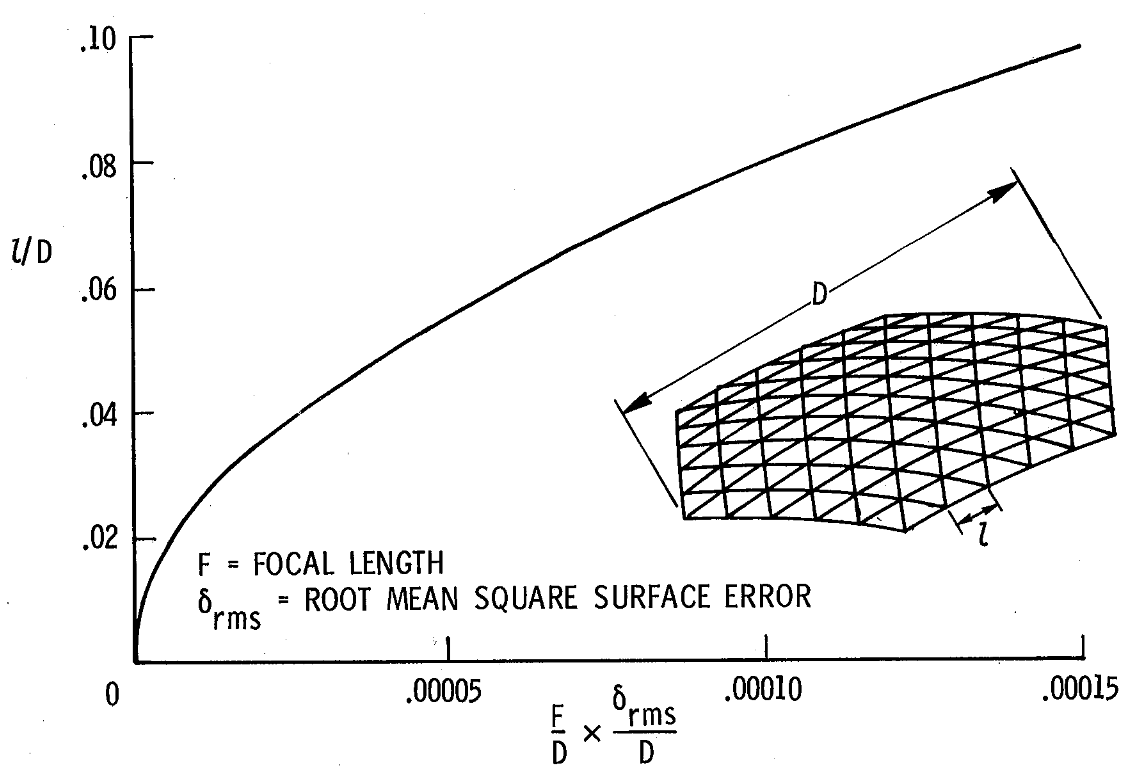


Fig. 10. Generalized design curve for reflector surface with flat facets.

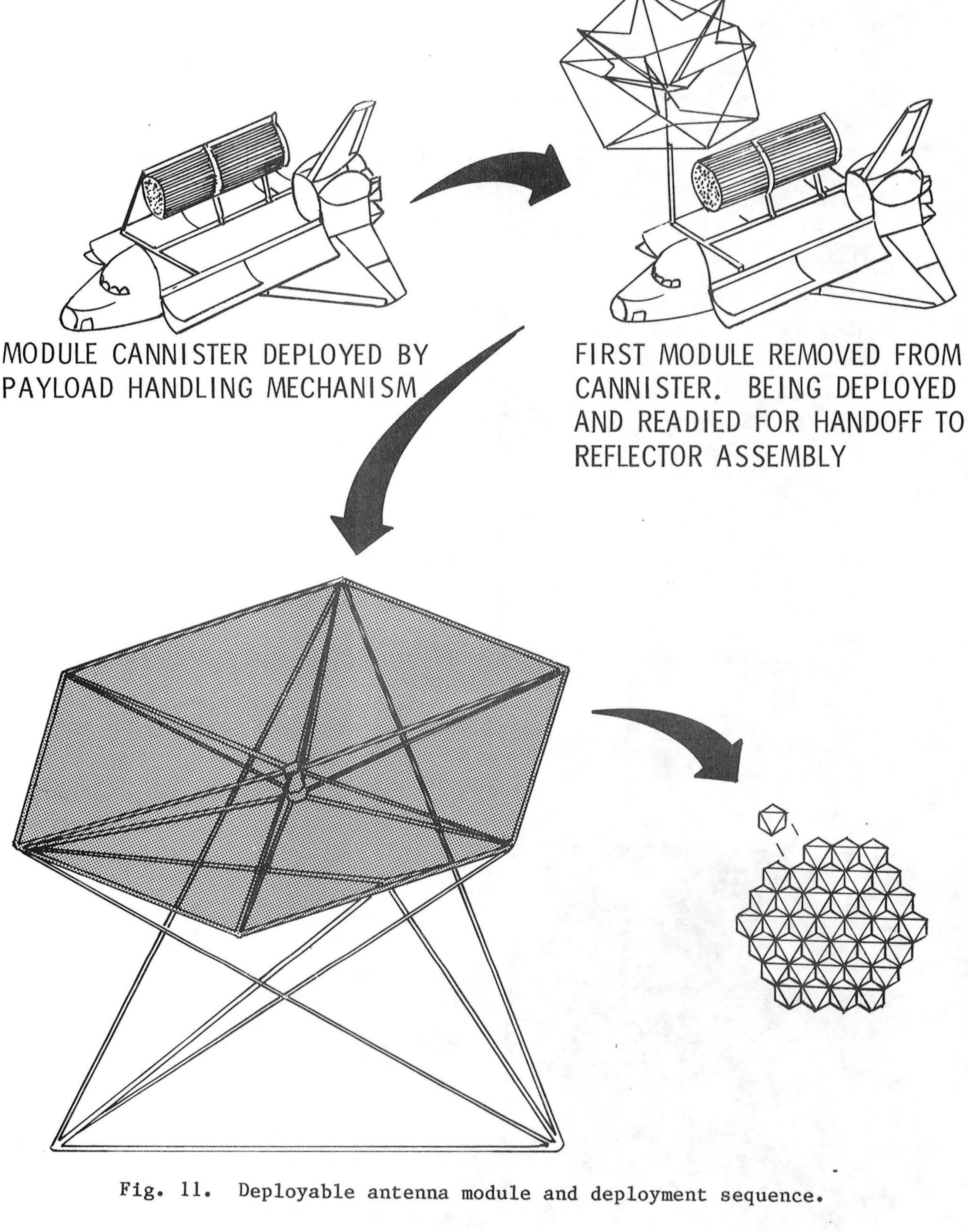


Fig. 11. Deployable antenna module and deployment sequence.

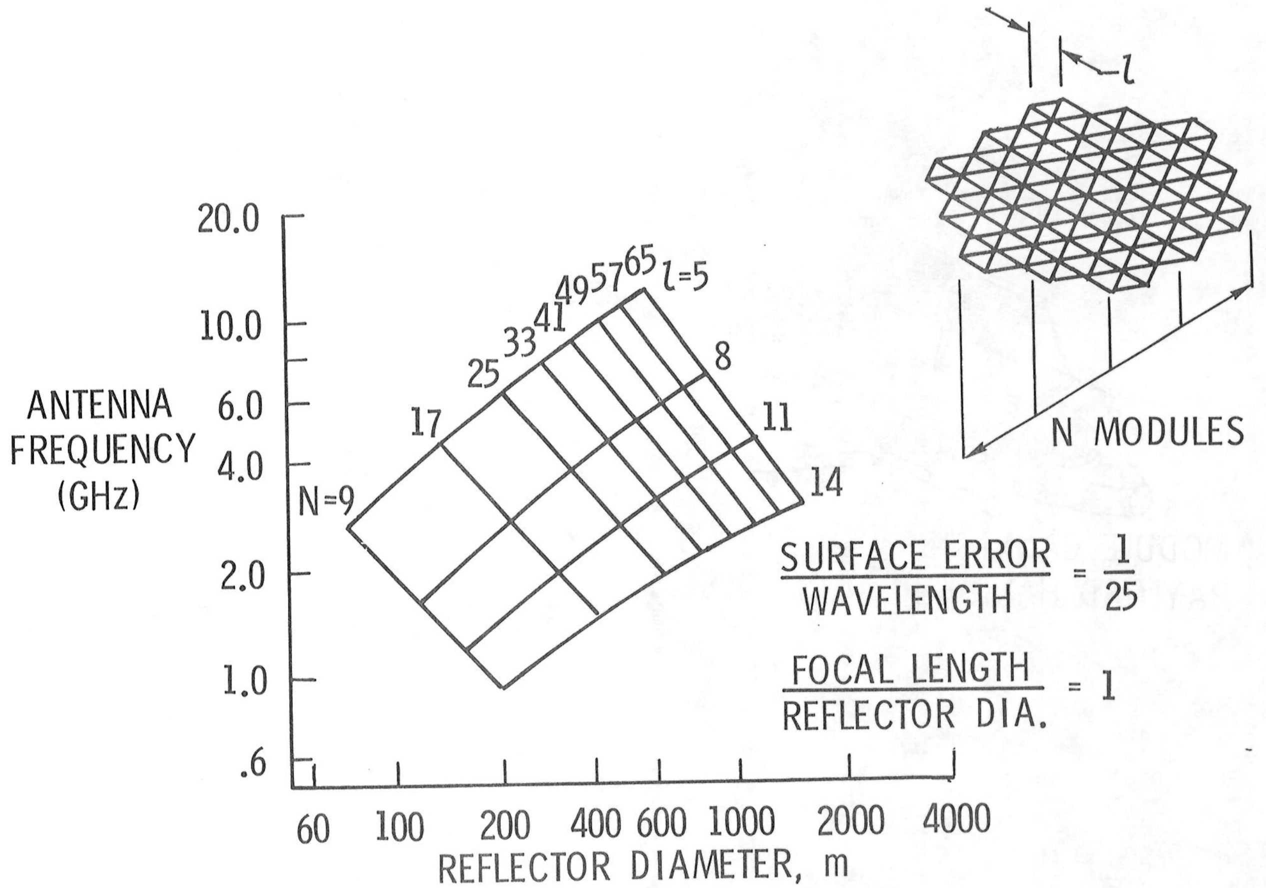


Fig. 12. Performance characteristics of antenna reflectors built from deployable modules (includes thermal effects).

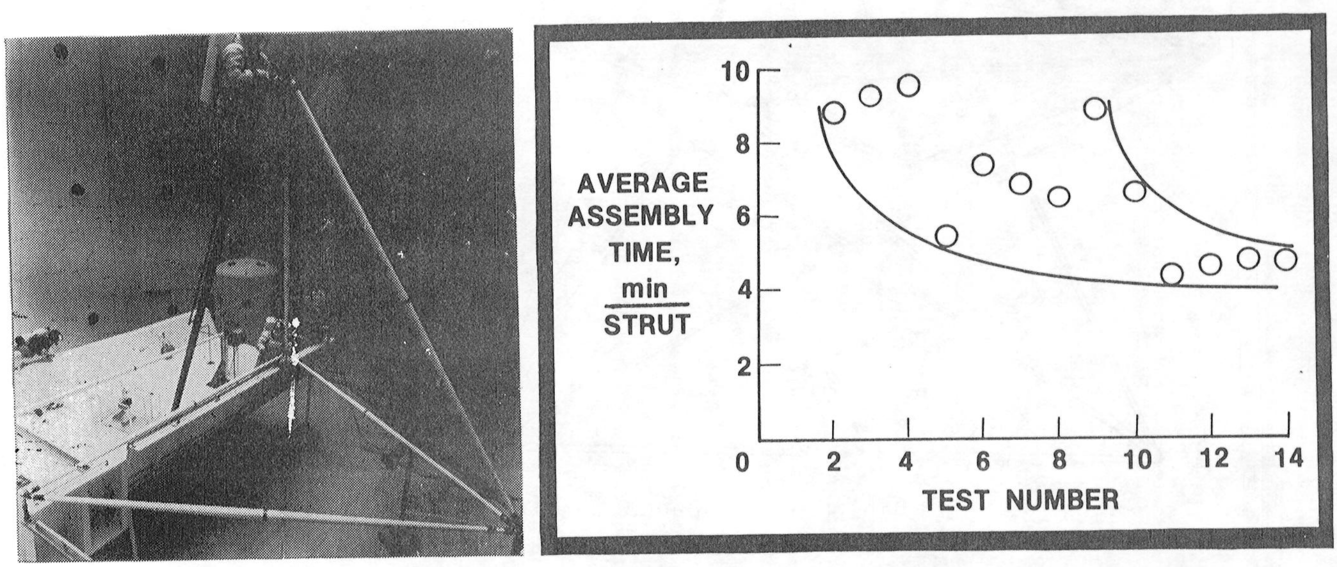
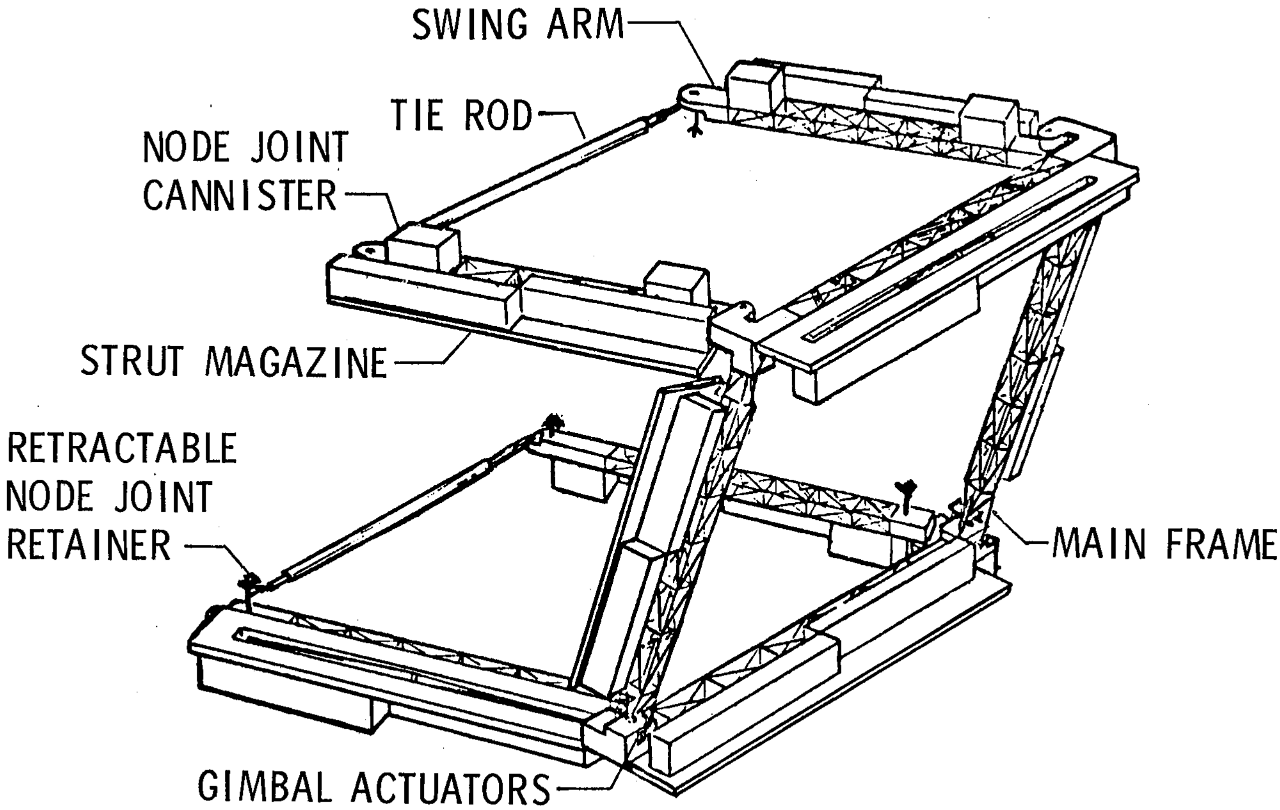
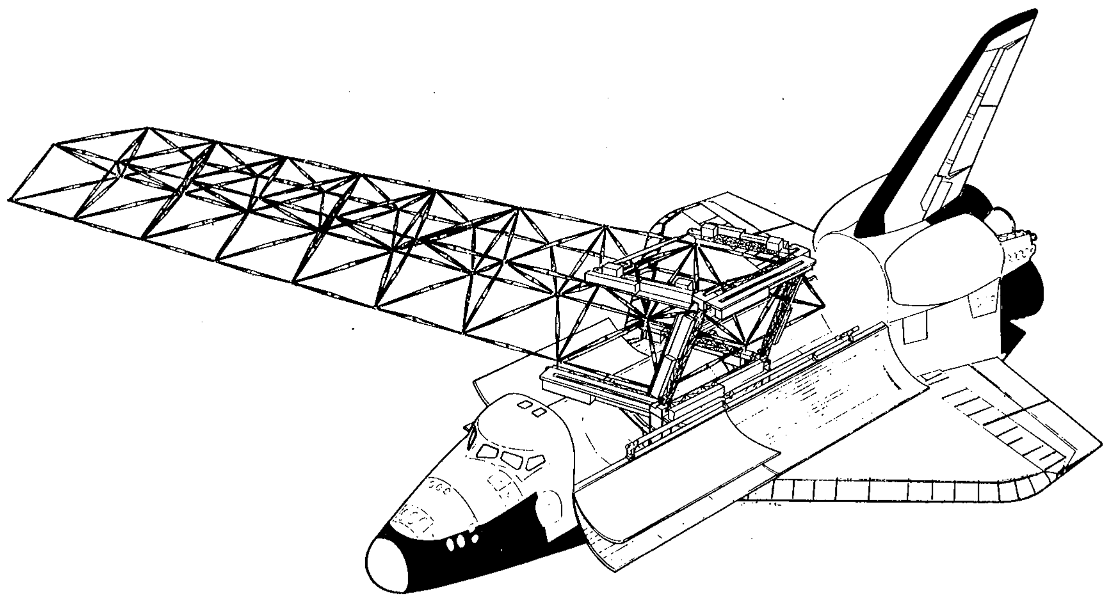


Fig. 13. Simulated astronaut EVA assembly experiment and timelines.



(a) Automated assembler details.



(b) Shuttle - attached mode.

Fig. 14. Automated tetrahedral truss assembler.

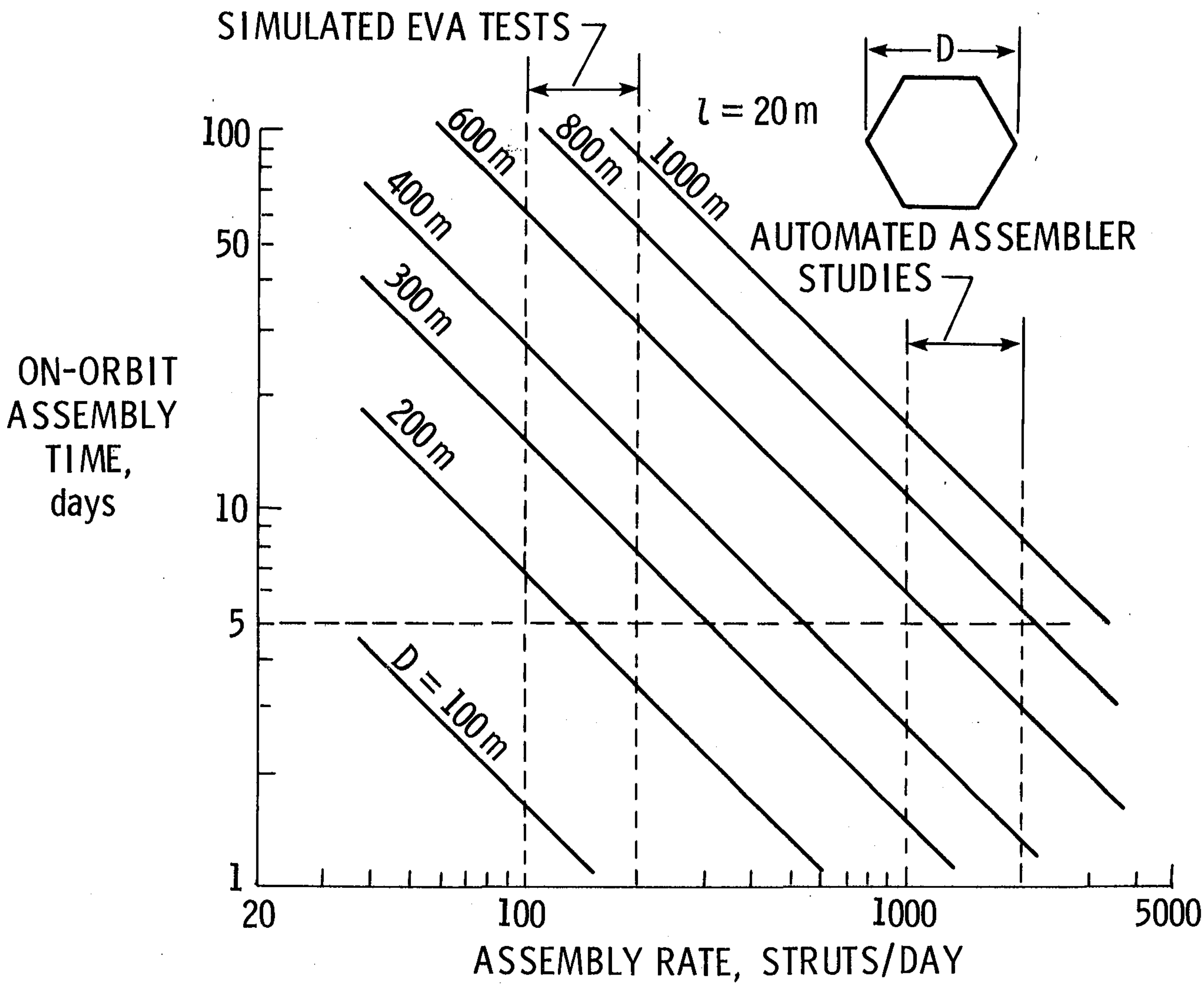


Fig. 15. Current perspective on assembly of erectable structure on orbit.

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15. Supplementary Notes

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16. Abstract

Ultra-low mass deployable and erectable truss structure designs for spacecraft are identified using computerized structural sizing techniques. Extremely slender strut proportions are shown to characterize minimum mass spacecraft which are designed for Shuttle transport to orbit. Analytical results are presented which demonstrate discrete element effects using a recently developed buckling theory for periodic lattice type structures. An analysis of fabrication imperfection effects on the surface accuracy of four different antenna reflector structures is summarized. This study shows the tetrahedral truss to have the greatest potential of the structures examined for application to accurate or large reflectors. A deployable module which can be efficiently transported is identified and shown to have significant potential for application to future antenna requirements. Recent investigations of erectable structure assembly are reviewed. Initial experiments simulating astronaut assembly by extra-vehicular activity (EVA) show that a pair of astronauts can achieve assembly times of 2-5 min/strut. Studies indicate that an automated assembler can achieve times of less than 1 min/strut on an around-the-clock basis.

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