NAS8-36043

DAA/MARSHALL

(NASA-CR-178753) HIGH-PERFORMANCE DEPLOYABLE STRUCTURES FOR THE SUPPORT OF HIGH-CONCENTRATION RATIO SOLAR ARRAY MODULES Final Report (Astro Aerospace Corp.) 79 p HC A05/MF A01 CSCL 13B G3/31

N86-16413

Unclas 04940

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HIGH-PERFORMANCE DEPLOYABLE STRUCTURES FOR THE SUPPORT OF HIGH-CONCENTRATION RATIO SOLAR ARRAY MODULES

by
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FINAL REPORT

AAC-TN-1142

31 October 1985

Prepared for
NASA Marshall Space Flight Center
Under Contract No. NAS8-36043

Prepared by
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SECTION 1
INTRODUCTION

This Final Report summarizes a study conducted by Astro Aerospace Corporation (Astro) for NASA Marshall Space Flight Center (MSFC) on High-Performance Deployable Structures for the support of High-Concentration Ratio Solar Array Modules.

Serious consideration is being given to the use of high-concentration ratio solar array modules for LEO applications such as Space Station. These concentrator solar array designs offer the potential of reduced cost, reduced electrical complexity, higher power per unit area, and improved survivability. Arrays of concentrators, such as the miniaturized Cassegrainian concentrator modules (see Ref. 1), present a serious challenge to the structural design because their mass per unit area (5.7 kg/m^2) is higher than that of flexible solar array blankets, and the requirement for accurate orientation towards the Sun (±0.5 degree) requires structures with improved accuracy potentials. In addition, use on Space Station requires relatively high structural natural frequencies (see Ref. 2) to avoid deleterious interactions with control systems and other large structural components.

The objective of this study is to identify and evaluate conceptual designs of structures suitable for deploying and accurately supporting high-concentration ratio solar array modules.

Section 2 of this report describes the mission selection and design criteria which were used to select the two structural concepts: the Extendible Support Structure (ESS, a synchronously-deploying structure) and the STACBEAM (Stacking Triangular Articulated Compact Beam, a sequentially-deploying mast). Sections 3 through 5 describe the candidate structures, parametric analysis and point design study, respectively. A summary is presented as Section 6.

SECTION 2
MISSION SELECTION/DESIGN CRITERIA

A Space Shuttle launch and the Space Station orbit were selected by MSFC for the baseline environmental requirements.

2.1 HIGH-CONCENTRATION RATIO SOLAR ARRAY

The baseline requirements for the solar array size are:

- A power of 15-kW BOL (Beginning of Life) per wing
- An aspect ratio of 2.46:1 (present Space Station solar array aspect ratio, Ref. 2)

The Cassegrainian and SLATS (Ref. 3) concentrator concepts have been evaluated as high-concentration ratio solar array modules. It was concluded that the requirements for the SLATS concentrator are not as critical as those for the Cassegrainian concentrator. A pointing accuracy of 0.5 degree over the entire array was established as a design requirement.

The Cassegrainian concentrator is capable of generating 160 W/m^2 BOL (current technology, Ref. 1); hence, a solar array with dimensions of 6.2 by 15.25 m is required.

2.2 DEPLOYABLE STRUCTURE

The general requirements for the deployable structure are based on the Space Shuttle launch, the Space Station environment, and the required size and pointing accuracy of the solar array.

The primary load during a Space Shuttle launch is due to random vibration (Ref. 4). The deployable structure in the stowed configuration is compact with its truss elements sitting on top of each other. Also, there will be some type of launch restraint to prevent any unwanted vibration responses. Hence, the launch environment will not be the primary design criteria for deployable structure strengths and stiffnesses. At this point, it is assumed that the deployable structure in the stowed configuration will be mounted to the hard points of the STEP pallet. If the launch of the present Space Station configuration (Ref. 2), however, is considered, the deployable structure in the stowed configuration will be mounted to the stowed transverse boom of Space Station inside the Space Shuttle. In that case, the required dimension of the deployable structure in the stowed configuration, including the deployer, will be a design driver, due to the available space inside the Space Shuttle.

For Space Station environments, the deployed structure will be mounted to Space Station as a solar array mast. The following load conditions were considered (see Ref. 2):

- o Gravity-gradient torques
- o Aerodynamic drag and torques (at 200 nmi)
- o Docking/berthing
- o Crew motion
- o RCS reboost firing

The acceleration due to RCS reboost firing will generate the highest bending moment (452 ft-lb) on the deployed structure (see Ref. 2) and was chosen as a primary requirement, with a safety factor of 5, to establish the required bending strength of the deployed structure. The fundamental vibrational natural frequency of the solar array mast given in Ref. 2 is about 0.16 Hz. Note that the computed natural frequency in Ref. 2 decreases to about 0.11 Hz if the solar array mast is attached to a tensioning-type solar array. The required pointing accuracy for the deployed structure is 0.5 degree (see Ref. 1). The deployable structure baseline requirements are given in Table 1.

TABLE 1. DEPLOYABLE STRUCTURE BASELINE REQUIREMENTS.

	Minimum Requirement	Design Goal
Length, m (ft)	15.25 (50)	15.25 (50)
Bending strength, m-N (ft-lb)	614 (452)	3068 (2260)
Fundamental vibrational natural frequency, Hz	0.11	0.16
Pointing accuracy, degrees	0.5	0.5

SECTION 3
CANDIDATE STRUCTURES

The Extendible Support Structure (ESS, a synchronously-deploying structure) and the STACBEAM (Stacking Triangular Articulated Compact Beam, a sequentially-deploying mast) truss structures have been considered for deploying and supporting high-concentration ratio solar array modules.

The primary reason for selecting the above structures is that their deployments are translational and they do not rotate about their longitudinal axes during the deployment or retraction. Hence, the solar array can be attached directly to the structure at each bay, both in stowed and deployed conditions.

In order to consider the merits of each in an unbiased manner, certain ground rules have been established.

3.1 STIFFNESS

It has been assumed that the solar array panels (solid panels) do not contribute to the overall stiffness of the support structure. Therefore, changes in solar array panel design have little effect on the structural behavior.

3.2 SMALL RELATIVE MASS

The mass of the solar array and its structure is small in comparison to the total spacecraft mass. Therefore, the cantilever vibration frequency approximates the lowest frequency mode.

3.3 ATTACHMENT OF SOLAR ARRAY TO THE STRUCTURE

The solar array will be attached to its support structure along its width at the two nodal points of the array's first vibrational free-free mode. Therefore, the solar array local natural frequency along its width would be maximum.

Hence, the ratio of the structure width w to solar array width b should be about 0.56.

SECTION 4
PARAMETRIC ANALYSIS AND SELECTION OF STRUCTURE

4.1 EXTENDIBLE SUPPORT STRUCTURE CONCEPT

The Extendible Support Structure (ESS) concept, originally developed by Astro Aerospace Corporation (Astro) to support the synthetic aperture radar antenna, was flown on the Seasat spacecraft. The ESS concept for deployment and support of a solar array panel is shown in Figures 1 and 2. The structure is of width w, depth h, and bay length ℓ. It is composed of truss members of diameter d and wall thickness t. For the Seasat applications, rigid solar panels were an integral part of the structure in both the packaged and deployed state and the same principle is applied for this case.

4.1.1 Structural Properties

4.1.1.1 DIMENSIONS

The minimum required length L of the structure is given in Table 1. The bay length ℓ of the structure depends on the number of solar array panels n (or number of bays) and is

$$\ell = \frac{L}{n} \tag{1}$$

The width of the structure w is obtained from Section 3.3 as

$$w = 0.56b \tag{2}$$

The structure depth h can vary and will be selected on the dimensional requirements of the stowed structure.

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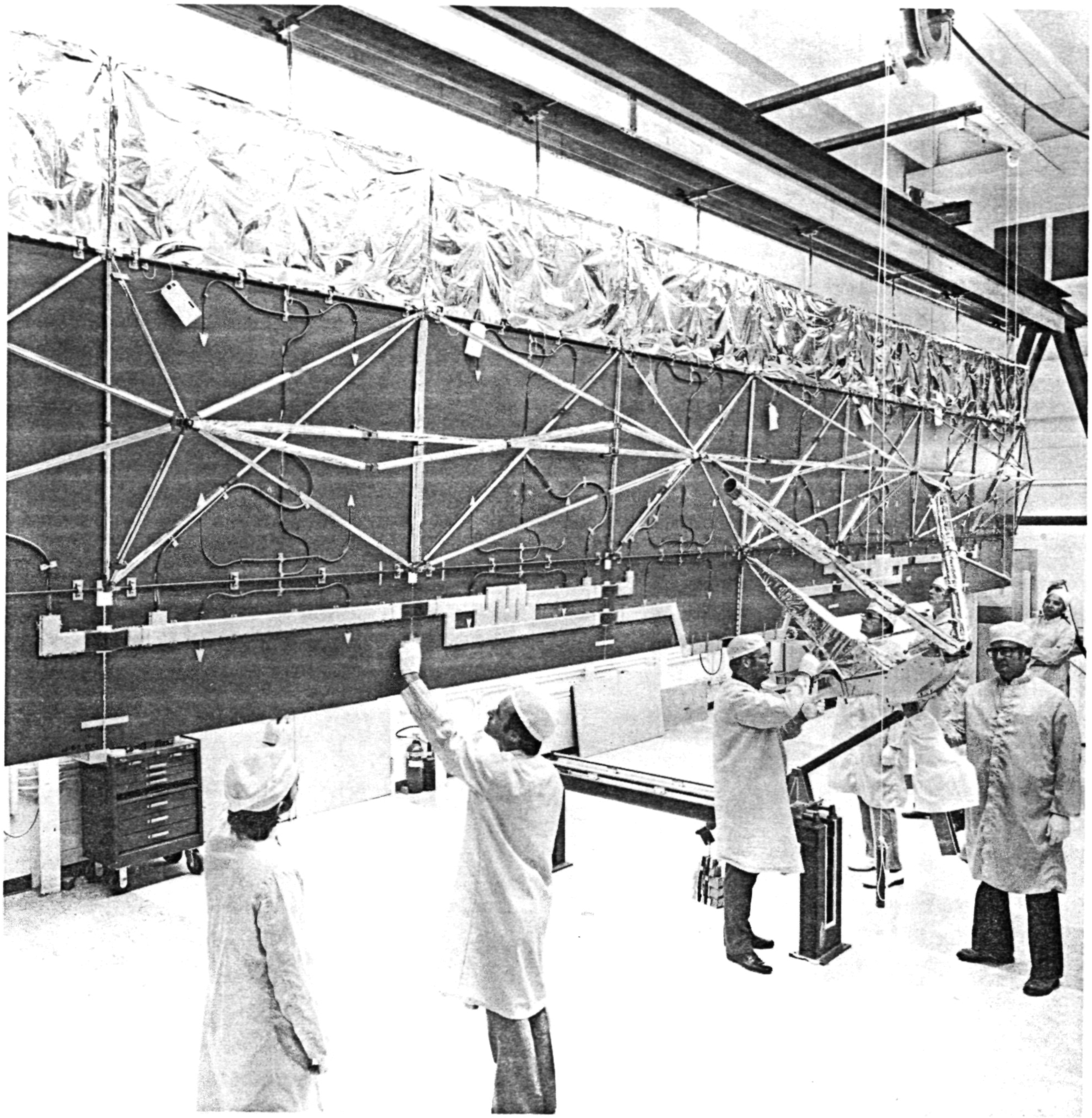


Figure 1. Extendible Support Structure (ESS) supporting Seasat SAR.

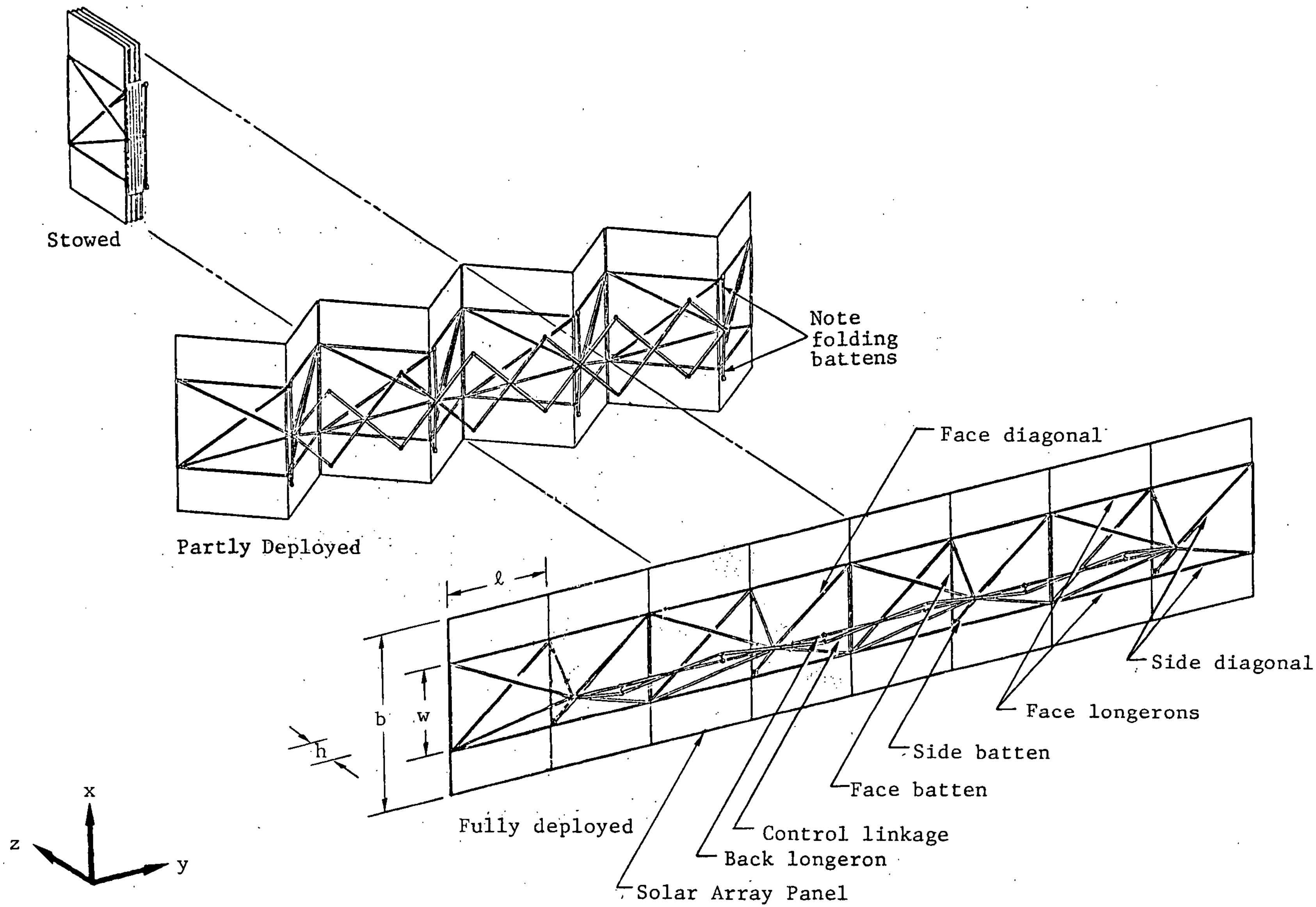


Figure 2. Extendible Support Structure (ESS) concept.

4.1.1.2 MASS

The mass of the ESS system includes the masses of its truss members and joints and the solar array payload itself, or

$$M_s = M_t + M_j + M_a \tag{3}$$

4.1.1.2.1 Mass of Truss Members

The mass of the truss members is determined by multiplying the linear density by the structure length, or

$$M_t = m_t L \tag{4}$$

The structure consists of longerons, face and side diagonals, and face and side battens so that

$$\begin{aligned} m_t &= m_\ell + m_{fd} + m_{sd} + m_{fb} + m_{sb} \\ &= 4\rho A_\ell + \rho A_{fd}\sqrt{1 + \left(\frac{w}{\ell}\right)^2} + 2\sqrt{1 + \left(\frac{w}{2\ell}\right)^2 + \left(\frac{h}{\ell}\right)^2}\left(\rho A_{sd}\right) \\ &\quad + \frac{w}{\ell}\rho A_{fb} + \rho A_{sb}\sqrt{\left(\frac{w}{2\ell}\right)^2 + \left(\frac{h}{\ell}\right)^2} \end{aligned} \tag{5}$$

where ρ is the material bulk density, and A is the truss member cross-sectional area.

4.1.1.2.2 Mass of Joints

The joint mass is expressed as a function of tube mass by

$$k \equiv \frac{M_j}{M_t} + 1$$

The joint factor k, multiplied by the truss member mass, gives the structure mass M_{st} and is estimated by investigating the Seasat ESS assembly. The joint mass in the ESS for Seasat was 8 kg, over a length of 10.7 m, so that

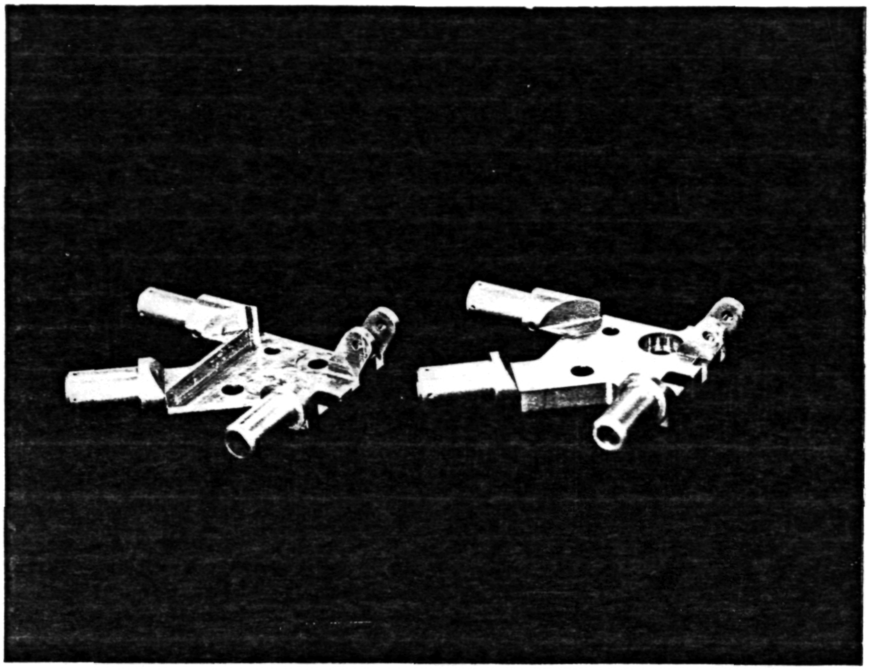
$$m_j' \text{ Seasat} = 0.75 \text{ kg/m}$$

The truss member diameter was 0.0127 m with a 0.00075-m wall thickness. The graphite tube mass per length is determined to be 0.40 kg/m. Therefore, for Seasat,

$$k = 2.88$$

This joint factor, obtained for an assembly having comparatively high wall thickness, should be greater for joints connecting thinner wall tubing. Efforts directed toward decreasing the Seasat joint weight (see Figure 3) have succeeded in lowering the factor. Projecting from these results, the following joint factors are assumed:

Truss Member Wall Thickness, t (mm)	Joint Factor k
1.00	1.6
0.75	1.9
0.50	2.2



Object on right: Joint J2-1 used on Seasat ESS structure. Mass: 92 gm.

Object on left: Joint J2-1 lightened as follows: Web reduced from 0.30 to 0.08 inch; hole diameter increased from 0.25 to 0.30 inch. Mass: 46 gm. Reduction: 50 percent.

Figure 3. Joint mass reduction.

4.1.1.2.3 Mass of Solar Array Panels

The mass of the solar array panels M_a is

$$M_a = m_a' A_a$$

$$= m_a' bL \tag{6}$$

where m_a' and A_a are the area density and the area of the solar array panels, respectively.

$m_a' = 5.7\ kg/m^2$ (see Ref. 1)

4.1.1.3 TRUSS MEMBER SIZE

The truss member sizes are based on both the minimum bending strength and natural frequency requirements presented in Table 1. At first, the truss member sizes are calculated to satisfy the bending requirement. Then the natural frequencies are calculated based on the computed dimensions from the bending requirements. If the computed natural frequency satisfies the requirements, then the calculation is complete. Otherwise, the order of calculation should be reversed and the truss member size should be based on the natural frequency requirement.

4.1.1.3.1 Bending Strength

The bending moment M is reacted by axial load P in the longeron

$$P = \frac{M}{h} \tag{7}$$

The axial load in the longeron should be less than its buckling load P_{cr}

$$P_{cr} = \pi^2 \frac{(EI)_\ell}{\ell_\ell^2} \tag{8}$$

where $(EI)_\ell$ is the bending stiffness of the longeron

$$(EI)_\ell = E \frac{\pi}{8} d^3 t \tag{9}$$

Substitution of Eqs. (8) and (9) into Eq. (7) results in

$$d = \left(\frac{8 \ell_\ell^2 M}{\pi^3 E t h} \right)^{\frac{1}{3}} \tag{10}$$

Note that the length of the back longeron ℓ_ℓ is two times the bay length.

4.1.1.3.2 Natural Frequencies

Bending Natural Frequency

The fundamental bending natural frequency f_b of the ESS system with cantilever boundary condition is given by

$$f_b = \frac{3.52}{2\pi} \left(\frac{EI}{M_s L^3} \right)^{\frac{1}{2}} \tag{11}$$

where the structure bending stiffness EI is given by

$$EI = \frac{2}{3} h^2 (EA)_\ell \tag{12}$$

$(EA)_\ell$ = the axial stiffness of longerons.

Torsional Natural Frequency

The fundamental torsional natural frequency f_t of the system with cantilever boundary condition is given by

$$f_t = \frac{1.57}{2\pi} \left(\frac{Gk}{J_s L} \right)^{\frac{1}{2}} \tag{13}$$

where Gk is the structure torsional stiffness and is given by (Reference 5)

$$Gk = \frac{w^2h^2}{\ell^2} \left(1 + 2 \frac{\ell^3_{sd}}{\ell^3} \frac{(EA)_\ell}{(EA)_{sd}} + \frac{\ell^3_{fd}}{\ell^3} \frac{(EA)_\ell}{(EA)_{fd}} + \frac{w^3}{\ell^3} \frac{(EA)_\ell}{(EA)_{fb}} \right)^{-1} (EA)_\ell \tag{14}$$

The mass moment of inertia J_s is the sum of structure and solar array mass moment of inertia.

$$J_s = J_{st} + J_a \tag{15}$$

Assuming that all of the structure joints are located along the longerons, then the structure mass moment of inertia is given by the following approximation

$$J_{st} = \left(2\rho A_\ell L + \frac{k-1}{2} M_t\right) \left(\frac{5}{9} h^2 + \frac{w^2}{4}\right) + (M_t - 4\rho A_\ell L) \left(\frac{w^2}{12} + \frac{h^2}{9}\right) \tag{16}$$

The mass moment of inertia of the solar array is given by

$$J_a = M_a \left(\frac{t_a^2 + b^2}{12} + \frac{h^2}{9}\right) \tag{17}$$

where t_a is the solar array panel thickness.

4.1.2 <u>Acceleration Capability</u>

4.1.2.1 DEPLOYED STRUCTURE

For a structure (beam), the limits on the acceleration are generally governed by the bending strength M of the structure; however, if the pointing accuracy is a requirement, then the limits on the acceleration are determined by the maximum response slope of the structure. The latter one usually refers to the accelerations during the normal operation. The translational and rotational accelerations for a structure with cantilever boundary condition are given as follows.

4.1.2.1.1. Translational Acceleration

The maximum acceptable translational acceleration a_a is

$$a_a = \frac{2M}{M_s L} \qquad (18)$$

and the maximum translational acceleration a_o during the operation is

$$a_o = \frac{6EI\theta}{M_s L^2} \qquad (19)$$

where θ is the maximum slope (pointing accuracy) of the structure.

4.1.2.1.2 Rotational Acceleration

The maximum acceptable rotational acceleration α_a is

$$\alpha_a = \frac{3M}{M_s L^2} \qquad (20)$$

and the maximum rotational acceleration α_o during the operation is

$$\alpha_o = \frac{8EI\theta}{M_s L^3} \qquad (21)$$

4.1.2.2 PARTIALLY DEPLOYED

The structural capability of the ESS structure during the deployment has not been determined by analysis. From past experience (Seasat project), however, the ESS structure alone can be deployed under 1 g load without any antigravity compensation when the load is acting along the X axis (see Figure 2). As a conservative assumption, 0.2 g is taken as the limiting acceleration capability of the ESS structure during deployments. Thus, the limiting acceleration capability of the ESS system during the deployent is given by

$$a_d = \frac{(0.2 \times 9.81)\, M_{st}}{M_s}$$

4.1.3 Dimensions of Stowed Configuration

The ESS system dimensions in the stowed configuration along three axes are given below (see Figure 2).

Axis	Dimensions
X	b
Y	$n\ (t_a + d)$
Z	$\sqrt{h^2 + \ell^2}$

4.1.4 Deployment/Retraction Mechanism

The ESS deployment mechanism consists of latching clamps which hold the packaged assembly rigidly together. Upon release of these clamps, the assembly is free to expand and does so in a controlled fashion by motorized extension of the rear scissors longeron (see Figures 4 and 5). There are three clamps, one for each stack of hinges, which make a direct load path to the spacecraft. Such an assembly is expected to have a mass approximately equal to the joint mass.

The retraction is made possible by retracting the rear scissors longeron. Note that at the start of retraction, the side battens should be buckled. The buckling of the side battens is done by the use of a synchronized joint which controls the motion of side battens with the motion of the rear scissors longeron.

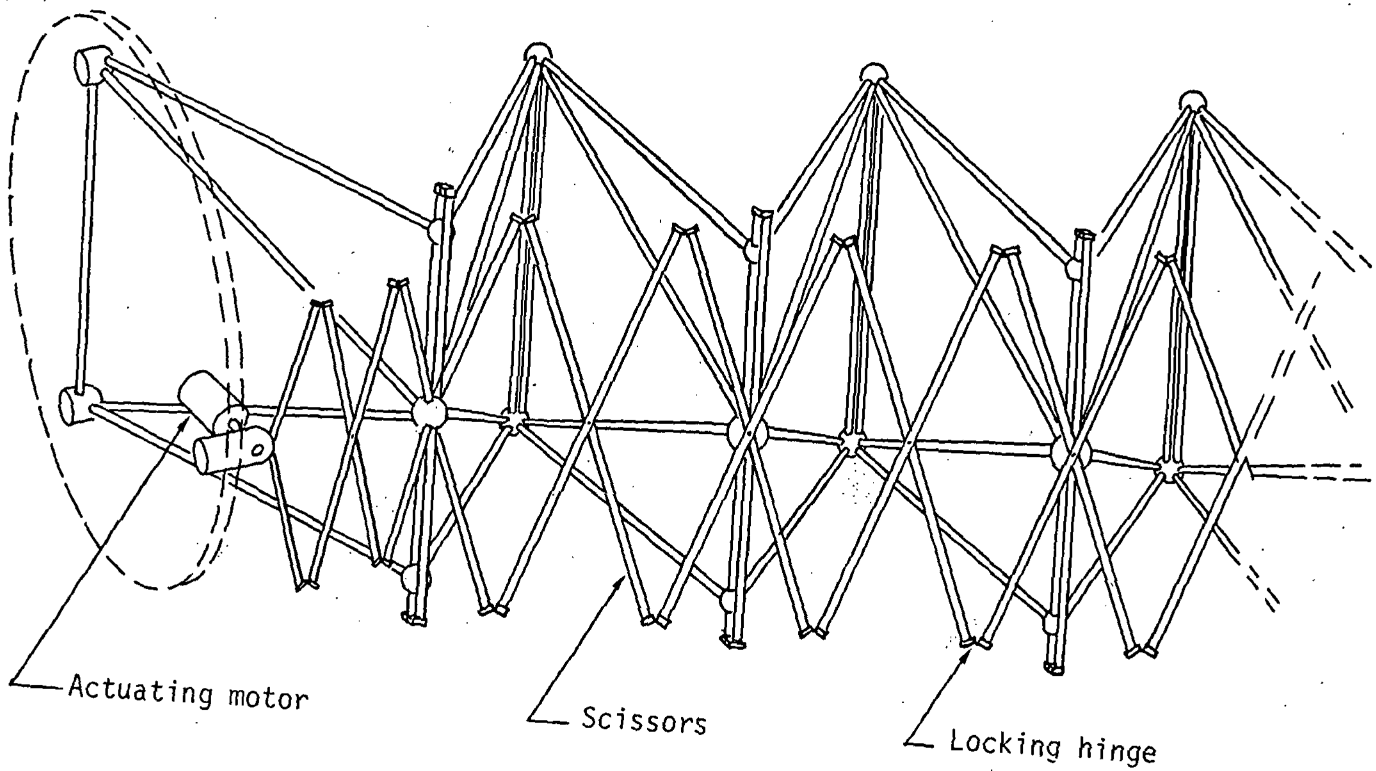


Figure 4. Deploying ESS.

85-L117

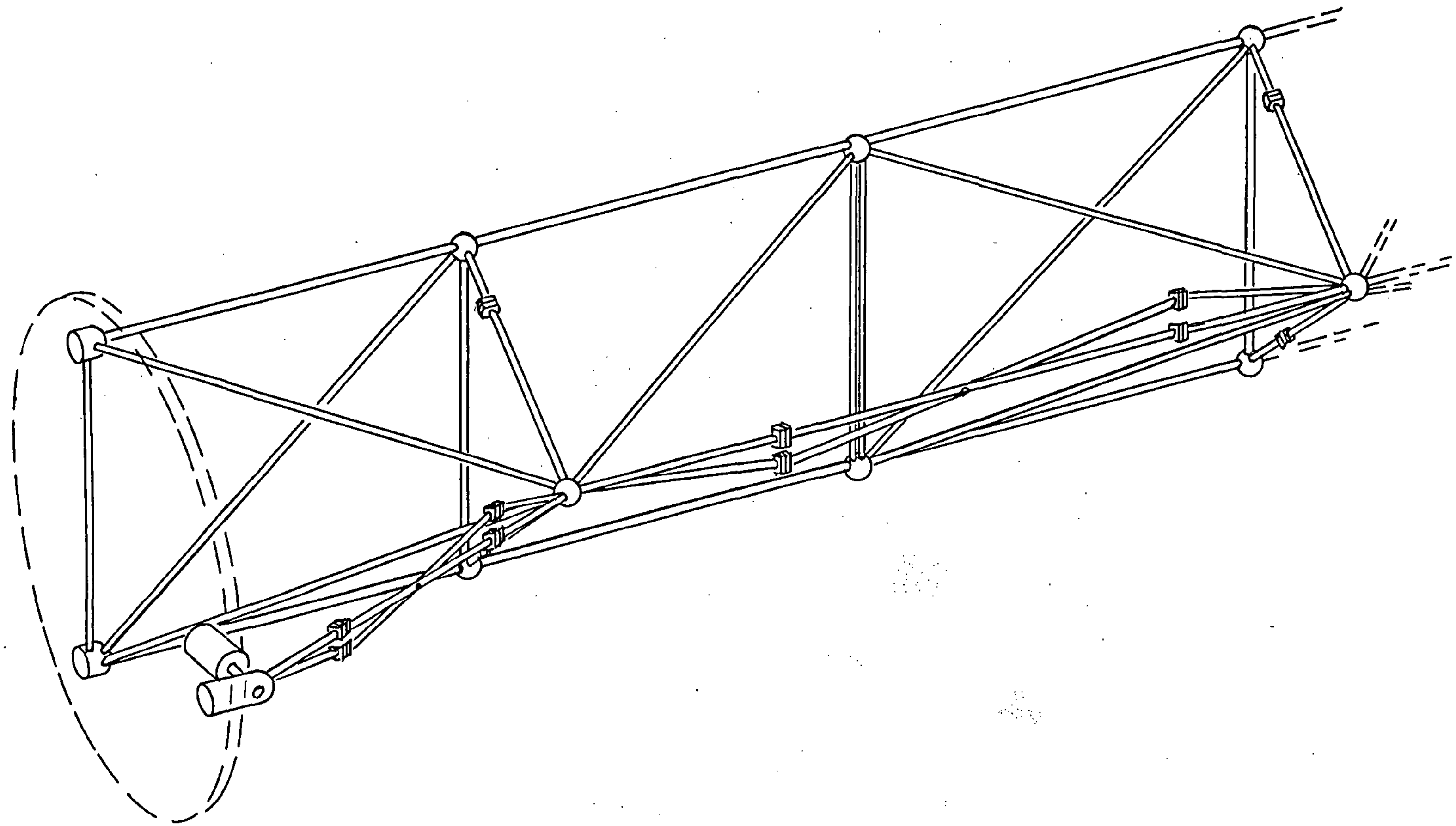


Figure 5. Deployed ESS.

85-L116

4.1.5 Results

For the baseline design, an eight-panel solar array is selected. In addition, the following physical data were used in the analysis:

$n = 8$
$L = 15.25$ m
$b = 6.2$ m
$M = 3068$ Nm
$E = 2.75 \times 10^{11}$ N/m^2 "VHM graphite/epoxy"
$\rho = 1520$ kg/m^3 "VHM graphite/epoxy"
$t = 1$ mm
$t_a = 15$ mm
$A_\ell = A_{fd} = A_{sd} = A_{fb} = A_{sb}$

Substitution of the above data into Eqs. (1), (2), and (6) results in

$\ell = 1.91$ m
$w = 3.472$ m
$M_a = 539$ kg

Equation (10) is solved for several structural depths h and results are presented in Figure 6. Note that $h = 3.006$ m corresponds to a structure with equilateral cross-section. Also, the plot of structure mass M_{st} versus the structure depth is presented in Figure 7. Note that the deployer mass is estimated by the joint mass or

$$\text{Mass of Deployer} = M_{st} \left(1 - \frac{1}{k}\right)$$

The above results were used to calculate the natural frequencies and ESS system stowed dimensions. The results are given in Figures 8 and 9. The resulting natural frequencies are above the required values; thus, the design drive for the truss members cross section is the bending strength requirement.

For the baseline, a structure with the depth of 1 m is selected which satisfies not only STEP available space but also it satisfies the present space station in stowed configuration (see Figures 10, 11, and 12). Its properties are given in Table 2.

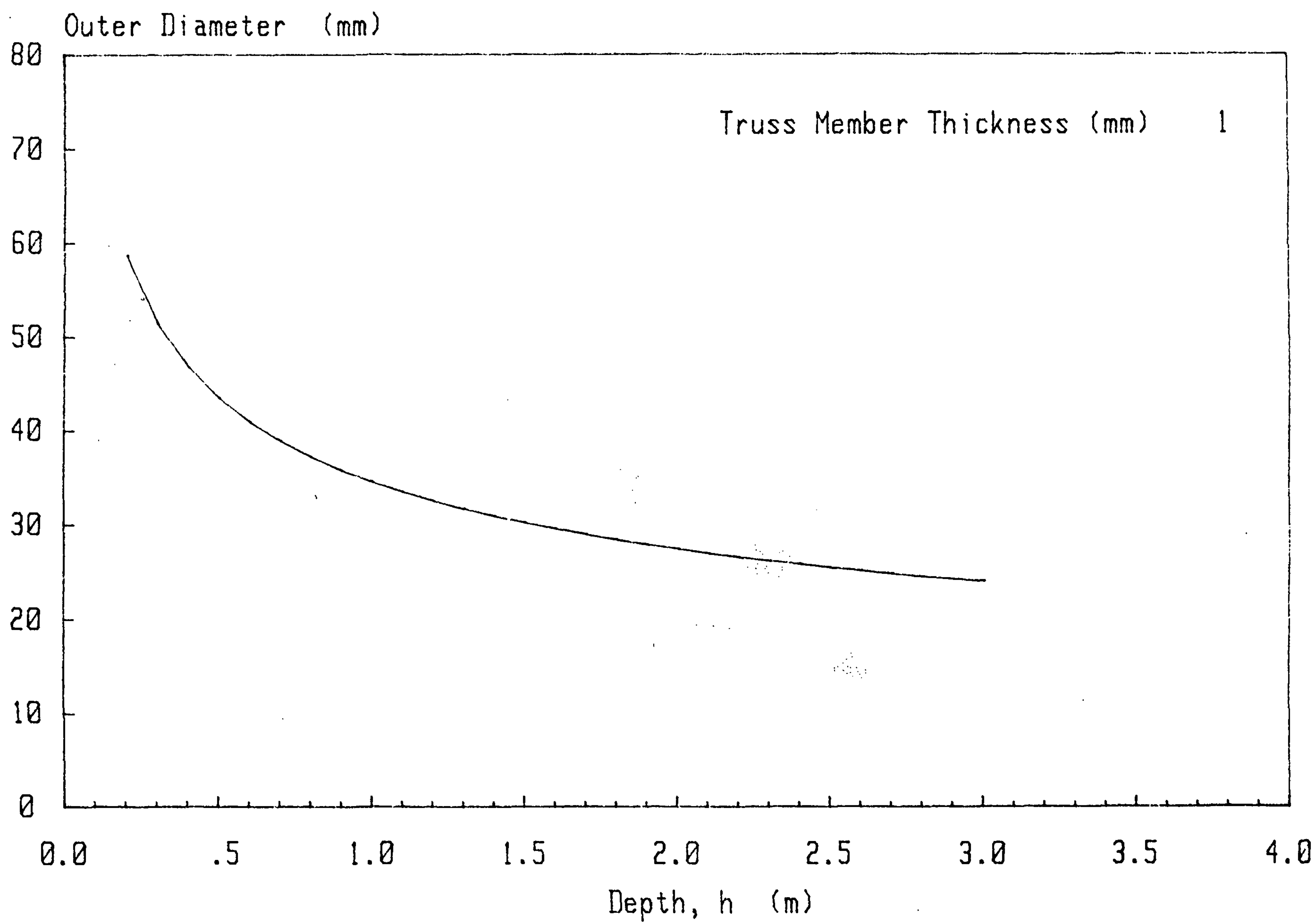


Figure 6. ESS truss member outside diameter.

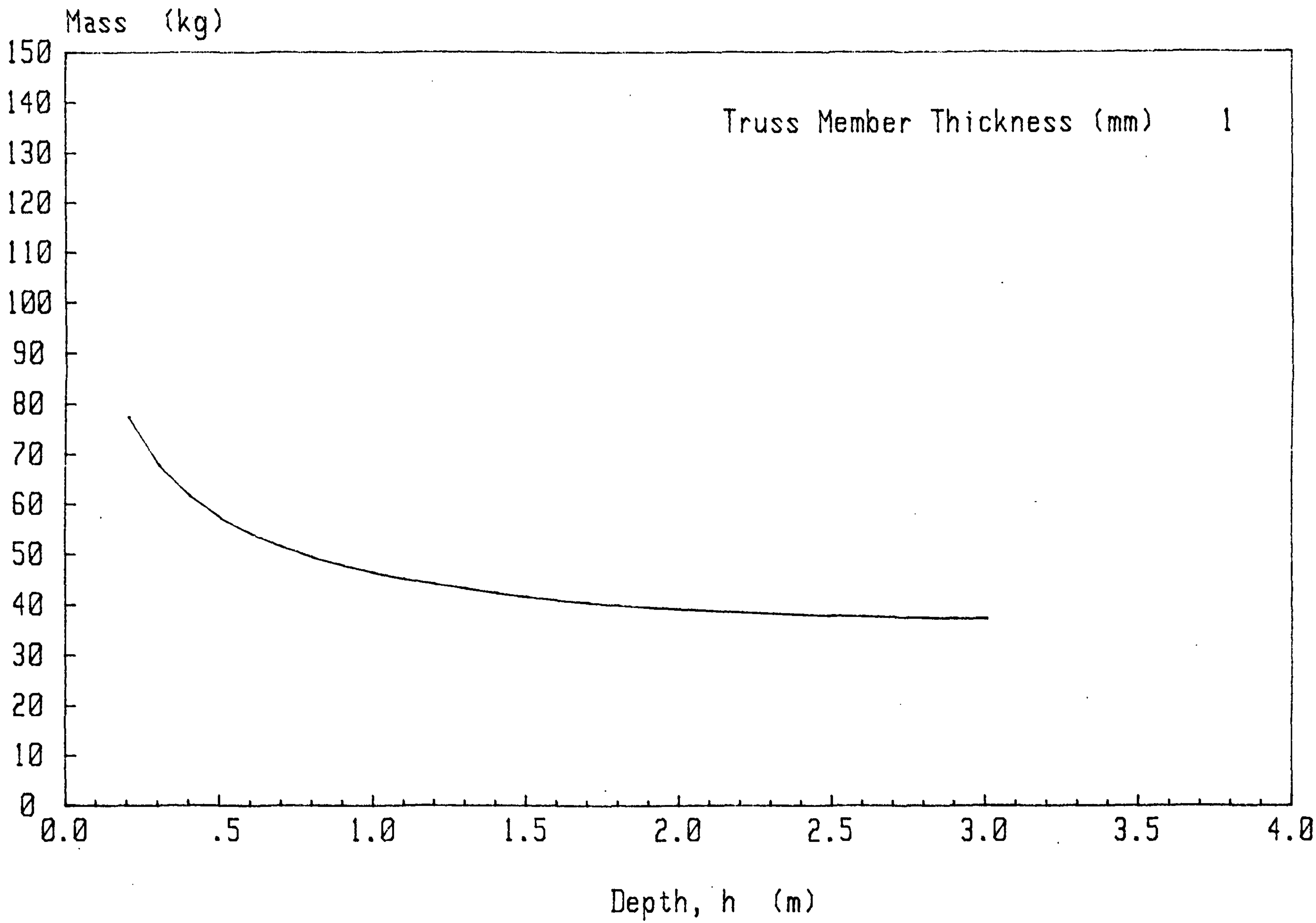


Figure 7. ESS mass.

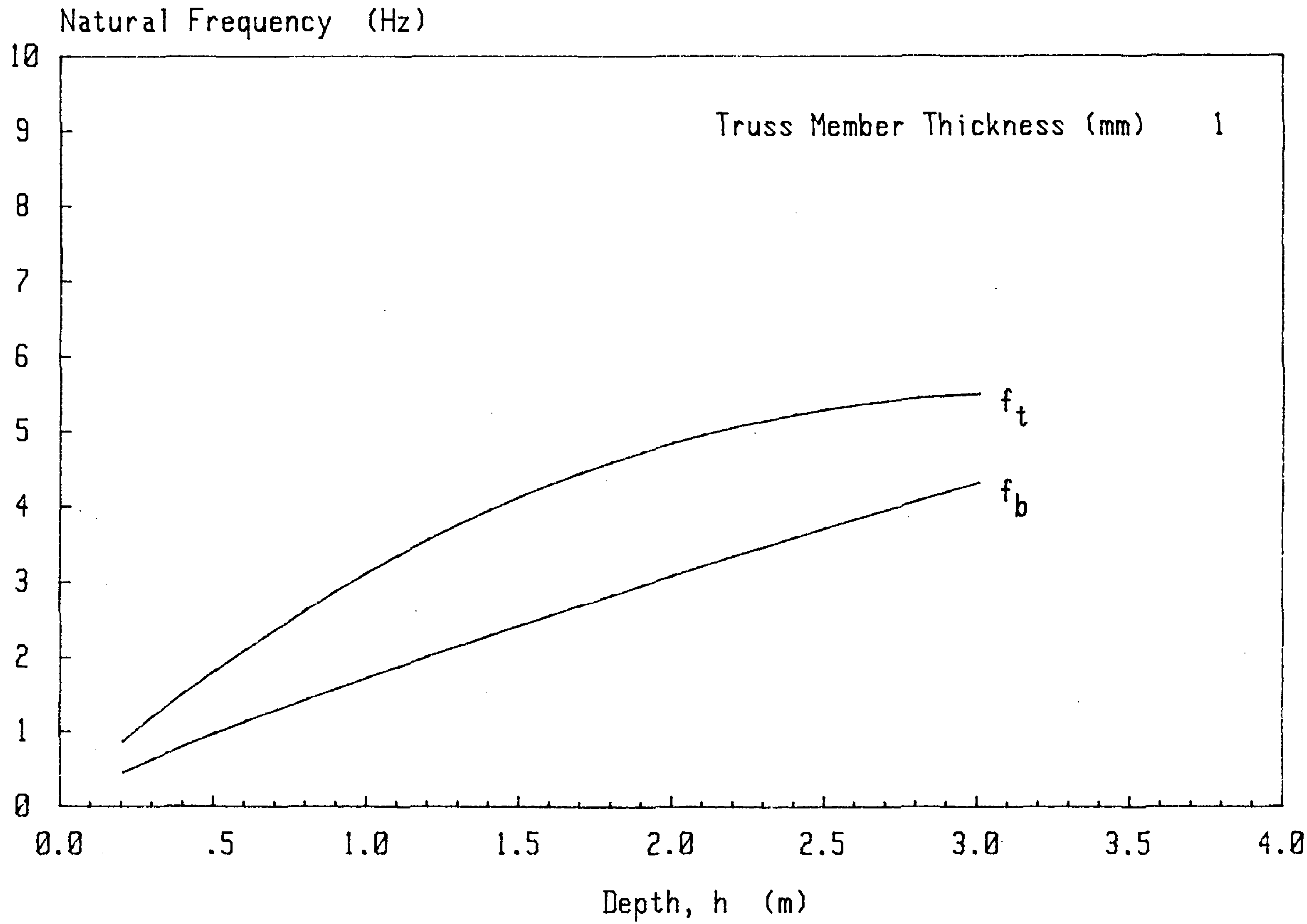


Figure 8. ESS system natural frequencies.

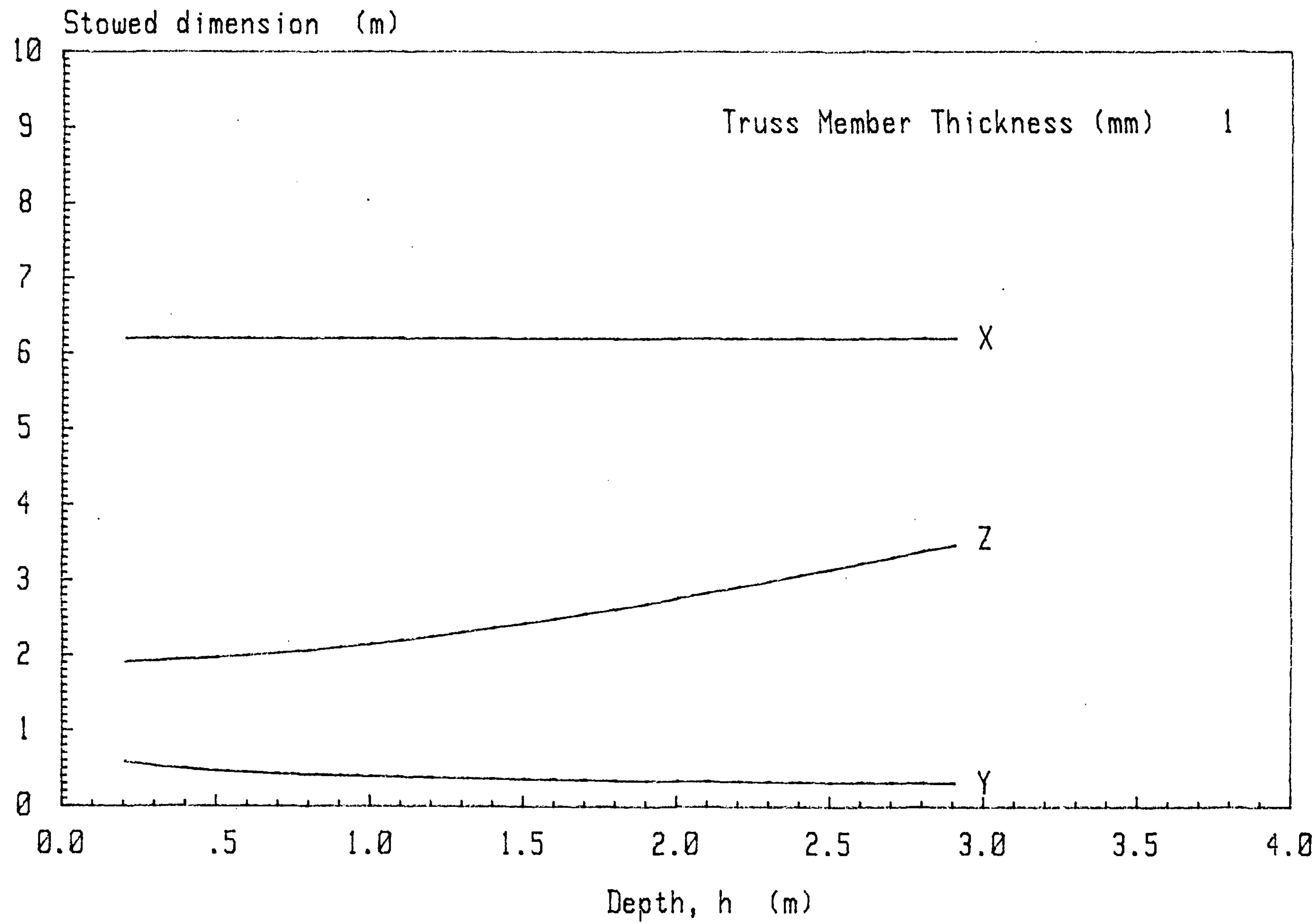


Figure 9. ESS system stowed dimensions.

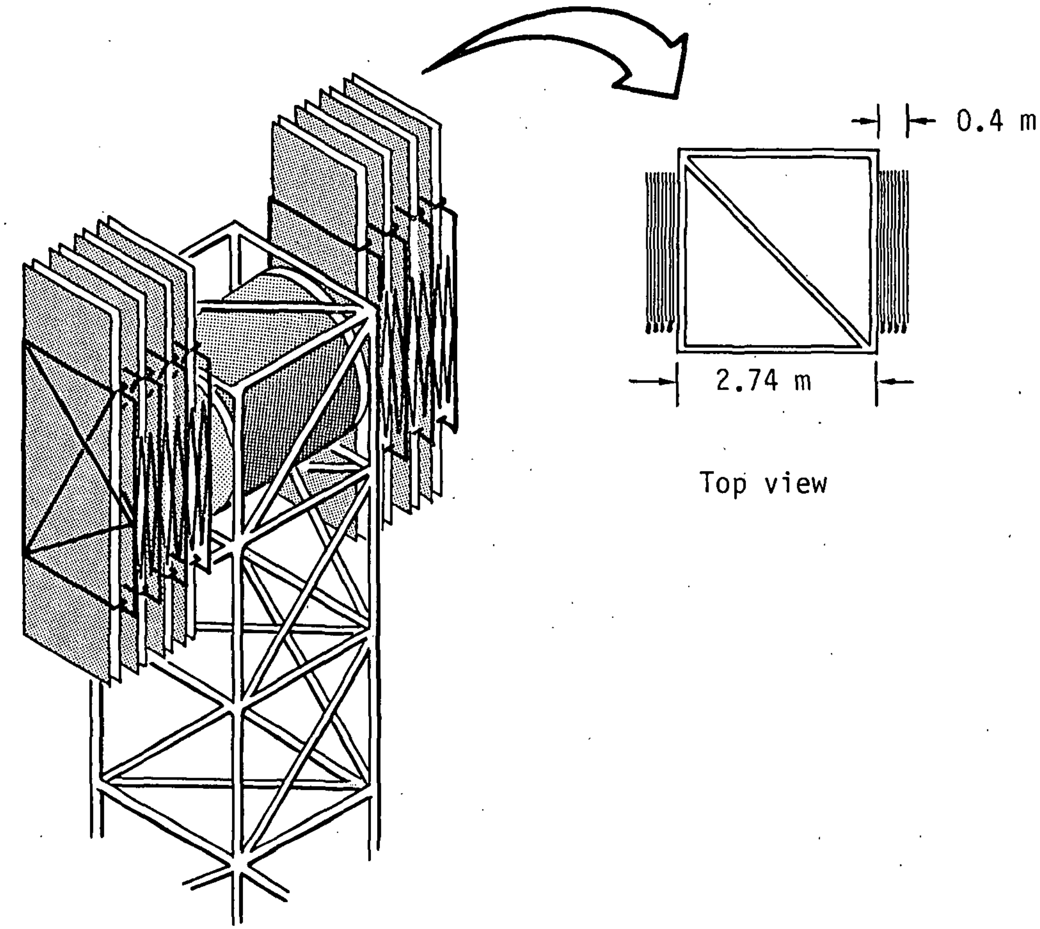


Figure 10. ESS system attached to Space Station, stowed configuration. 85-L112

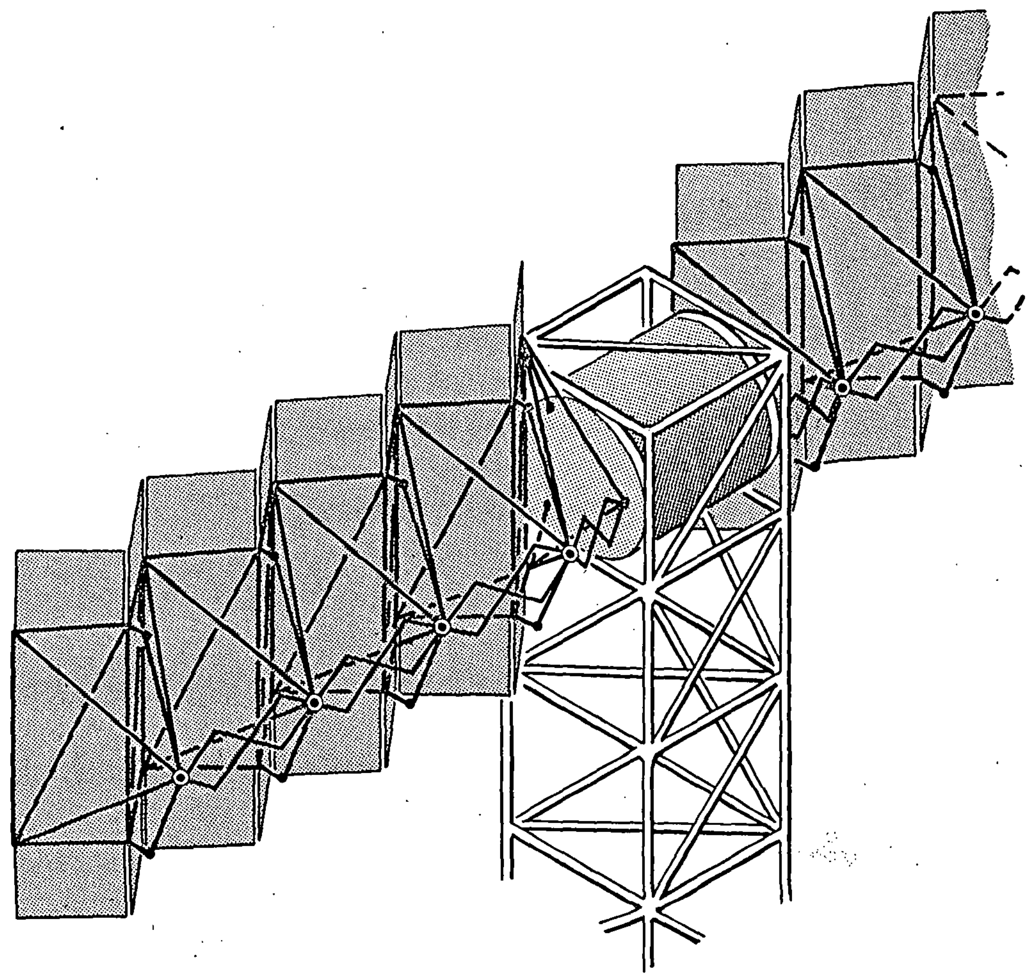


Figure 11. ESS system attached to Space Station, partially deployed.

85-L111

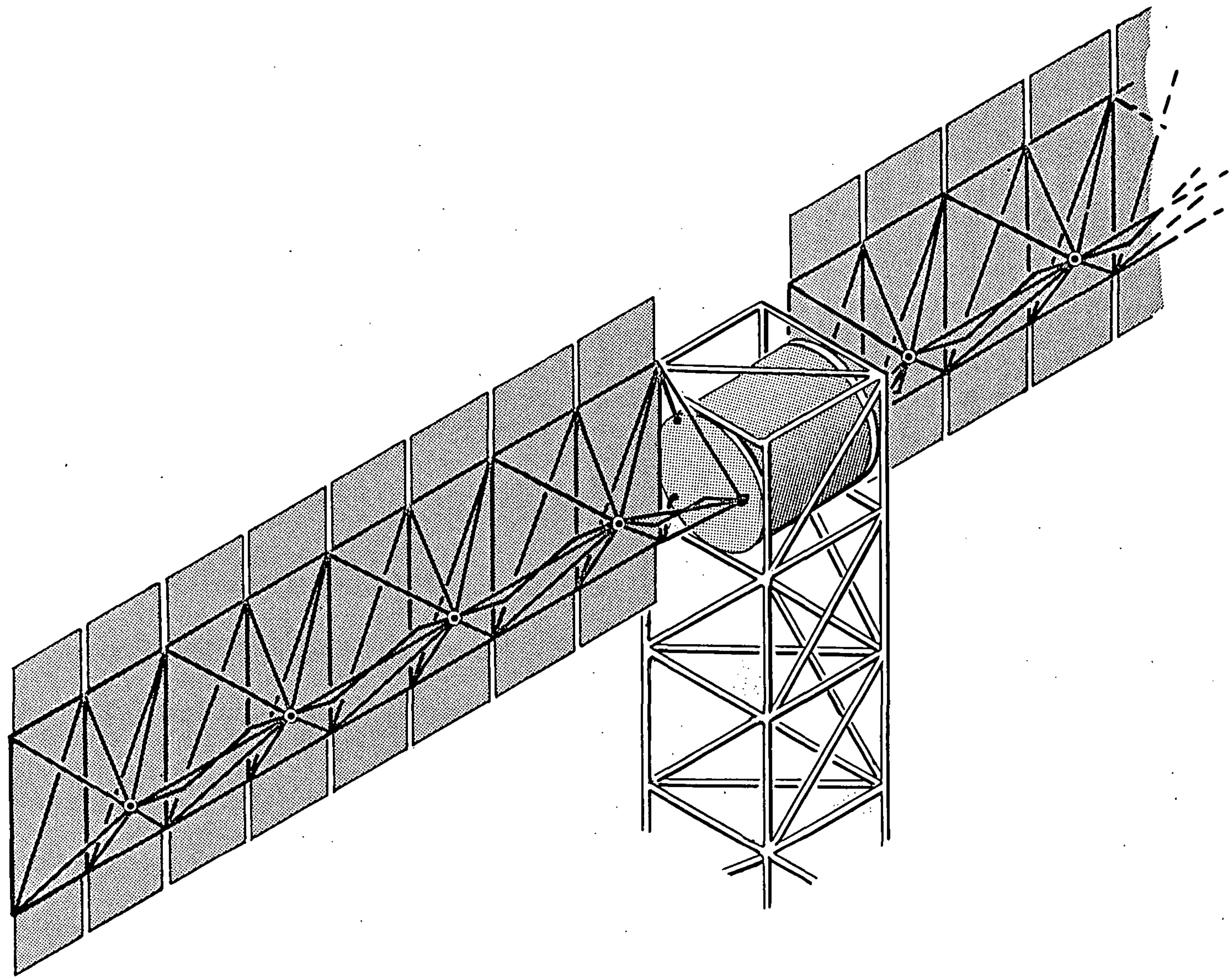


Figure 12. ESS system attached to Space Station, deployed configuration. 85-L110.

TABLE 2. ESS BASELINE DESIGN.

Bay number, n	8
Length, (m)	15.25
Width, (m)	3.472
Depth, (m)	1
Bay length, (m)	1.91
Truss member diameter, (mm)	34.6
Truss member thickness, (mm)	1
Mass (kg)	46.4
Mass moment of inertia ($kg\text{-}m^2$)	69
Bending stiffness, ($N\text{-}m^2$)	1.94×10^7
Torsional stiffness, ($N\text{-}m^2$)	4.36×10^6
Natural frequency (Hz)	
Bending	1.72
Torsion	3.1
Stowed dimension (m)	
X	6.2
Y	0.4
Z	2.15
Acceleration capability	
Translational, (m/sec^2)	0.69
Rotational, (rad/sec^2)	0.07
Pointing error due to maximum acceleration (degree)	
Translational	0.046
Rotational	0.054
Acceleration capability during the deployment, (m/sec^2)	0.077
Deployer Mass (kg)	17.4

The maximum acceptable translational and rotational acceleration are given in Table 2. The pointing error due to the above accelerations are also given in Table 2.

Note that the response bending moments due to the above accelerations are five times larger than the respose bending moment of the solar array mast of the present space station configuration.

The maximum acceleration capability during deployment is much higher than accelerations resulting from normal operation of the space station (docking/berthing and RCS reboost firing are not considered).

The above analyses were repeated for variation in the truss member thickness from 0.7 to 1.1 mm. Since there are no drastic changes in the result, the 1-mm thickness remained the baseline.

4.2 STACBEAM CONCEPT

The STACBEAM (Stacking Triangular Articulated Concept Beam) concept for deployment and support of solar array panels is shown in Figures 13 and 14. Special characteristics of the STACBEAM structure are as follows:

- o It deploys sequentially, one-bay-at-a-time by unfolding and locking hinges provided at the midpoint of each longeron and diagonal.
- o The batten moves linearly, without rotation, during this deployment.
- o All hinges are single-degree-of-freedom.

The panels are attached at each bay through standoffs to the two corner joints of the STACBEAM by hinges. At the time of full deployment, the midhinge of the panels would be locked to prevent any motion of the panels in a direction normal to its plane.

4.2.1 Structural Properties

4.2.1.1 DIMENSIONS

In the existing STACBEAM design, the bay length is equal to its radius R. The width of the structure w is determined in Section 4.1.1.1 and is 3.472 m. Since the cross-section of the STACBEAM is equilaterally triangular, then its radius is 2.004 m and consequently, its bay length is 2.004 m. The depth of the structure h is

$$h = 1.5R = 3.006 \text{ m}$$

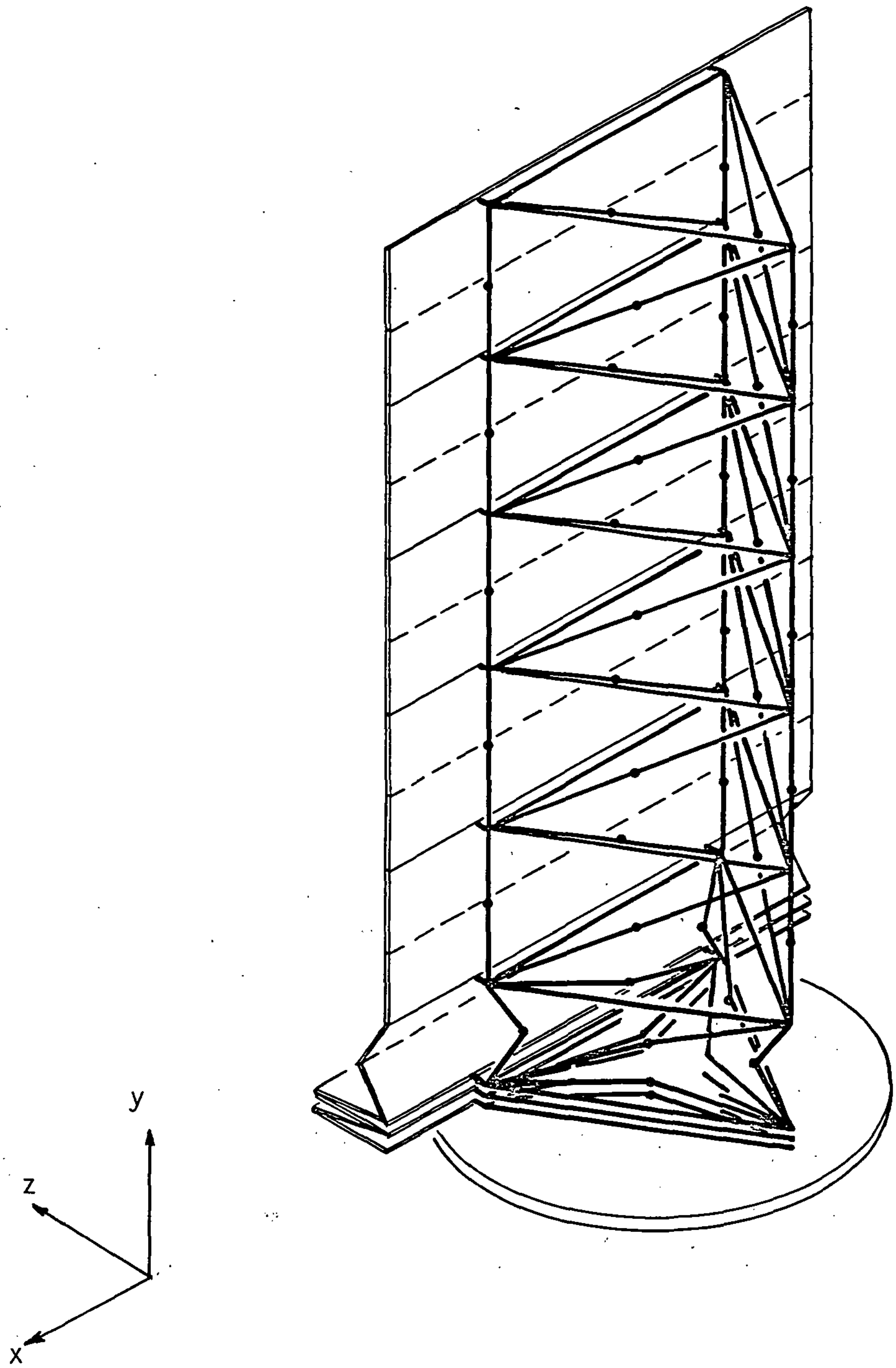


Figure 13. STACBEAM concept. 85-L114

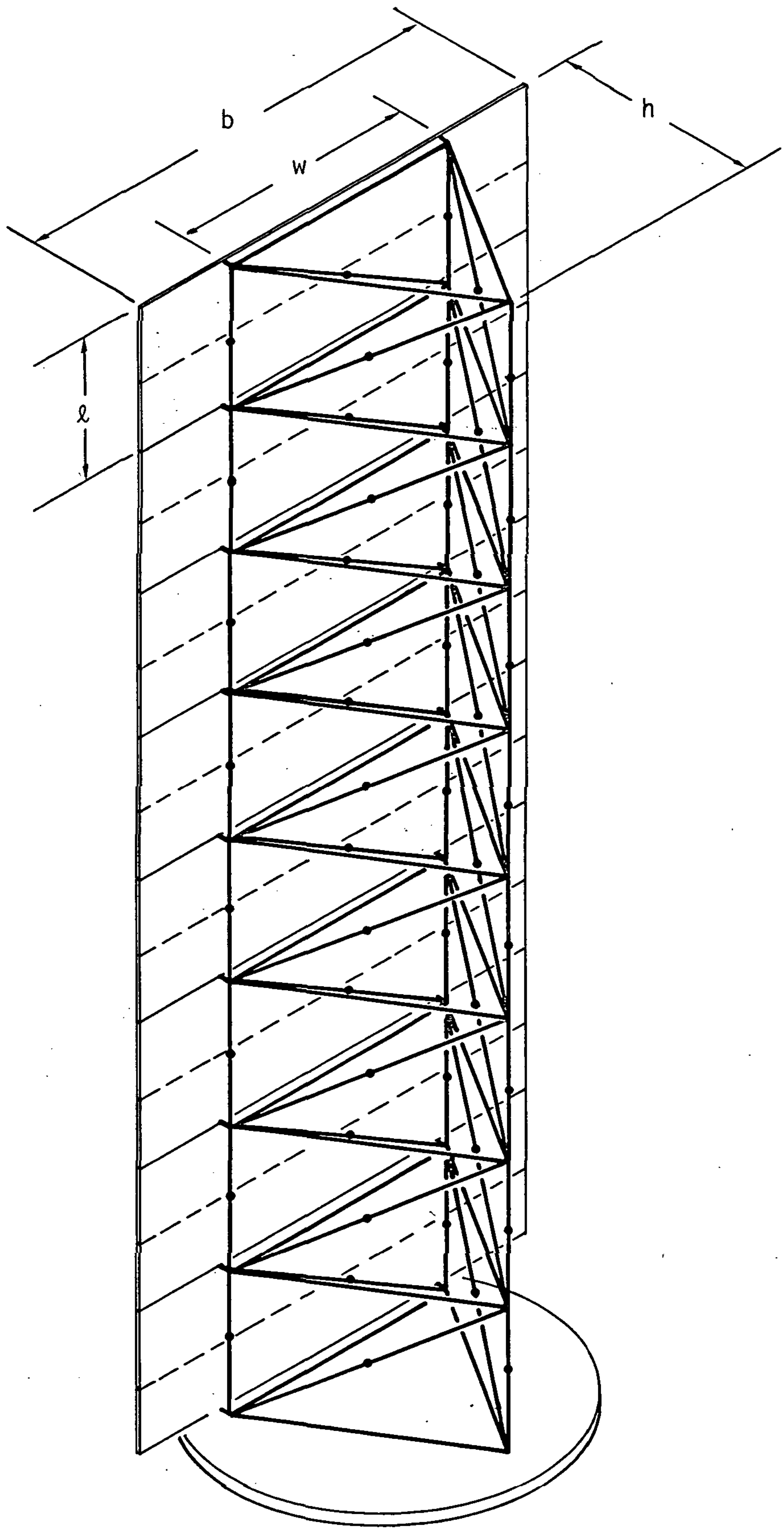


Figure 14. Deployed STACBEAM. 85-L113

The minimum required length of the structure L is 15.25 m (see Table 1). Hence the number of bays should be eight which results in a STACBEAM with 16.032-m length.

4.2.1.2 MASS

The mass of the STACBEAM system includes the masses of its truss members and joints and the solar array payload itself, or

$$M_s = M_t + M_j + M_a \tag{22}$$

4.2.1.2.1 Mass of Truss Members

The mass of the truss members is determined by multiplying the linear density by the structure length, or

$$M_t = m_t L \tag{23}$$

The structure consists of longerons, diagonals, and battens so that

$$m_t = m + m_d + m_b$$

$$= 3\rho A_\ell + 6\rho A_d + 3 \quad 3 \quad \rho A_b$$

$$= 14.2\rho A \quad \text{for } A_\ell = A_d = A_d = A_b \tag{24}$$

where ρ is the material bulk density and A is the truss member cross-sectional area.

4.2.1.2.2 Mass of Joints

The joint mass in the STACBEAM is 75 percent of truss member mass (see Ref. 6). Then the joint factor

$$k \equiv \frac{M_j}{M_t} + 1$$

is assigned the value of k = 1.75.

4.2.1.2.3 Mass of Solar Array Panels

The mass of a solar array panel is given in Section 4.1.1.2

4.2.1.3 TRUSS MEMBER SIZE

The procedure to determine the truss member size is given in Section 4.1.1.3.

4.2.1.3.1 Bending Strength

For the simplicity of design, it is desired that the length of the stowed STACBEAM and stowed solar array be equal. In order to satisfy the above condition, the longeron diameter d should be equal to the solar array thickness t_a (see Section 4.2.3). Since the longeron diameter is now limited to the solar array thickness, then the ratio of longeron diameter to its thickness may not be large enough to use Eq. (9).

Equation (9) is modified to

$$(EI)_\ell = \frac{E\pi}{64}(d^4 - d_i^4) \tag{25}$$

where d_i is the inner diameter of the longeron.

Substitution of Eqs. (25) and (8) into Eq. (7) results in

$$d_i = \left(d^4 - \frac{64\ell_\ell^2 M}{\pi^3 Eh}\right)^{\frac{1}{4}} \tag{26}$$

4.2.1.3.2 Natural Frequencies

Bending Natural Frequency

The fundamental bending natural frequency of the STACBEAM system with the cantilever boundary condition is given by Eqs. (11) and (12).

Torsional Natural Frequency

The fundamental torsional natural frequency of the STACBEAM system with cantilever boundary condition is given by Eq. (13).

The torsional stiffness Gk of STACBEAM is given by

$$Gk = \frac{3}{4} R^2 \left(\frac{1}{\sin\beta \cos^2\beta \, (EA)_d} + \frac{\tan^2\beta}{(EA)_\ell} + \frac{\sqrt{3}}{4(EA)_b} \right)^{-1} \tag{27}$$

where β = batten-diagonal angle = 30 degrees.

The mass moment of inertia J_S is given by Eqs. (15), (17), and

$$J_{st} = \left(3\rho A_\ell L + (k-1) M_t \right) R^2 + (M_t - 3\rho A_\ell L) \frac{h^2}{9} \tag{28}$$

4.2.2 Acceleration Capability

The translational and rotational acceleration capability of STACBEAM are given by Eqs. (18) and (20). The pointing accuracies are also given by Eqs. (19) and (21).

4.2.3 Dimensions of the Stowed Configuration

The STACBEAM system dimensions in the stowed configuration along three axes are given below (see Figure 13).

Axes	Dimensions
X	b
Y	$2nt_a$ or 2nd (whichever is larger)
Z	$h + U + \frac{\ell}{2} = 2R + U$

where n is the number of bays or solar array panels, and U is the space required between the STACBEAM and the solar array panels due to the deployer.

Note that the above dimensions do not include the deployer. The dimensions for an existing deployer concept with the STACBEAM system integrated into it are:

Axes	Dimensions
X	b
Y	$>\ell$
Z	$2R + U + d_d$

where d_d is the diameter of the main support tube of the deployer.

4.2.4 Deployment/Retraction Mechanism

The existing concept for the deployment/retraction mechanism (see Ref. 6) is presented in Figure 15. The deployer height is at least one bay length. Prior to deployment, the deployer itself is deployed to its minimum required height, one bay length plus stack height.

The deployment is initiated by the rotation of three lead screws which are threaded through the corner fittings of the top batten frame and are attached to three main supports of the deployer. The top batten frame is lifted with the rotation of the lead screws until the top bay is fully deployed; then, the second batten frame which was held by synchronized latches is released and engaged into the lead screws. The deployment is continued until full deployment.

The deployment/retraction mechanism retracts the STACBEAM system one bay at-a-time. The retraction of each bay, initiated by the simultaneous motion of a series of linkages and levers, pushes the longerons, diagonals and the solar array panel to unlock their mid-hinges. The estimated mass for the deployment/retraction mechanism is given in Appendix A.

4.2.5 Results

The following data were used in the analysis:

$M = 3068$ N-m

$\ell_\ell = 2.004$ m

$h = 3.006$ m

$E = 2.75 \times 10^{11}$ N/m^2 "VHM graphite/epoxy"

$\rho = 1520$ kg/m^3 "VHM graphite/epoxy"

$d = 0.015$ m

$A_\ell = A_b = A_d$

The results are given in Table 3.

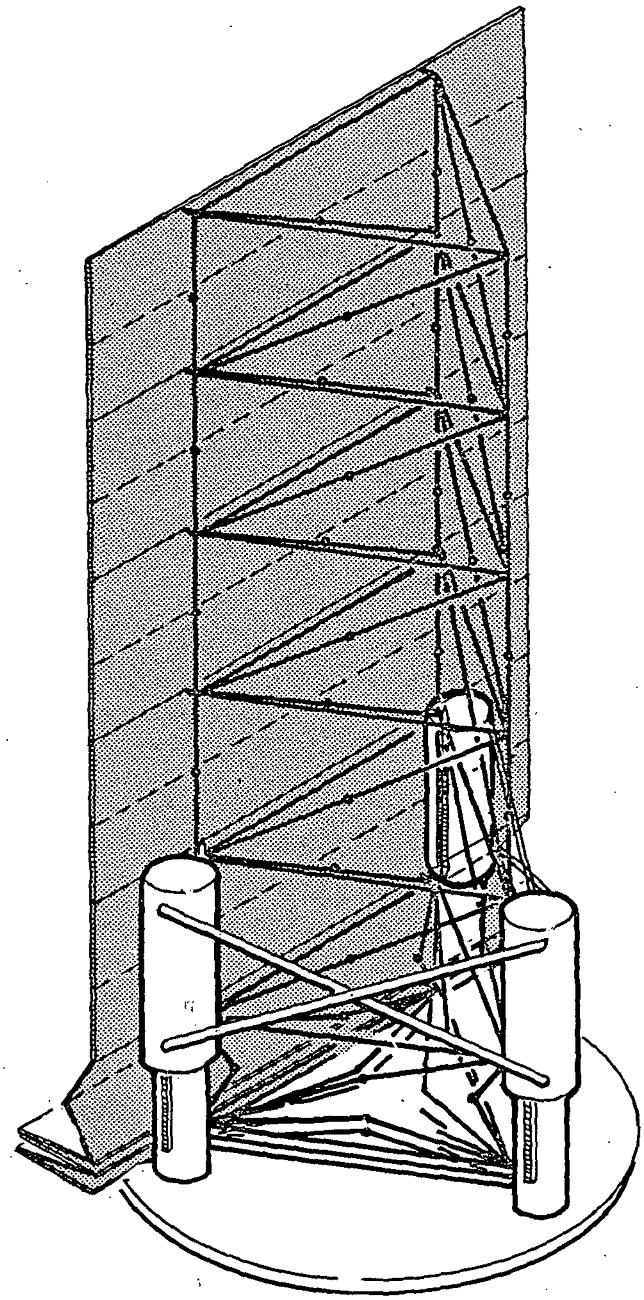


Figure 15. STACBEAM deployer concept. 85-L115

The resulting natural frequencies are higher than the design goal. Thus the design drive for truss member cross section is the bending strength requirement.

The stowed dimensions are larger than the available space of the STEP and the present Space Station stowed configuration. The maximum space available of the STEP along its width (z-axis) is 106 inches or 2.69 m. In order to fit the STACBEAM system with its deployer into the STEP, the following dimensions are required:

$\ell = R = 1.23$ m

$n = 13$

$W = 2.13$ m

Thus, the ratio of the STACBEAM width to that of the solar array is about 0.34.

TABLE 3. STACBEAM BASELINE DESIGN.

Bay number, n	8
Length, (m)	16.032
Width, (m)	3.472
Depth, (m)	3.006
Bay length, (m)	2.004
Truss member diameter, (mm)	15
Truss member thickness, (mm)	1.55
Mass (kg)	40
Mass moment of inertia (kg-m^2)	105.4
Bending stiffness, (N-m^2)	1.085×10^8
Torsional stiffness, (N-m^2)	1.58×10^7
Natural frequency (Hz)	
Bending	3.78
Torsion	5.1
Stowed dimension (m)	
X	6.2
Y	2.004
Z	4.24
Acceleration capability	
Translational, (m/sec^2)	0.66
Rotational, (rad/sec^2)	0.062
Pointing error due to maximum acceleration (degree)	
Translational	0.009
Rotational	0.01
Deployer Mass (kg)	33

4.3 COMPARISONS

The two structural concepts for the support of the solar array panels are evaluated by using several bases of comparison: attachment of the solar array to the structure, package size, simplicity of deployment, and system mass.

4.3.1 Attachment of the Solar Array to the Structure

One of the primary purposes of the deployable structure is to support the solar array panels accurately when it is fully deployed. For that reason, it is important how and at what location the solar array is attached to the structure.

- The solar array will be mounted directly on the ESS at any two locations along its width without being constrained by the package requirement. The solar array will be an integral part of the ESS and its relative position to the front face of the ESS will not be changed during deployment.

- The solar array will be mounted on the STACBEAM through standoffs due to the deployer constraints. The width of the STACBEAM is constrained by the package requirement; thus, the two mounting points (corner fittings of the STACBEAM) cannot be selected arbitrarily. Since the relative position of the solar array to the front face of the STACBEAM changes during the deployment, the solar array is mounted at its end on the standoff by hinges and also has two midhinges.

4.3.2 Package Size

The two concepts have two distinct package shapes. The ESS system package is a flat box, and its dimensions have no constraints on the ESS width. The STACBEAM system package is a triangular prism plus a flat box, and its dimensions have constraints on the STACBEAM width. The dimensions are given in Sections 4.1.3 and 4.2.3.

4.3.3 Deployment

Aspects of deployment which are factors in the evaluation are simplicity, reliability, and natural frequency during deployment. The simplicity and relative reliability of deployment of each concept can be compared by considering their special characteristics:

- The ESS deploys by simultaneously opening all bays so that each member receives its deployment force by transmission through the assembly.

- o The STACBEAM requires synchronized engagement and lifting of the three corners of each triangular batten frame. This can be accomplished electronically or mechanically.

Since the full stiffness of the ESS is not developed until it is completely deployed, the system frequency is degraded during deployment. This situation is not encountered in the other system.

4.3.4 System Mass

The two structures have basically equal masses. The mass of the two structures with the same depth (h = 3.006 m) is used for comparison:

Mass of ESS = 37 kg

Mass of STACBEAM = 40 kg

The estimations for the deployer mass are also

Mass of the ESS deployer = 13.9 kg

Mass of the STACBEAM deployer = 33 kg

4.3.5 Selection

The ESS structure is selected over the STACBEAM for the reasons given in Sections 4.3.1 and 4.3.2. In addition, note that the deployment mechanism for each ESS structure is much simpler than the one for STACBEAM.

SECTION 5
POINT DESIGN STUDY

5.1 NATURAL FREQUENCY ANALYSIS BY FINITE ELEMENT METHOD

As a part of point design, the ESS system's natural frequencies were analyzed by the finite element method using the COSMOS 7 Program.

The finite element model contains 23 nodal points and 61 truss elements, each representing a single truss member as represented in Figure 16. To account for the mass of the hinges and connections at the joints, the truss member material density was increased by the joint factor, k = 1.6.

Furthermore, the mass of the solar array panels was accounted for by including additional lumped masses at only those nodes on the solar array surface. The solar array panels were assumed not to contribute to the structural stiffness. Appendix B lists the input data to the COSMOS 7 Program.

The first ten natural frequencies of the ESS system were determined by the subspace method and are listed in Table 4.

Appendix C lists coordinate displacements of the structural nodes for the normal mode shapes corresponding to the first ten natural frequencies. Also presented in Figures 17, 18 and 19 are various views of mode shapes corresponding to the first three natural frequencies. The first natural frequency is the first bending about the x-axis and agrees very closely with the one given in Table 2. The second natural frequency is the first torsional frequency and is about six percent (6%) lower than the one given in Table 2.

5.2 GROUND HANDLING

During the ground handling (1 g) of the deployable structure, it may become necessary to handle the truss members with special care to prevent any damage or fracture to them. If the special handling of the truss members become a problem, it can easily be solved by increasing the ratio of the truss member thickness to its diameter.

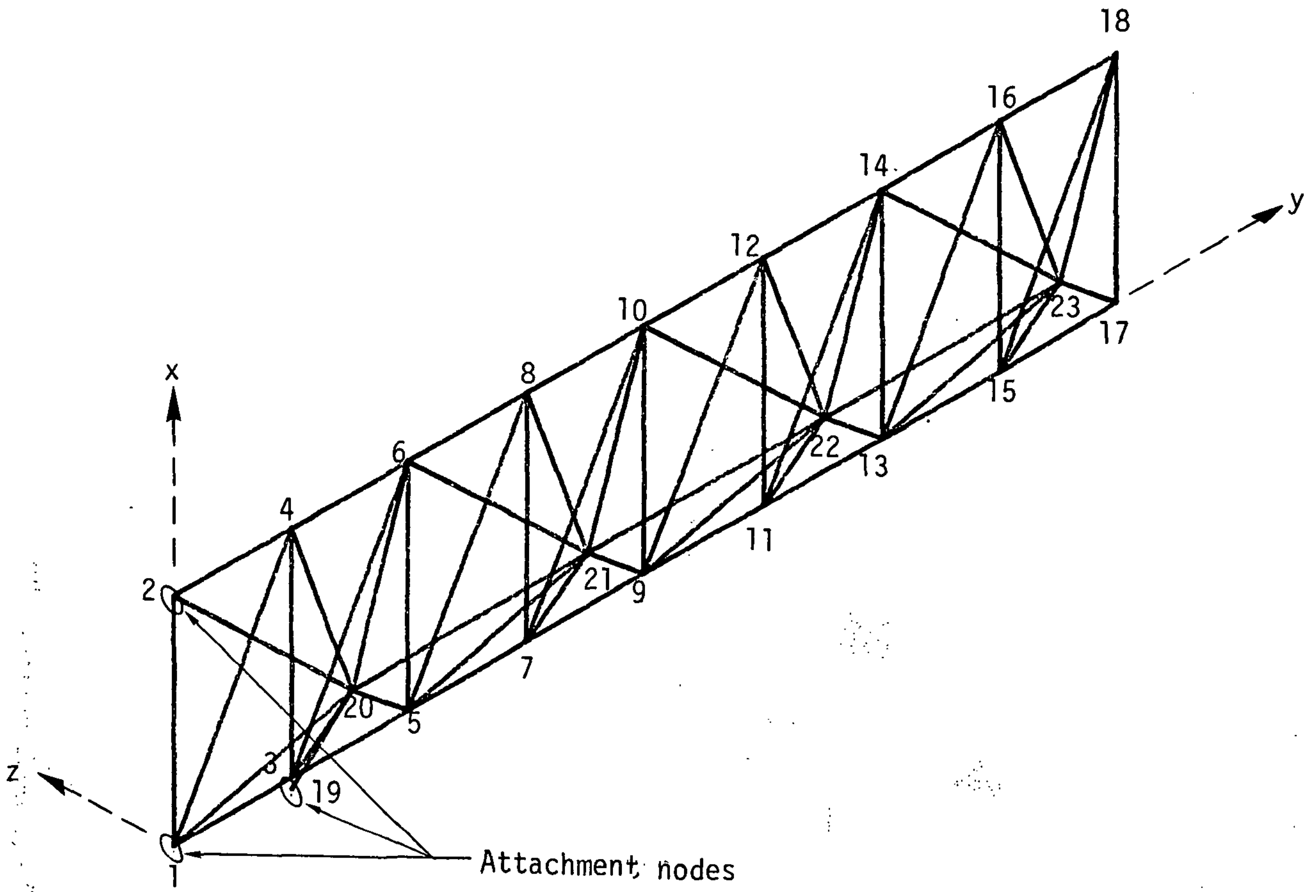


Figure 16. ESS system finite element model

TABLE 4. NATURAL FREQUENCIES OF VIBRATION OF THE ESS SYSTEM

Mode No.	Natural Frequency, Hz
1	1.76
2	2.93
3	5.23
4	8.84
5	9.31
6	14.58
7	18.97
8	19.93
9	21.67
10	24.11

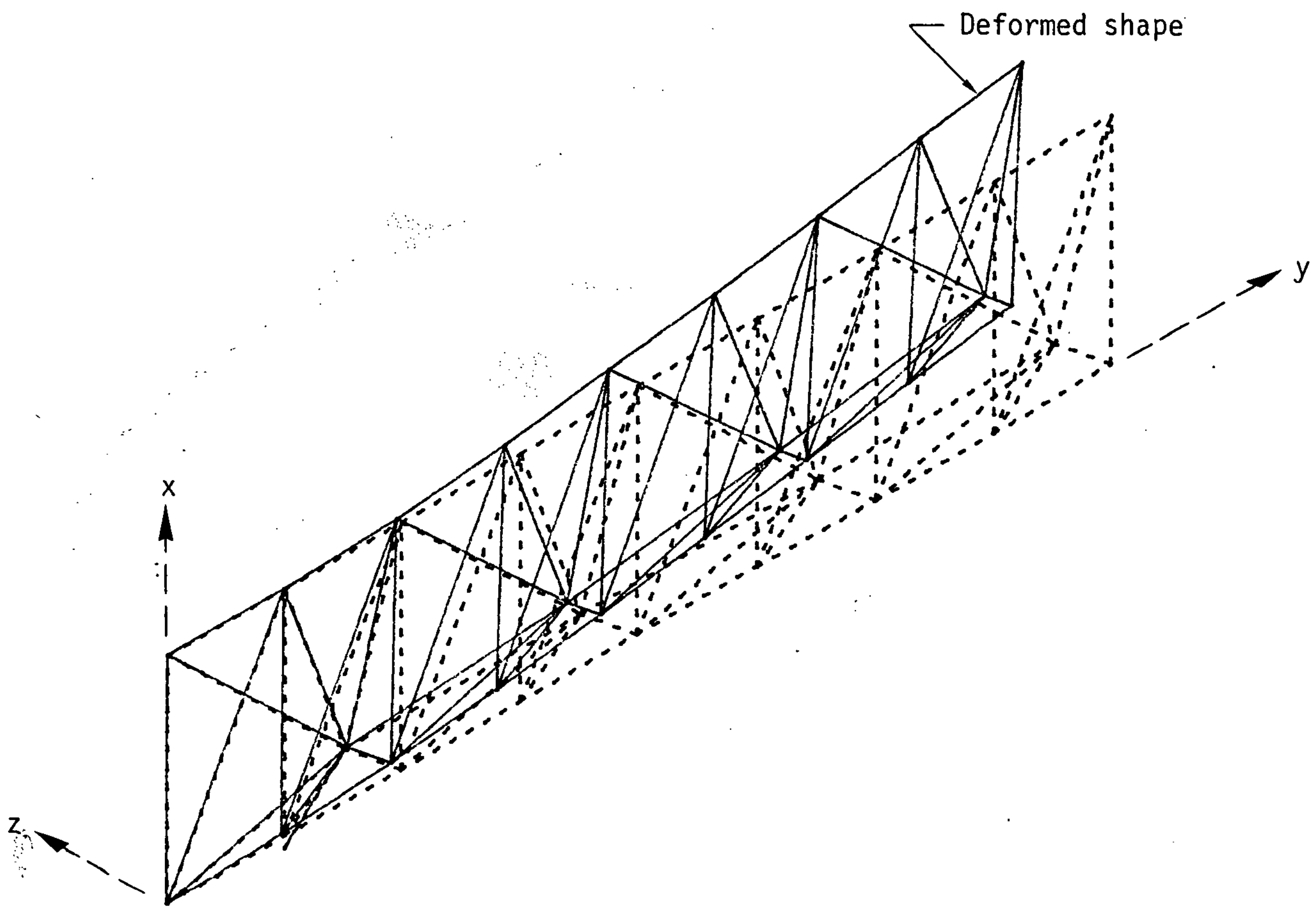


Figure 17a. ESS system first mode shape (perspective)
(f_1 = 1.76 Hz)

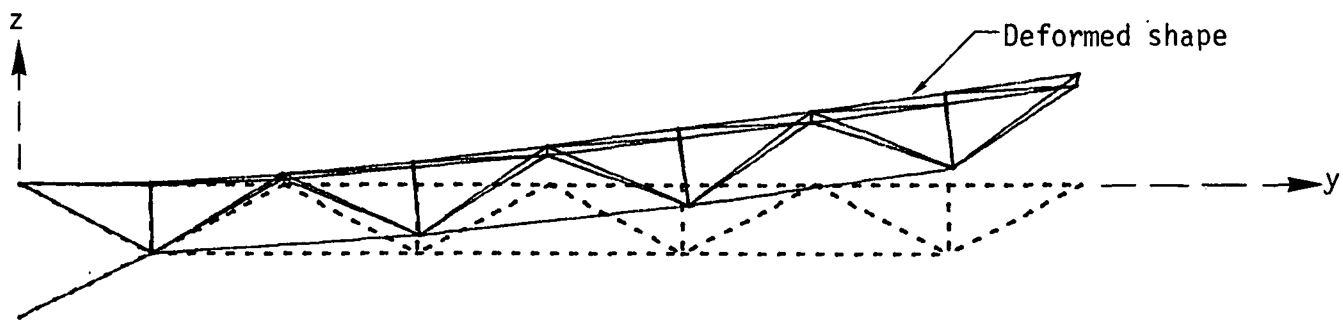


Figure 17b. ESS system first mode shape (y-z plane)
(f_1 = 1.76 Hz)

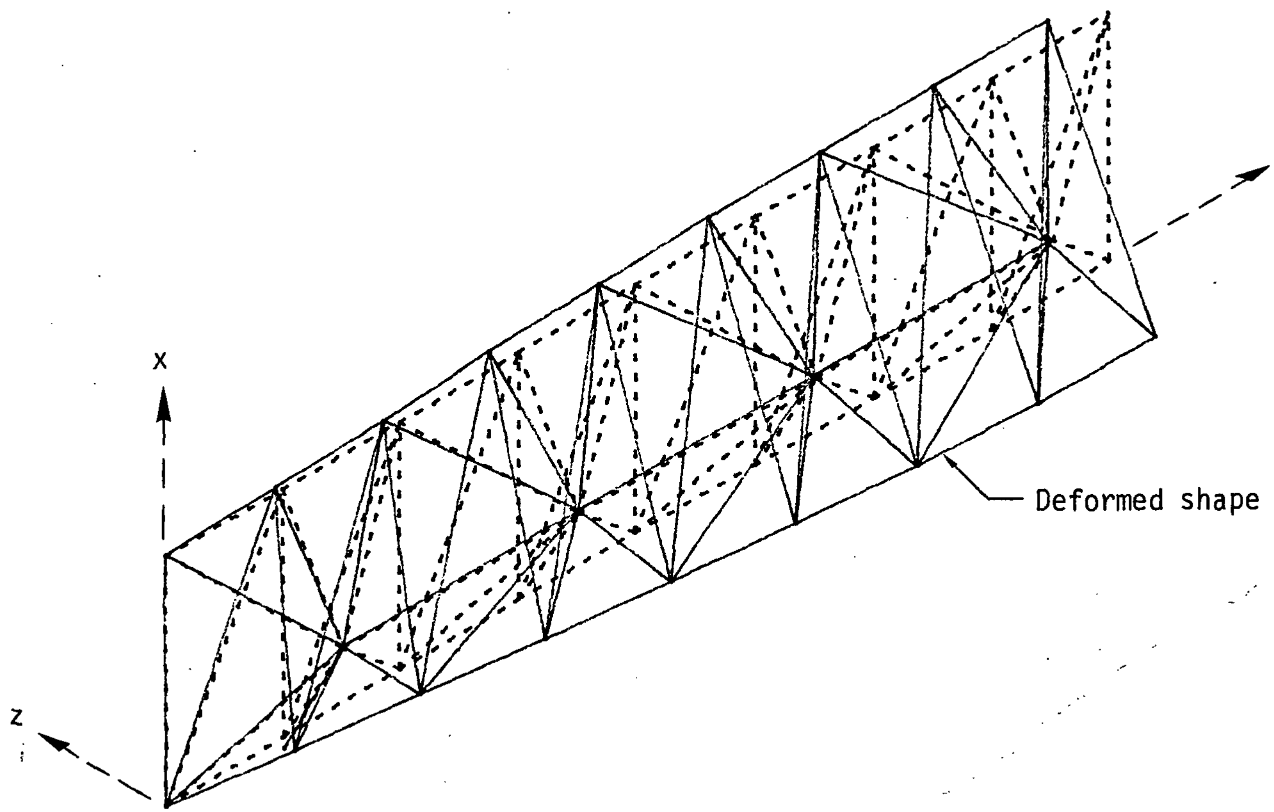


Figure 18a. ESS system second mode shape (perspective)
(f_2 = 2.93 Hz)

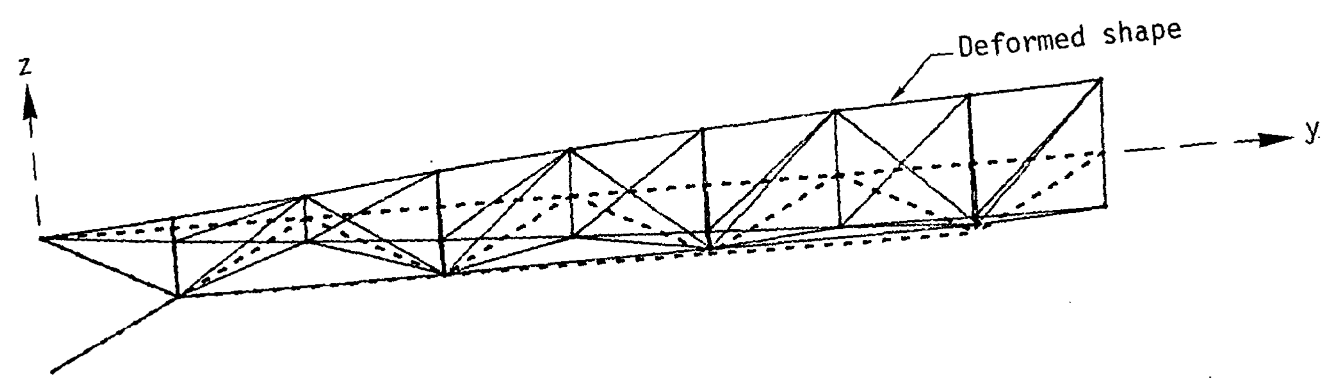


Figure 18b. ESS system second mode shape (y-z plane)

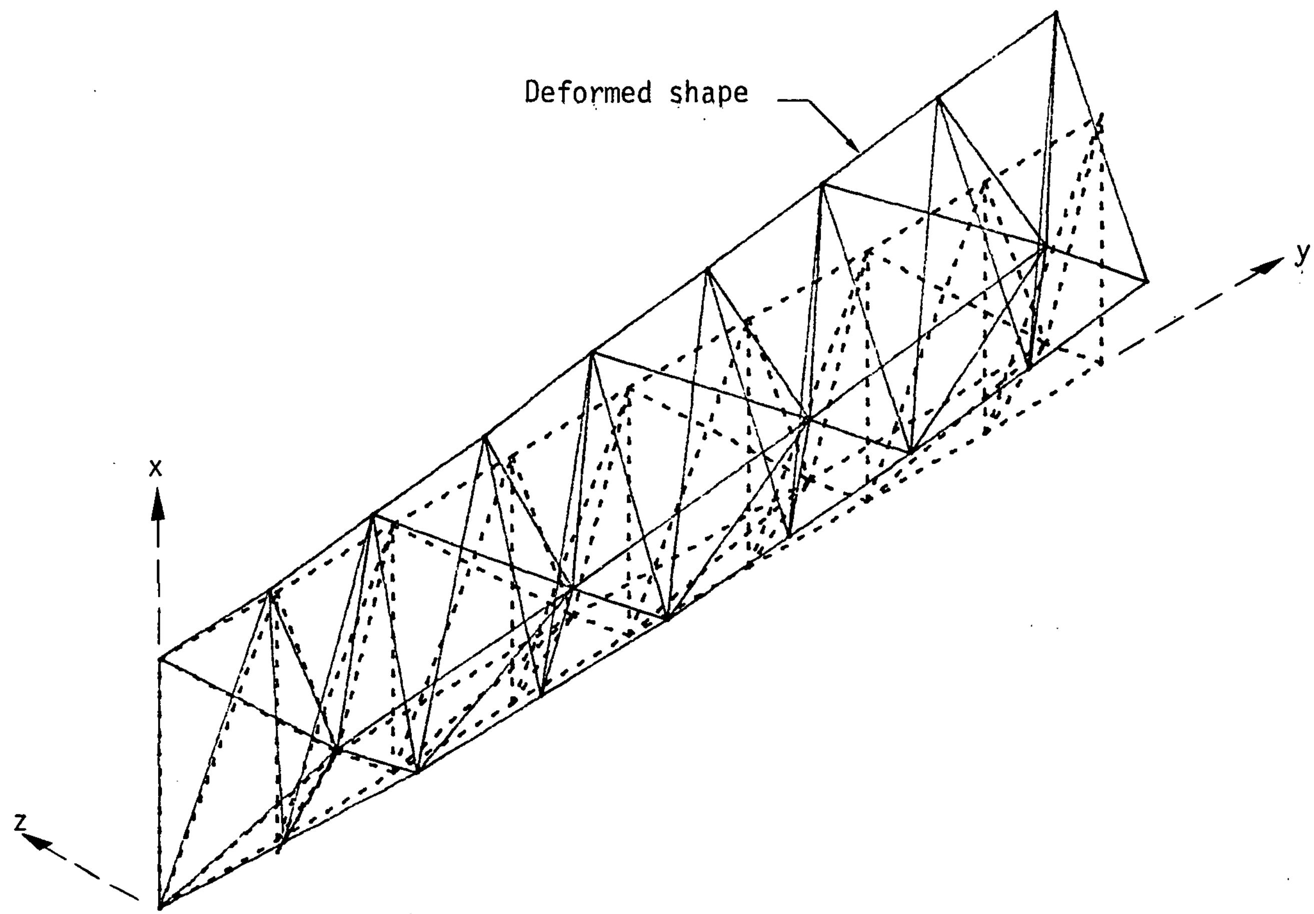


Figure 19a. ESS system third mode shape (perspective) (f_3 = 5.23 Hz)

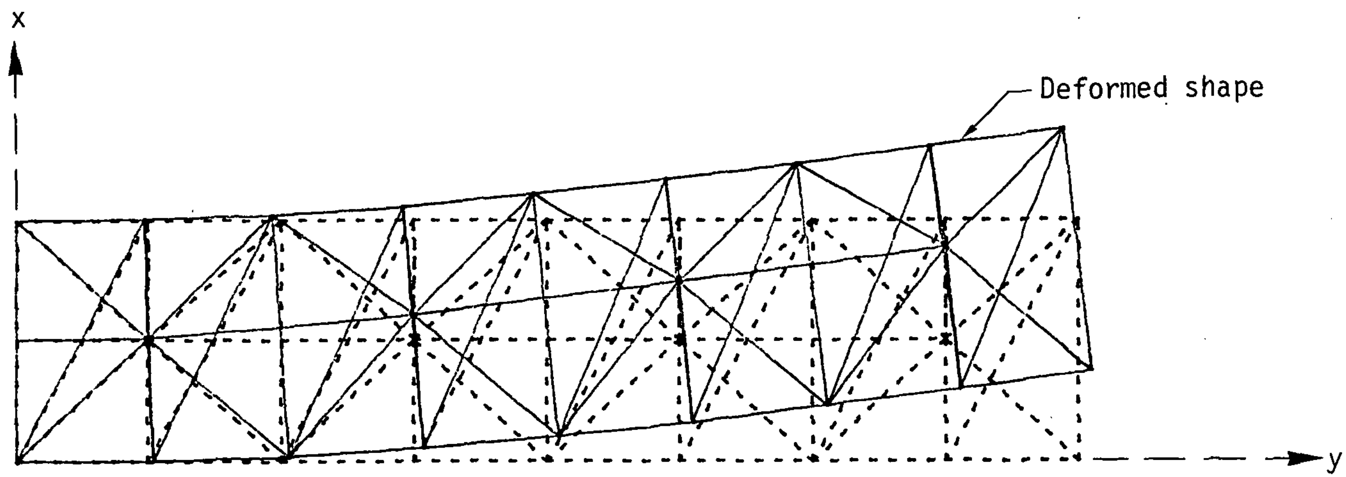


Figure 19b. ESS system third mode shape (x-y plane)
($f_3 = 5.23$ Hz)

In order to investigate the effect of the above change on the overall behavior of the ESS system, Equation 10 is modified to

$$d = \left(\frac{8\ell^2 M_\ell}{\pi^3 Ehc} \right)^{\frac{1}{4}} \tag{29}$$

where $c = t/d$.

The ratio c was increased from 1/34.6 (see Table 2) to 1/20; the results are given in Table 5.

As expected, the deployable structure mass was increased by twenty percent (20%), but the stiffnesses and natural frequencies were also increased.

TABLE 5. ESS DESIGN FOR t/d = 1/20

Bay number, n	8
Length, (m)	15.25
Width, (m)	3.472
Depth, (m)	1
Bay length, (m)	1.91
Truss member diameter, (mm)	30.2
Truss member thickness, (mm)	1.51
Mass (kg)	56
Mass moment of inertia (kg-m^2)	83.34
Bending stiffness, (N-m^2)	2.49×10^7
Torsional stiffness, (N-m^2)	5.61×10^6
Natural frequency (Hz)	
Bending	1.93
Torsion	3.51
Stowed dimension (m)	
X	6.2
Y	0.36
Z	2.15
Acceleration capability	
Translational, (m/sec^2)	0.68
Rotational, (rad/sec^2)	0.066
Pointing error due to maximum acceleration (degree)	
Translational	0.036
Rotational	0.04

5.3 CRITICAL COMPONENTS

The operation and reliability of the synchronized joint controlling the motion of the side battens with the motion of the rear scissors longeron is the primary concern. Its operation is not only required for the retraction, but it is essential to a synchronized deployment. The synchronized joint presented in Figure 20 has been used in the Seasat project and its operation and reliability have been demonstrated. Note that the Seasat synchronized joint was controlling the motion of the side diagonal with the motion of the rear scissors longeron since there were no retraction requirements, but the basic principles are the same. Presented in Appendix D are sketches (Class C drawings) of the overall configuration of the ESS structure.

5.4 ROUGH COST ESTIMATES

Cost estimates for both the engineering development of a mission specific design and the recurring unit costs have been developed on the basis of the following assumptions:

- Cost plus fixed fee contract (full requirements not defined)
- Costs in 1985 dollars
- Non-recurring costs include:

  Mission specific design (analysis, specification and drawings)
  Preliminary Design Review at Astro's facility
  Engineering model fabrication
  Functional and life cycle tests
  Critical Design Review at Astro's facility

- Recurring unit costs include:

  Manufacturing of flight hardware (twelve units)
  Qualification of testing including vibration, thermal vacuum, E.M.I
  Refurbishment of qualification unit as flight spare
  Acceptance tests and documentation
  Brush-type dc motor
  Standard Astro quality plan
  Shipping container
  F.O.B. Carpinteria, California

On this basis, the non-recurring costs are estimated at $750,000 and the recurring costs at $650,000 per unit.

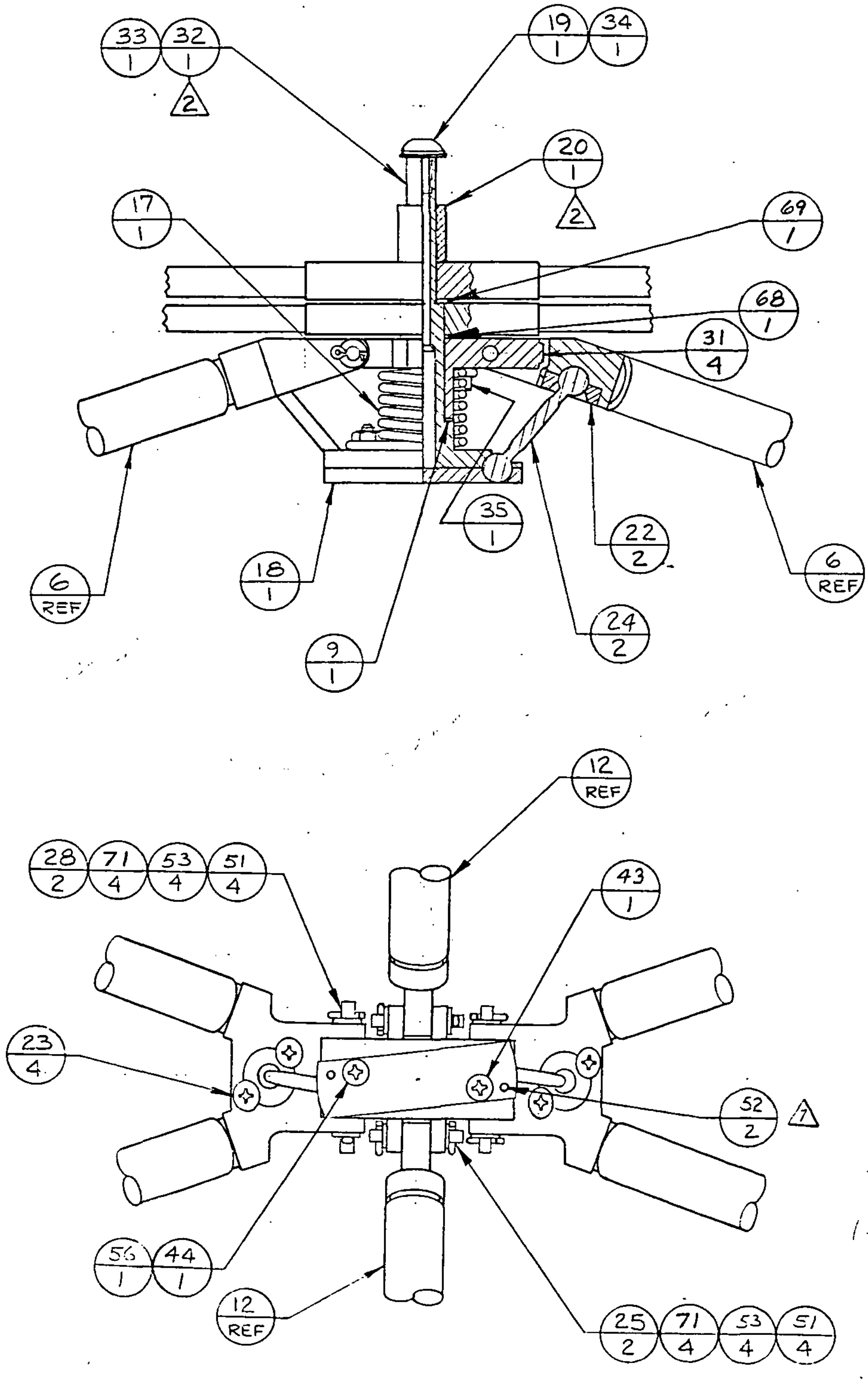


Figure 20. Synchronized joint.

SECTION 6
SUMMARY

The Extendible Support Structure (ESS, a synchronously deploying structure) is selected to deploy and accurately support the high-concentration ratio solar array modules, such as the miniaturized Cassegrainian Concentrator Solar Array.

The ESS structure provides high stiffness, high strength and low mass (less than a tenth of the solar array modules' mass). The ESS system (ESS structure plus the solar array modules) can stand the space station environment under the worst conditions with a safety factor of five, and its fundamental vibrational natural frequency is about 1.7 Hz. Due to its high stiffness, the pointing error under worst conditions is 0.054 degree. The ESS system in the stowed condition can be attached to the stowed transverse boom of the space station inside the space shuttle.

REFERENCES

1. Patterson, Robert E.: Study of Multi-Kilowat Solar Arrays for Earth Orbit Applications. TRW Document No. 38172-6001-UE-00, 15 October 1983.

2. Space Station Reference Configuration Description. JSC-19989, August 1984.

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6. Adams, Louis and von Roos, Angelika I.; STACBEAM II, Final Report, Phase VI, Astro Document No. AAC-TN-1134, 23 April 1983.

APPENDIX A
STACBEAM DEPLOYER MASS

APPENDIX A

STACBEAM DEPLOYER MASS

The deployer mass is estimated as the sum of several masses, as follows:

- Primary support. It is assumed that the deployer itself is truss-like with stiffness equal to that of the beam. The mass of this component is taken as the mass of an equivalent length of beam, or 5 kg.
- Lead screws. These are assumed to be composite graphite/epoxy and titanium so that thermal effects are minimized. The mass of three 0.02-m diameter screws is calculated to be about 4 kg.
- Lead screw drives and supports. Includes upper and lower bearings, three mid-span supports, and gearing on each of the three lead screws. Assume 2 kg.
- Corner posts. These posts provide substantial backing for the lead screw supports so that the beam is held with full stiffness at any intermediate deployment position. Graphite/epoxy tubes of 0.08-m diameter and 0.004-m wall thickness used for this purpose have a mass of 3 kg each. Total of 9 kg.
- Motor. Two kg.
- Synchronization. Two composite tubes, transferring rotational motion from the single motor-driven assembly to each of the two slave assemblies. Associated gearing. Total of 2 kg.
- Retraction. Mechanisms required for retraction include three longeron pushers, three diagonal pushers, three escapements (synchronized latches) and a stack mover. The longeron and diagonal pushers would be triggered by beam motion through the deployer. Longeron pusher linkages would be close to the corner posts and of relatively low mass: 1.5 kg total. The diagonal pusher linkages must extend to the area between the posts, and the two situated away from the payload would total 2 kg. The third diagonal pusher must be free-standing (because of the beam-payload connections) and would have a mass of perhaps 3 kg. Escapements are driven by lead screws; total of 0.5 kg. The stack mover keeps the top of the stack at the lead screw entrance level and would consist of three separate racks at the corners, driven by the lead screws, and having 2 kg mass. Total retraction mass: 9 kg.

The total deployer/retractor mass is therefore 33 kg.

APPENDIX B

ESS SYSTEM FINITE ELEMENT INPUT DATA

Appendix B

```
MARSHALL HPDS
*CONTROL, 23, 61
M1, 3D, L, E
M2, 1, 0, 16, 0
M3, 1
*RENUMBER
*PLOT
*NODES
C, 1, 2, 1, NM
C, 19, 19, 1, NM
1, 0. 0, 0. 0, 0. 0, 2
17, 0. 0, 15. 25, 0. 0, 0
2, 3. 472, 0. 0, 0. 0, 2
18, 3. 472, 15. 25, 0. 0, 0
19, 1. 736, 0. 0, -1. 90625, 0
20, 1. 736, 1. 90625, -1. , 1
23, 1. 736, 13. 34375, -1. , 0
*MASSES
NM, 3, 16, 1, 33. 68, 33. 68, 33. 68
NM, 17, 18, 1, 16. 84, 16. 84, 16. 84
*TRUSS, L, 61
1, 1, 1, 0
1.
2. 75E11, 0, 1. 0556E-4, 2432. , 0
1, 1, 3, 1, 0, 0, 0, 1
17, 1, 2, 1, 0, 0, 0, 2
26, 1, 4, 1, 0, 0, 0, 2
34, 19, 20, 1, 0, 0, 0, 1
38, 1, 20, 1, 0, 0, 0, 1
39, 2, 20, 1, 0, 0, 0, 1
40, 3, 20, 1, 0, 0, 0, 1
41, 4, 20, 1, 0, 0, 0, 1
42, 5, 20, 1, 0, 0, 0, 1
43, 6, 20, 1, 0, 0, 0, 1
44, 5, 21, 1, 0, 0, 0, 1
45, 6, 21, 1, 0, 0, 0, 1
46, 7, 21, 1, 0, 0, 0, 1
47, 8, 21, 1, 0, 0, 0, 1
48, 9, 21, 1, 0, 0, 0, 1
49, 10, 21, 1, 0, 0, 0, 1
50, 9, 22, 1, 0, 0, 0, 1
51, 10, 22, 1, 0, 0, 0, 1
52, 11, 22, 1, 0, 0, 0, 1
53, 12, 22, 1, 0, 0, 0, 1
54, 13, 22, 1, 0, 0, 0, 1
55, 14, 22, 1, 0, 0, 0, 1
56, 13, 23, 1, 0, 0, 0, 1
57, 14, 23, 1, 0, 0, 0, 1
58, 15, 23, 1, 0, 0, 0, 1
59, 16, 23, 1, 0, 0, 0, 1
60, 17, 23, 1, 0, 0, 0, 1
61, 18, 23, 1, 0, 0, 0, 1
*FREQUENCIES
12, S, 1000. , 0, 1, 1, 0, 0, 0
*FINISH
```

APPENDIX C
ESS SYSTEM MODE SHAPES

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Appendix C

MODE SHAPE NO. 1

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	0.541264E-03	-0.682360E-03	0.142115E-02
4	0.486291E-03	-0.735139E-03	-0.510122E-03
5	0.110029E-02	-0.138063E-02	0.781268E-02
6	0.104383E-02	-0.145328E-02	0.394488E-02
7	0.151732E-02	-0.179243E-02	0.181919E-01
8	0.145771E-02	-0.189978E-02	0.128872E-01
9	0.193886E-02	-0.221651E-02	0.300691E-01
10	0.187604E-02	-0.233105E-02	0.234213E-01
11	0.222442E-02	-0.239085E-02	0.438964E-01
12	0.215840E-02	-0.252348E-02	0.363833E-01
13	0.250393E-02	-0.257213E-02	0.581416E-01
14	0.243439E-02	-0.270483E-02	0.498613E-01
15	0.268690E-02	-0.259579E-02	0.728174E-01
16	0.261533E-02	-0.273402E-02	0.641096E-01
17	0.282307E-02	-0.262008E-02	0.870908E-01
18	0.278266E-02	-0.275787E-02	0.781184E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	-0.417953E-04	0.998420E-03	0.407250E-03
21	-0.385174E-04	0.322041E-02	0.154691E-01
22	0.301100E-04	0.437856E-02	0.400343E-01
23	0.146118E-03	0.471648E-02	0.683191E-01

MODE SHAPE NO. 2

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	-0.472506E-02	-0.772501E-03	-0.103527E-01
4	-0.304699E-02	0.949011E-03	0.759707E-02
5	-0.994316E-02	-0.104837E-02	-0.188507E-01
6	-0.835238E-02	0.138443E-02	0.169114E-01
7	-0.153748E-01	-0.150028E-02	-0.266111E-01
8	-0.139349E-01	0.208793E-02	0.277390E-01
9	-0.207157E-01	-0.154360E-02	-0.323614E-01
10	-0.194838E-01	0.232894E-02	0.362805E-01
11	-0.257127E-01	-0.172786E-02	-0.378639E-01
12	-0.247407E-01	0.276156E-02	0.448091E-01
13	-0.301474E-01	-0.165728E-02	-0.410935E-01
14	-0.294772E-01	0.285470E-02	0.507422E-01
15	-0.338318E-01	-0.168189E-02	-0.427522E-01
16	-0.334950E-01	0.302587E-02	0.554845E-01
17	-0.367729E-01	-0.165033E-02	-0.424795E-01
18	-0.366928E-01	0.303703E-02	0.576018E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	0.126667E-02	0.244951E-03	0.833276E-04
21	0.947002E-03	0.803281E-03	0.181189E-02
22	-0.149437E-02	0.110448E-02	0.430477E-02
23	-0.546333E-02	0.119501E-02	0.663736E-02

MODE SHAPE NO. 3

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	0.713478E-04	0.306364E-02	-0.441225E-02
4	0.674043E-03	-0.292071E-02	0.333223E-02
5	0.373437E-02	0.629080E-02	-0.143028E-01
6	0.421684E-02	-0.602280E-02	0.130606E-01
7	0.106270E-01	0.818425E-02	-0.182236E-01
8	0.109240E-01	-0.784455E-02	0.173456E-01
9	0.200766E-01	0.101177E-01	-0.240926E-01
10	0.201822E-01	-0.976258E-02	0.234662E-01
11	0.315174E-01	0.109587E-01	-0.261447E-01
12	0.314595E-01	-0.106280E-01	0.260295E-01
13	0.441560E-01	0.117355E-01	-0.278882E-01
14	0.440107E-01	-0.114681E-01	0.283251E-01
15	0.573843E-01	0.118775E-01	-0.283387E-01
16	0.572487E-01	-0.116651E-01	0.292743E-01
17	0.705719E-01	0.119601E-01	-0.278580E-01
18	0.705205E-01	-0.117829E-01	0.292883E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	0.257961E-02	0.363762E-04	-0.111490E-04
21	0.209115E-01	0.140947E-03	-0.176610E-03
22	0.463564E-01	0.219779E-03	-0.107262E-03
23	0.737344E-01	0.250957E-03	0.345158E-03

MODE SHAPE NO. 4

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	-0.118293E-01	0.441297E-03	-0.295790E-01
4	-0.791935E-02	0.261908E-02	0.155319E-01
5	-0.206904E-01	0.180931E-02	-0.589089E-01
6	-0.183101E-01	0.390346E-02	0.201317E-01
7	-0.225369E-01	0.112010E-02	-0.732905E-01
8	-0.223974E-01	0.287947E-02	0.142023E-01
9	-0.180325E-01	-0.124705E-03	-0.625991E-01
10	-0.201076E-01	0.160755E-02	-0.320458E-03
11	-0.836442E-02	-0.105166E-02	-0.313694E-01
12	-0.119222E-01	-0.111030E-02	-0.153916E-01
13	0.285589E-02	-0.329085E-02	0.130572E-01
14	-0.964885E-03	-0.268947E-02	-0.248331E-01
15	0.112822E-01	-0.353977E-02	0.582496E-01
16	0.847680E-02	-0.410951E-02	-0.250097E-01
17	0.148805E-01	-0.416646E-02	0.885136E-01
18	0.137678E-01	-0.445011E-02	-0.111384E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	0.272549E-02	-0.126421E-02	-0.341730E-02
21	0.197018E-02	-0.668200E-03	-0.285294E-01
22	-0.568060E-02	0.441848E-02	-0.257615E-01
23	-0.133754E-01	0.748992E-02	0.136821E-01

MODE SHAPE NO. 5

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	-0.740895E-02	-0.193822E-02	-0.114897E-01
4	-0.465305E-02	-0.386807E-03	0.180550E-01
5	-0.119491E-01	-0.314969E-02	-0.299148E-03
6	-0.110113E-01	-0.175838E-02	0.495228E-01
7	-0.133983E-01	-0.135955E-02	0.159037E-01
8	-0.147308E-01	-0.124683E-03	0.745637E-01
9	-0.100000E-01	0.101767E-03	0.317050E-01
10	-0.131761E-01	0.128244E-02	0.729169E-01
11	-0.384156E-02	0.253723E-02	0.343307E-01
12	-0.759716E-02	0.252786E-02	0.449592E-01
13	0.243864E-02	0.406377E-02	0.241522E-01
14	-0.548109E-03	0.451150E-02	0.119258E-02
15	0.670666E-02	0.464329E-02	-0.123777E-02
16	0.576923E-02	0.431497E-02	-0.523283E-01
17	0.754456E-02	0.492322E-02	-0.339619E-01
18	0.792084E-02	0.478836E-02	-0.909267E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	0.219309E-02	0.246437E-02	0.556466E-02
21	0.226409E-02	0.218726E-02	0.425604E-01
22	-0.276079E-02	-0.663630E-02	0.350558E-01
23	-0.798365E-02	-0.122341E-01	-0.266987E-01

MODE SHAPE NO. 6

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	0.179142E-01	-0.578430E-03	0.488601E-01
4	0.127481E-01	-0.166696E-02	-0.381061E-01
5	0.179519E-01	-0.160232E-02	0.513244E-01
6	0.203398E-01	-0.898937E-03	-0.507512E-01
7	-0.478622E-03	-0.143147E-02	0.157286E-01
8	0.735046E-02	0.830753E-03	-0.215115E-01
9	-0.211341E-01	0.141467E-02	-0.355442E-01
10	-0.146677E-01	0.663018E-03	0.286181E-01
11	-0.250002E-01	0.277679E-02	-0.528006E-01
12	-0.259456E-01	0.754469E-03	0.568674E-01
13	-0.839329E-02	0.255004E-02	-0.165509E-01
14	-0.157965E-01	-0.219280E-03	0.279038E-01
15	0.143037E-01	0.302492E-02	0.301868E-01
16	0.768570E-02	-0.310299E-02	-0.299603E-01
17	0.260144E-01	0.216044E-02	0.471128E-01
18	0.240778E-01	-0.329176E-02	-0.581795E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	-0.765519E-02	-0.893652E-04	0.450307E-03
21	-0.640714E-02	-0.122530E-03	0.414219E-02
22	0.351386E-02	-0.549047E-04	0.104547E-02
23	-0.490301E-02	-0.102618E-02	-0.564044E-02

MODE SHAPE NO. 7

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0. 000000E+00	0. 000000E+00	0. 000000E+00
2	0. 000000E+00	0. 000000E+00	0. 000000E+00
3	-0. 834984E-02	-0. 230507E-02	-0. 103454E-01
4	-0. 782959E-02	-0. 769967E-03	0. 437823E-01
5	0. 208419E-02	-0. 485383E-02	0. 443433E-01
6	-0. 628908E-02	-0. 319001E-02	0. 655859E-01
7	0. 126427E-01	-0. 324263E-02	0. 704248E-01
8	0. 577384E-02	-0. 194406E-02	0. 350316E-01
9	0. 596501E-02	-0. 115129E-02	0. 135543E-01
10	0. 878313E-02	0. 439514E-03	-0. 989655E-02
11	-0. 780029E-02	-0. 530925E-02	-0. 585667E-01
12	-0. 152336E-03	-0. 248452E-02	-0. 291764E-01
13	-0. 108919E-01	-0. 896972E-02	-0. 590162E-01
14	-0. 861486E-02	-0. 671721E-02	-0. 163933E-01
15	0. 186423E-02	-0. 109679E-01	0. 111073E-01
16	-0. 320598E-02	-0. 104715E-01	0. 245510E-02
17	0. 129668E-01	-0. 137495E-01	0. 802758E-01
18	0. 833935E-02	-0. 124872E-01	0. 200699E-01
19	0. 000000E+00	0. 000000E+00	0. 000000E+00
20	0. 533028E-02	0. 152446E-02	0. 148432E-01
21	0. 433125E-03	-0. 935852E-02	0. 394274E-01
22	0. 331049E-02	-0. 913387E-02	-0. 311272E-01
23	-0. 281604E-02	0. 544324E-02	0. 143645E-02

MODE SHAPE NO. 8

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0. 000000E+00	0. 000000E+00	0. 000000E+00
2	0. 000000E+00	0. 000000E+00	0. 000000E+00
3	-0. 234380E-01	0. 132593E-02	-0. 671343E-01
4	-0. 184621E-01	0. 452338E-02	0. 396084E-01
5	-0. 134380E-01	0. 130422E-02	-0. 377100E-01
6	-0. 194055E-01	0. 563789E-02	0. 302675E-02
7	0. 664518E-02	0. 199603E-02	0. 292793E-01
8	0. 382628E-02	0. 332716E-03	-0. 711678E-01
9	0. 314791E-03	0. 291473E-02	0. 266663E-01
10	0. 713714E-02	-0. 158760E-02	-0. 458577E-01
11	-0. 185637E-01	0. 764740E-02	-0. 213660E-02
12	-0. 138591E-01	0. 181352E-02	0. 375966E-01
13	-0. 149968E-01	0. 130743E-01	-0. 102005E-01
14	-0. 203356E-01	0. 214814E-02	0. 617225E-01
15	0. 994360E-02	0. 156764E-01	0. 577429E-02
16	0. 305799E-02	0. 568944E-03	-0. 388741E-02
17	0. 269298E-01	0. 160312E-01	-0. 169923E-02
18	0. 261256E-01	0. 124071E-02	-0. 643973E-01
19	0. 000000E+00	0. 000000E+00	0. 000000E+00
20	0. 507007E-02	-0. 780892E-04	-0. 732922E-02
21	-0. 192497E-01	0. 540037E-02	-0. 201731E-01
22	-0. 652586E-02	0. 662633E-02	0. 190895E-01
23	0. 414563E-02	-0. 271109E-02	-0. 517820E-02

MODE SHAPE NO. 9

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	-0.112354E-01	-0.331019E-02	0.163490E-01
4	-0.578946E-02	0.432406E-02	-0.264350E-01
5	-0.339855E-01	-0.443040E-02	0.107345E-01
6	-0.274014E-01	0.776885E-02	-0.142772E-01
7	-0.483409E-01	0.412559E-02	0.254874E-01
8	-0.464343E-01	0.373654E-02	-0.134854E-02
9	-0.450766E-01	0.129816E-01	0.153652E-01
10	-0.472901E-01	-0.207312E-02	0.306101E-03
11	-0.264977E-01	0.213880E-01	0.348512E-01
12	-0.259887E-01	-0.118462E-01	-0.456994E-01
13	-0.126324E-01	0.298304E-01	-0.156999E-01
14	-0.848845E-02	-0.200009E-01	-0.119132E-01
15	0.159840E-01	0.326494E-01	-0.205616E-01
16	0.150061E-01	-0.231487E-01	0.229964E-01
17	0.539696E-01	0.333014E-01	0.175450E-02
18	0.517092E-01	-0.255941E-01	0.260583E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	-0.185978E-01	0.153045E-02	0.600096E-03
21	-0.537126E-01	0.330833E-02	0.115325E-01
22	-0.452300E-01	0.304446E-02	-0.399693E-02
23	0.257623E-01	0.823337E-02	0.147763E-03

MODE SHAPE NO. 10

NODE	X-DISPLACEMENT (m)	Y-DISPLACEMENT (m)	Z-DISPLACEMENT (m)
1	0.000000E+00	0.000000E+00	0.000000E+00
2	0.000000E+00	0.000000E+00	0.000000E+00
3	-0.146228E-01	-0.332774E-02	-0.328957E-01
4	-0.144201E-01	0.543186E-03	0.469168E-01
5	0.353514E-02	-0.851627E-02	0.436372E-01
6	-0.541648E-02	-0.180959E-02	0.970471E-02
7	-0.376248E-02	-0.970295E-02	0.332324E-01
8	0.439690E-02	-0.696608E-02	-0.527129E-01
9	-0.300489E-01	-0.633425E-02	-0.491569E-01
10	-0.227175E-01	-0.114030E-01	0.224322E-01
11	-0.855158E-02	-0.621928E-02	-0.139388E-01
12	-0.183943E-01	-0.166998E-01	0.239663E-01
13	0.228116E-01	-0.969848E-02	0.593793E-01
14	0.182919E-01	-0.198952E-01	-0.392667E-01
15	0.392054E-02	-0.108727E-01	0.457520E-03
16	0.160286E-01	-0.186044E-01	-0.159536E-01
17	-0.169124E-01	-0.767974E-02	-0.661780E-01
18	-0.104427E-01	-0.186917E-01	0.635397E-01
19	0.000000E+00	0.000000E+00	0.000000E+00
20	0.329564E-02	-0.157968E-02	0.560990E-02
21	-0.188692E-01	-0.103304E-01	-0.467254E-03
22	-0.501107E-02	-0.987528E-02	-0.465713E-02
23	0.631105E-02	-0.132297E-01	0.450445E-02

APPENDIX D
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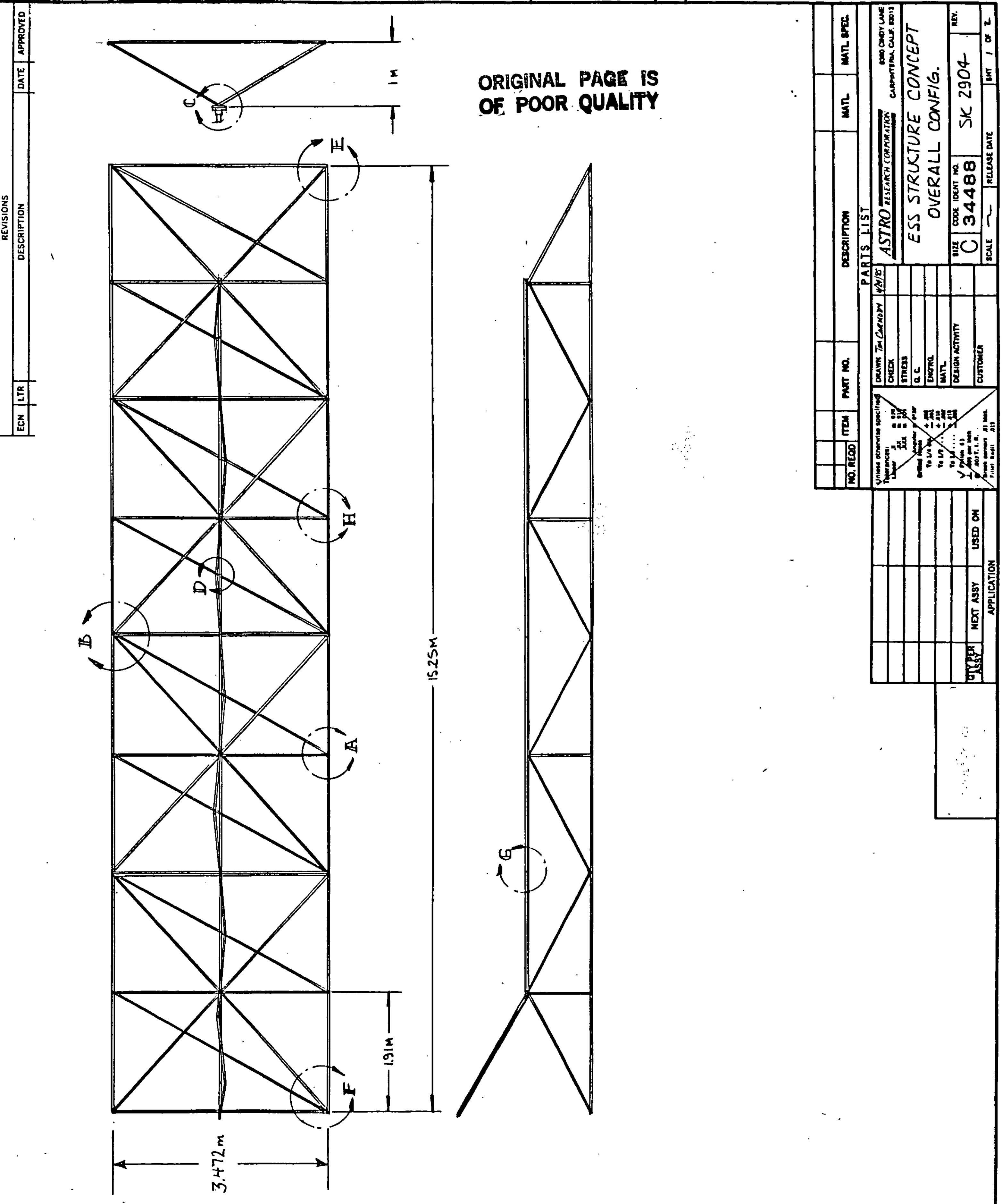

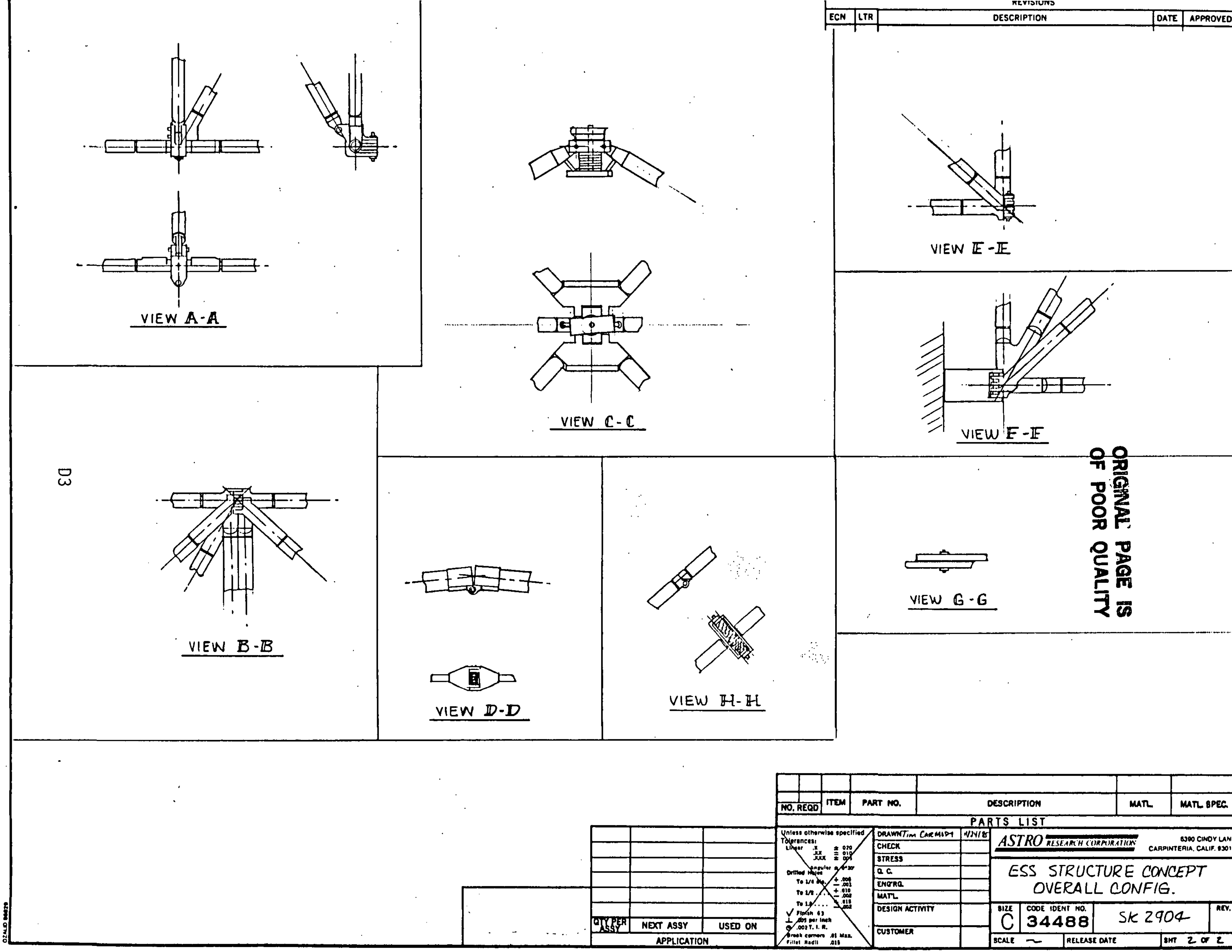
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LTR
DESCRIPTION
DATE
APPROVED
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VIEW B-B
VIEW C-C
VIEW D-D
VIEW E-E
VIEW F-F
VIEW G-G
VIEW H-H
ORIGINAL PAGE IS OF POOR QUALITY
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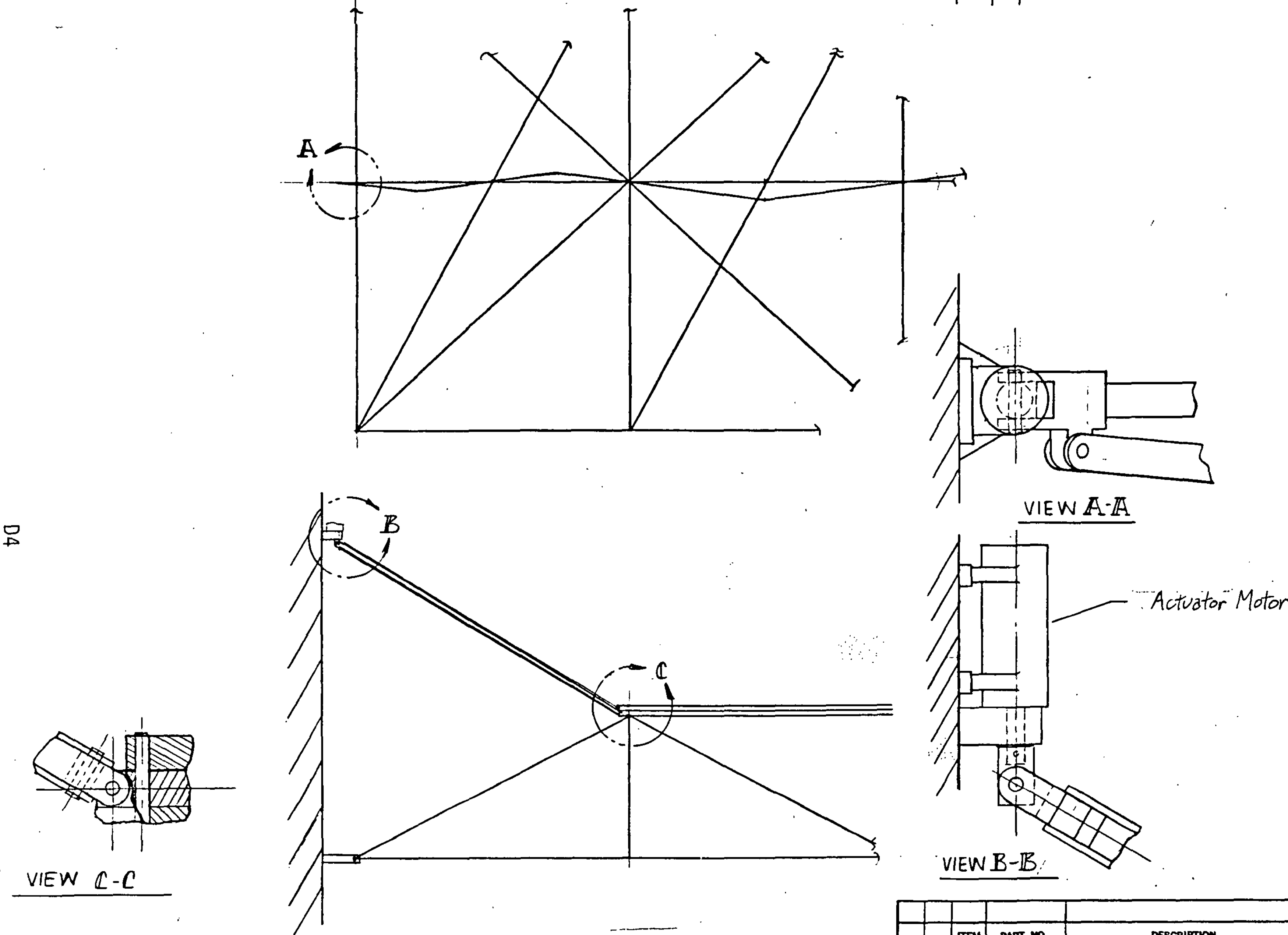
ITEM
PART NO.
DESCRIPTION
MATL.
MATL. SPEC.
PARTS LIST
Unless otherwise specified
Tolerances:
DRAWN Tim Carmody
CHECK
STRESS
Q. C.
ENG'RG.
MAT'L
DESIGN ACTIVITY
CUSTOMER
ASTRO RESEARCH CORPORATION
6390 CINDY LANE
CARPINTERIA, CALIF. 93013
ESS STRUCTURE CONCEPT
OVERALL CONFIG.
SIZE C
CODE IDENT NO. 34488
SK 2904
REV.
SCALE ~
RELEASE DATE
SHT 2 OF 2
QTY PER ASSY
NEXT ASSY
USED ON
APPLICATION

ECN	LTR	DESCRIPTION	DATE	APPROVED



PARTS LIST

NO. REQD	ITEM	PART NO.	DESCRIPTION	MATL.	MATL. SPEC.

DRAWN	Tim Darmody 11/21/80
CHECK	
STRESS	
Q.C.	
ENG'RG.	
MAT'L.	
DESIGN ACTIVITY	
CUSTOMER	

ASTRO RESEARCH CORPORATION — 6390 CINDY LANE, CARPINTERIA, CALIF. 93013

ESS STRUCTURE CONCEPT DEPLOYMENT MECH.

SIZE	CODE IDENT NO.		REV.
C	34488	SK 2905	-
SCALE ~	RELEASE DATE		SHT 1 OF 1

QTY PER ASSY	NEXT ASSY	USED ON
	APPLICATION	

ASTRO
A SPAR COMPANY

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