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Volume 2 Final Report

Boeing Aerospace Company

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16. Abstract

This document is the final report prepared under contract NAS3-23248, "Study of Auxiliary Propulsion Requirements for Large Space Systems." There are three technical tasks described herein. In Task 1 a range of single shuttle launched large space systems were identified and characterized including a NASTRAN and loading dynamics analysis. Task 2 consisted of an analysis of the disturbance environemnt, characterization of thrust level and APS mass requirements, and a study of APS/LSS interactions. In the final task, state-of-the-art capabilities for chemical and ion propulsion were compared with the generated propulsion requirements to assess the state-of-the-art limitations and benefits of enhancing current technology.

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ABSTRACT

This document is the final report prepared under contract NAS3-23248, "Study of Auxiliary Propulsion Requirements for Large Space Systems." There are three technical tasks described herein. In Task 1 a range of single shuttle launched large space systems were identified and characterized including a NASTRAN and loading dynamics analysis. Task 2 consisted of an analysis of the disturbance environment, characterization of thrust level and APS mass requirements, and a study of APS/LSS interactions. In the final task, state-of-the-art capabilities for chemical and ion propulsion were compared with the generated propulsion requirements to assess the state-of-the-art limitations and benefits of enhancing current technology.

KEY WORDS

Attitude Control

Auxiliary Propulsion

Large Space Structures

Shape Control

Stationkeeping

SUMMARY

The objective of contract NAS3-21952, "Study of Auxiliary Propulsion Requirements for Large Space Systems," was to establish key APS requirements and state-of-the-art improvement benefits for a range of future spacecraft. The key issues raised or examined in the study included LEO deployment and operation, GEO stationkeeping duty cycles, structural modeling, and the technology areas to improve. To examine these issues, three technical tasks were performed. These tasks are shown below:

Task 1: Definition of Advanced Structural Concepts

Task 2: Establishment of APS Requirements

Task 3: Assessment of Technology Improvement Benefits

In Task 1, six vehicle classes were analyzed including four large antenna structures and two space platform designs. NASTRAN analysis was conducted to determine the mode shapes, structural frequencies, and to verify a dynamic loading analysis. The loading analysis was conducted to determine the effect of primary thrust g-loading on the mass properties of each LSS.

Task 2 was accomplished in four steps. A disturbance analysis for LEO deployment altitudes and GEO operational altitudes was first performed. The force and torque requirements for each LSS were used to establish the thruter requirements. These requirements indicated a need for widely separated thrust levels between LEO and GEO and indicated throttling g requirements for GEO operation of 2:1 to 6:1. In the next subtask APS mass was characterized for monopropellant, bipropellant, and ion systems. It was found that duty cycle played the major role in determining which propulsion system was the most viable for GEO operation. Duty cycles of 3 hours/orbit or greater favored ion systems, whereas shorter duty cycles required thrust levels which could not be met with state-of-the-art propulsion. As a final analysis, the interactions of the propulsion system with the structure were examined. For thrust levels of 7 to 30 Newtons (depending upon the configuration) significant defocusing of antenna systems was found.

In Task 3 the state-of-the-art capabilities for monopropellant, bipropellant, and ion systems were determined. These capabilities were compared with the requirements generated in Task 1 and limitations to current technology identified. There were four major limitations identified and these limitations are shown below.

- Monopropellant I_{sp} limits mission lifetime (<5-7 years) for centaur G' delivery capability

- Bipropellant need lower thrust capability (<2-5 N)

- Ion thrusters need very long duty cycles (>3-5 hours/orbit) for GEO operation

These limitations were a key to assessing the enhanced technology benefits. A brief listing of those technology areas which would enhance or enable the LSS missions identified is shown below.

- Increasing chemical system I_{sp} to > 300 seconds is mission enabling
- Minimum firing times of < .01 seconds yields mass advantage of jets over MMD's for 3-axis control
- Valve cycling of 2 x 10^7 cycles enables jet systems for 3-axis control
- Thruster levels of .1 to .4 N enhance ion propulsion for GEO operation
- I_{sp} range for ion systems of 1000-2000 seconds optimum (using state-of-the-art PPU's)
- Ion power system mass must be reduced for ion systems to be competitive with shorter duty cycle, higher thrust engines

INTRODUCTION

With increasing fervor, plans to utilize the resources of space are being made within NASA, DOD, and private industry. Many of these plans call for the use of Large Space Systems (LSS) to accomplish this wide variety of goals. These LSS will require new technology in analysis techniques and hardware to be enabled and utilized in the most cost effective fashion. To assess the propulsion technology requirements and recommend high leverage advances in propulsion, a study was performed examining auxiliary propulsion requirements for a range of single shuttle launched LSS. This study considers auxiliary propulsion only and will supplement othe work examining prime propulsion requirements (Ref. 1).

This study is a more focused follow-on to contract NAS3-21952 (Ref. 2), "Study of Electrical and Chemical Propulsion Systems for Auxiliary Propulsion of Large Space Systems." The focus of this study was narrowed to examine only single shuttle launched LSS with two exceptions - the Space Operations Center (SOC) and the Science and Applications Space Platform (SASP). Also in this study, only advanced deployable LSS which had a heritage of ongoing preliminary design were examined. To add a final sharpening of focus, only well established propulsion options were examined and extrapolation of their capabilities was rooted in accepted scaling laws based on theory, test, and existing hardware. By establishing a narrow width for analysis, the depth of the analysis was enhanced. Details of the effects of primary g-load on structure mass and the effect of a range of thrust levels on antenna performance were examined. Stationkeeping duty cycles and tolerance effects were studied and regions of operation for each propulsion system identified. The study was also able to make specific recommendations for auxiliary propulsion thrust level, I_{sp}, minimum impulse bit, and cycle number for the range of LSS identified.

Several key assumptions were groundruled in the study. These assumptions are listed below. The first two assumptions and the propulsion option assumption have been previously discussed.

- Single shuttle launched (exception SOC, SASP)
- Advanced preliminary design deployable LSS
- LEO (300-500 km) and GEO operation
- 10 year mission life
- NASA neutral atmospheric model assumed
- Only well established propulsion options examined (mono, biprop, ion)
- No factors of conservatism were employed

For the antenna systems the LEO altitude range given is the assumed deployment altitude. This range corresponds to the STS delivery capability. These systems are then transferred to GEO for the 10 year mission operation. The space platforms examined are assumed to operate in the LEO altitude range shown.

The NASA neutral atmosphere was used as a basis of comparison for LEO torque and drag makeup calculations. This atmosphere is a worst case, long term density model and yields conservative but realistic worst case results. Other models are discussed in Task 2. No contingency factors were used for propellant or thrust level calculations. It was felt that the application of such factors might vary with each mission, and because the purpose of the study was to illuminate trends in propulsion requirements, a solid basis of comparison was needed.

Several key issues arose in the course of the study which drove the propulsion requirements and technology recommendations. These issues are listed below.

- Structural modeling
- LEO deployment and operation
- GEO operation duty cycles
- APS system mass impacts

The importance of having detailed and accurate structural models became very clear when the issue of thruster interaction was examined. Antenna defocusing analysis is sensitive to section property and materials property assumptions which must be modeled in NASTRAN to obtain the fundamental frequencies and mode shapes. Small differences in wall thickness or section spacing can result in significantly different interactions. The results presented in Task 2 are based on numerous iterations of mass properties and section properties to match previous results of actual hardware tests (Ref. 3).

Operational issues at LEO and GEO are primary drivers for thrust level and Isp requirements. LEO deployment drove stationkeeping thruster size and propellant mass for even short stays at low altitude to such a degree that LEO deployment seemed unadvisable for most LSS. GEO duty cycles were another key issue in the study because as duty cycle changed from a few minutes a week to a few hours per orbit, thrust requirements went from chemical capability to electric thruster capability. Longer duty cycles would require autonomous operation or high ground in the loop software costs.

Auxiliary propulsion system mass can be 30-50% of the total system mass using chemical systems for 10 year GEO missions. Reductions of this percentage by only 5 or 10% allow very large mass savings and hence lower launch costs. To effect these changes, state-of-the-art limitations in chemical I_{sp}, power processor mass, and autonomous operation must be overcome as described in Task 3.

The program task flow is shown in Figure 1. Task 1 determined the relevant missions and spacecraft properties which would be used to define propulsion requirements. The NASTRAN models and loads analysis gave us an insight into the variation of mass with primary thrust g-loading and were also used to determine the APS/LSS interactions in Task 2. Thrust requirements, impulse bit requirements, Isp effects, and hardware masses were determined in Task 2. These requirements were compared with current capabilities and a set of limitations found in Task 3. The benefits in terms of enhanced mission capture and reduced APS mass were assessed in the final analysis of Task 3.

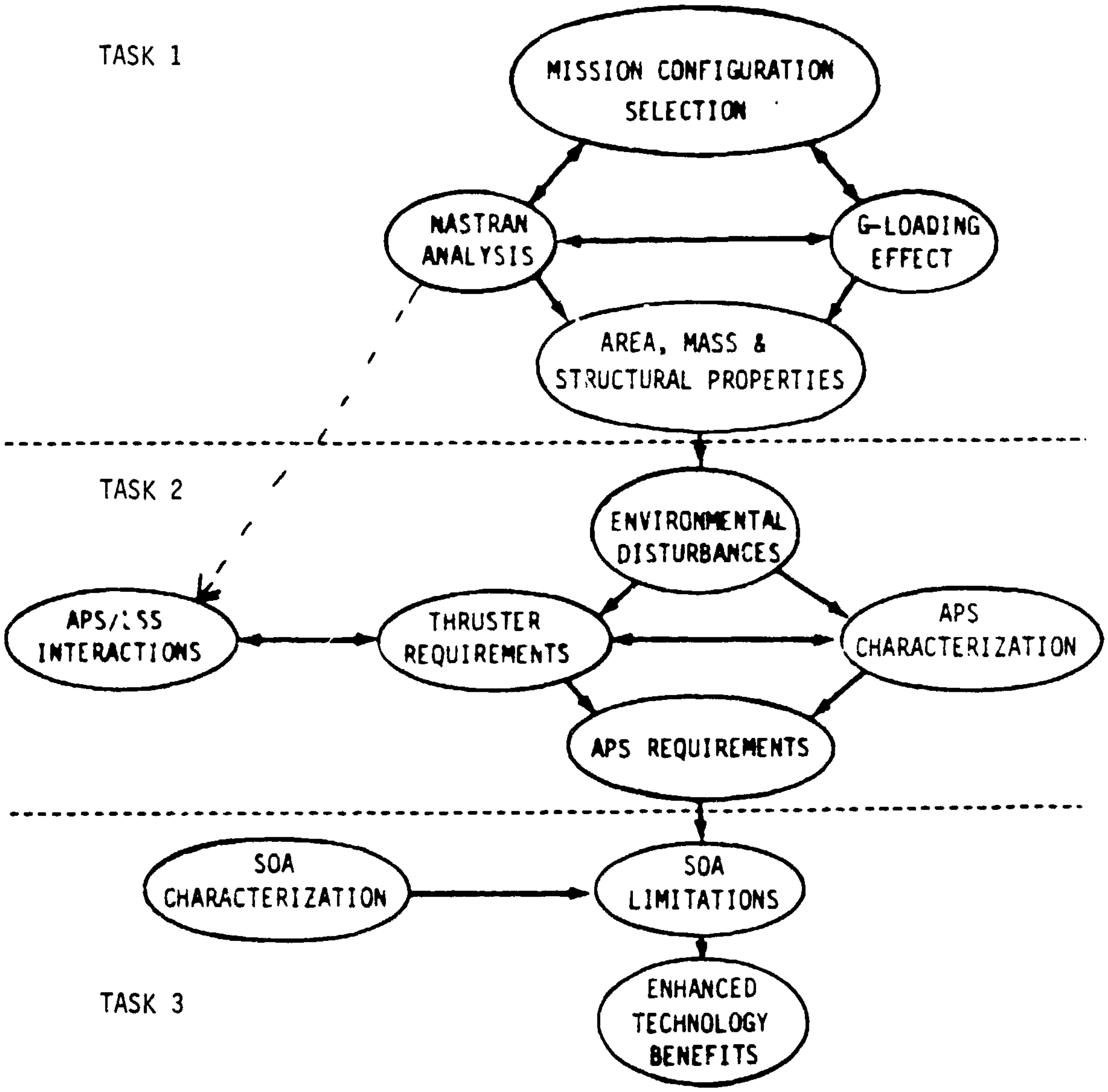

FIGURE 1. PROGRAM TASK FLOW

1.0 DEFINITION OF ADVANCED STRUCTURAL CONCEPTS

The objective of Task 1 was to select and characterize classes of large space systems. To accomplish this objective, three major subtasks were executed. The first subtask involved the selection of configurations which met the study assumptions outlined in the introduction. These configurations were selected from previous studies, other relevant literature, and personal contact with potential users of deployable LSS. The second subtask was to perform a NASTRAN analysis of the selected configurations. To do this, detailed section properties were formulated using existing preliminary designs or in some cases derived section properties from known data such as structural frequency and member mass properties. NASTRAN models were then developed and a normal modes analysis executed. The final characterization subtask estimated the effects of changing the primary transfer acceleration for LEO-GEO transfer of the deployed LSS. Loading equations were develoed which showed the sensitivity of system mass to changing acceleration levels. Key assumptions in Task 1 are outlined in Table 1 below.

Table 1. Task 1 Assumptions

1.1 Selection of Configuration

- Civilian GEO missions (exception SOC & SASP)
- Single shuttle launched
- Preliminary designs available

1.2 NASTRAN Analysis

- Modeling was done to the level of detail available
- Section mass properties & g-load were given from the literature
- Analysis conducted for .15 g's

1.3 G-Loading Effects

- Individual elements scaled
- Uniform mass distribution for each element

In Subtask 1.1 the focus of the study is shown to center around antenna systems that are deployed in LEO by a single shuttle and then transferred to GEO for their operational life. The NASTRAN analysis was conducted for .15 g's because the section properties available showed that .15 g's strength produced the first modal frequency expected of .1 Hz. This frequency was determined to be reasonable based on the data available in the preliminary designs and on the Boeing Company's previous experience with other LSS. In the g-loading analysis critical elements such as antenna support booms, solar array booms, and other truss structures were analyzed individually which resulted in a very detailed g-load sensitivity model. Differences in the overall scaling of mass with g-load in this study and others (Ref. 1) were attributed to this detailed modeling.

The key issues which drove the selection and characterization of each LSS were threefold. First, the mission opportunities were made as broad as possible. Mission selection included electronic mail, direct TV broadcast, mobile communications, forest fire detection and others. Configurations selected spanned all of these missions and are felt to be representative of LSS for the 1990's. Configurations were also selected so as to span the range of propulsion requirements. Wide variations in center of pressure/center of gravity, inertia matrices, and area/mass ratios were sought. Critical structure element definition was also a key issue because it drove the NASTRAN modeling results and consequently the thruster/structure interactions conclusions.

1.1 Selection of Configurations

A set of six preliminary designs which pose a wide range of propulsion requirements was selected in this subtask. The designs are sufficiently detailed to allow good fidelity in defining APS requirements and APS/LSS interactions. At the same time, these designs may be used for a variety of purposes by simply changing the electronics and/or scaling the LSS either up or down in size. The classes and representative missions are in Table 2 and discussed in more detail in Appendix A.

Each of the generic classes selected fits the study ground rules of a single shuttle launch with the exception of the SOC which will be considered as representative of a multiple shuttle launched LSS of the 1990's. The scaling of each LSS from the baseline also fits the ground rules of a single shuttle launchable LSS with an assumed orbit transfer propulsion to GEO. Figures 2, 3, and 4 show the configurations selected for analysis in this study.

Table 2. Generic Class Selection

Class		Example Mission
I	Large Aperature Phase Array Antenna	Personal communications, educational TV, electronic mail
II	Land Mobile Satellite System - Wrap Rib	Mobile communications, space based radar, jamming satellites
III	Land Mobile Satellite System - Hoop Column	Mobile communications, personal communications
IV	Geostationary Platform - Option 4A	Contains many separate payloads
V	Science and Applications Space Platform (SASP)	Has 25 kw or 12.5 kw power supply for various payloads
VI	Space Operations Center (SOC)	Manned operations center which provides a location for construction, flight support, servicing, research, and testing.

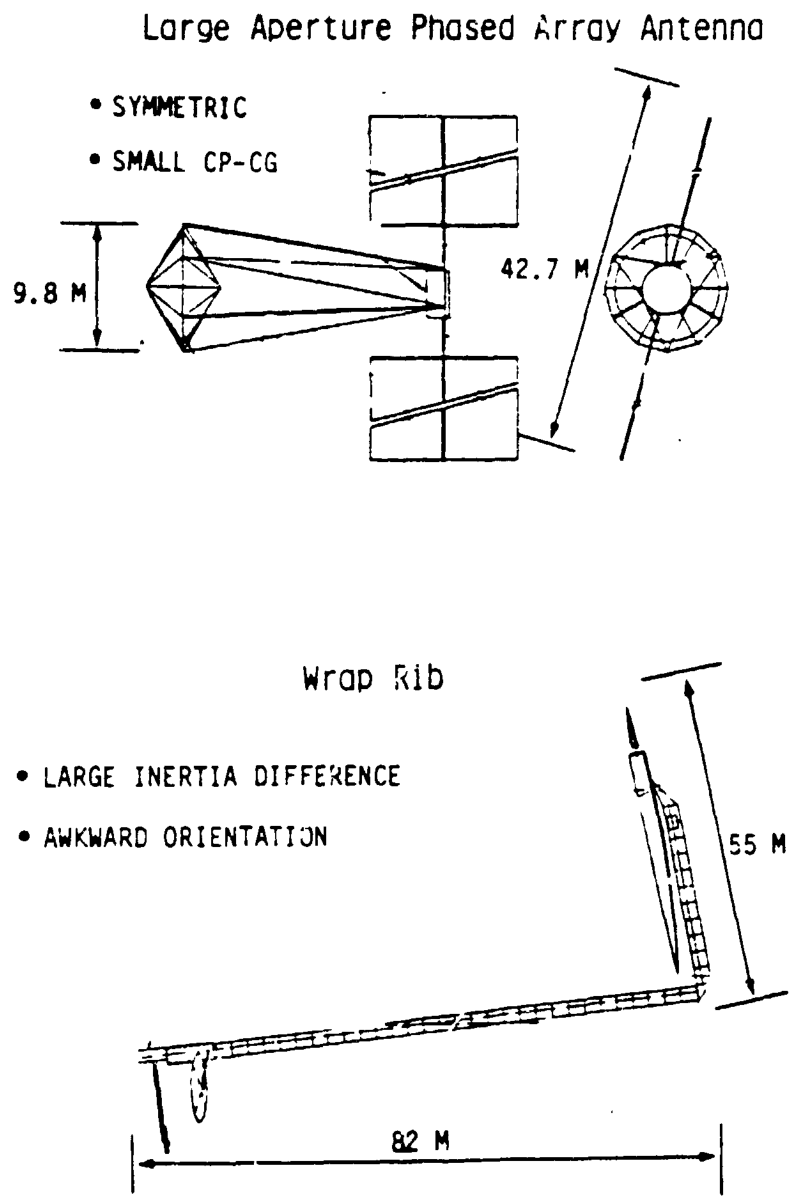

FIGURE 2. PHASED ARRAY AND WRAP RIB ANTENNAS

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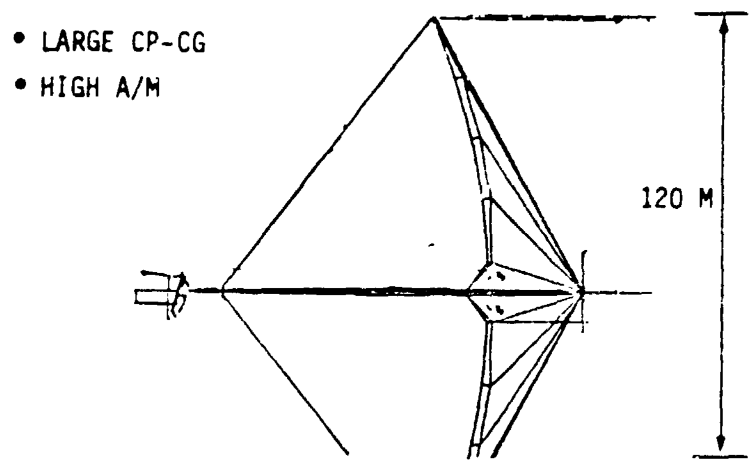
Hoop Column



Geoplatform

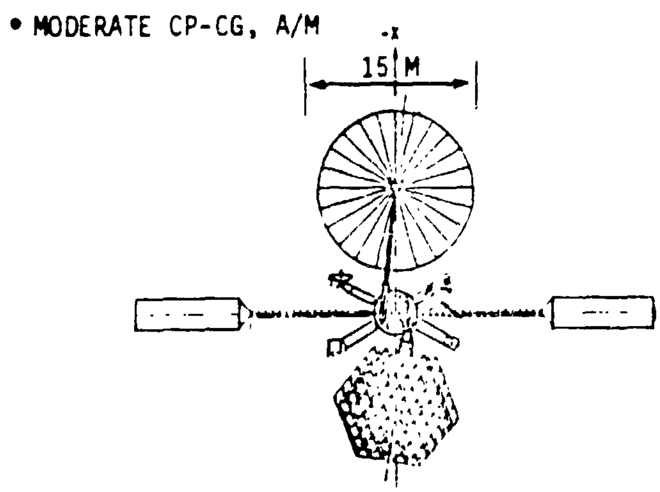


FIGURE 3. HOOP COLUMN ANTENNA AND GEOPLATFORM DESIGNS

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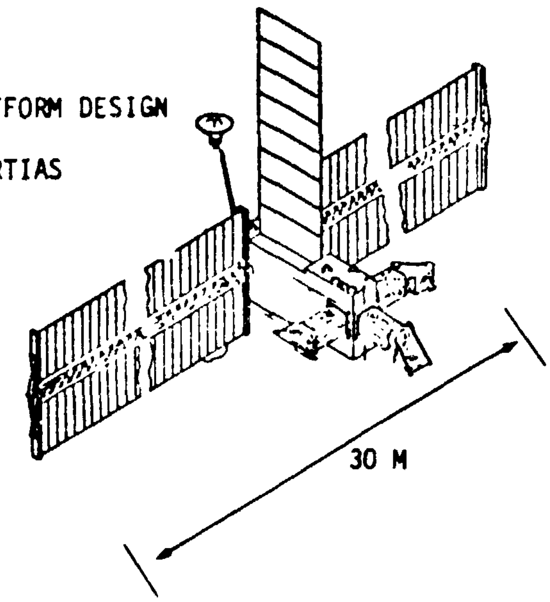
SASP

- REPRESENTATIVE SPACE PLATFORM DESIGN
- LARGE MASS, MODERATE INERTIAS
- MODERATE A/M



SOC

- REPRESENTATIVE SPACE STATION DESIGN
- VERY LARGE MASS, INERTIAS
- LOW A/M

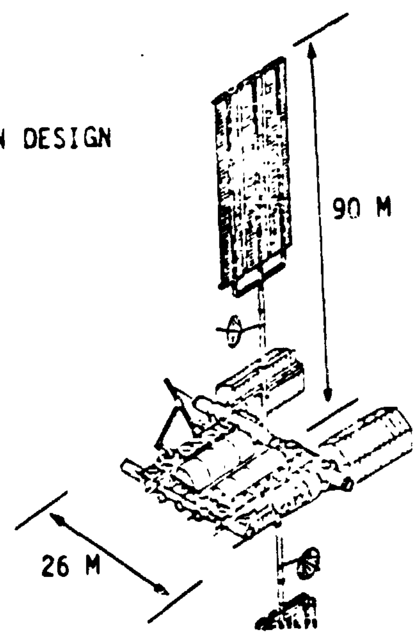


FIGURE 4. SASP AND SOC SPACE PLATFORMS

The Large Aperture Phased Array and SASP were sized using two already designed versions with the main difference in each design being the power requirement. Therefore, the main sizing change is in the solar arrays. The SOC is sized using two of its designed versions - the initial baseline and the operational baseline. The operational baseline is a growth of the initial baseline and has more elements, mass, and area. The other three generic classes will be sized using scaling outlined in Appendix A.

Four generic classes were chosen to investigate for their g-loading characteristics. These are Large Aperture Phased Array Antenna, LMSS - Wrap Rib, LMSS - Hoop Column, and the Geostationary Platform. Each of these structures is designed with critical elements closely associated with flexible members and, therefore, most susceptable to changes in mass and packaging characteristics due to g-loading. Three g-loading designs will be determined for each of these four structures and sizes.

The SOC and SASP were not studied for g-loading effects because of their relatively rigid structure. Their critical elements are concentrated in a central and rigid mass area with only the solar arrays extending from flexible members. Solar array support structures may be stiffened, if necessary, without significant impact on mass or auxiliary propulsion requirements. An additional reason not to look at varying g-loading characteristics of the two space platform designs is to avoid a proliferation of separate designs, sizes, and g-loading parameters. Such a large number of discrete cases would take away from the major thrust of this study. Table 3 shows the sizes selected for each generic class.

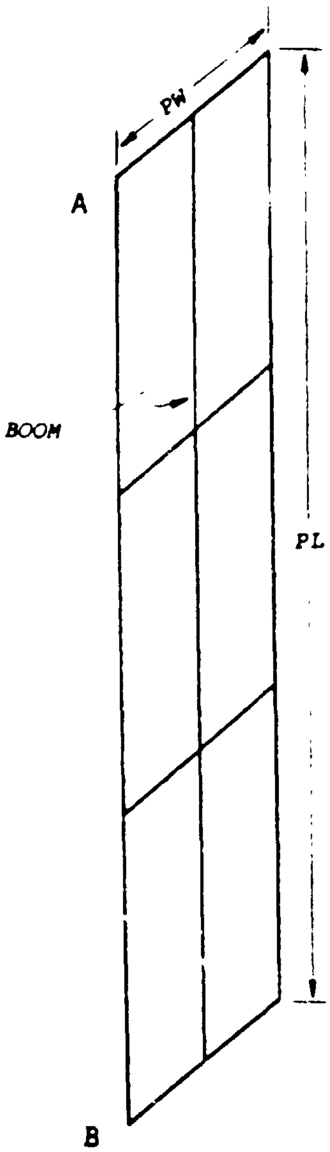
1.2 NASTRAN Analysis

NASA Structural Analyzer (NASTRAN) models were developed to be used in the thruster/structure interactions study conducted in Task 2. To develop these models detailed mass property and section properties had to be determined. Once the mass, material, and dimensions of a given element was determined, the various sections could be linked together by specifying the stiffness properties at the interfaces. In addition to the interface point, node points along truss work, columns, and other elements had to be specified. This process was a tedious one and forced the study to consider only the antenna systems for NASTRAN modeling.

To avoid duplication and thus save time, general models of components common to more than one class of LSS (i.e., solar arrays) were defined. These components are combined with components unique to each class of structure. Figure 5 shows the general model of just such a component - the solar array. When the models were completed, we used a NASTRAN dynamic analysis to determine the structural frequencies and mode shapes of each LSS design.

Table 3. Generic Class Sizes

LSS	Size
I Large Aperture Phase Array Antenna	
Electronic Mail	10 kw
Educational TV	65 kw
II LMSS - Wrap Rib Antenna	55 m (antenna diameter) 25 m (antenna diameter)
III LMSS - Hoop Column Antenna	120 m (antenna diameter) 60 m (antenna diameter)
IV Geostationary Platform	50 x 33 m (9 payloads)
V Science & Applications Space Platform (SASP)	
12.5 kw	12.5 kw
25.0 kw	25.0 kw
VI Space Operations Center (SOC)	
Initial	120 m x 16 m (2 shuttles)
Operational	120 m x 25 m (5 shuttles)



SOLAR ARRAY

PW = panel width
PL = panel length
NDIV = divisions along panel length (shown as =3)
PWT = wt/unit area of panel
STIFWT = wt/unit length of stiffening bar at end A
BOXWT = wt/unit length of box in which panel is stored before deployment (end B)
BAREA = cross sectional area of boom
BMOMX = area moment of inertia of boom about x axis
BMOMY = area moment of inertia of boom about y axis
BOOMWT = wt/unit length of boom

FIGURE 5. GENERAL MODEL OF THE SOLAR ARRAY

Large Aperture Phased Array

The following is a description of the NASTRAN model of the Large Aperture Phased Array employed for the analysis. All components described are labeled in Figure 6. The column, array astromasts, and main astromasts were modeled as triangular trusses made of graphite epoxy tubes with tie rods. The antenna rim was modeled as a graphite/epoxy tube in twelve segments. The lens staves and stabilizing lines were assumed to be graphite rods. Section properties for all members are shown in Table 4.

The three lens films in the antenna were assumed to be 2 mils (5.067×10^{-5} m) thick each. Design stress for each lens was assumed to be 20 n/m^2. The tension in the three lens was modeled with rod elements between the rim and column. Each solary array was modeled as a bar with rigid body elements across its width. The feed horn cluster and cylinder were modeled as a rigid body.

The weight breakdown for the entire structure is summarized in Table 5. The weight of the lens (includes the weight of the phase shifters) was distributed as follows: 50% at twelve points around the rim, 45% at the center of the column, and 2.5% at each end of the column. The weight of the antenna rim was distributed evenly along its length as was that of the column. The weight of the antenna rim was distributed evenly along its length as was that of the column. The weight of the main astromasts was also distributed evenly along their lengths. For the array astromasts the weight of the wiring and astromasts was divided in half and lumped at either end - half at the feed horn, half at the edge of the array. The weight of the antenna feed, all the equipment inside the cylinder was lumped at the center of the cylinder. The array orientation equipment was assumed to be on the main structure, so its weight was also lumped at the center of the cylinder. The weight of the solar arrays was lumped at either end of the panel assuming the following breakdown:

- 82% panel
- 10% boom along center of panel
- 5% box in which panel is stored
- 3% stiffening rod at far end of panel

Pretension loads of 6.0 N in the staves and 12.0 N in the stabilizing lines were applied to prevent these members from going slack under a 0.06 g load applied at the antenna feed. Pretension loads in the staves and lens produced a differential stiffness matrix. This matrix was input to a NASTRAN Normal Modes Analysis to find the natural frequencies and mode shapes of the structure. The first, second, and third mode frequencies are .093, .110, and .160 Hz. Mode shapes for these three modes are shown in Figure 7, 8 and 9.

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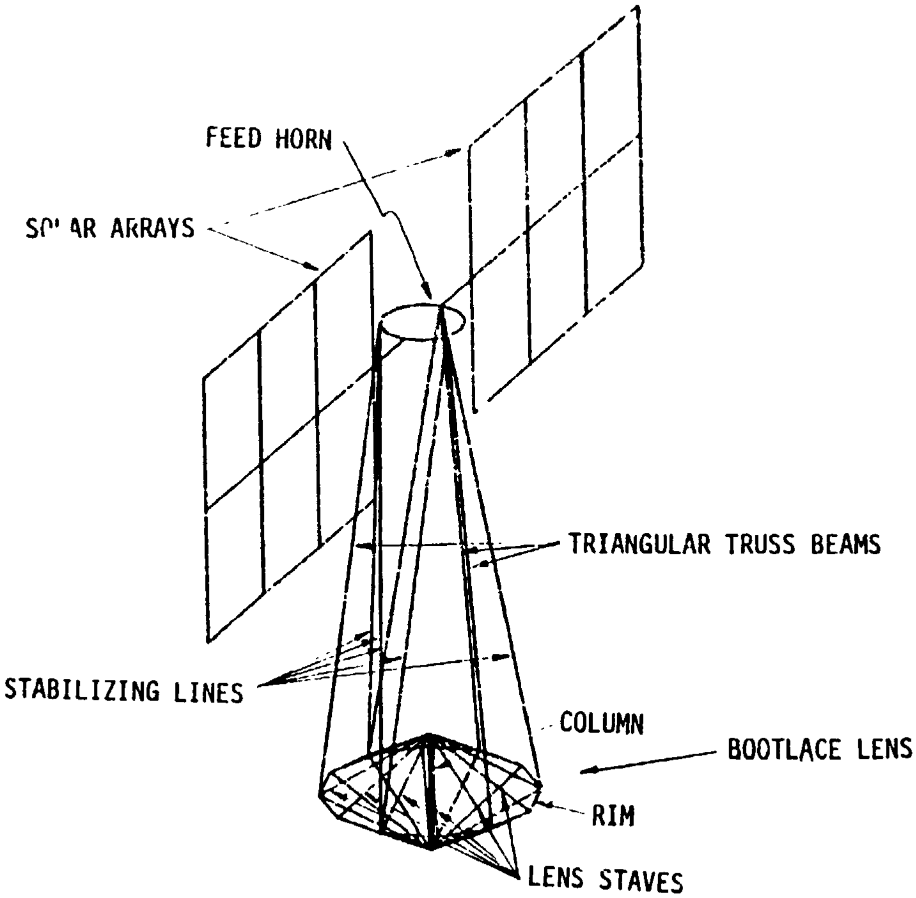
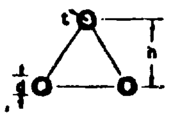
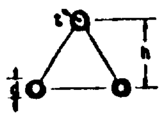
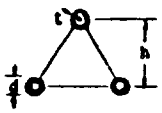


FIGURE 6. LARGE APERTURE PHASED ARRAY ANTENNA - NASTRAN MODEL

TABLE 4. PHASED ARRAY ANTENNA ASSUMED SECTION PROPERTIES

MEMBER	VIEW OF MEMBER X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL	$A(m^2)$***	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
COLUMN		BAR	triangular truss d = .010 m t = .001 m h = .05 m	GR/EP *	8.48E-5	4.80E-8	4.80E-8	9.60E-8
ARRAY ASTROMASTS		BAR	triangular truss d = .016 m t = .001 m h = 0.40 m	GR/EP *	1.41E-4	5.03E-6	5.03E-6	1.01E-5
ASTROMASTS		BAR	triangular truss d = .012 m t = .001 m h = 0.16 m	GR/EP *	1.04E-4	5.91E-7	5.91E-7	1.18E-6
RIM		BAR	tube d = .034 m t = .001 m	GR/EP *	1.04E-4	1.41E-8	1.41E-8	2.82E-8
STAVES		ROD	rod d = 1.01 mm	GR **	8.01E-7	–	–	0
STABILIZING LINES		ROD	rod d = 1.01 mm	GR **	8.01E-7	–	–	0

* GR/EP TUBE: $E = 73.7 \times 10^9\ N/M^2$, $\nu = 0.15$
** GR RODS: $E = 83.0 \times 10^9\ N/M^2$, ν = 0.[illegible]4
*** A = Combined x-sectional areas of all three longerons

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<u>ANTENNA</u>	
RIM (assume 1.8 KG/M, 30.18 M)	54.2
LENS, STAVES, PHASE SHIFTERS, ETC.	207.2
COLUMN (1.8 KG/M, 5.49 M)	9.8
	271.2
<u>ASTROMASTS</u>	
3 @ 1.8 KG/M 21.9 M each	103.2
<u>ANTENNA FEED</u>	109.5
<u>CYLINDER</u>	
60% BASIC STRUCTURE	251.1
ELECTRICAL	979.6
MISSION	524.9
	1755.6
<u>SOLAR ARRAYS</u>	
2 @ 285.1	570.1
<u>ARRAY ORIENTATION</u>	
ARRAY ORIENTATION EQUIP	481.9
ARRAY BOOMS (1.8 KG/M, 5.76 M EACH)	45.3
	527.2
TOTAL	3337 KG

TABLE 5. MASS BREAKDOWN

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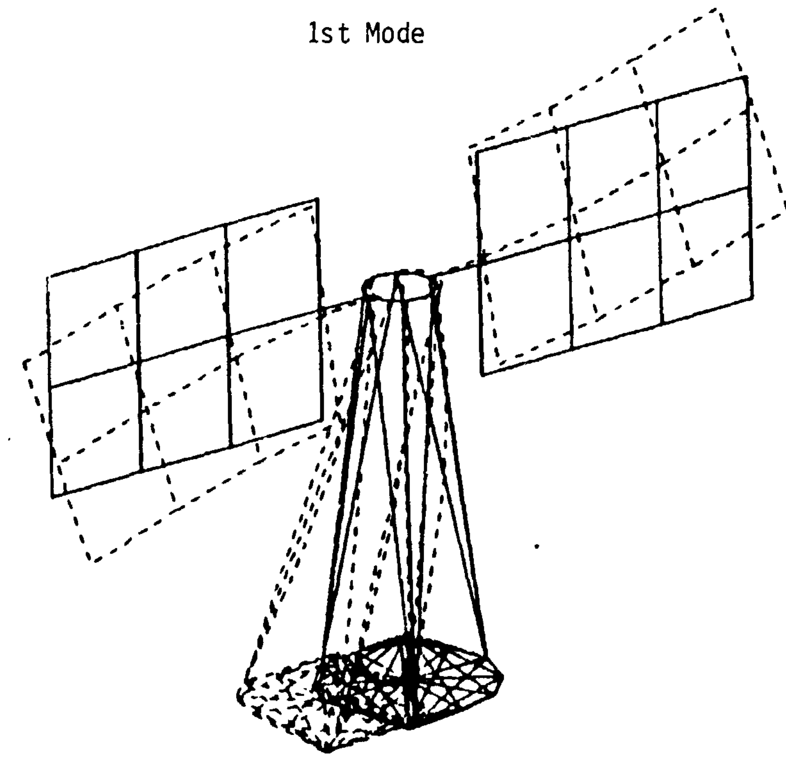

FIGURE 7. LARGE APERTURE PHASED ARRAY ANTENNA

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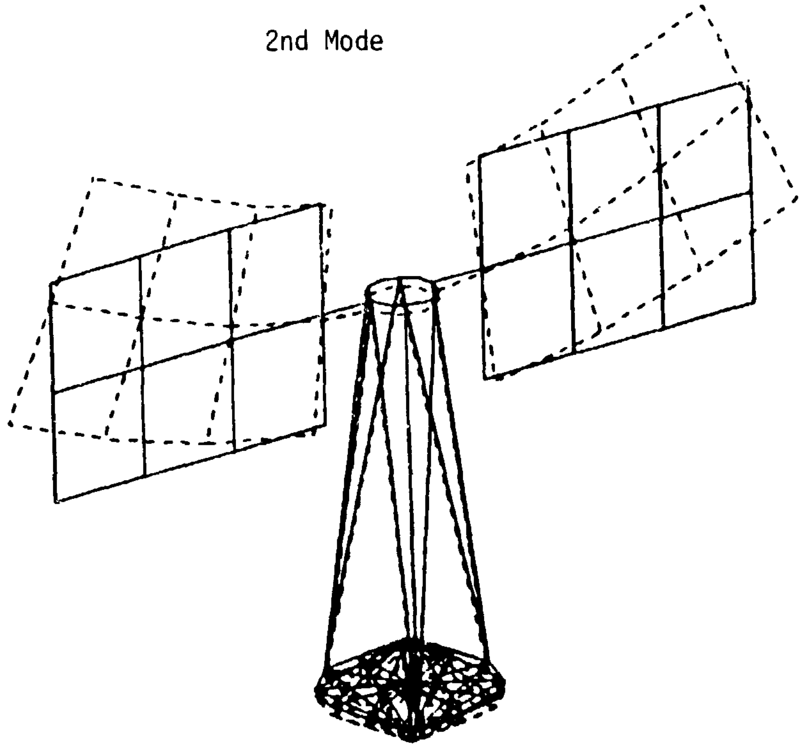


FIGURE 8. LARGE APERTURE PHASED ARRAY ANTENNA

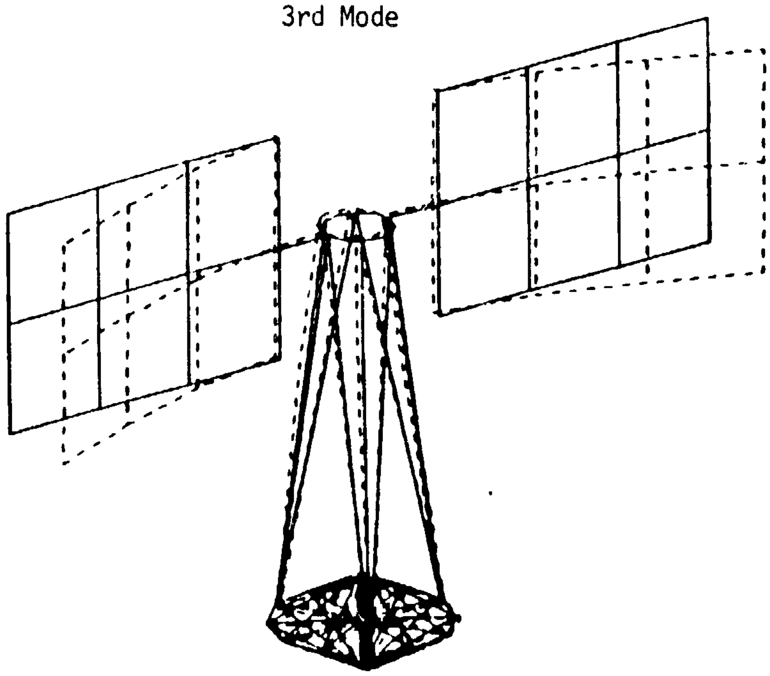


FIGURE 9. LARGE APERTURE PHASED ARRAY ANTENNA

LMSS - Wrap Rib

The following is a description of the NASTRAN model developed from the design of the Land Mobile Satellite System (LMSS) - Wrap Rib employed for the analysis. The components of the LMSS are labeled in Figure 10.

The inbound and outbound UHF booms, boom housing, solar array mast, solar array booms, and s-band reflector boom were modeled as triangular graphite/epoxy trusses. The UHF feed support and s-band feed boom were modeled as hollow graphite/epoxy tubes. The radial ribs in both reflector surfaces were modeled as hollow, collapsable, lenticular-shaped tubes of graphite/epoxy. The circumferential rings in both reflector surfaces were modeled as graphite rods. The bus was modeled as a solid cylinder. The molybenum mesh surface of each reflector was modeled as a thin membrane. The mesh was assumed to have the stiffness of a membrane 2 mils (5.067E-5 m) thick made of Kapton (E = 1.0E9 N/m). Although the actual reflectors will have pretension in the ribs and mesh to hold the mesh taut, there was insufficient design detail to include the effects of pretension at the time of this analysis. The section properties of all members are shown in Table 6.

Each solar array was modeled as a bar with rigid body elements across its width. The UHF feed was modeled in the same way.

The mass breakdown for the entire structure is summarized in Figure 11. The mass of the UHF booms and cables was distributed evenly along the booms. The mass of each reflector was lumped at the center of each reflector. The mass of the UHF feed was lumped as follows: 1/4 mass at the top edge and 3/4 mass at the bottom edge. The mass of the s-band feed was lumped at a point 0.3 meters from the end of the bus (0.3 meters in the x-y plane as shown in Figure 10). The mass of the following were lumped in the bus: RF electronics, control equipment and sensors, 1/2 solar array mast and mechanism, batteries and power conditioner, and the bus structure, cabling, T/C and cage. The mass of the outbound reaction wheels and sensors were lumped at the center of the UHF reflector. The mass of the inbound reaction wheels and sensors and 1/2 the mass of the s-band reflector boom were lumped in the boom housing. The mass of the solar array booms and 1/2 the mass of the solar array mast was lumped at the end of the solar array mast. The remaining mass of the solar arrays was lumped at either end of each panel assuming the following mass breakdown:

82% panel
10% boom along center of panel
5% box in which panel is stored
3% stiffening rod at far end of panel

A NASTRAN Normal Modes Analysis was employed to find the natural frequencies and mode shapes of the structure. The first, second, and third mode frequencies are 0.105, 0.111, and 0.131 Hz. Mode shapes for these three modes are shown in Figures 12, 13 and 14.

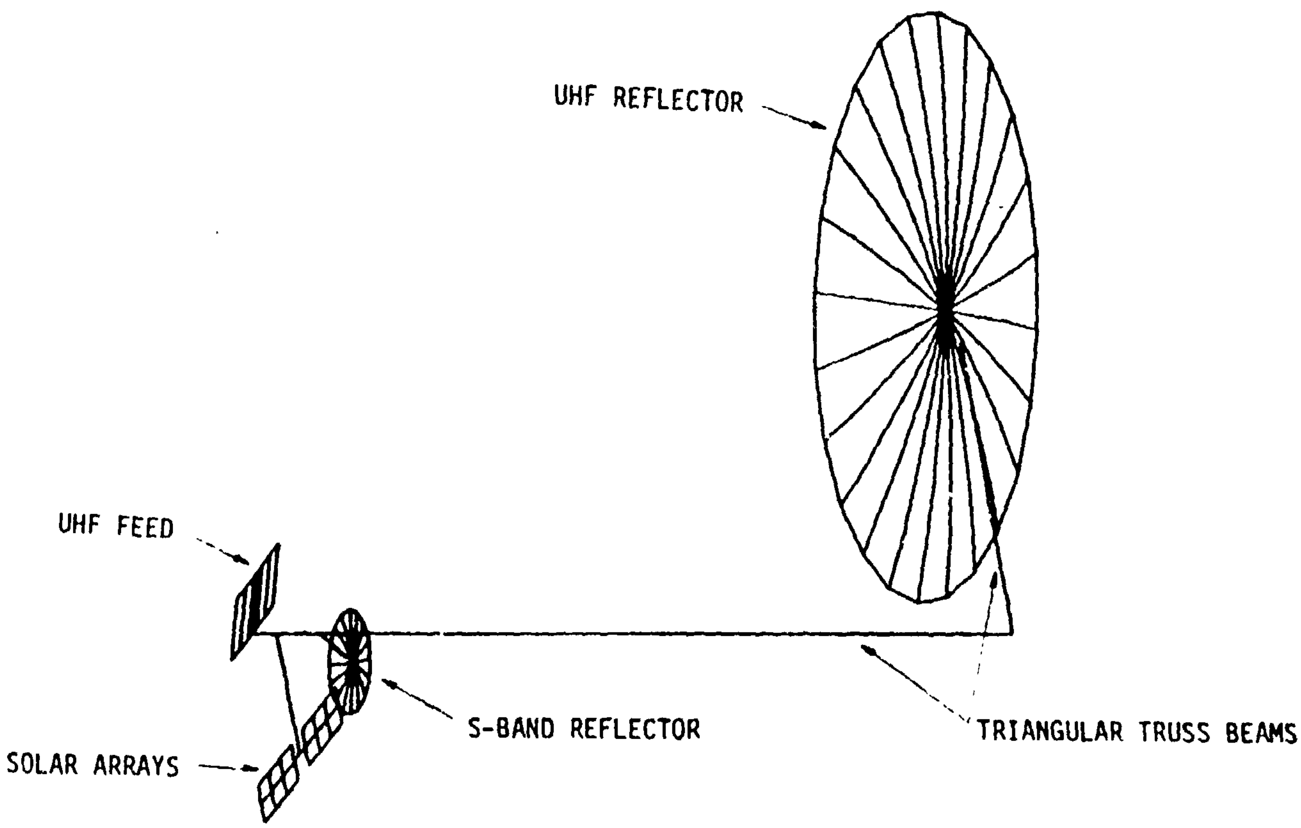


FIGURE 10. LMSS WRAP RIB - NASTRAN MODEL

TABLE 6. LMSS - WRAP RIB ASSUMED SECTION PROPERTIES

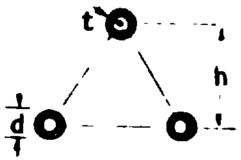
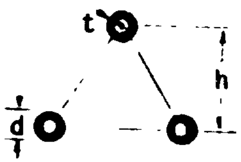
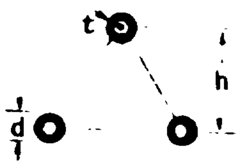
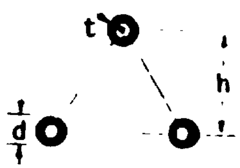
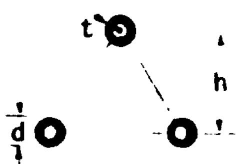
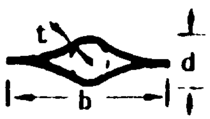
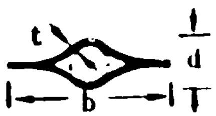
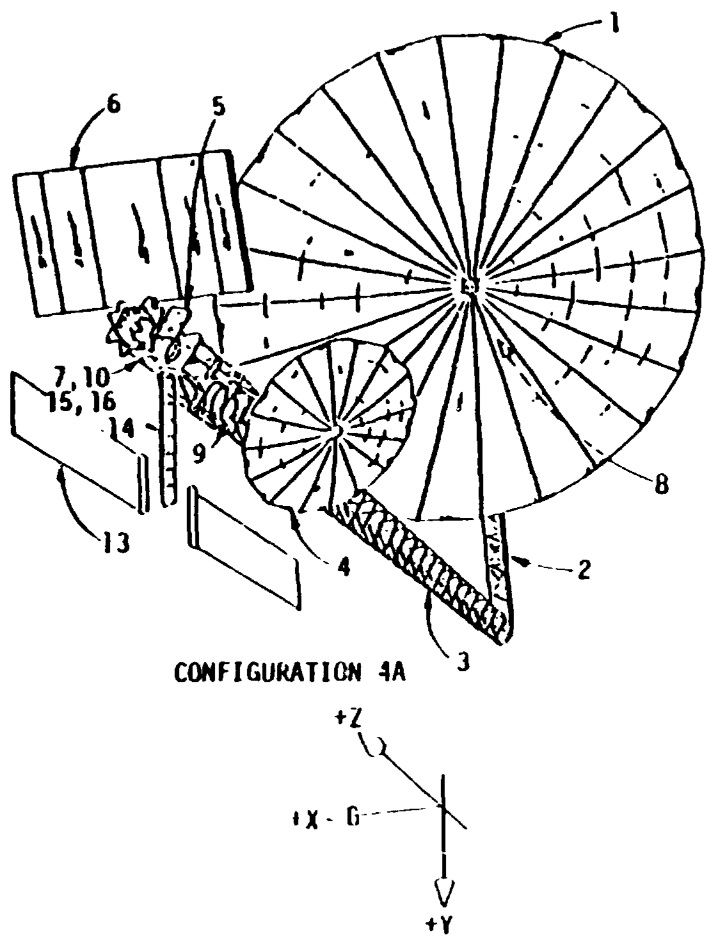
MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
UHF BOOMS		BAR	triangular truss d = 0.025 m t = 0.001 m h = 1.80 m	GR/EP	2.26E-4	1.63E-5	1.63E-4	3.26E-4
UHF BOOM HOUSING		BAR	triangular truss d = 0.050 m t = 0.005 m h = 1.88 m	GR/EP	2.12E-3	1.67E-3	1.67E-3	3.33E-3
S-BAND REFLECTOR BOOM		BAR	triangular truss d = 0.008 m t = 0.001 m h = 0.10 m	GR/EP	6.59E-5	1.47E-7	1.47E-7	2.94E-7
SOLAR ARRAY MAST		BAR	triangular truss d = 0.025 m t = 0.001 m h = 0.38 m	GR/EP	2.26E-4	7.27E-6	7.27E-6	1.45E-5
SOLAR ARRAY BOOMS		BAR	triangular truss d = 0.006 m t = 0.001 m h = 0.35 m	GR/EP	4.71E-5	1.28E-6	1.28E-6	2.56E-6
UHF FEED SUPPORT		BAR	tube d = 0.064 t = 0.002	GR/EP	3.89E-4	1.87E-7	1.87E-7	3.75E-7

TABLE 6. LMSS - WRAP RIB ASSUMED SECTION PROPERTIES (CONTINUED)

MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
S-BAND FEED BOOM		BAR	tube d = 0.012 t = 0.001	GR/EP	3.45E-5	5.27E-10	5.27E-10	1.05E-9
BUS		BAR	solid cylinder d = 1.50 m	GR/EP	1.77E+0	2.49E-1	2.49E-1	4.97E-1
UHF REFLECTOR RIBS		BAR	collapsable lenticular d = 0.036 m t = 0.001 m b = 0.150 m	GR/EP	3.00E-4	1.68E-8	5.05E-8	6.73E-8
S-BAND REFLECTOR RIBS		BAR	collapsable lenticular d = 0.015 m t = 0.001 m b = 0.07 m	GR/EP	1.40E-3	1.08E-9	3.25E-9	4.33E-9
UHF REFLECTOR RINGS		ROD	rod d = 1.01 mm	GR	8.01E-7	-	-	0
S-BAND REFLECTOR RINGS		ROD	rod d = 1.01 mm	GR	8.01E-7	-	-	0
UHF REFLECTOR MESH		CQUAD4 & CTRIA3	membrane t = 5.0E-5 m (2 mils)	Molybdenum	-	-	-	-
S-BAND REFLECTOR MESH		CQUAD4 & CTRIA3	membrane t = 5.0E-5 m	Molybdenum	-	-	-	-

* GR/EP TUBE: $E = 73.7 \times 10^9$ N/M^2, $\nu = 0.15$
GR ROD: $E = 83.0 \times 10^9$ N/M^2, $\nu = 0.34$
MOLYBDENUM MESH: $E = 1.0 \times 10^9$ N/M^2, $\nu = 0.33$
(aluminized kapton)

** A = combined x-sectional areas of all three longerons for triangular trusses



ITEM	WEIGHT KGS	WEIGHT LBS
1. UHF REFLECTOR & BOOM ATTACH	336	740
2. UHF BOOM-OUTBD & CABLE	41	90
3. UHF BOOM-INBD & CABLE	95	210
4. S-BAND BOOM & REFLECTOR	68	151
5. S-BAND FEED	78	171
6. UHF FEED	1166	2571
7. RF ELECTRONICS IN BUS	227	500
8. REACTION WHEELS & SENSORS - OUTBD	40	88
9. REACTION WHEELS - INBD 10. CONTROL EQUIP & SENSORS - BUS	256	565
13. SOLAR PANELS	166	367
14. SOLAR PANEL MAST & MECH	50	110
15. BATTERIES & POWER COND	131	288
16. BUS STRUCT, CABLING, T/C, & CAGE	386	850
TOTAL	3040	6791

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FIGURE 11. LMSS WRAP RIB WEIGHT STATEMENT

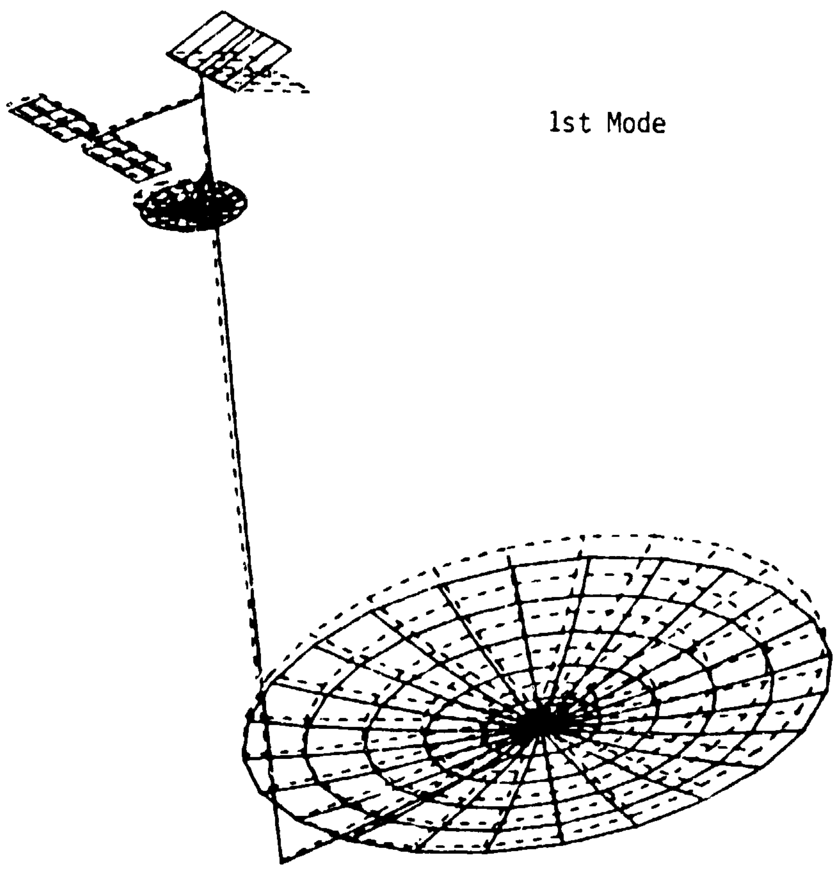

FIGURE 12. LMSS WRAP RIB

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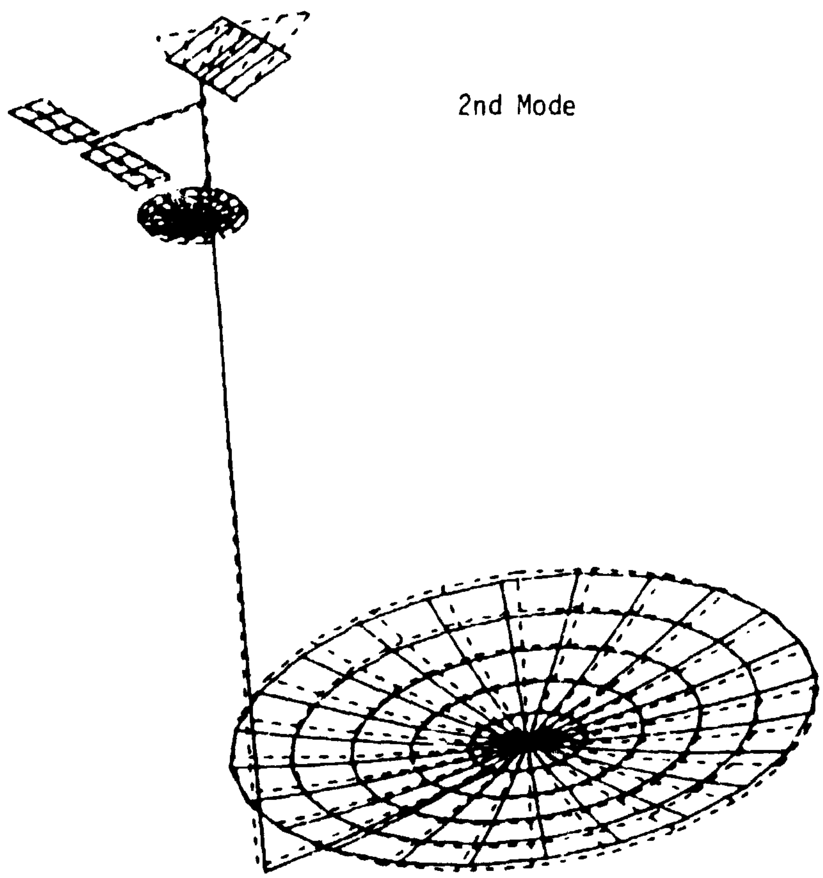


FIGURE 13. LMSS WRAP RIB

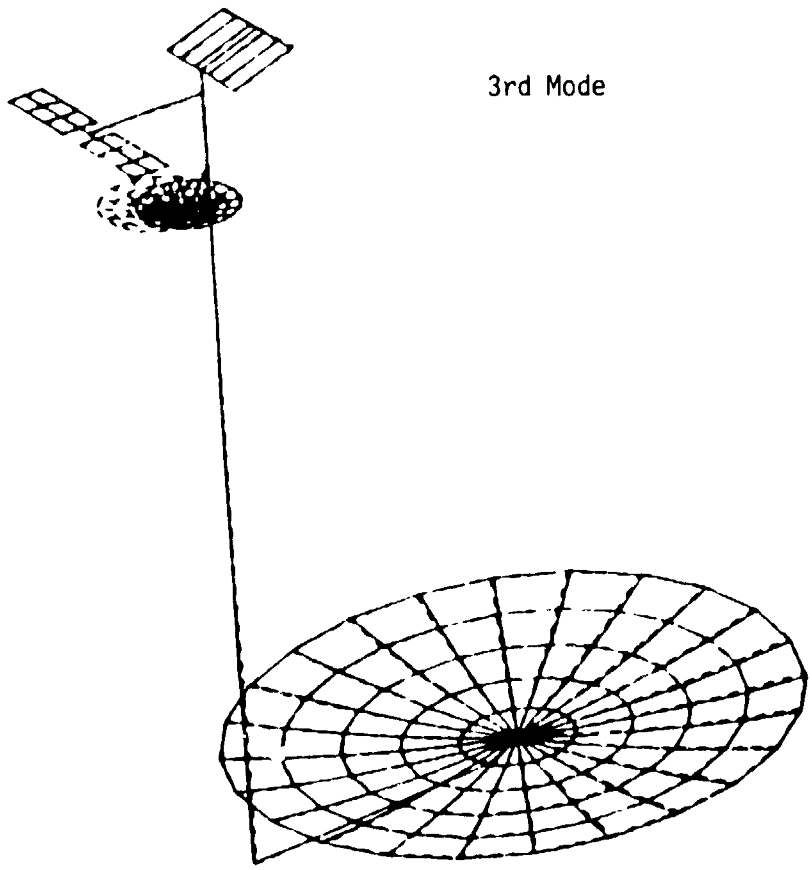


FIGURE 14. LMSS WRAP RIB

Based on the preliminary results, the finite element model will be modified as follows: the UHF feed support will be stiffened, and the mass of the UHF reflector ribds and mesh will be distributed to several grids on the reflector surface, rather than lumped at the center.

LMSS - Hoop and Column

The NASTRAN finite element model shown in Figure 15 consists of 282 grid-points and 555 elements and has 279 dynamic degrees-of-freedom. The central column is a telescoping open lattice truss structure made of graphite epoxy tubes and cables. It has a hexagonal cross section and is modeled as 24 bar elements all with the same cross sectional area but with area moments which are a function of the radius of each segment. The hoop is modeled as a .076 m diameter, 1. mm wall hollow graphite/epoxy tube. To reduce the number of degrees-of-freedom, the hoop is divided into 24 segments instead of the 48 segments shown in configuration drawings. The cables which support the hoop and the reflector surface are .00127 m diameter graphite rods (Celion fiber). To simplify the complex system of cables used to support and manage the reflector surface's shapes, the surface is modeled as a single gridwork of membrane elements bounded by graphite reinforcement ties (rod elements) to which the conical cable arrays are attached. The molybdenum mesh reflector surface cha characterisitcs are assumed to be approximated by a 2 mil (5.08E-5 meter) thick Kapton film (E = 1.0E9 N/m^2). To provide torsional stiffness to the antenna, the cables arranged in a "bicyle spoke" configuration. Otherwise there would be no torsional stiffness until geometric nonlinearities become effective.

Each of the four feed assemblies is modeled as a lumped mass located at its center and supported by a bar element sized to represent the characteristics of the tripod support shown in configuration drawings. Each solar array is modeled as a flexible bar with rigid elements across its width. The +Z solar array supports are modeled as .0254 m diameter graphite/epoxy tubes with .2 mm wall thickness. The -Z solar array support booms are modeled as triangular graphite/epoxy truss beams. The section properties of all structural elements are shown in Table 7.

The mass breakdown for the Hoop and Column LMSS is shown in Figure 16. The mass of the column is distributed uniformly along its length (the circumferential and diagonal structural elements are assumed to be a small percentage of the total column mass). The hoop mass and reflector mass are also uniformly distributed. The feed mass is divided between the four feeds and lumped at the center of each. The mass distribution for each solar array is as follows:

82% panel
10% boom along center of panel
5% box in which panel is stored
3% stiffner at outboard end of panel

The mass of the solar array support boom is divided between the inboard end of each solar array and the bus to which it is attached. The mass of the s-band feed and reflector are lumped in the +Z bus.

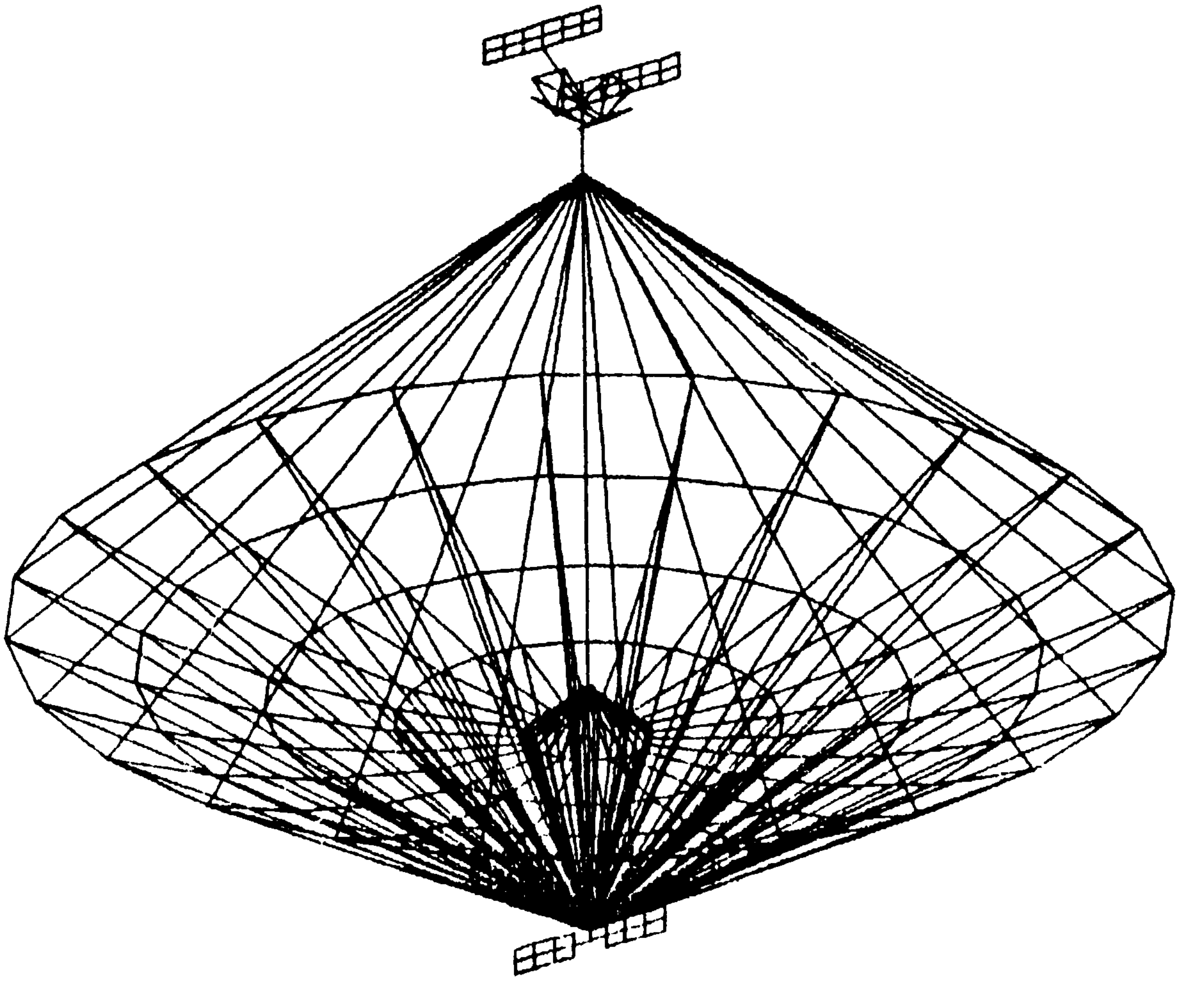


FIGURE 15. HOOP & COLUMN ANTENNA (LMSS) UNDEFORMED SHAPE

TABLE 7. ASSUMED SECTION PROPERTIES OF HOOP & COLUMN LMSS

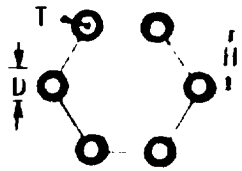
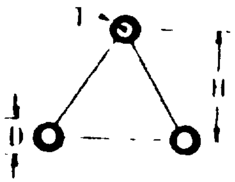
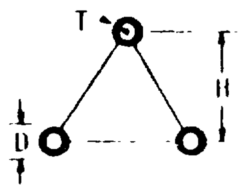
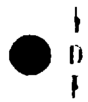
MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
COLUMN		BAR	HEXAGONAL TRUSS COLUMN D = .0228 m T = .00155 m H = Varies from .657 at the hub (center) to .259 m at each end	GR/EP	3.71E-3	Varies from 7.96E-5 to 1.07E-3	Varies from 7.96E-5 to 1.07E-3	Varies from 1.59E-4 to 2.13E-3
-Z SOLAR ARRAY ASTROMASTS & SUPPORT BOOMS		BAR	TRIANGULAR TRUSS R = .114 m D = .0127 m T = .001 m	GR/EP	1.10E-4	8.53E-7	8.53E-7	1.71E-6
+Z SOLAR ARRAY ASTROMASTS		BAR	TRIANGULAR TRUSS R = .114 D = .016 T = .001	GR/EP	1.41E-4	1.06E-6	1.06E-6	2.12E-6
+Z SOLAR ARRAY SUPPORT BOOMS		BAR	TUBE D = .0508 m T = .001 m	GR/EP	1.56E-4	5.15E-8	5.15E-8	1.03E-7
HOOP		BAR	TUBE D = .1524 m T = .001 m	GR/EP	4.79E-4	4.40E-7	4.40E-7	8.80E-7
FORE AND AFT CABLES		ROD	ROD D = 1.27E-3 m	CELION	1.27E-6	-	-	-

TABLE 7. ASSUMED SECTION PROPERTIES OF HOOP & COLUMN LMSS (CONTINUED)

MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
TIES IN REFLECTOR SURFACE		ROD	ROD D = 5.43E-4m	CELION	2.32E-7	-	-	-
REFLECTOR MESH		QUAD4	MEMBRANE t = 5.08E-5m	KAPTON	-	-	-	-

* GR/EP FOR HOOP & COLUMN: $E = 110 \times 10^9\ N/m^2$, = 0.3

GR/EP FOR ALL OTHER: $E = 172 \times 10^9\ N/m^2$, = 0.3

CELION: $E = 172 \times 10^9\ N/m^2$, = 0.3

KAPTON: $E = 1.0 \times 10^9\ N/m^2$, = 0.3

** A = COMBINED X-SECTIONAL AREA OF ALL LONGERONS

676	Column, Cables & Electrical Cabling
304	Hoop & Insulation
99	Reflector
76	-Z Solar Panels
154	+Z Solar Panels
59	S-Band Reflector
116	S-Band Feed, Boom, Coaxes
116	-Z Bus Structure, Batteries, Power Conditioner and Insulation
239	+Z Bus Structure, Batteries, Power Conditioner and Insulation
1070	Feeds & Electronics
2909 kg	Total

Figure 16. Hoop & Column LMSS Mass Breakdown

A NASTRAN buckling analysis was performed to obtain the differential stiffness matrix resulting from pretension in the hoop cables and the reflector surface. The preloads were applied to both the forward and aft hoop cable arrays and to the outboard edge of the reflector surface. The tension required in each aft hoop cable to prevent the forward cables from going slack at an orbit transfer g-load of 0.15 g is calculated to be 42. N. A reflector surface tension force at each of the 24 hoop attachments is aribitrarily chosen to be 10.0 N. The resulting differential stiffness maxtrix was used in a NASTRAN normal modes analysis to determine mode shapes and natural frequencies. The first three modal frequencies are 0.114, 0.118 and 0.138 Hz and are associated with motion of the +Z solar arrays (Figures 17, 18 and 19). The first mode which involves significant motion of the hoop/column is the ninth flexible mode whose frequency is 0.6 Hz. This mode is a torsion mode (Figure 20) where the column (including feeds and solar arrays) rotates about its axis and the hoop rotates in the opposite direction.

Experimental Geostationary Platform

The dynamic analysis of the Baseline Experimental Geostationary Platform 9BXGP) is described below. Where data was available, dimensions and member sizes are those given by General Dynamics, Convair Division. The wrap-rib and peta antenna booms, and the array astromasts were modeled as "Convair deployable trusses." The array support booms were modeled as triangular trusses (1/2 Convair deployable trusses). All trusses were assumed to have graphite/epoxy longerons and graphite tie rods between the longerons. The central core was modeled as a solid cylinder and was assumed to be a rigid body. The radiator and experiments 301, 501, 502 and 604 are attached to the core structure with "Convair space rails." Each space rail was modeled as a graphite/epoxy-honeycomb sandwich plate connected to a graphite/epoxy longeron with graphite tie rods to form a triangular cross section (see Figure 15). The section properties of all members are shown in Table 8.

The mass breakdown for the structure is summarized in Figure 21. The mass of the reflector booms was distributed evenly along each boom. The mass of each reflector was lumped at its center. The masses of the radiator, experiments 310, 501, 502 and 604, along with 1/2 the mass of each space rail was lumped at the outboard end of the space rails (501 and 502 are attached to the same space rail). The mass payload 401 was lumped at a point approximately 5 meters from the center of the core. The mass of payload 123 was lumped on the space rail which supports payloads 501 and 502. The solar array mass was lumped at either end of each panel assuming the following mass breakdown:

82% Panel
10% Astromast along center of panel
5% Box in which panel is stored
3% Stiffening rod at outboard end of panel

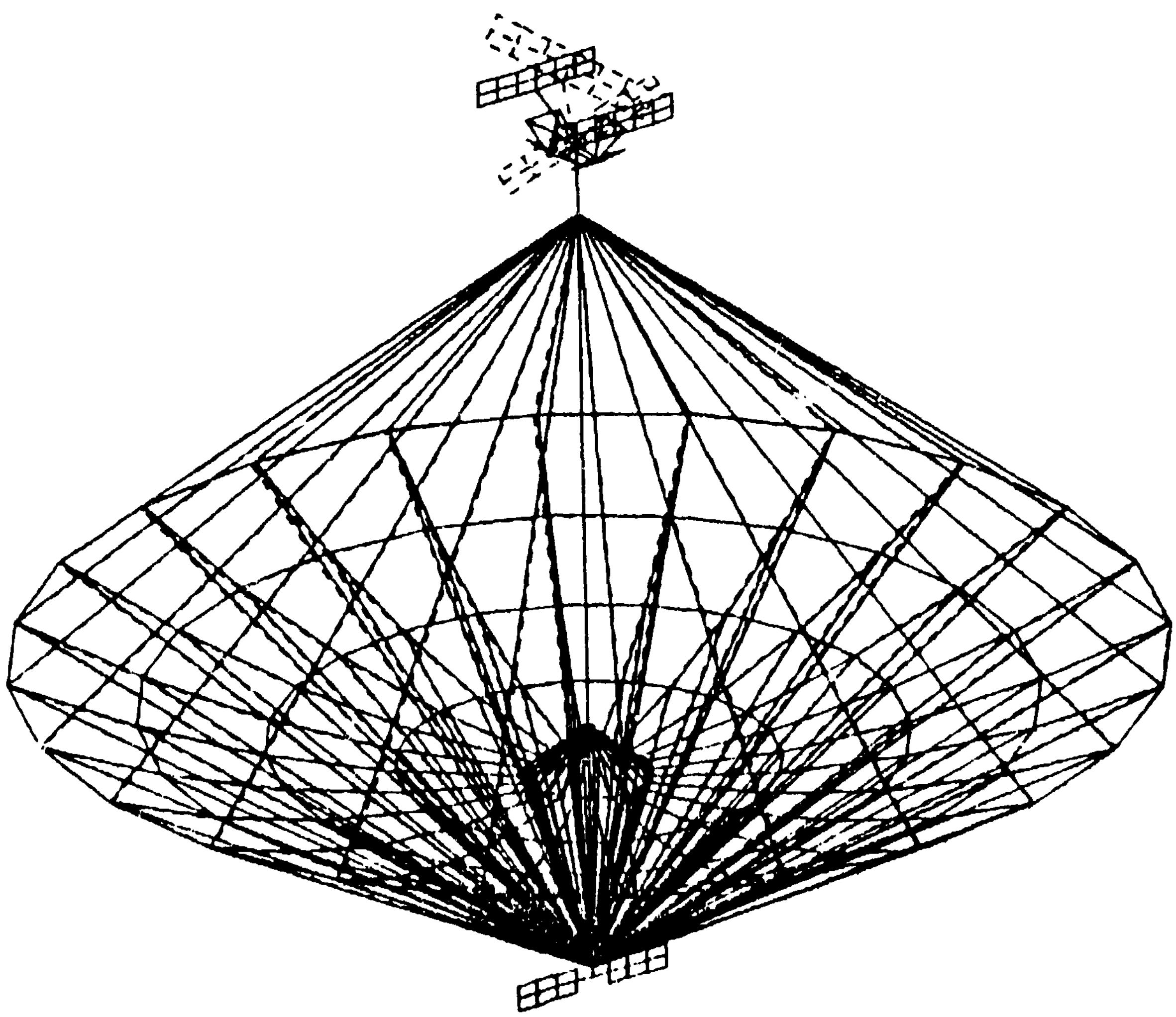


FIGURE 17. HOOP & COLUMN ANTENNA (LMSS) - 1st MODE, 0.114 HZ

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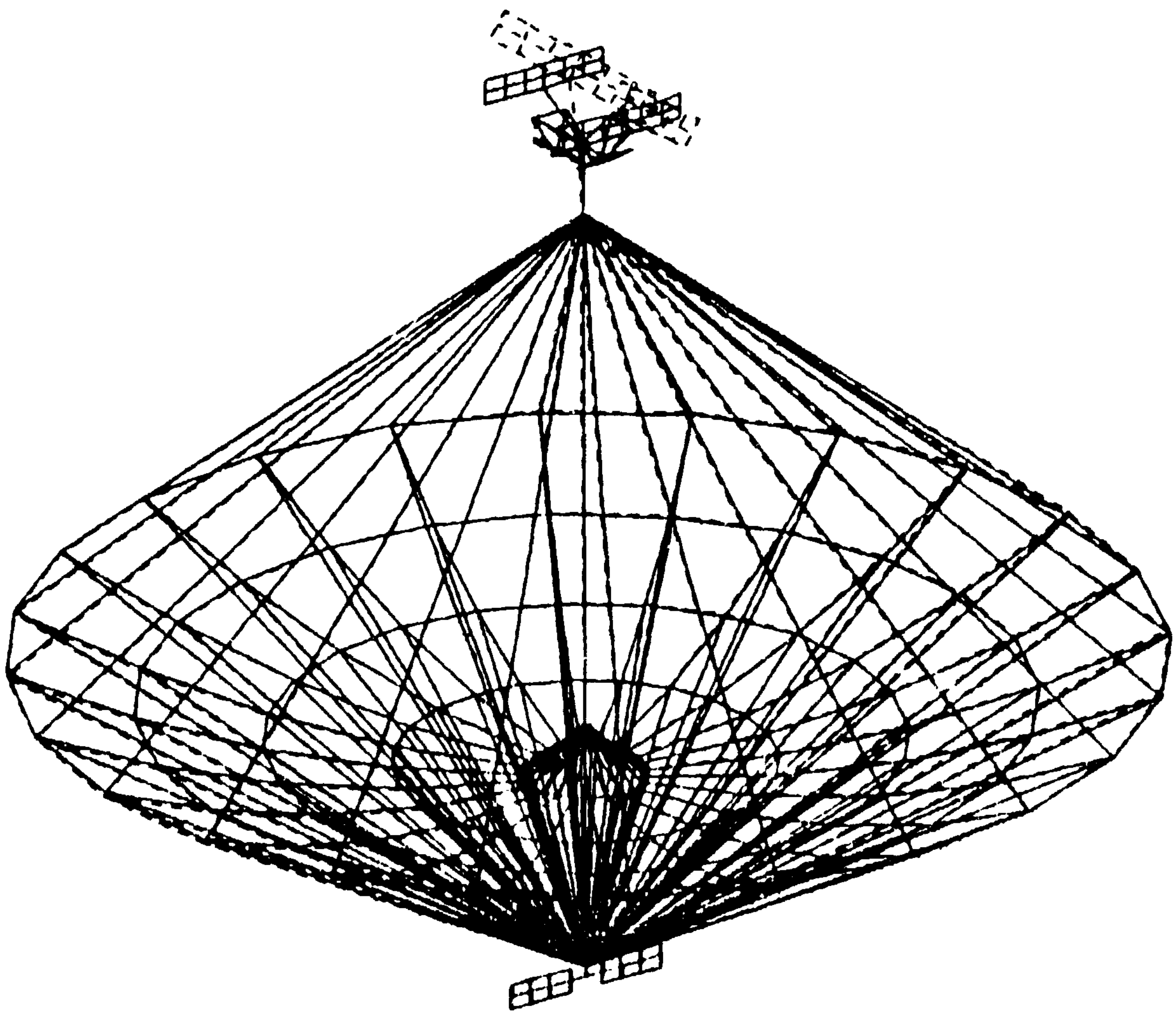


FIGURE 18. HOOP & COLUMN ANTENNA (LMSS) - 2nd MODE. 0.118 HZ

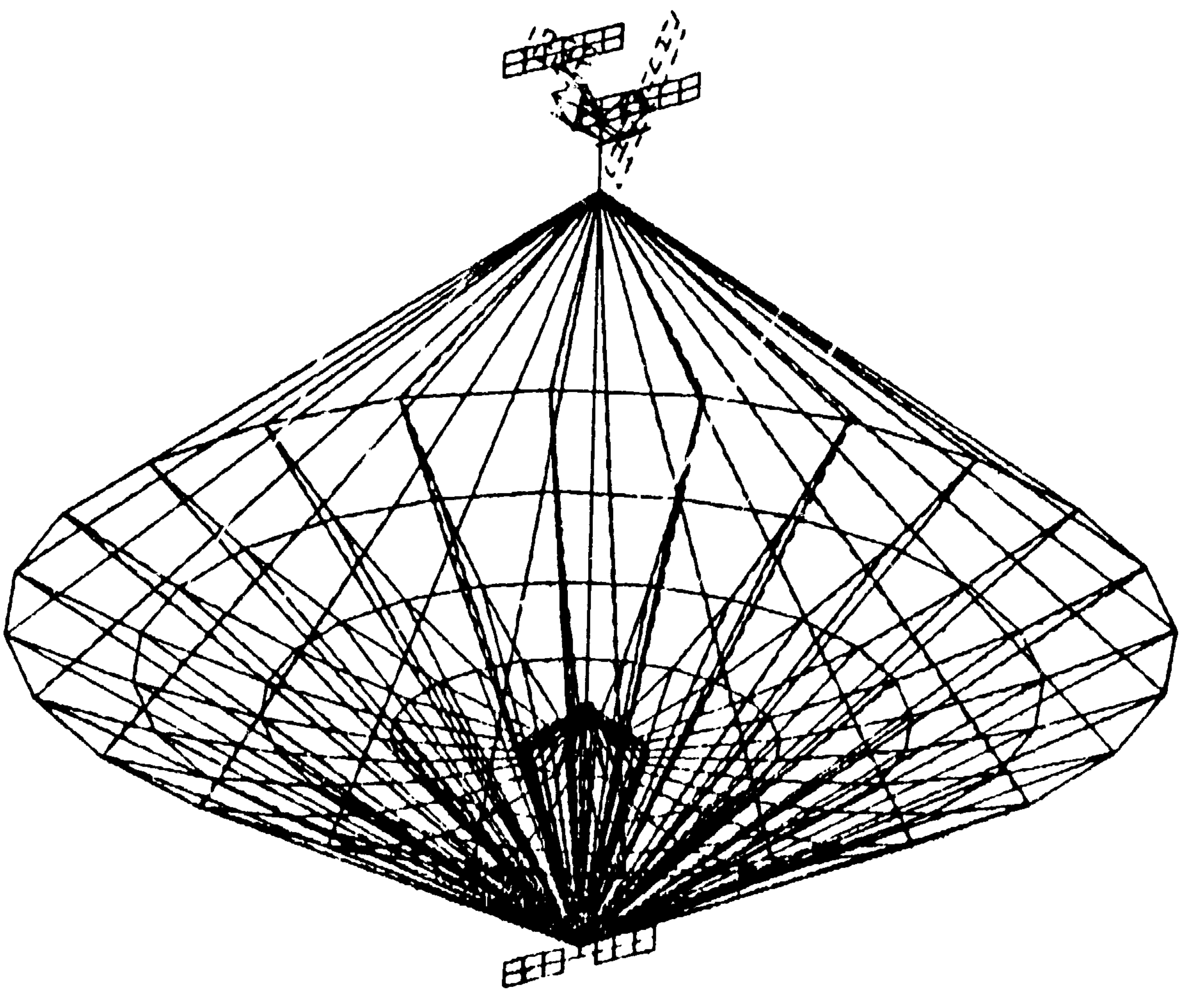


FIGURE 19. HOOP & COLUMN ANTENNA (LMSS) - 3rd MODE, 0.138 HZ

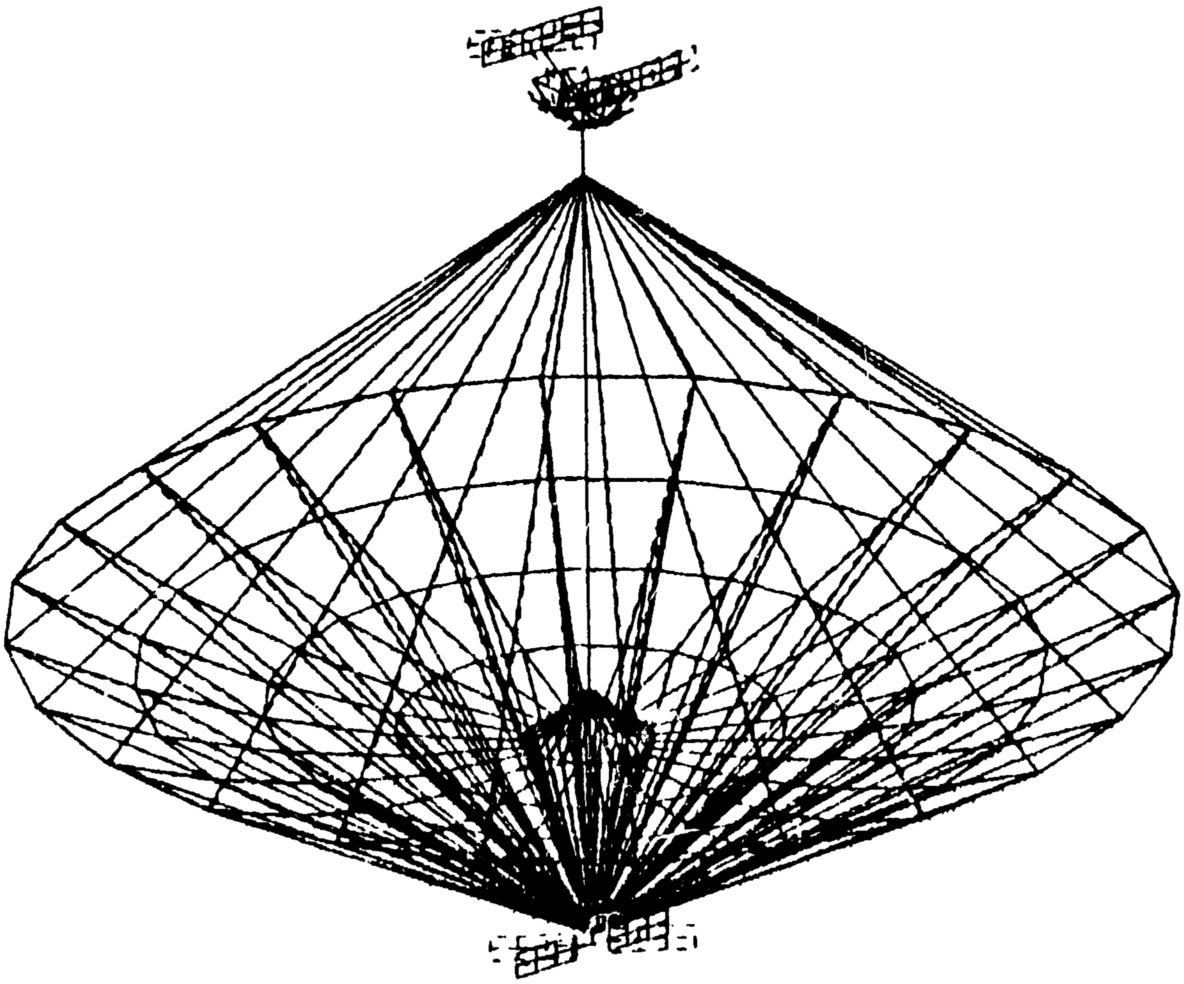


FIGURE 20. HOOP & COLUMN ANTENNA (LMSS) - 9th MODE, 0.601 HZ

TABLE 8. GEOSTATIONARY PLATFORM ASSUMED SECTION PROPERTIES

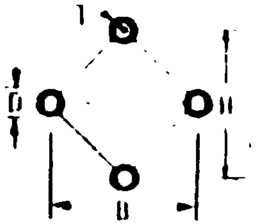
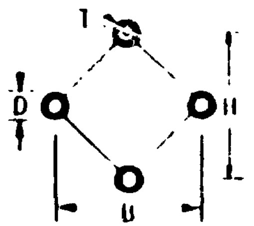
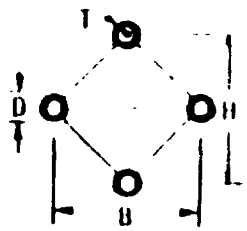
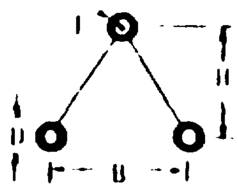
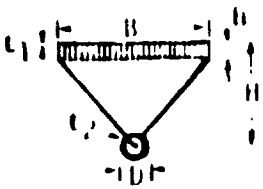
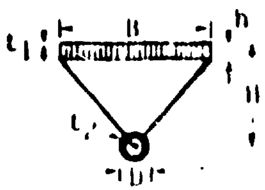
MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
WRAP RIB & PETA VERTICAL TRUSSES		BAR	CONVAIR DEPLOYABLE TRUSS H = 1.25 m B = 0.89 m D = 0.019 m T = 0.0015 m	GR/EP	3.30E-4	3.27E-5	6.44E-5	9.71E-5
WRAP RIB HORIZONTAL TRUSS		BAR	CONVAIR DEPLOYABLE TRUSS H = 0.94 m B = 0.67 m D = 0.016 m T = 0.00081 m	GR/EP	1.55E-4	8.68 E-6	1.71E-5	2.57E-5
SOLAR ARRAY ASTROMASTS		BAR	CONVAIR DEPLOYABLE TRUSS H = 0.25 m B = 0.35 m D = 0.006 m T = 0.0015 m	GR/EP	6.36E-5	1.30 E-6	6.63E-7	1.96E-6
SOLAR ARRAY SUPPORT BOOMS		BAR	½ GD TRUSS H = 0.47 m B = 0.67 m D = 0.019 m T = 0.0015 m	GR/EP	2.47E-4	1.85E-5	1.21E-5	3.07E-5

TABLE 8. GEOSTATIONARY PLATFORM ASSUMED SECTION PROPERTIES (CONTINUED)

MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*	$A(m^2)$**	$I_1(m^4)$	$I_2(m^4)$	$J(m^4)$
SPACE RAILS FOR RADIATOR & P/L 301		BAR	CONVAIR SPACE RAIL h = 0.08 m H = 0.4 m B = 0.8 m t_1 = .0005 m D = .010 m t_2 = .0008 m	GR/EP	8.23E-4	2.13 E-5	4.19E-6	2.55E-5
SPACE RAILS FOR P/L 501, P/L 502 & P/L 604		BAR	CONVAIR SPACE RAIL h = .06 m H = .3 m B = .6 m t_1 = .0005 m D = .010 m t_2 = .0008 m	GR/EP	6.23E-4	9.00E-6	2.16E-6	1.12E-5

* GR/EP TUBE: (OR GR/EP PLATE) FOR CTE CRITICAL ELEMENTS $E = 103 \times 10^9$ N/m^2, $\nu = 0.15$

FOR ALL OTHERS $E = 172 \times 10^9$ N/m^2, $\nu = 0.15$

** A = COMBINED X-SECTIONAL AREA OF ALL LONGERONS (AND PLATES FOR SPACE RAILS)

228.	Solar Arrays
95.	Solar Array Support Booms
115.	P/L 203 (Wrap-Rib Reflector)
92.	P/L 601 (Peta Reflector)
182.	Radiator
100.	P/L 604 (Sunflower Concept)
79.	P/L 501 (VAS)
50.	P/L 502 (DCS)
228.	P/L 301 (Imaging Spectrometric Observatory)
142.	Space Rails
1663.	Core
98.	2.5 m Feed (Wrap-Rib Feed)
49.	1.6 m Feed (Peta Feed)
65.	Wrap-Rib Vertical Mast
45.	Wrap-Rib Horizontal Mast
45.	Peta Vertical Mast
250.	Packing Boom
37.	Wrap-Rib Drive Mechanism
3737 kg	Total

FIGURE 21. EXPERIMENTAL GEOSTATIONARY PLATFORM MASS BREAKDOWN

One-half the mass of the array support booms was lumped at the inboard end of each panel. The mass of the following was lumped in the core: UHF feed, peta feed, 1/2 each space rail, 1/2 solar array support booms, 1/2 packing boom, and the core structure itself. The other 1/2 of the packing boom mass was lumped at a point 5.7 meters above the core (at the top of the packing boom). The mass of the wrap-rib drive was lumped at the intersection of the horizontal and vertical wrap-rib trusses.

A NASTRAN normal modes analysis was employed to find the natural frequencies and mode shapes of the structure. The model consisted of 22 lumped masses with a total of 87 dynamic degrees of freedom. The first, second, and third mode frequencies are 0.096, 0.133, 0.145 Hz. Mode shapes for these two frequencies are shown in Figure 22 and 23. The first two modes are primarily bending of the solar array support booms. The third mode is a combination of solar array support boom, and peta and wrap-rib antenna boom bending.

1.3 G-Loading and Mass Properties

Four generic classes were chosen to investigate for their g-loading characteristics. These are Large Aperture Phase Array antenna, LMSS - Wrap Rib, LMSS Hoop-Column, and the Geostationary Platform. Each of these structures is designed with critical elements closely associated with flexible members and, therefore, most susceptible to changes in mass and packaging characteristics due to g-loading. Three g-loading designs were determined for each of these four structures and sizes.

The SOC and the SASP will not be studied in detail for g-loading effects because of their relatively rigid structure. Their critical elements are concentrated in a central and rigid mass area with only the solar arrays extending from flexible members. Solar array support structures may be stiffended, if necessary, without significant impact on mass or auxiliary propulsion requirements. An additional reason not to look at varying g-loading characteristics of the two space station designs was to avoid a proliferation of separate designs, sizes and g-loading parameters. Such a large number of discrete cases would take away from the major thrust of this study.

To define the range of g-loading that each of the classes will experience in transfer from LEO to GEO or the other orbits, it is necessary to groundrule an OTV design. The specific characteristic of the OTV that is important to correlate thrust level with g-loading is the burnout or dry mass. This mass combined with the LSS mass was used to derive the maximum acceleration that the LSS must endure during transfer. Thrust level will be treated as a parameter and used only to gauge the requirements placed on the OTV engine as a side issue. In addition to OTV mass, the size of the OTV is necessary to define for an insight into packing requirements.

The OTV chosen for this study (Figure 24) is capable of transporting a 6200 lb payload to GEO and return to LEO for reuse or a 16400 lb payload with an expendable OTV. Thrust levels between 150 lb and 15000 lb can be achieved as shown in Figure 24 depending upon the degree of nozzle extension and pump speed. An expendable OTV will be used for the nominal large space

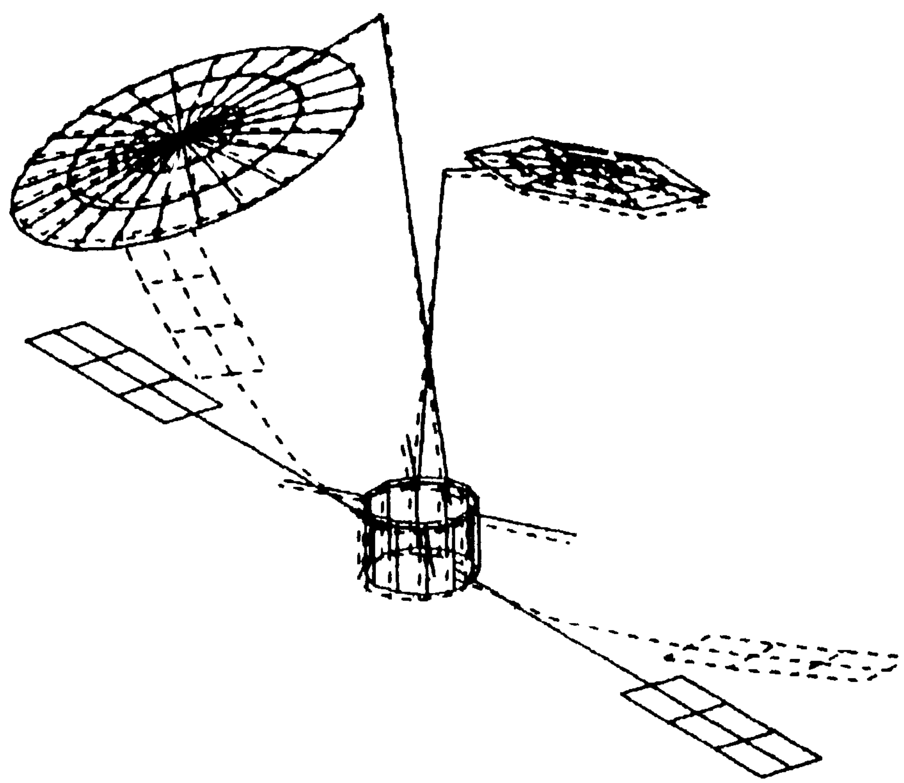


FIGURE 22. EXPERIMENTAL GEOSTATIONARY PLATFORM - 1st MODE, 0.096 HZ

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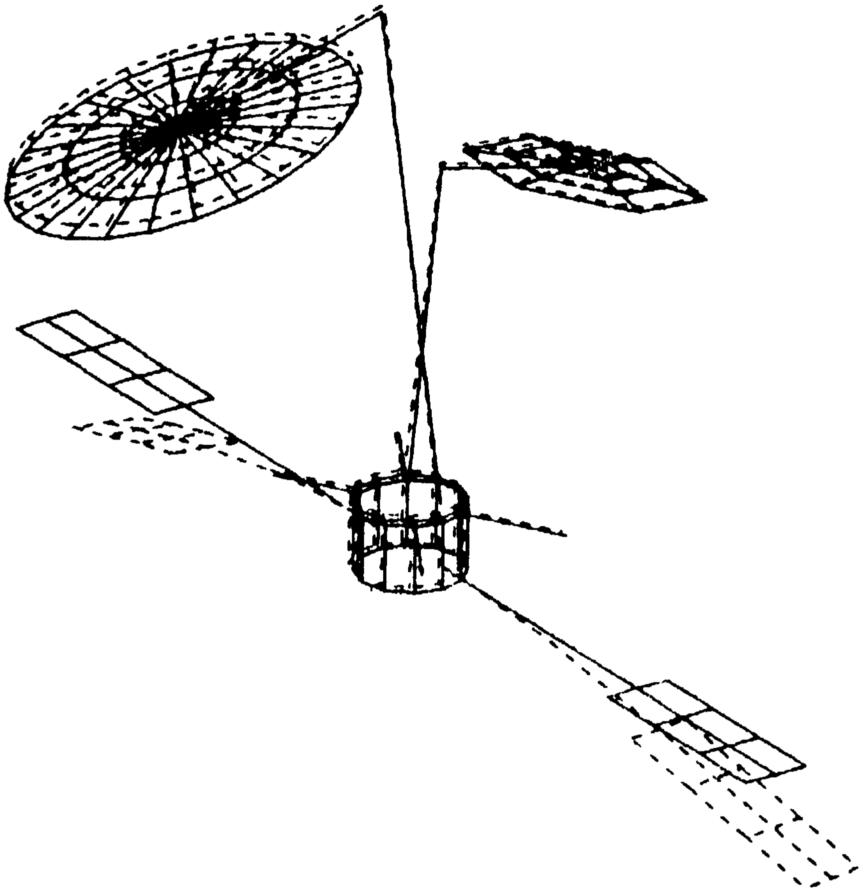
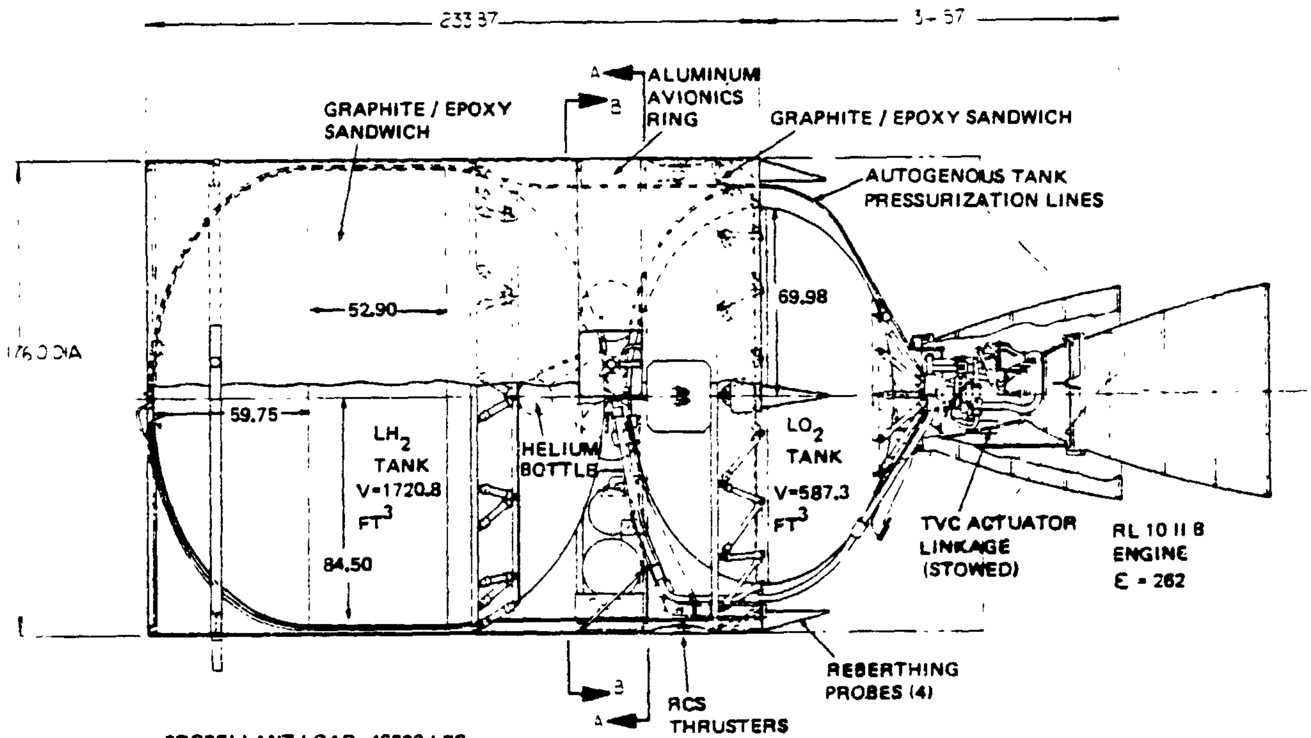


FIGURE 23. EXPERIMENTAL GEOSTATIONARY PLATFORM - 2nd MODE, 0.133 HZ



PROPELLANT LOAD: 46500 LBS
MIXTURE RATIO: 5.75:1

A. PERFORMANCE

1. THRUST:
   a. MAINSTAGE = 15,000LB' LB.
   b. PUMPED IDLE = 3,750 LB. (NOZZLE EXTENDED)
      = 750-1200 LB. (NOZZLE RETRACTED)
   c. TANK HEAD IDLE = 150-500 LB. ONLY AT FIXED INLET PRESSURE
2. DESIGN POINT MIXTURE RATIO = 6.0
   a. OTV MAXIMUM PERFORMANCE MIXTURE RATIO = 5.75
3. DESIGN POINT I_s = 462.5 SEC.
   a. OFF-DESIGN I_s = SEE FIGURE 3.5.2-5.
4. PUMPED IDLE I_s = 452 SEC. @ F = 3,750 LB. (NOZZLE EXTENDED)
   = 436 SEC. @ F = 3,750 LB. (NOZZLE RETRACTED)
   = 412-419 SEC. @ F = 750-1,200 LB. (NOZZLE RETRACTED)
5. TANK HEAD IDLE I_s = 393-405 SEC. @ F = 150-500 LB. (NOZZLE RETRACTED)

Figure 24. OTV ENGINE CHARACTERISTICS

systems in this study since their weights exceed 6000 lb. A typical sequential mass statement for a GEO transfer mission is shown in Figure 25. For a given thrust value, the highest steady stage g-loads will occur when the OTV is nearly empty of fuel.

$$G = \frac{T}{W_{OTV} + W_{PL}}$$

where T = steady thrust
W_{OTV} = OTV weight
W_{PL} = payload weight

Using the high value of thrust in the tank head idle mode (T = 500 lb), an OTV weight of 6560 lb and a dynamic mangification factor of 2.0 to account for thrust start-up transients, the minimum g-load which each of the four baseline space systems must be sized to withstand is shown in Table 9.

Table 9: Minimum Design Load Factors

Satellite Class	W(lb)	g-load
Large Aperture Phased Array	9800	.061
Wrap Rib Antenna w/Offset Feed	9695	.062
Hoop-Column Antenna	10340	.059
Experimental Geostationary Platform	11722	.055

The g-loading with respect to thrust for each of the four flexible designs is shown in Figure 26. The critical members of each design and the type of load encountered are shown in Figures 27 through 30. The location and direction of the primary propulsion load (T) is identified also. We chose

Expressions for the loads in each of the critical elements identified were derived for each structure. The loads were derived as functions of g-load and pretension parameters. A discussion of each structure follows:

Phased Array Antenna

Using the Educational TV satellite as an example, expressions for the loads in critical elements due to g-loading are derived. Orbit transfer thrust is applied at the feed horn cluster module.

USABLE MAIN PROP. MASS	36300	NOTE: MASS IN POUNDS • VELOCITY IN FT/SEC • ISP IN SECONDS
NOMINAL BURNOUT MASS	6279	
START MISSION MASS	59390	
PAYLOAD	16390	

MAIN ENG. ISP = 464.6
AUX. PROP. ISP = 220

EVENT	DELTA V	PROP. USAGE	LOSSES	MASS
STARTMISSION				59390
SEPERATE	10	83.8	8.8	59297.4
PHASE	0	0	13.6	59283.8
PHASE INJECT	4494	15393.4	48.2	43842.1
COAST	0	0	3.7	43838.4
TRANS. INJECT	3672	9548.2	19.1	34271
COAST	50	124.2	6.2	34140.7
GEO CIRC.	5828	11022.8	19.2	23098.7
TRIM	30	97.7	14.9	22986.1
UNLOAD P/L	10	32.5	1.2	6562.42
PHASE	0	0	1.2	6561.18
PHASE INJECT	94	44.6	19	6497.55
COAST	0	0	15.3	6482.28
DISP. CIRC.	93	43.6	19	6419.65
RESERVES	300	127.6	21.4	6270.7

NOMINAL MAIN PROPELLANT = 36176.9

RESERVE MAIN PROPELLANT = 127.6

NOMINAL AUX. PROPELLANT = 213.989

RESERVE AUX. PROPELLANT = 21.3989

TOTAL LOSSES = 189.435

FIGURE 25. EXPENDABLE MODE GEO DELIVERY MISSION (OFF-LOADED FOR 65 K STS) SEQUENTIAL MASS STATEMENT

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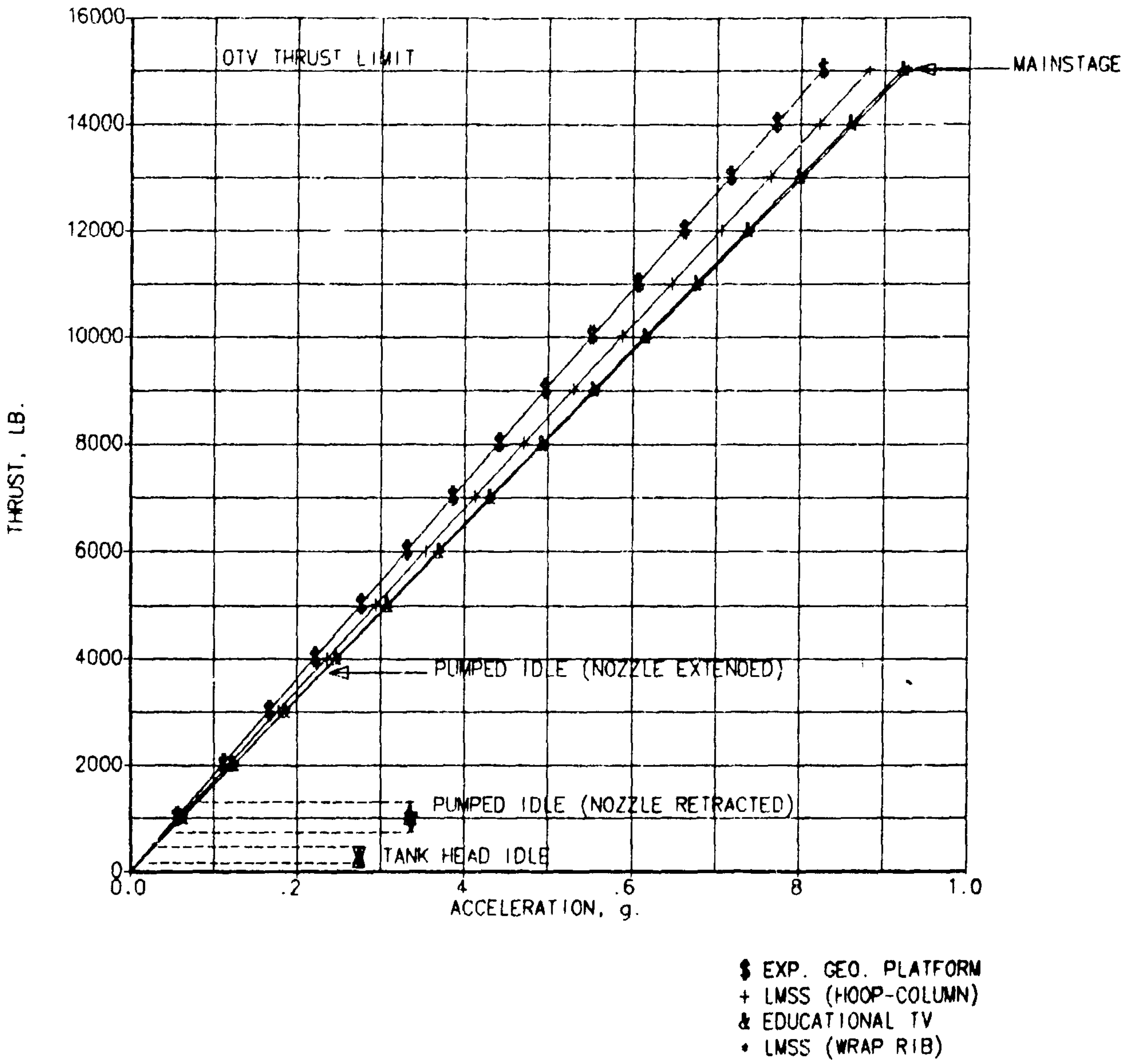
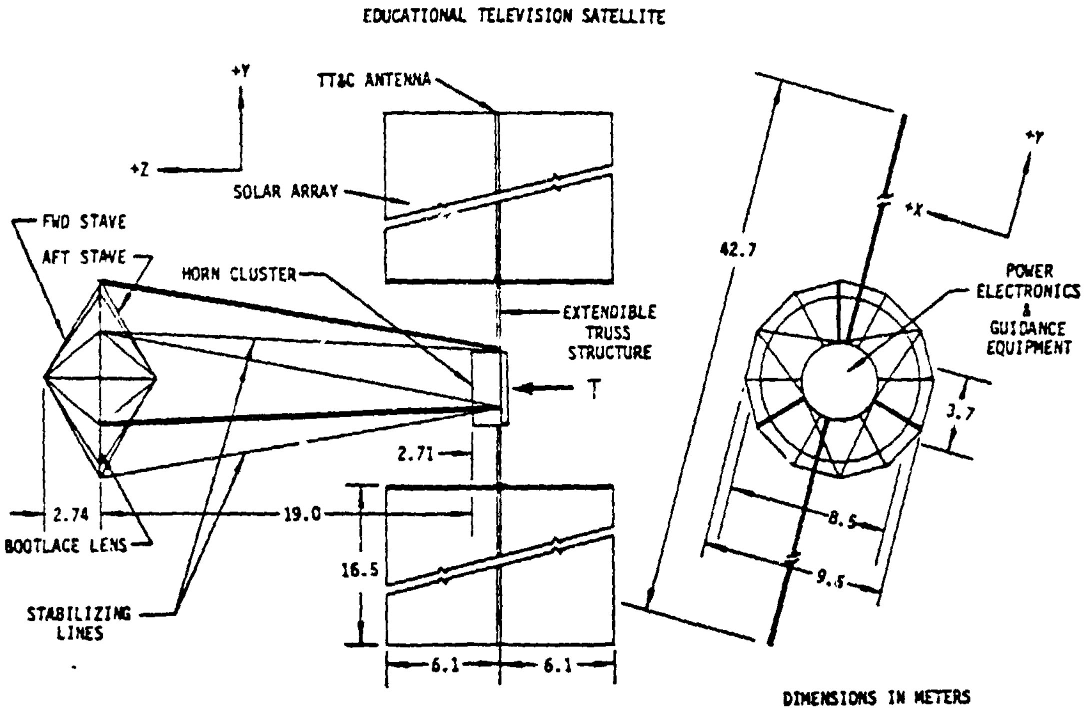


FIGURE 26. G-LOADING vs THRUST FOR FOUR FLEXIBLE DESIGN CLASSES



CRITICAL MEMBERS FOR PRIMARY PROPULSION LOADS

1. EXTENDIBLE S/A BOOMS (IF S/A'S ARE DEPLOYED)
   [BENDING]
2. DEPLOYABLE MASTS
   [AXIAL LOADS (BUCKLING)]
3. AFT STAVES
   [TENSION]
4. LENS COMPRESSION RING
   [COMPRESSION]

FIGURE 27. THE CRITICAL MEMBERS OF EDUCATIONAL TELEVISION SATELLITE

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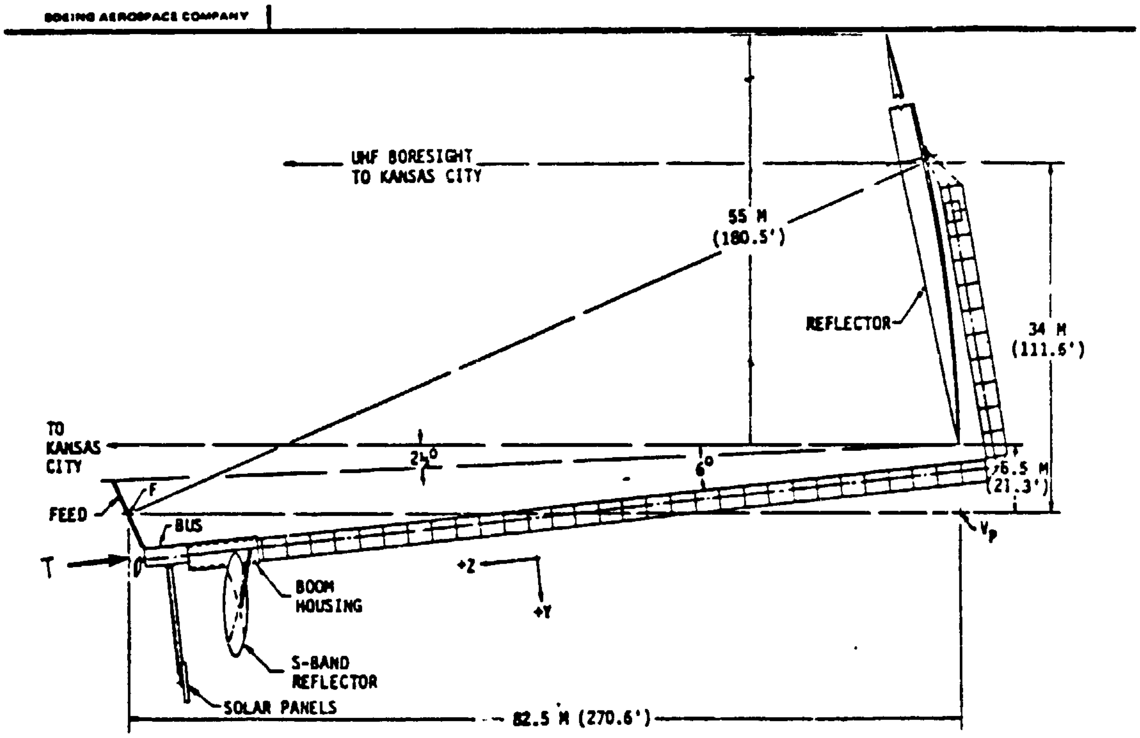
LMSS WRAP RIB SPACECRAFT

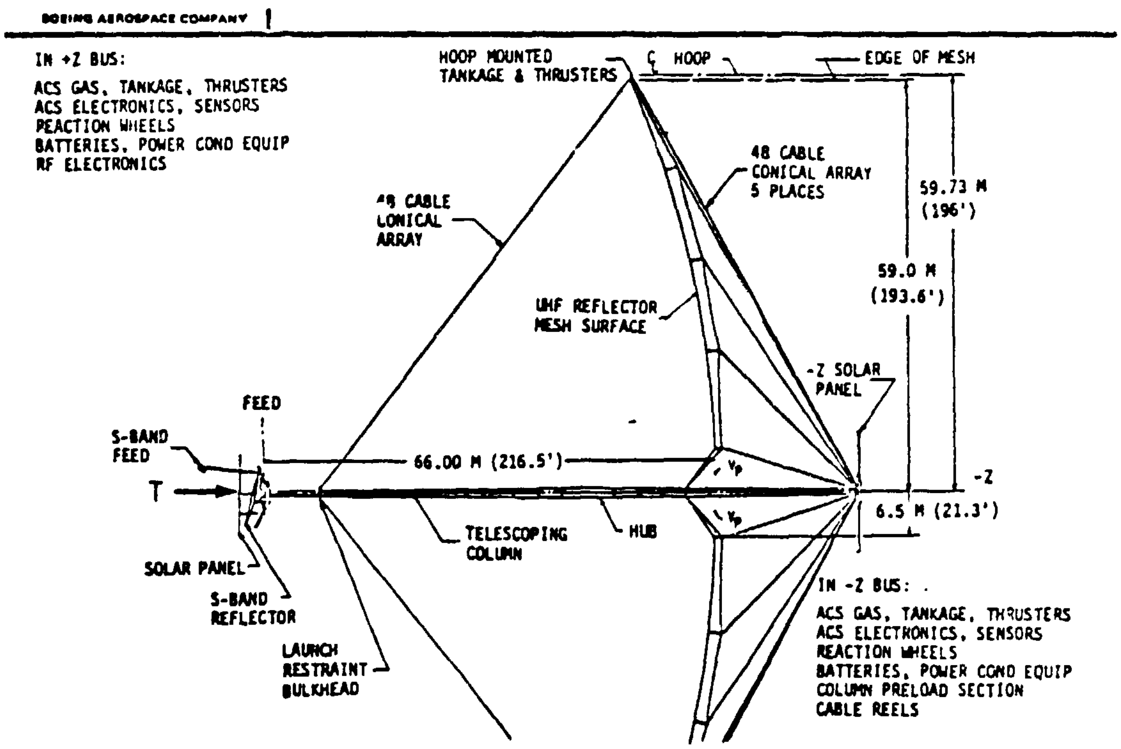


CRITICAL MEMBERS FOR PRIMARY PROPULSION LOADS

1. DEPLOYABLE BOOM
   [BENDING]
2. REFLECTOR RIBS
   [BENDING]
3. SOLAR ARRAY SUPPORT BOOM (IF DEPLOYED)
   [BENDING]

FIGURE 28. THE CRITICAL MEMBERS OF LMSS WRAP RIB SPACECRAFT

LMSS HOOP COLUMN SPACECRAFT



CRITICAL MEMBERS FOR PRIMARY PROPULSION LOADS

1. TELESCOPING COLUMN
   [COMPRESSION (BUCKLING)]
2. HOOP
   [COMPRESSION]
3. CONICAL CABLE ARRAYS
   [TENSION]
4. SOLAR PANEL SUPPORT BOOMS
   [BENDING]

FIGURE 29. THE CRITICAL MEMBERS OF LMSS - HOOP COLUMN

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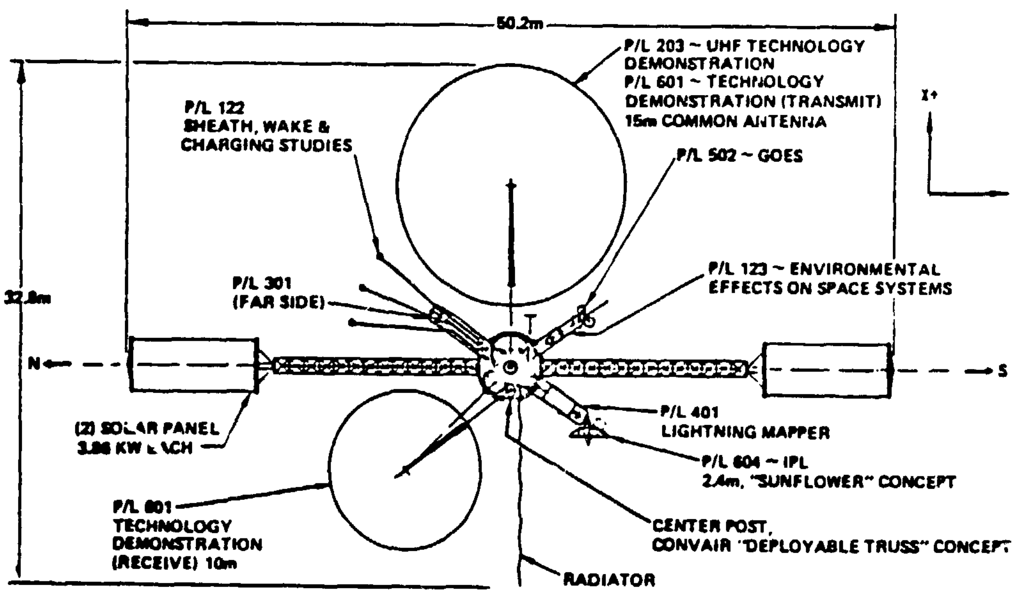
EXPERIMENTAL GEOSTATIONARY PLATFORM - OPTION 4A
VIEW LOOKING TOWARDS EARTH



CRITICAL MEMBERS FOR PRIMARY PROPULSION LOADS

1. "DEPLOYABLE TRUSS" STRUCTURE
   [COMPRESSION AND LOCAL BENDING]
2. P/L SUPPORT STRUCTURE
   [BENDING]
3. S/A SUPPORT MASTS
   [BENDING]

FIGURE 30. THE CRITICAL MEMBERS OF GEOSTATIONARY PLATFORM

Antenna Mast

The critical load in the antenna mast is compression and occurs at the aft end of the mast since the total mass of the mast is supported at the aft stave attachment. Assuming a tension, T_1, in each of the 12 staves, the preload in the mast is:

$$F_{pt} = 12(T_1)\cos\theta$$

where θ is the angle between a stave and the mast. The g-load contribution to the load results from the mass of the mast plus the mass of a portion of the lens which is attached to the mast. Assuming 25% of the lens mass is supported by the column:

$$F_g = (M_{mast} + .25M_{lens})\ 9.8\ g$$

The total compression load is the sum of these two contributions:

$$F_{mast} = 12(T_1)\ \cos\theta + M_{mast} + .25M_{lens})\ 9.8\ g\ \text{(Newtons)}$$

with

$$M_{mast} = 9.9\ \text{kg}$$

$$M_{lens} = 207.2\ \text{kg}$$

$$\theta = 61.1\ \text{deg.}$$

$$F_{mast} = 5.79\ T_1 + 604.4\ g$$

Antenna Staves

The highest stave tension occurs in the aft staves which must support the mass of the mast in addition to providing pretension forces. The stave tension is the mast load distributed to the 12 staves.

$$F_{staves} = F_{mast}/12\ \cos\theta$$

$$= T_1 + 104.2\ g\ \text{(Newtons)}$$

Antenna Rim

Stave tension (T_1) and lens tension (T_2) applied at each of the 12 attachments plus the g-load in the lense membrane results in radial loads which are reacted by compression forces in the antenna rim.

The pretension radial load is:

$$F_R = 2T \sin\theta + T_2$$

The lens under a g-load acts like a circular membrane under a pressure load. The running load in the perimeter of the membrane is:

$$N = (.328)(Ep^2Rt)^{1/3} \quad (N/M)$$

where

E = Young's modulus

R = radius of membrane

t = membrane thickness

and, the equivalent "pressure" (p) is a function of the g-load (g):

$$P = (M_{lens}/\pi R^2)\ 9.8\ g$$

The resulting radial force at each attachment is:

$$F_R = 2\ R_N\ (.75)$$

The .75 factor results from the fact that the antenna lens is supported by the mast at the center and the membrane tension equation applies to a membrane supported only at its edge. Therefore, approximately 75% of the lens weight contributes to tension.

The g-load on the staves also contributes a small amount to the radial rim load.

$$F_R = M_{stave} \sin\theta\ g$$

Once the total radial load at each point is calculated, the compression load in the rim elements is:

$$F_{rim} = (F_R/2.)(1./\sin\theta/12)$$

where:

T_1 = lens stave pretension (N)

g = g-load (g's)

Antenna Staves Tension

$$F_{stave} = T_1 + 104.2g \text{ (Newtons)}$$

Antenna Rim (Compression)

$$F_{rim} = 3.38\ T_1 + 1.93\ T_2 + 993.g^{2/3} + 13.6g \text{ (Newtons)}$$

where:

T_2 = lens pretension at each attachment

Lens Support Struts (Compression)

$$F_{strut} = 2.0\ T_3 + 1204.\ g$$

where

T_3 = stabilizing line pretension

Solar Array Boom (Bending)

$$BM_{S/A} = 31420.\ g \text{ (N-m)}$$

The effect of increased g-loading on the mass of the Educational TV and Electronic Mail were determined. Although preliminary mass statements for this satellite are available, many assumptions were required to establish structural parameters (size, material, pretension loads, etc.) necessary for these calculations.

The most significant factor in determining the effect of g-loading on spacecraft weight is the criteria used to design it. If the structure is a strength design, i.e., designed to withstand a given set of loads, then any increase in loading will result in resizing the structure with an appropriate increase in weight. Most spacecraft designs, however, would be too flexible if designed entirely using strength as a criterion. The resulting resonant frequencies would fall in the control system bandwidth and cause significant control and alignment problems. Therefore, stiffness criteria are often used to reduce structure/control interaction and improve satellite performance. A stiffness designed spacecraft, therefore, has more strength capability than is required for the expected loads and could withstand higher g-loads with no increase in weight. The magnitude of g-load which would cause a resizing of a portion of the structure is unknown until a specific satellite is designed.

The assumption of a strength designed structure, therefore, provides an upper bound on the weight increase caused by increased g-loads. The second assumption made is that increased strength capability is accomplished by increasing member cross sectional areas instead of using higher strength materials. For example, for the triangular expandable trusses, the areas of the three longitudinal elements are increased while the interconnecting elements remain constant. Increased bending capability of the solar array booms was also accomplished by increasing longitudinal element areas and not by changing the triangular dimensions. The third assumption is that the increase in structural weight of the load carrying elements of a member (axial elements in the previous example) is proportional to the increases in the member load. The fourth assumption is that the structure is designed for a g-load of 0.06 g. For the triangular expandable beams, it was assumed that half of the beam weight is in the longitudinal load carrying elements.

Figures 31 and 32 show the effect of g-load on weight for the Phased Array Designs Satellite and identifies the incremental weight for the structural elements contributing to the increase. The main spacecraft body and antenna feed comprise approximately 70 percent of the total weight and are assumed to be unaffected by increased g-loads.

LMSS (Hoop and Column)

Expressions for element loads are based on the assumption that tension in the forward and aft hoop cables is defined by tension (T_C) in the 48 aft (-Z) cables and that tension in the reflector surface (T_S) is applied at each of the hoop attachment locations. Orbit transfer thrust is applied in the -Z direction at the +Z Bus.

Hoop (compression): Hoop loads are the results of pretension and g-loads

$$F_{hoop} = 11.41\ T_C + 10.64\ T_S + 1063.g \text{ (Newtons)}$$

Cables (Tension): Tension in each of the 48 cables in each of the five conical cable arrays (ring 1 is closest to the column) are as follows:

$$T_1 \text{ (aft)} = .32T_s + 1.07g$$

$$T_1 \text{ (fwd)} = .46T_s$$

$$T_2 = .08T_s + 4.97g$$

$$T_3 = .15T_s + 15.43g$$

$$T_4 = .35T_s + 49.09g$$

$$T_5 \text{ (aft)} = T_C + 91.88g$$

$$T_5 \text{ (fwd)} = .58T_s + .78T_C$$

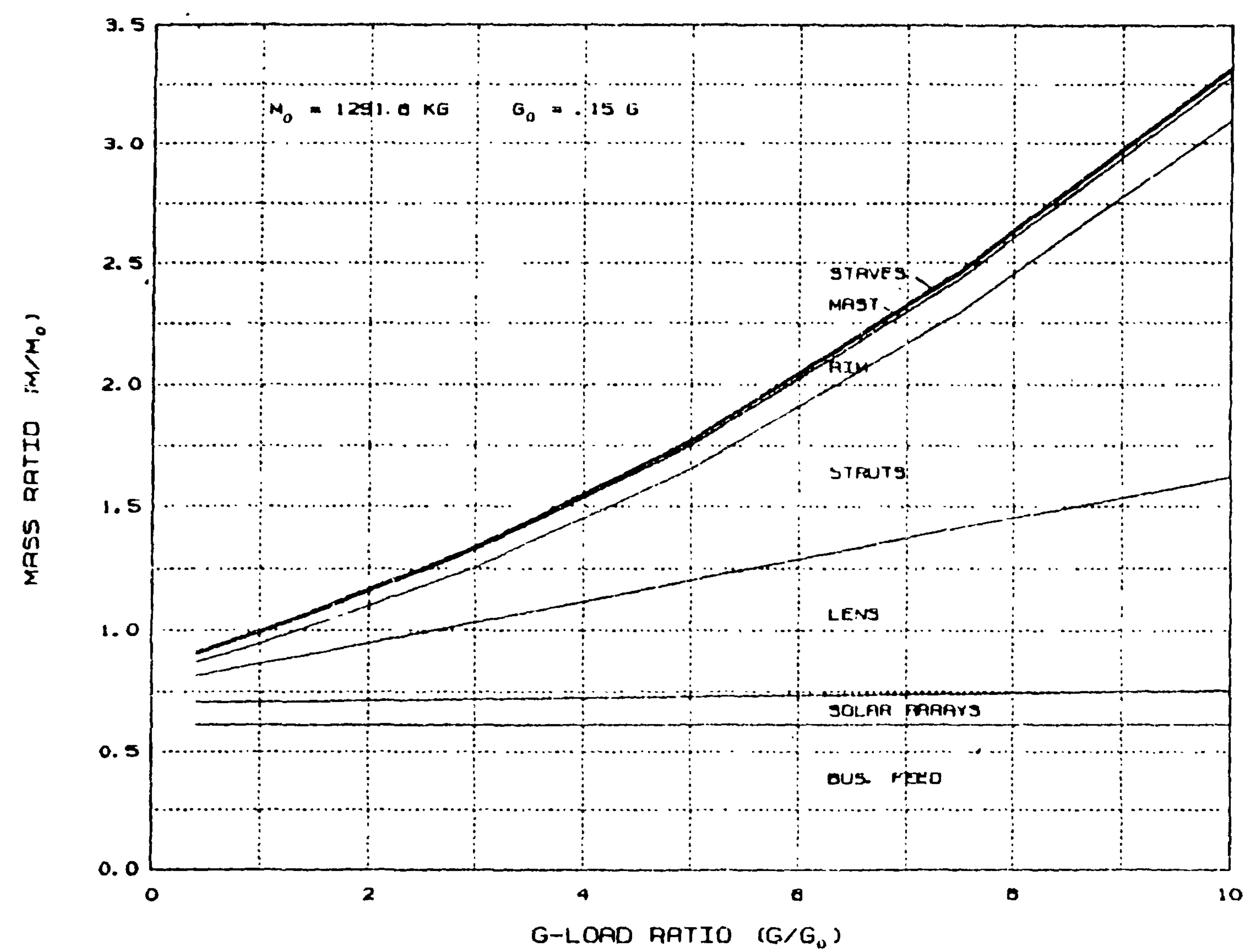


FIGURE 31. EFFECT OF G-LOAD ON MASS - ELECTRONIC MAIL SATELLITE

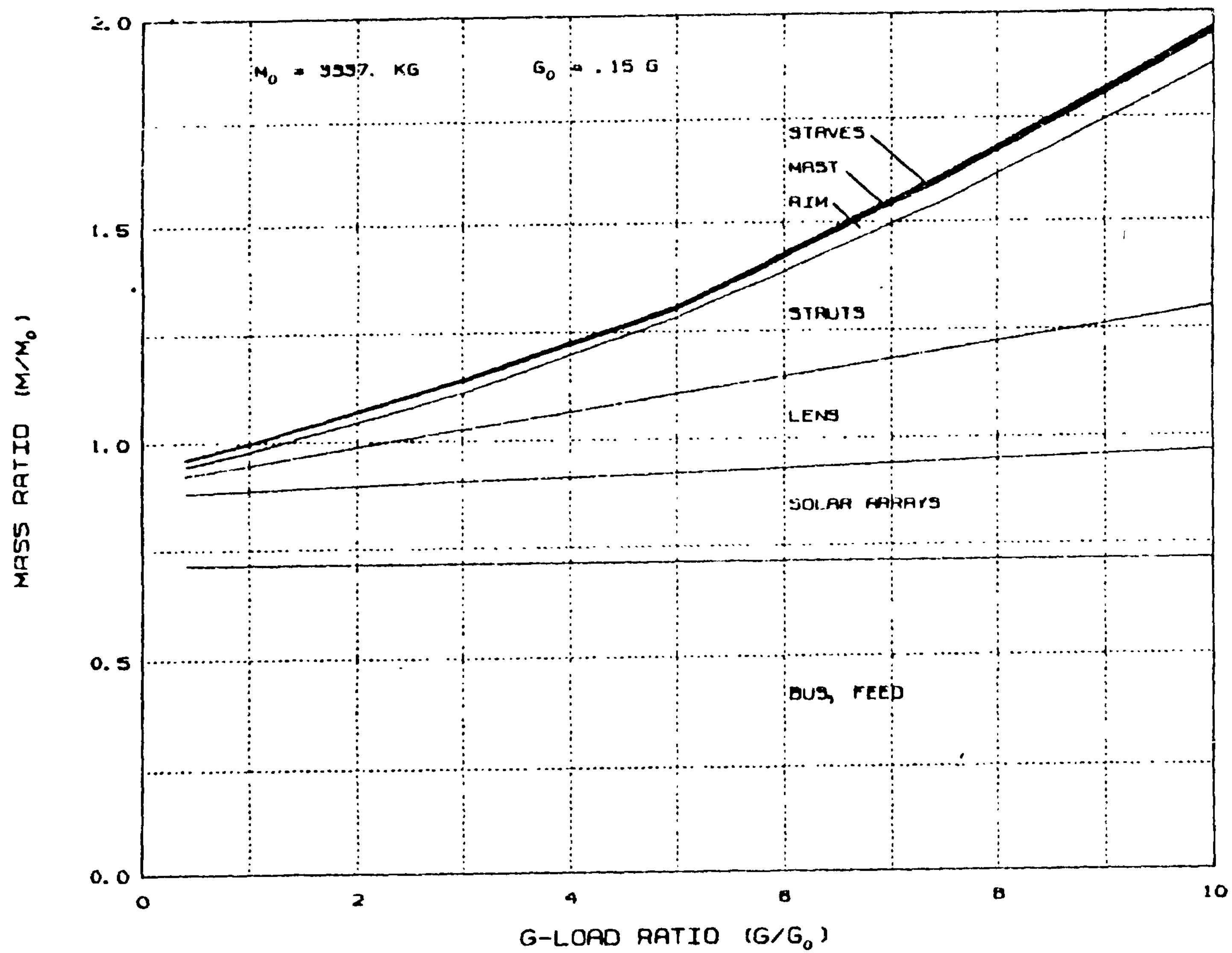


FIGURE 32. EFFECT OF G-LOAD ON MASS - EDUCATIONAL TV SATELLITE

Solar Array Supports (Bending): For the +Z solar arrays, the critical loads are at the inboard end of the support.

$$BM_{S/A} = 5080.g \text{ (N-M)}$$

Feed Assembly Supports (Bending): For each of the four feed arrays, the bending moment at the +Z Bus attachment is:

$$BM_{feed} = 7290.g \text{ (N-M)}$$

The effect of g-loading on the mass of the LMSS (hoop and column) spacecraft was determined using the same assumptions as the Educational TV Satellite described in the previous section (i.e., a strength-designed spacecraft, structural capability increased through increases in cross-sectional area which are proportional to the increase in member load, etc.). Figures 33 and 34 show the effect of g-load on mass for the LMSS (Hoop and Column) spacecrafts and identifies the incremental mass for the structural elements contributing to the increase. The mass of both the +Z and -Z Bus are assumed to be unaffected by increased g-load. Also the increase in solar array and feed support mass contribute an insignificant amount to the total spacecraft mass.

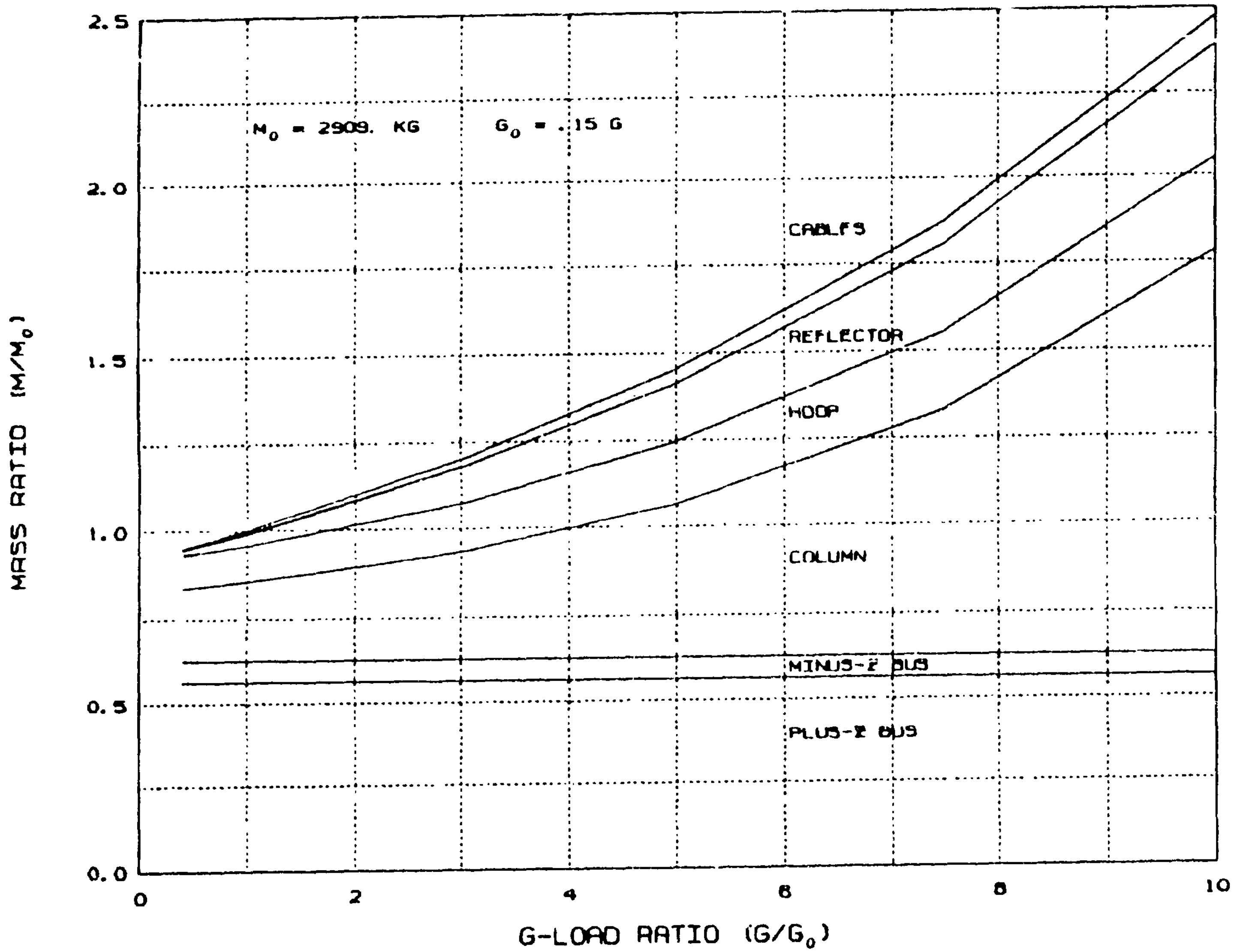


FIGURE 33. EFFECT OF G-LOAD ON MASS - LMSS SPACECRAFT (HOOP AND COLUMN)

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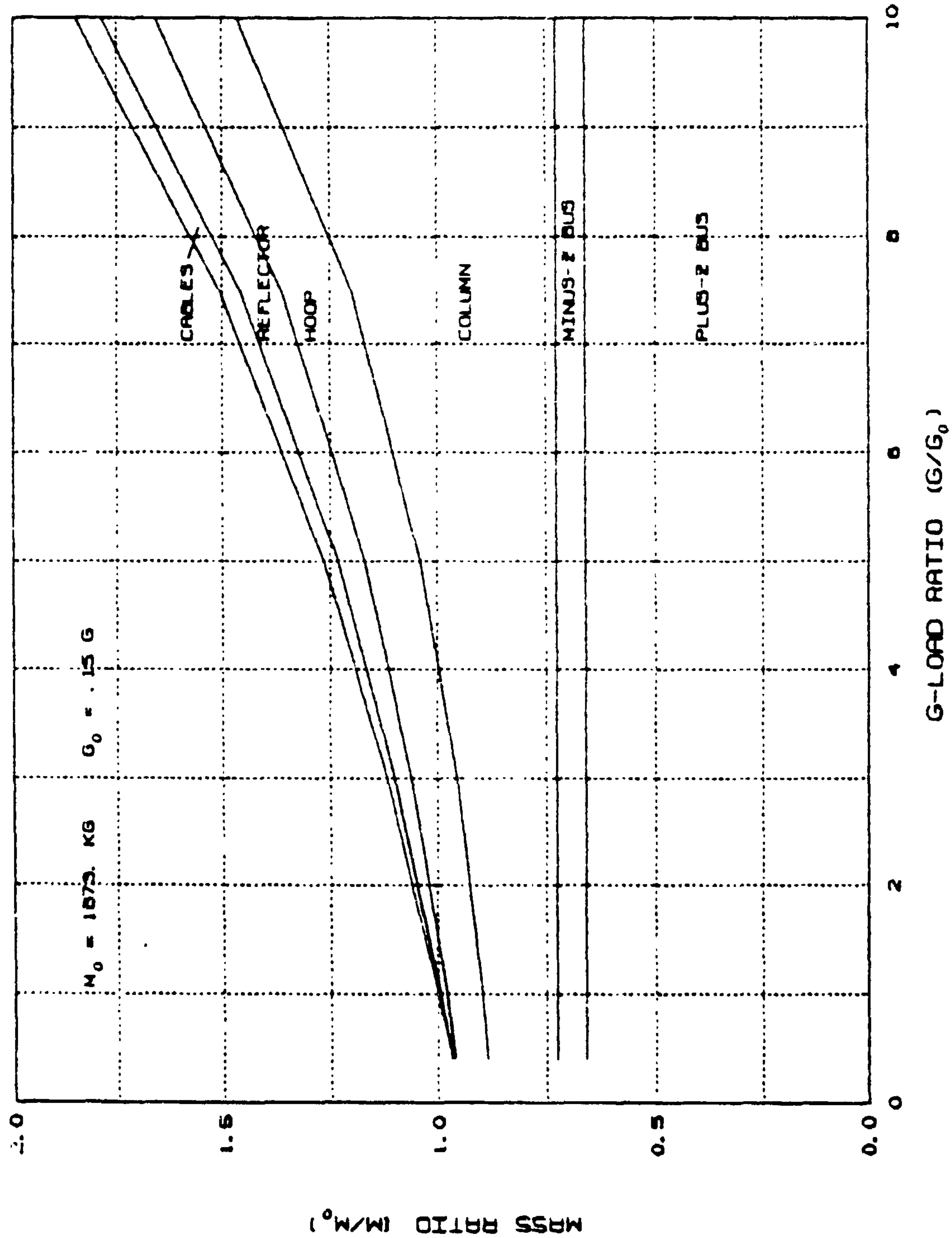

FIGURE 34. EFFECT OF G-LOAD ON MASS - 60 M DIAMETER HOOP AND COLUMN

LMSS (Wrap Rib)

Critical element loads are based on preloads in the antenna ribs and g-loads. Orbit transfer thrust is assumed to be applied to the bus.

Ribs (Bending): Pretension in the reflector ribs is a function of the bending stiffness (EI) and the deflected shape of each rib. Sufficient structural detail is not available at this point to determine the preload bending moment (BM_O) at the root of each rib.

$$BM_{rib} = BM_O + 748.g \text{ (N-M)}$$

Boom (Bending & Compression): With the orbit transfer thrust applied to the bus, the critical load in the expandable boom occurs just outside of the boom housing. The load is the result of the combination of compression in the long boom and bending which results form the offset reflector and short boom.

$$BM_{boom} = 1.17 \times 10^5 g \text{ (N-M)}$$

$$F_{boom} = 5020.g \text{ (N)}$$

UHF Feed Support (Bending): Bending in the UHF Feed support structure is caused by g-loading.

$$BM_{feed} = 4.0 \times 10^4 g \text{ (N-M)}$$

Solar Array Support Boom (Bending): The bending moment at the base of the solar array boom is:

$$BM_{S/A} = 2.15 \times 10^4 g \text{ (N-M)}$$

Figures 35 and 36 show the effects on mass of varying g-load for the two wrap rib designs.

Geostationary Platform

The only elements of consequence for the geoplatform were the solar arrays and wrap rib antenna. These elements have been described in the previous sections. Figure 37 shows the simple relations for these elements.

Mass Property Summary

Table 10 summarizes the mass properties, g-loading effects, and nodal frequencies for each LSS.

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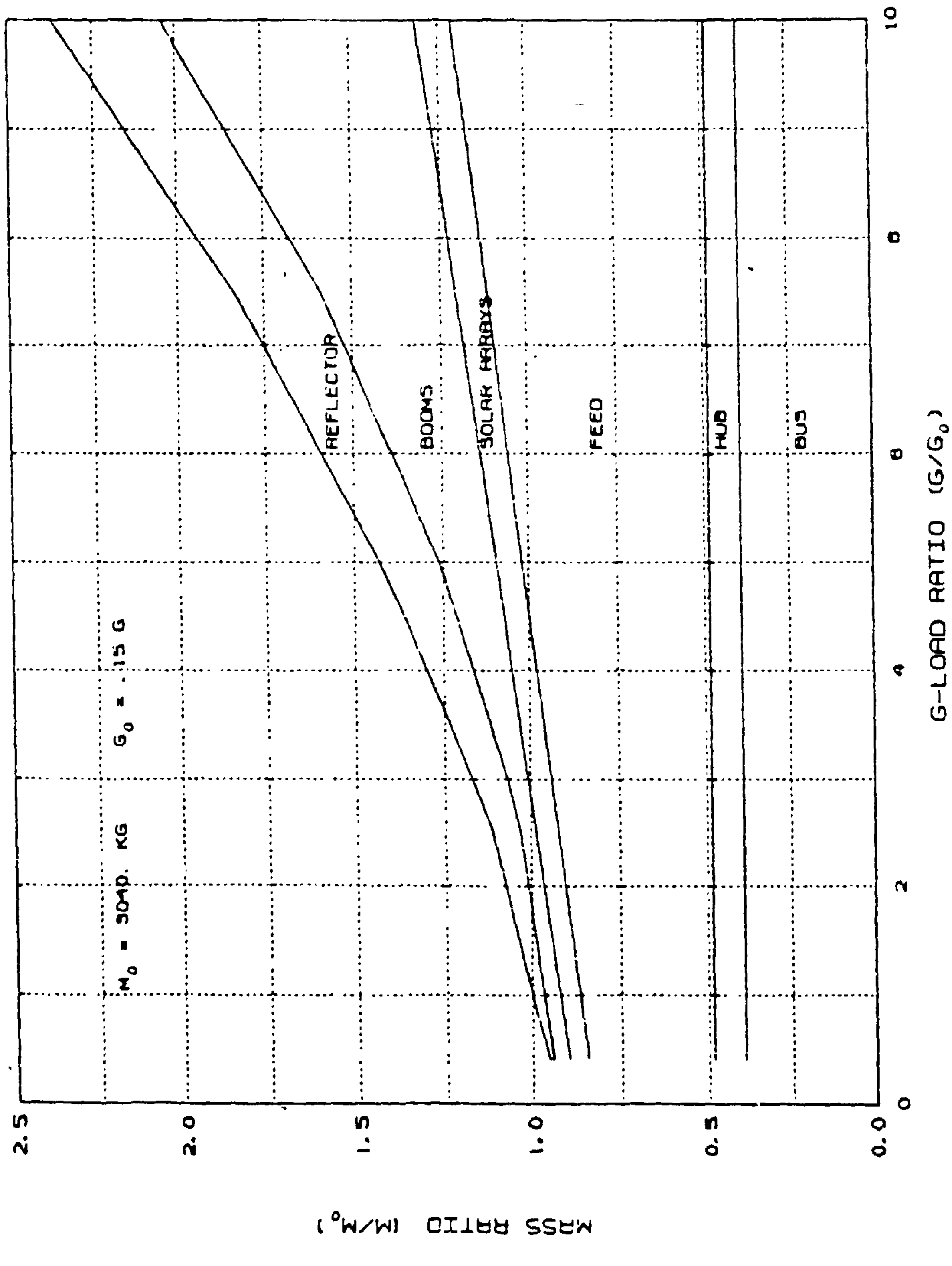

FIGURE 35. EFFECT OF G-LOAD ON MASS - LMSS SPACECRAFT (WRAP RIB)

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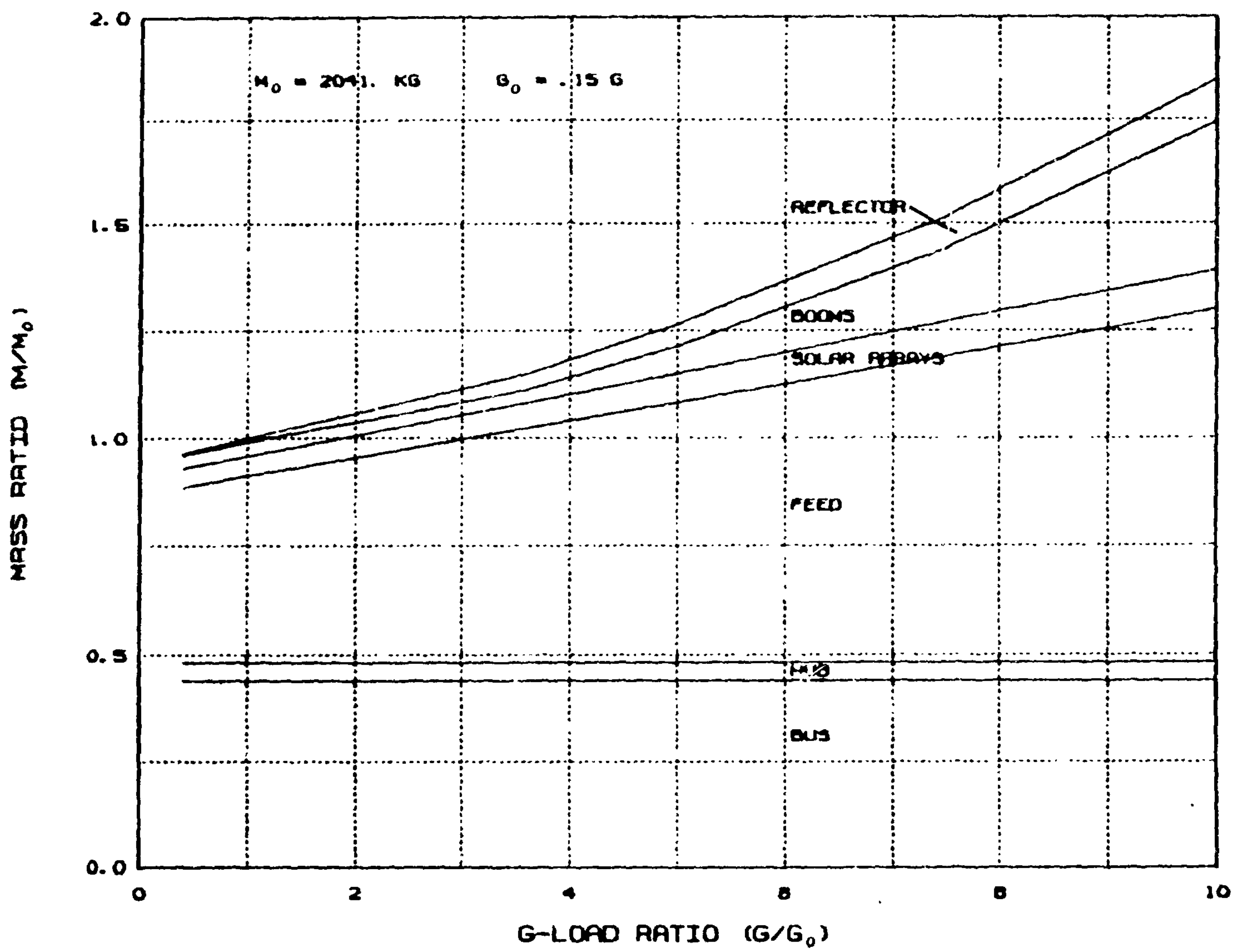

FIGURE 36. EFFECT OF G-LOAD ON MASS - LMSS SPACECRAFT (25 M WRAP RIB)

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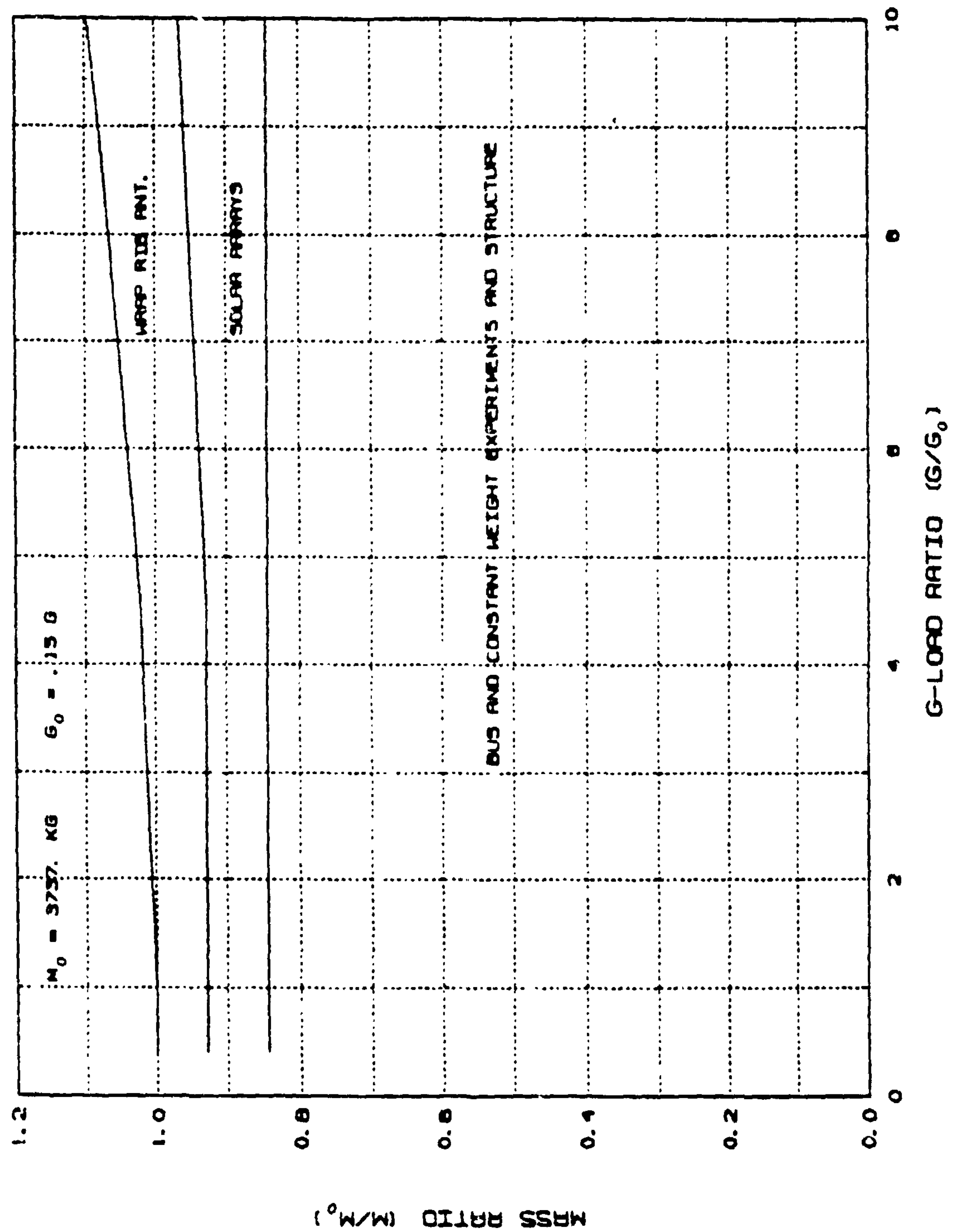

FIGURE 37. EFFECT OF G-LOAD ON MASS - BASELINE EXPERIMENTAL GEOSTATIONARY PLATFORM

	LSS	SIZE	G-LOADING	MASS(kg)	MODAL FREQUENCIES 1.
I.	LARGE APERATURE PHASED ARRAY ANTENNA				
	Electronic Mail Educational TV	13KW 65KW	.06, .15, 1.0	1182, 1292, 2867 3212, 3337, 5048	.093, .110, .160
II.	LMSS -WRAP RIB ANTENNA	55 m (ant. dia.) 25 m "	.06, .15, 1.0 .06, .15, 1.0	2897, 3036, 4353 1970, 2042, 2714	.105, .111, .131
III.	LMSS-HOOP COLUMN ANTENNA	120 m " 60 m "	.06, .15, 1.0 .06, .15, 1.0	2754, 2909, 4989 1814, 1873, 2658	.114, .118, .138
IV	GEOSTATIONARY PLATFORM	50 X 33 m (9 payloads)	.06, .15, 1.0	3722, 3737, 3944	.096, .133, .145
V	SCIENCE AND APPLICATION SPACE PLATFORM (SASP)				
	12.5 KW 25.0 KW	12.5 KW 25.0 KW	NA NA	8780 14731	
VI	SPACE OPERATIONS CENTER (SOC)				
	Initial	120 m x 16 m (2 shuttles)	NA	57242	
	Operational	120 m x 25 m (5 shuttles)	NA	125500	

1. For baseline configuration (sized for 0.15 g)

TABLE 10. CHARACTERIZATION SUMMARY

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2.0 ESTABLISHMENT OF APS REQUIREMENTS

The objective of Task 2 was to establish the propulsion requirements due to environmental, operational and structural constraints. To accomplish this objective, four major subtasks were executed. The first subtask involved a disturbance environment characterization and a stationkeeping and torquing requirements determination at LEO and GEO. To fully define the thrust thruster and minimum bit requirements, the second subtasks established a set of criteria to place thrusters on each of the selected vehicles and used this criteria to locate and size the thrusters. With the preliminary thruster requirements and locations determined, the third subtask characterized APS mass and converged thrust/thruster requirements. Both chemical and ion systems were used for APS scaling. In the final subtask, the interactions between the auxiliary propulsion system and the structure were investigated. This critical subtask gave the first indication that large space structure/propulsion interaction may be a driving issue in the design of the structure and integrated propulsion system. The key assumptions used in each subtask are shown below in Table 11.

Table 11. Task 2 Assumptions

2.1	Disturbance Environment Analysis
	. NASA Neutral Atmosphere
	. CD = 2.5, reflectivity = 1.0
2.2	Thruster Location
	. Maximum moment arms
	. 0 torque ΔV requirements
2.3	APS Characterization
	. Monopropellant, bipropellant, ion (Hg, SEPS)
	. No resupply
2.4	APS/LSS Interactions
	. 10% power loss with and without APS mass

In subtask 2.1, conservation assumptions were used for the atmospheric model, drag coefficient and reflectivity. The atmospheric model was varied to understand effects of the model assumption on orbit decay, however, the NASA neutral model was employed to derive propulsion requirements trends. This model is a long term worst case model and thus yields conservative, but realistic answers. The drag coefficient was set at 2.5 which may be a little on the high side. Other studies have used drag coefficients at 2.0

to 2.7 which correspond to difference momentum exchange surface properties. Reflectivity was set at a relatively high value which made solar pressure torques somewhat exaggerated for certain lower reflective surfaces. Solar pressure did not add significantly to the torque requirements and only in a few cases were stationkeeping requirements effected, therefore small changes in this assumption would not affect the study conclusions.

The assumptions used to locate thrusters are decribed in more detail in Section 2.2. The two driving assumptions were maximum moment arms and 0 torque ΔV requirement. Moment arm was not as important as was thought beforehand, and, in fact actually drove minimum impulse bit requirements for pointing control lower than the state-of-the-art. Pure ΔV with no torque created a throttling requirement for thrusters which had to be located non-symmetrically around the CG. Subtask 2.3 generated scaling equations for monopropellant, biopropellant and ion (Hg, SEPS technology) thrusters. These scaling equations were based on existing hardware and, in the case of ion thrusters, accepted theory.

An assumption was made in subtask 2.4 that a 10% proven loss in the antenna beam was the maximum structural information allowed. This assumption was based on discussions with the Boeing Space Antenna Systems group. For most missions, a defocusing of the beam beyond 7-10% would be considered unacceptable.

The driving key issues of Task 2 were threefold. First, the aerodynamic disturbances in LEO were so large for most of the antenna structures examined that operation even for short periods of time proved difficult. LEO deployment and checkout of the large antenna systems imposed much higher thrust and large ΔV requirements versus the GEO operational requirements, second, the stationkeeping strategy at GEO drove the state-of-the-art limitations depending on the duty cycle of thrusting. For short duty cycles (<1 hour/orbit), chemical system thrust levels were required. The solar array duty cycles had to become very long (>3 hour/orbit) before ion systems were viable. The final key issue was the allowed APS mass fraction at GEO. If the cost of transportation is more effected by the volume rather than mass of payload as it is in certain STS missions, then low I_{sp} systems are acceptable. If the mass becomes critical because of STS or transfer stage capability, then higher I_{sp}'s are more desirable. It was shown that the delivery systems were challenged for very low I_{sp} (200's) examined, however, delivery costs were beyond the scope of the contract, and a firm notion of where I_{sp} should lie will be effected by such an analysis.

2.1 Disturbance Environment Analysis

This subtask consisted of three separate analysis which provided a detailed examination of disturbance torques, LEO stationkeeping forces and effects, and GEO stationkeeping forces and effects. LEO disturbances were dominated by aerodynamic influences for both forces and torques. GEO disturbances were dominated by gravitational influences. Gravity gradient torques and solar/lunar gravitational attractions imposed the most significant propulsion requirements for systems sized for GEO operation. Solar pressure forces and torques were of lower magnitude at GEO than gravitational influences and orders of magnitude lower than aerodynamics in LEO.

2.1.1 Disturbance Torque Analysis

Table 12 shows a summary of the disturbance torques relevant for this study. The first three disturbances were treated in detail in this study. Magnetic torques were shown in a previous analysis (Reference 2) to be of only minor importance for the composite antenna structures examined. A discussion of aerodynamic, gravity gradient and solar pressure follows:

Aerodynamic Disturbance

Aerodynamic force on the configuration was determined by the equation:

$$F_{AERO} = C_D A \frac{V^2 \rho}{2}$$

where

C_D = Drag Coefficient

A = Cross Sectional

ρ = Atmospheric Density

V = Orbit Velocity

Atmospheric density is the most difficult parameter to accurately estimate. Density is affected by two factors which relate to solar activity - the geomagnetic index and the solar flux. Both of these factors vary with time due to changes in the solar activity cycle. Actual measurements for 1979 through mid-1980 are shown in Figure 38. The solar cycle peaked in 1978 and will again reach a maximum around 1980.

In these studies, four atmospheric models were considered in deriving the orbit decay data. See Figure 39. The nominal model is the U.S. Standard Atmosphere, 1976. The other three models were generated via the quick-look density model in Appendix B for a latitude of 0. The NASA Neutral and Short Time Maximum Models use values suggested for space shuttle studies. The NASA Neutral Model is a high solar activity model, with a value of 230 for the mean 10.7 cm solar flux and a geomagnetic index (A) of 20.3. The Short Time Maximum Model uses a 10.7 cm solar flux of 230 and a geomagnetic index of 400. These conditions would occur only for a time of 12 to 36 hours during an extremely large magnetic storm. The Minimum Model uses figures of 73.3 for the 10.7 cm solar flux and 10.9 for the geomagnetic index. The solar flux and geomagnetic index figures are the 97.7 percentile figures for June 1987 form the Marshall Space Flight Center predictions.

The "NASA neutral" is considered to be the worst long-term or continuous case applicable to any reasonable resupply cycle or propellant loading analysis.

DISTURBANCE	DEPENDENCE	WHERE IMPORTANT	COMMENTS
AERODYNAMIC	AREA, SHAPE ALTITUDE	BELOW 500 KM	DENSITY DEPENDENT ON SOLAR FLUX, GEOMAGNETIC INDEX, AND ALTITUDE
GRAVITY GRADIENT	INERTIA TENSOR, ALTITUDE, ATTITUDE	ALL ALTITUDES	TORQUE MAY BE GREATER THAN AERODYNAMIC TORQUES FOR SPACE STATION
SOLAR PRESSURE	AREA, REFLECTIVITY	ALL ALTITUDES	SHADOWING AND SOLAR ARRAY OPERATIONS ARE MAJOR CONCERNS
MAGNETIC	DIPOLE INDUCED BY MAGNETIC MATERIALS, UNCLOSED CURRENT LOOPS	BELOW 1000 KM	DIFFICULT TO ESTIMATE, HOWEVER, GENERALLY OF VERY LOW ORDER

TABLE 12. DISTURBANCE TORQUE SUMMARY

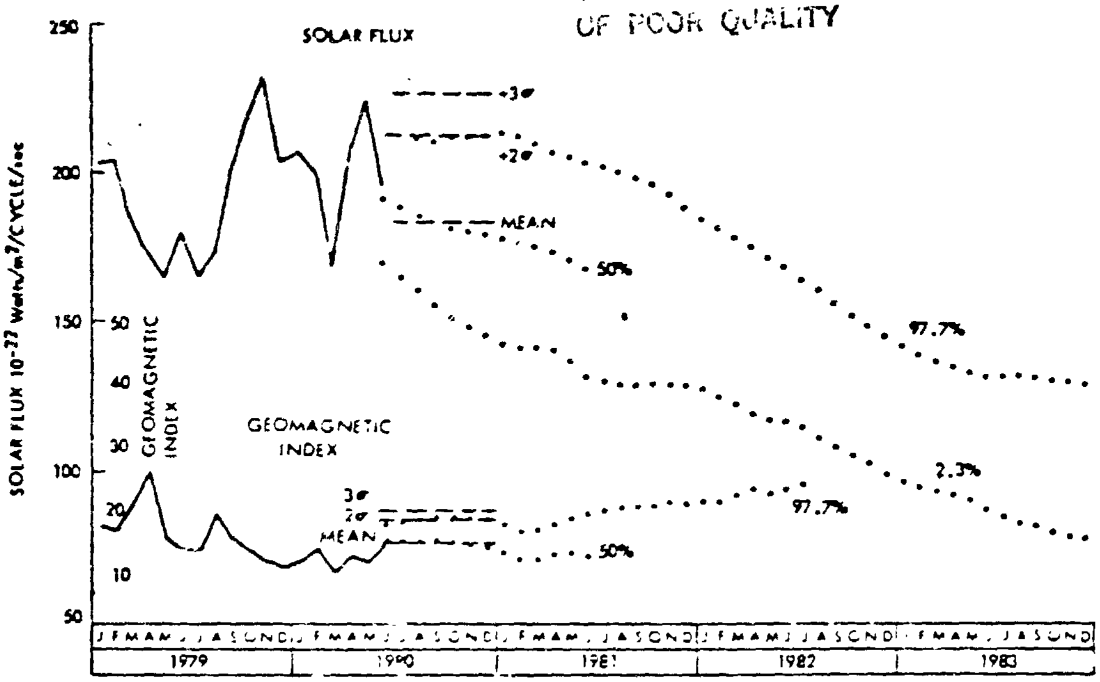

FIGURE 38. GEOMAGNETIC INDEX AND SOLAR FLUX MEASUREMENTS

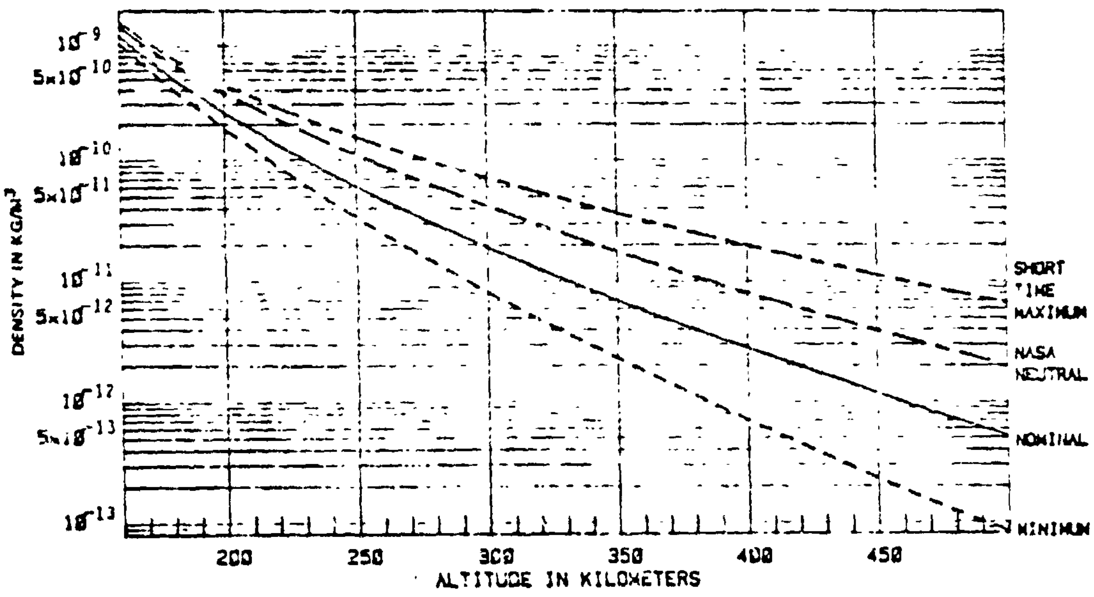

FIGURE 39. ATMOSPHERE DENSITY MODELS

Gravity Gradient

Gravity follows an inverse square law, and, as a consequence, mass elements near the earth are attracted more strongly than those farther away. When these forces are summed over a body, the point of application; i.e., the center of gravity, is found to be a little closer to the earth than the center of mass. The separation is very small with respect to a characteristic dimension of a structure but does lead to a gravity torque. General expressions can be found in References 5, 6, and 7. If the body axes are chosen as principal axes of inertia, the body axis torque expressions simplify to

$$T_X = \frac{3\mu}{2\rho^3} (I_{ZZ} - I_{YY}) \cos^2\theta \sin 2\phi$$

$$T_Y = \text{"} \quad (I_{ZZ} - I_{XX}) \cos\phi \sin 2\theta$$

$$T_Z = \text{"} \quad (I_{XX} - I_{YY}) \sin\phi \sin 2\theta$$

In these expressions, ϕ, θ, and ω are the roll, pitch and yaw Euler angles, $\mu = GM_{earth} = 3.986 \times 10^5$ km^3/sec^2, and ρ = radius of orbit.

Radiation Disturbances

In the analysis of radiation disturbances for earth orbital missions, three sources of radiation require consideration. The primary disturbance is from direct solar radiation which contributes both electromagnetic forces from photons and a plasma force from the solar wind. A secondary disturbance is earth illumination which can be reflected sunlight or infrared emission. Finally, small effects can result from spacecraft asymmetrical radiation emission in the form of thermal hot spots or radio transmissions. This latter disturbance is many orders of magnitude lower than the other two and was not examined.

There are also three factors to be considered in the determination of forces from any radiation source. The quality of incident radiation determined by the intensity, spectrum, and direction is the first determinant. Second, is the geometry of the spacecraft including the shape of the surface and the location of the sun with respect to the spacecraft mass center. Finally, the optical properties of the surface upon which the radiation is incident or from which it is emitted must be considered. Table 13 summarizes the radiation sources and force determination factors to be used during this study.

Direct Solar Radiation

The two sources of direct solar radiation, photon pressure and the solar wind plasma force, are separated by four orders of magnitude. The solar wind is so much weaker than the photon radiation forces that its effect can safely be ignored.

Table 13. Radiation Disturbance Factors

Sources of Radiation	Force Determination Factors
I Direct Solar Radiation	I Incident Radiation Properties
A. Photons	A. Intensity
B. Solar Wind	B. Spectrum
	C. Direction
II Spacecraft Geometry	II Spacecraft Geometry
A. Reflected Sunlight	A. Surface Shape
B. Infrared Emission	B. Location of Sun
III Space Emission	III Surface Optical Properties
A. Thermal Hot Spots	A. Reflection
B. Radio or Power Transmission	B. Emission
	C. Absorbtion

The sun provides essentially collimated radiation with a reasonably well defined intensity and spectrum. The solar photon radiation may be characterized by the solar constant I_0 which is the rate of which energy at all wavelengths is received per unit area. The best estimate of this value is 1353 ± 20 W/m^2 which when converted to force yields 4.513 x 10^{-6} N/m^2. Because this constant has uits of force per unit area, it is often called a pressure. This terminology can be misleading as the pressure here is in reality a vector quantity not a scalar.

The solar constant follows an inverse square law which is important for interplanetary flight, however for earth orbit missions the only source of distance variation is the eccentricity of the earth's orbit. The variation due to eccentricity changes the value by 3.5 percent and can, for the purposes of this investigation, be ignored. Solar radiation, therefore, is taken to be a constant of 1353 W/m^2 from a collimated source.

Earth Illumination (Albedo)

In addition to the direct solar radiation falling on a spacecraft, reflected radiation from the earth also exerts a pressure. The effect is a maximum at noon and tends to partially cancel the direct radiation forces. The earth and its atmosphere act as a diffuse reflector with the result that the albedo radiation is not collimated. This considerably complicates the determination of the resulting forces. Often these forces are ignored on the grounds that their omission will lead to conservative estimates of the total direct and reflected radiation effects. While this approach is often justified, large vehicles in relatively low orbits can experience significant relief from the albedo radiation and it may be important to include the effect.

Assuming the earth to be a perfectly diffuse reflector obeying Lambert's cosine law, the radiation emitted from an element of area dA_1 is $kU\cos\theta dA_1$ N/m^2 per unit solid angle in a direction inclined θ to the surface normal. k can be identified as the albedo coefficient and U is the incident radiation. The radiation pressure at a distance r is

$$V = \frac{kU\cos\theta\, dA_1}{\pi r^2}$$

direct along $\vec{r}$.

The normal and tangential components of radiation on an area dA , as shown in Figure 40 can be expresssed

$$V_N = \frac{U}{\pi}\int \frac{k\cos\theta\cos\alpha}{r^2}\, dA_1$$

$$= \frac{-U}{\pi}\int \frac{k\cos\theta\,\vec{r}\cdot\hat{n}}{r^3}\, dA_1$$

and

$$V_T = \frac{U}{\pi}\int \frac{k\cos\theta\sin\alpha}{r^2}\, dA_1$$

$$= \frac{U}{\pi}\int \frac{k\cos\theta\,\hat{n}x(\vec{r}\times\hat{n})}{r^3}\, dA_1$$

where n is a unit vector from surface element dA_2.

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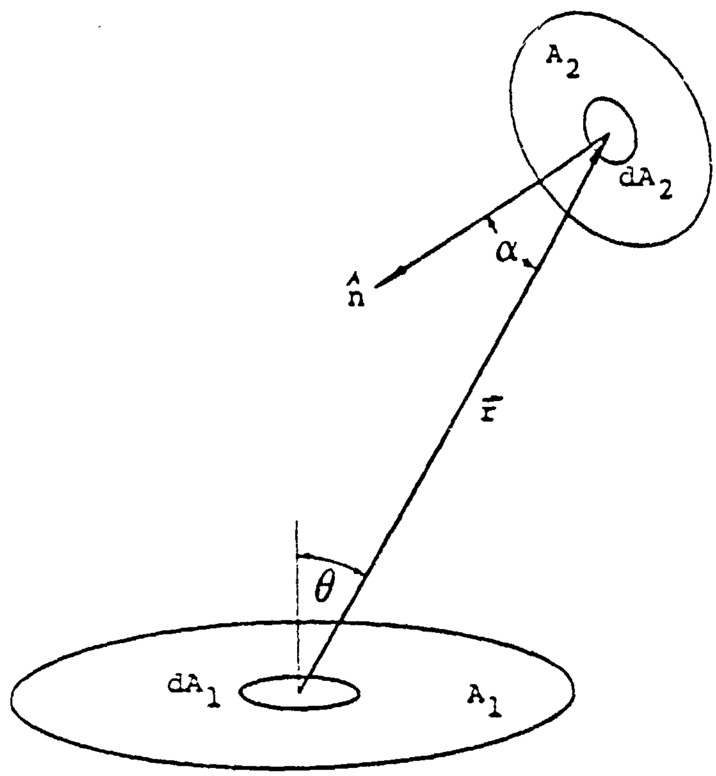

FIGURE 40. RADIATION GEOMETRY

Earth Radiation

The other source of disturbance from the earth and its atmosphere is a diffuse radiation with a spectrum approximated by the spectrum of a 288°K black body. This temperature varies with the transparency of the atmosphere from 218°K to 288°K with about 95 percent of the emitted radiation originating from the earth or the lower atmosphere. The radiation is not collimated and may be treated in the same way as the earth reflectance problem with the following result

$$I_e = \frac{I_e^0}{\pi} \int_{Esss} \cos\psi \, ds/d^2$$

where

I_e^0 = global average emmission constant (243 W/m²)

dS = element of differential area on the surface of the earth

d = distance from satellite to dS

ψ = angle between the normal dS and d

Esss = earth surface as seen by satellite

Figure 41 shows the relative values of solar radiation, earth reflectance and earth radiation for a spherical satellite for a range or orbit radii.

Disturbance Torque Calculations

Before summarizing the complete disturbance torque analysis for each vehicle, an example of the calculations is shown below for the 12.5 kw SASP configuration at 300 km. LEO altitude treated in this study ranged from 300 to 500 km. It is noted at the outset that torques at 300 km were an order of magnitude higher than 500 km due to increased atmospheric density. Torques at GEO are 3 or 4 orders of magnitude lower than those at 300 km. This sensitivity proved to make radical differences in the thrust/thruster requirements for torque cancelation at LEO versus GEO. The same conclusion will be shown when stationkeeping is considered in the following sections.

As an initial example, the smaller SASP (12.5 kw) configuration at 300 km altitude is examined. Several assumptions were made to model the aerodynamic, solar radiation, and gravity gradient disturbances. Some of these assumptions came from Reference 8. Assumptions are as follows:

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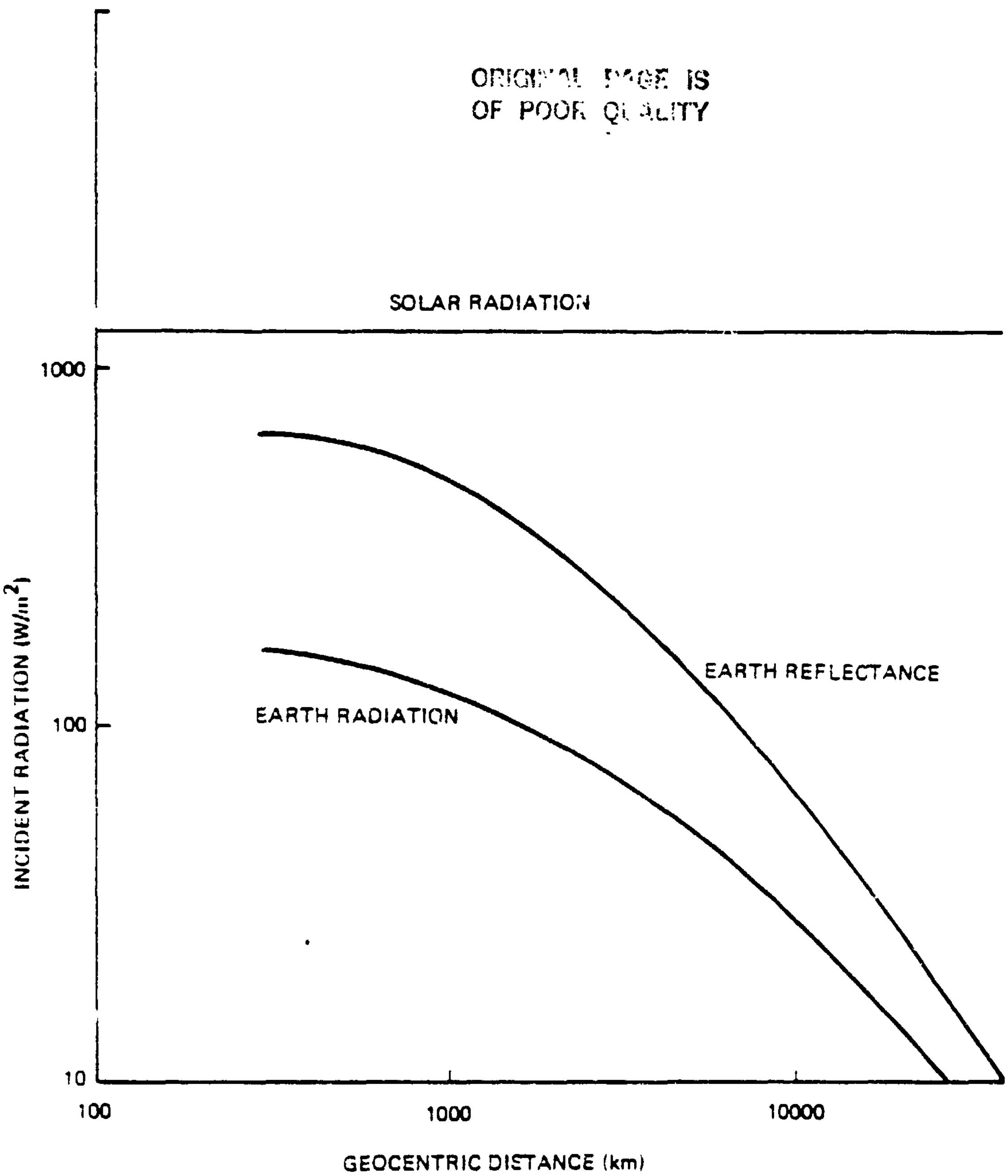

FIGURE 41. RADIATION DISTURBANCE FORCES COMPARED

1. The positions of the forces on the satellite are described using a spherical coordinate system (ϕ, θ).

2. The wind is considered to be a unit vector in the direction of the translational velocity, and the solar radiation is a unit vector exactly opposite to the wind. (This was varied for the analyses that follows.)

3. Solar radiation pressure = 4.70×10^{-6} N/m^2

4. Coefficient of drag (C_D) = 2.5

5. Gas density (Rho) = 4.0×10^{-11} kg/m^3 (NASA Neutral Model) for 300 km altitude

6. Solar radiation is either absorbed, reflected specularly, reflected diffusely or some combination. A combination of all three was used with the absorption coefficient and the coefficient of diffuse reflection, each having different values for the front and back surfaces of the satellite.

	Front	Back
Absorption coefficient	0.133	0.433
Coefficient of specular reflection	0.367	0.367
Coefficient of diffuse reflection	0.50	0.20

$C_a + C_s + C_d = 1.0$

For future analysis, we assumed 0 absorption, 3 diffuse, and .7 specular. The spherical coordinate system is shown in Figures 42 through 45. Aerodynamic drag and solar radiation calculations were made for ϕ values from 0 to 180 degrees in 15 degree increments and θ values from 30 to 360 degrees in 30 degree increments. To calculate a sum of the forces, it was arbitrarily decided to add together the forces occurring when the wind is exactly opposite to the solar radiation, Figures 6 and 8. Later calculations considered a nominal position of the satellite in orbit. In this position, a sum of forces were made using the wind vector as a constant and varying the radiation vector, Figure 45. The spherical coordinate system is shown overlaid onto SASP in Figure 46. This also shows the direction of the maximum force on SASP due to aerodynamic and radiation forces at 300 km altitude.

The following figures show the variation of torque with ϕ and θ at 300 km altitude. Figures 47, 48, and 49 illustrate the aerodynamic, gravity gradient and radiation pressure torques at low altitude. Figure 50 sums these torques to show the RSS totals for the worst case axis. It is seen that aerodynamics dominate the composite total. Appendix B shows a similar analysis at 500 km. At this altitude, aerodynamics is still dominant. However, gravity gradient is now 10% of the total. Radiation torques have decreased due to the increased radius and consequently decreasing earth reflection and albedo contribution.

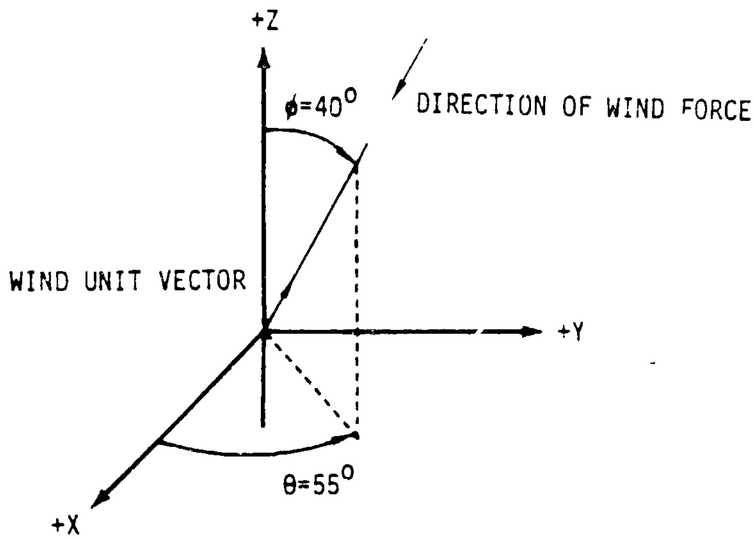

FIGURE 42. REFERENCE AXES FOR AERODYNAMIC DRAG CALCULATIONS

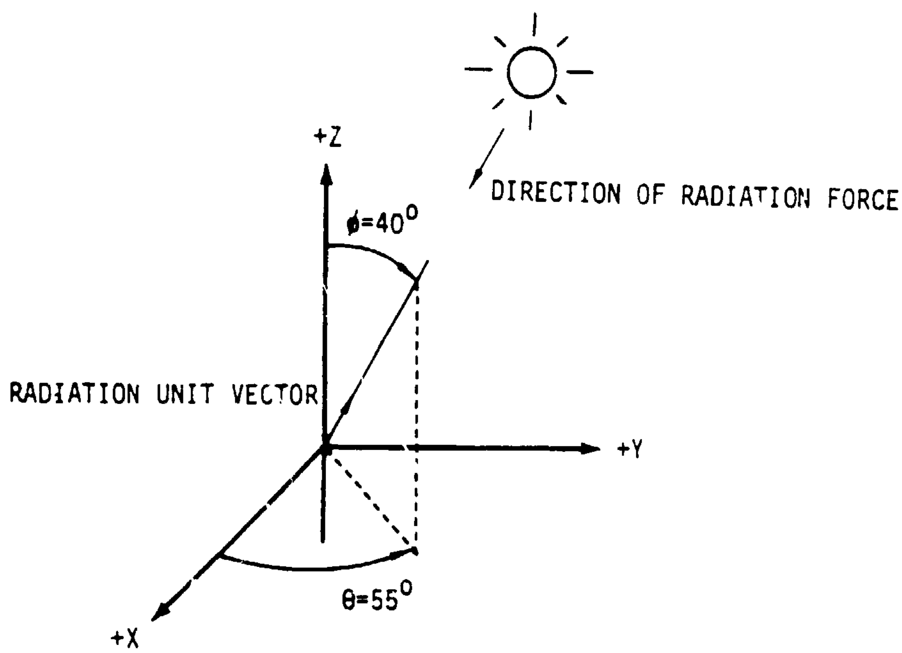

FIGURE 43. REFERENCE AXES FOR SOLAR RADIATION CALCULATIONS

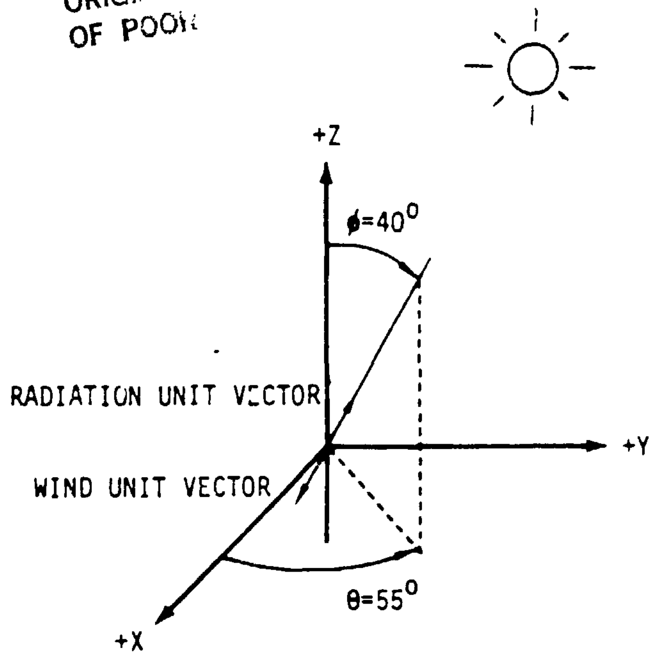

FIGURE 44. WIND IS EXACTLY OPPOSITE TO SOLAR RADIATION -- ORIENTATION USED FOR SUMMATION OF DISTURBANCE CALCULATIONS (PHI AND THETA REFER TO SOLAR RADIATION VECTOR)

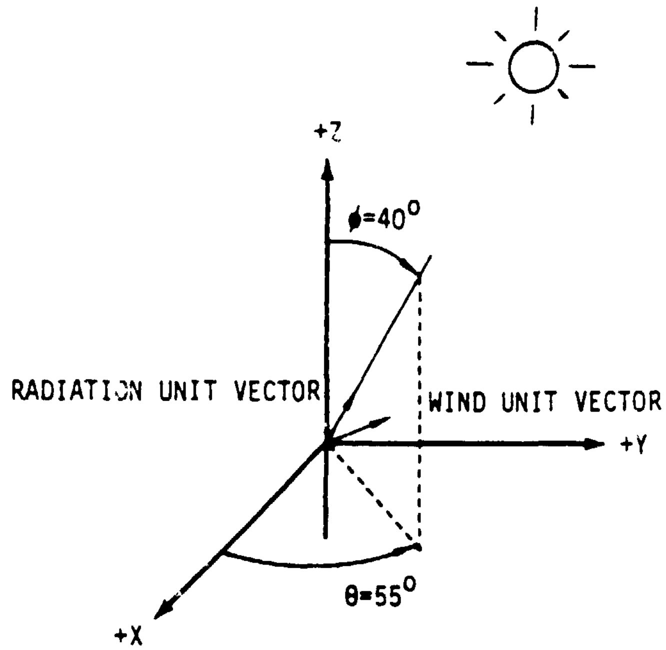

FIGURE 45. WIND IS HELD CONSTANT & SOLAR RADIATION IS VARIED -- POSSIBLE ORIENTATION FOR SUMMATION OF DISTURBANCE CALCULATIONS (PHI & THETA REFER TO SOLAR RADIATION VECTOR)

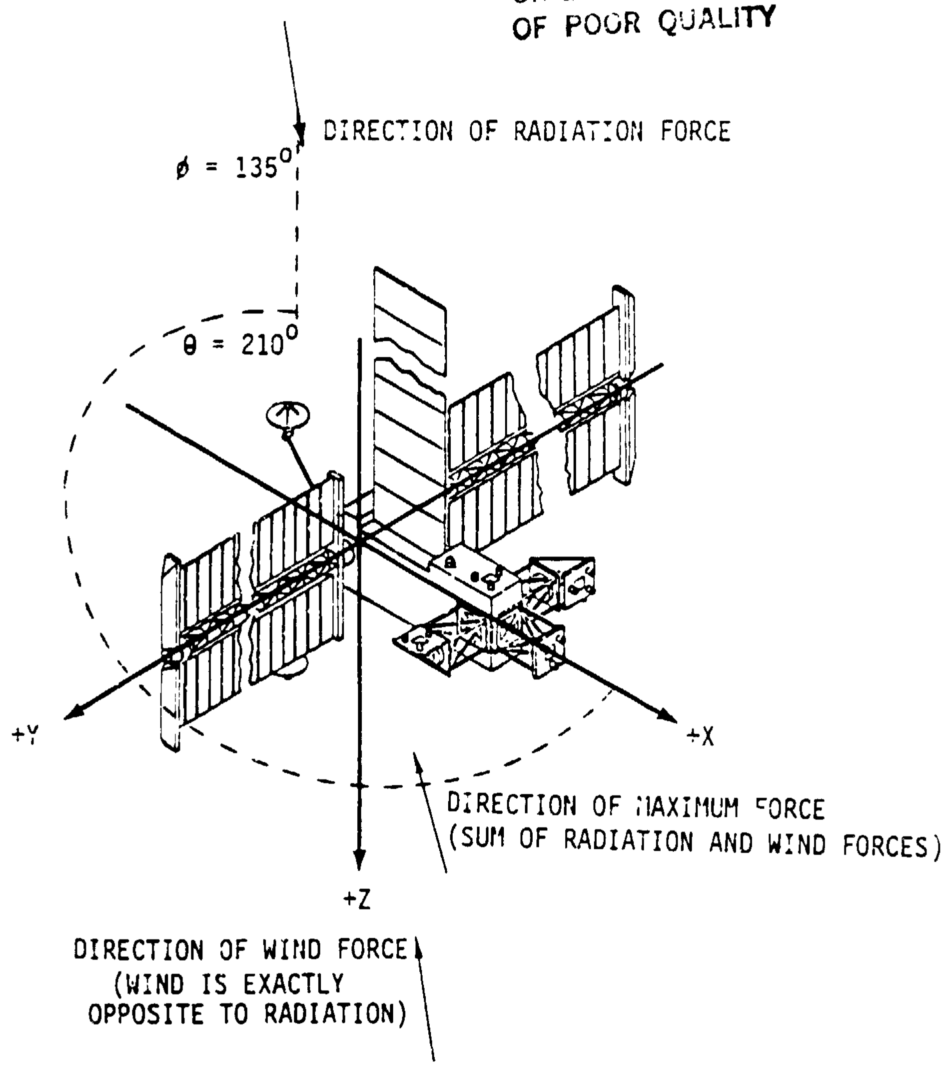

FIGURE 46. SPHERICAL COORDINATE REFERENCE ANGLES FOR MAXIMUM FORCE ON SASP (12.5 KW) 300 KM ALTITUDE

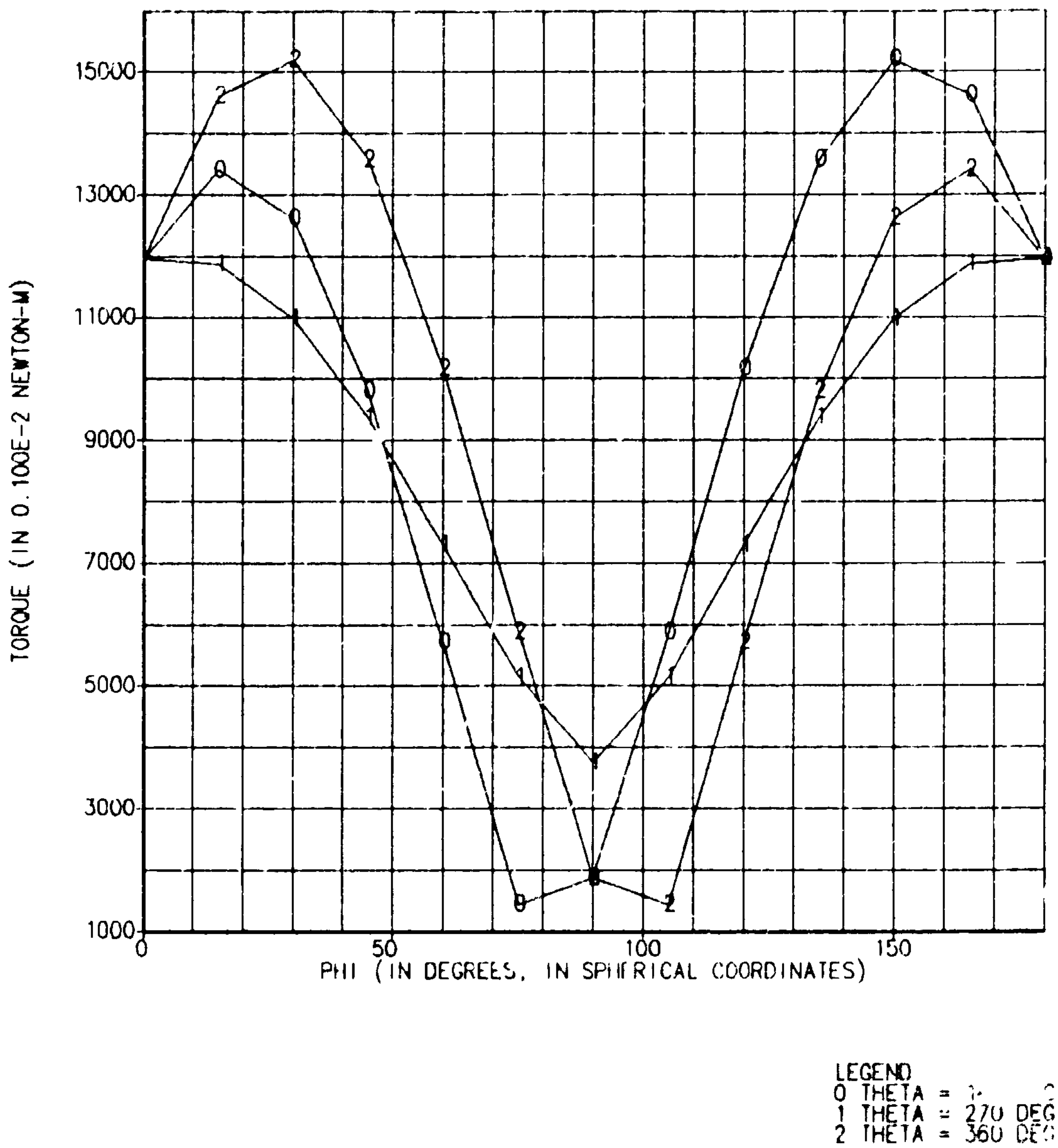

FIGURE 47. TORQUE UPON SASP (12.5 KW) DUE TO AERODYNAMIC DRAG, 300 KM ALTITUDE

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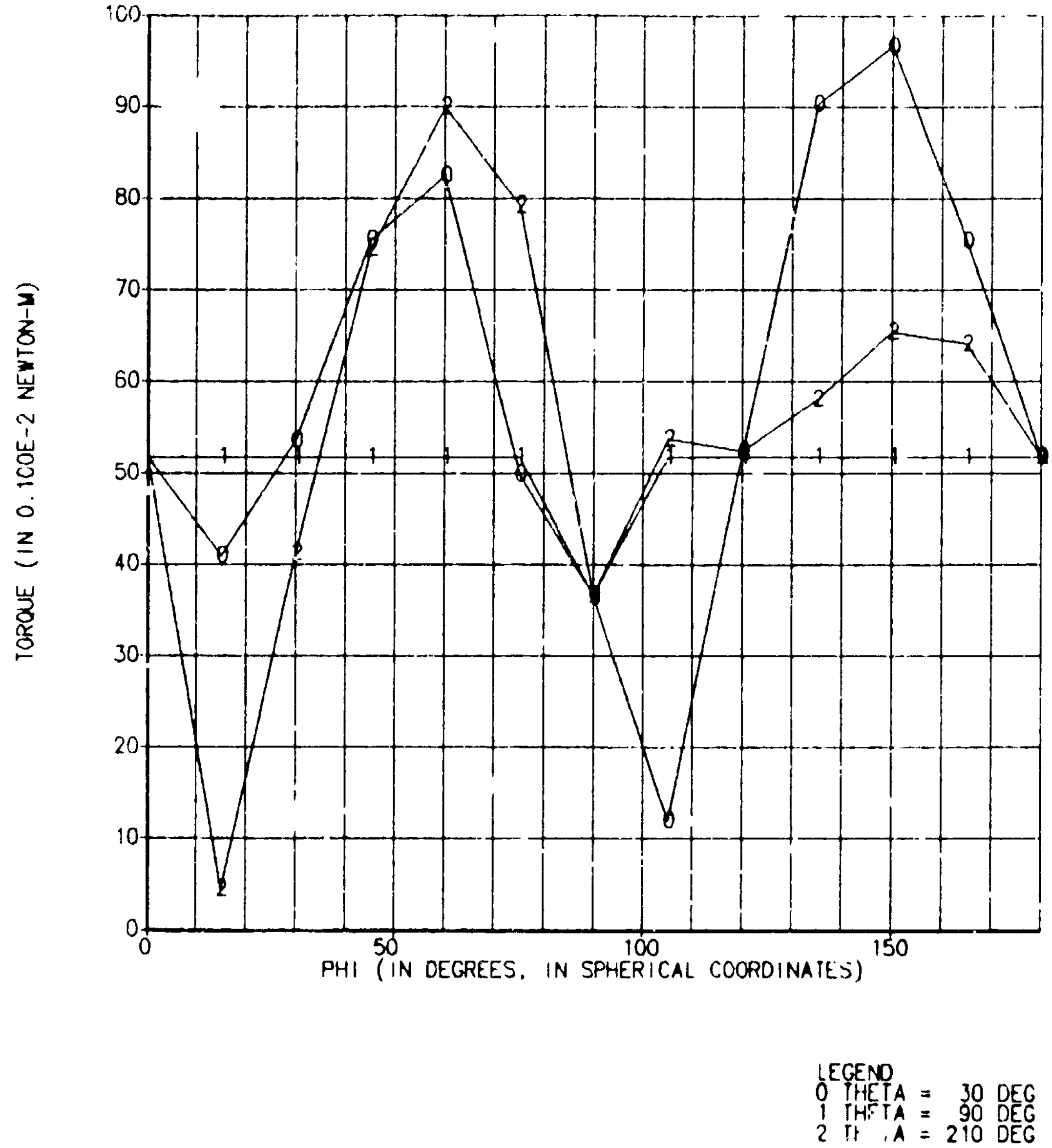

FIGURE 48. TORQUE UPON SASP (12.5 KW) DUE TO GRAVITY GRADIENT, 300 KM ALTITUDE

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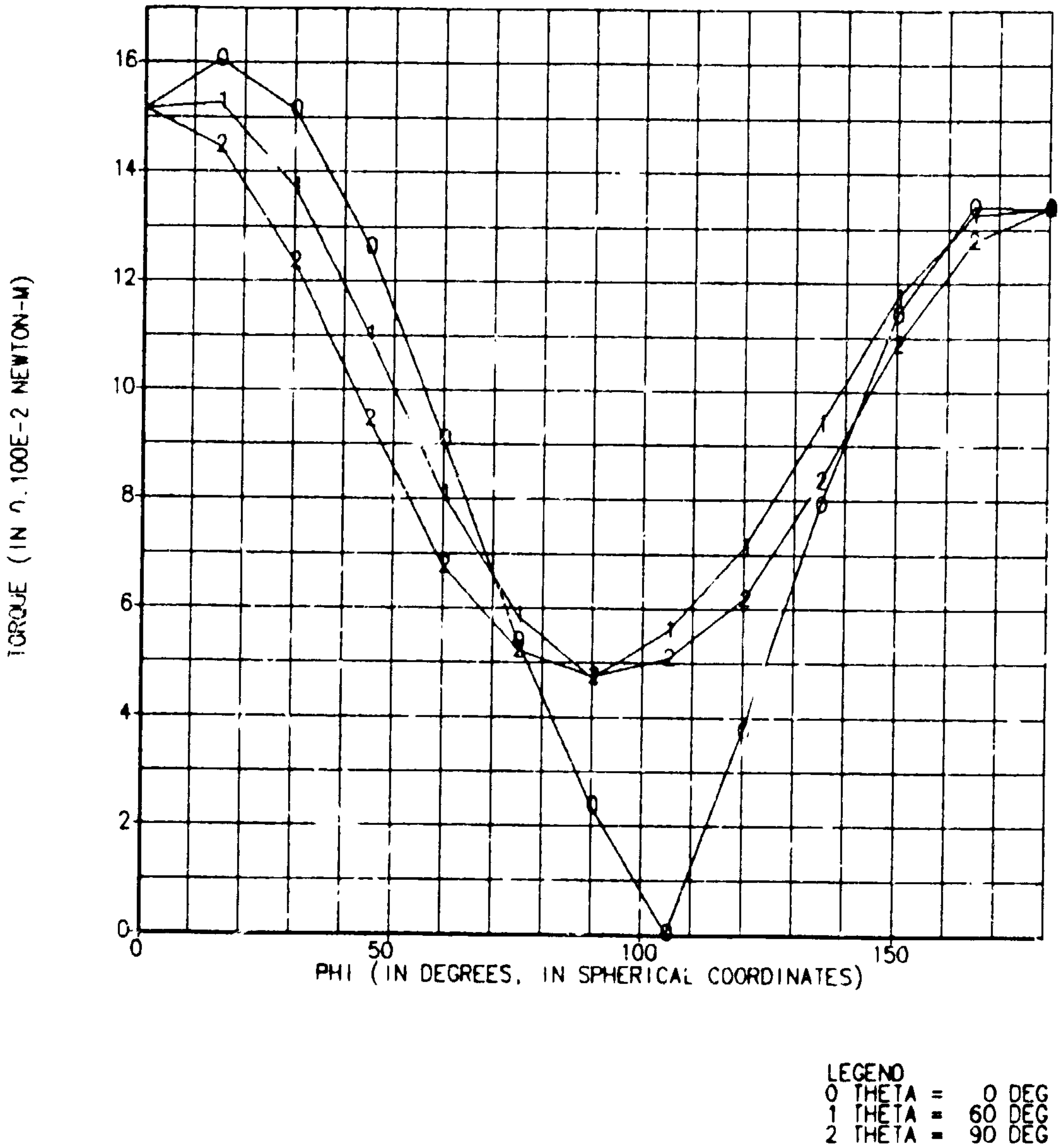

FIGURE 49. TORQUE UPON SASP (12.5 KW) DUE TO RADIATION PRESSURE, 300 KM ALTITUDE

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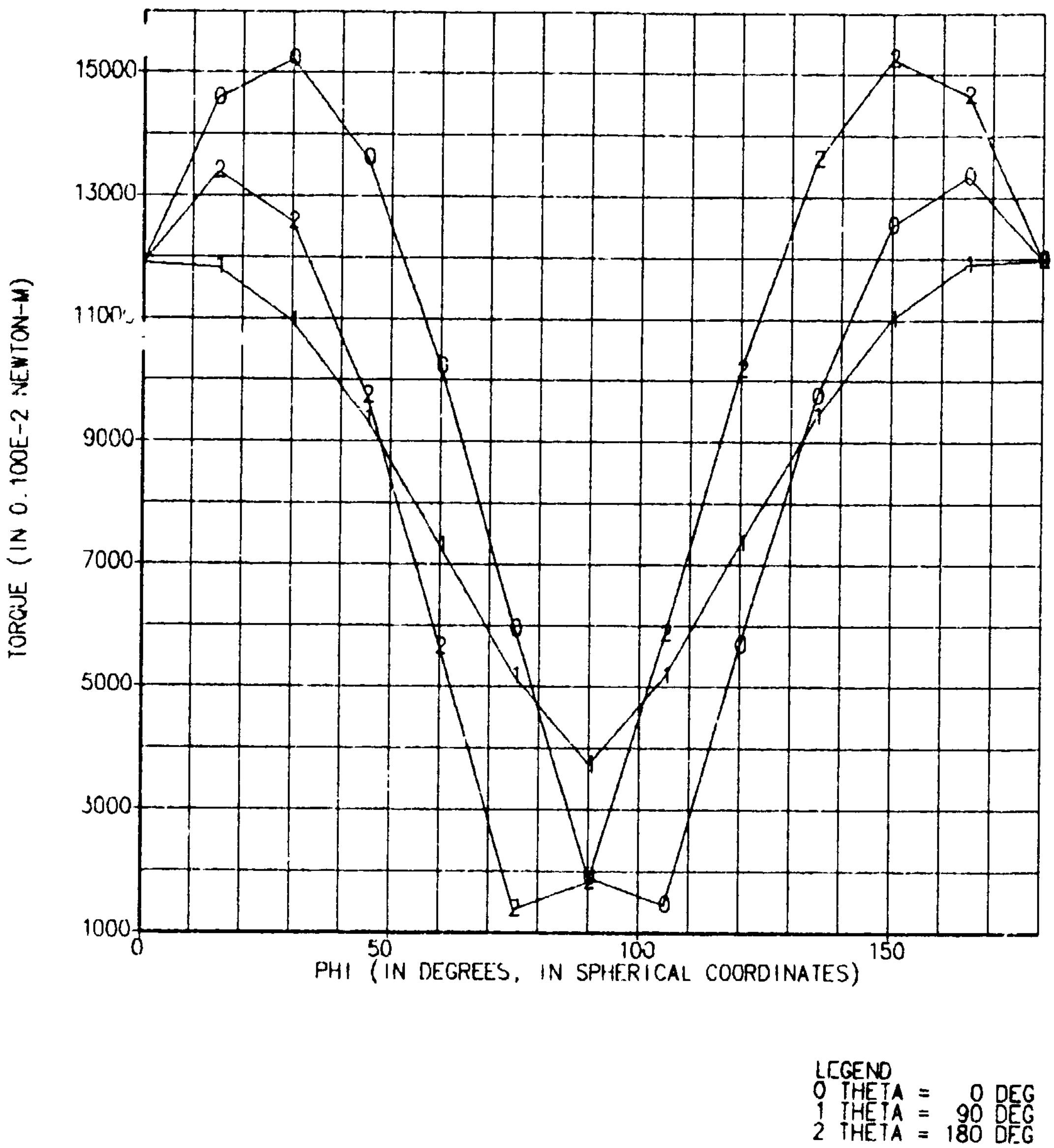

FIGURE 50. TORQUE UPON SASP (12.5 KW) DUE TO SUM OF AERODYNAMIC AND RADIATION AND GRAVITY GRADIENT TORQUE, 300 KM ALTITUDE

After this initial calculation was made, a change in the spherical coordinate system was made to Cartesian coordinates and the more familiar roll (x-axis) or nominal velocity vector), pitch (y-axis) and yaw (z-axis or earth nadir). Nominal or operational attitudes were also compared with worst case orientations. The sum angle was varied within appropriate orbit constraints to find the worst case radiation contribution in both cases. These orientations are summarized in Table 14.

Table 14. Nominal and Worst Case Orientations

<u>Nominal Orientation</u>

- 300, 400, 500 km and GEO
- Varied roll, pitch, yaw 10 in all axes - minimum bit requirements
- Used worst case sun angle
- Selected worst case attitude and torque for this 10 range

<u>Worst Case Orientation</u>

- 300, 400, 500 km and GEO
- Varied roll, pitch, yaw 360 in all axes
- Used worst case sun angle
- Selected worst case attitude, torque

A summary of the disturbance torques for each vehile size is shown in Tables 15-18. The mass properties for this set of tables were taken for a g-load of .15 g's. Additional information for the other g-loads of .06 and 1.0 can be found between the g-loads. This resulted from a nonlinear and nonsymmetric addition of mass to structural members for increasing g-loads. As mass was added, inertia properties and CP-CG momentum arms were changed in a noncorrelating and vehicle specific manner.

Table 15 shows the LEO nominal orientation torques for each vehicle. Table 16 shows the same altitudes but in a worst case condition. The variation of torques by altitude is shown to be around an order of magnitude from 300 to 500 km. Variations of torques by class also vary by orders of magnitudes due to the changing aerodynamic and mass property variations. The wrap rib and hoop/column designs have very high area/mass ratios and large CP-CG offsets and are dominated by aero torques. An interesting result for the SOC designs was that the initial version had higher torques than the operational version. The cross products of inertia and the CP-CG offset for the smaller version were greater than the more symmetric larger SOC design. This indicates that configuration optimization from a torque

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TABLE 15. DISTURBANCE TORQUES AT LEO FOR NOMINAL ORIENTATIONS

NOMINAL DISTURBANCE TORQUES ($\pm 10^0$ IN EACH AXIS, N-M)

		300 km				400 km				500 km			
CLASS	SIZE	TX	TY	TZ	RSS	TX	TY	TZ	RSS	TX	TY	TZ	RSS
LAPAA	13 kw ELM	-.3932	2.033	.0011	2.033	-.1358	.4932	.0010	.4962	.0765	.1498	.0010	.1577
	65 kw ETV	-1.057	5.537	.0134	5.537	-.2665	1.409	.0128	1.409	-.0895	.4835	.0123	.4835
WRAP RIB	55 m	13.24	38.17	-12.87	40.80	6.124	10.46	-3.513	11.77	4.404	4.212	-1.403	5.794
HOOP/COL.	120 m	-10.10	48.67	.2095	49.40	-3.546	12.91	.0513	13.29	-2.032	4.868	.0160	5.228
GEO PLT.	50 x 33 m 9 PAYLOADS	-.6061	2.538	1.025	2.717	-.1834	.5711	.2683	.6247	-.0872	.1334	.0983	.1682
SASP	12.5 kw	.2627	-4.115	2.392	4.367	.7073	-.9845	.5758	1.048	.0275	-.2847	.1700	.3067
	25.0 kw	.4715	-8.998	4.331	8.998	.1217	-2.251	1.060	2.251	.0439	-.7388	.3282	.7389
SOC	INITIAL	-25.71	13.81	121.5	121.7	-6.609	3.039	29.58	29.60	-.2319	.6694	9.028	9.038
	OPER.	9.008	32.60	.6689	33.81	3.918	8.418	.5547	9.273	2.704	2.990	.512	4.021

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TABLE 16. DISTURBANCE TORQUES AT LEO FOR WORST CASE ORIENTATIONS

WORST CASE DISTURBANCE TORQUES (N-M)

CLASS	SIZE	300 km TX	300 km TY	300 km TZ	300 km RSS	400 km TX	400 km TY	400 km TZ	400 km RSS	500 km TX	500 km TY	500 km TZ	500 km RSS
LAPAA	13 kw	2.612	2.033	.0178	2.612	-.7510	.5073	.0170	.7510	-.3300	.2637	.0160	.3300
	65 kw	2.378	-5.540	.2258	5.540	.6046	-1.439	.2160	1.439	-.2075	-.5600	.2067	.5602
WRAP RIB	55 m	-42.82	42.52	-13.70	49.18	-13.24	13.45	-4.300	14.57	-6.931	7.027	-2.268	7.432
HOOP/ COL.	120 m	77.96	-7[illegible].20	.2995	82.56	22.15	22.20	.0802	23.24	9.559	-9.562	-.0314	9.862
GEO PLT.	50 x 33 m 9 PAYLOADS	4.830	6.454	2.927	6.844	1.242	1.751	.809	1.825	.4403	.6919	.3342	.7070
SASP	12.5 kw	3.240	14.20	8.270	14.10	.7870	3.448	-2.058	3.448	-.2380	1.068	-.6700	1.068
	25.0 kw	-13.49	-26.00	14.60	26.00	-3.273	-6.482	-3.710	6.482	-.9880	-2.115	-1.270	-2.115
SOC	INITIAL	-61.57	-22.63	122.1	122.4	-15.36	-6.276	30.18	30.24	-5.011	-2.587	9.632	9.642
	OPER.	48.18	37.80	9.603	53.22	14.95	3.712	7.984	16.75	8.622	3.430	7.396	9.371

point of view could significantly reduce momentum management and desaturation requirements.

Table 17 shows the GEO disturbance levels for each axis and the RSS total. These torques were used to size thrust/thruster requirements (worst case) and to investigate the implications on minimum impulse bit (nominal orientation) for pointing control. Gravity gradient was the dominant influence with solar pressure playing a significant role for the wrap rib and hoop/column designs. Table 18 shows a summary of the RSS torques for 400 km, 500 km and GEO. It is again noted that the difference between the LEO and GEO requirements is one to two orders of magnitude. Also nominal and worst case torques are similar for some designs indicating some configuration optimization potential.

2.1.2 LEO Stationkeeping Requirements

Using an operational scenario of LEO deployment and checkout, the requirements to maintain orbit altitude in LEO must be considered. To analyze these requirements a Boeing proprietary simulation program called LTESOP (Long Term Earth Satellite Orbit Prediction Program) was used. This program incorporates all significant perturbations in LEO. These perturbations are summarized below.

- 4th order spherical harmonic expansion for earth potential
- Gravitational attracion of sun and moon
- Atmospheric drag
- Solar radiation pressure with shadowing from the earth

The ΔV and thrust level requirements are a function of the tolerance allowed for recovery to the deployment altitude. A range of altitude tolerances was considered from 0 (continuous thrusting) to 50 km tolerance. Nonlinear effects from density variation, solar/lunar gravity and earth triaxiality became pronounced for tolerances in excess of 10 km.

An additional complication in this analysis was the solar array angle to the "wind." Figure 51 shows that S/A angle has a major impact on ΔV requirement for the SASP design. This angle is a function of orbit, body orientation, and time of the year. An assumption was made that S/A angle would be treated as a constant at 20 degrees angle of attack (90 degrees = flat to the wind). This shallow angle was thought to be a reasonable average because the array may be "feathered" on the dark side and because a flat array would only occur around the terminator. It is suggested that a complete simulation of S/A incidence angle be conducted for future analysis to verify this assumption.

The atmospheric model and orbit altitude assumed also had a major impact in the calculation of ΔV. Figure 52 illustrates these two effects for the operational SOC design. The small oscillations in the curves are due to the 28 day lunar cycle. As stated previously, we assumed the NASA neutral atmosphere and examined altitudes from 300 to 500 km for each design. It

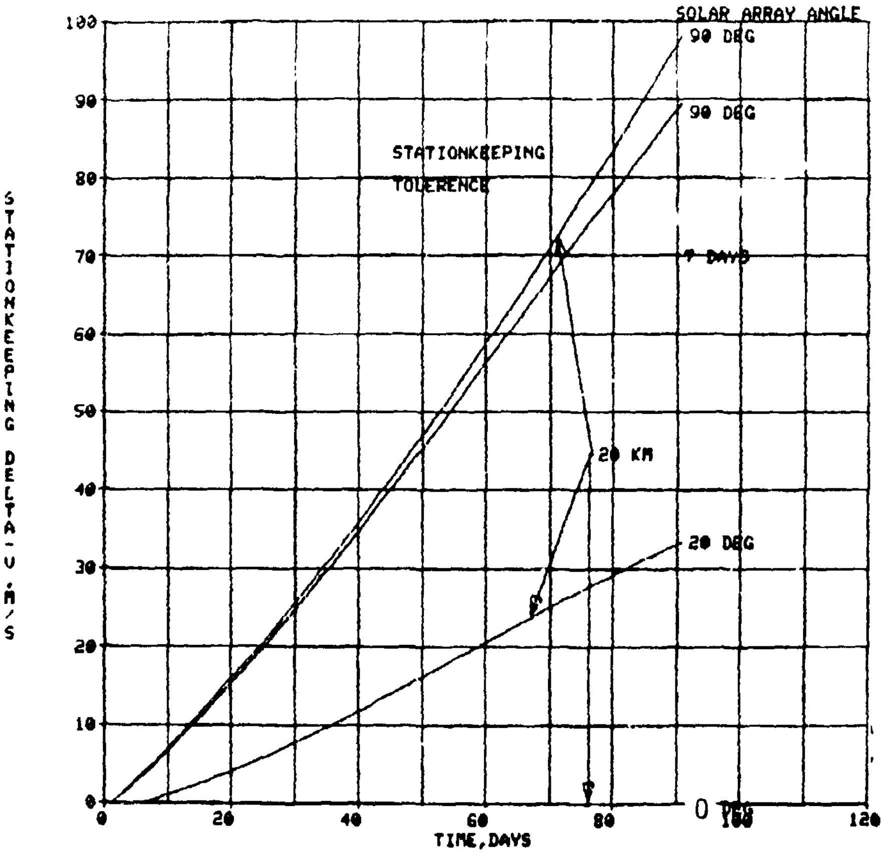
TABLE 17. DISTURBANCE TORQUES AT GEO

GEOSYNC TORQUES (N-M)

CLASS	SIZE	NOMINAL $\pm 10^{o}$				WORST CASE			
		TX	TY	TZ	RSS	TX	TY	TZ	RSS
LAPAA	13 kw (EM)	.41E-3	.21E-2	.41E-5	.22E-2	.0022	.0022	7.E-5	.0022
	65 kw (ETV)	-.63E-3	.60E-2	.53E-4	.60E-2	.0013	.0060	.0009	.0060
WRAP RIB	55 m	.0217	.0407	-.0141	.0458	.0455	.0490	-.0164	.0515
HOOP/COL.	120 m	-.0113	.0430	.17E-3	.0441	.0656	-.0659	-.0002	.0668
GEO PLT.	50 x 33 m 9 PAYLOADS	-.57E-3	.18E-2	.98E-3	.20E-2	.0040	.0063	-.0015	.0064
SASP	12.5 kw	.13E-3	-.33E-2	.14E-2	.34E-2	.0034	.0128	.0052	.0128
	25.0 kw	.20E-3	-.78E-2	.25E-2	.78E-2	.0142	-.0235	-.0095	.0235
SOC	INITIAL	-.0167	.0104	.1283	.1285	.0384	-.0193	.1308	.1311
	OPER.	.0141	.0324	.23E-2	.0353	.0600	.0338	.0328	.0630

TABLE 18. DISTURBANCE TORQUE (N-M) RSS SUMMARY

	LEO (400 KM)		LEO (500 KM)		GEO	
	NOMINAL	WORST CASE	NOMINAL	WORST CASE	NOMINAL	WORST CASE
LAPAA 13 KW	.5	.8	.2	.4	.004	.044
LAPAA 65 KW	3	4	.9	1	.009	.009
WRAP RIB 55M	10	20	6	9	.06	.06
HOOP/COLUMN 120 M	20	30	6	10	.04	.05
GEOSTATIONARY PLT.	1	2	.3	.8	.003	.007
SASP 12.5 KW	1	4	.4	1	.004	.02
SASP 25 KW	2	7	.7	2	.009	.03
SOC INITIAL	40	40	10	10	.2	.2
SOC OPERATIONAL	10	20	4	10	.04	.08



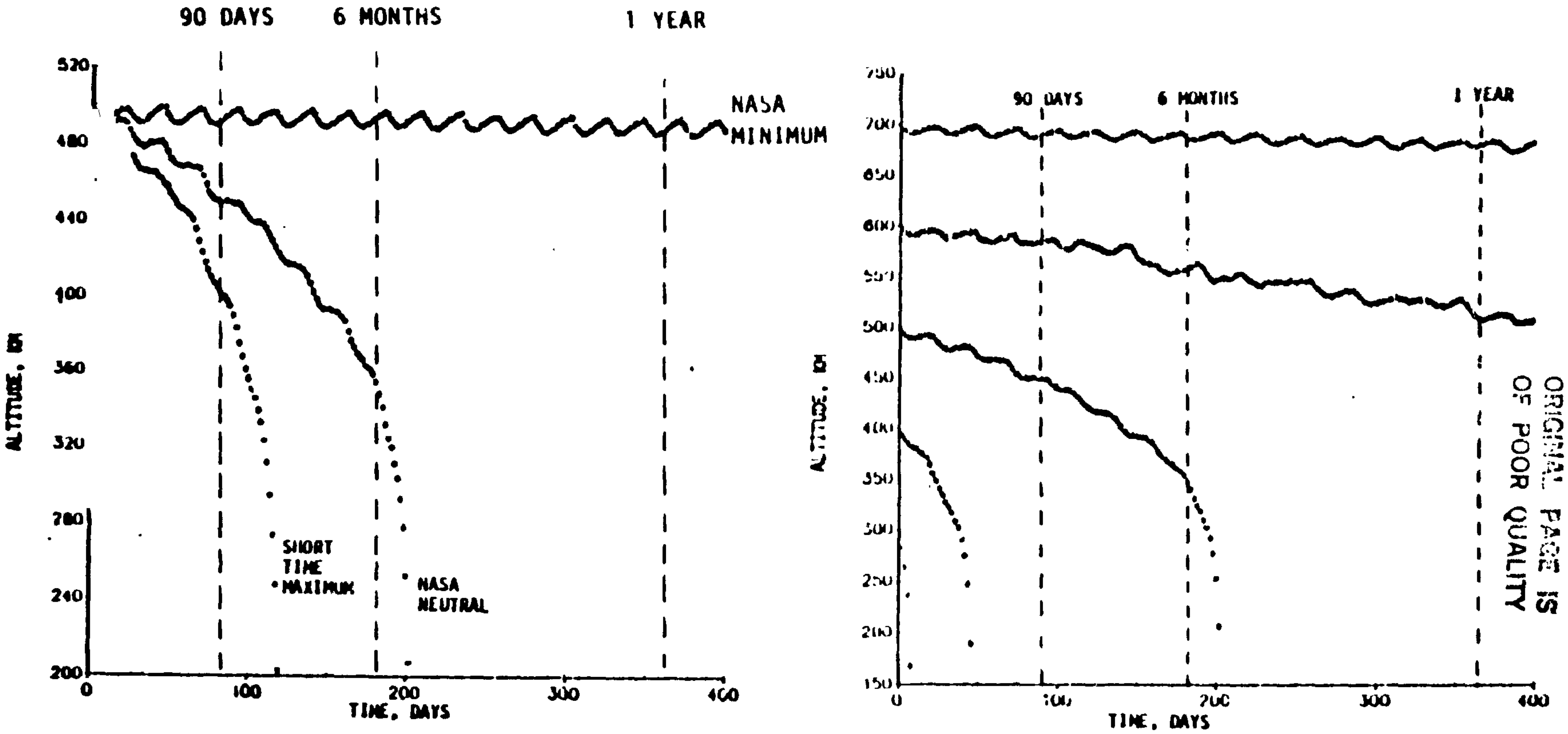
- SASP 12.5 KW
- NASA NEUTRAL ATMOSPHERE
- 500 KM INITIAL ALTITUDE

FIGURE 51. LEO STATIONKEEPING REQUIREMENTS FOR VARYING S/A ANGLES

• NO STATIONKEEPING ASSUMED

Atmospheric Modeling Impacts

Initial Altitude Impacts



• Operational SOC

• NASA neutral atmospheric model
• Operational SOC

FIGURE 52. IMPACT OF ATMOSPHERIC MODELING AND INITIAL ALTITUDE ON ORBIT DECAY

became apparent early in this analysis that 300 km was an unreasonable altitude to maintain for any of the classes studied. Figure 53 illustrates the rapid decay of orbit altitude for representative classes. Based on this initial data 300 km was dropped from any further consideration.

Altitude tolerance effects were shown to have a major impact on the ΔV requirements for all vehicles. This effect is illustrated in Figure 54 for the operational SOC design. At lower altitudes, for this design, the increasing atmospheric density dominates the requirements and continuous thrusting yields a lower ΔV. For higher altitudes the density effects are much smaller and higher tolerances yield more efficient operation and less ΔV. For the other designs less sensitivity is seen to tolerance as shown in Tables 19 and 19-1. A summary the LEO stationkeeping requirements using a 10 km tolerance is shown in Figure 55. This figure shows that ΔV for LEO stationkeeping is a linear function of area to mass. The implications on the propellant mass required for LEO operation are illustrated in Table 19 for various I_{sp}'s and two altitudes. This data is compiled for 90 day LEO operation. Shorter time periods would, of course, considerably lessen this requirement. The magnitude of the propellant requirements does indicate that even for short period of time 100's of kg of propellant would be required to maintain altitude. This requirement must be traded against the benefit of LEO checkout in future studies.

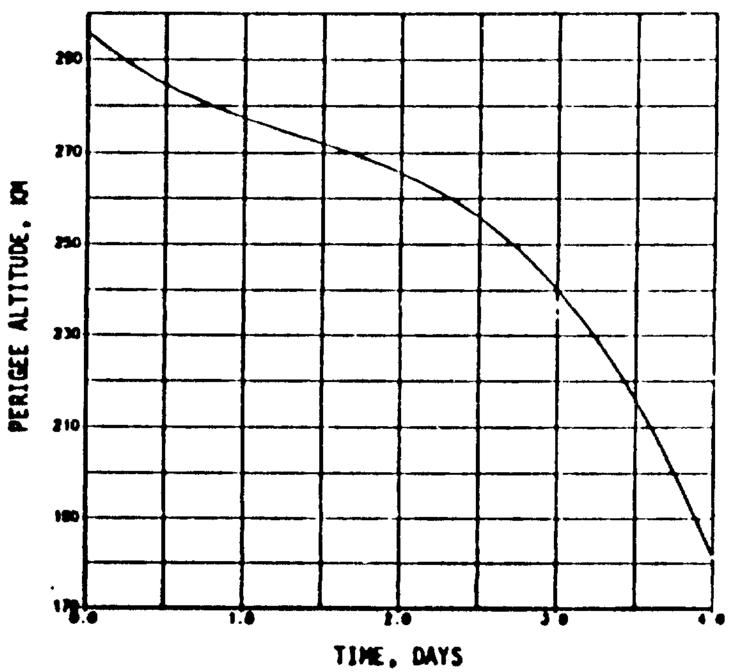
The thrust requirements to maintain altitude were calculated for a range of duty cycles or thrusting times. The propellant requirements to maintain altitude for 90 days were added to the structure to understand the effect of this increased mass on the thrust level requirement. Generally this effect was insignificant as shown in the lower graph of Figure 56. This figure shows the total thrust requirements for LEO stationkeeping. It indicates that for reasonably short periods, chemical propulsion is required to maintain altitude. Thrust times in hours must be used to lower the total thrust level to electric thruster range. Additional thrust level data for each class is contained in Appendix B.

2.1.3 Geosynchronous Stationkeeping

An analysis of the geosynchronous stationkeeping requirements for the principal LSS designs was performed. The analysis used the area and mass numbers presented in Appendix A. These numbers give the total area and mass for the structure. The propellant and thruster masses were not added in because they were determined in subtask 2C. When the APS mass is determined, the stationkeeping requirements must be recalculated with the total mass (structure + APS mass) and the resulting ΔV's used to adjust the APS mass. This iterative process is performed until a converged value for the APS mass is obtained. The ΔV's, propellant mass and thrust requirements presented here are just the first cut in determining the stationkeeping requirements. Final answers will differ by a percentage from 10 to 20%. The trends shown in the preliminary data will remain unchanged.

- 300 KM INITIAL ALTITUDE
- NASA NEUTRAL ATMOSPHERE

SASP 12.5 Kw



Electronic Mail

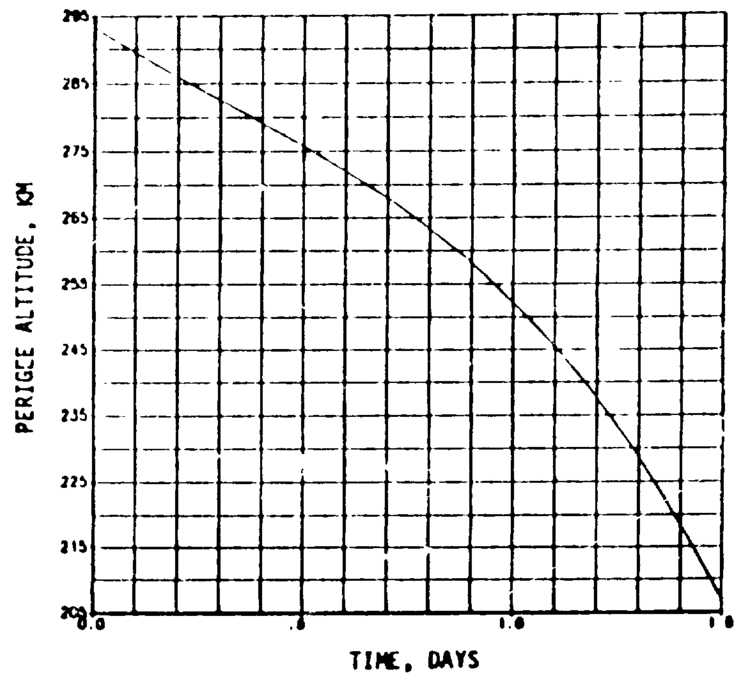


FIGURE 53. 300 KM ALTITUDE DECAY

• SOC Operational Configuration

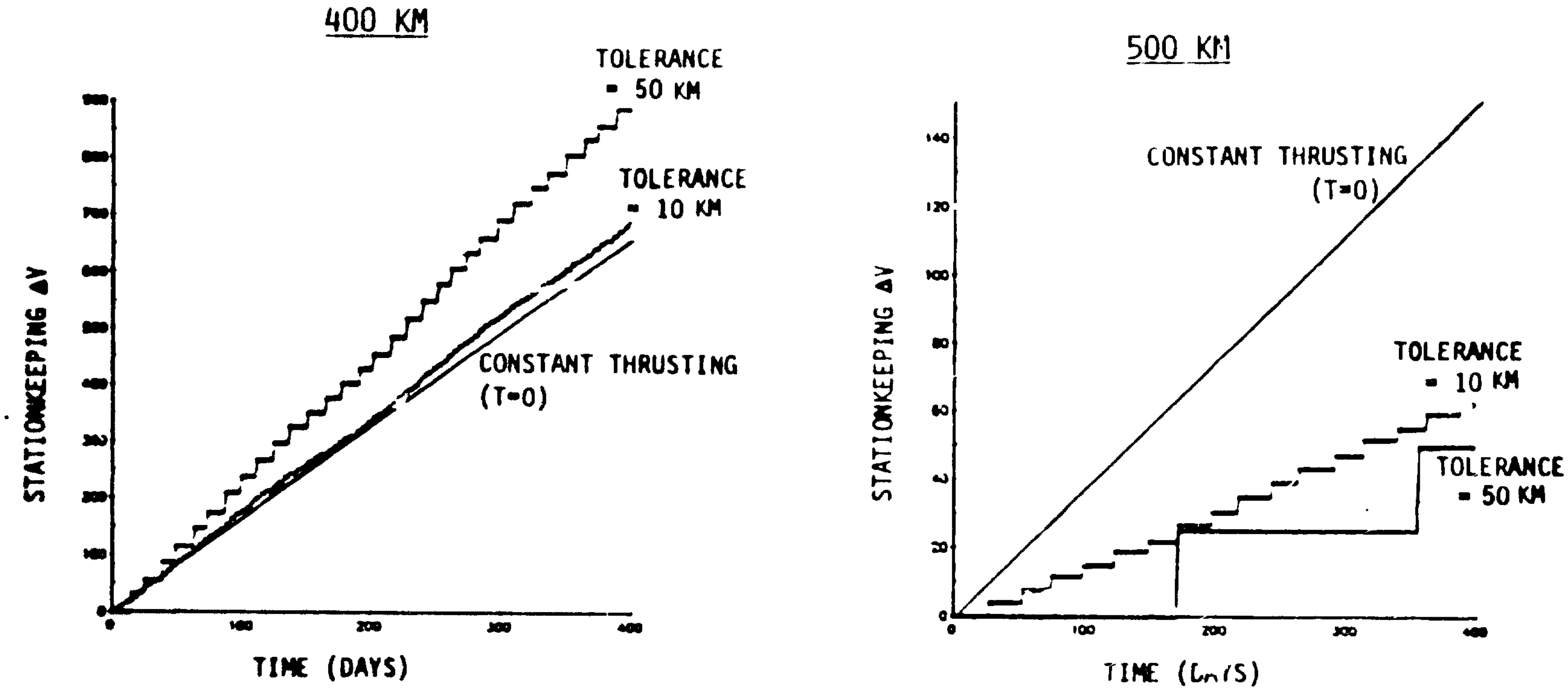


FIGURE 54. EFFECTS OF LEO STATIONKEEPING FOR DIFFERENT ALTITUDE TOLERANCES

TABLE 19. ΔV REQUIREMENT PER 90 DAYS (M/SEC AT 400 KM ALTITUDE)

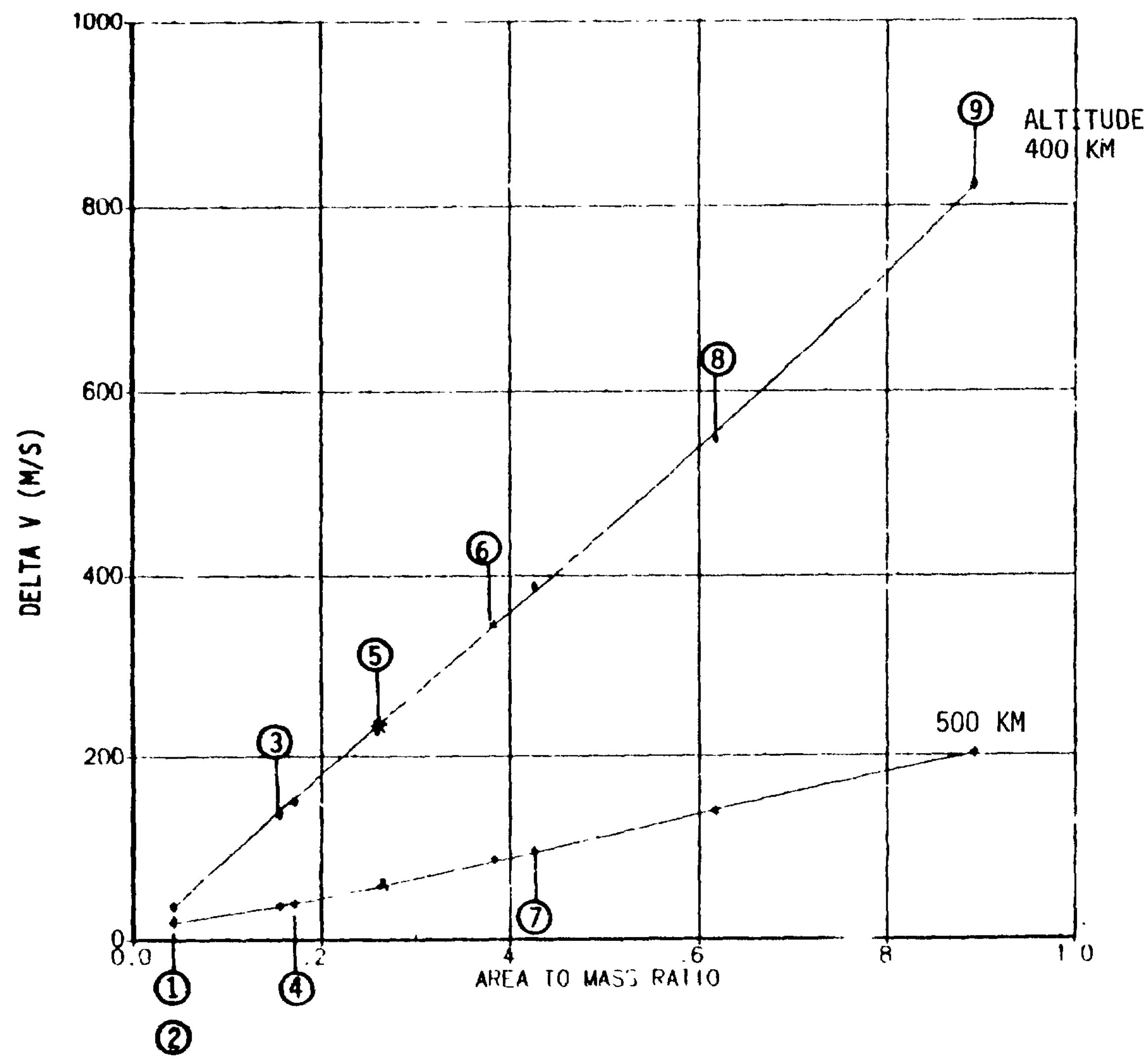
SATELLITE CLASS AND SIZE	CONDITION FOR STATIONKEEPING ALTITUDE CHANGE (km)			
	50	20	10	5
ELECTRONIC MAIL	484.42	393.45	345.21	324.23
EDUCATIONAL TV	882.42	627.57	549.29	540.67
LMSS WRAP RIB (55M)	--	1026.8	812.32	822.76
LMSS WRAP RIB (25M)	1147.3	687.53	584.91	584.91
LMSS HOOP COLUMN (120M)	--	--	3371.9	3371.9
LMSS HOOP COLUMN (60M)	1293.7	1292.8	976.24	976.24
GEOSTATIONARY PLATFORM	564.44	436.56	388.57	362.41
SASP 12.5 kW	174.69	148.25	135.26	131.33
SASP 25 kW	169.56	160.14	145.89	145.86
SOC INITIAL	27.654	34.383	35.413	37.027
SOC OPERATIONAL	28.384	33.446	32.187	36.665

1. SOLAR ARRAYS AT 20^{0} ANGLE OF ATTACK

TABLE 19-1. VELOCITY INCREMENT PER 90 DAYS (M/SEC AT 500 KM ALTITUDE)

SATELLITE CLASS AND SIZE	CONDITION FOR STATIONKEEPING ALTITUDE CHANGE (km) 50	20	10	5	DAYS 7
ELECTRONIC MAIL	109.72	85.707	83.593	82.476	89.336
EDUCATIONAL TV	166.09	141.49	135.72	134.13	151.75
LMSS WRAP RIB (55 M)	251.41	218.61	202.64	197.97	235.27
LMSS WRAP RIB (25 M)	173.68	163.16	146.25	146.62	164.78
LMSS HOOP COLUMN (120 M)	920.07	681.55	589.69	589.69	-
LMSS HOOP COLUMN (60 M)	310.69	251.27	232.56	226.61	284.80
GEOSTATIONARY PLATFORM	104.96	95.941	91.565	91.805	99.966
SASP 12.5 KW	26.373	32.329	35.173	36.067	36.206
SAPS 25 KW	28.062	33.438	35.210	38.090	39.127
SOC INITIAL	0.[2.]	7.6550	19.339	32.356	32.478
SOC OPERATIONAL	0.[3.]	7.522	15.740	32.668	30.246

1. SOLAR ARRAYS AT 20^{o} ANGLE OF ATTACK
2. SOC INITIAL HAD DROPPED < 50 KM IN 90 DAYS
3. SOC OPERATIONAL HAD DROPPED < 50 KM IN 90 DAYS



- 90 day ΔV requirements (m/s)
- 10 km tolerance
- S/A at 20^0 angle to flow

LEGEND	(m^2/kg)
① SOC OPERATIONAL	.041
② SOC INITIAL	.042
③ SASP 12.5 KW	.154
④ SASP 25 KW	.170
⑤ LMSS HOOP COLUMN	.260
⑥ LAPAA 10 KW	.382
⑦ GEOPLATFORM	.423
⑧ LAPAA 65 KW	.617
⑨ LMSS WRAP RIB	.891

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FIGURE 55. LEO STATIONKEEPING ΔV AS A FUNCTION OF AREA TO MASS RATIO

- THRUST (N)
- 10 KM TOLERANCE
- PROPELLANT FOR 90 DAYS ADDED (I_{SP} = 200 SEC)

CLASS	THRUST TIME (HRS) / SIZE	400 KM 0.5	400 KM 5	400 KM 100	500 KM 0.5	500 KM 5	500 KM 100
LAPAA	10 KW	11	1.1	.05	2.8	.3	.014
	65 KW	5.3	.5	.03	1.2	.1	.006
LMSS WRAP R113	25 M	6.4	.6	.03	1.9	.2	.009
	55 M	13	1.3	.07	3.6	.4	.018
LMSS HOOP/COL.	60 M	9.8	1.0	.05	2.6	.3	.013
	120 M	52	5.2	.26	9.6	1.0	.048
GEO PLATFORM		17	1.7	.09	4.0	.4	.02
SASP	12.5 KW	28	2.8	.14	7.1	.7	.036
	25 KW	50	5.0	.25	10.4	1.0	.052
SOC	INITIAL	105	10.5	.53	60	6.0	.3
	OPERATIONAL	210	21.0	1.05	100	10.0	.5

- I_{SP} HAS MINIMAL EFFECT
- WORST CASE HOOP/COLUMN (60M) SHOWN
- 400 KM

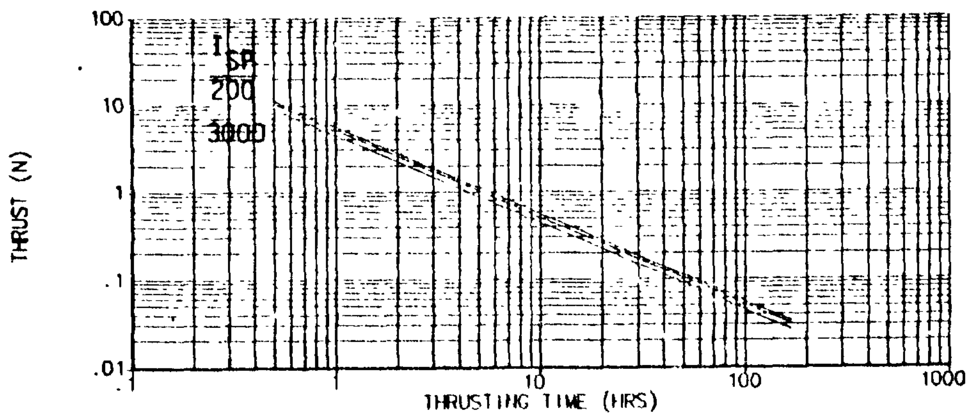

FIGURE 56. LEO TOTAL THRUST LEVEL REQUIREMENTS

Geostationary orbit stationkeeping requirements derive from three sources. A North/South or inclination perturbation results from a single source - gravity perturbations from the sun and moon. East/West or longitudinal perturbations result from two sources. The first source is the earth's triaxiality (oblateness and equatorial ellipticity) and the second is from solar pressure disturbances. These three disturbance effects were described in detail in Reference 9.

There are four standard methods of overcoming the solar pressure effect on a geostationary orbit. These methods are described in detail in Reference 9. Method 1 is to continuously cancel the effect of solar pressure by thrusting in a direction toward the sun. This method is highly inefficient and results in ΔV's which are 20-40% higher than the other methods. Method 2 is to circularize the orbit each time the eccentricity becomes equal to some tolerance. This tolerance can be related to a longitudinal drift tolerance and corrected with E/W thrusting. Method 3 is to rotate the line of apsides in such a manner that the solar pressure will cause the eccentricity to decrease to zero before increasing again. The final method maintains the eccentricity nearly equal to zero* by frequently rotating the apsidal line in such a manner that the longitude of perigee is equal to the longitude of the sun. Methods 3 and 4 are more complicated than Method 2 and generally the difference in ΔV for A/M ratios of .05 or greater between Methods 2, 3, and 4 is small. Method 2 is, therefore, the method we will assume when calculating APS mass. Figure 57 summarizes the GEO stationkeeping perturbations.

The results of the GEO stationkeeping ΔV requirements are displayed in Tables 20, 21, and Figure 58. These tables illustrate the ΔV and propellant mass of each LSS design. We have selected representative duty cycles for high thrust (p=.01=.24 hours/day) and low thrust (p=.4=9.6 hours/day) systems for comparing ΔV requirements. The propellant requirements are based on the total ΔV's in Table 20 and are yearly or, more precisely, estimates for a 10-year mission were made when the total APS mass estimates fed back to recalculate stationkeeping requirements.

Figure 58 shows that solar pressure adds significant ΔV for area to mass ratios greater than around a tenth. Another feature of stationkeeping is that N/S ΔV is independent of mass and area and is, therefore, a constant for a given correction frequency. Also, triaxiality contributes little to the E/W requirement. In comparing the high thrust table with the low thrust table, we find that changing the duty cycle from .01 (high thrust) to .4 (low thrust) increases the ΔV requirement by approximately 7%. The added ΔV would be more than compensated for by an increased Isp for low thrust systems.

Table 21 shows the first year propellant requirements using the total ΔV listed in Table 20. As a conservative estimate, a ten-year mission would require 10 times the numbers shown. For the Educational TV Satellite assuming a hydrazine ($I_{sp} \approx 200$ sec) system, the propellant required for a 10-year mission would be 36% of the total system mass. For other classes, the fraction ranges from 20 to 40%. Figure 59 summarizes the yearly propellant requirement.

- North/South (Inclination)
  - Gravity perturbations - sun, moon
  - ΔV = f(duty cycle) → duty cycle = thrust time on/orbit time (24 hrs)
  - Thrust = f(duty cycle, mass, allowed Δlat, correction duration)

N/S Thrust Frequency	
Lat. (deg)	Time Between Corrections
.01	~ Every week
.1	~ Every month
1.0	~ 1/year

- East/West (Longitudinal)
  - Triaxiality - 1.75 m/s/year, f(long)
  - Solar pressure (SP) - rotates the line of Apisides, induces eccentricity & E/W drift
  - SP ΔV = f (A/M, duty cycle, method)
  - Thrust = f(A/M, duty cycle, long, correction duration, method)

E/W Solar Pressure Methods		
1	-	Continuous thrusting
2	-	Tangential thrusting when tolerance met
3,4	-	Rotate line of Apisides to correct solar influence

Method 2 chosen

FIGURE 57. GEO STATIONKEEPING PERTURBATIONS

TABLE 20. GEOSYNCHRONOUS ΔV REQUIREMENTS

- ΔV (M/S) / YEAR
- G-loading = .15 g's
- Solar pressure method 2
- Duty Cycle - .01 = 15 minutes, .4 = 9.6 hours

CLASS	SIZE	N/S	TRIAXIALITY	E/W	TOTAL	N/S	TRIAXIALITY	E/W	TOTAL
LAPAA	10 kw	46.0	1.75	21.7	69.4	49.2	1.75	23.1	74.0
	65 kw	"	"	25.7	73.5	"	"	27.5	78.4
LMSS - WRAP RIB	55 m	"	"	16.2	63.9	"	"	17.3	68.2
LMSS - HOOP/COLUMN	120 m	"	"	47.1	94.9	"	"	50.4	101.3
GEOPLATFORM				9.5	57.3			10.2	61.1
SASP	12.5 kw	"	"	7.4	55.2	"	"	7.9	58.9
	15 kw	"	"	8.5	56.3	"	"	9.2	60.1
SOC	INITIAL	"	"	1.7	49.5	"	"	1.8	52.7
	OPERATIONAL	"	"	1.6	49.4	"	"	1.7	52.6
		1% DUTY CYCLE				40% DUTY CYCLE			

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TABLE 21. PROPELLANT REQUIREMENTS FOR GEO

PROPELLANT REQUIREMENTS FOR GEOSYNCHRONOUS STATIONKEEPING 1.

(ESTIMATED AMOUNT REQUIRED FOR FIRST YEAR)

DUTY CYCLE	1%			40%		
I_{SP} (SEC.)	200	500	3000	200	500	3000
LSS						
LAPAA 10 KW	44.035	17.614	2.936	46.991	18.796	3.133
LAPAA 65 KW	119.979	47.992	7.999	128.041	51.217	8.536
LMSS-WRAP RIB	96.138	38.455	6.409	102.577	41.031	6.838
LMSS-HOOP COLUMN	132.575	53.030	8.838	141.532	56.613	9.435
GEOSTATIONARY PLATFORM	107.073	42.829	7.138	114.223	45.689	7.615
SASP-12.5 KW	243.219	97.288	16.215	259.440	103.776	17.296
SASP-25 KW	415.730	166.292	27.715	443.471	177.388	29.565
SOC-INITIAL	1438.088	575.235	95.873	1533.677	613.471	102.245
SOC-OPERATIONAL	3147.297	1258.919	209.820	3356.48	1342.594	223.766

1. PROPELLANT = KG.
   MAXIMUM ALLOWED ERROR = 0.1 DEGREES

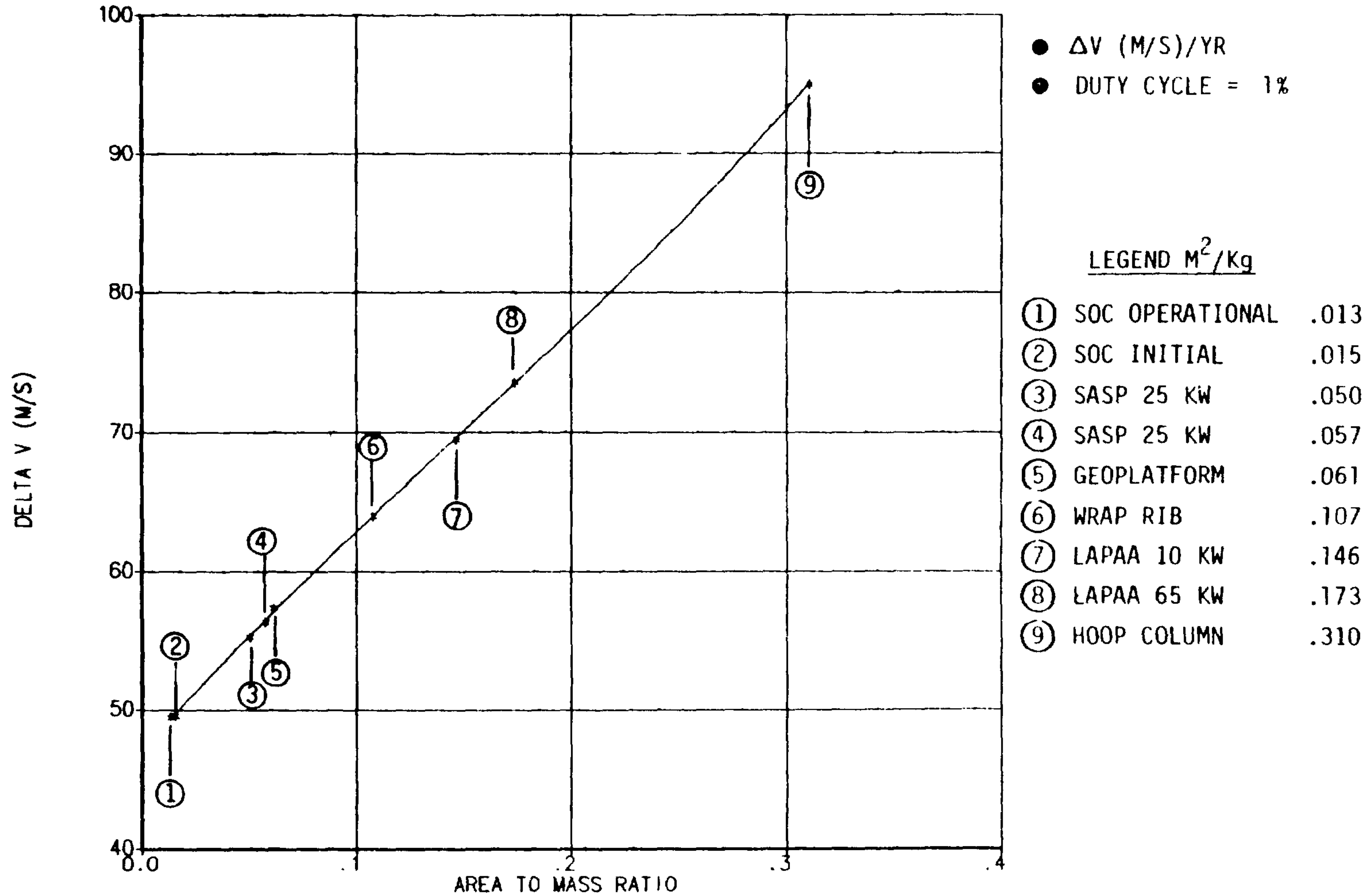

FIGURE 58. GEO STATIONKEEPING ΔV

- PROPELLANT FOR 1 YEAR
- DUTY CYCLE = 1%

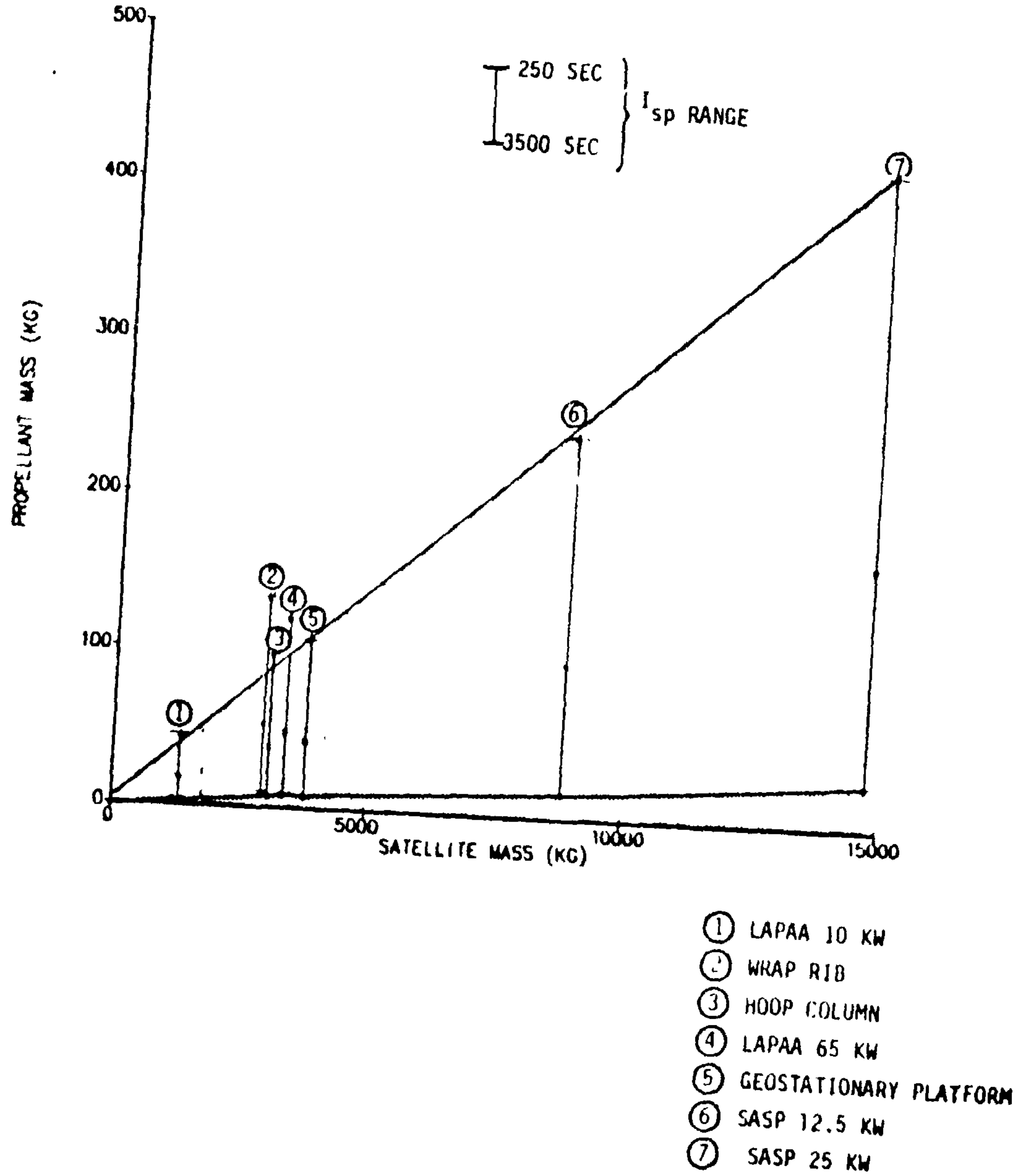

FIGURE 59. GEO STATIONKEEPING PROPELLANT REQUIREMENTS

GEO stationkeeping thrust requirements were calculated for the two duty cycles and for E/W and N/S requirements. Corrections to these numbers which took into account the added mass of the APS system were made in subtask 2c. The numbers shown in Table 22 are, however, representative of the requirements. N/S requirements were seen to be higher in general than E/W requirements, howver, these requirements were not trivial for the systems considered and thrusters for N/S and E/W stationkeeping must be added to the structure. Some currently orbiting systems ignore the E/W components. This table illustrates the total thrust requirements. Thrust/thruster requirements are addressed in the following section. A summary of the GEO stationkeeping analysis is shown below:

- North/South requirements dominate up to A/M of .31
- East/West contributions 20-30% of total propellant for selected vehicles
- Correction frequencies of once/week required for future LSS - $.01^{0}$ tolerance
- GEO stationkeeping propellant requirements are 25-30% of payload mass for low Isp systems

2.2 Thruster Location and Sizing

To establish thrust/thruster requirements for each vehicle, the locations of the thrusters must be determined. Locating the thrusters is recognized as a complex process involving packaging, tank location, propellant line length, etc. In this study, however, the primary concerns were providing 3-axis control and meeting stationkeeping ΔV requirements. Consequently, seven criteria for establishing thruster locations were groundruled. These were:

1. Maximum moment arms used.
2. N/S and E/W stationkeeping capability from nominal orientation.
3. Zero delta-V maneuvering capability.
4. Zero torque stationkeeping capability.
5. Minimal heat flux and contamination from plume impingement.
6. No thruster mounting on S/A surface or at the ends of S/A's.
7. Minimize the number of thrusters used.

To meet the fifth criteria, we ground ruled that thrusters will be canted at a minimum of 45 degrees away from critical components such as solar arrays on antenna surfaces. The consequence of the first criteria was that minimum impulse bits were driven below state-of-the-art capability for some

LSS classes. Certain optimization of thruster may lessen this requirement. In general, however, the deployed LSS had to have long thruster moment arms because of the CG location and large distances required to surround the CG with thrusters. The consequence of criteria 2-5 was that a minimum of 12 thrusters were required for each LSS. In some cases up to 18 thruster locations were needed because of canting requirements. Figures 60-64 and associated Tables 23-28 show the locations and directions assigned for each thruster on each configuration. The SASP design presented problems meeting all location criteria. Three axis control using thrusters could not be achieved because the CG location and panel positions did not allow the CG to be fully encompassed. Thrusters mounted on booms or a redesign for this configuration was considered beyond the scope of this study. The SASP design was dropped at this point from further consideration.

The thrust per thruster was calculated using a general purpose thrust requirements computer program. This program handles arbitrary configurations and thruster location/directions. The inputs to the program are torque and stationkeeping requirements, configuration CG location, thruster locations, thruster direction cosines and thruster purpose (such as E/W or X torquing). Thrusters will generally be multiple in that they will provide both torque and delta-V. To assure that requirements will be met and stationkeeping and torquing will be decoupled, the program must solve the following simultaneous equations:

Stationkeeping:

Eq. 1 - ΣThrust(x,y or z) = Required Stationkeeping(x,y or z)

Eq. 2 & 3 - ΣThrust(x,y or z) = 0

Eq. 4,5,6 - ΣTorque(x,y and z) = 0

and

Torquing:

Eq. 1 - ΣTorque(x,y or z) = Required Torque(x,y or z)

Eq. 2 & 3 - ΣTorque(x,y or z) = 0

Eq. 4,5,6 - ΣThrust(x,y and z) = 0

If there are four thrusters available for each operation, the simulation equations cannot be solved exactly (i.e., six equations, four unknowns). The unknowns were solved by using a pseudo inverse operation:

$$A\overline{X} = B$$

$$\overline{X} = (A^TA)^{-1} A^TB$$

where

A is the NXM matrix of coefficients (N > M).

$\overline{X}$ is the thrust requirement vector of order M.

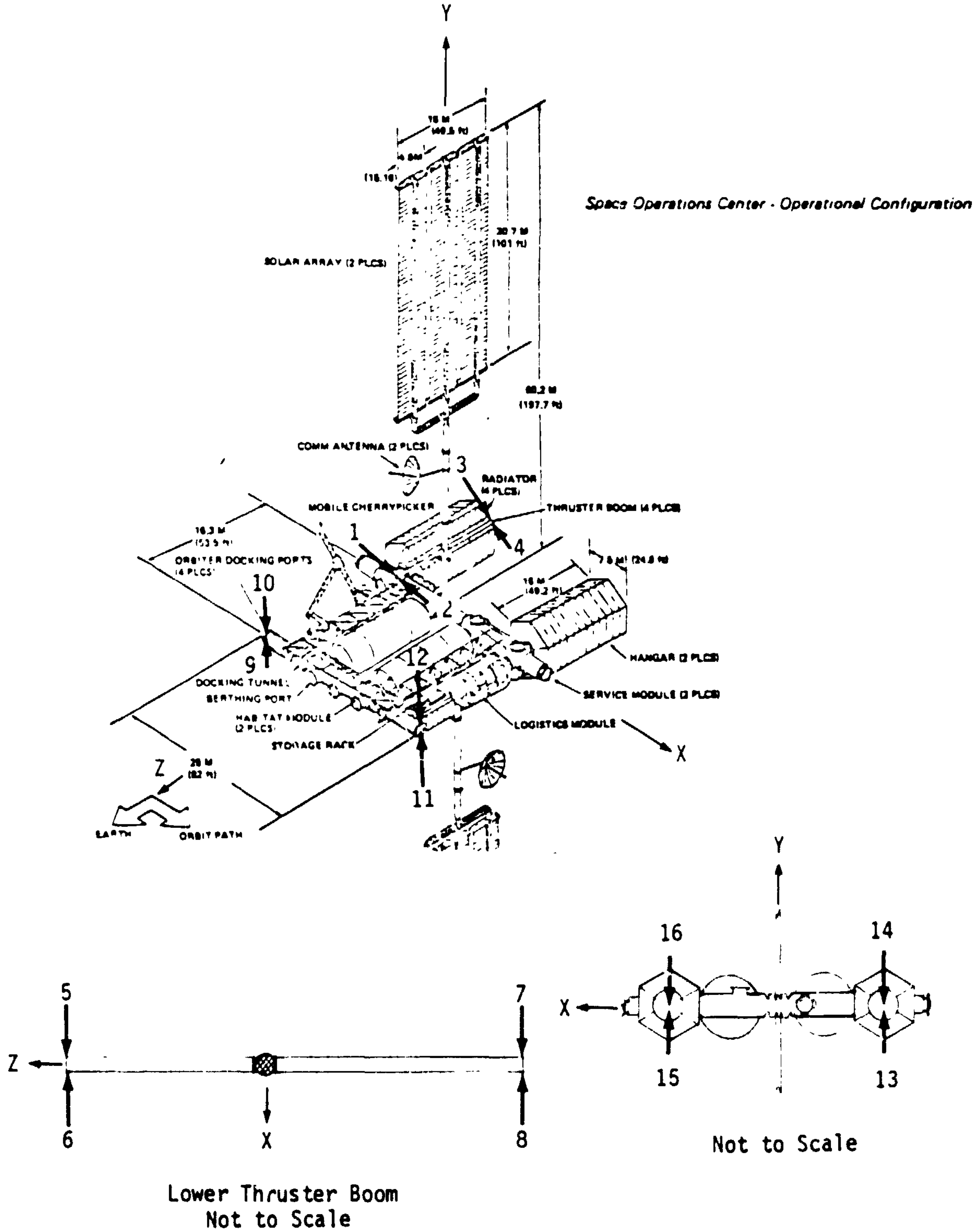

Figure 60 Configuration Drawing with Thruster Locations for Space Operations Center - Operational

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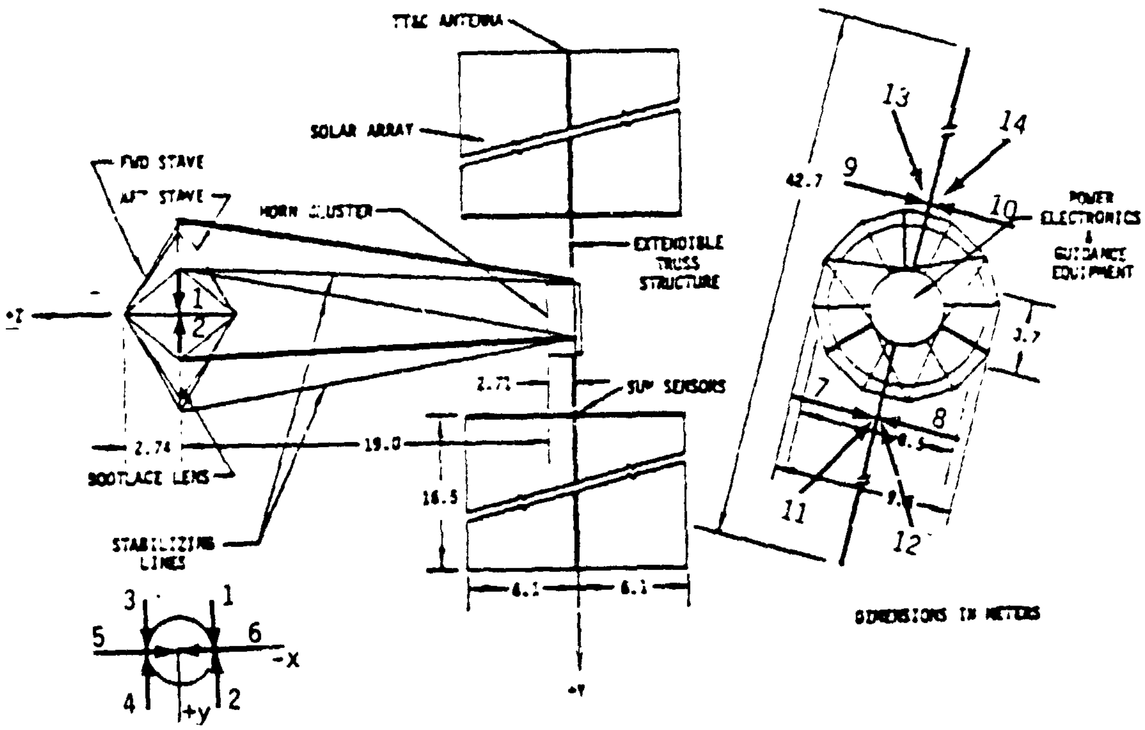

Figure 61 Configuration Drawing with Thruster Locations for LAPAA - Electronic Mail and Educational TV

BASELINE EXPERIMENTAL GEOSTATIONARY PLATFORM

VIEW LOOKING TOWARDS EARTH

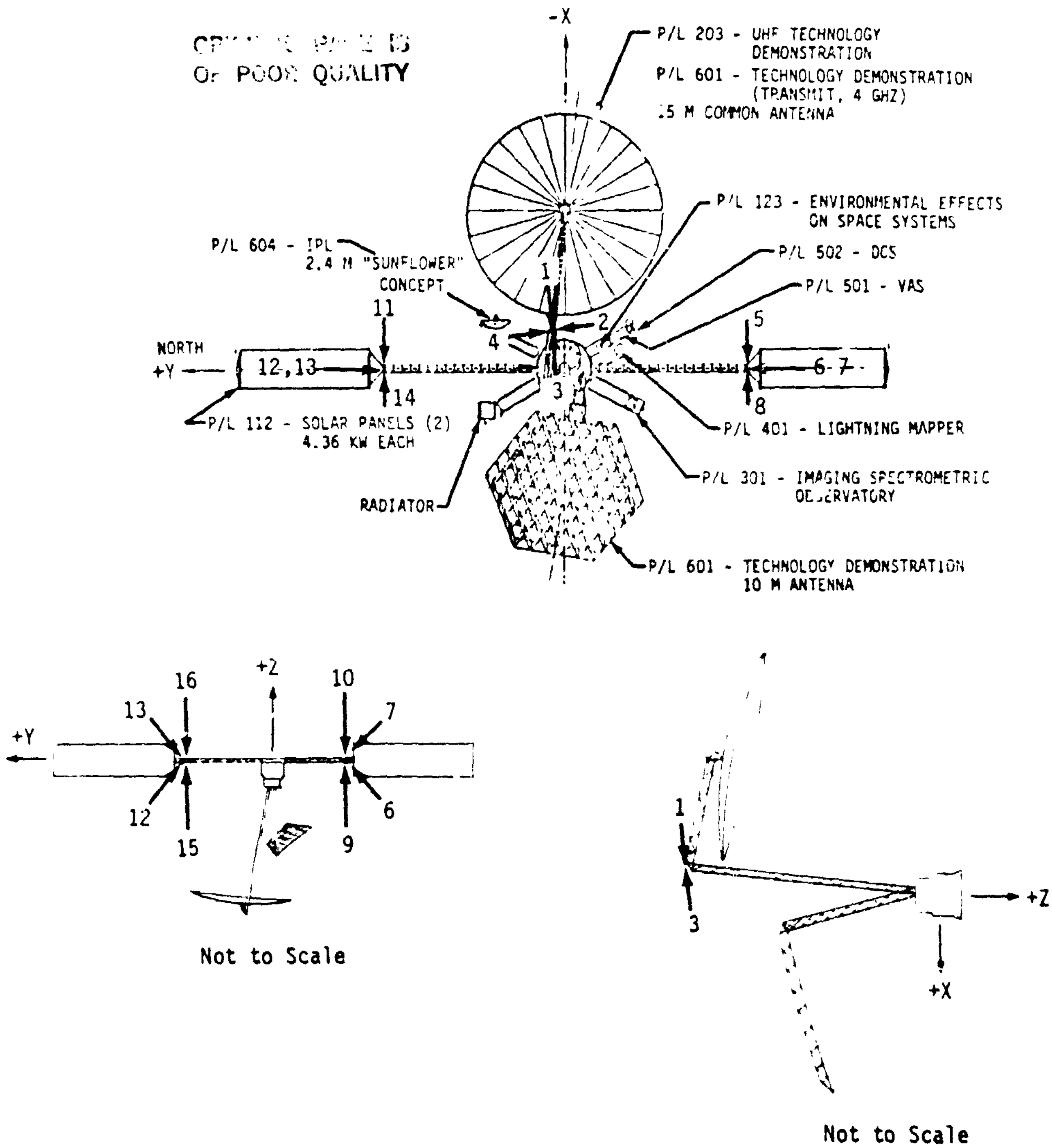

Figure 62 Configuration Drawing with Thruster Locations for Geostationary Platform

LMSS HOOP COLUMN SPACECRAFT

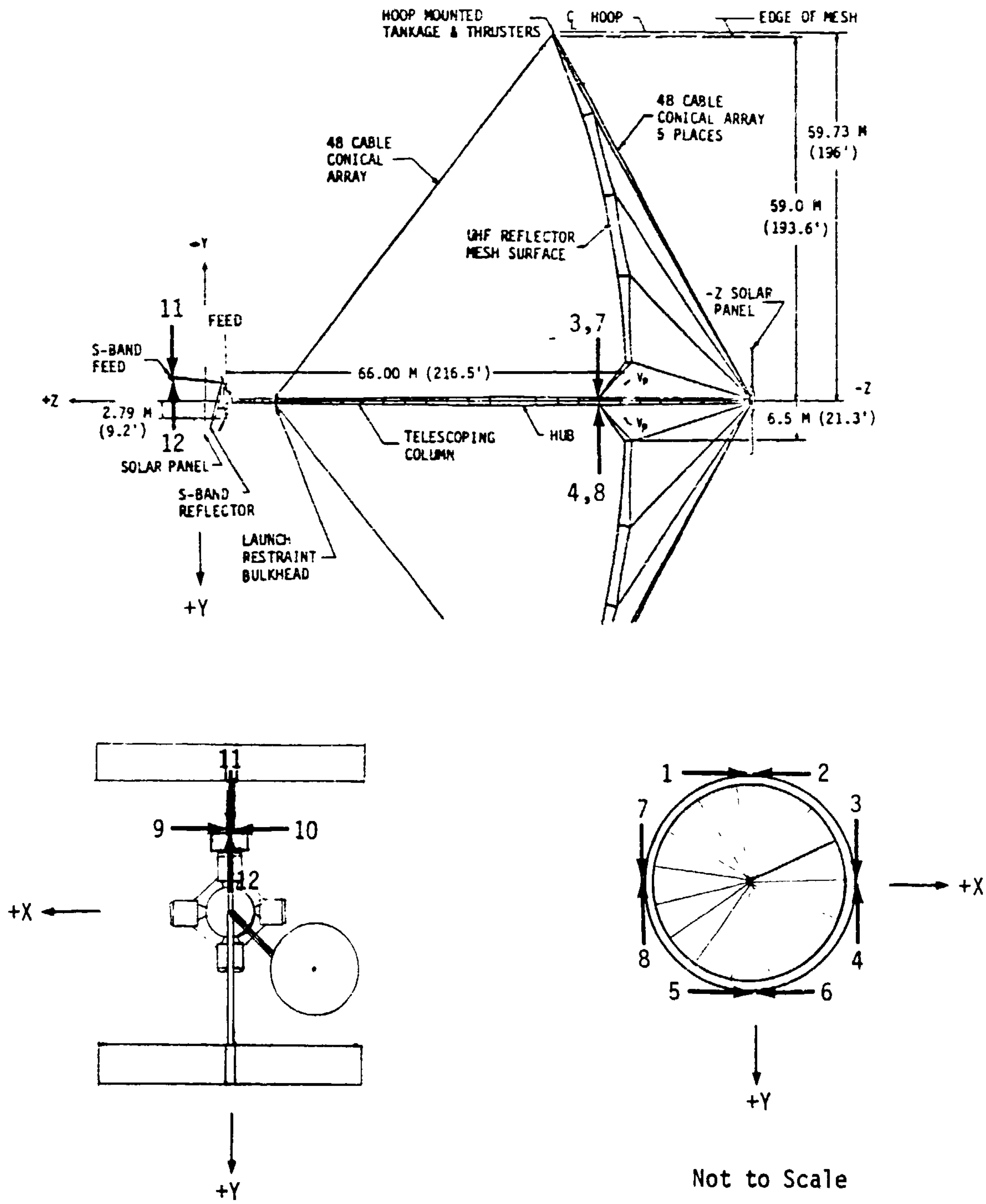

Figure 63 Configuration Drawing with Thruster Locations for
LMSS - Hoop Column

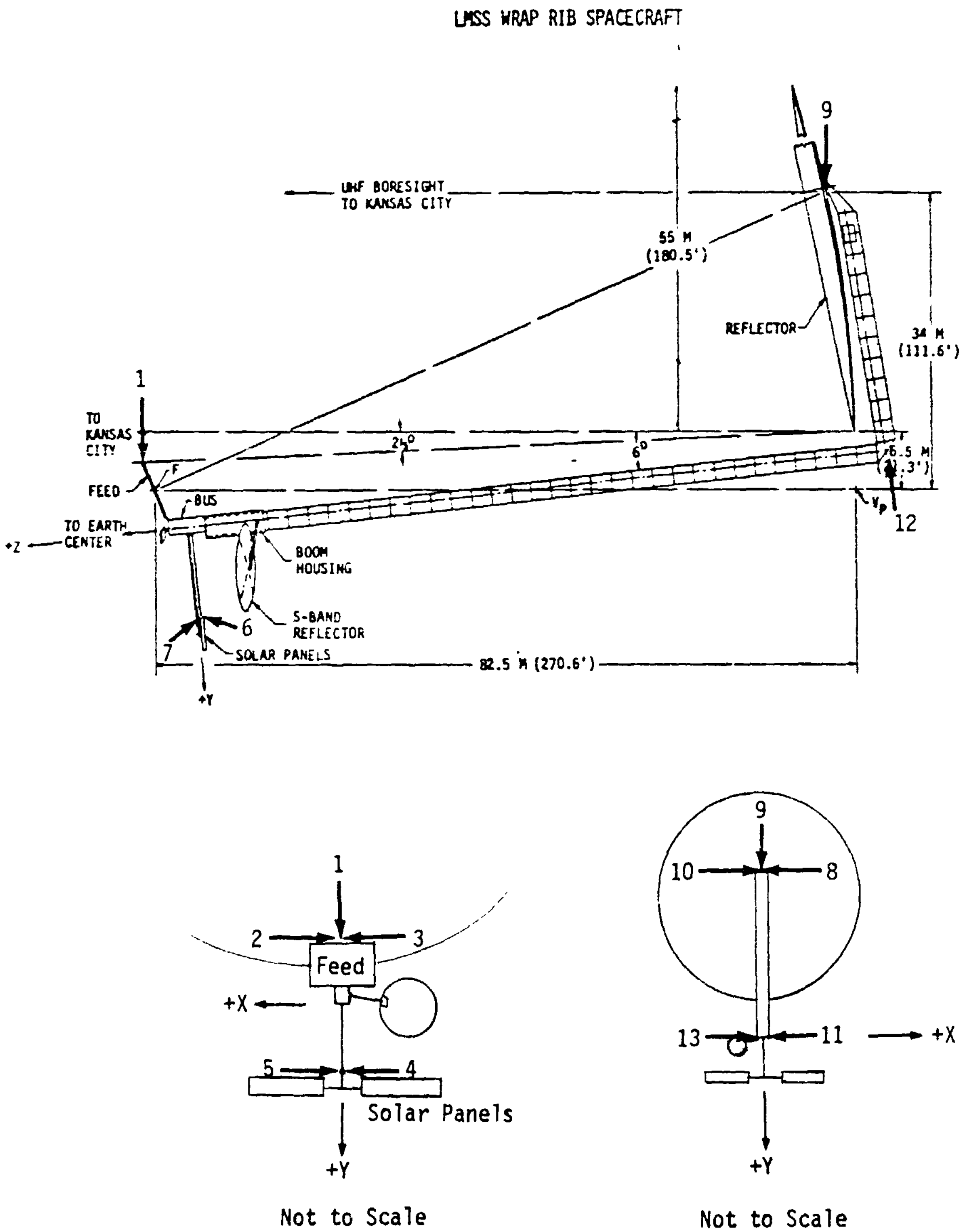

Figure 64 Configuration Drawing with Thruster Locations for LMSS - Wrap Rib

TABLE 22. THRUST REQUIREMENTS FOR GEOSYNCHRONOUS STATIONKEEPING[1]

CORRECTION FREQUENCY	ONCE PER ORBIT				ONCE PER WEEK			
DUTY CYCLE	0.01		0.4		0.01		0.4	
PERTURBING FORCES	N/S	E/W(SP2)[2]	N/S	E/W (SP2)[2]	N/S	E/W(SP2)[2]	N/S	E/W(SP2)[2]
LSS								
ELECTRONIC MAIL	0.1886	0.1770	0.005052	0.004742	1.331	0.1770	0.03540	0.004742
EDUCATIONAL TV	0.4873	0.4573	0.01305	0.01225	3.438	0.4573	0.09146	0.01225
LMSS-WRAP RIB	0.4438	0.4165	0.01189	0.01116	3.131	0.4165	0.08330	0.01116
LMSS-HOOP COLUMN	0.4247	0.3985	0.01137	0.01068	2.996	0.3985	0.07971	0.01068
GEOSTATIONARY PLATFORM	0.5456	0.5120	0.01461	0.01371	3.849	0.5120	0.1024	0.01371
SASP-12.5 KW	1.282	1.203	0.03433	0.03222	9.043	1.203	0.2406	0.03222
SASP-25 KW	2.151	2.018	0.05760	0.05406	15.173	2.018	0.4036	0.05406
SOC-INITIAL	8.357	7.842	0.2238	0.2101	58.959	7.842	1.568	0.2101
SOC-OPERATIONAL	18.323	17.194	0.4907	0.4606	129.265	17.194	3.439	0.4606

1. THRUST = NEWTONS
CORRECTION LASTING ONE ORBIT

2. FOR SOLAR PRESSURE ΔV CALCULATIONS THE CORRECTION FREQUENCY IS SET BY THE MAXIMUM ALLOWED ERROR OF 0.1 DEGREES

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TABLE 23. LAPAA THRUSTER COORDINATES - ELECTRONIC MAIL AND EDUCATIONAL TV

	Location (m)*			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-4.800	0.000	21.700	0.000	1.000	0.000
2	-4.800	0.000	21.700	0.000	-1.000	0.000
3	4.800	0.000	21.700	0.000	1.000	0.000
4	4.800	0.000	21.700	0.000	-1.000	0.000
5	4.800	0.000	21.700	-1.000	0.000	0.000
6	-4.800	0.000	21.700	1.000	0.000	0.000
7	0.000	2.000	0.000	-1.000	0.000	0.000
8	0.000	2.000	0.000	1.000	0.000	0.000
9	0.000	-2.000	0.000	-1.000	0.000	0.000
10	0.000	-2.000	0.000	1.000	0.000	0.000
11	0.000	2.000	0.000	-0.707	-0.707	0.000
12	0.000	2.000	0.000	0.707	-0.707	0.000
13	0.000	-2.000	0.000	-0.707	0.707	0.000
14	0.000	-2.000	0.000	0.707	0.707	0.000

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

TABLE 24. GEOSTATIONARY PLATFORM THRUSTER COORDINATES

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-2.200	0.788	-23.000	1.000	0.000	0.000
2	-2.200	0.788	-23.000	0.000	1.000	0.000
3	-2.200	0.788	-23.000	-1.000	0.000	0.000
4	-2.200	0.788	-23.000	0.000	-1.000	0.000
5	0.000	-15.800	0.000	1.000	0.000	0.000
6	0.000	-15.800	0.000	0.000	0.707	0.707
7	0.000	-15.800	0.000	0.000	0.707	-0.707
8	0.000	-15.800	0.000	-1.000	0.000	0.000
9	0.000	-15.800	0.000	0.000	0.000	1.000
10	0.000	-15.800	0.000	0.000	0.000	-1.000
11	0.000	15.800	0.000	1.000	0.000	0.000
12	0.000	15.800	0.000	0.000	-0.707	0.707
13	0.000	15.800	0.000	0.000	-0.707	-0.707
14	0.000	15.800	0.000	-1.000	0.000	0.000
15	0.000	15.800	0.000	0.000	0.000	1.000
16	0.000	15.800	0.000	0.000	0.000	-1.000

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

TABLE 25. LAND MOBILE SATELLITE SYSTEM WRAP RIB THRUSTER COORDINATES

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-0.119	-7.790	5.530	0.000	1.000	0.000
2	-1.000	-7.790	5.530	-1.000	0.000	0.000
3	1.000	-7.790	5.530	1.000	0.000	0.000
4	-0.119	11.100	0.000	-1.000	0.000	0.000
5	-0.119	11.100	0.000	1.000	0.000	0.000
6	-0.119	11.100	0.000	0.000	-0.707	0.707
7	-0.119	11.100	0.000	0.000	-0.707	-0.707
8	1.000	-29.960	-75.410	-1.000	0.000	0.000
9	-0.119	-29.960	-75.410	0.000	1.000	0.000
10	-1.000	-29.960	-75.410	1.000	0.000	0.000
11	1.000	0.000	-82.450	-1.000	0.000	0.000
12	-0.119	0.000	-82.450	0.000	-1.000	0.000
13	-1.000	0.000	-82.450	1.000	0.000	0.000

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

TABLE 26. LMSS HOOP COLUMN THRUSTER COORDINATES

	Location (m)			Direction		
Thruster *	X	Y	Z	X	Y	Z
1	0.000	-59.730	-57.320	1.000	0.000	0.000
2	0.000	-59.730	-57.320	-1.000	0.000	0.000
3	59.730	0.000	-57.320	0.000	1.000	0.000
4	59.730	0.000	-57.320	0.000	-1.000	0.000
5	0.000	59.730	-57.320	1.000	0.000	0.000
6	0.000	59.730	-57.320	-1.000	0.000	0.000
7	-59.730	0.000	-57.320	0.000	1.000	0.000
8	-59.730	0.000	-57.320	0.000	-1.000	0.000
9	0.000	-4.790	3.800	-1.000	0.000	0.000
10	0.000	-4.790	3.800	1.000	0.000	0.000
11	0.000	-4.790	3.800	0.000	1.000	0.000
12	0.000	-4.790	3.800	0.000	-1.000	0.000

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

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TABLE 27. SPACE OPERATIONS CENTER (INITIAL) THRUSTER COORDINATES

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	0.000	9.144	10.414	1.000	0.000	0.000
2	0.000	9.144	10.414	-1.000	0.000	0.000
3	0.000	9.144	10.414	0.000	-0.707	-0.707
4	0.000	9.144	-7.870	1.000	0.000	0.000
5	0.000	9.144	-7.870	-1.000	0.000	0.000
6	0.000	9.144	-7.870	0.000	-0.707	0.707
7	0.000	-9.144	-1.270	-1.000	0.000	0.000
8	0.000	-9.144	-1.270	1.000	0.000	0.000
9	0.000	-9.144	-1.270	0.000	1.000	0.000
10	-19.500	0.000	0.000	0.000	-1.000	0.000
11	-19.500	0.000	0.000	0.000	1.000	0.000
12	-3.500	0.000	18.000	0.000	-1.000	0.000
13	-3.500	0.000	18.000	0.000	1.000	0.000
14	0.000	-9.144	-1.270	0.000	0.707	0.707

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

TABLE 28. SPACE OPERATIONS CENTER (OPERATIONAL) THRUSTER COORDINATES

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	0.000	9.144	10.414	1.000	0.000	0.000
2	0.000	9.144	10.414	-1.000	0.000	0.000
3	0.000	9.144	-7.870	1.000	0.000	0.000
4	0.000	9.144	-7.870	-1.000	0.000	0.000
5	0.000	-9.144	7.870	1.000	0.000	0.000
6	0.000	-9.144	7.870	-1.000	0.000	0.000
7	0.000	-9.144	-10.414	1.000	0.000	0.000
8	0.000	-9.144	-10.414	-1.000	0.000	0.000
9	-12.500	0.000	16.300	0.000	1.000	0.000
10	-12.500	0.000	16.300	0.000	-1.000	0.000
11	12.500	0.000	16.300	0.000	1.000	0.000
12	12.500	0.000	16.300	0.000	-1.000	0.000
13	-12.500	0.000	-15.000	0.000	1.000	0.000
14	-12.500	0.000	-15.000	0.000	-1.000	0.000
15	12.500	0.000	-15.000	0.000	1.000	0.000
16	12.500	0.000	-15.000	0.000	-1.000	0.000

B is the solution matrix of order N.

The pseudo inverse provides the optimal thrust levels based on decoupled stationkeeping and torquing. The program will not allow more than four thrusters to perform any one maneuver. This limitation did not cause a problem for any of the configurations and thruster locations considered.

Using the requirements generated in substask 2a, the thrust/thruster requirements for each thruster were generated. Some thrusters had only disturbance torque cancelation requirements, while most thrusters had both stationkeeping and torquing requirements. If both requirements existed for a given thruster, the thruster was sized for the higher level. This was the stationkeeping requirement in all cases. Appendix C shows the detailed outputs of the thrust determination program. A summary of this data for each design at .15 g-loading is shown in Table 29. Because of time and funding constraints, the small wrap-rib (25m) and hoop column (60m) were not treated beyond this point. This table shows that LEO thrust/thruster requirements considerably exceeded the E/W requirements at GEO. This is also true for N/S requirements when longer duty cycles were employed. It also shows that to lower thrust levels to electric propulsion levels (.01-.1 N/thruster) long duty cycles were required. This fact led to conclusions which will be discussed in more detail in Task 3.

An additional conclusion can be reached from the data presented in Appendix C. Because of the unequal moment arms for stationkeeping thrusters, throttling may be indicated for stationkeeping with 0 torque. This consequence is illustrated in Figure 65. Throttling ratios of 2:1 to 6:1 are required.

2.3 APS Characterization

In this subtask, the number of thrusters, thrust levels, and ΔV requirements derived in previous subtasks were utilized to generate APS mass and converged thrust level requirements. The first step to characterizing APS mass was the development of chemical and electric system scaling laws. These laws must have thrust level, I_{sp} and propellant mass estimates as inputs. Hardware scaling is performed by derived scaling laws and then added along with the propellant estimate to the structure mass. A recalculation of thrust and propellant mass for the 10 year assumed mission life was then made. Interation was performed until a 1% difference between old and new system mass was obtained. This process is described in Figure 66.

The scaling equations for chemical systems were derived from curve fits of existing hardware. Table 30 shows the data base for the mono and biprop scaling. Equations for chemical thruster mass, including thruster, valves and mounting structure are shown below:

Mono Thrust/Weight = 1.7 Thrust + 8.2 in kg

Biprop Thrust/Weight = .722 Thrust + 13.1 in kg

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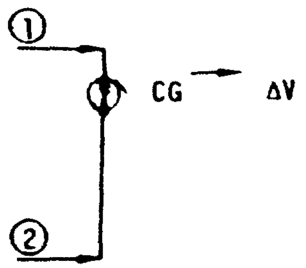
TABLE 29. THRUST/THRUSTER (N) RANGE FOR STATIONKEEPING

	LEO (400 km)	GEO Correction Frequency = Once/Week			
	Thrust Time = ½ Hour	Duty Cycle = .01		Duty Cycle = .4	
		N/S	E/W	N/S	E/W
ELECTRONIC MAIL	.8 - 3	.4 - .5	.005 - .02	.01	.0001 - .0005
EDUCATIONAL TV	.7 - 7	.4 - 2	.006 - .06	.01 - .04	.0002 - .002
WRAP RIB	1 - 8	.4 - 2	.008 - .02	.01 - .06	.0002 - .001
HOOP COLUMN	2 - 6	.7 - 2	.02 - .04	.02 - .04	.0005 - .001
GEOSTATIONARY PLT.	3 - 7	.9 - 2	.02 - .04	.02 - .06	.0005 - .001
SOC INITIAL	4 - 60	10 - 30	.05 - .8	.3 - .7	.001 - .02
SOC OPERATIONAL	3 - 100	20 - 40	.2 - 2	.5 - 1	.003 - .04

Table 30. Chemical Thruster SOA Summary

	Thrust (N)	I_{sp} (sec)	Mass (kg)	T/W (N/kg)	Mgr.*	Remarks
Monopropellant (N_2H_4)	.90	218	.39	2.28	BL	Includes structural support
	.90	225	.136	6.54	HS	REA-10, TC + Valve
	.90	220	.317	2.80	RR	MR-102
	2.22	225	.181	12.26	HS	TC + Valve
	4.45	236	.308	14.42	HS	REA-17, TC + Valve
	22.24	234	.408	54.47	HS	REA-16, TC + Valve
	22.24	232	.544	40.86	RR	MR-50
	22.24	227	.485	45.83	AJ	TC + Valve
	53.37	228	.544	98.06	HS	REA-22, TC + Valve
	133.44	236	.884	150.86	HS	REA-22, TC + Valve
	177.9	232	.930	191.34	HS	TC + Valve
	177.9	225	.885	201.15	BL	TC + Valve
	444.8	230	1.54	240.35	RR	MR-104
	556.0	237	2.31	288.42	HS	REA-20
	667.2	234	1.32	517.22	MQ	R-30
	2668.8	210	7.71	346.10	RR	MR-80
Bipropellant (N_2O_4/MMH)	2.224	265	.27	8.17	AJ	AJ10-207
	22.24	285	.59	37.72	AJ	AJ10-181, Engine Assy.
	22.24	290	.54	40.86	MQ	R-6C
	80.06	280	1.08	73.55	BL	ϵ=1.0, Scarfed Nozzles
	80.06	285	1.59	50.43	RD	ϵ=2.5, Scarfed Nozzles
	88.96	282	1.18	75.44	AJ	Engine Assy.
	102.3	285	1.22	83.53	BL	ϵ=6.0, Scarfed
	111.2	286	1.41	79.08	RD	Engine Assy, ϵ = 60
	111.2	284	1.59	70.04	MQ	R-1E
	333.6	272	3.18	105.06	AJ	Engine Assy, ϵ = 40
	444.8	283	2.45	181.59	RD	Engine Assy, ϵ = 40
	444.8	310	3.36	132.52	MQ	R-4D-11
	1334.4	291	6.12	217.92	RD	RS-2101C
	1445.6	298	5.72	252.94	BL	TC + Valve, ϵ = 50
(LO_2/LH_2)	111.2	400	1.72	64.5	AJ	TC + Valves, ϵ = 70
	111.2	390	1.27	87.5	RD	TC + Valves, ϵ = 50
	2224	465	28.48	78.07	RD	Engine Assy, ϵ = 400
	2224	465	38.7	57.41	AJ	Engine Assy, ϵ = 400

* BL - Bell Aerospace AJ - Aerojet
HS - Hamilton Standard MQ - Marquardt
RR - Rocket Research RD - Rocketdyne



OPTIONS

Ⓐ THRUST LEVEL ① = ② , BUT ② IS VECTORED FOR EQUIVALENT MOMENT ARM

Ⓑ THRUST LEVEL ① = ② , ② IS PULSED FOR EQUIVALENT MOMENT ARM

Ⓒ THRUST LEVEL ① = ② , USE MOMENTUM MANAGEMENT FOR COMPENSATION

Ⓓ THRUST LEVEL ① > ②

IMPACTS

Ⓐ INTRODUCED POTENTIALLY UNDESIRABLE ΔV
Ⓑ MAY EXCITE FLEXIBLE MODES
Ⓒ COMPLICATED - ADDITIONAL PROPELLANT NEED FOR MMD DESATURATION
Ⓓ MUST HAVE THROTTLING IF SAME THRUSTERS ARE USED, THIS WILL ALSO ACCOUNT FOR CG DRAFT OVER LIFE TIME

THROTTLING RATIOS

	DUTY CYCLE	
	.01	.4
LAPAA 10 KW	1.3	1
LAPAA 65 KW	5	5
WRAP RIB	5	6
HOOP COLUMN	2.9	2
GEOSTATIONARY PLT	2.2	3

FIGURE 65. THRUST RATIO REQUIREMENTS

SYSTEM MASS GENERATED FOR

- MONOPROPELLANT N_2H_4
- BI PROPELLANT MMH/N_2O_4
- ION H_g (SEPS TECHNOLOGY)

SYSTEMS WERE SIZED FOR GEO OPERATION ONLY
MOMENTUM MANAGEMENT ASSUMED FOR POINTING CONTROL
DESATURATION PROPELLANT MASS INCLUDED

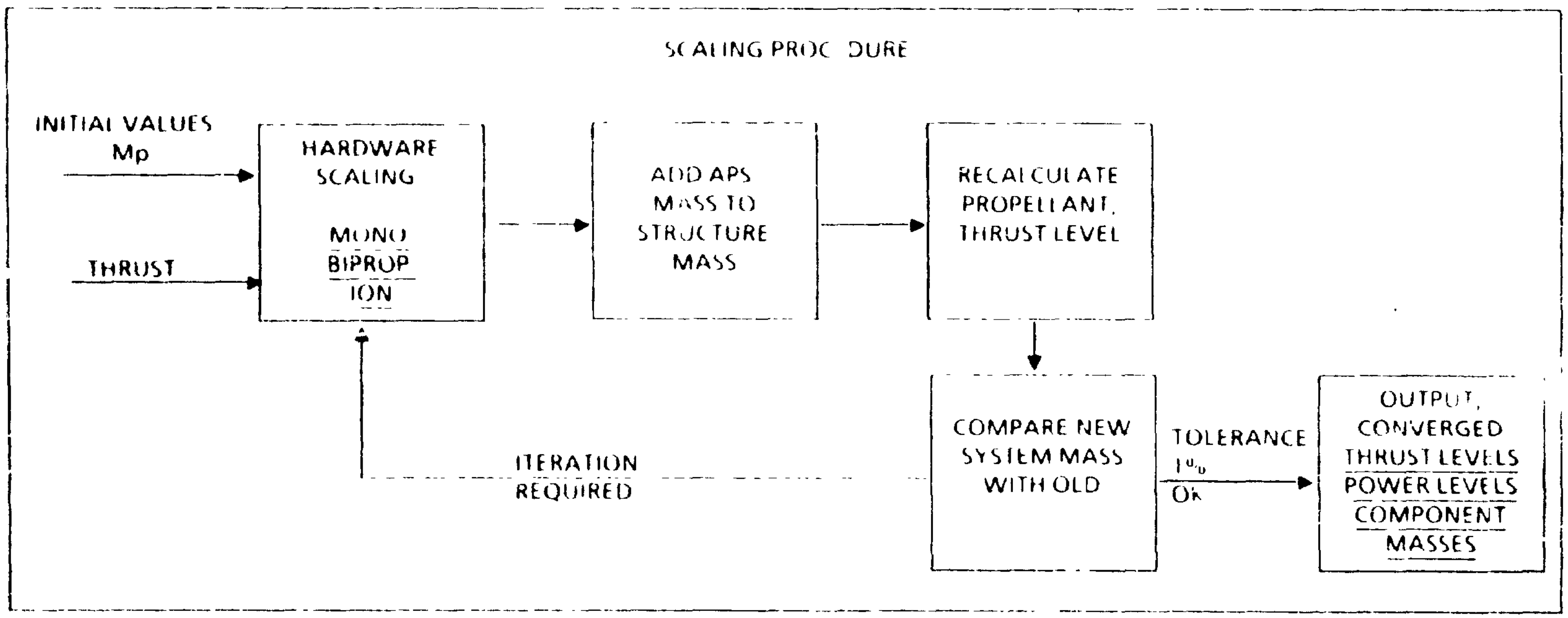


FIGURE 66. APS CHARACTERIZATION METHOD

For the electric propulsion systems, the equations were derived as follows:

$$M_T = K_1 D^n$$

$$J_B = K_2 D^2$$

$$\Gamma = K_3 J_B Isp$$

$$F = K_4 D_2 Isp$$

where

M_t = thruster mass

D = thrust diameter

J_B = beam current

$$M_T = K_5(F/I_{sp})^{n/2}$$

where

K_1 through K_5 are constants

The scaling equations used for each APS system are:

$T/W = 1.7T + 8.2$ (N_2H_4)

$T/W = .722T + 13.1$ (N_2O_4/MMH)

thruster mass = $(1/(T/W))T$

thruster mass = $34000(T/I_{sp})^{.75}$ (Electric Ion Propulsion)

M_p = propellant mass = $M_s\ (e^{\Delta V/GI_{sp}} - 1)$

T_V = tank volume = $M_p \neq v$

T_R = tank radius = $\sqrt[3]{\frac{3\ Tv}{4\pi}}$

T_A = tank area = $4\pi\ T_R^2$

tank mass = $5.62\ T_A$

In addition, for electric ion propulsion

P = power = $9.8\ (T_{max})\ (I_{sp})/(2\eta_{sys} \times 1000)$

$\wedge$ solar array mass = 13.5 P

Δ solar array area = 8.96 P

mass of power processing unit = 2.1 x 6.5 x P

where

T/W = thrust/thruster mass

T = thrust/thruster

M_S = satellite mass

The relevant scaling equations are summarized in Figure 67.

Tables 31 through 37 show the results of the APS scaling exercise in kg. The LEO propellant mass is done at 400 km for the Electronic Mail to 1885 kg for the operational SOC design using chemical systems. It is again noted that a high price is paid in propellant mass for short-term operation in LEO, and LEO deployment is an issue deserving careful consideration. A summary of GEO operation scaling is shown in Table 38. This table shows a number of interesting conclusions. First, when considering chemical systems only, the percentage of APS mass to total system mass is relatively constant. For mono-propellant systems, four of the five antenna systems have APS percentaage of 24-29%. Bi-props are similar and range between 18-23%. The difference between the 1% and 40% duty cycles makes only a small difference for chemical systems. However, electric systems did not even converge which indicated that power system mass and S/A area were growing so fast that the added thrust requirement due to this added mass and area drove the next iteration upward just as much as the first. At 40% duty cycle, the converged percentage of APS mass were often 1/3, and in some cases, 1/5 of that for mono-chemical systems.

In summary, the GEO scaling study showed the following conclusions:

- EP dominated by power system mass (thrust level)
- State-of-the-art electronic ion propulsin unfeasible at short duty cycles (< 2-3 hr.)
- EP looks attractive at longer duty cycles
  - For .4 duty cycle:
    - EP mass savings over mono (500-1500 kg) Avg = 85% savings
    - EP mass savings over bi-prop (300-1000 kg) Avg = 78% savings
- Chemical systems dominated by propellant requirements, unaffected by duty cycle
- For .01 duty cycle:
  - Bi-prop mass saving over mono (150-500 kg) Avg = 30% savings

CHEMICAL SYSTEMS

THRUSTER MASS (Includes Valves, Mounting Structure)	MONO	$T/W = 1.7\,T + 8.2$	in KG	Derived from existing engine set)
	BIPROP	$T/W = .722T + 13.1$	in KG	

ELECTRIC SYSTEM

THRUSTER MASS — ION: $M_{THRUSTER} = 34000\,(T/Isp)^{.75}$ in KG
(Derived using 8 cm, 15 cm and 30 cm data)

POWER MASS (SEPS) — POWER LEVEL $P = 9.8\,(T)\,(I_{sp})\,/2N_{sys}$ in Watts

$N_{sys} = 70\%$

SOLAR ARRAY $M_{S/A} = 13.5\,\text{r}$ (in KW)

PPU $M_{PPU} = 13.65\,P$ (in KW)

BOTH SYSTEMS

PROPELLANT MASS — $M_p = M_S\,(e^{\Delta V \cdot LIFE/go\,I_{sp}} - 1)$

TANK MASS — Scaled from M_p, Specific Volume of Propellant

FIGURE 67. APS SCALING EQUATIONS

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TABLE 31. APS MASS SUMMARY FOR ELECTRONIC MAIL

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.3000E+01	.2231E+00	.1002E+02	.2238E+03	.2340E+03	LEO FOR 90 DAY MISSION
.3000E+01	.2231E+00	.2421E+04	.8410E+06	.8435E+06	LEO FOR 10 YR MISSION
.5000E+00	.5495E-01	.1687E+02	.4891E+03	.5060E+03	.01 DUTY GEO FOR 10 YR MISSION
.1000E-01	.1213E-02	.1776E+02	.5279E+03	.5457E+03	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.3000E+01	.1963E+00	.8030E+01	.1606E+03	.1688E+03	LEO FOR 90 DAY MISSION
.3000E+01	.1963E+00	.7614E+03	.1483E+06	.1491E+06	LEO FOR 10 YR MISSION
.5000E+00	.3709E-01	.1332E+02	.3430E+03	.3563E+03	.01 DUTY GEO FOR 10 YR MISSION
.1000E-01	.7618E-03	.1399E+02	.3690E+03	.3830E+03	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.300E+01	.191E+02	.295E+00	.152E+02	.155E+04	.103E+04	.157E+04	.316E+04	LEO FOR 90 DAY MISSION
.300E+01	.191E+02	.408E+01	.786E+03	.155E+04	.103E+04	.157E+04	.393E+04	LEO FOR 10 YR MISSION
.500E+00	.499E+01	.471E+00	.308E+02	.375E+03	.249E+03	.379E+03	.790E+03	.01 DUTY GEO FOR 10 YR MISSION
.100E-01	.265E+00	.492E+00	.329E+02	.101E+02	.667E+01	.102E+02	.539E+02	.4 DUTY GEO FOR 10 YR MISSION

TABLE 32. APS MASS SUMMARY FOR EDUCATIONAL TV

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.7000E+01	.3431E+00	.2656E+02	.9658E+03	.9927E+03	LEO FOR 90 DAY MISSION
.7000E+01	.3431E+00	.5865E+05	.1003E+09	.1004E+09	LEO FOR 10 YR MISSION
.2000E+01	.1708E+00	.3323E+02	.1352E+04	.1385E+04	.01 DUTY GEO FOR 10 YR MISSION
.4000E-01	.4820E-02	.3498E+02	.1460E+04	.1495E+04	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.7000E+01	.3852E+00	.2110E+02	.6838E+03	.7053E+03	LEO FOR 90 DAY MISSION
.7000E+01	.3852E+00	.9377E+04	.6413E+07	.6422E+07	LEO FOR 10 YR MISSION
.2000E+01	.1373E+00	.2618E+02	.9452E+03	.9715E+03	.01 DUTY GEO FOR 10 YR MISSION
.4000E-01	.3042E-02	.2750E+02	.1018E+04	.1045E+04	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.700E+01	.361E+02	.758E+00	.628E+02	.318E+04	.211E+04	.322E+04	.650E+04	LEO FOR 90 DAY MISSION
.700E+01	.361E+02	.116E+02	.377E+04	.318E+04	.211E+04	.322E+04	.102E+05	LEO FOR 10 YR MISSION
.200E+01	.141E+02	.922E+00	.843E+02	.972E+03	.645E+03	.982E+03	.205E+04	.01 DUTY GEO FOR 10 YR MISSION
.400E-01	.750E+00	.963E+00	.900E+02	.260E+02	.172E+02	.263E+02	.144E+03	.4 DUTY GEO FOR 10 YR MISSION

TABLE 33. APS MASS SUMMARY FOR WRAP RIB

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.8000E+01	.3613E+00	.3379E+02	.1386E+04	.1420E+04	LEO FOR 90 DAY MISSION
.8000E+01	.3613E+00	.1481E+07	.1273E+11	.1273E+11	LEO FOR 10 YR MISSION
.2000E+01	.1708E+00	.2799E+02	.1045E+04	.1073E+04	.01 DUTY GEO FOR 10 YR MISSION
.6000E-01	.7199E-02	.2943E+02	.1127E+04	.1156E+04	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.8000E+01	.4234E+00	.2653E+02	.9641E+03	.9910E+03	LEO FOR 90 DAY MISSION
.8000E+01	.4234E+00	.9844E+05	.2182E+09	.2183E+09	LEO FOR 10 YR MISSION
.2000E+01	.1373E+00	.2215E+02	.7355E+03	.7578E+03	.01 DUTY GEO FOR 10 YR MISSION
.6000E-01	.4558E-02	.2324E+02	.7908E+03	.8140E+03	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.800E+01	.399E+02	.926E+00	.649E+02	.400E+04	.265E+04	.404E+04	.817E+04	LEO FOR 90 DAY MISSION
.800E+01	.399E+02	.163E+02	.625E+04	.400E+04	.265E+04	.404E+04	.144E+05	LEO FOR 10 YR MISSION
.200E+01	.141E+02	.788E+00	.666E+02	.883E+03	.586E+03	.893E+03	.186E+04	.01 DUTY GEO FOR 10 YR MISSION
.600E-01	.102E+01	.823E+00	.711E+02	.236E+02	.157E+02	.239E+02	.120E+03	.4 DUTY GEO FOR 10 YR MISSION

TABLE 34. APS MASS SUMMARY FOR HOOP COLUMN

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.3000E+02	.4967E+00	.1339E+03	.1094E+05	.1107E+05	LEO FOR 90 DAY MISSION
.3000E+02	.4967E+00	.1170E+21	.8989E+31	.8989E+31	LEO FOR 10 YR MISSION
.2000E+01	.1708E+00	.3724E+02	.1604E+04	.1641E+04	.01 DUTY GEO FOR 10 YR MISSION
.4000E-01	.4820E-02	.3931E+02	.1740E+04	.1779E+04	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.3000E+02	.8626E+00	.9197E+02	.6225E+04	.6318E+04	LEO FOR 90 DAY MISSION
.3000E+02	.8626E+00	.1519E+16	.4197E+24	.4197E+24	LEO FOR 10 YR MISSION
.2000E+01	.1373E+00	.2905E+02	.1105E+04	.1134E+04	.01 DUTY GEO FOR 10 YR MISSION
.4000E-01	.3042E-02	.3058E+02	.1193E+04	.1224E+04	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.300E+02	.108E+03	.239E+01	.353E+03	.163E+05	.108E+05	.165E+05	.333E+05	LEO FOR 90 DAY MISSION
.300E+02	.108E+03	.214E+03	.299E+06	.163E+05	.108E+05	.165E+05	.332E+06	LEO FOR 10 YR MISSION
.200E+01	.141E+02	.100E+01	.952E+02	.847E+03	.562E+03	.856E+03	.181E+04	.01 DUTY GEO FOR 10 YR MISSION
.400E-01	.750E+00	.105E+01	.102E+03	.226E+02	.150E+02	.229E+02	.149E+03	.4 DUTY GEO FOR 10 YR MISSION

TABLE 35. APS MASS SUMMARY FOR GEOSTATIONARY PLATFORM

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.7000E+01	.3431E+00	.2216E+02	.7363E+03	.7588E+03	LEO FOR 90 DAY MISSION
.7000E+01	.3431E+00	.8460E+04	.5496E+07	.5505E+07	LEO FOR 10 YR MISSION
.2000E+01	.1708E+00	.2957E+02	.1135E+04	.1164E+04	.01 DUTY GEO FOR 10 YR MISSION
.6000E-01	.7199E-02	.3106E+02	.1222E+04	.1253E+04	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.7000E+01	.3852E+00	.1773E+02	.5263E+03	.5449E+03	LEO FOR 90 DAY MISSION
.7000E+01	.3852E+00	.2307E+04	.7826E+06	.7849E+06	LEO FOR 10 YR MISSION
.2000E+01	.1373E+00	.2346E+02	.8020E+03	.8256E+03	.01 DUTY GEO FOR 10 YR MISSION
.6000E-01	.4558E-02	.2461E+02	.8613E+03	.8860E+03	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.700E+01	.361E+02	.648E+00	.496E+02	.486E+04	.322E+04	.491E+04	.986E+04	LEO FOR 90 DAY MISSION
.700E+01	.361E+02	.917E+01	.264E+04	.486E+04	.322E+04	.491E+04	.125E+05	LEO FOR 10 YR MISSION
.200E+01	.141E+02	.840E+00	.734E+02	.109E+04	.722E+03	.110E+04	.228E+04	.01 DUTY GEO FOR 10 YR MISSION
.600E-01	.102E+01	.878E+00	.783E+02	.290E+02	.192E+02	.293E+02	.138E+03	.4 DUTY GEO FOR 10 YR MISSION

TABLE 36. APS MASS SUMMARY FOR SOC INITIAL

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.6000E+02	.5330E+00	.2619E+02	.9457E+03	.9724E+03	LEO FOR 90 DAY MISSION
.6000E+02	.5330E+00	.3884E+03	.5404E+05	.5443E+05	LEO FOR 10 YR MISSION
.3000E+02	.4967E+00	.1633E+03	.1473E+05	.1489E+05	.01 DUTY GEO FOR 10 YR MISSION
.7000E+00	.7410E-01	.1713E+03	.1583E+05	.1600E+05	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.6000E+02	.1063E+01	.2127E+02	.6820E+03	.7143E+03	LEO FOR 90 DAY MISSION
.6000E+02	.1063E+01	.2961E+03	.3596E+05	.3626E+05	LEO FOR 10 YR MISSION
.3000E+02	.8626E+00	.1300E+03	.1046E+05	.1059E+05	.01 DUTY GEO FOR 10 YR MISSION
.7000E+00	.5137E-01	.1362E+03	.1122E+05	.1136E+05	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.600E+02	.181E+03	.805E+00	.688E+02	.322E+05	.214E+05	.326E+05	.651E+05	LEO FOR 90 DAY MISSION
.600E+02	.181E+03	.966E+01	.286E+04	.322E+05	.214E+05	.326E+05	.679E+05	LEO FOR 10 YR MISSION
.300E+02	.108E+03	.470E+01	.969E+03	.167E+05	.111E+05	.169E+05	.346E+05	.01 DUTY GEO FOR 10 YR MISSION
.700E+00	.642E+01	.490E+01	.103E+04	.446E+03	.290E+03	.451E+0[illegible]	.194E+04	.4 DUTY GEO FOR 10 YR MISSION

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TABLE 37. APS MASS SUMMARY FOR SOC OPERATIONAL

CHEMICAL MONOPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.1000E+03	.5491E+00	.4147E+02	.1885E+04	.1927E+04	LEO FOR 90 DAY MISSION
.1000E+03	.5491E+00	.6015E+03	.1041E+06	.1047E+06	LEO FOR 10 YR MISSION
.4000E+02	.5142E+00	.2751E+03	.3221E+05	.3249E+05	.01 DUTY GEO FOR 10 YR MISSION
.1000E+01	.1003E+00	.2887E+03	.3463E+05	.3491E+05	.4 DUTY GEO FOR 10 YR MISSION

CHEMICAL BIPROPELLANT

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	TOTAL APS MASS	
.1000E+03	.1172E+01	.3368E+02	.1379E+04	.1414E+04	LEO FOR 90 DAY MISSION
.1000E+03	.1172E+01	.4614E+03	.6997E+05	.7043E+05	LEO FOR 10 YR MISSION
.4000E+02	.9524E+00	.2191E+03	.2289E+05	.2311E+05	.01 DUTY GEO FOR 10 YR MISSION
.1000E+01	.7224E-01	.2296E+03	.2455E+05	.2478E+05	.4 DUTY GEO FOR 10 YR MISSION

ELECTRICAL PROPULSION

THRUST PER THRUSTER	THRUSTER MASS	TANK MASS	PROPELLANT MASS	SOLAR ARRAY MASS	SOLAR ARRAY AREA	POWER PROC UNIT MASS	TOTAL APS MASS	
.100E+03	.265E+03	.126E+01	.137E+03	.638E+05	.423E+05	.645E+05	.129E+06	LEO FOR 90 DAY MISSION
.100E+03	.265E+03	.153E+02	.569E+04	.638E+05	.423E+05	.645E+05	.134E+06	LEO FOR 10 YR MISSION
.400E+02	.133E+03	.791E+01	.212E+04	.366E+05	.243E+05	.371E+05	.760E+05	.01 DUTY GEO FOR 10 YR MISSION
.100E+01	.839E+01	.826E+01	.226E+04	.977E+03	.649E+03	.988E+03	.424E+04	.4 DUTY GEO FOR 10 YR MISSION

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TABLE 38. CONVERGED APS MASS REQUIREMENTS FOR GEO STATIONKEEPING

	Mass of Satellite	1% Duty Cycle			40% Duty Cycle		
		APS Mass (kg)	Total Mass (kg)	% APS	APS Mass (kg)	Total Mass (kg)	% APS
LAPAA 10 KW	1292						
monopropellant		506	1798	28.1	546	1838	29.7
bipropellant		356	1648	21.6	383	1675	22.9
electrical propulsion		14858	16150	92	59.5	1351.5	4.4
LAPAA 65 KW	3336						
monopropellant		1385	4721	29.3	1495	4831	30.9
bipropellant		972	4308	22.6	1045	4381	23.9
electrical propulsion			No Convergence		197.9	3533.9	5.6
LMSS Wrap Rib	3036						
monopropellant		1073	4109	26.1	1156	4192	27.6
bipropellant		758	3794	20.0	814	3850	21.1
electrical propulsion			No Convergence		214.5	3250.5	6.6
LMSS Hoop Column	2907						
monopropellant		1641	4548	36.1	1779	4666	38.0
bipropellant		1134	4041	28.1	1224	4131	29.6
electrical propulsion			No Convergence		212.1	3119.1	6.8
Geostationary Platform	3737						
monopropellant		1164	4901	23.8	1253	4990	25.1
bipropellant		826	4563	18.1	886	4623	19.2
electrical propulsion			No Convergence		234.3	3971.3	5.9
SOC Initial	57242						
monopropellant		14890	72132	20.6	16000	73242	21.9
bipropellant		10590	67832	15.6	11360	68602	16.6
electrical propulsion			No Convergence		2823.1	60065.1	4.7
SOC Operational	125500						
monopropellant		32490	157990	20.6	34910	160410	21.8
bipropellant		23110	148610	15.6	24780	150280	16.5
electrical propulsion		376500	502000	75	4821.9	130321.9	3.7

The effect of iteration on the thrust level requirements is shown in Figure 68. This effect is very noticeable for the shorter duty cycles using electric propulsion due to the very large power penalty associated with high thrust levels. For chemical systems, the increase was between 30 and 40%.

Another output of the scaling exercise was electric power requirements for electric systems. As discussed above, the 1% duty cycle was unrealistic for electric propulsion (EP). For example, at a duty cycle of .01, the increase of total LSS mass due to the APS is about 60%. At a duty cycle of .4, the increase is only about 4%. The decrease is attributed to the lower thrust levels required, which leads to lower power requirements, and consequently, lower thruster mass, solar array mass, and power processing unit mass. It should be noted that the propellant mass increases with increasing duty cycle. This is expected because there are greater cosine losses with longer duty cycle. Therefore, chemical APS, which do not require as much hardware mass due to power, have mass increases with increasing duty cycle. Since EP shows a considerable savings in mass at the longer duty cycle, an investigation of duty cycle effects on power system requirements was made. Table 39 shows the approximate EP power requirements at .01 and .4 study cycles. The table shows that, in general, the .4 duty cycle requires one to two orders of mangitude less power. Figure 69 shows the total power required using a 40% duty cycle as a function of satellite mass. For the power levels being considered, the following factors are important.

- High voltage can cause arcing due to interactions with plasma near the satellite at LEO (this effect can be considered negligible at GEO).

- High currents can generate intense magnetic fields which interact with the earth's magnetic field causing disturbance torques (this may be very minor at GEO).

- High power requirements result in large transmission lines which will add mass to cabling systems (this mass may be very significant if power levels are high and transmission lines are long).

- High power requirements lead to grounding problems which can necessitate the coating of the LSS with a conductive substance which changes structural characteristics.

- If batteries are used they will contribute a substantial portion of the power system mass. For instance, in the proposed SOC design, batteries have been sized at 8000 lbs. Battery mass is largely a function of the depth of discharge (DOD). The lower the DOD the lower the battery weight required. DOD is defined as the percentage of energy needed versus the total energy available from the battery. (In general, a DOD of 50% is most desirable).

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	1% Duty Cycle		40% Duty Cycle	
	Original Thrust/Thruster (N)	CONVERGED Thrust/Thruster (N)	Original Thrust/Thruster (N)	CONVERGED Thrust/Thruster (N)
LAPAA 10 KW	.5		.010	
monopropellant		.70		.014
bipropellant		.64		.013
electrical propulsion		5.96		.010
LAPAA 65 KW	2		.040	
monopropellant		2.8		.058
bipropellant		2.6		.053
electrical propulsion		No Convergence		.042
LMSS Wrap Rib	2		.060	
monopropellant		2.7		.083
bipropellant		2.5		.076
electrical propulsion		No Convergence		.065
LMSS Hoop Column	2		.040	
monopropellant		3.1		.064
bipropellant		2.8		.057
electrical propulsion		No Convergence		.043
Geostationary Platform	2		.060	
monopropellant		2.6		.081
bipropellant		2.4		.075
electrical propulsion		No Convergence		.064
SOC Initial	30		.70	
monopropellant		37.8		.90
bipropellant		35.5		.84
electrical propulsion		No Convergence		.73
SOC Operational	40		1.0	
monopropellant		50.2		1.28
bipropellant		47.1		1.20
electrical propulsion		158		1.04

FIGURE 68. CONVERGED MAXIMUM APS THRUST REQUIREMENTS FOR GEO STATIONKEEPING

TABLE 39. POWER REQUIREMENTS FOR ELECTRICAL PROPULSION (KW)

	.01 Duty Cycle	.4 Duty Cycle
Electronic Mail	0.2778E+02	0.7449E+00
Educational TV	0.7197E+02	0.1923E+01
LMSS Wrap Rib	0.6544E+02	0.1751E+01
LMSS Hoop Column	0.6271E+02	0.1675E+01
Geostationary Platform	0.8059E+02	0.2146E+01
SOC Initial	0.1235E+04	0.3304E+02
SOC Operational	0.2715E+04	0.7239E+02

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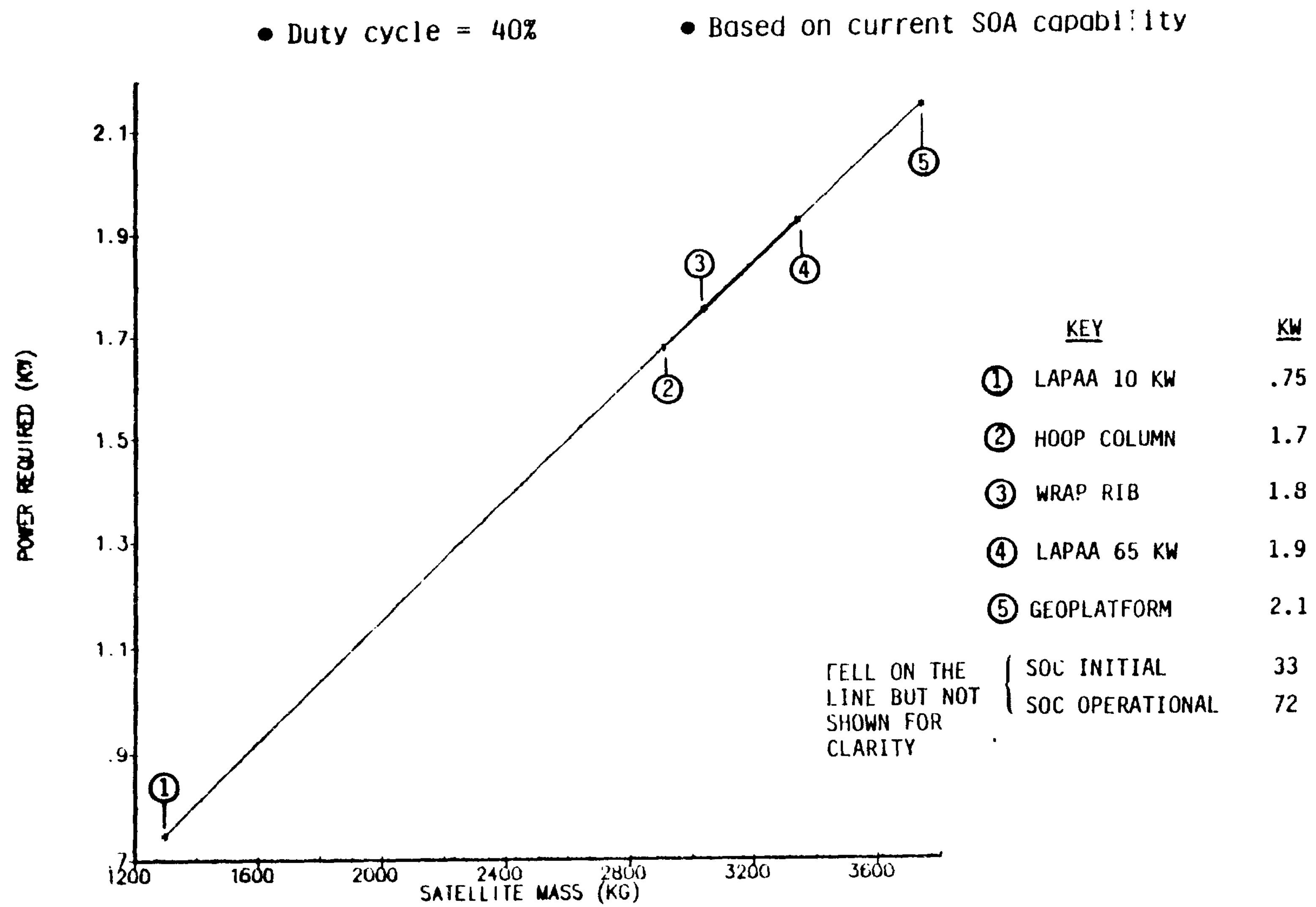

FIGURE 69. ELECTRIC ION PROPULSION POWER REQUIREMENTS

Two options exist for APS power supplies - solar arrays and batteries. If two batteries are used, the duty cycle and hence thrust level has little effect on the size of battery used. This is because the total energy for either duty cycle is about the same (energy = power x time). If solar arrays are used a longer duty cycle has a positive effect in lowering the required power level and the arrays may be smaller in size. A possible negative effect from longer duty cycles may result if the payload operations and APS power sources are the same. In most missions the peak power load is considerably below the average power required. Solar arrays sized for this peak power load may be used to supply power to the APS during off peak time. As the duty cycle increases, the likelihood of being able to draw on this "free" power source decreases. The extent of this penalty for longer duty cycles is very mission dependent and is noted here only as a qualitative observation.

2.4 APR/LSS Interactions

Interaction of the propulsion system with the structure becomes a key issue for LSS, particularly those systems which must operate continuously. If the antenna beam is defocused in any way, this translates into a power or gain loss in the signal and a degradation of user service. The approach taken to analyze this interaction is summarized below.

- Used NASTRAN mode shapes to simulate dynamic interactions.
- Examined steady state and transient response.
- Modeled with and without APS mass for higher (LEO) thrust values.
  - Thruster masses placed at thruster locations.
  - Propellant, tank masses at CG.
- Modeled without APS mass at lower (GEO) thrust levels.

It was found from the LEO analysis that thruster mass had little effect on degradation; therefore the GEO thrust level analysis was made without the APS mass to preserve resources.

The major areas of interest for this analysis were 1) the defocusing of the antenna, and 2) the stresses in the structural members. The structural response was computed with the NASTRAN finite element computer program, using the computer models developed in Task 1. A modal transient analysis was used to compute the forces in the structural members, the relative displacements, and the relative accelerations of the points on the structure. The mode shapes found in Task 1 were studied to determine the number of modes to be used for this analysis. The main consideration in choosing the modes was to include all modes which had significant modal deflection at any thruster location. It was decided that the first ten flexible modes would provide sufficient accuracy since all higher modes were local modes of components and would therefore have little effect on the analysis. The frequency range for the first ten flexible modes was 0.090 to 0.255 Hz.

Displacements computed with NASTRAN were verified using the following equations.

Steady State Modal Response

$$q_{ss} = 1/m\omega^2 \sum_j F_j \, \phi_j$$

where

q_{ss} = steady state modal response (m)

m = generalized mass (kg)

ω = frequency of response (rad/sec)

F = force of point j (N)

ϕ_j = mode shape at point j for response frequency, (m/m)

assuming damping is small

$$q_{max} \sim 2\, q_{ss}$$

maximum displacement due to load F_j

$$\delta j_{max} = \phi_j \, q_{max} \text{ (meters)}$$

Displacements calculated with these equations compared very well with the maximum displacements calculated using NASTRAN. (NASTRAN computes an entire displacement versus time history, while the above equations only compute the maximum value of displacement). The displacement calculated by NASTRAN were used to compute the amount of defocusing caused by each stationkeeping maneuver.

The question of structural integrity proved to be a non-issue. Maximum g-loading from even the short duty cycle LEO stationkeeping thrust levels was well below the .15 g's the structure was sized for. Figures 70 and 71 show typical bending moment and force responses for the LMSS Wrap Rib configuration. Tables 40 and 41 show that the percent of stress exhibited was always less than 1% of the maximum allowable. This conclusion does not mean defocusing did not occur, only that the flex in the structure did not threaten the structural integrity.

To analyze defocusing effects, four geometrical definitions of defocusing were utilized. These definitions have been previously employed on programs such as the Space Telescope. These four effects are illustrated in Figure 72. The motion of selected grid points was summed to find the various defocusing effects. This approach is illustrated in Figure 73.

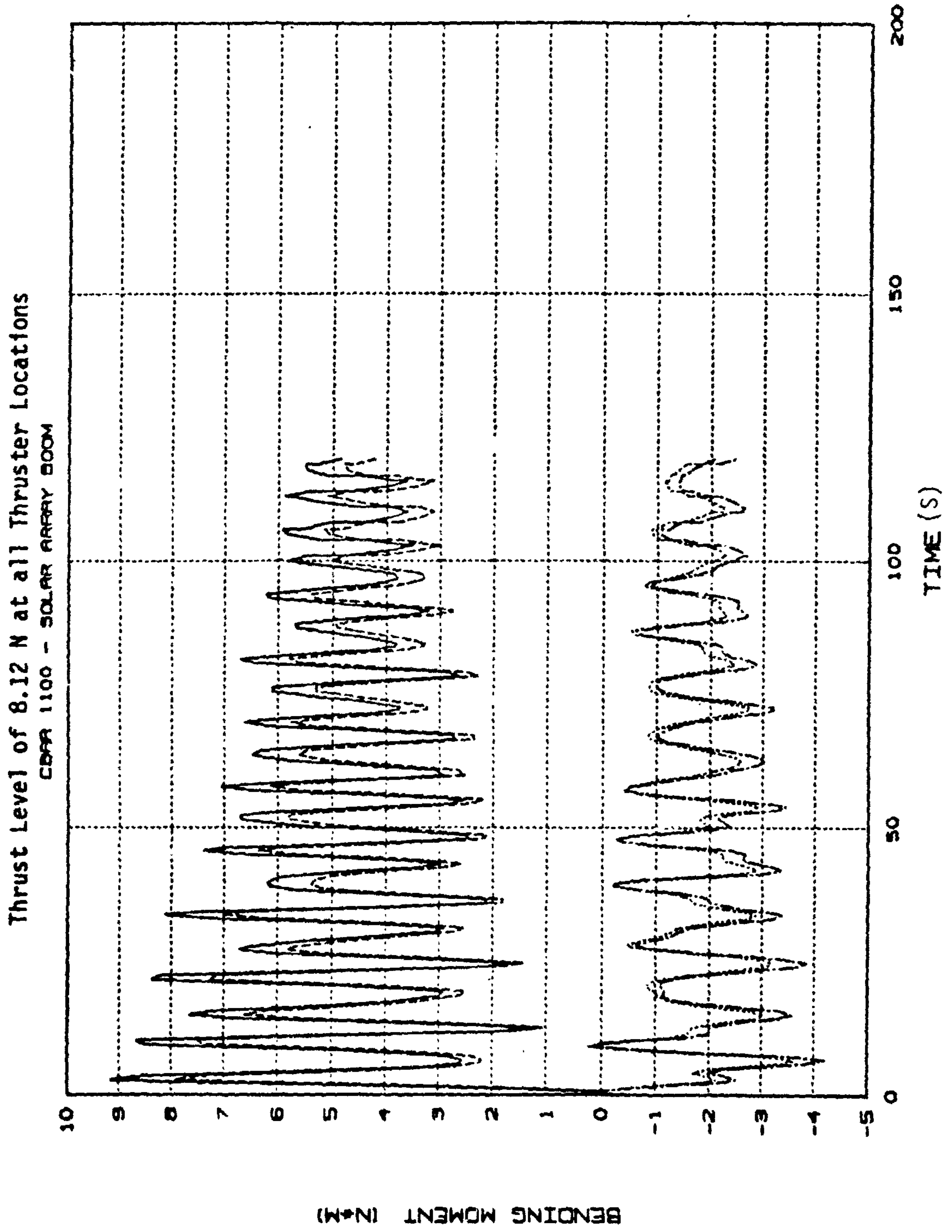

FIGURE 70. LMSS WRAP RIB - BENDING MOMENT IN SOLAR ARRAY BOOM

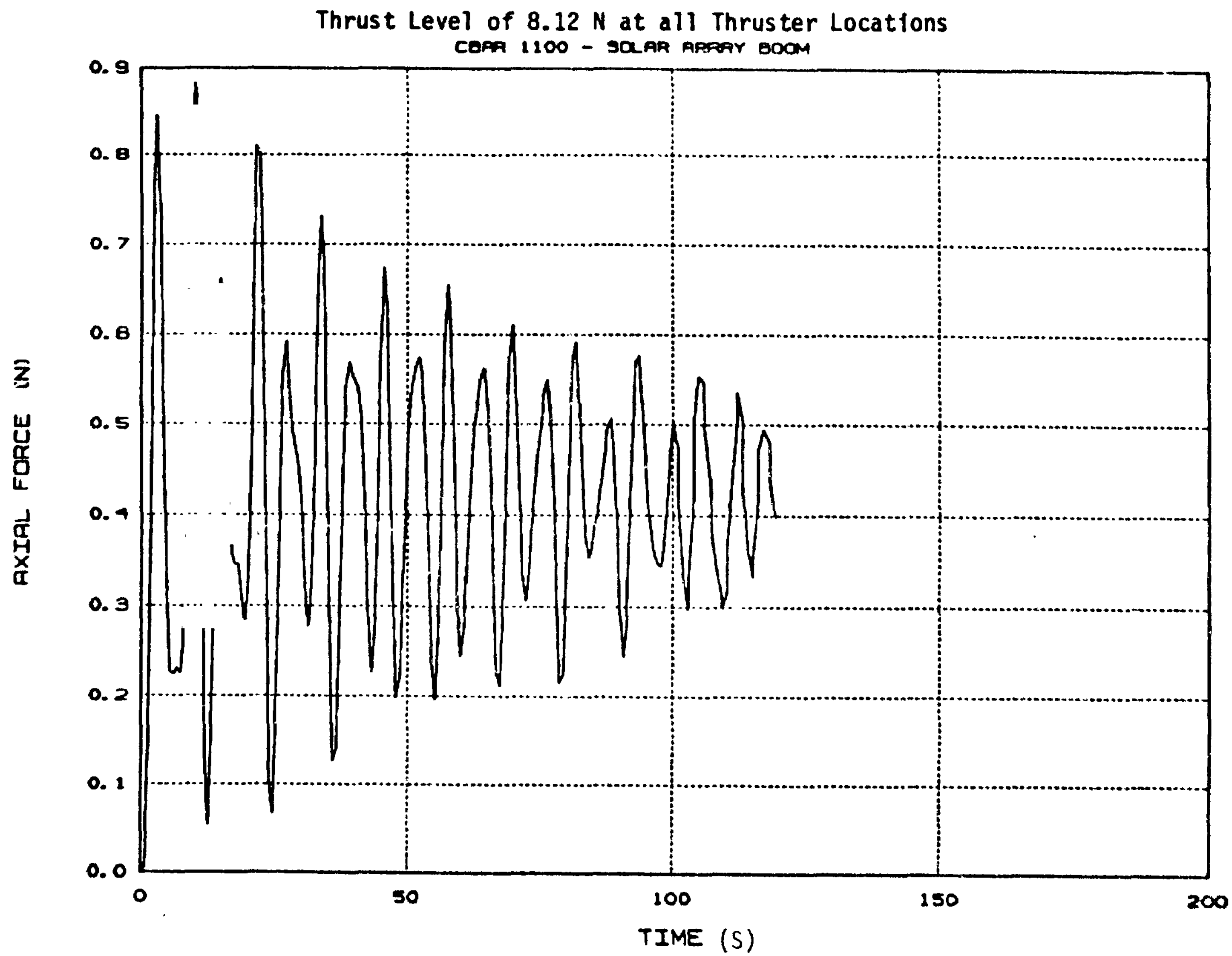

FIGURE 71. LMSS WRAP RIB - AXIAL FORCE IN SOLAR ARRAY BOOM

TABLE 40. LMSS WRAP RIB - MEMBER FORCES

Maximum Axial Force Thrust Level of 8.12 N at Each Thruster Location

NASTRAN Element ID No.	Description	Allowable Axial Force (N)	Actual Axial Force (N) Stationkeeping Purpose +X	-X	+Y	-Y	Percent of Allowable (Max for All Maneuvers)
4001→4005	Outbound Boom	150,000	0.16	0.16	1.5	0.16	.0001
4010→4019	Inbound Boom	150,000	0.37	0.37	1.2	0.52	.0008
4020→4021	Boom Housing	1.4×10^6	0.93	0.94	0.96	0.53	.0001
4022→4023	Bus	1.2×10^6	0.94	0.94	2.62	0.59	.0002
4550	UHF Feed Boom	7700	0.18	0.18	0.21	0.05	.003
3200	S Band Feed Boom	80	0.72	0.72	0.09	0.03	0.90
3000	S Band Reflector Boom	2000	0.63	0.63	0.06	0.02	.03
4301→4305	Solar Array Mast	8200	0.11	0.11	0.29	0.10	.004
1010→1600	Solar Array Booms	5700	0.88	0.88	0.05	.03	.015
2011→2245	UHF Antenna Ribs	6200	2.6	2.6	1.5	0.50	.042
2311→2545	UHF Antenna Rings	220,000	0.35	0.35	0.11	0.03	.0002
3011→3164	S Band Antenna Ribs	20	1.2×10^{-11}	1.2×10^{-11}	1.1×10^{-12}	6.3×10^{-12}	-
3511→3674	S Band Antenna Rings	91,000	5.4×10^{-12}	5.4×10^{-12}	2.3×10^{-12}	2.1×10^{-12}	-

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TABLE 41. LMSS WRAP RIB - MEMBER FORCES

Maximum Bending Moment Thrust Level of 8.12 N at Each Thruster Location

NASTRAN Element ID No.	Description	Allowable Bending Moment (N·m)	Max. Computed Bending Moment (N·m) Stationkeeping Purpose				Percent of Allowable (Max for All Maneuvers)
			+X	-X	+Y	-Y	
4001→4005	Outbound Boom	88,000	144	144	76.6	14.1	0.16
4010→4019	Inbound Boom	88,000	124	124	76.6	7.8	0.14
4020→4021	Boom Housing	860,000	31.1	31.1	53.0	7.5	.006
4022→4023	Bus	4.3×10^{10}	42.6	42.6	56.2	17.8	-
4550	UHF Feed Boom	360,000	103	103	39.9	16.8	.029
3200	S Band Feed Boom	26,000	0.32	0.32	0.09	0.08	.001
3000	S Band Reflector Boom	55,000	13.1	12.7	5.5	6.3	.024
4301→4305	Solar Array Mast	88,000	43.1	43.1	29.3	19.1	.049
1010→1600	Solar Array Booms	49,000	9.2	8.6	5.6	3.7	.019
2011→2245	UHF Antenna Ribs	220,000	7.0	7.0	3.6	1.2	.003
3011→3164	S Band Antenna Ribs	91,000	1.8×10^{-12}	1.8×10^{-12}	7.6×10^{-12}	1.1×10^{-12}	-

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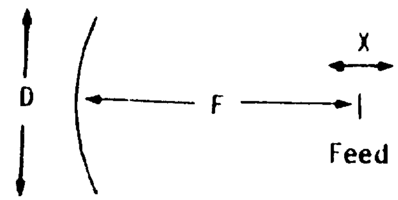
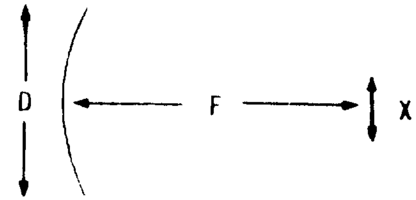
DESPACING



Definition: ΔLongitudinal distance between feed & antenna.

Impact: Phase error and gain loss & broadening of beam.

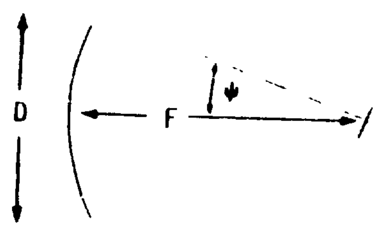
DECENTER



Definition: ΔLattitudinal distance feed/antenna.

Impact: Pointing loss; no gain loss unless ΔX gets larger than the beamwidth.

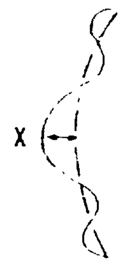
TILT



Definition: ΔAngle between focal line of feed and focal line of antenna.

Impact: Changes energy distribution across reflector - generally will even out.

DEFIGURE



Definition: Deviation of actual antenna shape with respect to perfect parabaloid.

Impact: Produces scattering of energy into side lobes - gain loss.

NOTE: Not examined due to lack of time

FIGURE 72. DEFOCUSING DEFINITIONS

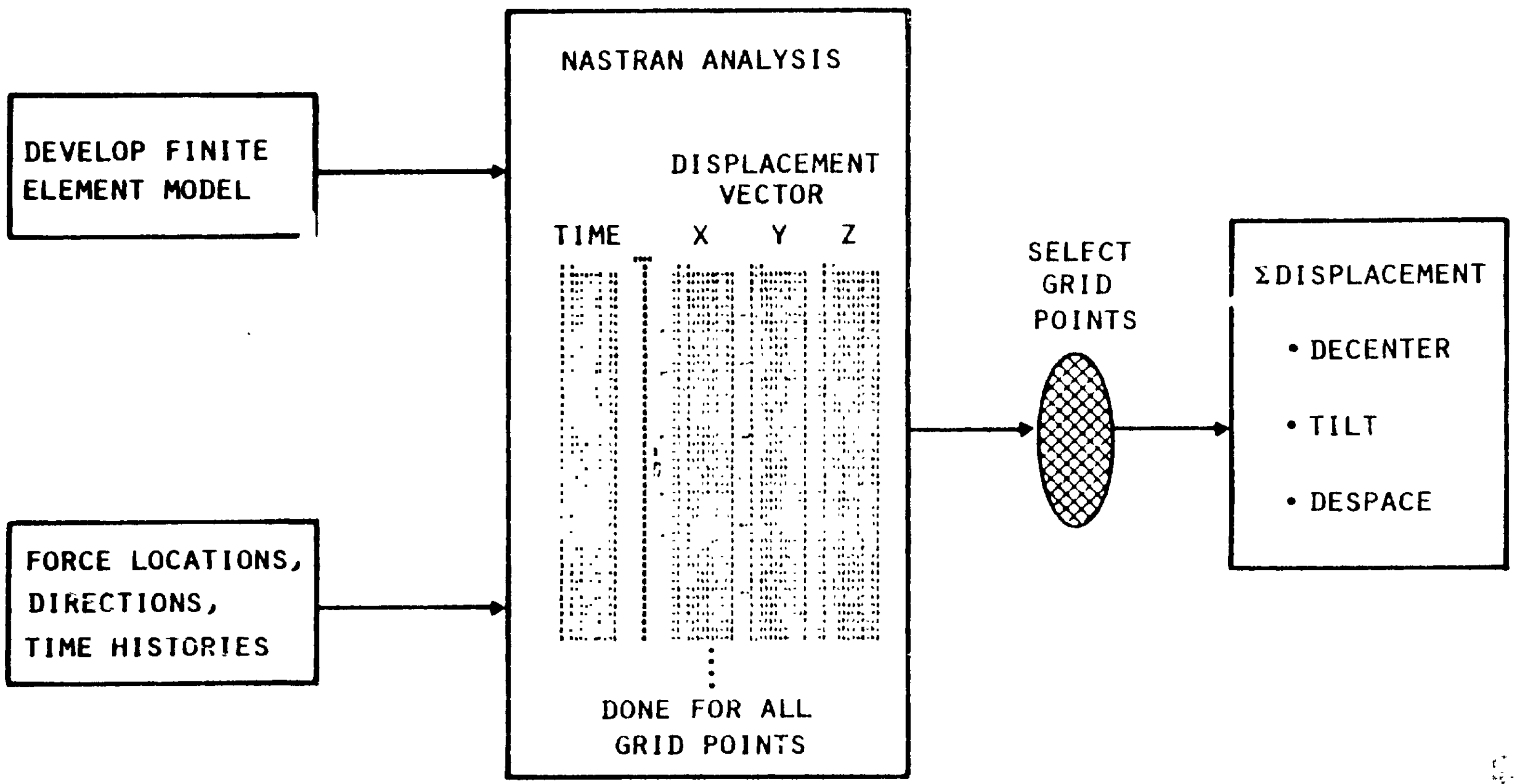


FIGURE 73. APS/LSS INTERACTIONS DETERMINATION

Sensitivity to defocusing is a function of frequency and f/d (focal length/diameter). Power loss of 10% was considered the maximum acceptable goal. Figures 74 through 78 show the sensitivity for the three effects analyzed.

Stationkeeping thrusts were initially applied to the LSS without adding APS mass (propellant, tank, and thruster masses). This enabled us to determine the structural response (stresses and displacements) of each LSS without biasing the results toward any particular propulsion system. The thrust/thruster for the first load case was chosen as the highest thrust required at any thruster to perform all stationkeeping and torquing maneuvers at LEO. These thrust levels were applied to the four models to determine structural response. From the displacements, three defocusing parameters (decenter, despace and tilt) and the power loss associated with each were calculated. Power loss was taken from Figures 74 through 78, where the operating frequency (i.e. UHF, SBAND) and f/d were given in the configuration data. The results of load case one, LEO stationkeeping thrust levels with no APS mass added to the structures, were as follows:

- Large Aperture Phased Array Antenna (LAPAA) - less than ten percent power loss for all three defocusing parameters.
- Geostationary Platform (GP) - less than ten percent power loss for all three defocusing parameters for both the UHF and peta antennae.
- Wrap Rib Land Mobile Satellite System (LMSS) - less than ten percent power loss due to decenter and despace, and ten to fifteen percent power loss due to tilt.
- Hoop Column LMSS - less than five percent power loss due to despace and tilt, and ten to fifteen percent power loss due to decenter.

For the second load case, the propellant system was assumed to be chemical bipropellant. Propellant and tank masses were placed as close to the c.g. as possible, while thruster masses were placed at each thruster location. Dynamic characteristics of each structure with APS mass were computed. To cut expenses, only the worst case direction of stationkeeping (x or y) found in load case one was computed for load case two. LEO stationkeeping thrust levels used in load case one were applied to the structures and structural response was computed. The change in defocusing parameters from load case one to two varied from structure to structure:

- LAPAA - all three parameters increase.
- GP - all parameters increase for the peta antenna; for the UHF antenna, decenter and tilt increase, while despace decreases.
- Wrap Rib LMSS - decenter and tilt increase, despace decreases.
- Hoop Column LMSS - all defocusing parameters decrease.

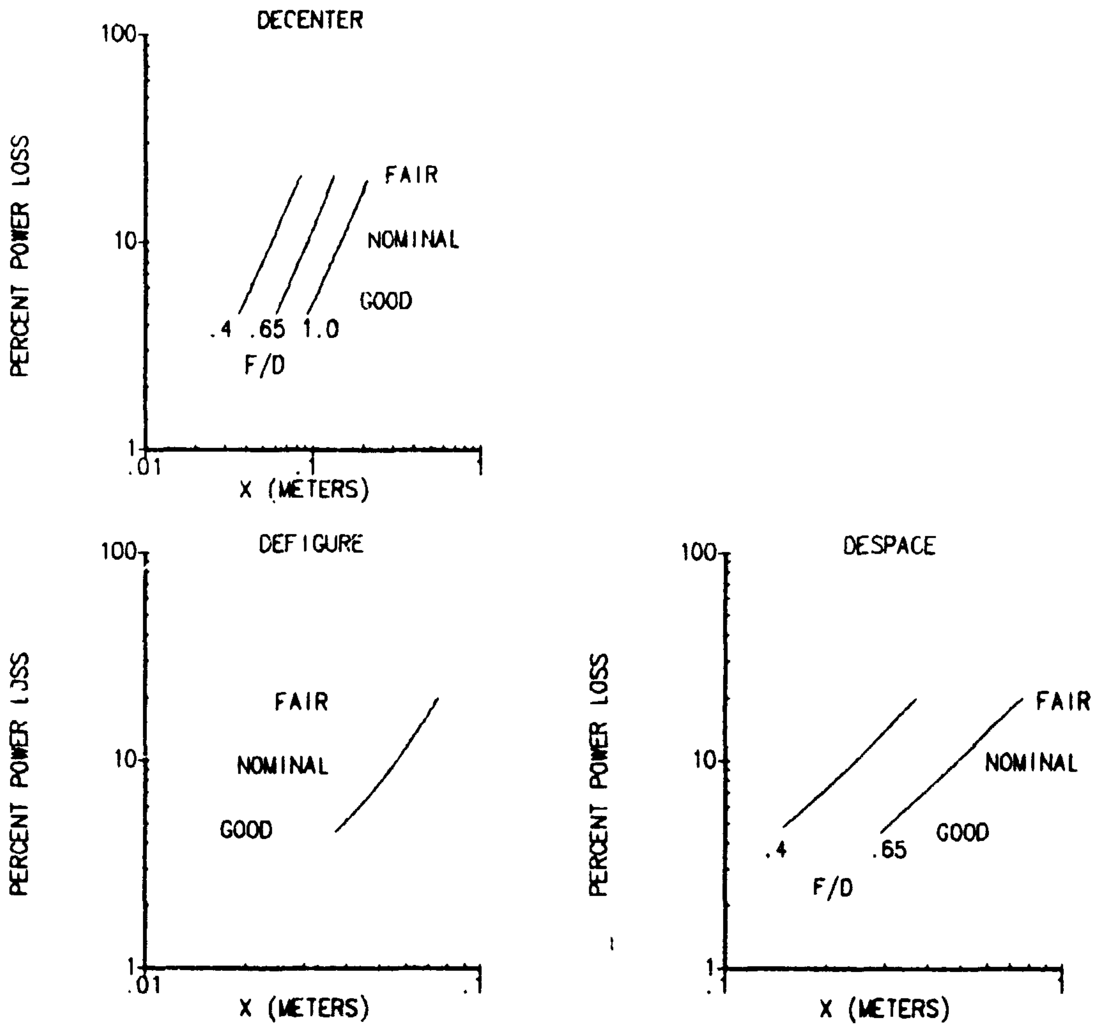


FIGURE 74. POWER LOSS FOR UHF BAND (400 MHZ)

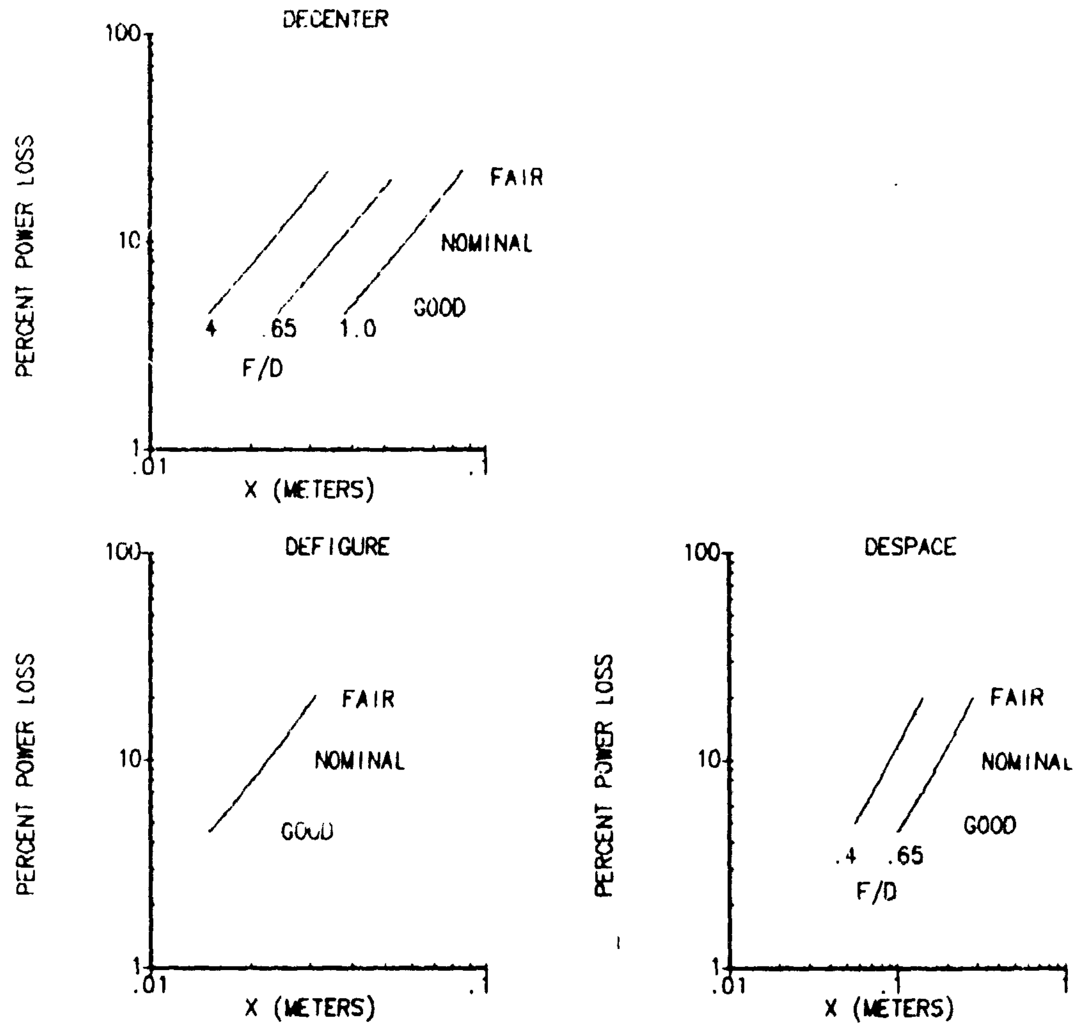


FIGURE 75. POWER LOSS FOR L-BAND (1 GHZ)

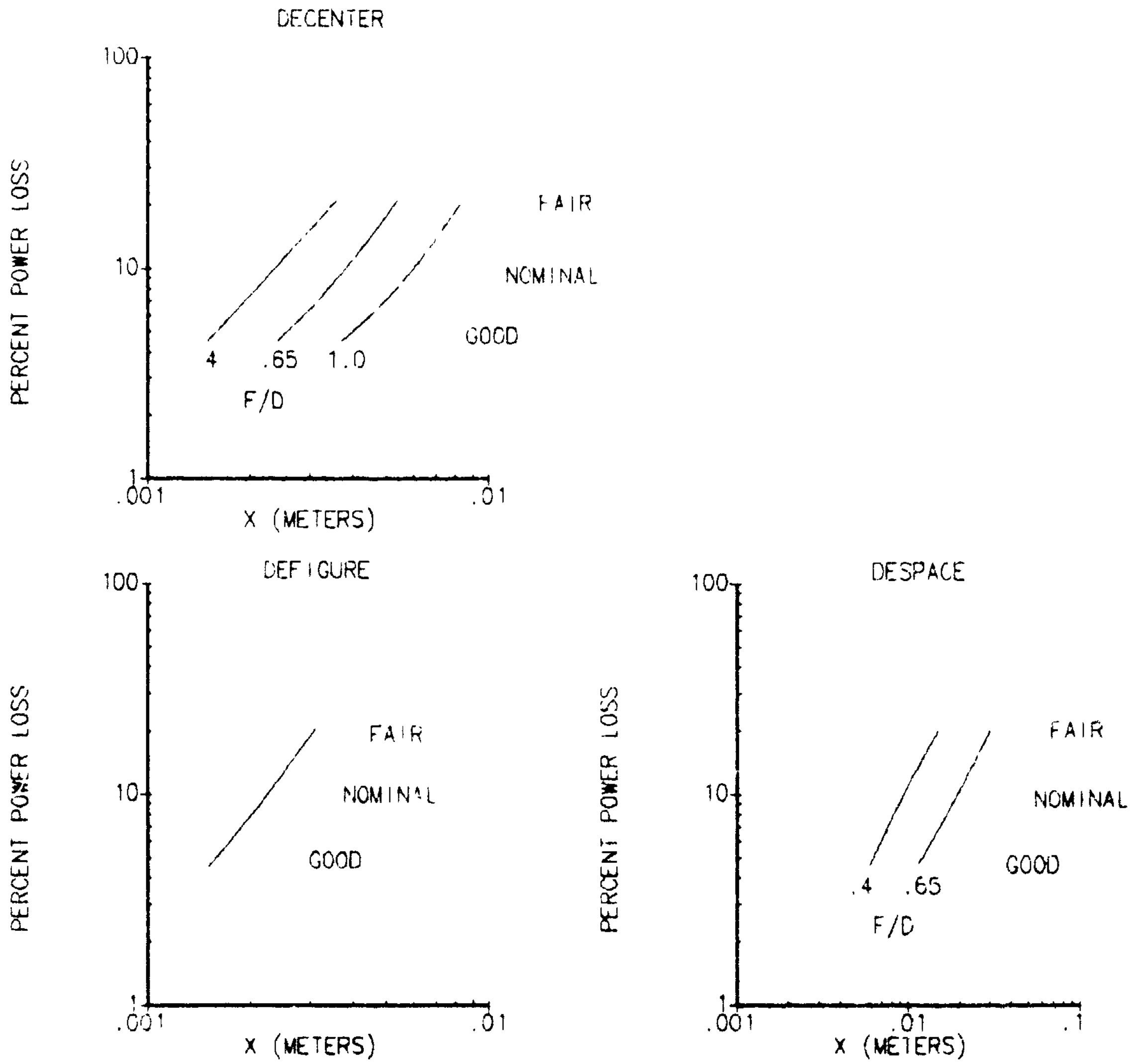


FIGURE 76. POWER LOSS FOR X-BAND (10 GHZ)

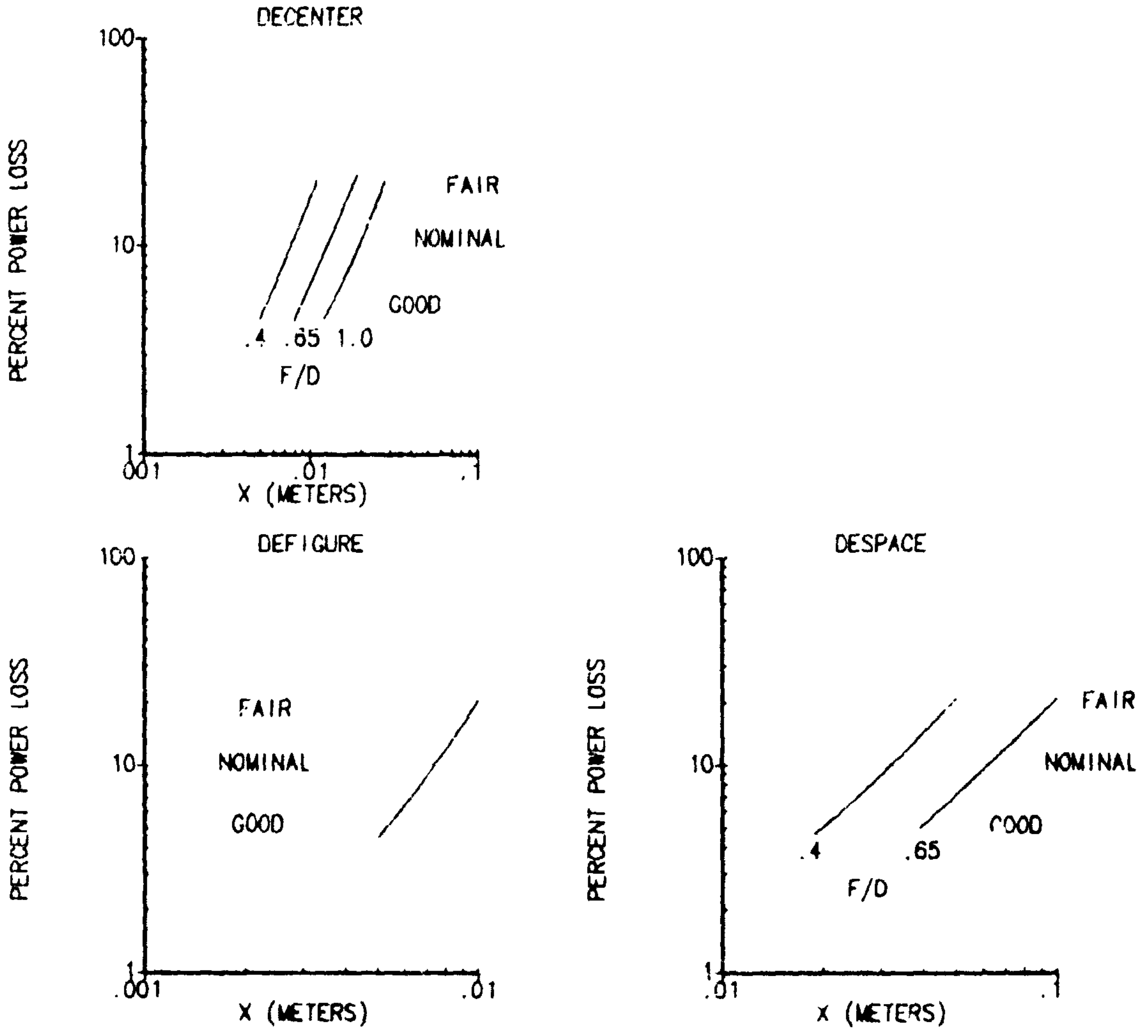


FIGURE 77. POWER LOSS FOR S-BAND (3 GHZ)

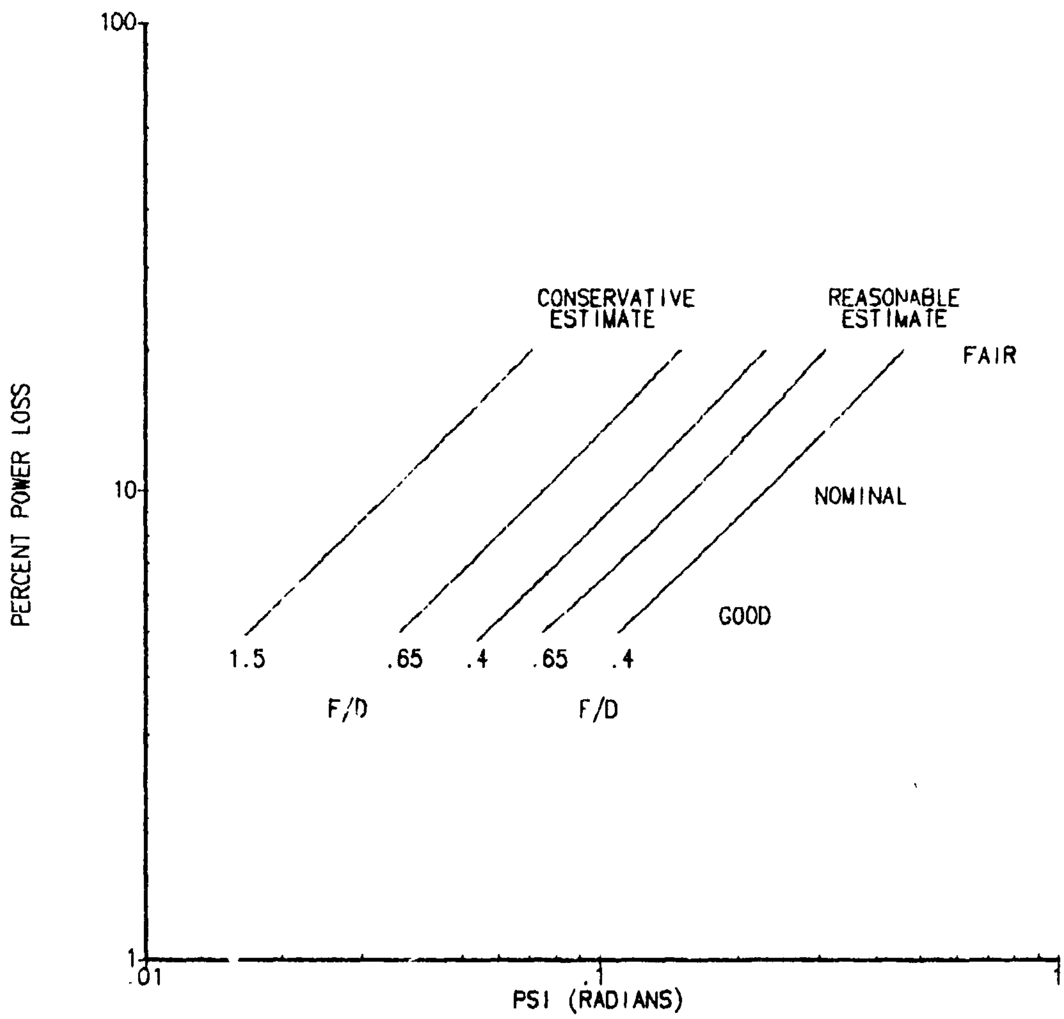


FIGURE 78. POWER LOSS DUE TO TILT (INDEPENDENT OF FREQUENCY)

Time and budget prevented us from fully checking out the reasons for the varied responses to adding APS mass. However, we feel that a more detailed study of the dynamic characteristics of each structure before and after the addition of APS mass could result in a systematic way of predicting the effect that the addition of a given APS mass distribution would have on the performance of the structure.

The third load case was done at GEO stationkeeping thrust levels, assuming the same APS mass distribution used in load case two. A nominal thrust level of 2.0 N thrust/thruster was used for all four models. This level is currently lower than the state-of-the-art for chemical bipropellant engines. It is also somewhat higher than those thrust levels available from electric systems. However, this thrust level is representative of GEO stationkeeping requirements. For this load case, all models except the Wrap Rib LMSS showed power losses of five percent or less associated with all three defocusing parameters for both x and y stationkeeping directions. The Wrap Rib LMSS had less than five percent power loss due to decenter and despace, but five to ten percent power loss due to tilt during y-stationkeeping and ten to fifteen percent power loss due to tilt during x-stationkeeping. The results of all three load cases are shown in Tables 42 through 45.

Tilt and decenter seem to be the limiting parameters in the performance of the Wrap Rib LMSS at LEO thrust levels. Assuming that a power loss of more than ten percent results in unacceptable performance, one can find the average decenter at ten percent power loss between Figures 74 and 75, then linearly interpolate between 8.12 N/thruster and 2.0 N/thruster, load cases 2 and 3, respectively, on a plot of decenter vs thrust level to determine that a thrust of approximately 7.3 N/thruster would produce ten percent power loss due to decenter. Tilt, however, is a problem even at GEO thrust levels (2.0 N) and an estimation of how low the thrust/thruster needs to be for a power loss of ten percent or less due to tilt is difficult to make.

For the Hoop Column, decenter limits performance at LEO. Assuming a linear relationship between thrust level and decenter, one can interpolate between 30.0 N/thruster and 2.0 N/thruster to determine that a thrust of approximately 5.0 N/thruster would result in ten percent power loss due to decenter. See Table 44 and Figure 74, f/d = .55.

In reviewing the results it is important to keep in mind that the power losses due to each defocusing parameter must be added to estimate the overall power loss of each antenna. Assuming that an overall power loss of ten percent or less is acceptable for these structures, the results can be summarized as follows:

- At the LEO stationkeeping thrust levels used in this analysis (LAPAA 6.96 N, Wrap Rib 8.12 N, Hoop Column 30.0 N, and Geo Platform 7.2 N), the performance of the LAPAA and GP seem to be acceptable, while the performance of the Wrap Rib LMSS and Hoop Column LMSS may prove to be unacceptable.

- At GEO stationkeeping thrust levels, performance of all but the Wrap Rib LMSS seems to be acceptable.

Table 42

Defocusing for Large Aperture Phased Array

CONDITIONS	STATIONKEEPING MANEUVER	DECENTER (METERS)	DESPACE (METERS)	TILT (RADIANS)
6.96 N/Thruster No thruster mass	X	.0211	.0000	.0006
	Y	.0612*	.0001	.0069
6.96 N/Thruster With thruster mass	Y	.0639*	.0001	.0077
2.0 N/Thruster With thruster mass	X	.0072	.0000	.0000
	Y	.0183	.0000	.0022

* 5 10% Power loss

Note: 0-5% power loss unless otherwise stated

Table 43

Defocusing for Wrap Rib Land Mobile Satellite System

CONDITIONS	STATIONKEEPING MANEUVERS	DECENTER (METERS)	DESPACE (METERS)	TILT (RADIANS)
8.12 N/Thruster No thruster mass	X	.1130 B	.0007 A	.0383 B
	Y	.0097 B	.0018 A	.0653 B
8.12 N/Thruster With thruster mass	X	.1162 C	.0006 A	.2323 C
2.0 N/Thruster With thruster mass	X	.0286 A	.0002 A	.1941 C
	Y	.0087 A	.0008 A	.0633 B

A = 0 → 5% power loss

B = 5 → 10% power loss

C = 10 → 15% power

Table 44

Defocusing for Hoop Column Land Mobile Satellite System

CONDITIONS	STATIONKEEPING MANEUVER	DECENTER (METERS)	DESPACE (METERS)	TILT (RADIANS)
30.0 N/Thruster No thruster mass	X	.5361 C	.0025 A	.0069 A
	Y	.4384 C	.0000 A	.0057 A
30.0 N/Thruster With thruster mass	X	.5360 C	.0016 A	.0069 A
	Y	.4343 C	.0000 A	.0056 A
2.0 N/Thruster With thruster mass	X	.0357 A	.0001 A	.0005 A
	Y	.0291 A	.0000 A	.0004 A

A = 0 5% power loss

B = 5 10% power loss

C = more than 10% power loss

Table 45
Defocusing for Geostationary Platform

CONDITIONS	STATIONKEEPING MANEUVER	UHF ANTENNA DECENTER (METERS)	UHF ANTENNA DESPACE (METERS)	UHF ANTENNA TILT (RADIANS)	PETA ANTENNA DECENTER (METERS)	PETA ANTENNA DESPACE (METERS)	PETA ANTENNA TILT (RADIANS)
7.2 N/Thruster No thruster mass	X	.0043	.0001	.0541*	.0016	.0048	.0001
	Y	.0030	.0024	.0002	.0084	.0107	.0006
7.2 N/Thruster With thruster mass	Y	.0038	.0020	.0002	.0083	.0099	.0006
2.0 N/Thruster With thruster mass	X	.0012	.0000	.0001	.0004	.0014	.0000
	Y	.0011	.0006	.0001	.0023	.0027	.0002

* 5—►10% Power loss

Note: 0—►5% power loss unless otherwise stated

Although time and budget prevented us from doing so, we feel the following would be worthy of further investigation.

- A more detailed analysis of the dynamic characteristics of each structure before and after the addition of APS mass.
- Methods of strengthening structure to minimize defocusing effects.
- Consequences of distributing APS mass on flexible structures.
- Utilizing distributed thrusters to perform slew maneuvers of flexible appendages.

3.0 ASSESSMENT OF TECHNOLOGY IMPROVEMENT BENEFITS

The objective of Task 3 was to identify state-of-the-art adequacy/deficiency and the benefits of increasing technology capabilities. To accomplish this objective, three major subtasks were executed. The first subtask was to characterize the state-of-the-art propulsion capabilities. This subtask was broadened from the more focused scaling exercise to include such systems as inert gas thrusters, resistojets, MPD thrusters, LO_2/LH_2 and others. The second subtask was to determine the state-of-the-art limitations. This was done in terms of delivery system capability (both STS and OTV), pointing control capability in terms of minimum bit and valve cycling requirements, and thrust level/I considerations. The third subtask was to assess the enhanced technology benefits. This closely paralleled the second subtask but a more indepth examination of momentum management versus jet control, electric propulsion system mass, and thrust level duty cycles were considered. The key assumptions used in Task 3 are shown below in Table 46.

Table 46. Task 3 Key Assumptions

A) State-of-the-art characterization

- Ion propulsion -- SEPS technology

B) State-of-the-art limitations

- Maximum moment arms
- Uniform thrust/thruster
- 30,000 kg STS capability
- 4,800 kg (max) LEO to GEO transfer capability (Centaur G')

C) Enhanced technology benefits

- Less mass means less cost
- Shorter duty cycles most desirable

3.1 State-of-the-Art Characterization

The systems considered for comparison with the propulsion requirements derived in Task 2 are shown in Table 47. In addition to the systems, certain systems exist which are less characterized in terms of scaling properties but have experimentally or theoretically verified performance regimes. Figure 79 shows the set of established and in-development thruster technologies.

TABLE 47. SOA CHARACTERIZATION

SYSTEMS PERFORMANCE COMPARISON

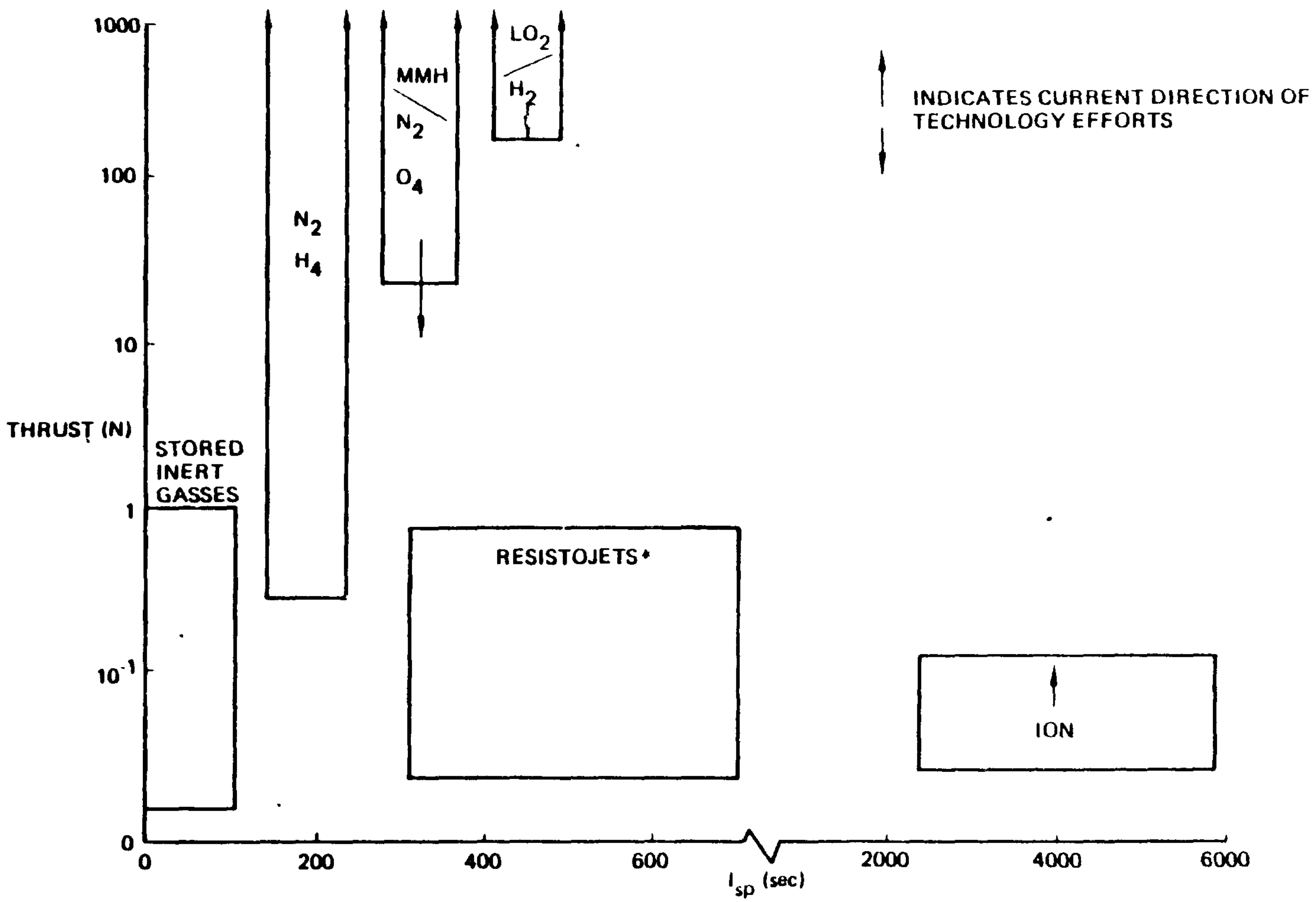
SYSTEM	THRUST RANGE (N)	ISP (SEC)	MINIMUM FIRING TIME (SEC)	COMMENTS
MONO (N_2H_4)	.5 - 2700	210 - 230	.05	STANDARD, WELL ESTABLISHED
BIPROP (N_2O_4/MMH)	22 - 1500	260 - 290	.1	2 N THRUSTER UNDER DEVL.
CRYO (LO_2/LH_2)	111 - 1×10^6	390 - 470	>.1	LONG LIFETIME STORAGE PROBLEMS
ION (Hg)	.001 - .15	2200 - 6000	?	INCREASED THRUST UP TO .5 N WITH 30 CM POSSIBLE

ION COMPONENT SPECIFIC MASSES

SYSTEM	SOA PERFORMANCE	PROJECTIONS
PPU	FM PPU 13.65 Kg/Kw @ 2.8 kw	5.0 Kg/Kw DIRECT EX. DISCH.
PPU S/A	SEPS 2 MIL 13.0 Kg/Kw @ 25 Kw	5.0 Kg/Kw GaAs
SYSTEM EFFICIENCY	SEPS 70% (CONSERV.)	90% W/PPU, THRUSTER REDESIGN

Figure 79

SOA Capability/Requirements Map



* NOT TREATED IN THIS STUDY

3.2 State-of-the-Art Limitations

The limitations of the state-of-the-art capabilities fall into two general categories - those which constitute mission disabling limitations and those which if eliminated would be mission enhancing. The limitations identified are in the following areas: transfer vehicle delivery thrust, APS I_{sp} impacts on STS delivery payload, minimum firing time, thruster cycling requirements, and thrust level requirements.

Transfer Vehicle Thrust

It was found that the deployed antenna systems were sized for .15 g's. In Task 1 it was also shown that significant penalties in structure mass existed for increased g-loading. Factors of 75% increase were found for 1.0 g's sizing. Figure 26 showed that a 2500-3000 lb_f engine was required for deployed LSS transfer. Current primary thrust engines, such as the RL-10, must operate in a less efficient mode for such low thrusts. A LO_2/LH_2 engine of 3000 lb_f would be mission enabling for LEO deployment and transfer.

STS/OTV Delivery Limitations

Total system masses for three different propulsion systems were calculated in Task 2. The capability of the shuttle/centaur g' to deliver a payload to GEO is 4810 kg. Using this payload as a benchmark the factor of conservatism allowed for the total system was calculated. Table 48 illustrates that a monopropellant APS allows little room for system mass growth. In one case, going to a bipropellant I_{sp} of 300 seconds is mission enabling. Considering the normal rate of growth of preliminary design mass estimates, the flight ready versions of these systems will require 300 second or greater I_{sp}.

Minimum Firing Time

To establish the feasibility and advisability of using jet systems to cancel disturbance torque and provide pointing control we have analyzed limit cycling under the influence of disturbance torques. In previous analysis of momentum devices versus jet systems it was concluded that at LEO many of the configurations had momentum requirements that exceeded the state-of-the-art momentum capability. It will be shown in this section that the propellant requirements for a jet system to point under the large disturbance torques encountered at LEO are in some cases greater than the structure mass itself. We have also shown that stationkeeping propellant at the lower altitudes (300-400 km) is also very great. In short, LEO deployment and operation of LSS may be precluded by the large APS requirements inherent in the LSS size and orbit altitude.

GEO operation is much more benign and lends itself to either momentum management or jet control for pointing. Jet control uses limit cycling to maintain pointing accuracy. Figure 80 shows limit cycling for no disturbance (Method 1) and under the presence of disturbance torques

TABLE 48. STS/OTV DELIVERY LIMITATIONS

- Total system masses compared to centaur G' capability (4810 KG)
- CONS = Fuel Conservatism allowed
- Chemical at 1% duty cycyle, ION at 40% duty cycle

TOTAL SYSTEM MASSES (M_{sys} in kg)

		MONO		BIPROP		ION	
		M_{sys}	CONS(%)	M_{sys}	CONS(%)	M_{sys}	CONS(%)
LAPAA	10KW	1800	100	1650	>100	1350	1000
	65KW	4720	[illegible]	4300	50	353	>100
WRAP RIB	55m	4100	66	3800	>100	3250	>100
HOOP COLUMN	120M	4550	[illegible]	4040	67	3120	>100
GEO PLATFORM		4900	[illegible]	4560	30	3970	>100

(hatched box) Less than 20% conservatism allowed

CONCLUSION

Mono propellant limits mission capture for proposed delivery systems

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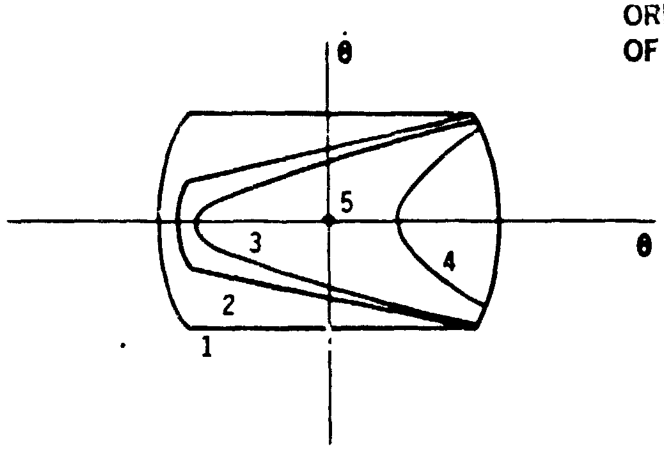


Method 1 - No disturbance torque limit cycling (2 pulses)

Method 2 - Small disturbance torque limit cycle (2 pulses)

Method 3 - Single pulse limit cycling with a critical disturbance torque level (D_c)

Method 4 - Single pulse limit cycling with a disturbance torque higher than D_c

Method 5 - Continuous thrusting against disturbance torques

General Comments:

- Method 3 uses the least propellant of any method.

- Method 3, 4 and 5 have the same average propellant consumption dependancy relation which is a function of disturbance torque, I_{sp}, and moment arm.

- Method 5 has unrealistically low thrust level requirements.

Figure 80. Phase Plane Pointing Method Guide

(Methods 2-5). For a certain combination of disturbance level, impulse bit, moment arm, inertia and point accuracy, method 3 results. This is a single pulse limit cycle which utilizes the disturbance torque to provide the second impulse rather than rely on an opposing jet as in 1 or 2. Method 3 require the lowest amount of propellant of any of those shown. The propellant consumption rates are defined in Table 49.

Propellant consumption is minimized by utilizing the disturbance torque to give you a single pulse limit cycle of the longest duration. This occurs when the disturbance torque is equal to D_C as shown in Figure 81. An example map was calculated for a certain set of LSS sizing and impulse bit as shown in Figure 82.

To minimize propellant consumption one would like to match the thrust requirements imposed at D_C. Before examining these thrust requirements, we have defined the propellant requirements to see if RCS is advisable for pointing control. It was determined that for disturbance torques of 10^{-3} N-M or less, just about any type of propulsion system will have an acceptable mass. For disturbances of 10^{-1} through 10^{-3} one is forced into higher I_{SP} and longer moment arms to compete with momentum management. For torques above 10^{-1} N-M momentum management will be required.

Reexamining Table 17 we can see that the two LMSS designs have disturbance torque levels that preclude the use of jets for pointing for all but very high (~3000 or greater) I_{SP} systems. The two SOC designs examined also require high I_{SP} and long moment arms to compete with momentum management. The other designs, electronic mail, educational TV, geoplatform and SASP, have much lower torques and jet systems of all three I_{SP}'s and can yield a significant mass advantage over momentum management devices.

APS Requirements

Minimum firing times and impulse bits have been calculated for the seven LSS. The results are tabulated in Table 50. Minimum impulse bit requirements are dominated by attitude control limit cycling. It was shown above that minimum propellant consumption for the ACS (attitude control system) is achieved by using a single pulse limit cycling scenario. The equations describing this type of limit cycling are as follows:

1) $$D_c = \frac{I\,\dot{\theta}_d^{\,2}}{4\,\theta_d}$$

2) $$\dot{\theta}_d = \frac{\tau}{2I}\,(Fe - D_c)$$

where D_C = critical disturbance torque

I = moment of inertia

θ_d = desired pointing accuracy

$\dot{\theta}_d$ = vehicle rotation rate

Table 49. Pointing Propellant Usage Guide

Definitions:

$\dot{\omega}$	- average propellant consumption rate
F	- thrust level
τ	- thrust time on
e	- moment arm
θ_d	- pointing accuracy requirement
I	- inertia
I_{sp}	- specific impulse
D	- disturbance torque
D_c	- critical disturbance torque
R	- ratio of D/F_e

Method 1 - no disturbance torque limit cycling (2 pulse)

$$\dot{\omega} = \frac{(F\tau)^2 e}{4\,\theta_d\,I\,I_{sp}} \qquad D = 0$$

Method 2 - small disturbance torque limit cycling (2 pulse)

$$\dot{\omega} = \frac{D}{e\,I_{sp}}\left(\frac{1 + R + (1-R)\sqrt{1-D/D_c}}{1 + R - (1-R)\sqrt{1-D/D_c}}\right) \qquad 0 < D < D_c$$

Method 3, 4 - single pulse disturbance torque limit cycling

$$\dot{\omega} = D/(e\,I_{sp}) \qquad D_c \leq D < F_e$$

Method 5 - continuous thrusting

$$\dot{\omega} = F/I_{sp} \qquad D = F_e$$

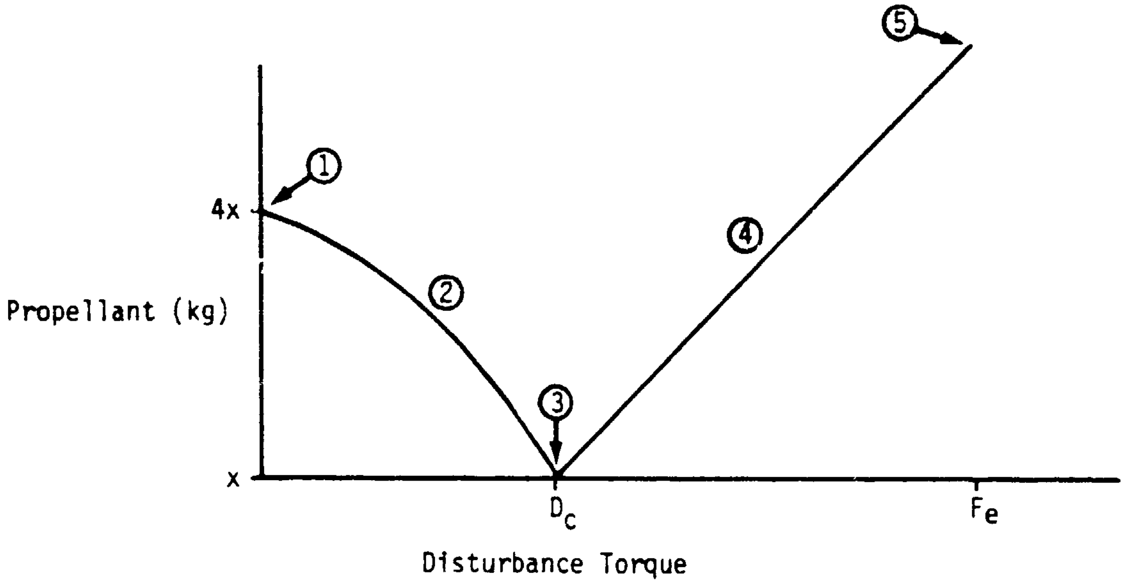


Figure 81. Propellant Map

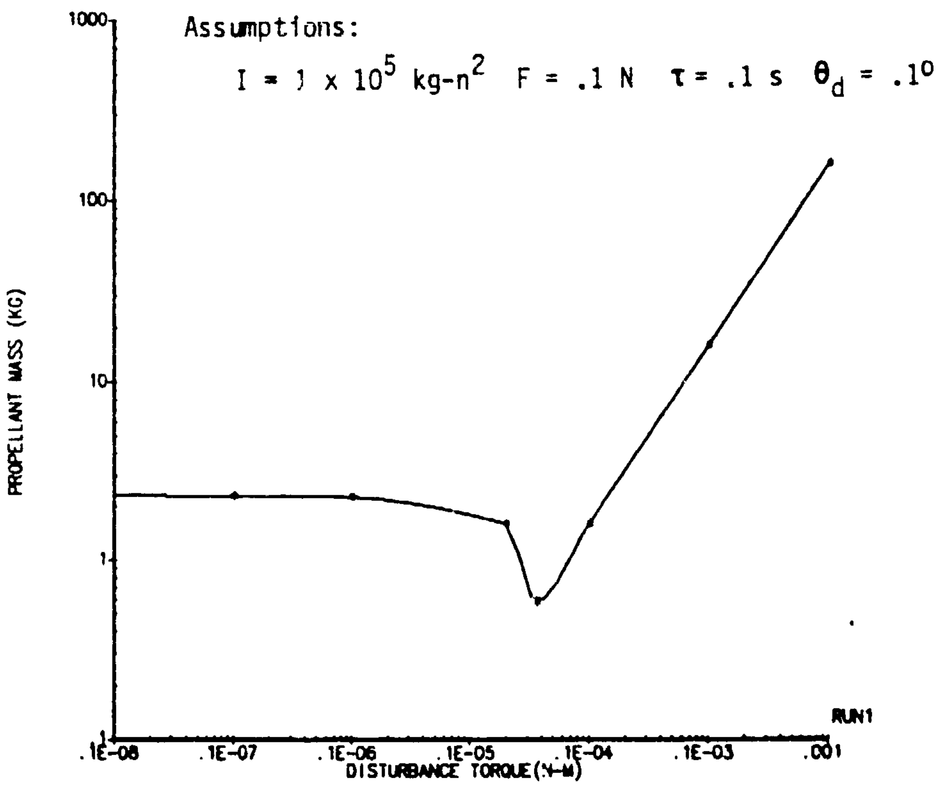


Figure 82. Propellant Map Example

Table 50. Minimum Firing Time/Minimum Bit Assessment

Approach:

- Used thruster locations (i.e., moment arms) identified in Task 2
- Calculated 0,0,0 orientation disturbance torques & forced these to be D_C (critical disturbance)
- Pointing requirements set at $.1^{0}$

Results:

LSS	LEO (.5 HR) MINIMUM FIRING TIME (S)	LEO (.5 HR) MINIMUM IMPULSE BIT (N-S)	GEO (1% DC) MINIMUM FIRING TIME (S)	GEO (1% DC) MINIMUM IMPULSE BIT (N-S)
LAPAA 13 kw ELECTRONIC MAIL	.3186E-4	.4748E-3	.1278E-4	.3060E-4
LAPAA 65 kw EDUCATIONAL TV	.1414E-3	.4949E-2	.4253E-4	.3190E-3
LMSS WRAP RIB	.1527E-1	.6108	.2646E-2	.3214E-1
LMSS HOOP COLUMN	.1062E-4	.1593E-2	.6106E-5	.4518E-4
GEOSTATIONARY PLATFORM	.1976E-2	.6917E-1	.2866E-3	.3253E-2
SOC INITIAL	.2412E-1	.7235E+1	.3447E-2	.4654
SOC OPERATIONAL	.6684E-3	.2842	.9344E-4	.1831E-1

☐ Indicates SOA deficiency

τ = thruster pulse duration

F = thrust level

e = moment arm

The procedure used to solve for the minimum thrust time is to solve equation (1) for $\dot{\theta}_d$ then solve equation (2) for τ. The minimum impulse bit is $F\tau$. The values used in these equations were:

D_c = the nominal disturbance torque calculated for each LSS

I = the x, y, or z inertia for each LSS

θ_d = .1 degree

F = maximum thruster value for each LSS multiplied by a factor of 5

e = sum of x, y, or z moment arms for each LSS

By using the calculated disturbance torques from Task 1, we force the nominal disturbance torque to be the critical disturbance torque for minimum proepllant consumption. A maximum thruster value is used for F, since we must size the system for the maximum thrust. The factor of 5 provides a margin of conservatism.

Table 50 shows that, on the whole, the minimum firing times and impulse bits exceed the state-of-the-art. This implies that either the state-of-the-art must be enhanced in this area, or alternative pointing scenarios are needed. Some of the alternatives include making the moment arms smaller, or using two pulse limit cycling. A detailed examination of each LSS, each mission requirement, and each propulsion option is required to adequately quantify the benefits of these options. The level of detail required for this trade study was felt to be beyond the scope of the current study.

Reliability of Thruster Pulsing

In addition to mass, reliability also has to be considered. The state-of-the-art pulse range life for chemical thrusters lies from 10^5 to 10^6 pulses. The worst case number of pulses for each satellite for different firing times was calculated. These are the equations used to calculate the number of pulses.

Single pulse -

$$\dot{\theta}_d = \frac{F e}{2I}$$

$$T = \frac{\theta_d}{\dot{\theta}_d}$$

$$\text{number of pulses} = \frac{\text{mission time}}{T}$$

Two pulse -

$$\dot{\theta}_d = \frac{F e}{8I}$$

$$T = \frac{\theta_d}{\dot{\theta}_d}$$

$$\text{number of pulses} = \frac{\text{mission time x 2}}{T}$$

where

F - thrust

e - moment arm

τ - firing time

I - inertia

θ_d - pointing accuracy

$\dot{\theta}_d$ - angular rate across the dead band

T - time of single cycle dead band crossing

The results are tabulated in Table 51. For a firing time of .01 seconds, most of the satellites have pulse ranges that push the state-of-the-art. By pushing the state-of-the-art in firing times and lowering τ, all of the pulse ranges will fall into an obtainable range.

Thrust Level Limitations

The limitations of thrust level fall into the category of mission enhancing. This is true with the exception of LEO operation. Chemical propulsion is required to meet the disturbance torque levels and stationkeeping requirements in LEO. The thrust level limitations are summarized in Table 52.

3.3 Enhanced Technology Benefits

Having identified areas of deficiency in pointing control, APS scaling (component and propellant mass) and thrust level, the benefits of enhancing state-of-the-art capability were addressed. Three areas of enhancement are discussed in the following paragraphs. The first deals with pointing control enhancement. This study traded APS mass against momentum management mass for 3-axis pointing control. The focal point in this area was I_{sp} and minimum firing time. The second study addressed APS mass benefits from enhancing electric propulsion technology. System efficiency, PPU and S/A specific mass and thrust level availability were examined. A comparison of EP mass to chemical system mass was then done to show the degree of mass savings for certain improvement ranges in the system parameters. In the third analysis a compilation of state-of-the-art characteristics for both existing and developmental systems (example MPD and pulsed plasma) was mapped against the limits placed on I_{sp} and thrust level by the requirements calculated for the range of configurations examined. The development of systems in the region indicated shows the technology enhancements needed and the benefits in terms of mission captive, minimized structural excitation, and system mass optimization.

3.3.1 Pointing Control Enhancement

Minimum firing times to allow single pulse limit cycling which produces a minimum pointing propellant requirement were identified in Section 3.2. The purpose of the pointing control enhancement exercise was to understand the benefits of reduced firing times in terms of comparison between momentum management mass versus propellant mass for 3-axis control. Specifically, the firing time to allow propellant mass to be reduced to equal the momentum management mass was calculated.

Momentum management systems consits of either reaction wheel or control moment gyros which "absorb" environmentally induced torques by either spinning at higher and higher rates (RW) or by changing the axis of large momentum vector and inducing an HXW torque (CMG's). Both systems will reach a saturation point where they can no longer absorb momentum in a given axis and must be desaturated by some other torquing device. Torques which do not vary in a cyclic fashion will cause saturation and are called

Table 51. Pointing Control Benefits from Increased Thruster Pulse Number

- 10 year mission
- 3 axis jet control
- Chemical SOA capability 1×10^6 pulses demonstrated
- GEO operation

TOTAL VALUE CYCLES REQUIRED

CLASS	Firing Time (s) .001	.006	.01	.04
Electronic Mail	5.15E+5	3.09E+6	5.15E+6	2.06E+7
Educational TV	2.34E+5	1.40E+6	2.34E+6	4.67E+6
LMSS Wrap Rib	5.18E+5	3.11E+6	5.18E+6	1.04E+7
LMSS Hoop Column	6.27E+4	3.76E+5	6.27E+5	2.51E+6
Geostationary Platform	1.68E+5	1.01E+6	8.38E+5	3.35E+6
SOC Initial	1.33E+5	7.95E+5	1.33E+6	2.65E+6
SOC Operational	6.22E+4	3.73E+5	6.22E+5	2.49E+6

☐ INDICATES CHEMICAL SOA DEFICIENCY

- Mission capture at .01 s firing time 3/7 for 1×10^6 pulses
- Mission capture at .01 s firing time 5/7 for 5×10^6 pulses
- 2×10^7 pulses captures all missions over desired firing time range

Table 52. Thrust Level Limitations

- Mono
  - Range available covers all requirements
- Bipropellant
  - Minimum available thrust exceeds maximum requirement for 15 minute duty cycle
  - Minimum available thrust causes defocusing for flexible antenna systems
- Ion
  - LEO thrust requirements cannot be met for reasonable duty cycles
  - GEO thrust requirements can be met for long duty cycles (2 - 5 hrs)

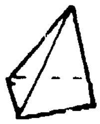
secular torques. Torques which reverse sign every 1/2 orbit can be handled quite nicely by MMD's providing they are sized to handle the momentum buildup in half an orbit. The cyclic and secular components of torque for our vehicles are shown in the following table.

Table 53. Nature of Disturbance Torques - Earth Oriented Vehicles

Disturbance Torques	Roll	Pitch	Yaw
Gravity Gradient	Cyclic	Secular	Cyclic
Aerodynamic	Cyclic	Secular	Cyclic
Solar Pressure	Cyclic	Cyclic	Cyclic
Magnetic	Cyclic	Cyclic	Cyclic

The assumptions used to size momentum management systems are listed below:

- Momentum Wheels Used (Small Torques)
- 4 Wheels Needed for Single Point Failure



- Sized for Worst Momentum Axis
- Cyclic Torques Behave As:

  $$T_{max} \int_0^{\pi} \sin wt \, dt$$

  Where Tmax is Maximum Nominal Disturbance
- Scaling Equations are Based on Actual Hardware Data

The MMD system being considered is a momentum wheel system which needs to be sized to the maximum angular momentum needed. Equations relating mass to angular momentum were developed based ondata from Sperry Flight Systems as shown in Figures 83 and 84.

For the momentum wheels,

$$Mass_{MW} = -2.8582 \times 10^{-6} H^2 + 3.5102 \times 10^{-2} H + 10.358$$

For the supporting electrical system,

$$Mass_{ES} = 2.4476 \times 10^{-3} H + 2.6631$$

$$MMD\ Mass = Mass_{MW} + Mass_{ES}$$

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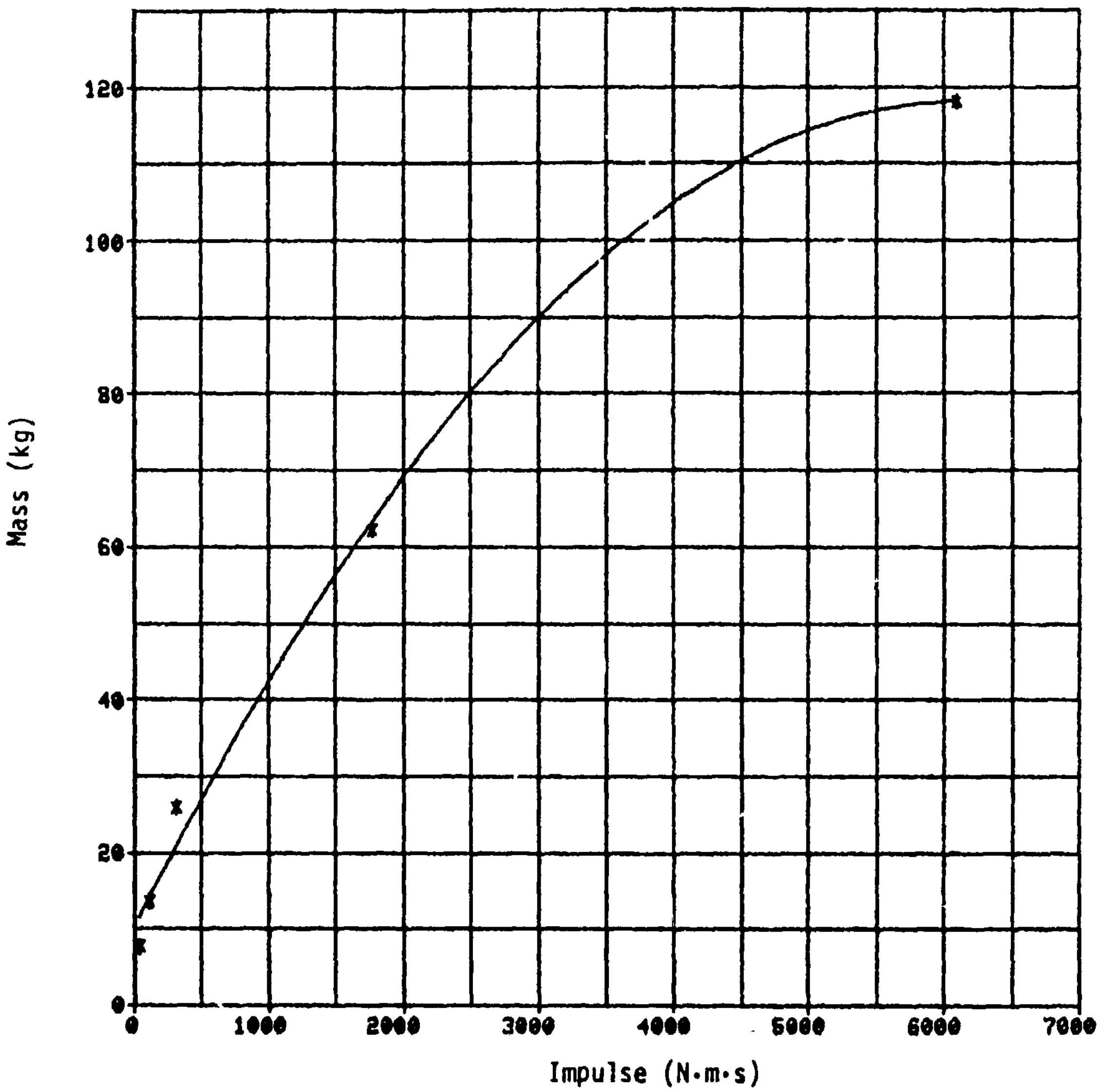

$-2.8582E-6\ x^2 + 3.5102E-2 + 1.0358E+1$

Figure 83. Momentum Wheel Mass vs Impulse

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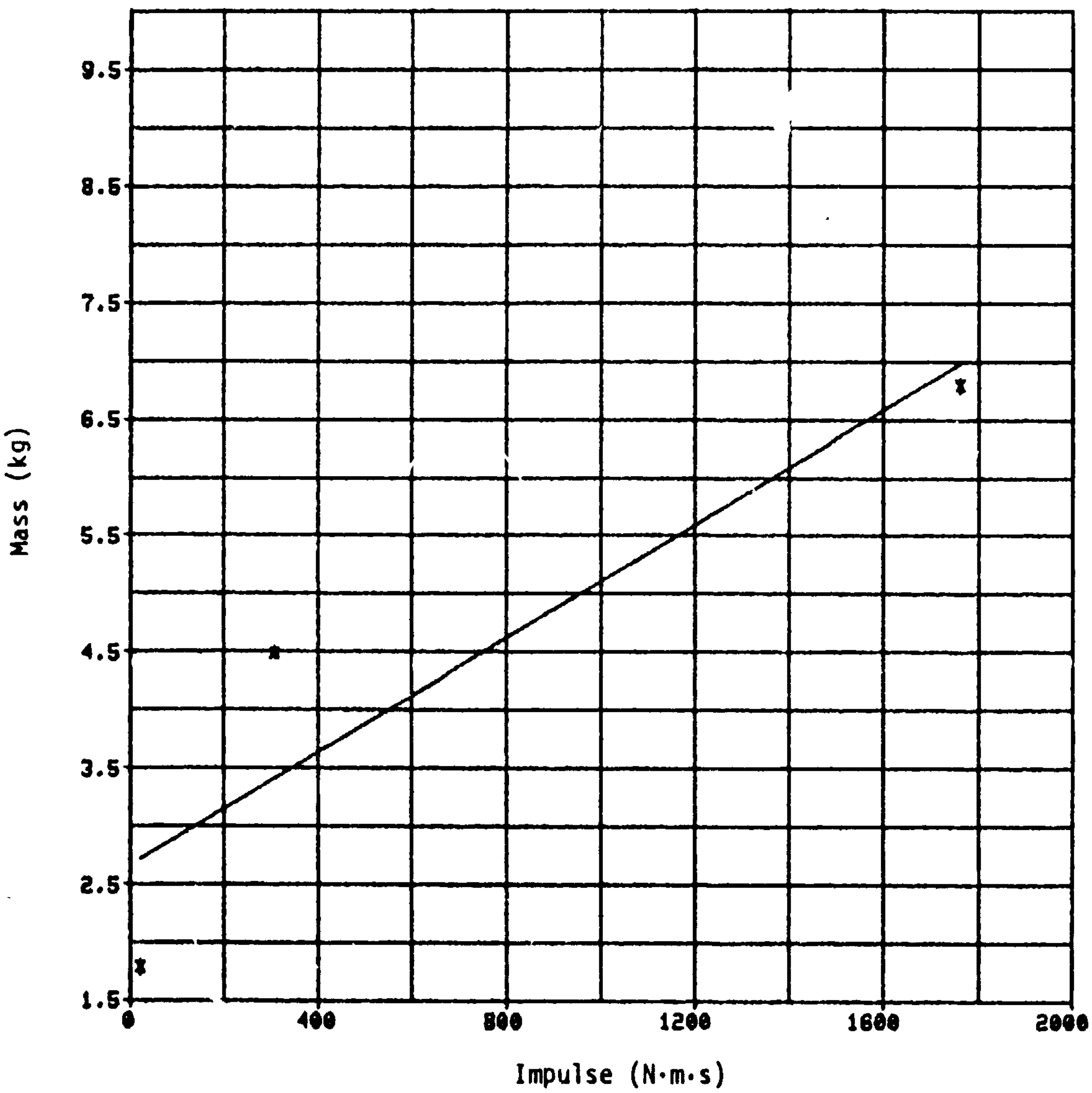

2.4476E-3 X + 2.6631

Figure 84. MMD Electrical System Mass vs Impulse

where H = angular momentum (N·m·s)

The torques are cyclic, therefore

$$H = \frac{2T_{max}}{\omega} = \frac{T_{max}\tau}{\pi} \qquad \text{where} \quad = \frac{2\pi}{\tau}$$

for GEO τ = 86,400

so $H = 2.75 \times 10^4 \; T_{max}$

MMD mass was calculated for each satellite for one and four wheels. The results are in Table 54. The total MMD system mass is the sum of the momentum wheel mass, the supporting electrical system mass, and the secular pitch torque propellant mass for a 10 year mission. The difference in mass of the MMD system with the secular pitch torque propellant at I_{sp} = 220 and the mass at I_{sp} = 3000 is approximately 3% of the MMD mass and can be considered negligible. Therefore the MMD system mass is portrayed as unvarying with I_{sp}.

Figures 85 through 91 are graphs displaying both the APS propellant mass and the total MMD system mass. The trade off in mass between the two systems is clearly marked by the line representing the MMD system mass. The points where the lines intersect represent critical firing times and are tabulated in Table 55. At these points, the MMD system mass equals the APS propellant mass. For smaller firing times than the critical firing times (or at any point to the left of the MMD system mass line on the graph), the APS propellant mass is less than the MMD system mass.

3.3.2 Benefits from Enhanced Electric Propulsion Technology

The goal of this exercise was to identify the high leverage technology enhancements for ion electric propulsion in terms of total system mass and thrust level. The approach used for this analysis is described below:

- Utilize developed software - scaling, N/S Geo stationk[illegible] (4 thrusters used)
- Take EP scaling equations and vary:
    - Initial satellite mass 500 kg - 100,000 kg
    - EP system 70-90%
    - PPU and S/A specific mass (kg/kw) 13.5 - 5 kg/kw
    - Thrust level available .01 - 5 N
- Find GEO stationkeeping system mass for given assumptions
- Compare EP mass to chemical mass (220, 300, 500 sec)

Table 54. Mass for Momentum Management Devices

LSS	Maximum Required Impulse (N·m·s)	MMD Mass (kg)	
		Single Wheel	4 Wheels
Electronic Mail	103.13	16.863	67.453
Educational TV	219.41	21.122	84.489
LMSS Wrap Rib	1242.5	55.265	221.06
LMSS Hoop Column	929.29	45.447	181.79
Geostationary Platform	46.011	14.743	58.971
SOC Initial	5137.4	130.49	521.97
SOC Operational	1117.4	51.411	205.64

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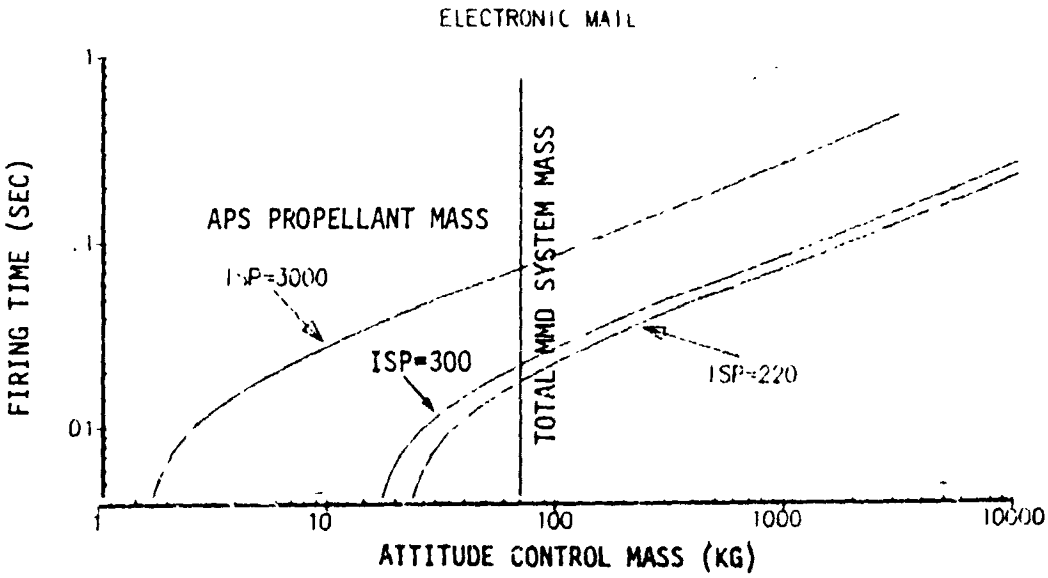

Figure 85. APS vs Momentum Management

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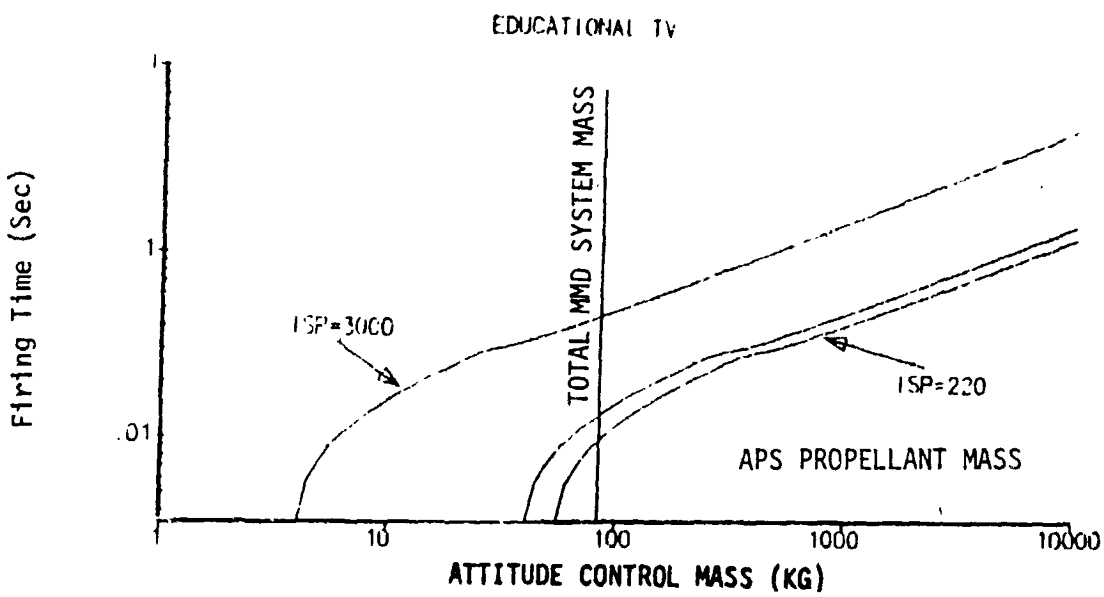

Figure 86. APS vs Momentum Management

C-3

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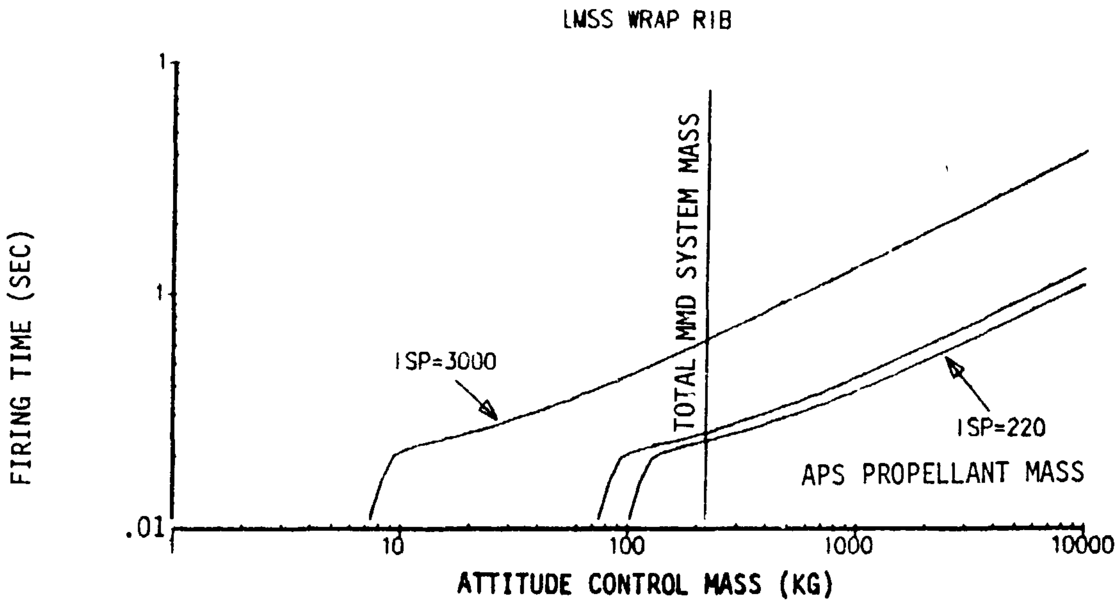

Figure 87. APS vs Momentum Management

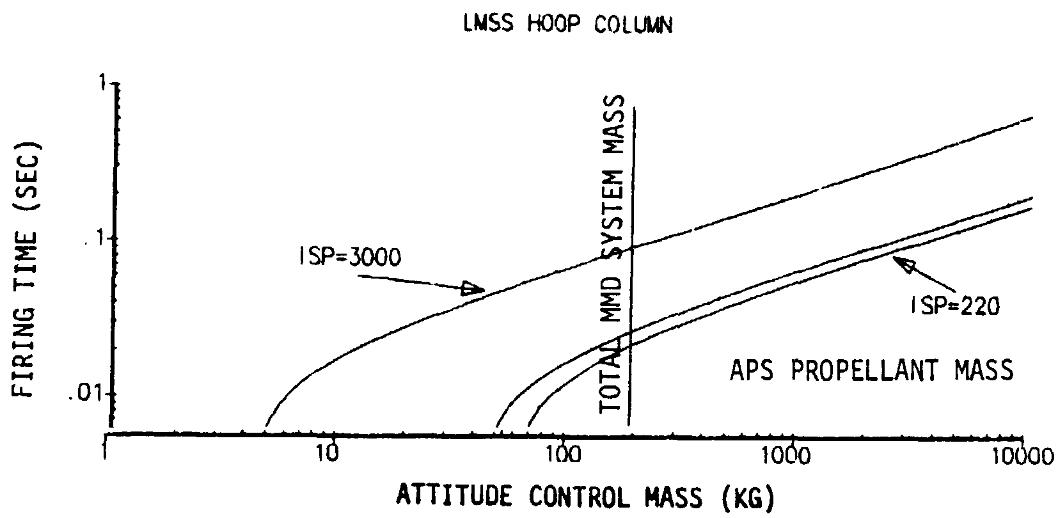

Figure 88. APS vs Momentum Management

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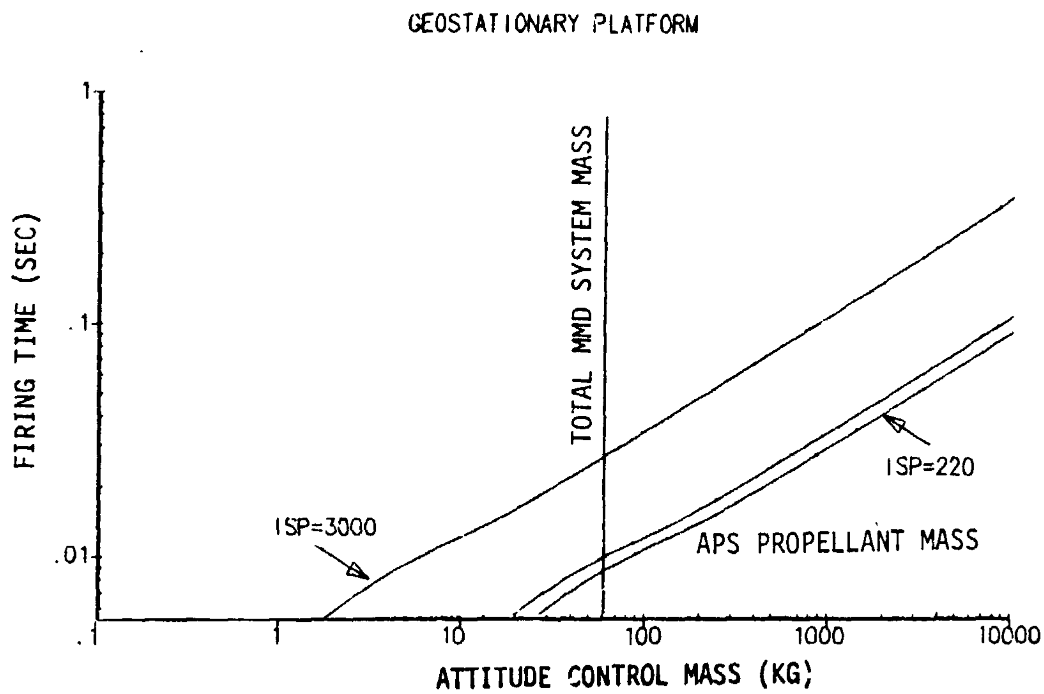

Figure 89. APS vs Momentum Management

SOC INITIAL

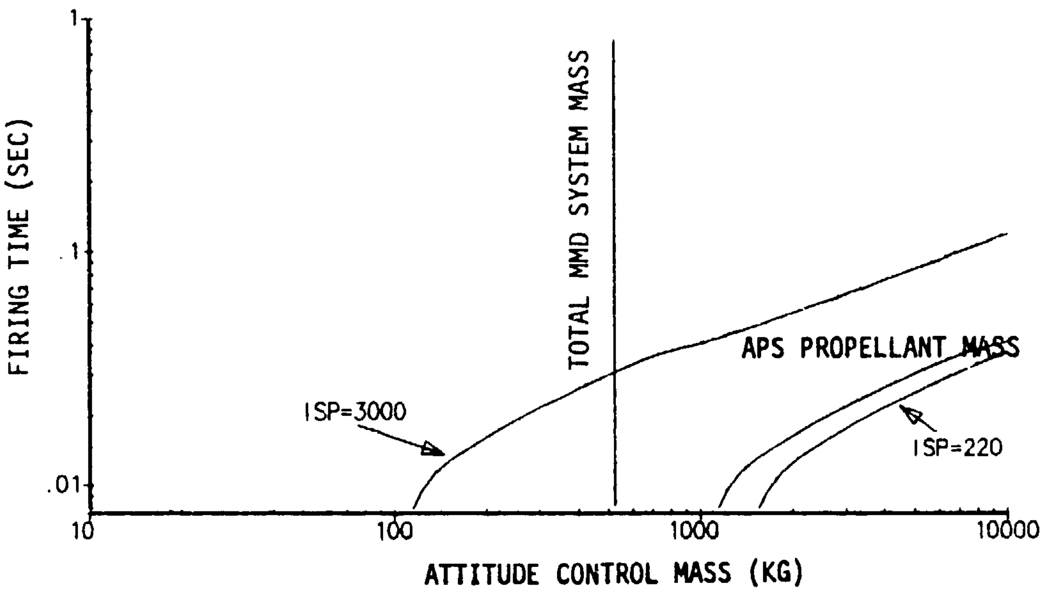

Figure 90. APS vs Momentum Management

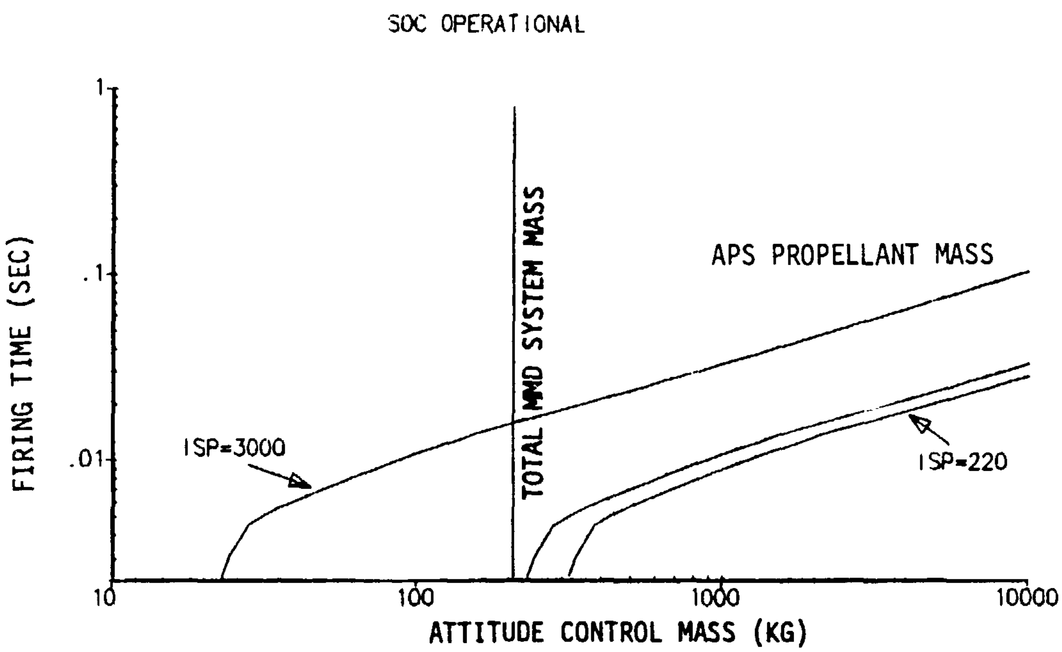

Figure 91. APS vs Momentum Management

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Table 55. Critical Firing Times for APS Mass to Equal MMD Mass

LSS	Total MMD System Mass (Kg)	Critical Firing Time (s)		
		I_{sp}=220	I_{sp}=300	I_{sp}=3000
Electronic Mail	67.6	.018	.024	.078
Educational TV	84.6	.012	.016	.050
LMSS Wrap Rib	221.5	.023	.027	.070
LMSS Hoop Column	182.5	.022	.028	.098
Geostationary Platform	59.1	.009	.010	.028
Soc Initial	522.6	- [1]	- [1]	.030
Soc Operational	205.9	.0001	.0015	.016

[1] MMD system mass is always less than APS propellant mass for SOC Initial when $I_{sp} \leq 300$

The results of the unenhanced state-of-the-art propulsion comparison is shown in Figure 92. Three points (A, B, and C) have been identified which will aid in the understanding of this figure. At point A, a .1 N (thrust/thruster) ion thruster system provides a net advantage over bipropellants for structure mass > 1000 kg. At point B a .05 N ion system has a net advantage over all chemical systems for structure mass > 1000 kg. At point C, a factor of 2 mass advantage is seen for state-of-the-art ion thrusters for a 2500 kg structure with a thrust/thruster of around .03 N. It is also seen that as thrust/thruster requirements approach .5 N all chemical systems have a mass advantage over electric ion systems. The operational scenario of stationkeeping thrusting is, therefore, closely tied to mass advantage. If short duty cycles are desired (< 1 hour/orbit), relatively high ion thrust levels are required as shown in Table 56.

Table 56. One Hour Duty Cycle Requirements

	Thrust/Thruster
LAPAA 10 kw	.05
65 kw	.23
Wrap Rib 55 m	.38
Hoop Column 120 m	.43
Geoplatform	.36

The conclusion of the state-of-the-art examination is that if short duty cycles are desired, technology advances to increase thrust density for only small increases in ion system mass are required.

Figure 93 shows the approximate regions of the state-of-the-art capability in chemical and electric systems. The systems in development, resistojets and stored inert gasses, were not considered in the APS scaling exercise. Overlaid on the capabilities map is the recommended thrust and I_{sp} regime for the classes studied. Due to the uncertainties inherent in the forecasts based on preliminary design, a large region of crosshatching extends the recommended region. A fundamental lower limit in I_{sp} for a 10 year mission results from STS-Centaur G' mass delivery limitations for most of the classes analyzed. An upper limit in I_{sp} is shown which indicates power system mass (including the power source and processing hardware) becomes dominant over propellant mass for ion systems. This limit varies with thrust level requirements and longer duty cycles of 2-5 hours/orbit would raise this limit. In addition, lower PPU specific mass would increase the I_{sp} limit to include existing ion thrusters.

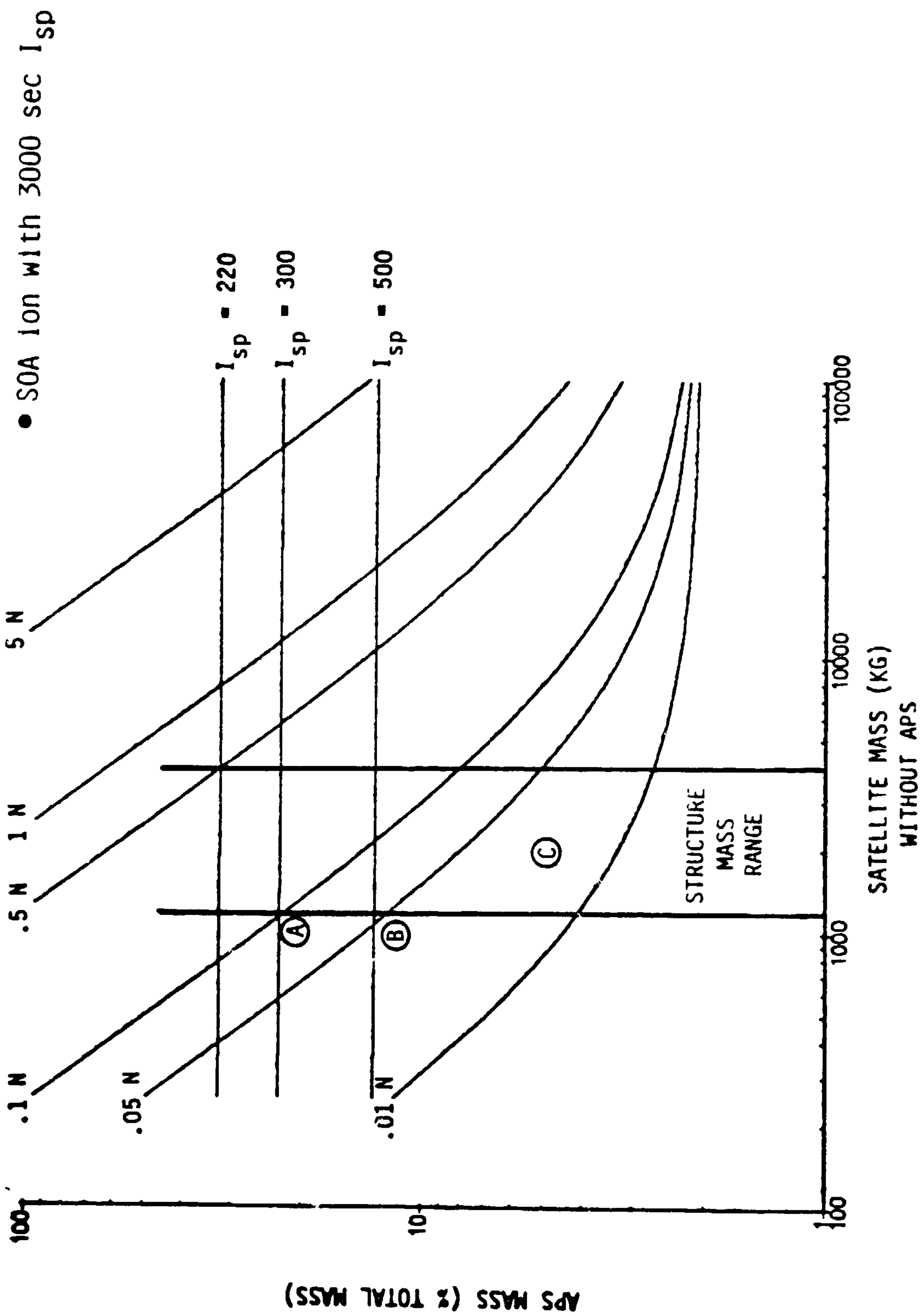

Figure 92. Propulsion Evaluation

SOA Capability/Requirements Map

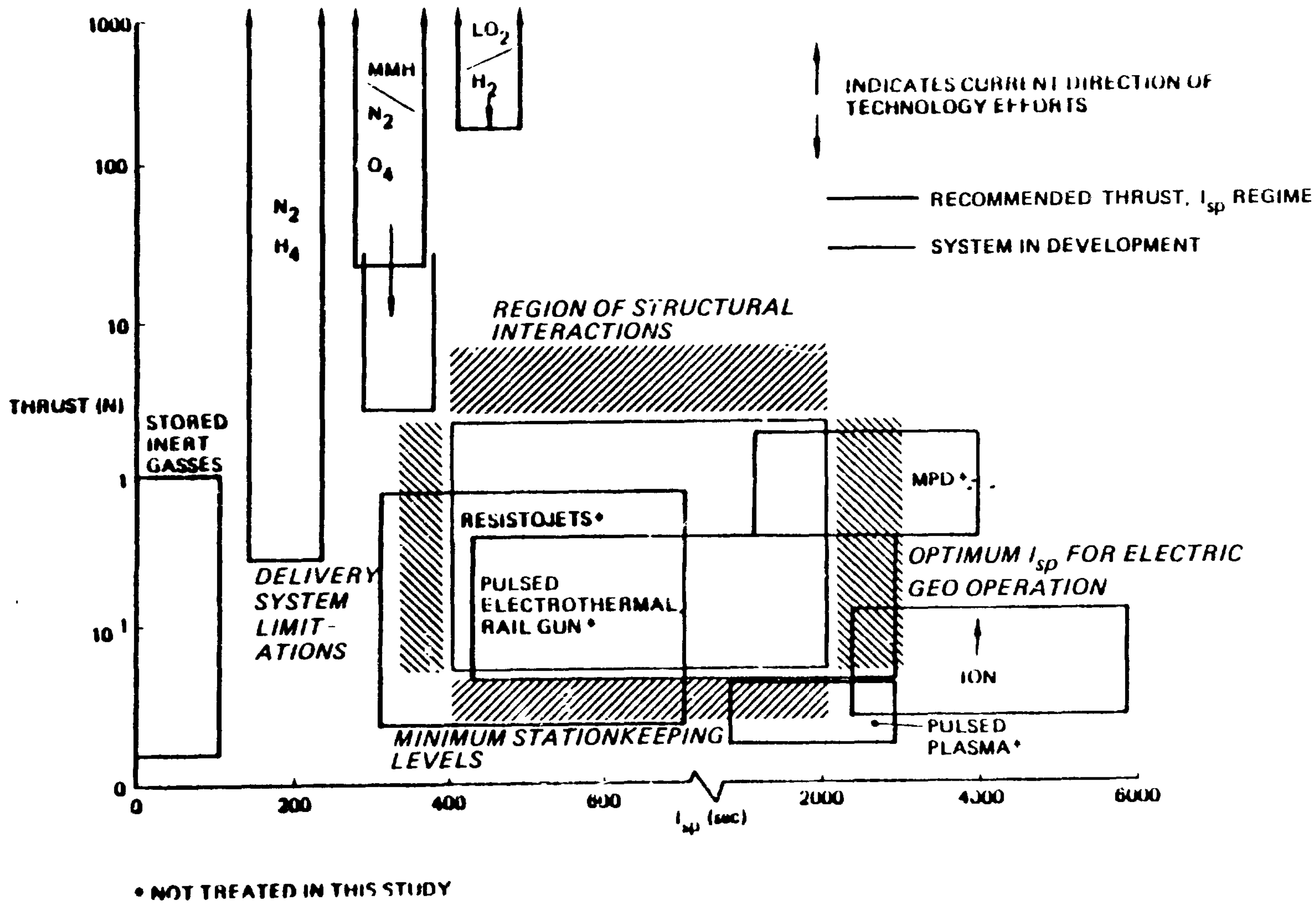

Figure 93. SOA Capability/Requirements Map

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Thrust level limitations vary greatly with LSS class and duty cycle. The lower limit range shown is for N/S stationkeeping with a long 9 hour/orbit duty cycle. Only the pulsed plasme class violates this range of limitations. Thruster lifetime limits for ion thrusters are also violated at these long duty cycles. For ion thrusters this limit is reached for a 10 year mission at duty cycles of only 5 hours/orbit. The region of structural interactions limits thrust/thruster to less than 10 N. This limit only applies to the large flexible antennas which must operate during a stationkeeping maneuver.

In conclusion, Figure 93 shows that propulsion systems such as augmented N_2H_4 and other forms of resistojets, low thrust bipropellants, and possibly low I_{sp} ion systems are in line with LSS requirements.

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APPENDIX A

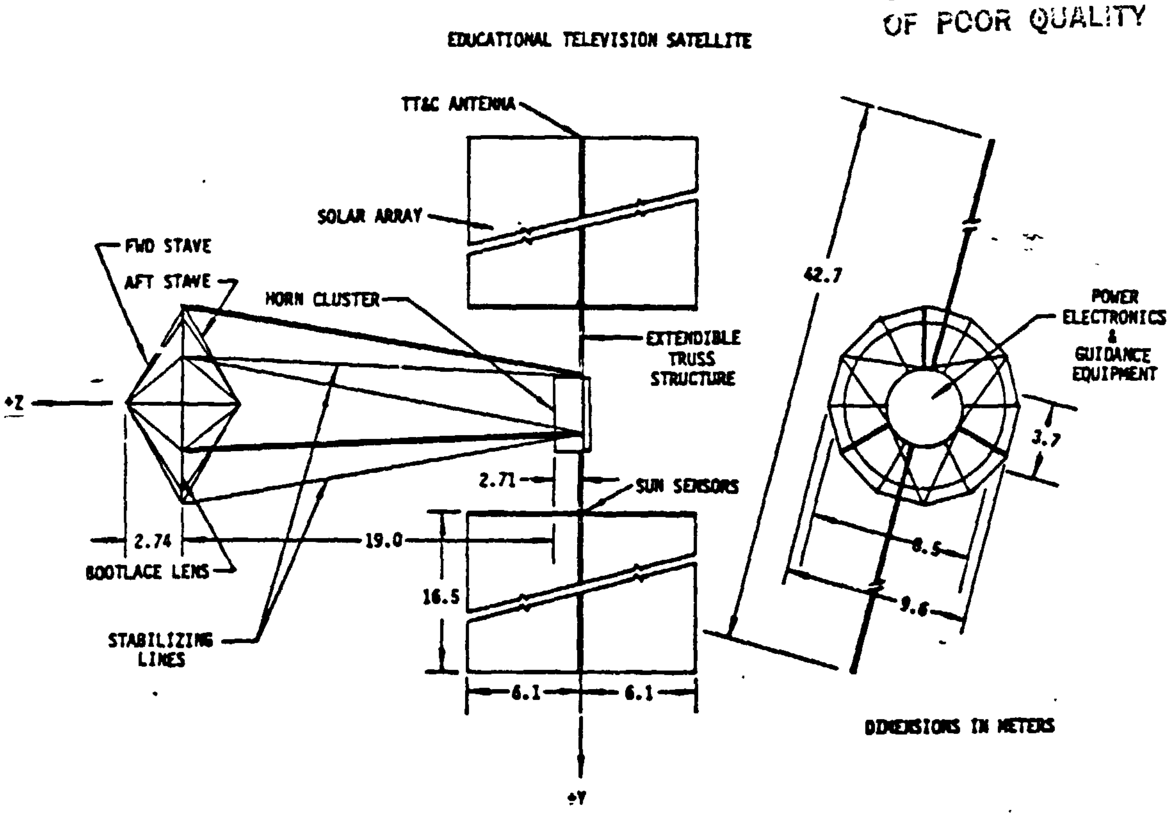
LSS Characterization

GENERIC CLASS	*NO.*
Large Aperature Phased Array Antenna	I. Page 1 of 5

OBJECTIVES

This satellite is to provide useful and needed services which are marketable. An attractive feature of a larger, more complex, heavier, and therefore more costly satellite is its complexity inversion phenomenon, which is the satellite's ability to service larger numbers of users with smaller and less expensive user equipment and to deliver lower priced services to thousands of users. Applications include personal, educational, or emergency communications and optical, i.e., optical heat detection systems for forest fires.

CONFIGURATION DRAWING



CONFIGURATION DESCRIPTION

The antenna is a series of three thin films which are stretched within compression beams and form a ground plane, input plane, and output plane for a bootlace lens. The lens is contained within a compression structure supported from a deployable mast with guy wires. This is supported to the feed horn cluster by space-extendable beams to form an antenna with its length approximately twice its diameter. The solar arrays form two paddles to be one-axis gimballed and sun oriented. They are sized for 65 kW in LEO, while the distribution, conditioning, and batteries sized for 50 kW at GEO. The lens portion will be closest to earth.

GENERIC CLASS:	Large Aperature Phased Array Antenna - Electronic Mail -

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 6000 km Polar Orbit GEO (35,871 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	1181.58	0	0	4.824
.15	1291.51	0	0	5.947
1.0	2866.57	0	0	11.297

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	94,157	86,776	15,334	0	0	0
.15	119,513	111,914	16,727	0	0	0
1.0	338,275	328,354	33,645	0	0	0

C_p (ORIGIN AT C_G, METERS)

	PLANE: XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
.06	0	0	5.366	0	0	4.286	0	0	-2.958
.15	0	0	4.243	0	0	3.164	0	0	-4.081
1.0	0	0	-1.107	0	0	-2.187	0	0	-9.432

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
.06	154.2	21.070	102.870	0.130503	0.017832	0.087061
.15	154.2	21.070	102.870	0.119395	0.016314	0.079651
1.0	154.2	21.070	102.870	0.053793	0.007350	0.035886

GENERIC CLASS: Large Aperature Phased Array Antenna - Educational TV -

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 6000 km Polar Orbit GEO (35,871 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	3212.15	0	0	2.134
.15	3336.07	0	0	2.649
1.0	5048.24	0	0	6.659

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	218,339	107,557	116,554	0	0	0
.15	256,458	142,335	120,947	0	0	0
1.0	628,081	481,999	166,294	0	0	0

C_p (ORIGIN AT C_G, METERS)

g-LOAD	PLANE: XY X	Y	Z	XZ X	Y	Z	YZ X	Y	Z
.06	0	0	8.056	0	0	7.987	0	0	-1.588
.15	0	0	7.541	0	0	7.472	0	0	-2.103
1.0	0	0	3.531	0	0	3.462	0	0	-6.113

g-LOAD	AREA (m^2) XY	XZ	YZ	AREA/MASS XY	XZ	YZ
.06	474.0	22.91	424.51	.147565	0.007132	.132158
.15	474.0	22.91	424.51	.142083	0.006867	.127249
1.0	474.0	22.91	424.51	.093894	0.004538	0.084091

SCALING LAWS Electronic Mail

Effect of g-Load on Mass $M_o = 1291.6$ kg $g_o = .15$ g

Bus and Feed: $\frac{M_{Bus}}{M_o} = 0.613$

Antenna Lens: $\frac{M_{Lens}}{M_o} = 0.0735\ (\frac{g}{g_o} + 1.0)$

Lens Staves: $\frac{M_{Staves}}{M_o} = 0.002\ \frac{g}{g_o}$

Solar Arrays: $\frac{M_{SA}}{M_o} = 0.093 + 0.0049\ \frac{g}{g_o}$

Mast: $\frac{M_{Mast}}{M_o} = 0.002\ \frac{g}{g_o} + 0.006$

Lens Rim: $\frac{M_{Rim}}{M_o} = 0.0238 + 0.00083\ \frac{g}{g_o} + 0.00074\ (\frac{g}{g_o})^2 + 0.0165\ (\frac{g}{g_o})^{2/3}$

Lens Support Struts: $\frac{M_{Strut}}{M_o} = 0.0447 + 0.0230\frac{g}{g_o} + 0.0102(\frac{g}{g_o})^2 + 0.00009(\frac{g}{g_o})^3 + 0.002(\frac{g}{g_o})^{5/3}$

SCALING LAWS Educational TV

Effect of g-Load on Mass $M_o = 3337$ $g_o = .15\ g$

Bus and Feed: $\frac{M_{Bus}}{M_o} = 0.714$

Antenna Lens: $\frac{M_{Lens}}{M_o} = 0.0304\ (\frac{g}{g_o} + 1.0)$

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Lens Staves: $\frac{M_{Staves}}{M_o} = 0.0009\ \frac{g}{g_o}$

Solar Arrays: $\frac{M_{SA}}{M_o} = 0.1652 + 0.0087\ \frac{g}{g_o}$

Mast: $\frac{M_{Mast}}{M_o} = 0.0022 + 0.00071\ \frac{g}{g_o}$

Lens Rim: $\frac{M_{Rim}}{M_o} = 0.0092 + 0.00032\ \frac{g}{g_o} + 0.00028\ (\frac{g}{g_o})^2 + 0.0064\ (\frac{g}{g_o})^{2/3}$

Lens Support Struts: $\frac{M_{Strut}}{M_o} = 0.0173 + 0.0089\frac{g}{g_o} + 0.0040(\frac{g}{g_o})^2 + 0.000035(\frac{g}{g_o})^3 + 0.00078(\frac{g}{g_o})^{5/3}$

REFERENCES

"Preliminary Definition and Evaluation of Advanced Space Concepts," The Aerospace Corp., Aerospace Report No. ATR-78(7674)-1, Vol. II, 30 June 1978, prepared for NASA/OSTS.

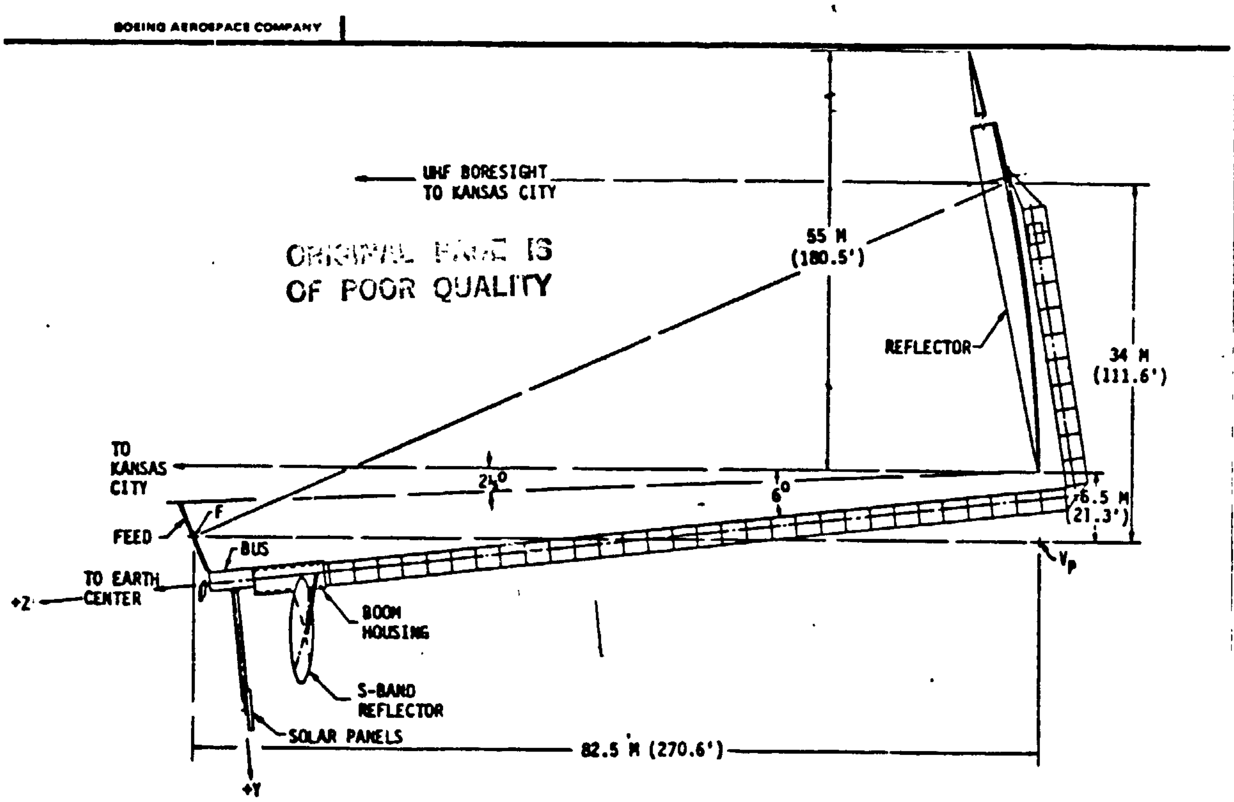
GENERIC CLASS	*NO.*
Land Mobile Satellite System (LMSS) -- Wrap Rib	II. Page 1 of 5

OBJECTIVES

The LMSS is capable of relaying radio messages to land mobile units throughout the Continental United States. It is intended to service units such as ambulances, police cars, taxies -- in essence all radio dispatched vehicles. Its position in geosynchronous orbit avoids present radio interferences caused by tall buildings, hills, and other factors. By using a sophisticated relay satellite in space, the mobile ground stations can remain small, light, and relatively inexpensive and still provide high quality communications.

CONFIGURATION DRAWING

LMSS WRAP RIB SPACECRAFT



CONFIGURATION DESCRIPTION

Looking at the 55 meter offset wrap rib concept, the long boom points at the earth's center. The shorter, vertical boom at the right points up to the north supporting the antenna reflector. The large panel at the left is the ultra-high-frequency feed. It and the 55 meter diameter wire mesh reflector are angled to point at the center of the United States near Kansas City. Multiple beams emanating from the feed panel are arranged to cover all contigous 48 states, Alaska, Hawaii and parts of Canada. The solar arrays are sized for 10 kW.

GENERIC CLASS: Land Mobile Satellite System (LMSS)
- Wrap Rib, 25 meter diameter -

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 5600 km Polar Orbit GEO (36,000 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Attitude Control ± 0.10°
Pointing Stability ± 0.03°

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	1970.46	-0.119	-2.184	-2.008
.15	2041.61	-0.115	-2.303	-2.094
1.0	2713.53	-0.086	-3.123	-2.679

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	251,546	222,341	38,661	1030	-4.0	-33,792
.15	274,274	242,180	42,957	1058	16	-39,383
1.0	485,720	428,454	81,447	1250	153	-90,676

C_p (ORIGIN AT C_G, METERS)

PLANE:	XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
.06	0.0627	-3.60	-13.14	-0.093	-1.872	-12.920	0.0276	-9.566	-29.232
.15	0.0587	-3.481	-13.054	-0.097	-1.753	-12.835	0.0236	-9.446	-29.146
1.0	0.0297	-2.661	-12.469	-0.126	-0.933	-12.249	-0.005	-8.627	-28.561

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
.06	135.352	103.385	49.914	0.068691	0.052467	0.025331
.15	135.352	103.385	49.914	0.066297	0.050639	0.024448
1.0	135.352	103.385	49.914	0.049880	0.038010	0.018395

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 5600 km Polar Orbit GEO (36,000 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Attitude Control ± 0.10°
Pointing Stability ± 0.03°

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	2897.06	-0.208	-3.823	-11.029
.15	3036.41	-0.198	-4.318	-12.001
1.0	4352.52	-0.138	-7.432	-18.109

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	2,437,290	2,223,871	275,508	4961	4032	-559,971
.15	2,781,766	2,523,995	345,003	5259	4617	-[illegible]58,662
1.0	5,798,378	5,170,587	952,443	7133	8293	-1,599,345

C_p (ORIGIN AT C_G, METERS)

g-LOAD	PLANE: XY X	Y	Z	XZ X	Y	Z	YZ X	Y	Z
.06	0.097	-6.380	-20.278	-0.216	-3.798	-19.263	0.0267	-19.680	-51.452
.15	0.087	-5.885	-19.306	-0.226	-3.303	-18.292	0.0167	-19.185	-50.481
1.0	0.027	-2.771	-13.198	-0.285	-0.189	-12.184	-0.0433	-16.071	-44.373

g-LOAD	AREA (m^2) XY	XZ	YZ	AREA/MASS XY	XZ	YZ
.06	270.703	206.770	99.825	0.093441	0.071372	0.034457
.15	270.703	206.770	99.825	0.089152	0.089152	0.032876
1.0	270.703	206.770	99.825	0.062195	0.047506	0.022935

SCALING LAWS 25 Meter Diameter

Effect of g-Load on Mass $M_o = 2041$ kg $g_o = .15$ g

Bus, etc.: $\frac{M_{Bus}}{M_o} = 0.439$

Hub, etc.: $\frac{M_{Hub}}{M_o} = 0.0436$

Feed and Support: $\frac{M_{Feed}}{M_o} = 0.386 + 0.043 \frac{g}{g_o}$

Ribs and Reflector: $\frac{M_{Refl}}{M_o} = 0.0103 \frac{g}{g_o}$

Solar Arrays: $\frac{M_{SA}}{M_o} = 0.0432 + 0.0048 \frac{g}{g_o}$

Booms: $\frac{M_{Boom}}{M_o} = 0.0304$, for $0 \leq \frac{g}{g_o} \leq 3.6$

$$\frac{M_{Boom}}{M_o} = \frac{0.0152 + 0.0112 \left(\frac{g}{g_o} - 2.6\right) + 0.00264 \left(\frac{g}{g_o} - 2.6\right)^2}{1 - 0.0431 \left(\frac{g}{g_o} - 2.6\right)} ,$$

for $\frac{g}{g_o} > 3.6$

SCALING LAWS 55 Meter Diameter

Effect of g-Load on Mass $M_o = 3040$ kg $g_o = .15$ g

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Bus, etc.: $\frac{M_{Bus}}{M_o} = 0.393$

Hub, etc.: $\frac{M_{Hub}}{M_o} = 0.09$

Feed and Support: $\frac{M_{Feed}}{M_o} = 0.345 + 0.038 \frac{g}{g_o}$

Ribs and Reflector: $\frac{M_{Refl}}{M_o} = 0.0329 \frac{g}{g_o}$

Solar Arrays: $\frac{M_{SA}}{M_o} = 0.049 + 0.0055 \frac{g}{g_o}$

Booms: $\frac{M_{Boom}}{M_o} = 0.045$, for $0 \leq \frac{g}{g_o} \leq 2.5$

$$\frac{M_{Boom}}{M_o} = \frac{0.0225 + 0.0160 \left(\frac{g}{g_o} - 1.5\right) + 0.0056 \left(\frac{g}{g_o} - 1.5\right)^2}{1 - 0.025 \left(\frac{g}{g_o} - 1.5\right)},$$

for $\frac{g}{g_o} > 2.5$

REFERENCES

"Configuration Development of the Land Mobile Satellite System (LMSS) Spacecraft," Third Annual Technical Review, Boeing Aerospace Co., Nov. 16-19, 1981, presented to JPL LSST Antenna Organization.

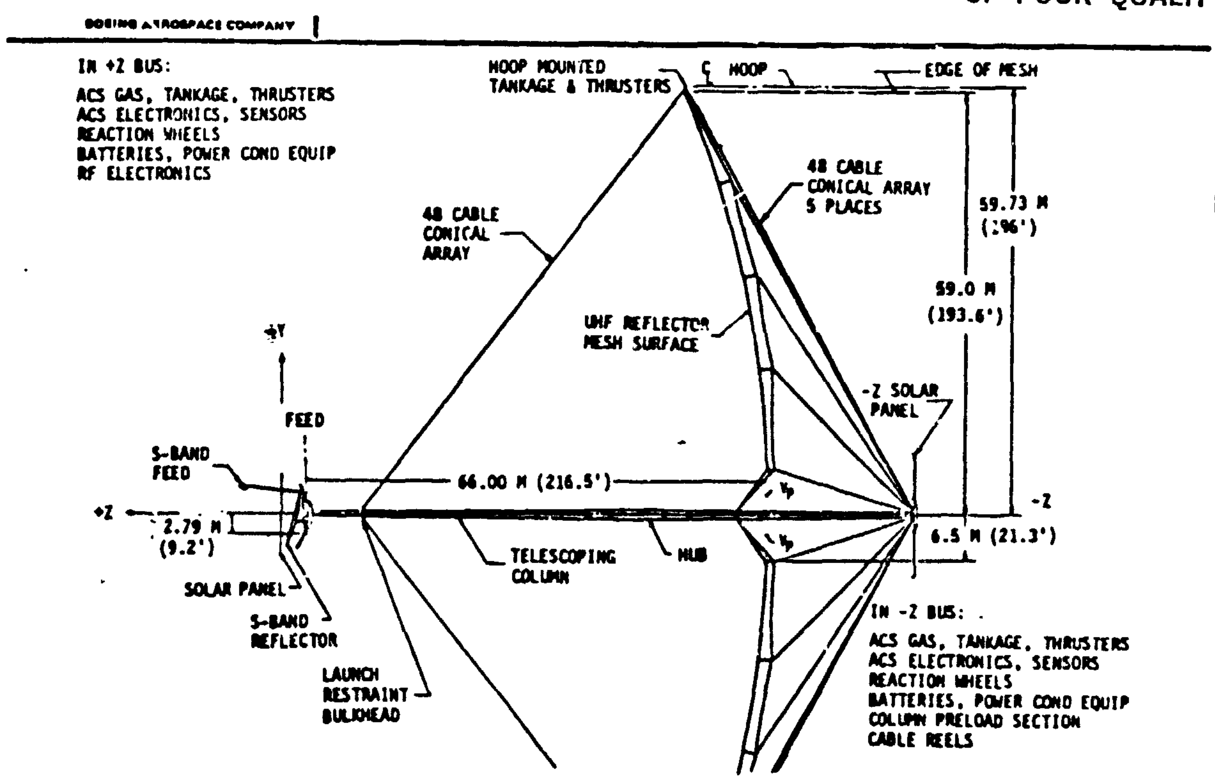
GENERIC CLASS	NO.
Land Mobile Satellite System (LMSS) -- Hoop Column	III. Page 1 of 5

OBJECTIVES

The LMSS is capable of relaying radio messages to land mobile units throughout the Continental United States. It is intended to service units such as ambulances, police cars, taxies -- in essence all radio dispatched vehicles. Its position in geosynchronous orbit avoids present radio interferences caused by tall buildings, hills, and other factors. By using a sophisticated relay satellite in space, the mobile ground stations can remain small, light, and relatively inexpensive and still provide high quality communications.

CONFIGURATION DRAWING

LMSS HOOP COLUMN SPACECRAFT



CONFIGURATION DESCRIPTION

The 120 meter hoop column concept features independent power units one at either end. The central column points at the center of the United States near Kansas City. Each of the four feed panels at the upper left project a multiple beam pattern onto its assigned quadrant on the large, molybdenum-mesh reflector. There are uplink and downlink feeds for both the eastern and western halves of the country. The radio beams are arranged to cover all contigous 48 states, Alaska, Hawaii, and parts of Canada.

GENERIC CLASS: Land Mobile Satellite System (LMSS) - Hoop Column, 60 meters -

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 5600 km Polar Orbit GEO (36,000 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Attitude Control $\pm 0.10^0$
Pointing Stability $\pm 0.03^0$

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BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	1813.80	0	0	-10.642
.15	1872.72	0	0	-11.155
1.0	2658.35	0	0	-15.552

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	451,670	392,790	129,822	0	0	0
.15	479,689	480,810	148,658	0	0	0
1.0	745,805	746,925	326,535	0	0	0

C_p (ORIGIN AT C_G, METERS)

	PLANE: XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
.06	0	0	-16.782	0	0	-9.756	0	0	-9.756
.15	0	0	-16.269	0	0	-9.243	0	0	-9.243
1.0	0	0	-11.872	0	0	-4.846	0	0	-4.846

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
.06	194.02	81.851	81.851	0.106969	0.045127	0.045127
.15	194.02	81.851	81.851	0.103603	0.043707	0.043707
1.0	194.02	81.851	81.851	0.072985	0.030790	0.030790

GENERIC CLASS: Land Mobile Satellite System (LMSS)
- Hoop Column, 120 meters -

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	LEO (300, 400, 500 km) 5600 km Polar Orbit GEO (36,000 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Attitude Control ± 0.10°
Pointing Stability ± 0.03°

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BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	2753.52	0	0	-25.319
.15	2907.47	0	0	-26.927
1.0	4988.83	0	0	-37.899

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	3,209,198	3,216,963	1,052,428	0	0	0
.15	3,[illegible]99,882	3,507,647	1,270,291	0	0	0
1.0	6,238,758	6,246,521	3,328,003	0	0	0

C_p (ORIGIN AT C_G, METERS)

	PLANE: XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
.06	0	0.00176	-28.761	0	0	-18.772	0	0	-18.772
.15	0	0.00176	-27.153	0	0	-17.164	0	0	-17.164
1.0	0	0.00176	-16.181	0	0	- 6.193	0	0	- 6.193

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
.06	756.6	219.66	219.66	.274776	0.079774	0.079774
.15	756.6	219.66	219.66	.260226	0.075550	0.075550
1.0	756.5	219.66	219.66	.151659	0.044030	0.044030

SCALING LAWS 60 Meter Diameter

Effect of g-Load on Mass $M_o = 1873$ kg $g_o = .15$ g

+Z Bus and Solar Array: $\frac{M_{+Z}}{M_o} = 0.658$

-Z Bus and Solar Array: $\frac{M_{-Z}}{M_o} = 0.067$

Column: $\frac{M_{Col}}{M_o} = 0.170 + \frac{0.338 \frac{g}{g_o}}{98.2 - \frac{g}{g_o}}$

Hoop: $\frac{M_{Hoop}}{M_o} = 0.0133 \frac{g}{g_o} + 0.0678$

Reflector Surface: $\frac{M_{Refl}}{M_o} = 0.0133 \frac{g}{g_o}$

Cables: $\frac{M_{Cables}}{M_o} = 0.0064 \frac{g}{g_o}$

SCALING LAWS 120 Meter Diameter

Effect of g-Load on Mass $M_o = 2909$ $g_o = .15$ g

+Z Bus and Solar Array: $\frac{M_{+Z}}{M_o} = 0.563$

-Z Bus and Solar Array: $\frac{M_{-Z}}{M_o} = 0.066$

Column: $$\frac{M_{Col}}{M_o} = \frac{0.1981 + 0.0125 \frac{g}{g_o} + 0.00286 \left(\frac{g}{g_o}\right)^2}{1 - 0.0472 \frac{g}{g_o}}$$

Hoop: $\frac{M_{Hoop}}{M_o} = 0.0184 \frac{g}{g_o} + 0.0861$

Reflector Surface: $\frac{M_{Refl}}{M_o} = 0.034 \frac{g}{g_o}$

Cables: $\frac{M_{Cables}}{M_o} = 0.0082 \frac{g}{g_o}$

REFERENCES

"Configuration Development of the Land Mobile Satellite System (LMSS) Spacecraft," Third Annual Technical Review, Boeing Aerospace Co., Nov. 16-19, 1981, presented to JPL LSST Antenna Organization.

GENERIC CLASS

Baseline Experimental Geostationary Platform

NO.

IV. Page 1 of 3

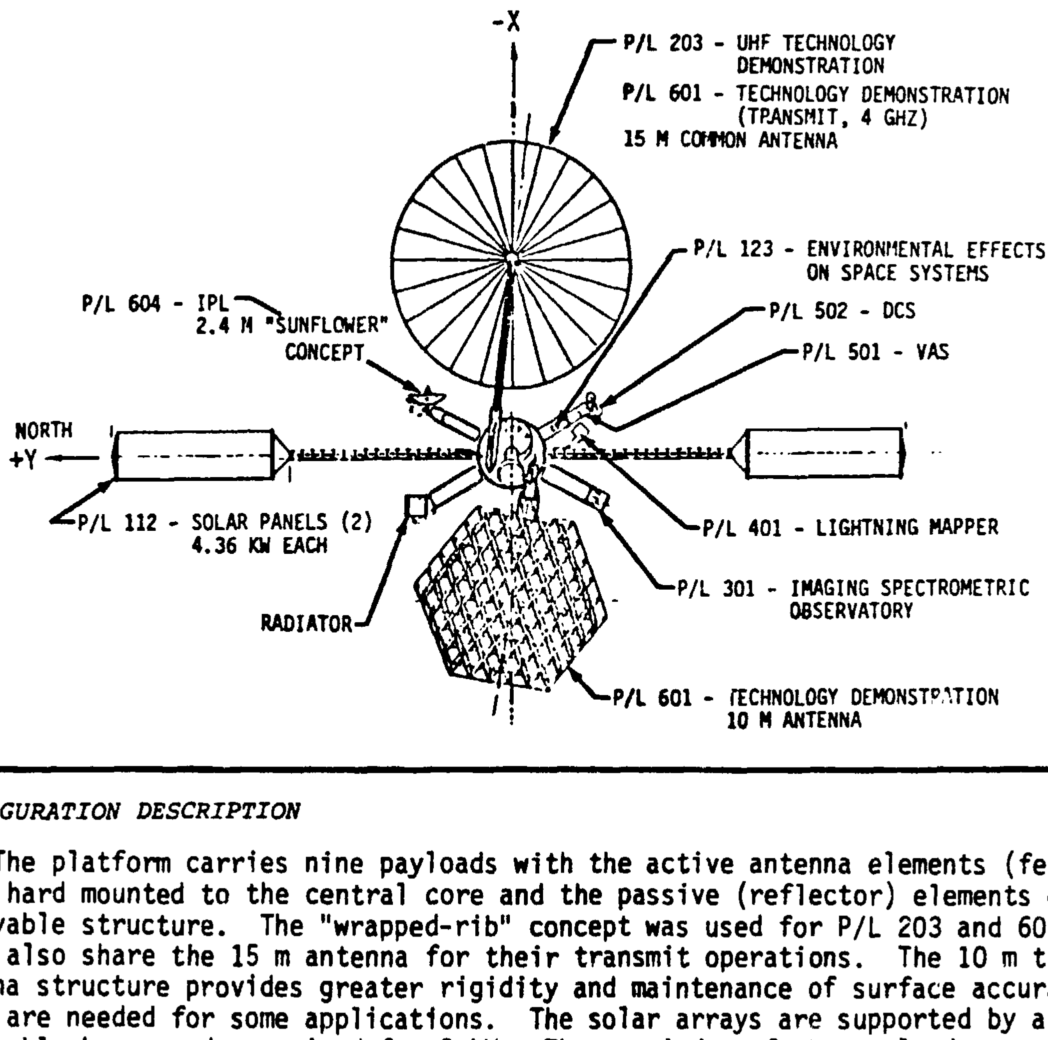
OBJECTIVES

The geostationary orbit is rapidly becoming an extremely valuable and limited earth resource. The objective of the geostationary platform is to make maximum use of a single geostationary orbital slot by providing common power and housekeeping services for a number of coexistent communications systems.

CONFIGURATION DRAWING

BASELINE EXPERIMENTAL GEOSTATIONARY PLATFORM

VIEW LOOKING TOWARDS EARTH



CONFIGURATION DESCRIPTION

The platform carries nine payloads with the active antenna elements (feed arrays) being hard mounted to the central core and the passive (reflector) elements on a deployable structure. The "wrapped-rib" concept was used for P/L 203 and 601 which also share the 15 m antenna for their transmit operations. The 10 m truss antenna structure provides greater rigidity and maintenance of surface accuracy which are needed for some applications. The solar arrays are supported by a deployable-boom, and are sized for 8 kW. The remainder of the payloads are mounted on three rigid structures. The solar arrays will be closest to earth.

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	Leo (300, 400, 500 km) GEO (36,000 km)	16 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Attitude: Pitch $\pm 0.1^{o}$, Roll $\pm 0.1^{o}$, Yaw $\pm 0.1^{o}$

Stationkeeping: Constellation Longitude $\pm 0.03^{o}$
Constellation Latitude $\pm 0.03^{o}$

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
.06	3722.75	-0.568	-0.148	-3.991
.15	3736.60	-0.593	-0.146	-4.048
1.0	3944.38	-0.811	-0.126	-4.484

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
.06	294,449	194,594	191,637	-1.011	-37.174	7.271
.15	299,130	200,547	192,915	-0.986	-38.754	7.364
1.0	387,514	255,189	227,592	-0.774	-53.460	8.165

C_p (ORIGIN AT C_G, METERS)

	PLANE: XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
.06	-3.968	0.194	-4.482	-2.045	0.601	-7.008	-1.113	0.780	-1.445
.15	-3.943	0.192	-4.425	-2.020	0.599	-6.951	-1.088	0.778	-1.388
1.0	-3.725	0.172	-3.989	-1.802	0.579	-6.515	-0.870	0.758	-0.952

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
.06	196.600	70.700	134.400	0.052810	0.018991	0.036102
.15	196.600	70.700	134.400	0.052615	0.018921	0.035969
1.0	196.600	70.700	134.400	0.049843	0.017924	0.034074

SCALING LAWS

Effect of g-Load on Mass $M_o = 3737$ kg $g_o = .15$ g

All experiments and appendages are good for $g/g_o = 10.0$ except the 15 m wrap rib antenna assembly and the solar array assemblies.

Bus and Constant Weight Structure: $\frac{M_{Bus}}{M_o} = 0.8435$, for $\frac{g}{g_o} \leq 10.0$

Wrap Rib Antenna Assembly:

$$\frac{M_{Rib}}{M_o} = 0.064 + 0.0062 \frac{g}{g_o} \quad , \text{ for } 0 \leq \frac{g}{g_o} \leq 8.9$$

$$\frac{M_{Rib}}{M_o} = 0.0611 + 0.0062 \frac{g}{g_o} + 0.00294 \left(\frac{g}{g_o} - 7.9\right) \quad , \text{ for } \frac{g}{g_o} > 8.9$$

Solar Array Assembly:

$$\frac{M_{SA}}{M_o} = 0.0864 \quad , \text{ for } \frac{g}{g_o} \leq 4.6$$

$$\frac{M_{SA}}{M_o} = 0.0226+0.00233\left(\frac{g}{g_o} - 3.6\right)+1.227 \times 10^4\left(\frac{g}{g_o} - 3.6\right)^2+0.048+0.003\left(\frac{g}{g_o} - 3.6\right) \; ,$$

$$\text{for } \frac{g}{g_o} > 4.6$$

REFERENCES

"Geostationary Platform Systems Concepts Definition Study," General Dynamics Convair Div., Report No. GDC-GPP-79-006(II), June 1980, prepared for NASA/MSFC.

"Geostationary Platform Systems Concepts Definition Follow-On Study," General Dynamics Convair Div. and Comsat General Corp., Report No. GDC-GPP-79-012, 28 July 1981, presented to NASA/MSFC.

"Geostationary Platform Systems Concepts Definition Follow-On Study," Vol. IIB Technical Report, General Dynamics Convair Div. and Comsat General Corp., Report No. GDC-GPP-79-010 (IIB), September, 1981, prepared for NASA/MSFC.

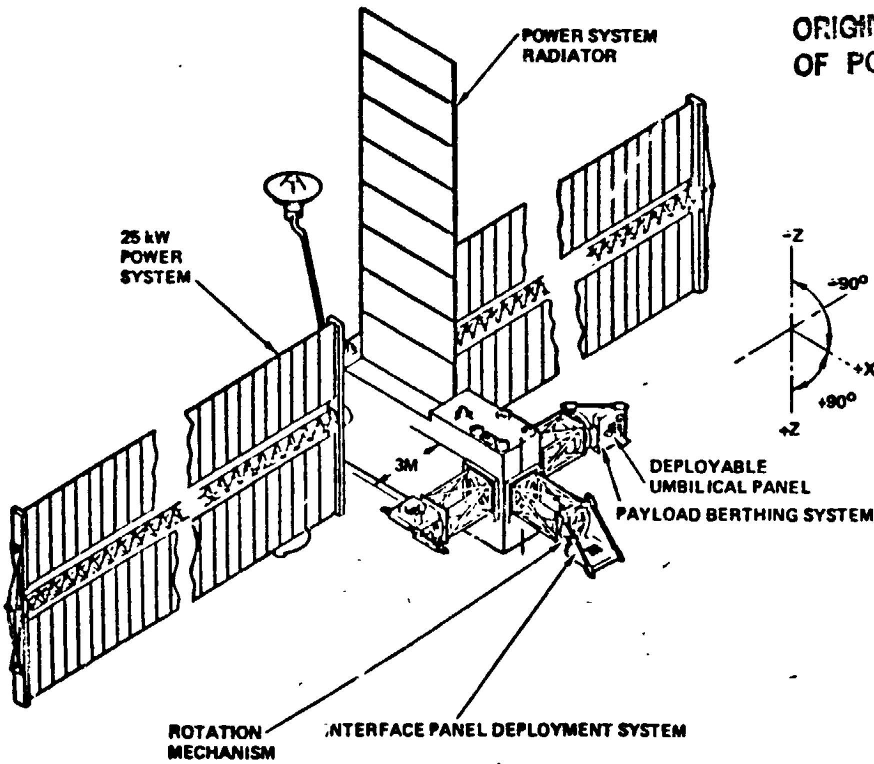
GENERIC CLASS	NO.
Science and Applications Space Platform (SASP)	V. Page 1 of 3

OBJECTIVES

The purpose of SASP is to provide a long duration free-flight platform in low earth orbit which will have the flexibility to effectively accommodate a broad variety of payloads and the routine, dedicated use of the orbiter for delivery, revisit, and exchange. Payloads include those which previously flew on Spacelab pallets, those requiring periodic earth return, on-orbit modification, maintenance or replenishment, and large payloads requiring a centralized orbit rendezvous, assembly and resource facility.

CONFIGURATION DRAWING

FIRST-ORDER PLATFORM CONFIGURATION



CONFIGURATION DESCRIPTION

The First Order Platform consists of three stub arms attached directly to the Power System aft section. Attached to these arms are deployable, rotatable payload berthing systems to which payload elements may be connected. The deployment and/or rotation of the payload berthing systems will probably occur when they are being attached and the positions will not be commandable during flight. Power System subsystems will provide payload support. The solar arrays are sized for 25 kW. The vehicle orientation will be variable.

GENERIC CLASS: Science and Applications Space Platform (SASP)
Size: 12.5 kw

INITIAL ORBIT	MISSION ORBITS	LIFETIME
LEO	57°/400 km 28.5°/400 km 98°/705 km GEO (36,000 km)	10 Years

ATTITUDE STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

Body Pointing Accuracy	1-10 $\hat{s}$
Stability	1-10 $\hat{s}$
Jitter Rate	0.6-1.5 $\hat{s}$/s

BASELINE g-LOAD = 0.15 g

g-LOAD	MASS (kg)	CG LOCATION (m) X	Y	Z
	8780.	5.401	0	-0.874

INERTIAS (ABOUT C_G, kg-m^2)

g-LOAD	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
	89,463	131,563	116,532	0	9.115	0

C_p (ORIGIN AT C_G, METERS)

	PLANE: XY			XZ			YZ		
g-LOAD	X	Y	Z	X	Y	Z	X	Y	Z
	-5.2739	0	.8395	-1.567	0	-4.518	-5.129	0	.839

	AREA (m^2)			AREA/MASS		
g-LOAD	XY	XZ	YZ	XY	XZ	YZ
	359.64	123.770	353.440	0.040961	0.014097	0.040255

SCALING LAWS

REFERENCES

"Conceptual Design Study Science and Applications Space Platform (SASP), Vol. II Technical Report," McDonnell Douglas Astronautics Co., Report No. MDC G9246, October 1980, prepared for NASA/MSFC.

"Payloads Requirements/Accommodations Assessment Study for Science and Applications Space Platforms, Second Quarterly Review," TRW, June 10, 1980, prepared for NASA/MSFC.

"Payloads Requirements/Accommodations Assessment Study for Science and Applications Space Platforms, Vol II: Technical Report," TRW, Report No. 36254-6001-UE-00, 26 November 1980, prepared for NASA/MSFC.

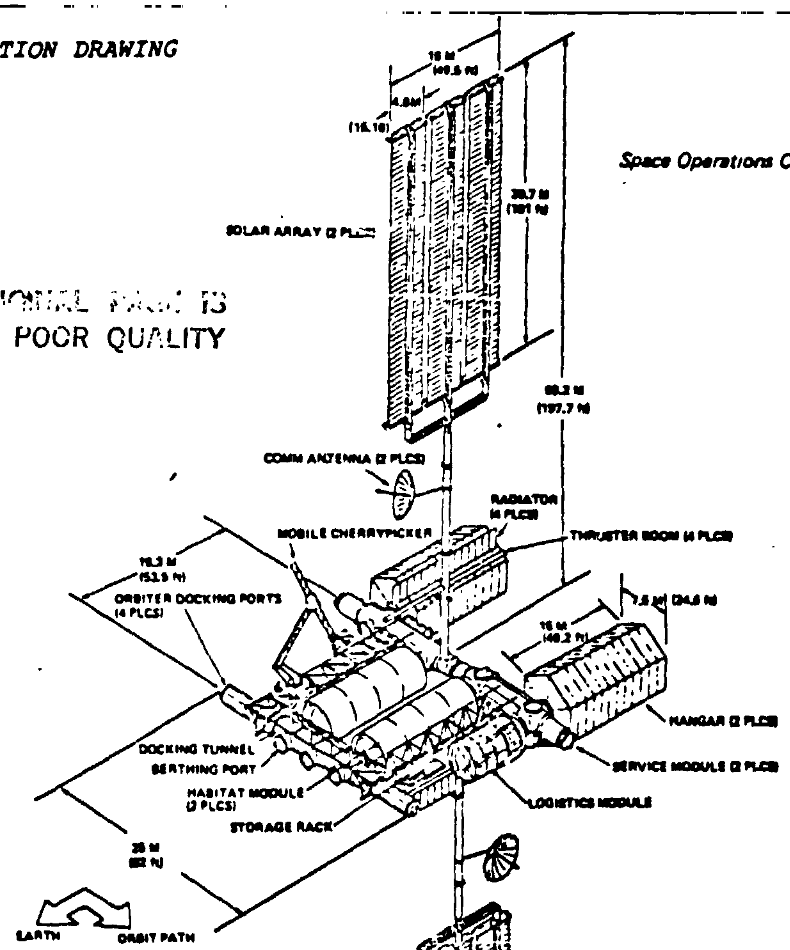
"Analysis of Requirements for Free Flying Spacelab-Type Payloads, Vol I--Design Reference Missions and STS Operations," Teledyne Brown Engineering, Report No. SP81-MSFC-2565, November 1981, prepared for NASA/MSFC.

GENERIC CLASS	NO.
Space Operations Center (SOC)	VI. Page 1 of 3

OBJECTIVES

The SOC is a manned operations center supporting a crew of four which will be rotated every 90 days. It provides a location for construction, flight support, satellite servicing, science and applications research, space technology testing, spacecraft test and checkout, and for military derivatives. Some applications are: a payload storage facility used to check out and mate upper stages with their payloads; the retrieval of "small" satellites to the SOC for servicing and then replacing them in their orbital slot; and servicing a communications platform with a manned servicing vehicle.

CONFIGURATION DRAWING



Space Operations Center - Operational Configuration

CONFIGURATION DESCRIPTION

SIZE AND MAX G RANGES

SCALING PARAMETER	*SIZE*	*MAX G ALLOWED*

INITIAL ORBIT

LEO

MISSION ORBITS

LEO (300, 400, 500 km)
Molniyn
GEO (36,000 km)
Sun Synchronous

MASS

SIZE	*MASS*	*INERTIAS (1000 kg-m²)* I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
Initial Baseline	57242	2564	2163	2211	-143	-202	104
Operational Baseline	125500	8884	12840	9269	52	116	0

ATTITUDE, STATIONKEEPING, AND SHAPE CONTROL TOLERANCES

LIFETIME

10 years

MASS AND AREA PROPERTIES

SIZE	C_G *LOCATION* X	Y	Z	C_P *LOCATION* XZ	YZ	*AREA* XZ	YZ
Initial Baseline	-6.2	0.47	4.3	3.8,-10.9	38.8,-2.8	508	539
Operational Baseline	-1.5	0.0	4.0	0.61,-8.7	0.0,-3.9	838	1113

AREA/MASS

SIZE	XZ	YZ
Initial Baseline	0.008875	0.009416
Operational Baseline	0.006677	0.008869

ALL UNITS ARE MKS

SCALING LAWS

REFERENCES

"Space Operations Center System Analysis," Midterm Briefing, Boeing Aerospace Co., Report No. D180-26715-1, October 15, 1981, prepared for NASA/Lyndon B. Johnson Space Ctr.

"Space Operations Center System Analysis," Monthly Progress Report No. 3, Boeing Aerospace Co., December 1, 1981, prepared for NASA/Lyndon B. Johnson Space Ctr.

"Space Operations Center System Analysis," Final Report, Vol. I, Executive Summary, Boeing Aerospace Co., Report No. D180-26495-3, July, 1981, prepared for NASA/Johnson Space Center.

APPENDIX B

Disturbance Environment Data

TORQUE UPON SASP (12.5 KW) DUE TO
AERODYNAMIC DRAG
500 KM ALTITUDE

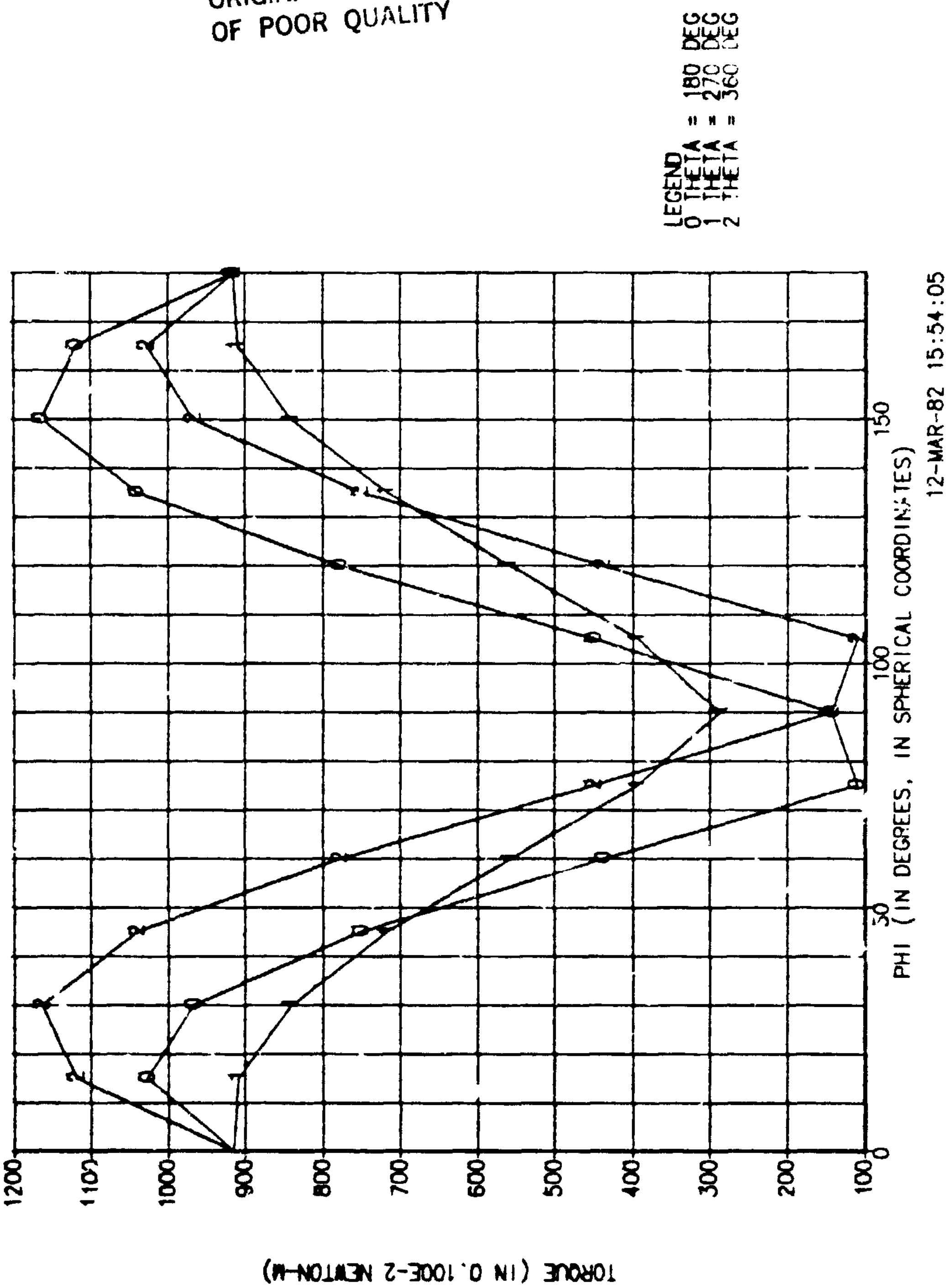


FIGURE 20

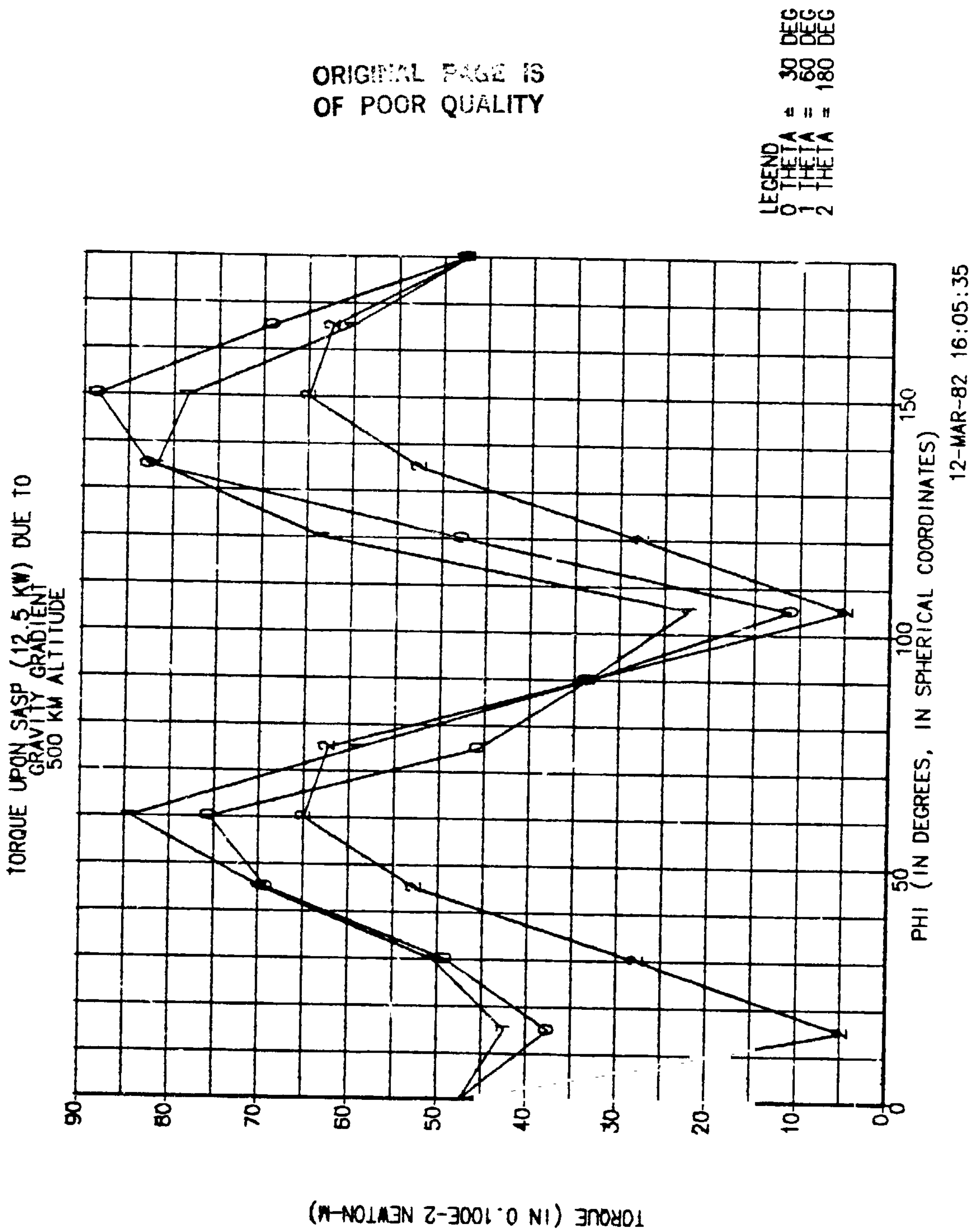

TORQUE UPON SASP (12.5 KW) DUE TO
GRAVITY GRADIENT
500 KM ALTITUDE
LEGEND
0 THETA = 30 DEG
1 THETA = 60 DEG
2 THETA = 180 DEG
TORQUE (IN 0.100E-2 NEWTON-M)
0
10
20
30
40
50
60
70
80
90
PHI (IN DEGREES, IN SPHERICAL COORDINATES)
0
50
100
150
12-MAR-82 16:05:35

FIGURE 22

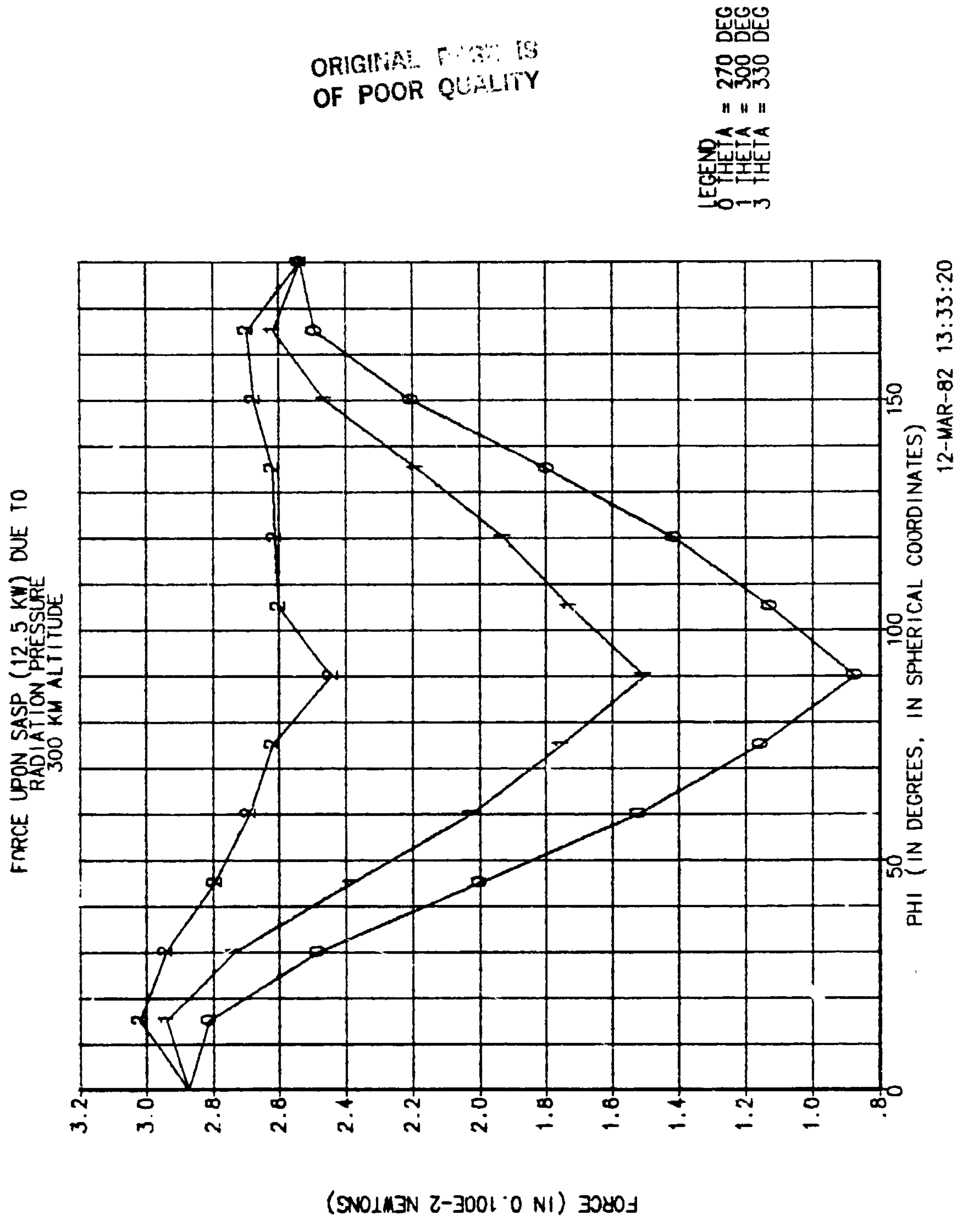

FORCE UPON SASP (12.5 KW) DUE TO
RADIATION PRESSURE
300 KM ALTITUDE
LEGEND
0 THETA = 270 DEG
1 THETA = 300 DEG
3 THETA = 330 DEG
FORCE (IN 0.100E-2 NEWTONS)
PHI (IN DEGREES, IN SPHERICAL COORDINATES)
12-MAR-82 13:33:20
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
0
50
100
150

FIGURE 10

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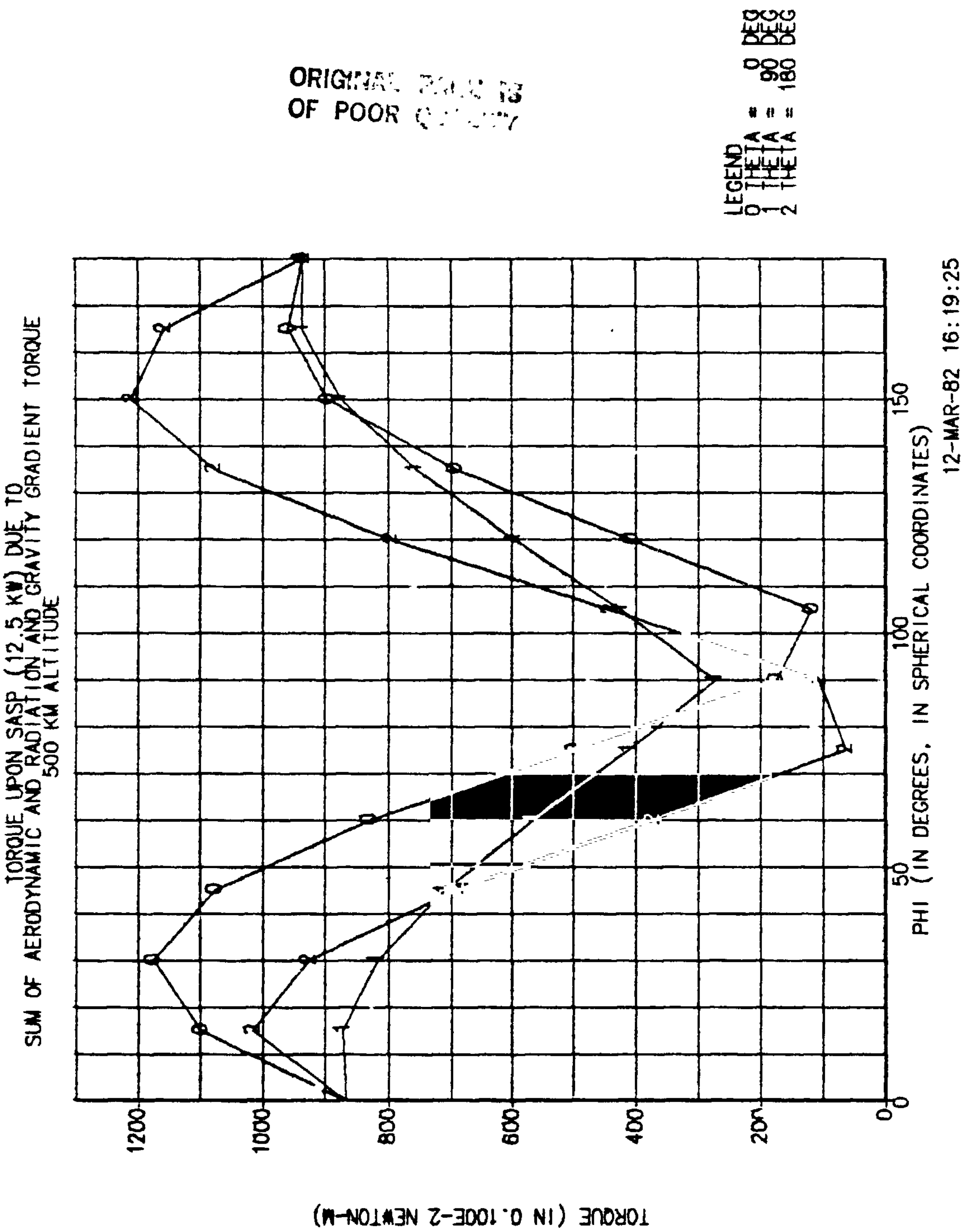

FIGURE 24

Table 2 WORST CASE DISTRIBUTION TORQUE ORIENTATION @ 300 KM (DEGREES)

LSS	T_x Yaw	T_x Pitch	T_x Roll	T_y Yaw	T_y Pitch	T_y Roll	T_z Yaw	T_z Pitch	T_z Roll
ELECTRONIC MAIL									
g-load = .06	270	180	320	5	315	190	355	315	270
g-load = .15	90	180	140	0	0	355	355	315	270
g-load = 1.0	320	335	140	180	10	350	355	315	270
EDUCATIONAL TV									
g-load = .06	270	0	45	185	45	185	355	315	270
g-load = .15	280	10	225	195	325	340	355	315	270
g-load = 1.0	30	325	225	180	180	230	355	315	270
LMSS WRAP RIB									
g-load = .06	70	190	220	355	30	205	180	335	205
g-load = .15	70	345	220	355	330	335	200	5	95
g-load = 1.0	120	160	230	5	330	25	5	25	200
LMSS HOOP COLUMN									
g-load = .06	265	180	140	180	320	190	320	320	80
g-load = .15	95	180	320	180	320	190	320	320	80
g-load = 1.0	95	180	320	355	320	0	320	320	80
GEOSTATIONARY PLT.									
g-load = .06	100	40	335	155	235	200	115	235	120
g-load = .15	280	200	145	155	235	200	250	230	55
g-load = 1.0	95	5	330	190	120	0	110	230	125
SASP 12.5 kw									
g-load = .15	295	90	205	180	65	0	230	45	295
SASP 25 kw									
g-load = .15	320	90	230	0	65	0	120	355	210
SOC - INITIAL									
g-load = .15	330	35	325	215	340	190	180	180	245
SOC - OPERATIONAL									
g-load = .15	115	220	340	335	15	25	0	310	90

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Table 3 WORST CASE DISTRIBUTION TORQUE ORIENTATION @ 400 km (DEGREES)

	T_x			T_y			T_z		
LSS	Yaw	Pitch	Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll
ELECTRONIC MAIL									
g-load = .06	270	180	320	5	315	180	355	315	270
g-load = .15	270	180	225	180	180	45	355	315	270
g-load = 1.0	315	165	40	180	200	185	355	315	270
EDUCATIONAL TV									
g-load = .06	90	180	225	355	225	185	355	315	270
g-load = .15	260	170	315	355	220	185	355	315	270
g-load = 1.0	150	210	320	5	355	45	355	315	270
LMSS WRAP RIB									
g-load = .06	290	170	45	355	35	200	0	330	25
g-load = .15	250	195	40	355	330	335	200	5	90
g-load = 1.0	115	185	335	5	325	20	5	35	200
LMSS HOOP COLUMN									
g-load = .06	275	180	140	355	220	0	315	225	90
g-load = .15	265	180	140	355	220	0	315	225	90
g-load = 1.0	275	180	135	185	225	180	315	225	90
GEOSTATIONARY PLT.									
g-load = .06	280	340	145	195	125	5	120	230	115
g-load = .15	280	195	145	195	125	5	60	310	245
g-load = 1.0	95	5	330	340	305	10	300	310	295
SASP 12.5 kw									
g-load = .15	320	90	230	180	65	0	320	230	285
SASP 25 kw									
g-load = .15	335	90	65	0	65	0	60	185	330
SOC - INITIAL									
g-load = .15	205	220	335	215	340	190	180	180	245
SOC - OPERATIONAL									
g-load = .15	115	200	335	335	15	25	0	315	90

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Table 4 WORST CASE DISTRIBUTION TORQUE ORIENTATION @ 500 km (DEGREES)

LSS	T_x Yaw	T_x Pitch	T_x Roll	T_y Yaw	T_y Pitch	T_y Roll	T_z Yaw	T_z Pitch	T_z Roll
ELECTRONIC MAIL									
g-load = .06	270	0	315	5	225	180	355	315	270
g-load = .15	270	180	225	175	235	0	355	315	270
g-load = 1.0	45	355	220	0	35	180	355	315	270
EDUCATIONAL TV									
g-load = .06	90	0	225	355	225	185	355	315	270
g-load = .15	260	10	315	0	220	180	355	315	270
g-load = 1.0	30	335	220	10	10	140	355	315	270
LMSS WRAP RIB									
g-load = .06	70	355	235	355	40	200	0	215	20
g-load = .15	70	345	220	185	145	340	200	5	90
g-load = 1.0	115	180	335	175	140	20	175	320	200
LMSS HOOP COLUMN									
g-load = .06	265	0	140	355	40	180	315	225	90
g-load = .15	95	180	320	175	320	180	315	225	90
g-load = 1.0	95	180	315	355	225	0	315	225	90
GEOSTATIONARY PLT.									
g-load = .06	280	345	145	190	235	180	310	310	285
g-load = .15	260	10	145	165	235	185	50	310	255
g-load = 1.0	95	185	325	165	230	185	315	310	280
SASP 12.5 kw									
g-load = .15	265	90	175	0	245	0	220	50	285
SASP 25 kw									
g-load = .15	90	180	180	180	115	180	120	5	330
SOC - INITIAL									
g-load = .15	335	40	335	35	200	10	180	175	245
SOC - OPERATIONAL									
g-load = .15	115	190	325	335	20	25	180	225	270

Table 5 WORST CASE DISTRIBUTION TORQUE ORIENTATION @ GEO km (DEGREES)

LSS	T_x Yaw	T_x Pitch	T_x Roll	T_y Yaw	T_y Pitch	T_y Roll	T_z Yaw	T_z Pitch	T_z Roll
ELECTRONIC MAIL									
g-load = .06	270	180	325	320	5	85	355	315	270
g-load = .15	270	180	220	180	5	0	355	315	270
g-load = 1.0	310	355	140	180	165	0	355	315	270
EDUCATIONAL TV									
g-load = .06	270	0	35	180	180	45	355	315	270
g-load = .15	280	355	215	180	340	0	355	315	270
g-load = 1.0	270	0	320	0	355	0	355	315	270
LMSS WRAP RIB									
g-load = .06	265	175	165	180	205	200	180	200	205
g-load = .15	260	200	35	180	200	150	175	5	90
g-load = 1.0	265	180	160	180	215	200	0	330	20
LMSS HOOP COLUMN									
g-load = .06	275	185	150	5	330	0	315	315	90
g-load = .15	95	180	330	5	330	0	315	315	90
g-load = 1.0	275	180	140	355	220	0	315	315	90
GEOSTATIONARY PLT.									
g-load = .06	270	180	170	150	250	210	335	310	280
g-load = .15	270	180	170	330	290	30	25	310	260
g-load = 1.0	270	180	170	165	250	195	335	310	275
SASP 12.5 kw									
g-load = .15	320	90	230	140	280	220	315	125	245
SASP 25 kw									
g-load = .15	335	270	115	225	100	225	150	120	210
SOC - INITIAL									
g-load = .15	265	30	355	15	190	15	180	180	145
SOC - OPERATIONAL									
g-load = .15	85	10	340	10	355	195	180	230	270

Table 6 Worst Case Distribution Torque Orientation - RSS (Degrees)

LSS	300 km Yaw	300 km Pitch	300 km Roll	400 km Yaw	400 km Pitch	400 km Roll	500 km Yaw	500 km Pitch	500 km Roll	GEO Yaw	GEO Pitch	GEO Roll
ELECTRONIC MAIL												
g-load = .06	265	350	320	260	195	320	290	20	320	270	180	325
g-load = .15	265	350	320	260	195	320	290	20	320	270	180	325
g-load = 1.0	180	180	225	270	180	225	270	180	225	185	355	225
	355	190	5	355	200	5	0	35	180	180	165	340
EDUCATIONAL TV												
g-load = .06	280	215	130	335	230	180	190	45	180	180	180	45
g-load = .15	355	320	175	5	220	185	5	220	180	180	340	0
g-load = 1.0	180	180	225	180	180	225	355	10	220	180	185	150
LMSS WRAP RIB												
g-load = .06	315	345	25	315	340	30	230	155	40	180	200	210
g-load = .15	315	195	25	315	200	30	135	335	210	5	165	220
g-load = 1.0	215	160	25	200	215	185	340	40	185	355	330	35
LMSS HOOP COLUMN												
g-load = .06	310	150	155	235	335	150	310	30	150	275	180	150
g-load = .15	310	30	155	55	335	330	310	30	150	95	180	330
g-load = 1.0	230	330	150	130	30	330	120	155	325	275	180	140
GEOSTATIONARY PLT.												
g-load = .06	340	60	185	335	55	175	15	305	5	215	250	145
g-load = .15	340	60	185	335	55	175	200	235	180	330	70	150
g-load = 1.0	335	60	180	25	305	355	25	310	350	200	250	160
SASP 12.5 kw												
g-load = .15	180	65	0	180	65	0	0	245	0	140	280	220
SASP 25 kw												
g-load = .15	0	65	0	0	65	0	180	115	180	225	100	225
SOC - INITIAL												
g-load = .15	180	180	245	180	180	245	180	175	245	180	180	245
SOC - OPERATIONAL												
g-load = .15	225	140	145	315	330	145	315	330	135	105	205	335

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Table 1 LEO Nominal Disturbance Torques

LSS	300 km TX	300 km TY	300 km TZ	300 km RSS	400 km TX	400 km TY	400 km TZ	400 km RSS	500 km TX	500 km TY	500 km TZ	500 km RSS
LAPAA 13 kw ELM												
g-load = .06	.2405	-.1201E+1	.8812E-3	.1221E+1	.9231E-1	-.3251	.8428E-3	.3366	.5772E-1	-.1276	.8065E-3	.1394
g-load = .15	-.5679	.0346E+1	.9072E-3	.3046E+1	-.1796	.7392	.8677E-3	.5464	.9336E-1	.2251	.8304E-3	.2317
g-load = 1.0	-.1560	.7253E+1	.1184E-2	.7255E+1	-.5049	.1909E+1	.1133E-2	.1924E+1	.2736	.7084	.1084E-2	.7391
LAPAA 65 kw ETV												
g-load = .06	.7476	.4891E+1	.1323E-1	.4891E+1	-.1973	.1187E+1	.1265E-1	.1187E+1	-.6281E-1	.3583	.3583	.3583
g-load = .15	.2043E+1	-.1113E+2	.1362E-1	.1122E+2	.5044	-.2717E+1	.1303E-1	.2747E+1	.1602	-.8697	-.8697	.8795
g-load = 1.0	-.3460E+1	.1883E+2	.1744E-1	.1883E+2	-.9756	.4569E+1	.1668E-1	.4574E+1	-.4146	.1480E+1	.1480E+1	.1460E+1
Wrap Rib 55 m												
g-load = .06	.1385E+2	.4821E+2	-.1699E+2	.5198E+2	.5762E+1	.1280E+2	-.4411E+1	.1385E+2	.3848E+1	.4830E+1	.4830E+1	.5900E+1
g-load = .15	.1122E+2	.4724E+2	-.1600E+2	.5069E+2	.3454E+1	.1297E+2	-.3929E+1	.1374E+2	-.2106E+1	.5237E+1	.5237E+1	.5689E+1
g-load = 1.0	.1709E+2	.4123E+2	-.1338E+2	.4419E+2	.1037E+2	.1250E+2	-.4074E+1	.1549E+2	.8619E+1	.5964E+1	.5964E+1	.1002E+2
Hoop/Column 120 m												
g-load = .06	-.1200E+2	.6379E+2	.2670E-2	.6466E+2	-.3841E+1	.1650E+2	.1243E-2	.1687E+2	.2041E+1	.5886E+1	.8976E-3	.6176E+1
g-load = .15	-.1124E+2	.5939E+2	.2670E-2	.6022E+2	-.3690E+1	.1547E+2	.1243E-2	.1583E+2	.2032E+1	.5607E+1	.8976E-3	.5907E+1
g-load = 1.0	-.6192E+1	.2952E+2	.2670E-2	.3009E+2	.2857E+1	.8560E+1	.1242E-2	.8968E+1	.2086E+1	.3815E+1	.8974E-3	.4314E+1
Geostationary Plt.												
g-load = .06	-.6675	.3567E+1	.1235E+1	.3755E+1	-.1629	.9143	.3078	.9553	-.4499E-1	.3192	.1003	.3284
g-load = .15	-.6564	.3491E+1	.1226E+1	.3680E+1	-.1623	.8973	.3055	.9386	-.5158E-1	.3153	.9948E-1	.3247
g-load = 1.0	-.5679	.2923E+1	.1151E+1	.3116E+1	-.1448	.7858	.2904	.8261	-.5484E-1	.3048	.9749E-1	.3132
SASP - 12.5 kw	.3256	-.4826E+1	.2990E+1	.5172E+1	.8573E-1	-.1158E+1	.7199	.1244E+1	.3181E-1	-.3377	.2126	.3664
SASP - 25 kw	.4328	-.9933E+1	.5765E+1	.9933E+1	-.1042	-.2408E+1	.1395E+1	.2408E+1	-.3069E-1	-.7250	.4180	.7250
SOC - Initial	.3056E+2	.1448E+2	.1519E+3	.1522E+3	-.7563E+1	.3920E+1	.3696E+2	.3700E+2	-.2592E+1	.9344	.1127E+2	.1127E+2
SOC - Operational	-.1015E+2	.4065E+2	.6249	.4189E+2	.4097E+1	.1035E+2	.5110	.1111E+2	.2763E+1	.3563E+1	.4598	.4451E+1

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Table 2 LEO Worst Case Disturbance Torques

LSS	300 km TX	300 km TY	300 km TZ	300 km RSS	400 km TX	400 km TY	400 km TZ	400 km RSS	500 km TX	500 km TY	500 km TZ	500 km RSS
LAPAA 13 kw ELM												
g-load = .06	.3479E+1	-.3174E+1	.1484E-1	.3480E+1	.9429	-.8811	.1419E-1	.9434	.3727	.3635	.1358E-1	.3738
g-load = .15	.2807E+1	.3046E+1	.1528E-1	.3052E+1	-.8153	.7392	.1461E-1	.8153	-.3647	-.2666	.1398E-1	.3647
g-load = 1.0	.4206E+1	-.7251E+1	.1994E-1	.7252E+1	-.1384E+1	.1982E+1	.1907E-1	.1982E+1	-.7681	.9158	.1825E-1	.9158
LAPAA 65 kw ETV												
g-load = .06	.1452E+2	.1406E+2	.2227	.1454E+2	.3526E+1	.3546E+1	.2130	.3601E+1	.1068E+1	.1190E+1	.2038	.1197E+1
g-load = .15	-.1403E+2	.1683E+2	.2294	.1681E+2	.3423E+1	.4265E+1	.2194	.4282E+1	.1052E+1	.1449E+1	.2100	.1452E+1
g-load = 1.0	-.9524E+1	.1883E+2	.2937	.1884E+2	.2624E+1	.4592E+1	.2808	.4609E+1	-.1093E+1	.1497E+1	.2688	.1518E+1
Wrap Rib 55 m												
g-load = .06	-.5531E+2	.5301E+2	.1790E+2	.6328E+2	-.1602E+2	.1561E+2	-.5031E+1	.1769E+2	-.7418E+1	.7364E+1	.2207E+1	.7880E+1
g-load = .15	-.5409E+2	.5224E+2	.1902E+2	.6305E+2	-.1635E+2	.1597E+2	.6560E+1	.1905E+2	-.7770E+1	.7870E+1	.3695E+1	.9325E+1
g-load = 1.0	-.4203E+2	.4664E+2	-.1424E+2	.5000E+2	.1717E+2	.1803E+2	-.5600E+1	.1908E+2	.1183E+2	.1175E+2	.3805E+1	.1241E+2
Hoop/Column 120 m												
g-load = .06	.1008E+3	-.1008E+3	.1921E-1	.1069E+3	.2745E+2	-.2744E+2	-.1575E-1	.2890E+2	.1093E+2	.1091E+2	-.1453E-2	.1135E+2
g-load = .15	.9494E+2	-.9493E+2	.1921E-1	.1006E+3	.2614E+2	-.2613E+2	-.1575E-1	.2746E+2	.1063E+2	-.1061E+2	-.1453E-1	.1101E+2
g-load = 1.0	.5554E+2	.5552E+2	.1920E-1	.5767E+2	.1760E+2	.1758E+2	-.1575E-1	.1811E+2	.8963E+1	-.8949E+1	-.1453E-1	.9089E+1
Geostationary Plt.												
g-load = .06	.5784E+1	.8242E+1	.3702E+1	.8670E+1	.1404E+1	.2135E+1	.1018E+1	.2222E+1	.4257	.7640	.4216	.7831
g-load = .15	.5725E+1	.8157E+1	.3671E+1	.8581E+1	.1396E+1	.2118E+1	.1009E+1	.2204E+1	.4285	.7632	.4173	.7815
g-load = 1.0	.5269E+1	.7533E+1	.3476E+1	.7901E+1	.1311E+1	.2033E+1	.1006E+1	.2105E+1	.4266	.8022	.4582	.8163
SASP - 12.5 kw	.4057E+1	.1760E+2	.1031E+2	.1760E+2	.9846	.4297E+1	.2552E+1	.4297E+1	.2977	.1322E+1	.8153	.1322E+1
SASP - 25 kw	.1687E+2	-.3079E+2	.1868E+2	.3079E+2	-.4094E+1	-.7465E+1	-.4520E+1	.7465E+1	-.1238E+1	-.2251E+1	-.1354E+1	.2251E+1
SOC - Initial	-.7678E+2	-.2807E+2	.1525E+3	.1529E+3	-.1902E+2	-.7590E+1	.3757E+2	.3765E+2	-.6091E+1	-.2978E+1	.1186E+1	.1188E+2
SOC - Operational	.5969E+2	.4725E+2	.1004E+2	.6561E+2	.1743E+2	.1199E+2	.8056E+1	.1956E+2	.9193E+1	.4104E+1	.7415E+1	.1006E+2

Table 3 GEO Nominal and Worst Case Disturbance Torques

LSS	NOMINAL $\pm 10^{o}$ TX	TY	TZ	RSS	WORST CASE TX	TY	TZ	RSS
Electronic Mail								
g-load = .06	.3472E-3	-.5072E-3	.3501E-5	.5692E-3	.1638E-2	-.1250E-2	.5895E-4	.1638E-2
g-load = .15	.3285E-3	.3785E-2	.3604E-5	.3658E-2	-.1563E-2	-.3784E-2	.6069E-4	.3848E-2
g-load = 1.0	.1052E-2	.9290E-2	.4706E-5	.9308E-2	.3083E-2	.9391E-2	.7923E-4	.9407E-2
Educational TV								
g-load = .06	-.1104E-3	.6020E-2	.5255E-4	.6020E-2	.3719E-2	.6020E-2	.8847E-3	.6020E-2
g-load = .15	.5289E-3	-.8914E-2	.5413E-4	.8915E-2	-.3654E-2	.9463E-2	.9114E-3	.9403E-2
g-load = 1.0	.1411E-2	.2346E-1	.6929E-4	.2346E-1	.4074E-2	.2344E-1	.1167E-2	.2347E-1
LMSS - Wrap Rib								
g-load = .06	.1736E-1	.5225E-1	-.1910E-1	.5636E-1	.4949E-1	.5522E-1	-1.956E-1	.5875E-1
g-load = .15	-.9601E-2	.5359E-1	-.1735E-1	.5646E-1	-.5063E-1	.5786E-1	.2800E-1	.6286E-1
g-load = 1.0	.3753E-1	.5331E-1	-.1870E-1	.6467E-1	.6217E-1	.6828E-1	-.2327E-1	.7222E-1
LMSS - Hoop Column								
g-load = .05	.9266E-2	.4731E-1	.3675E-5	.4800E-1	.5646E-1	.5641E-1	.6268E-4	.5651E-1
g-load = .15	.9181E-2	.4413E-1	-.3675E-5	.4487E-1	.5380E-1	.5375E-1	.6268E-4	.5385E-1
g-load = 1.0	.9092E-2	.2288E-1	.3674E-5	.2448E-1	.3883E-1	-.3376E-1	.6266E-4	.3885E-1
Geostationary Plt.								
g-load = .06	-.3608E-3	.2678E-2	.1095E-2	.2852E-2	.4544E-2	.7450E-2	.2255E-2	.7469E-2
g-load = .15	-.3675E-3	.2614E-2	.1090E-2	.2792E-2	.4519E-2	.7413E-2	.2231E-2	.7432E-2
g-load = 1.0	-.3803E-3	.2208E-2	.1065E-2	.2398E-2	.4284E-2	.7207E-2	.2372E-2	.7223E-2
SASP - 12.5 kw	-.2200E-3	-.3698E-2	.6508E-3	.3731E-2	.4994E-2	.1718E-1	-.3215E-2	.1718E-1
SASP - 25 kw	-.9796E-3	-.8539E-2	.1242E-2	.8539E-2	.2076E-1	-.302E-1	.4862E-2	.3025E-1
SOC - Initial	-.9271E-2	.1260E-1	.1873	.1876	-.5173E-1	-.1875E-1	.1899	.1903
SOC - Operational	.1392E-1	.4175E-1	.2221E-2	.4373E-1	.7658E-1	.4173E-1	.3402E-1	.7746E-1

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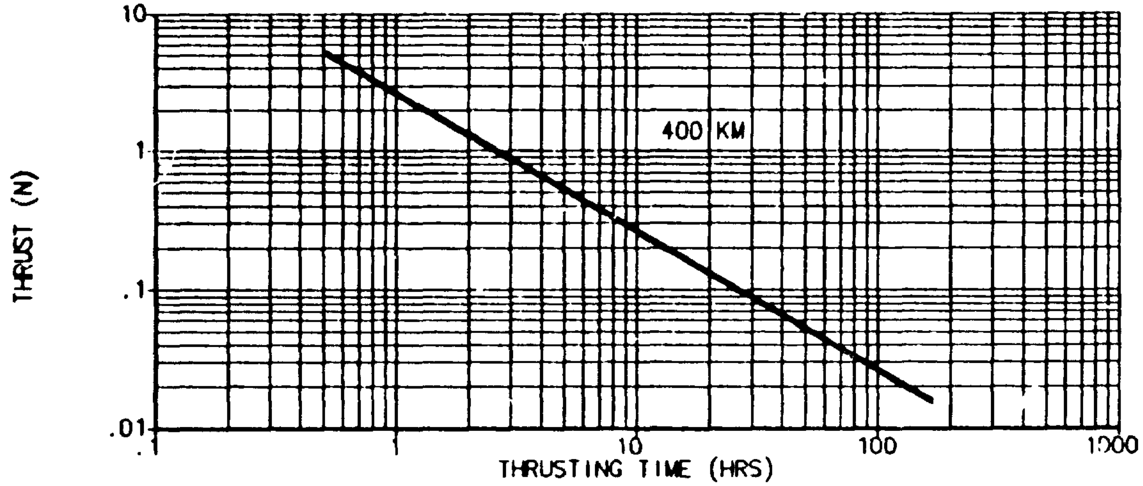
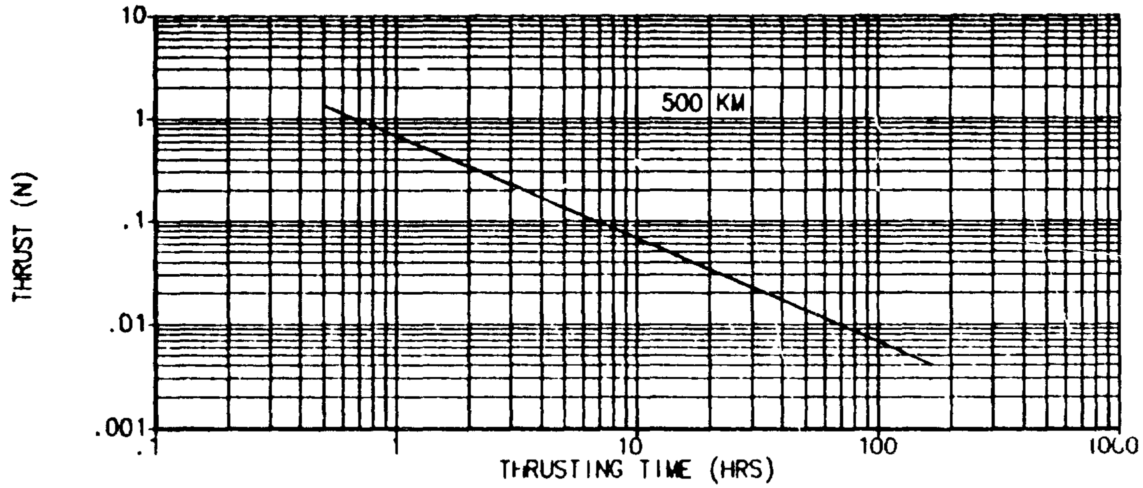
LEO STATIONKEEPING THRUST REQUIREMENTS
ELECTRONIC MAIL
(ALLOWED ALTITUDE CHANGE = 10 KM)





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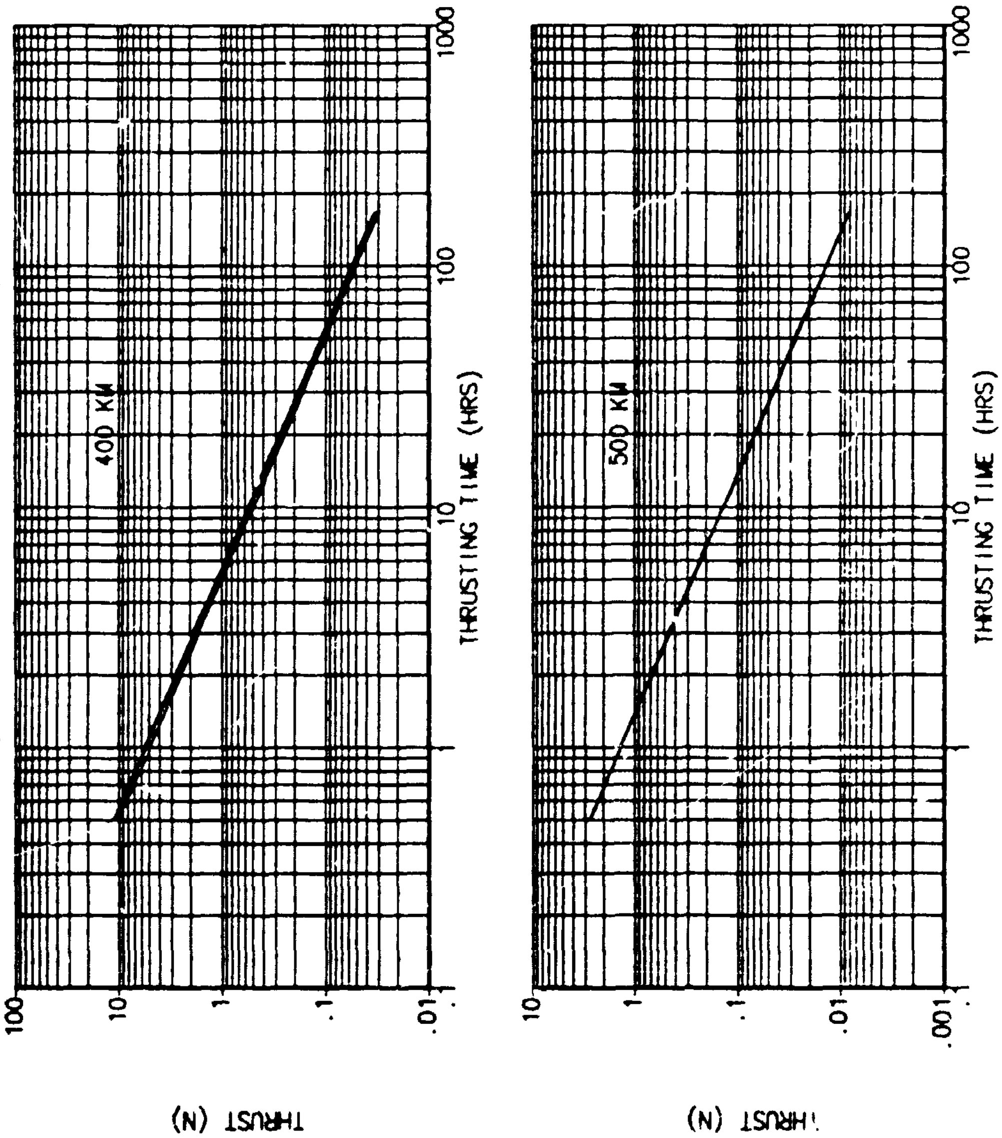
LEO STATIONKEEPING THRUST REQUIREMENTS
EDUCATIONAL TV
(ALLOWED ALTITUDE CHANGE = 10 KM)



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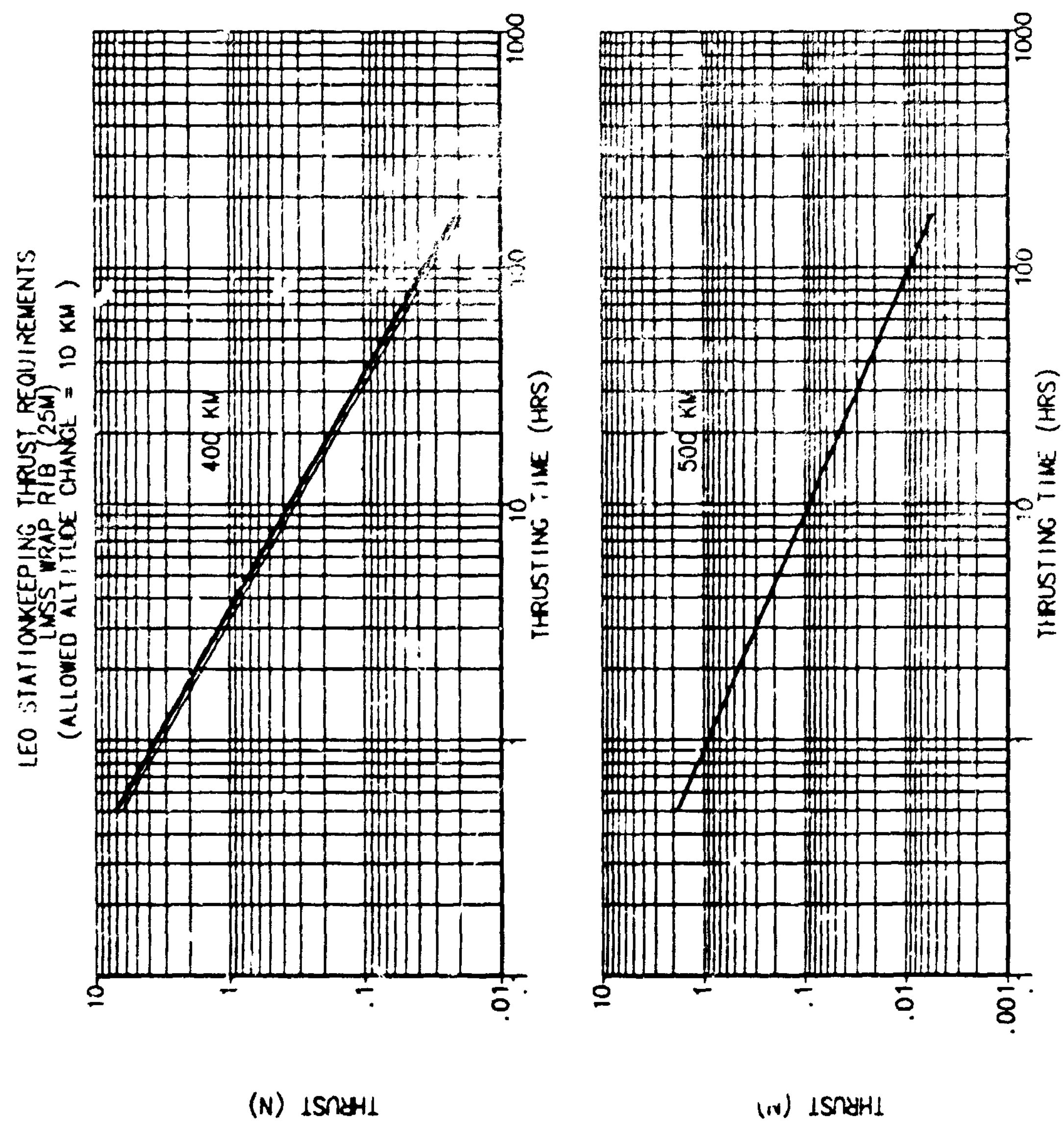
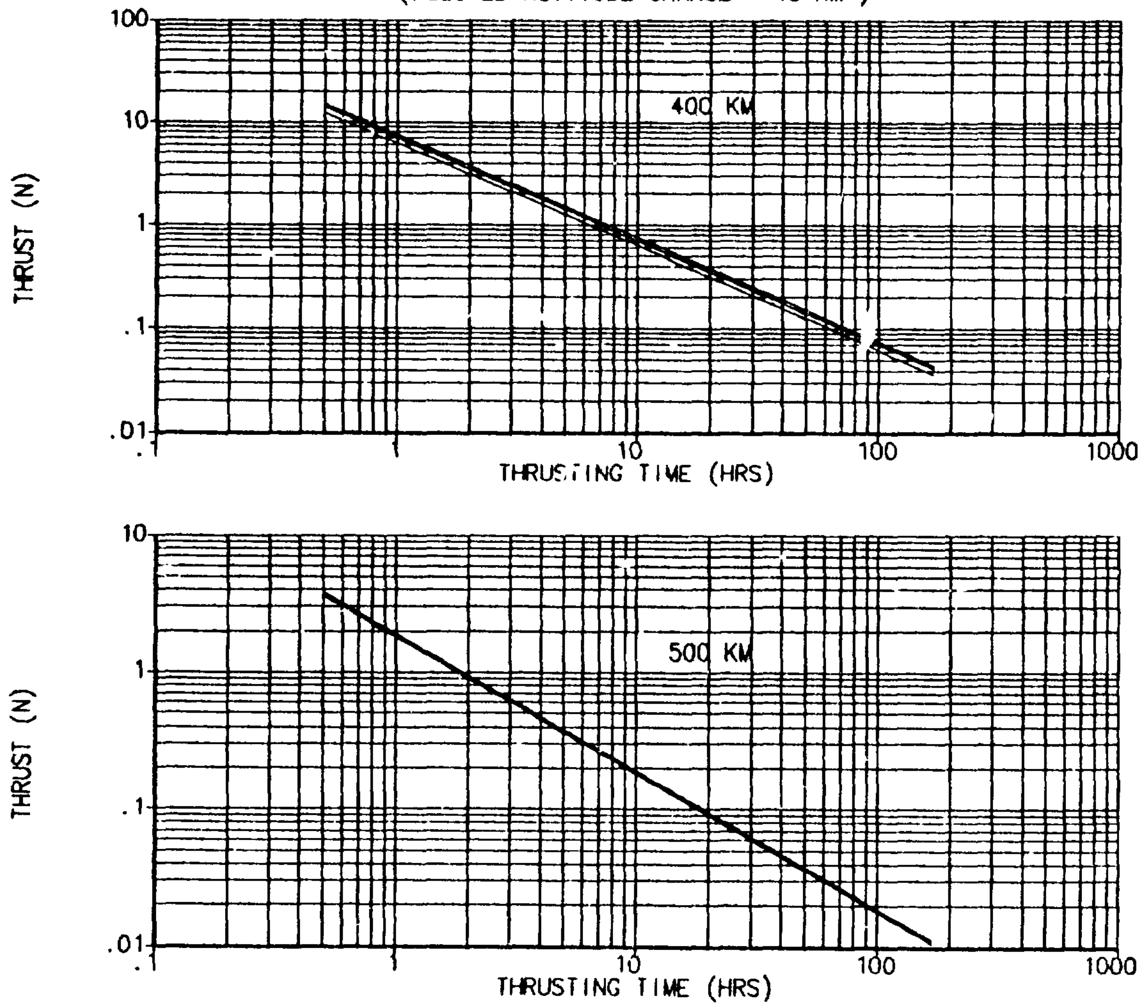


LEO STATIONKEEPING THRUST REQUIREMENTS
LMSS WRAP RIB (55M)
(ALLOWED ALTITUDE CHANGE = 10 KM)



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LEO STATIONKEEPING THRUST REQUIREMENTS
LMSS HOOP COLUMN (60M)
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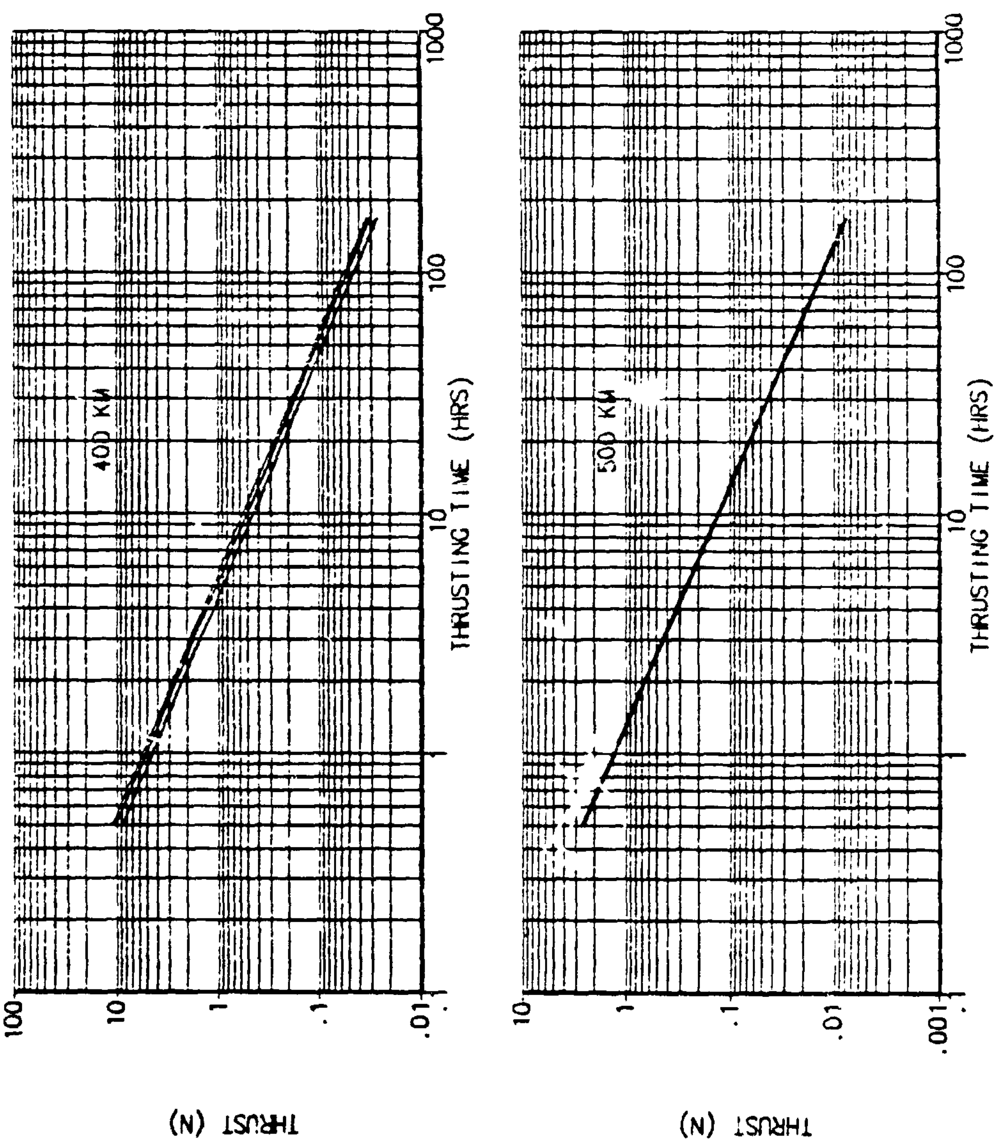

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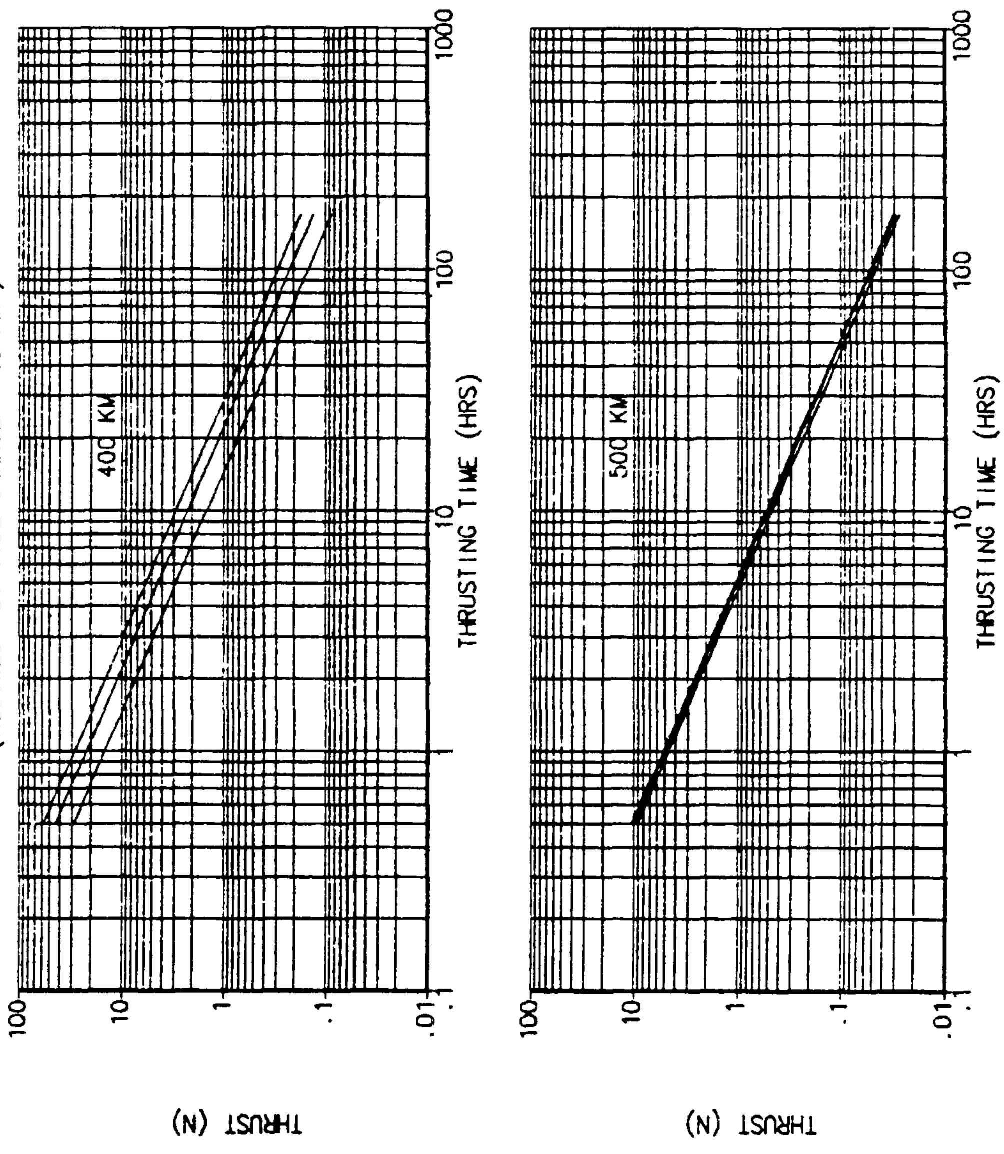
LEO STATIONKEEPING THRUST REQUIREMENTS
LMSS HOOP COLUMN (120M)
(ALLOWED ALTITUDE CHANGE = 10 KM)



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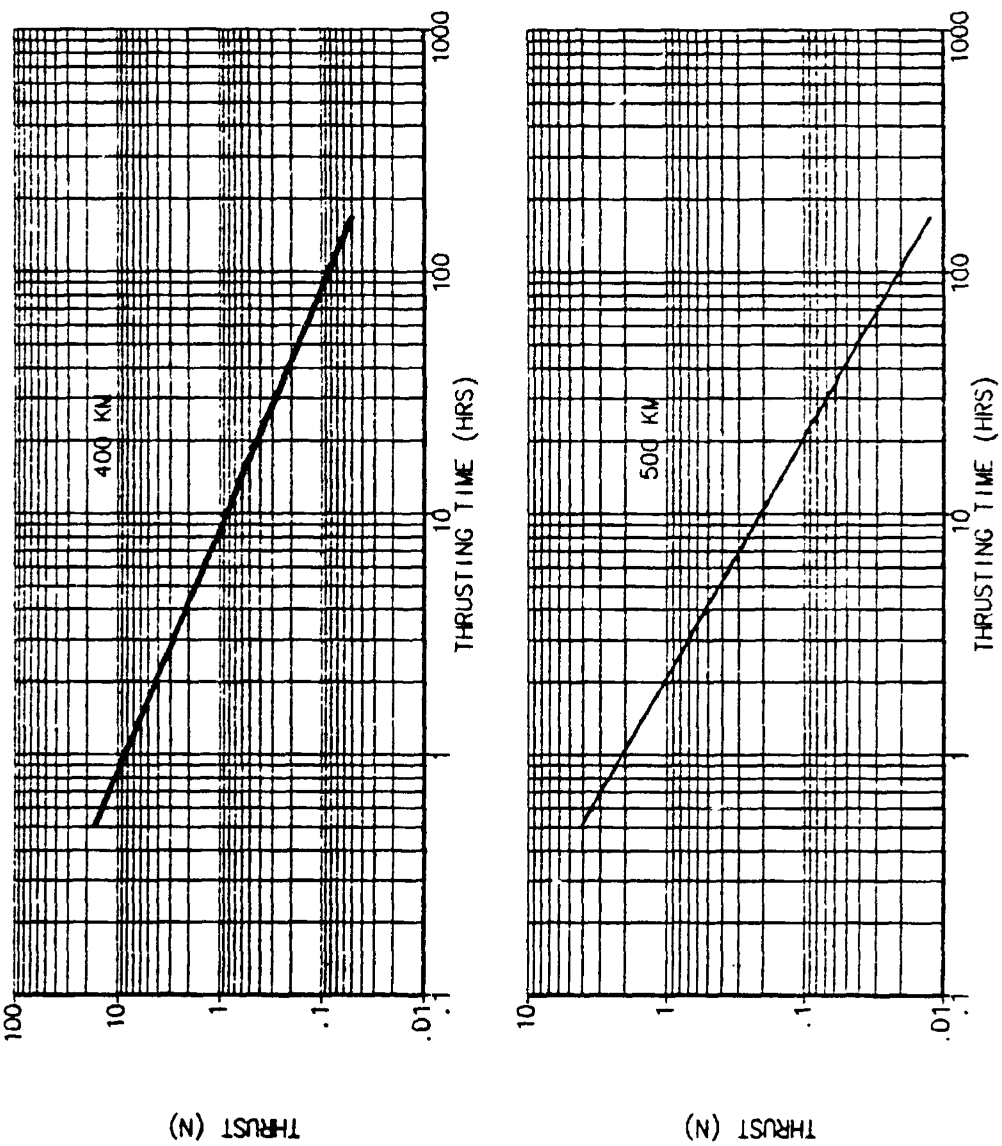
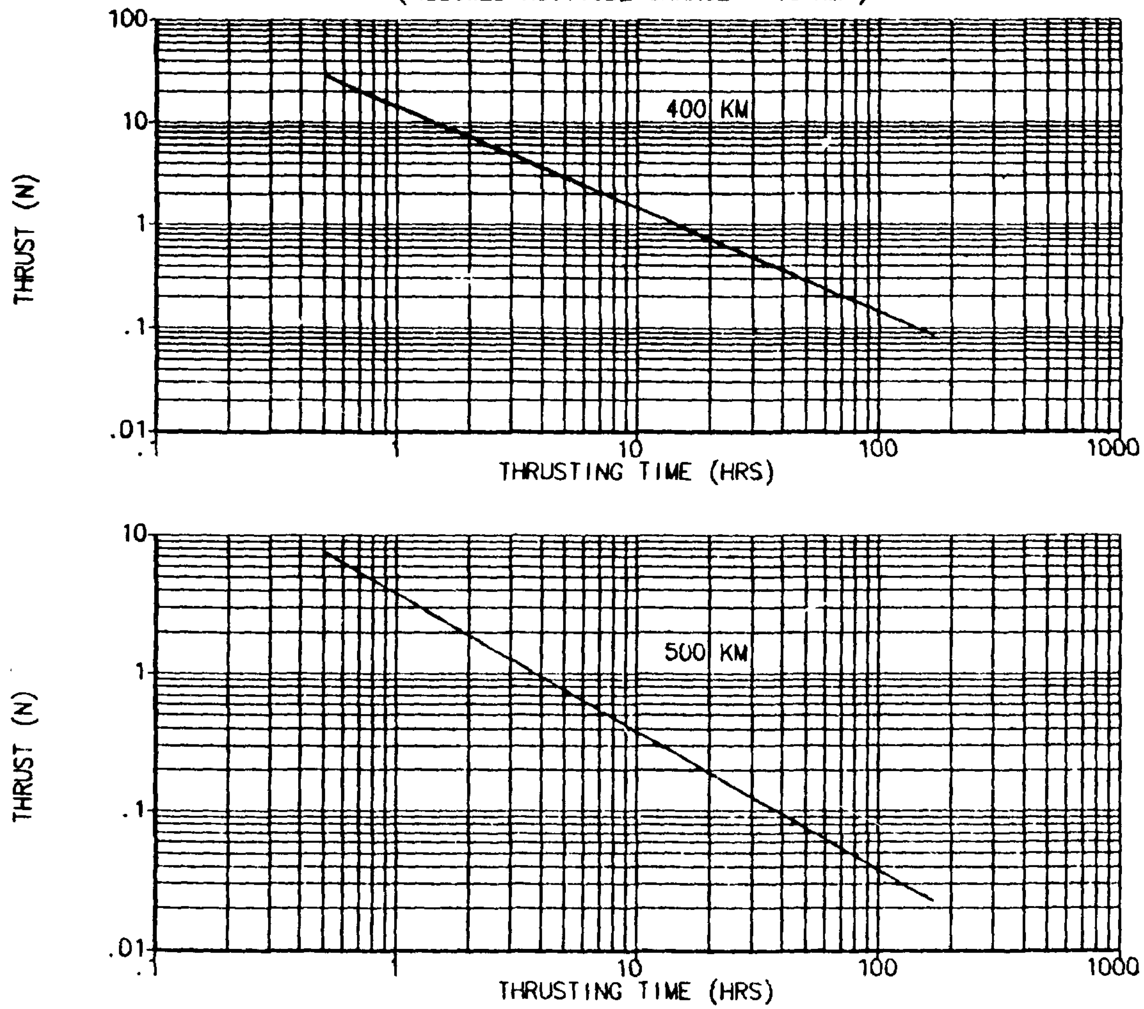
LEO STATIONKEEPING THRUST REQUIREMENTS
GEOSTATIONARY PLATFORM
(ALLOWED ALTITUDE CHANGE = 10 KM)



LEO STATIONKEEPING THRUST REQUIREMENTS
SASP 12.5 KW
(ALLOWED ALTITUDE CHANGE = 10 KM)



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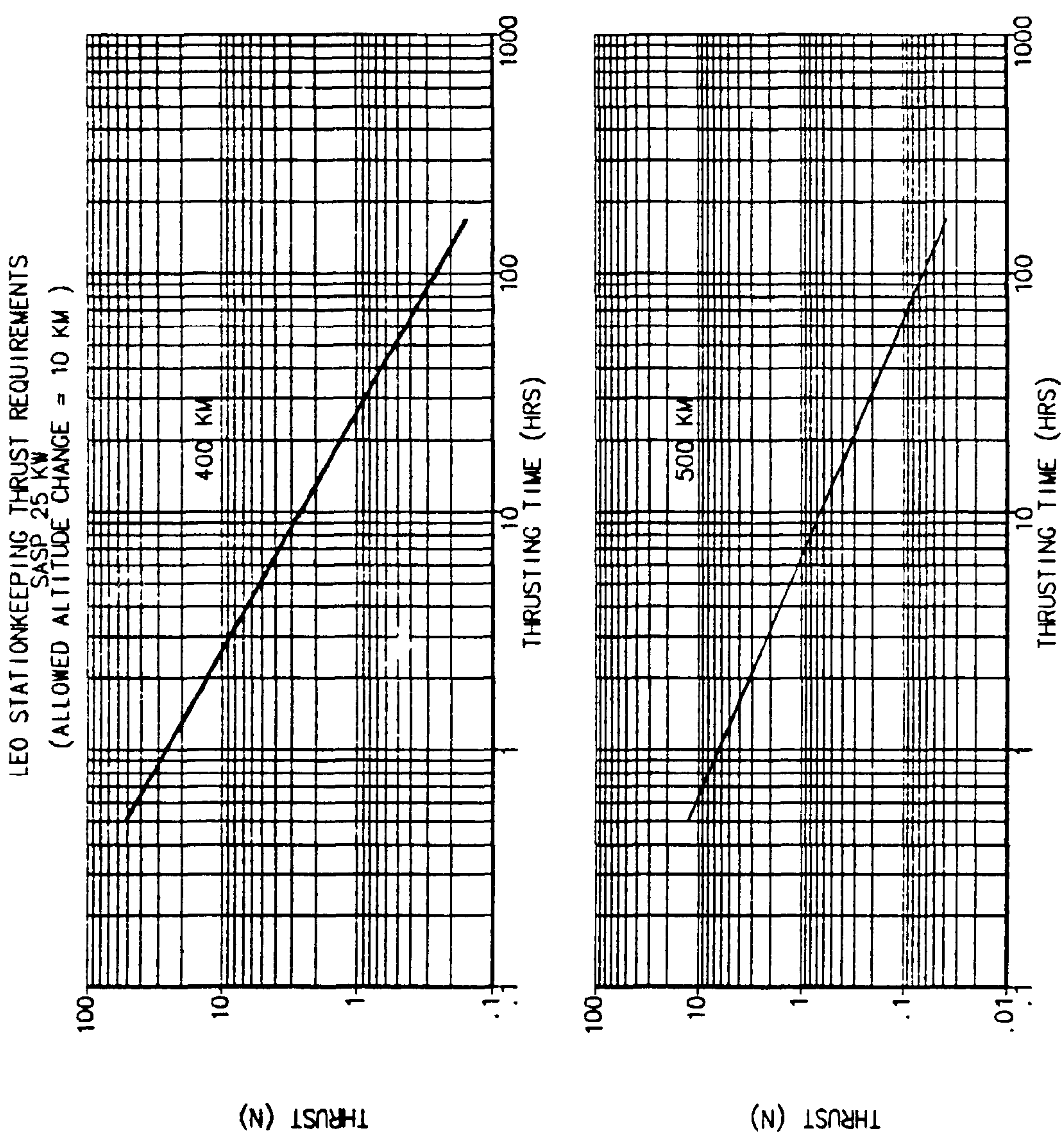
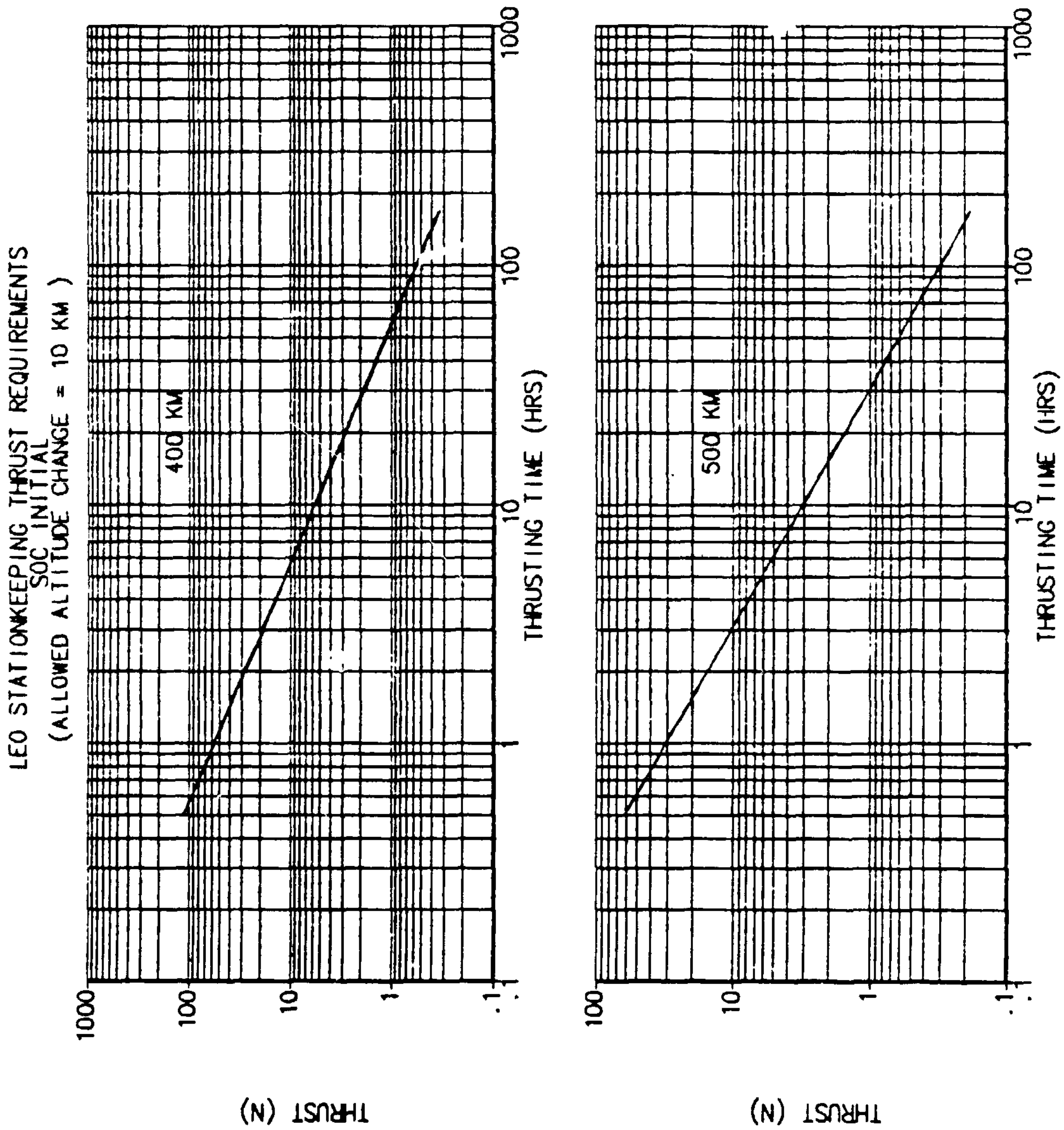
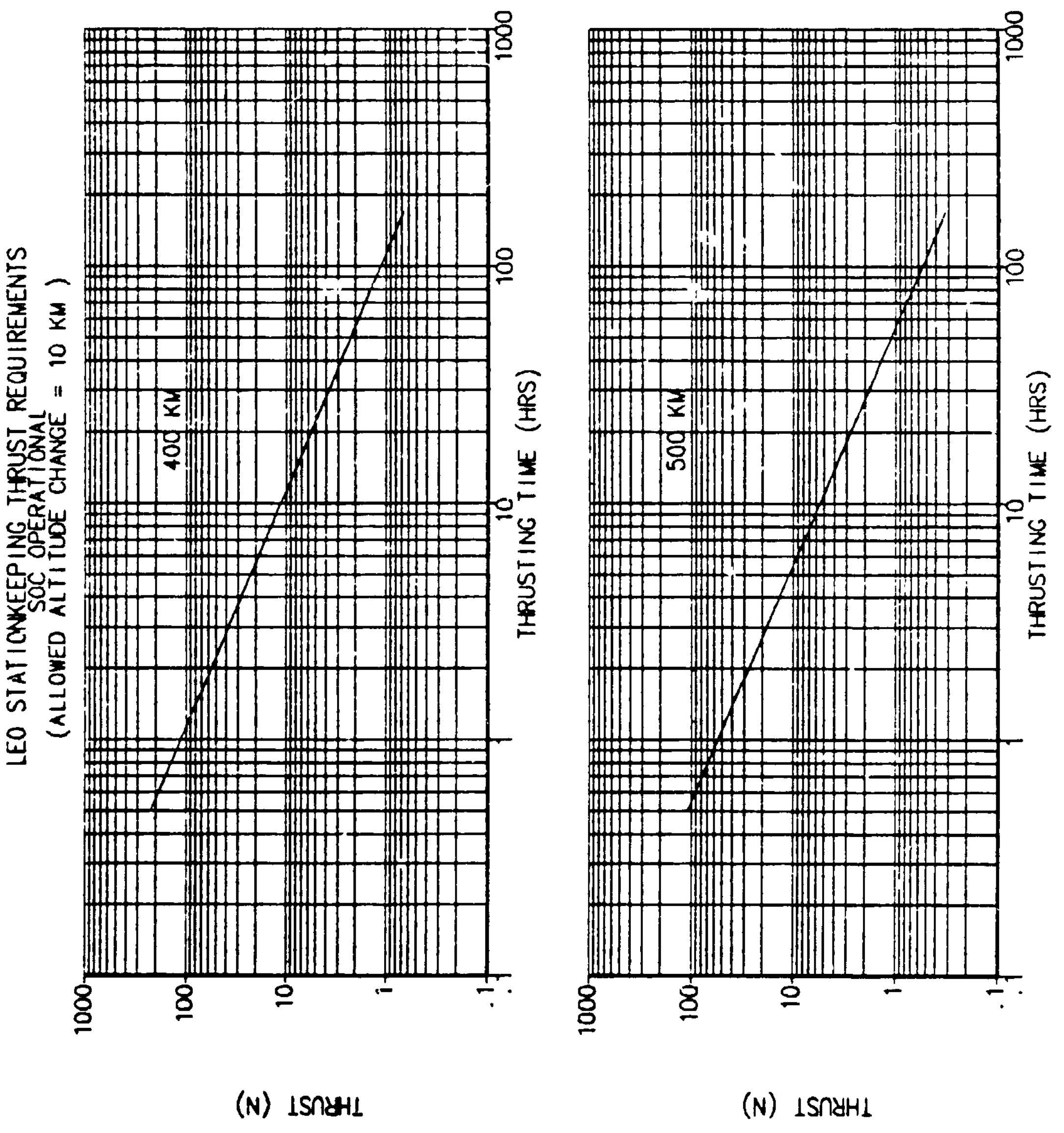



LEO STATIONKEEPING THRUST REQUIREMENTS
SOC INITIAL
(ALLOWED ALTITUDE CHANGE = 10 KM)
400 KM
THRUST (N)
1000
100
10
1
.1
THRUSTING TIME (HRS)
1
10
100
1000
500 KM
THRUST (N)
100
10
1
.1
THRUSTING TIME (HRS)
1
10
100
1000


LEO STATIONKEEPING THRUST REQUIREMENTS
SOC OPERATIONAL
(ALLOWED ALTITUDE CHANGE = 10 KM)
400 KM
500 KM
THRUST (N)
THRUSTING TIME (HRS)
1000
100
10
1
.1

APPENDIX C

Thruster Requirements

LAPAA - Electronic Mail and Educational TV

	Location (m)*			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-4.800	0.000	21.700	0.000	1.000	0.000
2	-4.800	0.000	21.700	0.000	-1.000	0.000
3	4.800	0.000	21.700	0.000	1.000	0.000
4	4.800	0.000	21.700	0.000	-1.000	0.000
5	4.800	0.000	21.700	-1.000	0.000	0.000
6	-4.800	0.000	21.700	1.000	0.000	0.000
7	0.000	2.000	0.000	-1.000	0.000	0.000
8	0.000	2.000	0.000	1.000	0.000	0.000
9	0.000	-2.000	0.000	-1.000	0.000	0.000
10	0.000	-2.000	0.000	1.000	0.000	0.000
11	0.000	2.000	0.000	-0.707	-0.707	0.000
12	0.000	2.000	0.000	0.707	-0.707	0.000
13	0.000	-2.000	0.000	-0.707	0.707	0.000
14	0.000	-2.000	0.000	0.707	0.707	0.000

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

Table A1 LAPAA Thruster Coordinates

Thrust/Thruster Requirements (N)

Electronic Mail (LAPAA), g-load = .15

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km	
	.5	5	100
1	0.750E+00	0.750E-01	0.365E-02
2	0.750E+00	0.750E-01	0.365E-02
3	0.750E+00	0.750E-01	0.365E-02
4	0.750E+00	0.750E-01	0.365E-02
5	0.000E+00	0.000E+00	0.000E+00
6	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00
8	0.000E+00	0.000E+00	0.000E+00
9	0.000E+00	0.000E+00	0.000E+00
10	0.000E+00	0.000E+00	0.000E+00
11	0.281E+01	0.281E+00	0.137E-01
12	0.281E+01	0.281E+00	0.137E-01
13	0.281E+01	0.281E+00	0.137E-01
14	0.281E+01	0.281E+00	0.137E-01

Table A2 Stationkeeping Thrust Requirements - Electronic Mail

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Thrust/Thruster Requirements (N)

Electronic Mail, g-load = .06

Thruster #	Correction Frequency	GEO Stationkeeping Requirements Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.446E-02	0.119E-03	0.446E-02	0.119E-03
2		0.446E-02	0.119E-03	0.446E-02	0.119E-03
3		0.446E-02	0.119E-03	0.446E-02	0.119E-03
4		0.446E-02	0.119E-03	0.446E-02	0.119E-03
5		0.332E+00	0.888E-02	0.474E-01	0.126E-02
6		0.332E+00	0.888E-02	0.474E-01	0.126E-02
7		0.439E+00	0.118E-01	0.628E-01	0.167E-02
8		0.439E+00	0.118E-01	0.628E-01	0.167E-02
9		0.439E+00	0.118E-01	0.628E-01	0.167E-02
10		0.439E+00	0.118E-01	0.628E-01	0.167E-02
11		0.167E-01	0.447E-03	0.167E-01	0.447E-03
12		0.167E-01	0.447E-03	0.167E-01	0.447E-03
13		0.167E-01	0.447E-03	0.167E-01	0.447E-03
14		0.167E-01	0.447E-03	0.167E-01	0.447E-03

Table A3 Stationkeeping Thrust Requirements
Electronic Mail

Thrust/Thruster Requirements (N)

Electronic Mail, g-load = .15

Thruster #	Correction Frequency / Duty Cycle	GEO Stationkeeping Requirements: Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.487E-02	0.130E-03	0.487E-02	0.130E-03
2		0.487E-02	0.130E-03	0.487E-02	0.130E-03
3		0.487E-02	0.130E-03	0.487E-02	0.130E-03
4		0.487E-02	0.130E-03	0.487E-02	0.130E-03
5		0.382E+00	0.971E-02	0.518E-01	0.140E-02
6		0.382E+00	0.971E-02	0.518E-01	0.140E-02
7		0.479E+00	0.128E-01	0.686E-01	0.185E-[illegible]
8		0.479E+00	0.128E-01	0.686E-01	0.185E-02
9		0.479E+00	0.128E-01	0.686E-01	0.185E-02
10		0.479E+00	0.128E-01	0.686E-01	0.185E-02
11		0.182E-01	0.488E-03	0.182E-01	0.488E-03
12		0.182E-01	0.488E-03	0.182E-01	0.488E-03
13		0.182E-01	0.488E-03	0.182E-01	0.488E-03
14		0.182E-01	0.488E-03	0.182E-01	0.488E-03

Table A4 Stationkeeping Thrust Requirements
Electronic Mail

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Thrust/Thruster Requirements (N)

Electronic Mail, g-load = 1.0

Thruster #	GEO Stationkeeping Requirements			
Correction Frequency	Once/Week		Once/Day	
Duty Cycle	.01	.4	.01	.4
1	0.108E-01	0.288E-03	0.108E-01	0.288E-03
2	0.108E-01	0.288E-03	0.108E-01	0.288E-03
3	0.108E-01	0.288E-03	0.108E-01	0.288E-03
4	0.108E-01	0.288E-03	0.108E-01	0.288E-03
5	0.806E+00	0.215E-01	0.115E+00	0.307E-02
6	0.806E+00	0.215E-01	0.115E+00	0.307E-02
7	0.107E+01	0.285E-01	0.152E+00	0.406E-02
8	0.107E+01	0.285E-01	0.152E+00	0.406E-02
9	0.107E+01	0.285E-01	0.152E+00	0.406E-02
10	0.107E+01	0.285E-01	0.152E+00	0.406E-02
11	0.404E-01	0.108E-02	0.404E-01	0.108E-02
12	0.404E-01	0.108E-02	0.404E-01	0.108E-02
13	0.404E-01	0.108E-02	0.404E-01	0.108E-02
14	0.404E-01	0.108E-02	0.404E-01	0.108E-02

Table A5 Stationkeeping Thrust Requirements
Electronic Mail

Thrust/Thruster Requirements (N)

Electronic Mail, g-load = .06

	Disturbance Torques					
	Nominal			Worst Case		
Thruster #	400 km	500 km	GEO	400 km	500 km	GEO
1	0.213E-02	0.133E-02	0.800E-05	0.217E-01	0.859E-02	0.377E-04
2	0.213E-02	0.133E-02	0.800E-05	0.217E-01	0.859E-02	0.377E-04
3	0.213E-02	0.133E-02	0.800E-05	0.217E-01	0.859E-02	0.377E-04
4	0.213E-02	0.133E-02	0.800E-05	0.217E-01	0.859E-02	0.377E-04
5	0.150E-03	0.588E-02	0.234E-04	0.406E-01	0.168E-01	0.576E-04
6	0.150E-01	0.588E-02	0.234E-04	0.406E-01	0.168E-01	0.576E-04
7	0.749E-02	0.294E-02	0.117E-04	0.203E-01	0.838E-02	0.288E-04
8	0.749E-04	0.294E-02	0.117E-04	0.203E-01	0.838E-02	0.288E-04
9	0.749E-02	0.294E-02	0.117E-04	0.203E-01	0.838E-02	0.288E-04
10	0.749E-04	0.294E-02	0.117E-04	0.203E-01	0.838E-02	0.288E-04
11	0.301E-02	0.188E-02	0.113E-04	0.307E-01	0.121E-01	0.534E-04
12	0.301E-02	0.188E-02	0.113E-04	0.307E-01	0.121E-01	0.534E-04
13	0.301E-02	0.188E-02	0.113E-04	0.307E-01	0.121E-01	0.534E-04
14	0.301E-02	0.188E-02	0.113E-04	0.307E-01	0.121E-01	0.534E-04

Table A6 Disturbance Torque Thruster Requirements
Electronic Mail

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Thrust/Thruster Requirements (N)

Electronic Mail, g-load = .15

Thruster #	Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.414E-02	0.215E-02	0.757E-05	0.188E-01	0.840E-02	0.360E-04
2	0.414E-02	0.215E-02	0.757E-05	0.188E-01	0.840E-02	0.360E-04
3	0.414E-02	0.215E-02	0.757E-05	0.188E-01	0.840E-02	0.360E-04
4	0.414E-02	0.215E-02	0.757E-05	0.188E-01	0.840E-02	0.360E-04
5	0.341E-01	0.104E-01	0.174E-03	0.341E-01	0.123E-01	0.175E-03
6	0.341E-01	0.104E-01	0.174E-03	0.341E-01	0.123E-01	0.175E-03
7	0.170E-01	0.519E-02	0.872E-04	0.170E-01	0.614E-02	0.876E-04
8	0.170E-01	0.519E-02	0.872E-04	0.170E-01	0.614E-02	0.876E-04
9	0.170E-01	0.519E-02	0.872E-04	0.170E-01	0.614E-02	0.876E-04
10	0.170E-01	0.519E-02	0.872E-04	0.170E-01	0.614E-02	0.876E-04
11	0.585E-02	0.304E-02	0.107E-04	0.266E-01	0.119E-01	0.509E-04
12	0.585E-02	0.304E-02	0.107E-04	0.266E-01	0.119E-01	0.509E-04
13	0.585E-02	0.304E-02	0.107E-04	0.266E-01	0.119E-01	0.509E-04
14	0.585E-02	0.304E-02	0.107E-04	0.266E-01	0.119E-01	0.509E-04

(Column group heading: Disturbance Torques)

Table A7 Disturbance Torque Thruster Requirements

Electronic Mail

Thrust/Thruster Requirements (N)

Electronic Mail, g-load = 1.0

	Disturbance Torques					
	Nominal			Worst Case		
Thruster #	400 km	500 km	GEO	400 km	500 km	GEO
1	0.116E-01	0.630E-02	0.242E-04	0.319E-01	0.177E-01	0.710E-04
2	0.116E-01	0.630E-02	0.242E-04	0.319E-01	0.177E-01	0.710E-04
3	0.116E-01	0.630E-02	0.242E-04	0.319E-01	0.177E-01	0.710E-04
4	0.116E-01	0.630E-02	0.242F-04	0.319E-01	0.177E-01	0.710E-04
5	0.880E-01	0.326E-01	0.428E-03	0.913E-01	0.422E-01	0.433E-03
6	0.880E-01	0.326E-01	0.428E-03	0.913E-01	0.422E-01	0.433E-03
7	0.440E-01	0.163E-01	0.214E-03	0.457E-01	0.211E-01	0.216E-03
8	0.440E-01	0.163E-01	0.214E-03	0.457E-01	0.211E-01	0.216E-03
9	0.440E-01	0.163E-01	0.214E-03	0.457E-01	0.211E-01	0.216E-03
10	0.440E-01	0.163E-01	0.214E-03	0.457E-01	0.211E-01	0.216E-03
11	0.165E-01	0.892E-02	0.343E-04	0.491E-01	0.250E-01	0.100E-03
12	0.165E-01	0.892E-02	0.343E-04	0.451E-01	0.250E-01	0.100E-03
13	0.165E-01	0.892E-02	0.343E-04	0.451E-01	0.250E-01	0.100E-03
14	0.165E-01	0.892E-02	0.343E-04	0.451E-01	0.250E-01	0.100E-03

Table A8 Disturbance Torque Thruster Requirements

Electronic Mail

Thrust/Thruster Requirements (N)

Educational TV (LAPAA), g-load = .15

Thruster #	LEO Stationkeeping Requirements at 400 km Thrusting Time (Hrs) .5	5	100
1	0.684E+00	0.684E-01	0.343E-02
2	0.684E+00	0.684E-01	0.343E-02
3	0.684E+00	0.684E-01	0.343E-02
4	0.684E+00	0.684E-01	0.343E-02
5	0.000E+00	0.000E+00	0.000E+00
6	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00
8	0.000E+00	0.000E+00	0.000E+00
9	0.000E+00	0.000E+00	0.000E+00
10	0.000E+00	0.000E+00	0.000E+00
11	0.696E+01	0.696E+00	0.348E-01
12	0.696E+01	0.696E+00	0.348E-01
13	0.696E+01	0.696E+00	0.348E-01
14	0.696E+01	0.696E+00	0.348E-01

Table A9 Stationkeeping Thrust Requirements - Educational TV

Thrust/Thruster Requirements (N)

Educational TV, g-load = .06

Thruster #	Correction Frequency	GEO Stationkeeping Requirements			
		Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.539E-02	0.147E-03	0.539E-02	0.147E-03
2		0.539E-02	0.147E-03	0.539E-02	0.147E-03
3		0.539E-02	0.147E-03	0.539E-02	0.147E-03
4		0.539E-02	0.147E-03	0.539E-02	0.147E-03
5		0.402E+00	0.107E-01	0.574E-01	0.154E-02
6		0.402E+00	0.107E-01	0.574E-01	0.154E-02
7		0.144E+01	0.386E-01	0.206E+00	0.553E-02
8		0.144E+01	0.386E-01	0.206E+00	0.553E-02
9		0.144E+01	0.386E-01	0.206E+00	0.553E-02
10		0.144E+01	0.386E-01	0.206E+00	0.553E-02
11		0.548E-01	0.149E-02	0.548E-01	0.149E-02
12		0.548E-01	0.149E-02	0.548E-01	0.149E-02
13		0.548E-01	0.149E-02	0.548E-01	0.149E-02
14		0.548E-01	0.149E-02	0.548E-01	0.149E-02

Table A10 Stationkeeping Thrust Requirements

Educational TV

Thrust Thruster Requirements (N)

Educational TV, g-load = .15

Thruster #	Correction Frequency	GEO Stationkeeping Requirements: Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.560E-02	0.153E-03	0.560E-02	0.153E-03
2		0.560E-02	0.153E-03	0.560E-02	0.153E-03
3		0.560E-02	0.153E-03	0.560E-02	0.153E-03
4		0.560E-02	0.153E-03	0.560E-02	0.153E-03
5		0.418E+00	0.112E-01	0.596E-01	0.160E-02
6		0.418E+00	0.112E-01	0.596E-01	0.160E-02
7		0.150E+01	0.401E-01	0.214E+00	0.575E-02
8		0.150E+01	0.401E-01	0.214E+00	0.575E-02
9		0.150E+01	0.401E-01	0.214E+00	0.575E-02
10		0.150E+01	0.401E-01	0.214E+00	0.575E-02
11		0.569E-01	0.155E-02	0.569E-01	0.155E-02
12		0.569E-01	0.155E-02	0.569E-01	0.155E-02
13		0.569E-01	0.155E-02	0.569E-01	0.155E-02
14		0.569E-01	0.155E-02	0.569E-01	0.155E-02

Table A11 Stationkeeping Thrust Requirements
Educational TV

Thrust/Thruster Requirements (N)

Educational TV, g-load = 1.0

Thruster #	GEO Stationkeeping Requirements — Correction Frequency: Once/Week, Duty Cycle .01	Once/Week, .4	Once/Day, .01	Once/Day, .4
1	0.849E-02	0.226E-03	0.849E-02	0.226E-03
2	0.849E-02	0.226E-03	0.849E-02	0.226E-03
3	0.849E-02	0.226E-03	0.849E-02	0.226E-03
4	0.849E-02	0.226E-03	0.849E-02	0.226E-03
5	0.631E+00	0.169E-01	0.902E-01	0.242E-02
6	0.631E+00	0.169E-01	0.902E-01	0.242E-02
7	0.227E+01	0.606E-01	0.324E+00	0.869E-02
8	0.227E+01	0.606E-01	0.324E+00	0.869E-02
9	0.227E+01	0.606E-01	0.324E+00	0.869E-02
10	0.227E+01	0.606E-01	0.324E+00	0.869E-02
11	0.863E-01	0.230E-02	0.863E-01	0.230E-02
12	0.863E-01	0.230E-02	0.863E-01	0.230E-02
13	0.863E-01	0.230E-02	0.863E-01	0.230E-02
14	0.863E-01	0.230E-02	0.863E-01	0.230E-02

Table A12 Stationkeeping Thrust Requirements

Educational TV

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Thrust/Thruster Requirements (N)

Educational TV, g-load = .06

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.455E-02	0.145E-02	0.386E-05	0.812E-01	0.246E-01	0.857E-04
2	0.455E-02	0.145E-02	0.386E-05	0.812E-01	0.246E-01	0.857E-04
3	0.455E-02	0.145E-02	0.386E-05	0.812E-01	0.246E-01	0.857E-04
4	0.455E-02	0.145E-02	0.386E-05	0.812E-01	0.246E-01	0.857E-04
5	0.547E-01	0.165E-01	0.276E-03	0.163E+00	0.548E-01	0.276E-03
6	0.547E-01	0.165E-01	0.276E-03	0.163E+00	0.548E-01	0.276E-03
7	0.274E-01	0.826E-02	0.138E-03	0.817E-01	0.274E-01	0.138E-03
8	0.274E-01	0.826E-02	0.138E-03	0.817E-01	0.274E-01	0.138E-03
9	0.274E-01	0.826E-02	0.138E-03	0.817E-01	0.274E-01	0.138E-03
10	0.274E-01	0.826E-02	0.138E-03	0.817E-01	0.274E-01	0.138E-03
11	0.643E-02	0.205E-02	0.360E-05	0.115E+00	0.348E-01	0.121E-03
12	0.643E-02	0.205E-02	0.360E-05	0.115E+00	0.348E-01	0.121E-03
13	0.643E-02	0.205E-02	0.360E-05	0.115E+00	0.348E-01	0.121E-03
14	0.643E-02	0.205E-02	0.360E-05	0.115E+00	0.348E-01	0.121E-03

Table A13 Disturbance Torque Thruster Requirements

Educational TV

Thrust/Thruster Requirements (N)

Educational TV, g-load = .15

Thruster #	Disturbance Torques: Nominal, 400 km	Nominal, 500 km	Nominal, GEO	Worst Case, 400 km	Worst Case, 500 km	Worst Case, GEO
1	0.116E-01	0.369E-02	0.122E-04	0.789E-01	0.242E-01	0.842E-04
2	0.116E-01	0.369E-02	0.122E-01	0.789E-01	0.242E-01	0.842E-04
3	0.116E-01	0.369E-02	0.122E-04	0.789E-01	0.242E-01	0.842E-04
4	0.116E-01	0.369E-02	0.122E-04	0.789E-01	0.242E-01	0.842E-04
5	0.125E+00	0.401E-01	0.410E-03	0.197E+00	0.668E-01	0.436E-03
6	0.125E+00	0.401E-01	0.410E-03	0.197E+00	0.668E-01	0.436E-03
7	0.626E-01	0.200E-01	0.205E-03	0.983E-01	0.334E-01	0.218E-03
8	0.626E-01	0.200E-01	0.205E-03	0.983E-01	0.334E-01	0.218E-03
9	0.626E-01	0.200E-01	0.205E-03	0.983E-01	0.334E-01	0.218E-03
10	0.626E-01	0.200E-01	0.205E-03	0.983E-01	0.334E-01	0.218E-03
11	0.164E-01	0.522E-02	0.172E-04	0.112E+00	0.343E-01	0.119E-03
12	0.164E-01	0.522E-02	0.172E-04	0.112E+00	0.343E-01	0.119E-03
13	0.164E-01	0.522E-02	0.172E-04	0.112E+00	0.343E-01	0.119E-03
14	0.164E-01	0.522E-02	0.172E-04	0.112E+00	0.343E-01	0.119E-03

Table A14 Disturbance Torque Thruster Requirements

Educational TV

Thrust/Thruster Requirements (N)

Educational TV, g-load = 1.0

Thruster #	Disturbance Torques: Nominal, 400 km	Nominal, 500 km	Nominal, GEO	Worst Case, 400 km	Worst Case, 500 km	Worst Case, GEO
1	0.225E-01	0.955E-02	0.325E-04	0.605E-01	0.252E-01	0.939E-04
2	0.225E-01	0.956E-02	0.325E-04	0.605E-01	0.252E-01	0.939E-04
3	0.225E-01	0.955E-02	0.325E-04	0.605E-01	0.252E-01	0.939E-04
4	0.225E-01	0.955E-02	0.325E-04	0.605E-01	0.252E-01	0.939E-04
5	0.211E+00	0.682E-01	0.108E-02	0.212E+00	0.690E-01	0.108E-02
6	0.211E+00	0.682E-01	0.108E-02	0.212E+00	0.690E-01	0.108E-02
7	0.105E+00	0.341E-01	0.541E-03	0.106E+00	0.345E-01	0.540E-03
8	0.105E+00	0.341E-01	0.541E-03	0.106E+00	0.345E-01	0.540E-03
9	0.105E+00	0.341E-01	0.541E-03	0.106E+00	0.345E-01	0.540E-03
10	0.105E+00	0.341E-01	0.541E-03	0.106E+00	0.345E-01	0.540E-03
11	0.318E-01	0.135E-01	0.460E-04	0.855E-01	0.356E-01	0.133E-03
12	0.318E-01	0.135E-01	0.460E-04	0.855E-01	0.356E-01	0.133E-03
13	0.318E-01	0.135E-01	0.460E-04	0.855E-01	0.356E-01	0.133E-03
14	0.318E-01	0.135E-01	0.460E-04	0.855E-01	0.356E-01	0.133E-03

Table A15 Disturbance Torque Thruster Requirements

Educational TV

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Land Mobile Satellite System Wrap Rib

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-0.119	-7.790	5.530	0.000	1.000	0.000
2	-1.000	-7.790	5.530	-1.000	0.000	0.000
3	1.000	-7.790	5.530	1.000	0.000	0.000
4	-0.119	11.100	0.000	-1.000	0.000	0.000
5	-0.119	11.100	0.000	1.000	0.000	0.000
6	-0.119	11.100	0.000	0.000	-0.707	0.707
7	-0.119	11.100	0.000	0.000	-0.707	-0.707
8	1.000	-29.960	-75.410	-1.000	0.000	0.000
9	-0.119	-29.960	-75.410	0.000	1.000	0.000
10	-1.000	-29.960	-75.410	1.000	0.000	0.000
11	1.000	0.000	-82.450	-1.000	0.000	0.000
12	-0.119	0.000	-82.450	0.000	-1.000	0.000
13	-1.000	0.000	-82.450	1.000	0.000	0.000

Table A16 LMSS Wrap Rib Thruster Coordinates

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

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Thrust/Thruster Requirements (N)

Land Mobile Satellite System Wrap Rib

g-load = .15

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km		
		.5	5	100
1		0.000E+00	0.000E+00	0.000E+00
2		0.812E+01	0.727E+00	0.352E-01
3		0.812E+01	0.727E+00	0.352E-01
4		0.328E+01	0.294E+00	0.142E-01
5		0.328E+01	0.294E+00	0.142E-01
6		0.000E+00	0.000E+00	0.000E+00
7		0.000E+00	0.000E+00	0.000E+00
8		0.134E+01	0.120E+00	0.581E-02
9		0.000E+00	0.000E+00	0.000E+00
10		0.134E+01	0.120E+00	0.581E-02
11		0.134E+01	0.120E+00	0.581E-02
12		0.000E+00	0.000E+00	0.000E+00
13		0.134E+01	0.120E+00	0.581E-02

Table A17 Stationkeeping Thrust Requirements
LMSS Wrap Rib

Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = .06

Thruster #	Correction Frequency	Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.232E+01	0.649E-01	0.331E+00	0.882E-02
2		0.459E-01	0.127E-02	0.459E-01	0.121E-02
3		0.459E-01	0.127E-02	0.459E-01	0.121E-02
4		0.185E-01	0.513E-03	0.185E-01	0.489E-03
5		0.185E-01	0.513E-03	0.185E-01	0.489E-03
6		0.179E+01	0.501E-01	0.255E+00	0.680E-02
7		0.179E+01	0.501E-01	0.255E+00	0.680E-02
8		0.759E-02	0.210E-03	0.759E-02	0.200E-03
9		0.634E+00	0.178E-01	0.905E-01	0.241E-02
10		0.759E-02	0.210E-03	0.759E-02	0.200E-03
11		0.759E-02	0.210E-03	0.759E-02	0.200E-03
12		0.425E+00	0.119E-01	0.606E-01	0.162E-02
13		0.759E-02	0.210E-03	0.759E-02	0.200E-03

Table A18 Stationkeeping Thrust Requirements
LMSS Wrap Rib

Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = .15

Thruster #	GEO Stationkeeping Requirements			
	Correction Frequency: Once/Week		Once/Day	
	Duty Cycle .01	.4	.01	.4
1	0.243E+01	0.849E-01	0.347E+00	0.929E-02
2	0.481E-01	0.127E-02	0.481E-01	0.127E-02
3	0.481E-01	0.127E-02	0.481E-01	0.127E-02
4	0.194E-01	0.513E-03	0.194E-01	0.513E-03
5	0.194E-01	0.513E-03	0.194E-01	0.513E-03
6	0.187E+01	0.501E-01	0.268E+00	0.716E-02
7	0.187E+01	0.501E-01	0.268E+00	0.716E-02
8	0.795E-02	0.210E-03	0.795E-02	0.210E-03
9	0.884E+00	0.178E-01	0.950E-01	0.234E-02
10	0.795E-02	0.210E-03	0.795E-02	0.210E-03
11	0.79[illegible]-02	0.210E-03	0.795E-02	0.210E-03
12	[illegible]	0.119E-01	0.838E-01	0.170E-02
13	[illegible]-02	0.210E-03	0.795E-02	0.210E-03

Table A19 Stationkeeping Thrust Requirements

LMSS Wrap Rib

Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = 1.0

Thruster #	GEO Stationkeeping Requirements			
	Correction Frequency: Once/Week		Once/Day	
	Duty Cycle .01	.4	.01	.4
1	0.348E+01	0.929E-01	0.497E+00	0.183E-01
2	0.692E-01	0.184E-02	0.692E-01	0.184E-02
3	0.692E-01	0.184E-02	0.692E-01	0.184E-02
4	0.280E-01	0.745E-03	0.280E-01	0.745E-03
5	0.280E-01	0.745E-03	0.280E-01	0.745E-03
6	0.268E+01	0.716E-01	0.383E+00	0.102E-01
7	0.267E+01	0.716E-01	0.383E+00	0.102E-01
8	0.114E-01	0.305E-03	0.114E-01	0.305E-03
9	0.952E+00	0.254E-01	0.136E+00	0.363E-02
10	0.114E-01	0.305E-03	0.114E-01	0.305E-03
11	0.114E-01	0.305E-03	0.114E-01	0.305E-03
12	0.838E+00	0.170E-01	0.911E-01	0.243E-02
13	0.114E-01	0.305E-03	0.114E-01	0.305E-03

Table A20 Stationkeeping Thrust Requirements

LMSS Wrap Rib

Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = .06

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.655E-01	0.437E-01	0.197E-03	0.182E+00	0.843E-01	0.563E-03
2	0.[illegible]5E+00	0.472E-01	0.511E-03	0.153E+00	0.720E-01	0.540E-03
3	0.125E+00	0.472E-01	0.511E-03	0.153E+00	0.720E-01	0.540E-03
4	0.924E-01	0.332E-01	0.400E-03	0.105E+00	0.462E-01	0.410E-03
5	0.924E-01	0.332E-01	0.400E-03	0.105E+00	0.462E-01	0.410E-03
6	0.540E-01	0.361E-01	0.163E-03	0.150E+00	0.696E-01	0.464E-03
7	0.540E-01	0.361E-01	0.163E-03	0.150E+00	0.696E-01	0.464E-03
8	0.924E-01	0.332E-01	0.400E-03	0.105E+00	0.462E 01	0.410E-03
9	0.764E-01	0.510E-01	0.230E-03	0.212E+00	0.984E-01	0.656E-03
10	0.924E-01	0.332E-01	0.400E-03	0.105E+00	0.462E-01	0.410E-03
11	0.125E+00	0.472E-01	0.511E-03	0.153E+00	0.720E-01	0.540E-03
12	0.655E-01	0.437E-01	0.197E-03	0.182E+00	0.843E-01	0.563E-03
13	0.125E+00	0.472E-01	0.511E-03	0.153E+00	0.720E-01	0.540E-03

Table A21 Disturbance Torque Thruster Requirements
LMSS Wrap Rib

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Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = .15

	Disturbance Torques					
	Nominal			Worst Case		
Thruster #	400 km	500 km	GEO	400 km	500 km	GEO
1	0.393E-01	0.239E-01	0.109E-03	0.188E+00	0.875E-01	0.675E-03
2	0.127E+00	0.512E-01	0.524E-03	0.156E+00	0.769E-01	0.566E-03
3	0.127E+00	0.512E-01	0.524E-03	0.156E+00	0.769E-01	0.566E-03
4	0.823E-01	0.259E-01	0.363E-03	0.137E+00	0.774E-01	0.587E-03
5	0.823E-01	0.259E-01	0.363E-03	0.137E+00	0.774E-01	0.587E-03
6	0.324E-01	0.198E-01	0.900E-04	0.155E+00	0.722E-01	0.475E-03
7	0.324E-01	0.198E-01	0.900E-04	0.155E+00	0.722E-01	0.475E-03
8	0.823E-01	0.259E-01	0.363E-03	0.137E+00	0.774E-01	0.587E-03
9	0.458E-01	0.279E-01	0.127E-03	0.219E+00	0.102E+00	0.671E-03
10	0.823E-01	0.259E-01	0.363E-03	0.137E+00	0.774E-01	0.587E-03
11	0.127E+00	0.512E-01	0.524E-03	0.156E+00	0.769E-01	0.566E-03
12	0.393E-01	0.239E-01	0.109E-03	0.188E+00	0.875E-01	0.575E-03
13	0.127E+00	0.512E-01	0.524E-03	0.156E+00	0.769E-01	0.566E-03

Table A22 Disturbance Torque Thruster Requirements

LMSS Wrap Rib

Thrust/Thruster Requirements (N)

LMSS Wrap Rib, g-load = 1.0

Thruster #	Disturbance Torques Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.118E+00	0.980E-01	0.427E-03	0.195E+00	0.134E+00	0.707E-03
2	0.122E+00	0.583E-01	0.521E-03	0.176E+00	0.115E+00	0.668E-03
3	0.122E+00	0.583E-01	0.521E-03	0.176E+00	0.115E+00	0.668E-03
4	0.853E-01	0.410E-01	0.392E-03	0.117E+00	0.797E-01	0.487E-03
5	0.853E-01	0.410E-01	0.392E-03	0.117E+00	0.797E-01	0.487E-03
6	0.973E-01	0.808E-01	0.352E-03	0.161E+00	0.111E+00	0.583E-03
7	0.973E-01	0.808E-01	0.352E-03	0.161E+00	0.111E+00	0.583E-03
8	0.853E-01	0.410E-01	0.392E-03	0.117E+00	0.797E-01	0.487E-03
9	0.138E+00	0.114E+00	0.498E-03	0.228E+00	0.157E+00	0.824E-03
10	0.853E-01	0.410E-01	0.392E-03	0.117E+00	0.797E-01	0.487E-03
11	0.122E+00	0.583E-01	0.521E-03	0.176E+00	0.115E+00	0.668E-03
12	0.118E+00	0.980E-01	0.427E-03	0.195E+00	0.134E+00	0.707E-03
13	0.122E+00	0.583E-01	0.521E-03	0.176E+00	0.115E+00	0.668E-03

Table A23 Disturbance Torque Thruster Requirements
LMSS Wrap Rib

LMSS Hoop Column

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	0.000	-59.730	-57.320	1.000	0.000	0.000
2	0.000	-59.730	-57.320	-1.000	0.000	0.000
3	59.730	0.000	-57.320	0.000	1.000	0.000
4	59.730	0.000	-57.320	0.000	-1.000	0.000
5	0.000	59.730	-57.320	1.000	0.000	0.000
6	0.000	59.730	-57.320	-1.000	0.000	0.000
7	-59.730	0.000	-57.320	0.000	1.000	0.000
8	-59.730	0.000	-57.320	0.000	-1.000	0.000
9	0.000	-4.790	3.800	-1.000	0.000	0.000
10	0.000	-4.790	3.800	1.000	0.000	0.000
11	0.000	-4.790	3.800	0.000	1.000	0.000
12	0.000	-4.790	3.800	0.000	-1.000	0.000

Table A24 LMSS Hoop Column Thruster Coordinates

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

Thrust/Thruster Requirements (N)
LMSS Hoop Column, g-load = .15

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km		
		.5	5	100
1		0.000E+00	0.000E+00	0.000E+00
2		0.000E+00	0.000E+00	0.000E+00
3		(144E+02	0.740E+00	0.352E-01
4		0.144E+02	0.740E+00	0.352E-01
5		0.000E+00	0.000E+00	0.000E+00
6		0.000E+00	0.000E+00	0.000E+00
7		0.144E+02	0.740E+00	0.352E-01
8		0.144E+02	0.740E+00	0.352E·01
9		0.000E+00	0.000E+00	0.000E+00
10		0.000E+00	0.000E+00	0.000E+00
11		0.286E+02	0.146E+01	0.697E-01
12		0.286E+02	0.146E+01	0.697E-01

Table A23 Stationkeeping Thrust Requirements
LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = .06

Thruster #	Correction Frequency	GEO Stationkeeping Requirements			
		Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.653E+00	0.174E-01	0.933E-01	0.250E-02
2		0.653E+00	0.174E-01	0.933E-01	0.250E-02
3		0.190E-01	0.503E-03	0.190E-01	0.503E-03
4		0.190E-01	0.503E-03	0.190E-01	0.503E-03
5		0.765E+00	0.205E-01	0.109E+00	0.293E-02
6		0.765E+00	0.205E-01	0.109E+00	0.293E-02
7		0.190E-01	0.503E-03	0.190E-01	0.503E-03
8		0.190E-01	0.503E-03	0.190E-01	0.503E-03
9		0.140E+01	0.375E-01	0.200E+00	0.537E-02
10		0.140E+01	0.375E-01	0.200E+00	0.537E-02
11		0.376E-01	0.995E-03	0.376E-01	0.995E-03
12		0.376E-01	0.995E-03	0.376E-01	0.995E-03

Table A26 Stationkeeping Thrust Requirements

LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = .15

Thruster #	GEO Stationkeeping Requirements			
Correction Frequency	Once/Week		Once/Day	
Duty Cycle	.01	.4	.01	.4
1	0.690E+00	0.184E-01	0.986E-01	0.264E-02
2	0.690E+00	0.184E-01	0.986E-01	0.264E-02
3	0.201E-01	0.528E-03	0.201E-01	0.523E-03
4	0.201E-01	0.528E-03	0.201E-01	0.528E-03
5	0.808E+00	0.216E-01	0.116E+00	0.309E-02
6	0.808E+00	0.216E-01	0.116E+00	0.309E-02
7	0.201E-01	0.528E-03	0.201E-01	0.528E-03
8	0.201E-01	0.528E-03	0.201E-01	0.528E-03
9	0.148E+01	0.396E-01	0.212E+00	0.567E-02
10	0.148E+01	0.396E-01	0.212E+00	0.587E-02
11	0.397E-01	0.104E-02	0.397E-01	0.104E-02
12	0.397E-01	0.104E-02	0.397E-01	0.104E-02

Table A27 Stationkeeping Thrust Requirements
LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = 1.0

Thruster #	GEO Stationkeeping Requirements — Correction Frequency: Once/Week, Duty Cycle .01	Once/Week, .4	Once/Day, .01	Once/Day, .4
1	0.118E+01	0.317E-01	0.169E+00	0.451E-02
2	0.118E+01	0.317E-01	0.169E+00	0.451E-02
3	0.344E-01	0.930E-03	0.344E-01	0.930E-03
4	0.344E-01	0.930E-03	0.344E-[illegible]	0.930E-03
5	0.139E+01	0.372E-01	0.198E+00	0.529E-02
6	0.139E+01	0.372E-01	0.198E+00	0.529E-02
7	0.344E-01	0.930E-03	0.344E-01	0.930E-03
8	0.344E-01	0.930E-03	0.344E-01	0.930E-03
9	0.254E+01	0.681E-01	0.364E+00	0.970E-02
10	0.254E+01	0.681E-01	0.364E+00	0.970E-02
11	0.681E-01	0.184E-02	0.681E-01	0.184E-02
12	0.681E-01	0.184E-02	0.681E-01	0.184E-02

Table A28 Stationkeeping Thrust Requirements
LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = .06

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.146E+00	0.520E-01	0.418E-03	0.242E+00	0.964E-01	0.498E-03
2	0.146E+00	0.520E-01	0.418E-03	0.242E+00	0.964E-01	0.498E-03
3	0.314E-01	0.167E-01	0.758E-04	0.225E+00	0.894E-01	0.462E-03
4	0.314E-01	0.167E-01	0.758E-04	0.225E+00	0.894E-01	0.462E-03
5	0.124E+00	0.443E-01	0.356E-03	0.206E+00	0.821E-01	0.424E-03
6	0.124E+00	0.443E-01	0.356E-03	0.206E+00	0.821E-01	0.424E-03
7	0.314E-01	0.167E-01	0.758E-04	0.225E+00	0.894E-01	0.462E-03
8	0.314E-01	0.167E-01	0.758E-04	0.225E+00	0.894E-01	0.462E-03
9	0.270E+00	0.963E-01	0.774E-03	0.449E+00	0.179E+00	0.923E-03
10	0.270E+00	0.963E-01	0.774E-03	0.449E+00	0.179E+00	0.923E-03
11	0.828E-01	0.334E-01	0.152E-03	0.449E+00	0.179E+00	0.924E-03
12	0.828E-01	0.334E-01	0.152E-03	0.449E+00	0.179E+00	0.924E-03

Table A29 Disturbance Torque Thruster Requirements
LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = .15

Thruster #	Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.137E+00	0.495E-01	0.390E-03	0.231E+00	0.938E-01	0.475E-03
2	0.137E+00	0.495E-01	0.390E-03	0.231E+00	0.938E-01	0.475E-03
3	0.302E-01	0.166E-01	0.751E-04	0.214E+00	0.870E-01	0.440E-03
4	0.302E-01	0.166E-01	0.751E-04	0.214E+00	0.870E-01	0.440E-03
5	0.116E+00	0.422E-01	0.332E-03	0.197E+00	0.798E-01	0.404E-03
6	0.116E+00	0.422E-01	0.332E-03	0.197E+00	0.798E-01	0.404E-03
7	0.302E-01	0.166E-01	0.751E-04	0.214E+00	0.870E-01	0.440E-03
8	0.302E-01	0.166E-01	0.751E-04	0.214E+00	0.870E-01	0.440E-03
9	0.253E+00	0.917E-01	0.722E-03	0.428E+00	0.174E+00	0.879E-03
10	0.253E+00	0.917E-01	0.722E-03	0.428E+00	0.174E+00	0.879E-03
11	0.604E-01	0.332E-01	0.150E-03	0.428E+00	0.174E+00	0.880E-03
12	0.604E-01	0.332E-01	0.150E-03	0.428E+00	0.174E+00	0.880E-03

Disturbance Torques

Table A30 Disturbance Torque Thruster Requirements
LMSS Hoop Column

Thrust/Thruster Requirements (N)

LMSS Hoop Column, g-load = 1.0

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.756E-01	0.337E-01	0.202E-03	0.155E+00	0.791E-01	0.343E-03
2	0.756E-01	0.337E-01	0.202E-03	0.155E+00	0.791E-01	0.343E-03
3	0.234E-01	0.171E-01	0.744E-04	0.144E+00	0.733E-01	0.314E-03
4	0.234E-01	0.171E-01	0.744E-04	0.144E+00	0.733E-01	0.314E-03
5	0.644E-01	0.287E-01	0.172E-03	0.132E+00	0.673E-01	0.292E-03
6	0.644E-01	0.287E-01	0.172E-03	0.132E+00	0.673E-01	0.292E-03
7	0.234E-01	0.171E-01	0.744E-04	0.144E+00	0.733E-01	0.314E-03
8	0.234E-01	0.171E-01	0.744E-04	0.144E+00	0.733E-01	0.314E-03
9	0.140E+00	0.624E-01	0.374E-03	0.288E+00	0.146E+00	0.634E-03
10	0.140E+00	0.624E-01	0.374E-03	0.288E+00	0.146E+00	0.634E-03
11	0.467E-01	0.341E-01	0.149E-03	0.288E+00	0.147E+00	0.627E-03
12	0.467E-01	0.341E-01	0.149E-03	0.288E+00	0.147E+00	0.627E-03

Table A31 Disturbance Torque Thruster Requirements

LMSS Hoop Column

Geostationary Platform

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	-2.200	0.788	-23.000	1.000	0.000	0.000
2	-2.200	0.788	-23.000	0.000	1.000	0.000
3	-2.200	0.788	-23.000	-1.000	0.000	0.000
4	-2.200	0.788	-23.000	0.000	-1.000	0.000
5	0.000	-15.800	0.000	1.000	0.000	0.000
6	0.000	-15.800	0.000	0.000	0.707	0.707
7	0.000	-15.800	0.000	0.000	0.707	-0.707
8	0.000	-15.800	0.000	-1.000	0.000	0.000
9	0.000	-15.800	0.000	0.000	0.000	[illegible].000
10	0.000	-15.800	0.000	0.000	0.000	-1.000
11	0.000	15.800	0.000	1.000	0.000	0.000
12	0.000	15.800	0.000	0.000	-0.707	0.707
13	0.000	15.800	0.000	0.000	-0.707	-0.707
14	0.000	15.800	0.000	-1.000	0.000	0.000
15	0.000	15.800	0.000	0.000	0.000	1.000
16	0.000	15.800	0.000	0.000	0.000	-1.000

Table A32 Geostationary Platform Thruster Coordinates

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

Thrust/Thruster Requirements (N)

Geostationary Platform

g-load = .15

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km .5	5	100
1		0.301E+01	0.294E+00	0.146E-01
2		0.000E+00	0.000E+00	0.000E+00
3		0.301E+01	0.294E+00	0.146E-01
4		0.000E+00	0.000E+00	0.000E+00
5		0.718E+01	0.700E+00	0.347E-01
6		0.000E+00	0.000E+00	0.000E+00
7		0.000E+00	0.000E+00	0.000E+00
8		0.718E+01	0.700E+00	0.347E-01
9		0.000E+00	0.000E+00	0.000E+00
10		0.000E+00	0.000E+00	0.000E+00
11		0.691E+01	0.674E+00	0.334E-01
12		0.000E+00	0.000E+00	0.000E+00
13		0.000E+00	0.000E+00	0.000E+00
14		0.691E+01	0.674E+00	0.334E-01
15		0.000E+00	0.000E+00	0.000E+00
16		0.000E+00	0.000E+00	0.000E+00

Table A33 Stationkeeping Thrust Requirements
- Geostationary Platform

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Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = .06

Thruster #	Correction Frequency	GEO Stationkeeping Requirements			
		Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.180E-01	0.475E-03	0.180E-01	0.475E-03
2		0.882E+00	0.236E-01	0.126E+00	0.337E-02
3		0.180E-01	0.475E-03	0.180E-01	0.475E-03
4		0.885E+00	0.236E-01	0.126E+00	0.338E-02
5		0.428E-01	0.113E-02	0.428E-01	0.113E-02
6		0.226E+01	0.604E-01	0.323E+00	0.865E-02
7		0.181E+01	0.483E-01	0.258E+00	0.691E-02
8		0.428E-01	0.113E-02	0.428E-01	0.113E-02
9		0.000E+00	0.000E+00	0.000E+00	0.000E+00
10		0.000E+00	0.000E+00	0.000E+00	0.000E+00
11		0.412E-01	0.109E-02	0.412E-01	0.109E-02
12		0.226E+01	0.604E-01	0.323E+00	0.864E-02
13		0.181E+01	0.483E-01	0.258E+00	0.691E-02
14		0.412E-01	0.109E-02	0.412E-01	0.109E-02
15		0.000E+00	0.000E+00	0.000E+00	0.000E+00
16		0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table A34 Stationkeeping Thrust Requirements

Geostationary Platform

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Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = .15

Thruster #	GEO Stationkeeping Requirements: Correction Frequency Once/Week, Duty Cycle .01	Once/Week, .4	Once/Day, .01	Once/Day, .4
1	0.181E-01	0.475E-03	0.181E-01	0.510E-03
2	0.884E+00	0.236E-01	0.126E+00	0.256E-02
3	0.181E-01	0.475E-03	0.181E-01	0.510E-03
4	0.887E+00	0.236E-01	0.127E+00	0.357E-02
5	0.432E-01	0.113E-02	0.432E-01	0.122E-02
6	0.227E+01	0.604E-01	0.324E+00	0.912E-02
7	0.181E+01	0.483E-01	0.259E+00	0.729E-02
8	0.432E-01	0.113E-02	0.432E-01	0.122E-02
9	0.000E+00	0.000E+00	0.000E+00	0.000E+00
10	0.000E+00	0.000E+00	0.000E+00	0.000E+00
11	0.416E-01	0.109E-02	0.416E-01	0.117E-02
12	0.227E+01	0.604E-01	0.324E+00	0.911E-02
13	0.181E+01	0.483E-01	0.259E+00	0.729E-02
14	0.416E-01	0.109E-02	0.416E-01	0.117E-02
15	0.000E+00	0.000E+00	0.000E+00	0.000E+00
16	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table A35 Stationkeeping Thrust Requirements

Geostationary Platform

OF POOR QUALITY

Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = 1.0

Thruster #	GEO Stationkeeping Requirements			
Correction Frequency	Once/Week		Once/Day	
Duty Cycle	.01	.4	.01	.4
1	0.190E-01	0.510E-03	0.190E-01	0.510E-03
2	0.933E+00	0.249E-01	0.133E+00	0.356E-02
3	0.190E-01	0.510E-03	0.190E-01	0.510E-03
4	0.936E+00	0.250E-01	0.134E+00	0.357E-02
5	0.453E-01	0.122E-02	0.453E-01	0.122E-02
6	0.239E+01	0.640E-01	0.342E+00	0.912E-02
7	0.191E+01	0.511E-01	0.274E+00	0.729E-02
8	0.453E-01	0.122E-02	0.453E-01	0.122E-02
9	0.000E+00	0.000E+00	0.000E+00	0.000E+00
10	0.000E+00	0.000E+00	0.000E+00	0.000E+00
11	0.437E-01	0.117E-02	0.437E-01	0.117E-02
12	0.239E+01	0.639E-01	0.342E+00	0.911E-02
13	0.191E+01	0.511E-01	0.274E+00	0.729E-02
14	0.437E-01	0.117E-02	0.437E-01	0.117E-02
15	0.000E+00	0.000E+00	0.000E+00	0.000E+00
16	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table A36 Stationkeeping Thrust Requirements

Geostationary Platform

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Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = .06

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.398E-01	0.139E-01	0.116E-01	0.928E-01	0.332E-01	0.324E-03
2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
3	0.398E-01	0.139E-01	0.116E-01	0.928E-01	0.332E-01	0.324E-03
4	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
5	0.189E-01	0.659E-02	0.553E-02	0.441E-01	0.158E-01	0.154E-03
6	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
8	0.189E-01	0.659E-02	0.553E-02	0.441E-01	0.158E-01	0.154E-03
9	0.516E-02	0.142E-02	0.114E-04	0.444E-01	0.135E-01	0.144E-03
10	0.516E-02	0.142E-02	0.114E-04	0.444E-01	0.135E-01	0.144E-03
11	0.209E-01	0.729E-02	0.611E-02	0.487E-01	0.174E-01	0.170E-03
12	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
13	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
14	0.209E-01	0.729E-02	0.611E-02	0.487E-01	0.174E-01	0.170E-03
15	0.516E-02	0.142E-02	0.114E-04	0.444E-01	0.135E-01	0.144E-03
16	0.516E-02	0.142E-02	0.114E-04	0.444E-01	0.135E-01	0.144E-03

Table A37 Disturbance Torque Thruster Requirements
Geostationary Platform

Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = .15

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.390E-01	0.137E-01	0.113E-03	0.921E-01	0.332E-01	0.322E-03
2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
3	0.3[illegible]0E-01	0.137E-01	0.113E-03	0.921E-01	0.332E-01	0.322E-03
4	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
5	0.185E-01	0.651E-02	0.537E-04	0.437E-01	0.158E-01	0.153E-03
6	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
8	0.185E-01	0.651E-02	0.537E-04	0.437E-01	0.158E-01	0.153E-03
9	0.514E-02	0.163E-02	0.116E-04	0.442E-01	0.136E-01	0.131E-03
10	0.514E-02	0.163E-02	0.116E-04	0.442E-01	0.136E-01	0.131E-03
11	0.205E-01	0.720E-02	0.593E-04	0.483E-01	0.174E-01	0.169E-03
12	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
13	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
14	0.205E-01	0.720E-02	0.593E-04	0.483E-01	0.174E-01	0.169E-03
15	0.514E-02	0.163E-02	0.116E-04	0.442E-01	0.136E-01	0.131E-03
16	0.514E-02	0.163E-02	0.116E-04	0.442E-01	0.136E-01	0.131E-03

Table A38 Disturbance Torque Thruster Requirements

Geostationary Platform

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Thrust/Thruster Requirements (N)

Geostationary Platform, g-load = 1.0

	Disturbance Torques					
	Nominal			Worst Case		
Thruster #	400 km	500 km	GEO	400 km	500 km	GEO
1	0.342E-01	0.133E-01	0.960E-04	0.884E-01	0.349E-01	0.313E-03
2	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
3	0.342E-01	0.133E-01	0.960E-04	0.884E-01	0.349E-01	0.313E-03
4	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
5	0.162E-01	0.630E-02	0.456E-04	0.420E-01	0.166E-01	0.149E-03
6	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
8	0.162E-01	0.630E-02	0.456E-04	0.420E-01	0.166E-01	0.149E-03
9	0.458E-02	0.174E-01	0.120E-04	0.415E-01	0.135E-01	0.138E-03
10	0.458E-02	0.174E-01	0.120E-04	0.415E-01	0.135E-01	0.138E-03
11	0.179E-01	0.[illegible]36E-02	0.504E-04	0.464E-01	0.183E-01	0.184E-03
12	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
13	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
14	0.179E-01	0.696E-02	0.504E-04	0.464E-01	0.183E-01	0.184E-03
15	0.458E-02	0.174E-01	0.120E-04	0.415E-01	0.135E-01	0.138E-03
16	0.458E-02	0.174E-01	0.120E-04	0.415E-01	0.135E-01	0.138E-03

Table A39 Disturbance Torque Thruster Requirements

Geostationary Platform

Space Operations Center - Initial

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	0.000	9.144	10.414	1.000	0.000	0.000
2	0.000	9.144	10.414	-1.000	0.000	0.000
3	0.000	9.144	10.414	0.000	-0.707	-0.707
4	0.000	9.144	-7.870	1.000	0.000	0.000
5	0.000	9.144	-7.870	-1.000	0.000	0.000
6	0.000	9.144	-7.870	0.000	-0.707	0.707
7	0.000	-9.144	-1.270	-1.000	0.000	0.000
8	0.000	-9.144	-1.270	1.000	0.000	0.000
9	0.000	-9.144	-1.270	0.000	1.000	0.000
10	-19.500	0.000	0.000	0.000	-1.000	0.000
11	-19.500	0.000	0.000	0.000	1.000	0.000
12	-3.500	0.000	18.000	0.000	-1.000	0.000
13	-3.500	0.000	18.000	0.000	1.000	0.000
14	0.000	-9.144	-1.270	0.000	0.707	0.707

Table A40 SOC-Initial Thruster Coordinates

* Locations are relative to the arbitrary coordinate system used in the configuration drawing - not to the CG

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Thrust/Thruster Requirements (N)

Space Operations Center - Initial

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km .5	5	100
1		0.561E+02	0.561E+01	0.274E+00
2		0.561E+02	0.561E+01	0.274E+00
3		0.000E+00	0.000E+00	0.000E+00
4		0.355E+01	0.355E+00	0.174E-01
5		0.355E+01	0.355E+00	0.174E-01
6		0.000E+00	0.000E+00	0.000E+00
7		0.538E+02	0.538E+01	0.263E+00
8		0.538E+02	0.538E+01	0.263E+00
9		0.000E+00	0.000E+00	0.000E+00
10		0.000E+00	0.000E+00	0.000E+00
11		0.000E+00	0.000E+00	0.000E+00
12		0.000E+00	0.000E+00	0.000E+00
13		0.000E+00	0.000E+00	0.000E+00
14		0.000E+00	0.000E+00	0.000E+00

Table A41 Stationkeeping Thrust Requirements - SOC-Initial

Thrust/Thruster Requirements (N)

Space Operations Center - Initial

Thruster #	Correction Frequency	GEO Stationkeeping Requirements: Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.776E+00	0.208E-01	0.776E+00	0.208E-01
2		0.776E+00	0.208E-01	0.776E+00	0.208E-01
3		0.214E+02	0.573E+00	0.306E+01	0.817E-01
4		0.491E-01	0.131E-02	0.491E-01	0.131E-02
5		0.491E-01	0.131E-02	0.491E-01	0.131E-02
6		0.214E+02	0.573E+00	0.306E+01	0.817E-01
7		0.745E+00	0.199E-01	0.745E+00	0.199E-01
8		0.745E+00	0.199E-01	0.745E+00	0.199E-01
9		0.270E+02	0.721E+00	0.385E+01	0.103E+00
10		0.165E+02	0.442E+00	0.236E+01	0.631E-01
11		0.158E+02	0.423E+00	0.226E+01	0.603E-01
12		0.119E+02	0.318E+00	0.170E+01	0.453E-01
13		0.159E+02	0.426E+00	0.227E+01	0.608E-01
14		0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table A42 Stationkeeping Thrust Requirements

SOC - Initial

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Thrust/Thruster Requirements (N)

Space Operations Center - Initial

Thruster #	Disturbance Torques: Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.214E+00	0.511E-01	0.589E-03	0.415E+00	0.163E+00	0.103E-02
2	0.214E+00	0.511E-01	0.589E-03	0.415E+00	0.163E+00	0.103E-02
3	0.165E+01	0.555E+00	0.836E-02	0.407E+01	0.130E+01	0.111E-01
4	0.214E+00	0.511E-01	0.589E-03	0.415E+00	0.163E+00	0.103E-02
5	0.214E+00	0.511E-01	0.589E-03	0.415E+00	0.163E+00	0.103E-02
6	0.165E+01	0.504E+00	0.838E-02	0.168E+01	0.531E+00	0.850E-02
7	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
8	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
9	0.179E+01	0.546E+00	0.908E-02	0.182E+01	0.575E+00	0.921E-02
10	0.192E+01	0.585E+00	0.972E-02	0.195E+01	0.615E+00	0.986E-02
11	0.169E+01	0.515E+00	0.856E-02	0.172E+01	0.542E+00	0.868E-02
12	0.397E+00	0.136E+00	0.487E-03	0.999E+00	0.320E+00	0.272E-02
13	0.126E+00	0.385E-01	0.641E-03	0.128E+00	0.406E-01	0.650E-03
14	0.182E+01	0.555E+00	0.199E-02	0.407E+01	0.130E+01	0.111E-01

Table A43 Disturbance Torque Thruster Requirements
SOC - Initial

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Space Operations Center-Operational

	Location (m)			Direction		
Thruster #	X	Y	Z	X	Y	Z
1	0.000	9.144	10.414	1.000	0.000	0.000
2	0.000	9.144	10.414	-1.000	0.000	0.000
3	0.000	9.144	-7.870	1.000	0.000	0.000
4	0.000	9.144	-7.870	-1.000	0.000	0.000
5	0.000	-9.144	7.870	1.000	0.000	0.000
6	0.000	-9.144	7.870	-1.000	0.000	0.000
7	0.000	-9.144	-10.414	1.000	0.000	0.000
8	0.000	-9.144	-10.414	-1.000	0.000	0.000
9	-12.500	0.000	16.300	0.000	1.000	0.000
10	-12.500	0.000	16.300	0.000	-1.000	0.000
11	12.500	0.000	16.300	0.000	1.000	0.000
12	12.500	0.000	16.300	0.000	-1.000	0.000
13	-12.500	0.000	-15.000	0.000	1.000	0.000
14	-12.500	0.000	-15.000	0.000	-1.000	0.000
15	12.500	0.000	-15.000	0.000	1.000	0.000
16	12.500	0.000	-15.000	0.000	-1.000	0.000

Table A44 SOC-Operational Thruster Coordinates

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Thrust/Thruster Requirements (N)

Space Operations Center - Operational

Thruster #	Thrusting Time (Hrs)	LEO Stationkeeping Requirements at 400 km		
		.5		100
1		0.109E+03	0.105E+02	0.500E+00
2		0.109E+03	0.105E+02	0.500E+00
3		0.305E+01	0.752E+00	0.600E-01
4		0.305E+01	0.75[illegible]+00	0.600E-01
5		0.523E+02	0.567E+01	0.306E+00
6		0.523E+02	0.567E+01	0.306E+00
7		0.600E+02	0.555E+01	0.254E+00
8		0.600E+02	0.555E+01	0.254E+00
9		0.000E+00	0.000E+00	0.000E+00
10		0.000E+00	0.000E+00	0.000E+00
11		0.000E+00	0.000E+00	0.000E+00
12		0.000E+00	0.000E+00	0.000E+00
13		0.000E+00	0.000E+00	0.000E+00
14		0.000E+00	0.000E+00	0.000E+00
15		0.000E+00	0.000E+00	0.000E+00
16		0.000E+00	0.000E+00	0.000E+00

Table A45 Stationkeeping Thrust Requirements
SOC-Operational

Thrust/Thruster Requirements (N)

Space Operations Center - Operational

Thruster #	Correction Frequency	GEO Stationkeeping Requirements Once/Week		Once/Day	
	Duty Cycle	.01	.4	.01	.4
1		0.154E+01	0.427E-01	0.154E+01	0.427E-01
2		0.154E+01	0.427E-01	0.154E+01	0.427E-01
3		0.181E+00	0.336E-02	0.181E+00	0.336E-02
4		0.181E+00	0.336E-02	0.181E+00	0.336E-02
5		0.938E+00	0.236E-01	0.938E+00	0.236E-01
6		0.938E+00	0.236E-01	0.938E+00	0.236E-01
7		0.787E+00	0.225E-01	0.787E+00	0.225E-01
8		0.787E+00	0.225E-01	0.787E+00	0.225E-01
9		0.392E+02	0.104E+01	0.559E+01	0.149E+00
10		0.392E+02	0.104E+01	0.559E+01	0.149E+00
11		0.392E+02	0.104E+01	0.559E+01	0.149E+00
12		0.392E+02	0.104E+01	0.559E+01	0.149E+00
13		0.331E+02	0.882E+00	0.472E+01	0.126E+00
14		0.331E+02	0.882E+00	0.472E+01	0.126E+00
15		0.176E+02	0.469E+00	0.251E+01	0.669E-01
16		0.176E+02	0.469E+00	0.251E+01	0.669E-01

Table A46 Stationkeeping Thrust Requirements

Soc - Operational

Thrust/Thruster Requirements (N)

Space Operations Center - Operational

Thruster #	Nominal 400 km	Nominal 500 km	Nominal GEO	Worst Case 400 km	Worst Case 500 km	Worst Case GEO
1	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
2	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
3	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
4	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
5	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
6	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
7	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
8	0.283E+00	0.974E-01	0.114E-02	0.328E+00	0.112E+00	0.114E-02
9	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
10	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
11	0.854E-01	[illegible]41E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
12	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
13	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
14	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02
15	0.854E-01	0.441E-01	0.222E-03	0.274E+00	0.148E+00	0.122E-02
16	0.854E-01	0.441E-01	0.222E-03	0.278E+00	0.148E+00	0.122E-02

Column group heading: Disturbance Torques

Table A47 Disturbance Torque Thruster Requirements
SOC - Operational