EFFICIENT STRUCTURES FOR GEOSYNCHRONOUS-SPACECRAFT SOLAR ARRAYS*

John M. Hedgepeth
Astro Research Corporation
Carpinteria, California

INTRODUCTION

A program is outlined to create and evaluate structural concepts for deploying and supporting lightweight solar-array blankets for geosynchronous electrical power. First, the requirements for new, more mass-efficient solar arrays is established by describing future needs. Then analytical results are set forth which show that not only must lighter weight blankets be developed but also the supporting structure must be improved proportionately.

The SEPS configuration is taken to be the state-of-the-art point of departure for improved structural concepts. Several directions for improvement are indicated.

BACKGROUND

Recent studies (ref. 1) have indicated a need for power systems of up to 20 kW for geosynchronous communication satellites and platforms. They have also established that the projected capability of the Space Transportation Systems is insufficient for launch to geosynchronous altitudes unless significant advances are made in the mass efficiency of the several spacecraft subsystems. One of these subsystems, of course, is the solar-cell array which, in current communication satellites, occupies about 6 percent of the total spacecraft mass. In order to maintain this percentage as the power load is increased, the solar array must become much more mass efficient than those at present; need exists for efficiencies of 60 W/kg (all power levels quoted herein are beginning-of-life values) by 1985 and 200 W/kg by 1990.

In contrast to many other missions, the commercial satellite communication business is already well established. Revenues for private-line traffic reached two billion dollars in 1978 (ref. 2). Continued steady growth is expected, the growth being filled by a proliferation of small ground stations and by a continued reduction in the cost of service. Thus by the end of the century, the predictions are that the annual volume of purchases of spacecraft power systems will be several billions of dollars according to reference 1. If this potential market is going to be serviced from the United States, it is necessary to be

---

*This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by NASA under contract NAS7-100.

able to build solar arrays in the 5- to 50-kW range at a reasonable cost and to deliver 200 W/kg or better.

An array effectiveness of 200 W/kg is three times better than that of the Solar Electric Propulsion System (SEPS) array. Development of this array has proceeded far enough to enable it to represent the present hardware state-of-the-art. The factor of three, therefore, is the gain that needs to be achieved during the next decade.

The SEPS array delivers about 100 W/m^2 of blanket area (including spaces) (see ref. 3). The blanket weighs about 1 kg/m^2 and the supporting structure about one-half this much. Research programs for better arrays over the past few years have quite properly concentrated on the blanket. Not only is it the heaviest part of the system, but it is also the most costly. In addition, array performance is expected to be significantly enhanced by an increase in power density delivered by higher efficiency solar cells.

The push toward better blankets is being led by JPL in the United States and by AEG Telefunken in Europe. Progress to date is typified by the 50-μm-thick silicon solar cell with 14-percent efficiency. This cell was used by General Electric (GE) in their study aimed at 200 W/kg solar arrays. Their blanket delivers about 140 W/m^2 and weighs about 0.4 kg/m^2 (ref. 3). They mount the blanket on a structure that weighs about 0.25 kg/m^2. This design, of course, meets the 1990 requirements. Unfortunately, it is a "paper" design only. Furthermore, the radiation shielding of the solar cells has been deemed to be inadequate for long-time geosynchronous operation.

Work continues on the improvement of solar-cell blankets. For example, TRW has demonstrated a flight-production-capable blanket utilizing the 50-μm cells and including cover glasses with a weight of 0.55 kg/m^2 (ref. 4). Other studies indicate that silicon-cell blankets weighing as little as 0.25 kg/m^2 may exhibit good power efficiency and sufficient resistance to radiation degradation. Gallium arsenide is touted by many as being the material of the future, especially for arrays with concentrating reflectors. And basic research is being directed to more exotic approaches such as multibandgap cells for increased efficiency (see presentation by J. Mullin in ref. 2).

The time has come to improve the structural configurations that will support these blankets. If very lightweight blankets are a realistic expectation, then we should also have very lightweight supporting structures. Otherwise the performance gain from a better blanket will be vitiated by an overly heavy structure.

The influence of structural mass on the array performance is shown in figure 1. Here the ordinate is the ratio of array specific power to the blanket specific power and the abcissa is the ratio of the structural mass to the blanket mass. For mass ratios around one-half (values appropriate to the SEPS and GE rollout array designs) the specific power is around 65 percent of its blanket-only value. On the other hand, if the mass ratio were around one (FRUSA) or two (Hermes array), the resulting specific power would be only 50 percent or 35 percent, respectively, of the blanket-only value.

The consequence of simply substituting lighter blankets on unimproved structures is seen in figure 2. Here the structure-blanket mass ratio is plotted versus the array natural frequency. The curves are based on the parametric results reported in reference 3 for the SEPS fold-out and GE rollout arrays. Those curves labeled $m_{B\ell}$ = 0.940 kg/m^2 and 0.386 kg/m^2 for SEPS and GE respectively, come directly from Pages E-19 and E-144 of reference 3. The masses for the 200 W/kg array have been reduced by excluding the slip ring mass of 3.5 kg which is considered not to be part of the array. Note that the two examples have almost the same blanket area and wing length (~100 m^2 and ~25 m) so that the results are comparable from a structural point of view.

If a lighter blanket is mounted on the same structure, the effect will be to increase the structure-blanket mass ratio and to increase the natural vibration frequency. In figure 2, the frequency values are estimated by assuming that the frequency is proportional to the inverse square root of the blanket mass density. This relationship is particularly valid for situations in which the blanket comprises most of the sprung mass, as is the case for the present examples.

The curves show that decreasing the blanket weight causes a large increase in structure-blanket mass ratio without increasing the natural frequency nearly enough to compensate. The SEPS structure can be termed to be a good one for a blanket density of 0.940 kg/m^2. On the other hand, it is poor if the blanket density is reduced to 0.386 kg/m^2, for which the GE array is designed. It is unacceptable, even for low frequencies, for blankets with the smaller density of 0.250 kg/m^2. The GE array exhibits low structural mass with its design blanket but becomes marginal with a 0.250 kg/m^2 blanket, especially at the higher frequencies. Note that the terms "good," "poor," and "unacceptable" correspond to array-to-blanket efficiency ratios of about 65, 50, and 40 percent, respectively.

Comparison between the two designs should be made with care. The SEPS array, for example, is retractable with some attendant weight penalty. More importantly, the SEPS design has been proven through the engineering model stage and is currently being qualified for Shuttle flight, whereas the GE design is unproven. Nevertheless, the latter design should be more efficient inasmuch as it makes use of the blanket itself as part of its bending stiffness. If this approach can indeed be made to work, the factor of two advantage over the SEPS structure shown on figure 2 would be real.

JUSTIFICATION OF RESEARCH

Further work on advanced very lightweight structural configurations is needed because of the following reasons:

- The SEPS design is unsuitable for light blankets.
- The GE design is marginal for 0.250 kg/m^2 blankets for the higher frequencies.
- Alternative structural arrangements should be investigated.

The last of these reasons is probably the most important. Both present designs support the blanket only at its ends and depend on tension stiffening to control the blanket position. During the last few years, work on space structures has been directed to other arrangements. For example, the use of a truss type of structure proved highly successful as a deployer and support for the synthetic-aperture-radar antenna on Seasat. This structure, shown in figure 3, was designed and built by Astro to meet demanding accuracy requirements. The Europeans have taken a different route in their ULW array design, choosing to simplify packaging and deployment by foregoing a deep structure. These and other configurations should be evaluated for application to the efficient support of very lightweight blankets. The point must be made that the aforementioned multibillion dollar market for solar power systems will involve a large variety of vehicles and missions including dedicated spacecraft and multiuse platforms. The successful array design is the one which will be able to meet the variety of requirements posed by that diverse marketplace.

DESIGN REQUIREMENTS

Since 1977, we have been examining the requirements that govern the design of large space structures. This work is now in the process of being reported to the technical community (see refs. 5 through 10). The work takes full cognizance of the practical problems that must be solved in order to fabricate good flight hardware at a reasonable cost, as described generally in reference 6. For the critical requirements for the present application, the following comments are made.

Design and Fabrication Phase

The solar blanket is an expensive and fragile component. The design and fabrication processes must recognize this by maximizing the modularity and replaceability of the blanket components. The blanket components must be assembled to the structure as late in the fabrication process as possible so as to minimize the amount of handling of these items. In particular, no critical adjustment or bonding procedures should be allowed during or after blanket assembly to the structure.

Full cognizance must be paid to the provisions for the necessary harnesses and instrumentation.

Ground-Test Phase

The array is destined for deployment in geosynchronous orbit. The cost of assuring that this deployment can be done reliably will be reduced greatly if full ground deployment and test is possible without overelaborate gravity compensation fixtures. Reasonable toughness and detail strength is therefore required.

Launch Phase

During launch the main concern is to protect the blanket from damage. Experience has shown that ordinary care in packaging will avoid damage to the structure itself or its actuating mechanisms. The amount of care required for the blanket will depend greatly on its design. The difficulties with cover cracking reported in reference 4 should be noted.

During interorbit transportation the spacecraft will require power. The structural arrangement that allows this power to be supplied without auxiliary units is at an advantage.

Deployment Phase

All steps in the deployment should be fully controlled and capable of being stopped and restarted on command. The deployment rate should be slow enough so that dynamic loadings are inconsequential. Remote repackaging is specifically not a requirement for this application. On the other hand, any degree of automated packaging can be a great convenience in ground testing.

Operational Phase

Loads - During operation, the externally applied loads are small. In fact, figure 4 shows that at GEO the largest environmental load is solar pressure.

Loads induced by altitude controls should also be small. The loads due to station keeping and relocation may be important and should be evaluated.

Larger than any of the above will probably be the internal loads that are required for tension stiffening and pretensioning. These loads are, of course, dependent on the particular configuration chosen. They should be treated as the primary loads to which the structure is designed.

Stiffness - The stiffness required of the structure is a primary condition for the design. It can be characterized by the natural vibration frequencies allowable.

Present large arrays are designed for fairly low frequencies. The relatively small FRUSA array has a flight-measured lowest frequency of 0.25 Hz, and the Hermes array of 0.13 Hz. The larger SEPS and GE arrays are designed for about 0.5 Hz.

The allowable natural vibration frequency is usually chosen as a result of a complex and not completely rational process involving the interaction with the control system design and the desire to minimize residual vibrations due to transient events, such as solar eclipse. For ordinary geosynchronous applications with a usual amount of damping, values around 0.05 Hz are adequate. However, in cases in which very tight pointing accuracy is required or in which vibrational disturbance must be minimized, frequencies of 1 Hz or more are required. This topic is discussed in reference 11, which implies that antennas with very tight beams must be very stiff. If the arrays are not similarly stiff then they must be isolated from each antenna in some, possible expensive, manner. The conclusion is that the application of an array design to a large variety of spacecraft and platform missions would be considerably enhanced if it can deliver a high natural frequency with an attractive weight. Even if high-frequency requirements are irrational, meeting them may be necessary to capture the market. "The customer is always right."

Dimensional Accuracy - The unconcentrated solar-cell array places very modest demands on surface accuracy. Those demands should therefore present only secondary design requirements. Much more important are the internally generated problems. One of these is the spacecraft disturbance that would arise if large distortions occur in the array in passage from sunlight to shadow back to sunlight. These must be minimized. If the structure is designed to provide high stiffness, then these disturbances will be acceptable.

A more basic requirement is that the stiffness of the structure itself must be maintained. If axial-load-carrying members are permitted to curve, then their axial stiffness is reduced. This effect is of particular concern for the slender members composing very lightweight trusses. Also, those elements that are pretensioned must retain their pretension if full stiffness is to be maintained. The same is true of tension-stiffened portions. Inaccuracies in the internal preloading of the structure arises from the errors in fabricating the detail parts from which the structure is assembled. They are worsened by thermal strain, particularly if the structure is composed of materials with widely varying expansion coefficients. Keeping these errors within acceptable limits is a primary requirement for some configurations.

STRUCTURAL CONFIGURATIONS

State of the Art

The structural configurations for deployable arrays fall into two main groups: hinged panels which fold out like an accordion, and flexible blankets which are unrolled or unfolded by one or two separate extendible booms. The first group has so far been the configuration of choice for flight hardware. The FRUSA and Hermes arrays are the only flying representatives of the second group, and both of these flight programs were intended primarily for technology development. The upcoming Shuttle flight of the SEPS array is again technologically, rather than operationally oriented. The first operational use of a flexible-blanket array will be on the Space Telescope vehicle. This, incidentally, is the only such example currently under flight-hardware development. The accordion-folded panel arrays dominate the flight field.

Nevertheless, the flexible blanket approach must eventually prevail if lightweight arrays are to be flown. Of the accordion-folded arrays, only the ULW approach is lightweight; and it is actually a hybrid, utilizing flexible-blanket panels.

Supporting a flexible blanket is a straightforward task. Tension is applied to the edges of the panel which behaves structurally as a membrane. External structure is required to apply the tension and to position the edges properly.

Of course, there are a myriad of detailed problems encountered in an actual design. The SEPS array is an outstanding example of a successful solution to the problems. The structure is light enough for the purpose and is considered to work reliably. All expectations are that the Shuttle flight experiment will uncover only the normal small deficiencies that plague first-article flight programs.

The SEPS structure can be considered to be a sound point of departure for the creation of lighter weight structures. Various directions of improvement are outlined below.

Design Improvements

Partition the Blanket - The amount of tension necessary to stiffen the blanket to the desired amount is inversely proportional to the square of the blanket length. If the blanket were divided into small sections, the tension can be reduced to a very small value. This would essentially eliminate the reduction in bending stiffness caused by the tension. Note, however, that the contribution of the tension to the torsional stiffness would be lost. The boom must supply all that is needed.

Deepen the Structure - In order to increase the stiffness and to reduce the weight, the structure must be deepened. The GE array design goes in this direction. It is limited by the amount that the blankets can be tilted from perpendicularity with the sun's rays.

The structural depth of current designs is limited basically by the deployment devices chosen. Larger boom diameters require much longer and heavier canisters or deployers. One way to increase the depth economically would therefore be to eliminate the deployer and allow the boom to deploy itself. This would have the additional benefit of eliminating the canister weight, only part of which would be used to furnish the mechanisms needed to haul the blanket out on the fully deployed boom. Note that all Astromasts currently flying are of the self-deploying type.

The other approach to deepening the structure is to shift to a different type of structure entirely. For example, the Extendible Support Structure that served so admirably on Seasat can be modified to be suitable for supporting blanket panels. This structure can be made up of any number of bays, each one of which could support a panel of blanket which would be accordion pleated for packaging. Thus the advantages of blanket partitioning could also be realized.

A more advanced concept could be based on the modular column research that Astro has been conducting for the Large Space Structures program. The externally stiffened column described in references 5 and 12 and shown in figure 5 can be converted to a boom in which the only compression-carrying (and thus heavy) elements are the central boom (an Astromast) and the spokes. The boom could be a slender Astromast which would have the sole purpose of supplying the pretension to the external truss structure. Here again, interfacing with the blanket at a number of locations along the length would be possible.

Change the Planform - Flexible-blanket arrays are arranged as high-aspect-ratio wings. Many fold-out panel arrays, on the other hand, utilize the advantages of lower aspect ratio. The FRUSA geometry goes part way in this direction by attaching to each wing at its center, cutting its structural length in half, and multiplying the bending frequency by four. More efficiency is possible by further decrease in the aspect ratio at the expense of increased complexity. One interesting possibility would be to use the tetrahedral-truss type of structure. A modular version, which would require extensive modification to adapt to the present application, is described in reference 3.

PROGRAM DESCRIPTION

Various structural concepts should be created and examined with the aim being to provide stiffness with low weight while observing the necessary practical requirements of integrating with operational spacecraft. The study should consist of three parts.

I. Concept Generation

Array concepts should be generated that meet the following requirements:

1. Package, protect, deploy, and support fragile solar-cell blankets
2. Integrate with a variety of spacecraft and missions
3. Operation at geosynchronous orbit
4. Shuttle launch
5. Make extensive use of modularity
6. Capable of being built with a range of sizes with minimum redesign
7. Be ground testable

II. Concept Evaluation

Parametric analyses should be conducted on the above concepts. The outputs would be the structural geometry and weight required to support arrays with the following characteristics:

1. Array areas from 50 to 200 m^2/wing
2. Blanket densities of 0.4 kg/m^2 and 0.25 kg/m^2
3. Cantilever natural vibration frequencies of 0.05 to 1 Hz

III. Point Design

One concept shall be selected for point design. For a single size, blanket density, and vibration frequency, the array geometry will be determined with enough detail to exhibit the concept's workability. Those parts of the structure that are critical would be defined and their operation demonstrated by analysis or models as appropriate.

REFERENCES

1. Power Technology for Future Synchronous Satellites and Platforms. Space Systems and Technology Advisory Committee. NASA Advisory Council. Minutes of Meeting, 2 and 3 May 1979.
2. Power Technology for Future Synchronous Satellites and Platforms. Space Systems and Technology Advisory Committee. NASA Advisory Council. Minutes of Meeting, 13 and 14 December 1978.
3. Garba, J.A., et al: Parametric Study of Two Planar High Power Flexible Solar Array Concepts. JPL Publication 78-95, 15 December 1978.
4. Mesch, H.G.: Final Report on High-Temperature Low-Mass Solar Blanket. TRW Publication under JPL Contract No. 955139, August 1979.
5. Hedgepeth, J.M.: Required Strength and Stiffness of Large Space Structures. ARC-TN-1050, Astro Research Corporation, 28 October 1977.
6. Hedgepeth, J.M.; Mikulas, M.M.; and MacNeal, R.H.: Practical Design of Low-Cost Large Space Structures. Astronautics & Aeronautics. vol. 16, no. 10, October 1978, pp. 30-34.
7. Hedgepeth, J.M.: Requirements for the Structural Design of Large Antenna Reflectors. Oral Presentation to NASA Langley Research Center, 2 November 1979.
8. Hedgepeth, J.M.; and Miller, R.R.: Effects of Member-Length Imperfections on the Deformations and Loads in an Isogrid-Truss Structure. ARC-R-1012, Astro Research Corporation, 1 April 1980.
9. Hedgepeth, J.M.: Influence of Fabrication Tolerances on the Surface Accuracy of Large Antenna Structures. ARC-R-1013, Astro Research Corporation, 22 April 1980.
10. Hedgepeth, J.M.; Knapp, K.; and Finley, L.A.: Structural Design of Free-Flying Solar-Reflecting Satellites. SAWE Paper No. 1303; Presented to the 38th Annual Conference of the Society of Allied Weight Engineers, Inc., New York, 7-9 May 1979.
11. Fager, J.A.: Large Space Erectable Antenna Stiffness Requirements. J. Spacecraft, vol. 17, no. 2, Article No. 78-590R, March-April 1980.

12. Knapp, K.: Study and Fabrication of a Tension-Wire-Stiffened Column "Expandable Truss Column." ARC-TN-1060, Astro Research Corporation, 25 April 1978.

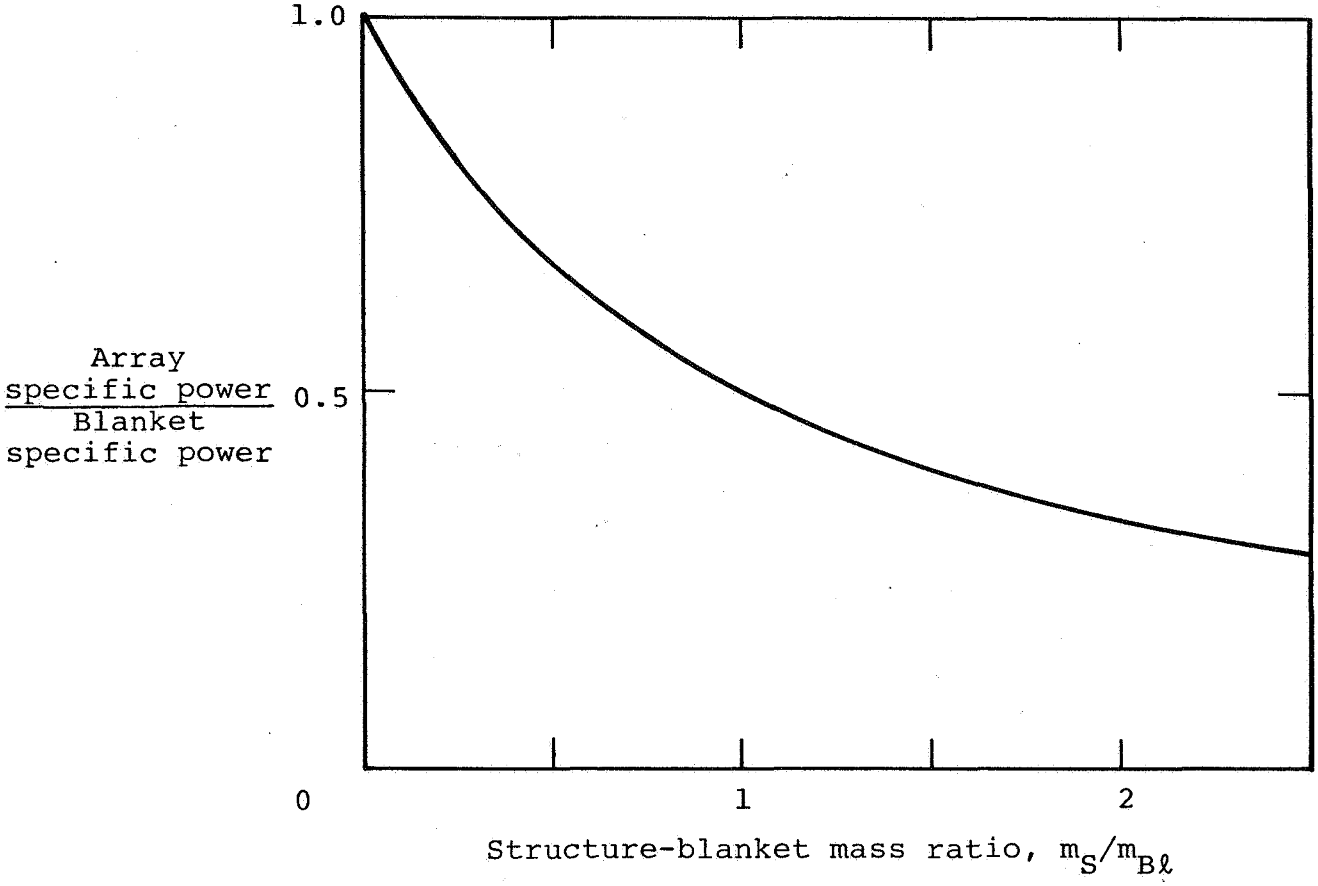

Figure 1. Effect of structural mass on array specific power.

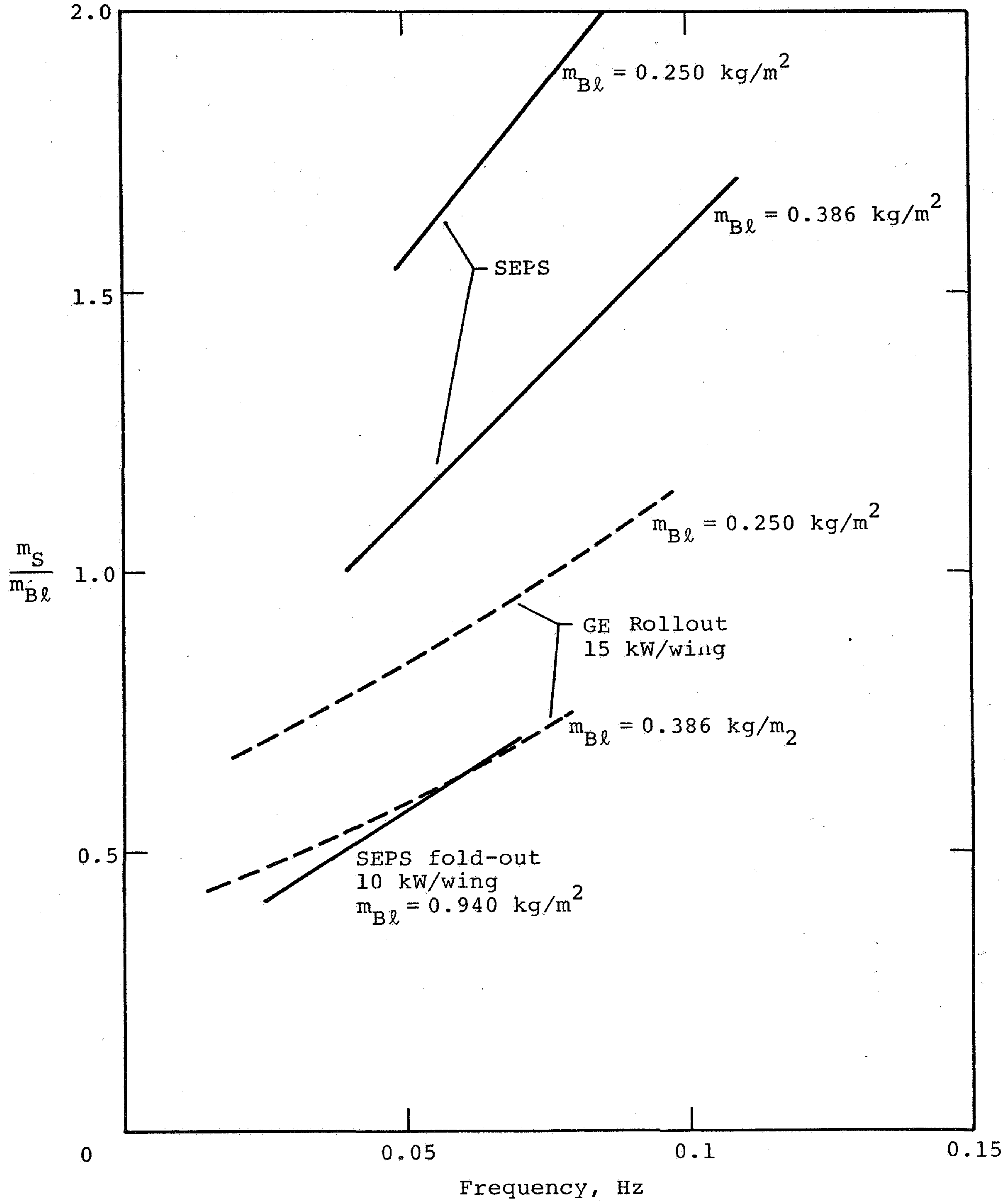

Figure 2. Structural-blanket mass ratio.

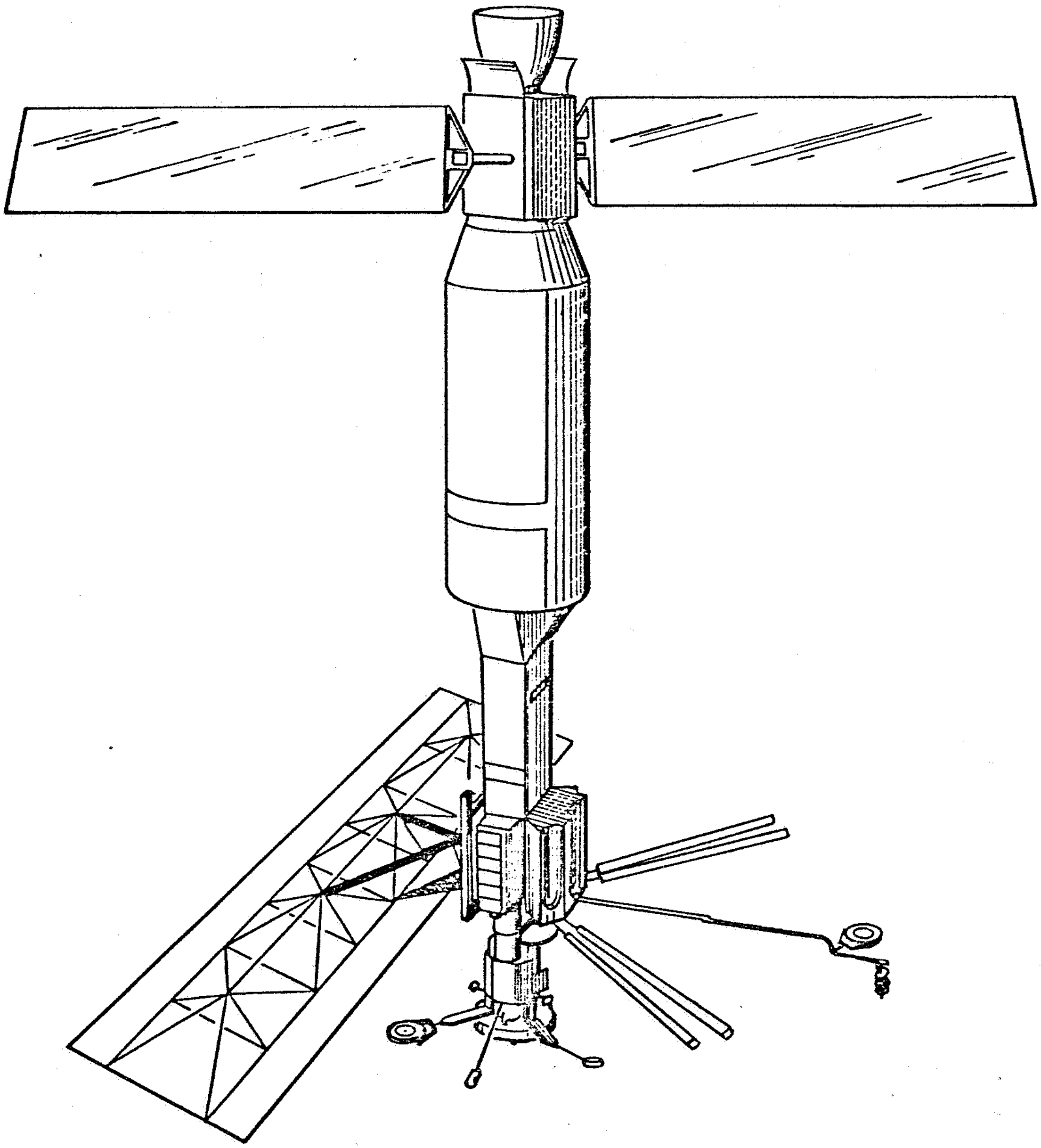

Figure 3. Extendible Support Structure for Seasat synthetic aperture radar antenna.

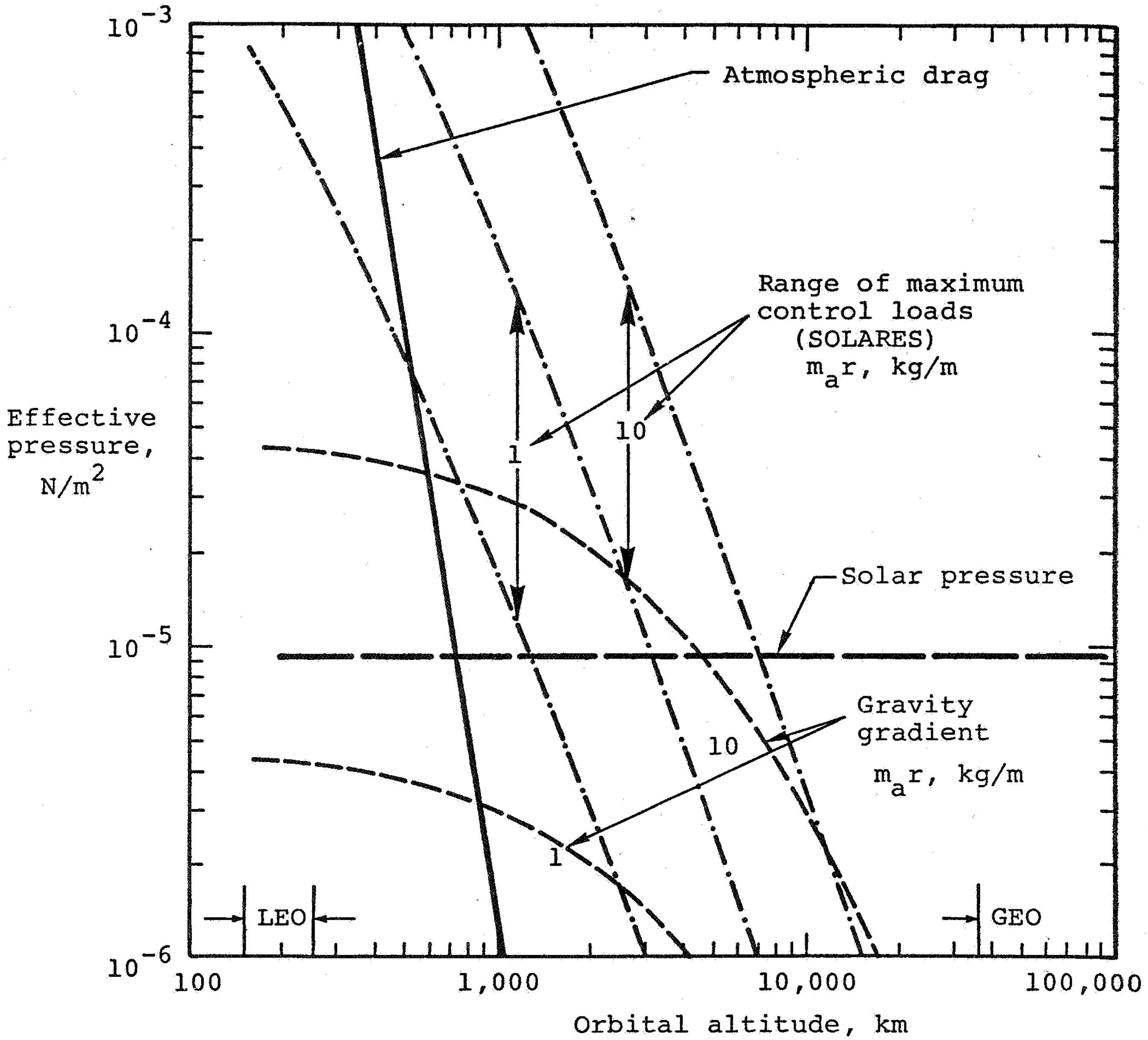

Figure 4. Maximum lateral loads on reflecting films at different orbital altitudes.

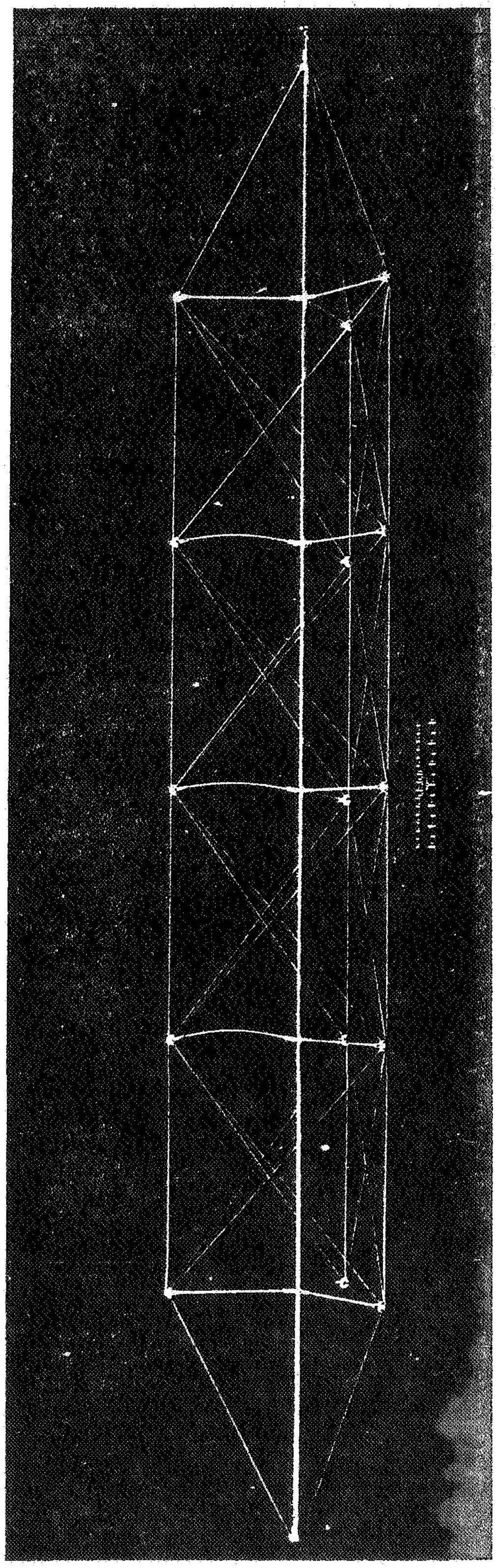

Figure 5. Expandable truss column.