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Auxiliary Propulsion Requirements for Large Space Systems

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Abstract

This paper presents an insight into auxiliary propulsion systems (APS) requirements for large space systems LSS launchable by a single shuttle. In an effort to scope the APS requirements for LSS, a set of generic LSSs were defined. For each generic LSS class a specific structural configuration, representative of that most likely to serve the needs of the 1980's and 1990's was defined. The environmental disturbance forces and torques which would be acting on each specific structural configuration in LEO and GEO orbits were then determined. Auxiliary propulsion requirements were determined as a function of: generic class specific configuration, size and openness of structure, orbit, angle of orientation, correction frequency, duty cycle, number and location of thrusters and direction of thrusters and APS/LSS interactions. The results of this analysis were used to define the APS characteristics of: (1) number and distribution of thrusters, (2) thruster modulation, (3) thrust level, (4) mission energy requirements, (5) total APS mass component breakdown, and (6) state-of-the-art adequacy/deficiency.

Introduction

To meet the needs of a variety of civilian and military mission objectives, large space systems (LSS) will become a greater percentage of our orbiting hardware. These LSS will be transported to low earth orbit (LEO) by the space transportation system (STS Shuttle). Concurrently, for LSS missions to orbit higher than LEO, the predominant mission scenario is that the LSS will be deployed or assembled in LEO and then transferred to a higher orbit. Once on-station, the LSS are expected to be operational for up to ten years.

In support of the LSS concepts, NASA has sponsored studies to determine LSS mission propulsion requirements. Propulsion can be divided into two categories; prime and auxiliary propulsion. Prime propulsion is used to place the spacecraft in orbit or to perform orbit transfer maneuvers, while auxiliary propulsion addresses the on-orbit functions of attitude control, shape control, and stationkeeping. This paper addresses auxiliary propulsion requirements for LSS.

The source of disturbance forces and torques and the resulting auxiliary propulsion system (APS) thrusting requirements were identified in Ref. 1 for several generic classes of LSS. Six specific LSS configurations, representative of the generic classes of LSS likely to be launched, as reported in Ref. 2, were analyzed to determine their APS requirements. The structural properties of the LSS configurations were sufficiently defined to develop finite element models and loading equations. This allowed the use of NASTRAN to perform a mass/thrust interaction simulation.

The APS requirements for the six specific LSS configurations were compared with state-of-the-art (SOA) chemical and electrical auxiliary propulsion characteristics in order to identify which LSS missions could be achieved with SOA auxiliary propulsion, and the direction for needed APS technology advances. Defined APS characteristics were: (1) thrust per thruster, (2) ΔV requirements, (3) minimum firing time, (4) duty cycle and correction frequency, (5) required cycles, and (6) number and location of thrusters.

Approach

Six LSS configurations representative of generic classes were identified and defined in sufficient detail to produce APS designs for analysis. Emphasis was placed on LSS configurations which could be launched with a single shuttle flight. Parameters which impact the APS requirements were identified. The sensitivities of the APS requirements with respect to those parameters were then established.

Once the specific LSS configurations were defined, Ref. 1 was used to identify disturbance forces and torques, which would be acting on the configurations for LEO and Geosynchronous (GEO) orbits. Knowing the disturbance forces and torques, it was possible to determine the required APS characteristics. These APS required characteristics were then compared with state-of-the-art (SOA) chemical and electrical propulsion characteristics in order to establish which LSS missions could be accomplished with SOA systems.

LSS Configuration

A description of each configuration studied is presented in this section. The locations and direction of the APS thrusters are indicated and example missions for each configuration are given.

Large Aperture Phased Array Antenna (LAPAA) - (Fig. 1)

The antenna is a series of three thin films which are stretched within compression beams to form a ground plane, an input plane, and an output plane for a bootlace lens. The lens is contained within a compression structure supported from a deployable mast with guy wires. This structure 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

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gimbaled and Sun oriented. They are sized for 65 kilowatts in LEO; the distribution conditioning and batteries are sized for 50 kilowatts at GEO. The lens portion will be closest to earth. Proposed missions would be personal communications, educational television, and electronic mail.

Land Mobile Satellite Systems (LMSS) - Wrap Rib - (Fig. 2)

Looking at the 55-meter offset wrap rib concept shows the long boom pointing at the earth's center. The shorter, vertical boom at the right points 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 contiguous 48 states, Alaska, Hawaii, and parts of Canada. The solar arrays are sized for 10 kilowatts. Proposed missions would be mobile communications, space-based radar, and jamming satellite.

Land Mobile Satellite System (LMSS) - Hopp Column - (Fig. 3)

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 projects 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 contiguous 48 states, Alaska, Hawaii, and parts of Canada. Proposed missions would be mobile communications and personal communications.

Geostationary Platform - (Fig. 4)

The platform carries nine payloads with the active antenna elements (feed arrays) being hard mounted to the central core and the passive (reflector) elements will be on a deployable structure. The wrap rib concept was used on P/L 203 and 601 which also share the 15-meter antenna for their transmit operations. The 10-meter antenna is located off the east-west axis to provide an optimum location for the radiator. The solar arrays are supported by a deployable boom and are sized for 8 kilowatts. The remainder of the payloads are mounted on three rigid structures. The solar arrays will be closest to earth. The platform is proposed for supporting various science experiments.

Science and Applications Space Platform (SASP) - (Fig. 5)

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 (science experiments) may be connected. The deployment 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 kilowatts. The vehicle orientation will be variable.

Space Operations Center (SOC) - (Fig. 6)

The initial space operations center (SOC) configuration essentially consists of a solar array, communication antenna, life support module, and logistic module. This configuration will support a crew of two. The operational SOC will have two of each of the modules listed for the initial SOC as well as a mobile cherry picker for satellite rendezvous and acquisition, two hangers, and additional docking and berthing ports. The operational configuration supports a crew of twelve. The SOC will provide for manned operations and provide a location for construction, flight support, servicing, research, and testing.

G-Loading

For the large aperture phased array antenna, LMSS with wrap rib, LMSS with hoop column, and SASP structures, g-loading designs for three g-levels, 0.06, 0.15, and 1.0 were determined. Finite-element models using NASTRAN were constructed for these four flexible LSS. Figure 7 shows the effect of g-loading on the LMSS-wrap rib mass. (As the g-loading is increased, mass must be added to various structure members to carry the increased g-loading.) Detailed models of the SOC and SASP were not generated.

During the g-loading design and dynamic interaction analysis, certain mass properties were determined or assumed for each configuration. The mass properties for the LMSS with wrap rib (55-m-diam antenna) are presented in Table I. Similar tables for the other specific configurations can be found in Ref. 2.

Analysis

NASTRAN Modeling

Finite element models of the four "flexible" designs mentioned above were constructed for use in a propulsion/structure interactions study. These models contained from 500 to 1500 elements and were sufficiently detailed to allow determinations of antenna/feed horn geometry changes with various thruster locations and thrust levels. The models were developed with two basic assumptions; a 0.15 g-member loading for each critical element and a lowest modal frequency of around 0.1 Hz. The lowest mode goal of 0.1 Hz was precisely that - a goal and not a requirement. The members were assumed to be strength rather than stiffness designed. A resulting modal map for the wrap rib antenna is shown in Fig. 8. This philosophy is summarized by Fig. 9 which shows that a strength design structure has significant mass impacts whereas a stiffness design will impact the volume of the undeployed structure.

Disturbance Analysis

Using the results reported in Refs. 1 and 3, the sources of environmental disturbances acting on the LSS configurations were identified. The disturbances of consequence to APS are radiation, gravity gradient, aerodynamic, and solar/lunar gravity effects. Which the dominant disturbance is a function of the specific configuration, orbit altitude, and angle of orientation.

Disturbance forces were calculated for the following conditions:

- Nominal*, earth oriented, and worst case orientations for LEO and GEO
- LEO 300, 400, and 500 km altitude

Disturbance Force and Torques

Having identified the ground rules and sources of the disturbances acting on the LSS, the forces and torques which must be counteracted by the APS were defined as a function of specific configurations, allowable g-loading, orbit, angle(s) of orientation, duty cycle, and frequency of correction. Figure 10(a) presents the sum of the environmental torques (aerodynamic, radiation, and gravity gradient) as a function of the angle of orientation (ϕ and θ - Fig. 10(b)) acting on the 12.5 kW SASP at a 300 km altitude. The sum of the environmental torque can vary by an order of magnitude due to a change in orientation. The breakdown of the total torque acting on the 12.5 kW SASP for an angle of $\theta = 0$ is shown in Fig. 11. Aerodynamic effect is the dominant cause of disturbance torque acting on the 12.5 kW SASP. At $\theta = 0$ the torque caused by gravity gradient is negligible for the 12.5 kW SASP.

Up to this point, the discussion of disturbance forces and torques at LEO has been focused on the 12.5 kW SASP. Similar results were obtained for the other configurations. Table II summarizes the total disturbance torques acting on the various LSS configurations at the LEO orbits of 400 km and 500 km. The aerodynamic effects at 400 km yield torques 2-4 times greater than those at 500 km. Table II also shows that for some of the configurations the nominal case and worst case torques are approximately equal. It should be noted that there is no "typical" spacecraft orientation, i.e., sun-facing spacecraft will have a variable orientation, whereas earth-facing spacecraft have a more or less fixed orientation with respect to the gravity gradient. Hence, the environmental torques which the APS must overcome are highly mission dependent.

Figure 12 shows the impact of environmental forces on the 12.5 kW SASP at 300 km. As shown in Fig. 12, if no auxiliary propulsion is used for stationkeeping, the 12.5 kW SASP would fall from orbit within three days.

ΔV at LEO

Having identified the environmental disturbances at LEO and determined the resulting forces and torques acting on the LSS configurations, the stationkeeping ΔV and resulting propellant requirements were calculated. Figure 13 shows these ΔV requirements as a function of altitude and the allowed altitude tolerances (change in altitude before correction). It can be seen that a constant thrusting strategy would require minimal ΔV at 400 km, but would result in maximum ΔV requirements at 500 km. At 400 km, the effect of atmospheric density is more dominant. As a spacecraft is allowed to drop further in altitude (below 400 km), the exponential increasing density requires larger amounts of thrusting, which increases ΔV requirements. At 500 km, the effect of earth triaxia and sun-moon gravity can be used to aid in altitude control and thus reduce the required ΔV. For missions of 50 days or longer, the ΔV requirements at 400 km are nearly an order of magnitude greater than those at 500 km. Figure 14 presents the propellant requirements for a 90 day mission at 400 km for the configurations analyzed. The propellant mass requirement for a 90 day LEO mission with a high area to mass ratio approaches 30 percent of the payload.

GEO

The disturbance forces which must be overcome by the APS at GEO are gravity gradient, solar pressure, and stationkeeping requirements. A summary of the GEO disturbance torques is given in Table III. For most of the configurations studies, the nominal and worst case GEO disturbance torques are equal or of the same magnitude. However, the disturbance torques at GEO are one to two orders of magnitude less than those at LEO orbits.

The GEO ΔV requirements were determined for two different duty cycles (1 and 40 percent). Table IV shows that the total ΔV requirement is slightly higher at a 40 percent duty cycle and that north/south requirements dominate. Using the requirements given in Table IV, the GEO propellant requirements were calculated for specific impulses of 200, 500, and 3000 sec (Table V). Comparing the propellant requirements with payload weight, it can be seen that for low I_{sp} the annual propellant requirements are 25 to 30 percent of the payload mass.

Thruster Location

The thrust (and thrust per thruster) requirements of a APS are dependent not only on the enviromental disturbance forces and torques, which must be overcome, but also on the location and number of thrusters. Consideration was given to minimizing the total APS mass (thruster weight, propellant and tankage weight, and changes in structural mass) in defining thruster location for each LSS configuration analyzed. The criteria used for selecting thruster location included:

- Maximum possible moment arms
- Stationkeeping capability at desired orientation
- Zero delta-V maneuvering requirements caused by thruster location and operation
- Zero torque stationkeeping requirements caused by thruster location and operation
- Minimal heat flux and contamination from plume impingement
- No thruster mounting on solar array surface or at the ends of solar arrays
- Minimize the number of thruster used

The heavier solid arrows on Figs. 1 to 6 indicate the selected thruster location and thrust direction for each configuration analyzed. The LSSs with unsymmetrical configuration required additional number of thrusters to allow the stationkeeping and torquing to be decoupled.

Thrust Per Thruster

Having determined the disturbance forces and torques acting on the LSS and having selected optimum thruster locations, the required thrust levels could then be established. Table VI is a

*Nominal orientation encompasses any pointing errors with sufficient margin to assure control and not so excessive as to force the APS size to be unrealistic.

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summary of the thrust per thruster requirements for the different configurations (assuming a 0.15 g loading limit) at 400 km LEO and at GEO. The values presented for the 400 km altitude are based upon the assumptions of a 1/2 hour thrusting time. From Table VII it can be seen that at 400 km LEO altitude, the thrust requirements could not be met by SOA ion thrusters (0.001 to 0.13 N).

At GEO, the thrust requirements consist of north/south and east/west stationkeeping components with the north/south requirements being approximately two orders of magnitude greater than east/west. Increasing the duty cycle from 1 to 40 percent results in lowering the thrust requirements by at least a factor of 10. Except for the SOC configurations, all of the thrust requirements for GEO at a duty cycle of 40 percent can be provided by SOA ion thrusters.

APS Mass

The APS mass was generated for three different types of propulsion system representative of three specific impulses ranges:

- Monopropellant N_2H_4 (I_{sp} = 200 sec)
- Bipropellant MMH/N_2O_4 (I_{sp} = 300 sec)
- Ion-Hg (I_{sp} = 3000 sec)

In determining APS mass, the total ΔV and specific impulse defines propellant mass and thus tankage mass requirements. The propellant mass was determined using Eq. (1):

$$M_p = M_s\left[e^{\left(\frac{\Delta V}{I_{sp} \cdot g_o}\right)} - 1\right]$$

where M_s is the satellite mass and g_o is the gravitational constant. Thrust level requirements then sized the remaining APS hardware.

Table VII presents the APS mass requirements for GEO stationkeeping for the duty cycles of 1 and 40 percent. The APS mass for both monopropellant and bipropellant systems are larger for a duty cycle of 40 percent than 1 percent - the longer thrusting time results in large propellant requirements. For electric propulsion (EP), as the thrust level is increased, the power requirements is proportionally increased and thus the mass of the power system increases. At a duty cycle of 1 percent the EP thrust levels are so high that they drive the power system requirements to unrealistic values.

From Table VII it can be observed that although EP is unfeasible at short duty cycles, it looks attractive at longer duty cycles - since the mass is dominated by propellant requirements. Bipropellant chemical systems offer a mass savings of ~30 percent over monopropellant systems.

APS/LSS Design-Interaction Considerations

LSS mission designers must consider the dynamic interaction of the APS with the structure. Since many of the planned LSS mission are for communications, the effect on mission degradation was addressed in this study. (Mission degradation is caused by feed/antenna defocusing which is a result of APS/structure interaction). Four possible modes of defocusing were identified:

- Despacing
- Tilt
- Decenter
- Defigure

Refer to Fig. 15

A mission was considered not achievable if the APS/structure interaction criterion of 10 percent or greater power loss was exceeded. It was found that communication missions which employed the wrap rib configuration (Fig. 2) would be difficult to achieve at either LEO or GEO. The mission using the Hoop Column (Fig. 3) at LEO would not be achievable. The rationale and results of this APS/structure interaction analysis is summarized in Fig. 16 and the details are given in Ref. 2.

SOA Adequacy/Deficiency

Having identified and defined the APS requirements for each LSS configuration, the SOA adequacy/deficiency and the possible benefits of increasing APS technology capabilities were addressed. Characteristics included were:

- Thrust level
- Pointing requirements/minimum firing time
- Throttling
- APS mass

Thrust levels and APS mass have already been discussed. Table VIII presents the SOA characteristics assumed for this study.

In order to obtain minimum propellant consumption to meet pointing requirements, firing times should be minimized. Using the thruster locations specified and maintaining a pointing requirement of 0.1°, minimum firing times for each specific configuration were calculated and are shown in Table IX. Since the SOA minimum firing time for chemical systems is 0.01 to 0.05 sec, it can be seen that only the wrap rib and SOC initial minimum firing times at LEO can be achieved with SOA chemical APS. If the pointing requirements for each LSS configuration were relaxed, longer firing times would result and the minimum firing times would be more compatible with SOA chemical APS.

Summary

The requirements for auxiliary propulsion for six specific configurations, which are representative of the different generic classes of LSS and most likely to be launched, were determined as a function of specific configuration, orbit, and angle of orientation. Of the configurations studied, four were large flexible structures and two were rigid structures. Insight into APS requirements for the LSS configuration obtained from the data generated under this study led to specific conclusions on the SOA-APS adequacies and/or deficiencies.

In order to analyze the dynamic interaction of the LSS structure and the APS (thruster locations and thrust levels) finite element models (consisting of 500 to 1500 elements) for the four flexible structures were developed. The effect of g-loading requirements on the LSS structures were analyzed. The g-loads of 0.060, 0.15, and 1.0 g's were considered. This resulted in LSS structures with: (1) masses of 1200 to 125 000 kg, (2) area to mass ratios of 0.007 to 0.27 m^2/kg, and (3) inertia range of 15 000 to 9 000 000 $kg\text{-}m^2$, being defined and analyzed.

An environmental disturbance analysis identified the disturbance forces and torques which would be acting on the LSS at LEO and GEO. The environmental torques which must be addressed at LEO range between 0.5 to 40 N-M and are approximately two orders of magnitude greater than those at LEO. Aerodynamic effects are dominant at LEO. The study showed that LEO deployment of LSS is unadvisable at altitudes of 400 km or less because of the large propellant requirements needed to provide thrust to overcome environmental disturbances.

Using the environmental disturbance, the APS requirements (thruster locations, size, propellant mass) for the six configurations were determined. Thrust requirements at GEO are two orders of magnitude less than those for LEO at 500 km. The thrust requirements at LEO (assuming a firing time of 1/2 hour per firing) are large enough to preclude the use of electric propulsion. However, the high ΔV requirements for LEO results in large propellant requirements (approaching 10 percent of payload mass for 90 days at LEO). This precludes the use of SOA chemical APS for continuous LEO operations. The propellant requirements for GEO stationkeeping are highly dependent on the propellant I_{sp}. For low I_{sp} systems, the GEO propellant requirement approaches 25 to 30 percent of the payload mass. Thus high I_{sp} (e.g. 3000 sec) systems are desirable. The GEO thrust per thruster requirements are a function of both thruster location and duty cycle, with longer duty cycles resulting in lower thrust requirements. Except for the SOC configuration, the thrust requirements for the LSS with a duty cycle of 40 percent can be met with SOA electric propulsion. The study also showed that for a duty cycle of 40 percent, the use of electric propulsion would result in the lowest APS mass.

Beside propellant mass, APS mass, and thruster per thruster, other characteristics of the LSS APS addressed in this study were duty cycle, firing time, pointing requirements (0.1° assumed for this study), and dynamic interactions with the structure. These characteristics for an LSS-APS were compared with SOA technology. These resulted in identifying SOA limitations and enhanced technology benefits as follows:

- SOA limitations
  - Monopropellant I_{sp} limits mission capture for proposed delivery systems (propellant mass becomes a large percent of total spacecraft mass)
  - Bipropellants need lower thrust capability (<2 N)
  - Ion thrusters not capable of delivering required thrust levels for LEO operation
  - Ion thrusters need long duty cycles (2 hr) for GEO operation
- Identified Enhanced Technology Benefits
  - Increasing chemical I_{sp} to 300 sec is mission enabling
  - Minimum firing times of <0.01 sec yield mass advantage for 3 axis jet control
  - Thruster levels of 0.1 to 0.4 N enhance ion propulsion for GEO operation
  - I_{sp} range for ion propulsion of 1000 to 2000 sec optimum
  - Ion power system mass must be reduced to enable reasonable duty cycles

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TABLE I. - LAND MOBILE SATELLITE SYSTEM (LMSS)

[Wrap rib, 55 m diam.]

Initial orbit	Mission orbits	Lifetime	Attitude stationkeeping and shape control tolerances
LEO	LEO (300, 400, 500 km) 5600 - km polar orbit GEO (36,000 km)	10 years	Attitude control, ±0.10° Pointing stability, ±0.03°

g-Load	Mass, kg	G location, m		
		X	Y	Z
0.16 .15 1.0	2897.06 3036.41 4351.51	-0.208 -.198 -.138	-3.823 -4.318 -7.432	-11.029 -12.001 -18.109

g-Load	Inertias (about C_G, kg-m^2)					
	I_{XX}	I_{YY}	I_{ZZ}	$-I_{XY}$	$-I_{XZ}$	$-I_{YZ}$
0.06 .15 1.0	2 437 290 2 781 766 5 798 378	2 223 871 2 523 995 5 170 587	275 508 345 003 952 442	4961 5259 7133	4032 4617 8293	-559 971 -668 662 -1 599 345

g-Load	C_p (origin at C_G, m)								
	Plane XY			Plane XZ			Plane YZ		
	X	Y	Z	X	Y	Z	X	Y	Z
0.06 .15 1.0	0.097 .087 .027	-6.380 -5.885 -2.771	-20.278 -19.306 -13.198	-0.216 -.226 -.285	-3.798 -3.303 -.189	-19.263 -18.292 -12.184	0.0267 .0167 -.0433	-19.680 -19.185 -16.071	-51.452 -50.481 -44.373

g-Load	Area, m^2			Area/mass		
	XY	XZ	YZ	XY	XZ	YZ
0.06 .15 1.0	270.703 270.703 270.703	206.770 206.770 206.770	99.825 99.825 99.825	0.093441 .089152 .062195	0.071372 .089152 .047506	0.034457 .032876 .022935

TABLE II. - SUMMARY OF DISTURBANCE TORQUES (N-M) AT LEO

	LEO (400 km)		LEO (500 km)	
	Nominal	Worst case	Nominal	Worst case
LAPAA 13 kW	0.5	0.8	0.2	0.4
LAPAA 65 kW	3	4	.9	1
Wrap Rib 55 m	10	20	6	9
Hoop Column 120 m	20	30	6	10
Geostationary Platform	1	2	.3	.8
SASP-12.5 kW	1	4	.4	1
SASP-25 kW	2	7	.7	2
SOC Initial	40	40	10	10
SOC Operational	10	20	4	10

TABLE III. - SUMMARY OF DISTURBANCE
TORQUES (N-M) AT GEO

	GEO	
	Nominal	Worst case
LAPAA 13 kW	0.004	0.044
LAPAA 65 kW	.009	.009
Wrap Rib 55 m	.06	.06
Hoop Column 120 m	.04	.05
Geostationary Platform	.003	.007
SASP-12.5 kW	.004	.02
SASP-25 kW	.009	.03
SOC Initial	.2	.2
SOC Operational	.04	.08

TABLE IV. - GEOSYNCHRONOUS ΔV REQUIREMENTS

- ΔV (m/s)/yr
- g-Loading - 0.15 g's
- Solar pressure method 2
- Duty cycle - 0.01 x Orbit time = 15 min, 0.4 x Orbit time - 9.6 hr

		1 percent Duty cycle				40 percent Duty cycle			
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

TABLE V. - PROPELLANT REQUIREMENTS FOR GEO

LSS	1 percent Duty cycle			40 percent Duty cycle			Payload weight, kg
	I_{sp}, sec						
	200	500	3000	200	500	3000	
	Propellant requirements for geosynchronous station-keeping[a] (estimated amount required for first year)						
LAPAA 10 kW	44.035	17.614	2.936	46.991	18.796	3.133	1 292
LAPAA 65 kW	119.979	47.992	7.999	128.041	51.217	8.536	3 336
LMSS-Wrap Rib	96.138	38.455	6.409	102.577	41.031	6.838	3 036
LMSS-Hoop Column	132.575	53.030	8.838	141.532	56.613	9.435	2 907
Geostationary Platform	107.073	42.829	7.138	114.223	45.689	7.615	3.737
SASP-12.5 kW	243.219	97.288	16.215	259.440	103.776	17.296	8 780
SASP-25 kW	415.730	166.292	27.715	443.471	177.388	29.565	14 731
SOC Initial	1438.088	575.235	95.873	1533.677	613.471	102.245	57 242
SOC Operational	3147.297	1258.919	209.820	3356.48	1342.594	223.766	125 500

[a]Propellant = kg; maximum allowed error = 0.1°

TABLE VI. - THRUST/THRUSTER (N) RANGE FOR STATIONKEEPING

	LEO (400 km)	GEO Correction frequency = once/week			
	Thrust time = 1/2 hr	Duty cycle = 0.01		Duty cycle = 0.01	
		N/S	E/W	N/S	E/W
Electronic mail	0.8 to 3	0.4 to 0.5	0.005 to 0.02	0.01	0.0001 to 0.0005
Educational TV	.7 to 7	.4 to 2	.006 to .06	0.01 to .04	.0002 to .002
Wrap Rib	1 to 8	.4 to 2	.008 to .02	.01 to .06	.0002 to .001
Hoop Column	2 to 6	.7 to 2	.02 to .04	.02 to .04	.0005 to .001
Geostationary Platform	3 to 7	.9 to 2	.02 to .04	.02 to .06	.0005 to .001
SOC Initial	4 to 60	10 to 30	.05 to .8	.3 to .7	.001 to .02
SOC Operational	3 to 100	20 to 40	.2 to 2	.5 to 1	.003 to .04

TABLE VIII. - SOA CHARACTERIZATION

(a) Systems performance comparison

System	Thrust range, N	Isp, sec	Minimum firing time sec	Comments
MONO (N_2H_4)	0.5 to 2700	210 to 230	0.05	Standard, well established
BIPROP (N_2O_4/MMH)	22 to 1500	260 to 290	.1	2 N thruster under development
CRYO (LO_2/LH_2)	111 to $1x10^6$	390 to 470	>.1	Long lifetime storage problems
ION (Hg)	0.001 to 0.15	2200 to 6000		Increased thrust up to 0.5 N with 30 cm possible

(b) Ion Component Specific Masses

System	SOA performance	Projections
PPU	FM PPU 13.65 kg/kW at 2.8 kW	5.0 kg/kW direct ex. disch.
PPU S/A	SEPS 2 MIL 13.0 kg/kW at 25 kW	5.0 kg/kW GaAs
System Efficiency	SEPS 70 percent (conserv.)	90 percent W/PPU, thruster redesign

TABLE IX. - MINIMUM FIRING TIME/MINIMUM BIT ASSESSMENT

LSS	Minimum firing time, sec	
	LEO (0.5 hr)	GEO (1 Percent Duty cycle)
LAPAA 13 kW Electronic Mail	[a]0.3166E-4	[a]0.1278E-4
LAPAA 65 kW Educational TV	[a]0.1414E-3	[a]0.4253E-4
LMSS Wrap Rib	0.1527E-1	[a]0.2646E-2
LMSS Hoop Column	[a]0.1062E-3	[a]0.6106E-5
Geostationary Platform	[a]0.1976E-2	[a]0.2866E-3
SOC Initial	0.2412E-1	[a]0.3447E-2
SOC Operational	[a]0.5684E-3	[a]0.9344E-4

[a]SOA deficiency.

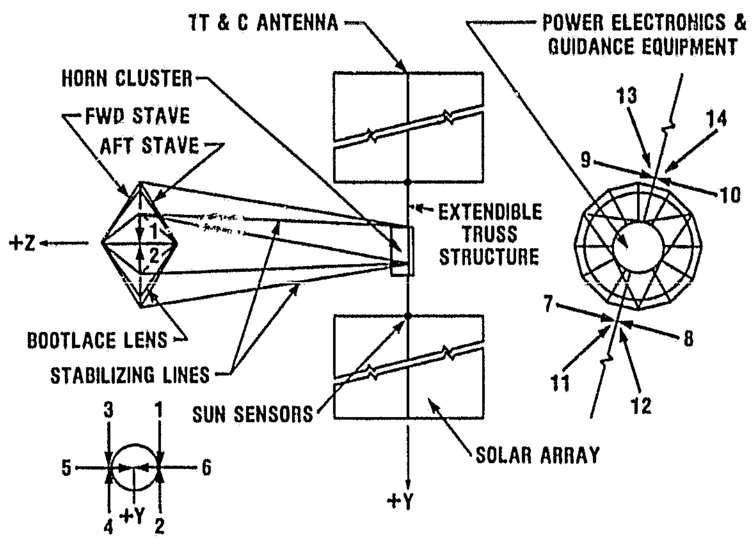
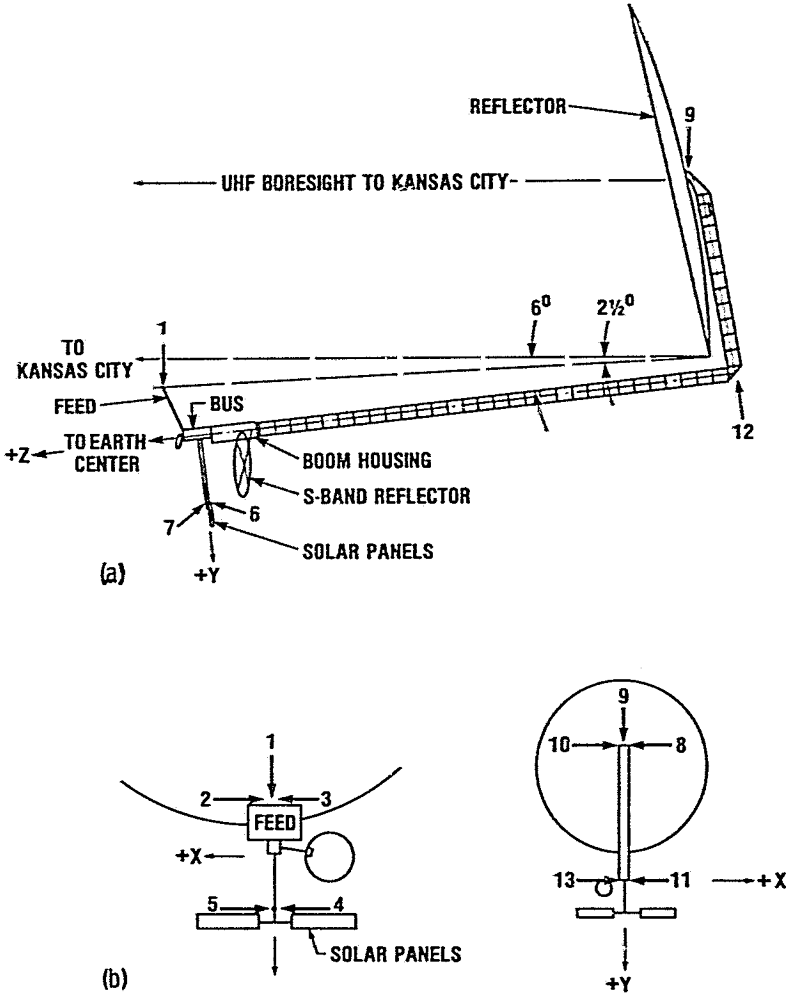
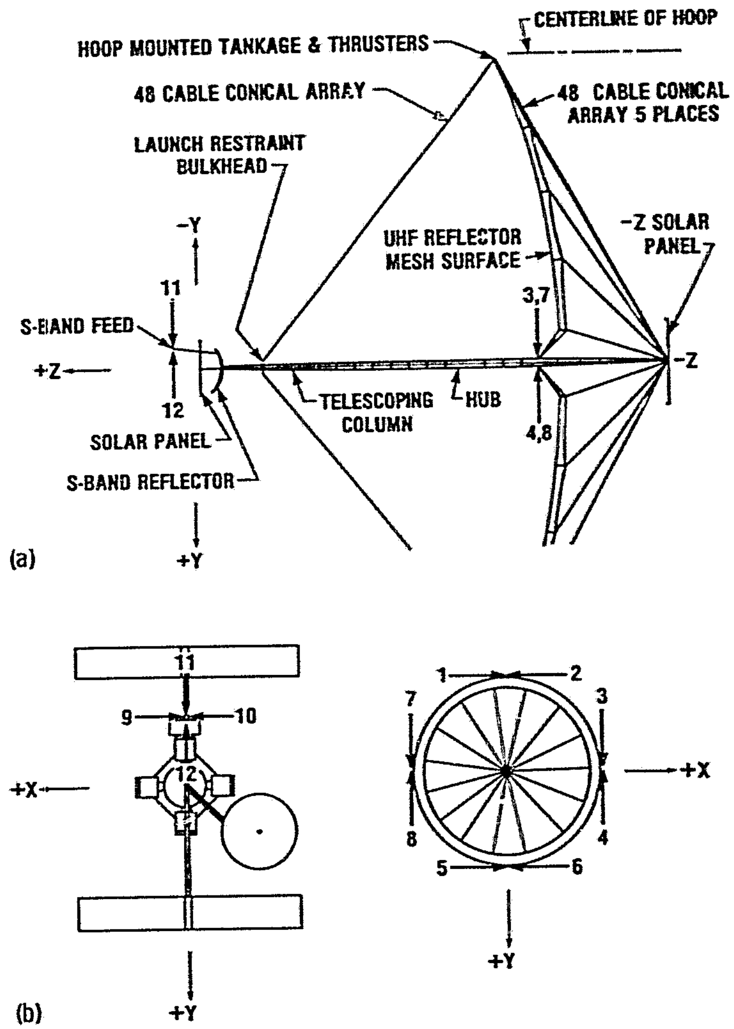


Figure 1. - LAPAA-electronic mail and educational TV.



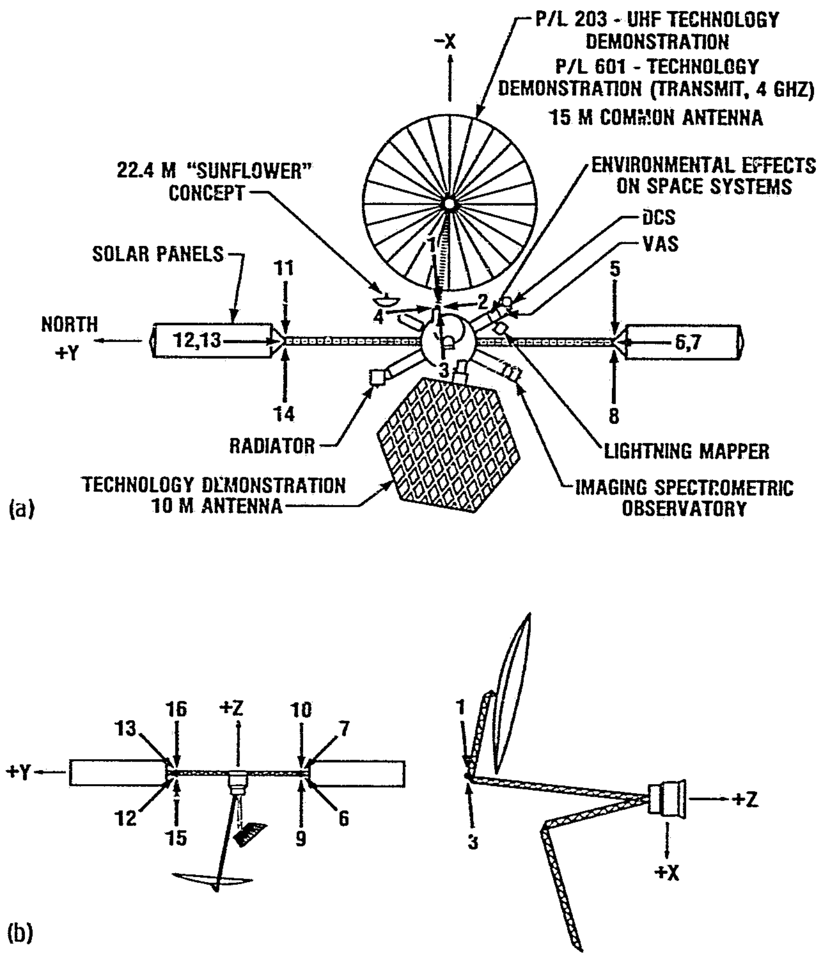
(a) Side view.
(b) End view.

Figure 2. - LMSS-wrap rib.



(a) Side view.
(b) End view.

Figure 3. - LMSS-hoop column.



(a) View looking towards earth.
(b) End and side view.

Figure 4. - Geostationary platform.

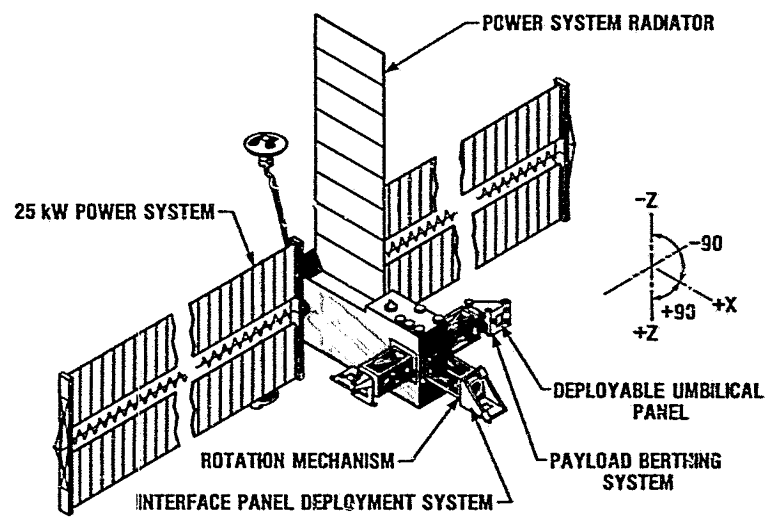


Figure 5. - First-order platform configuration.

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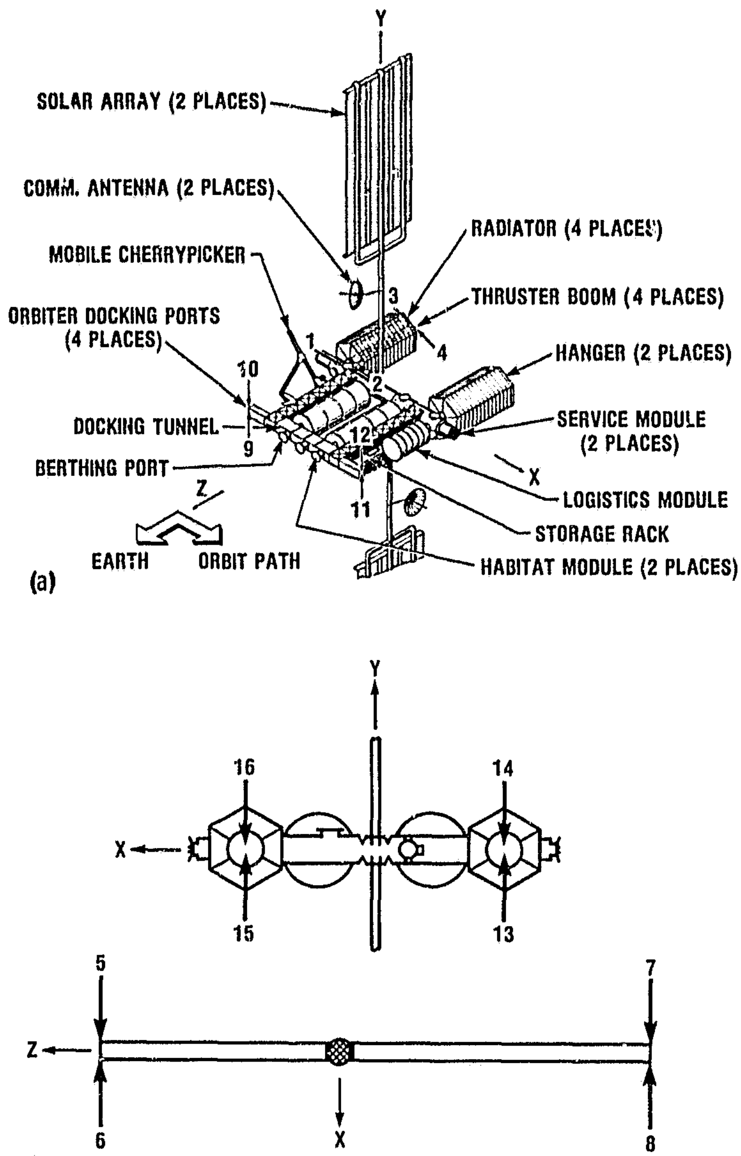

(a) Front view.
(b) Edge view.

Figure 6. - Space operations center-operational.

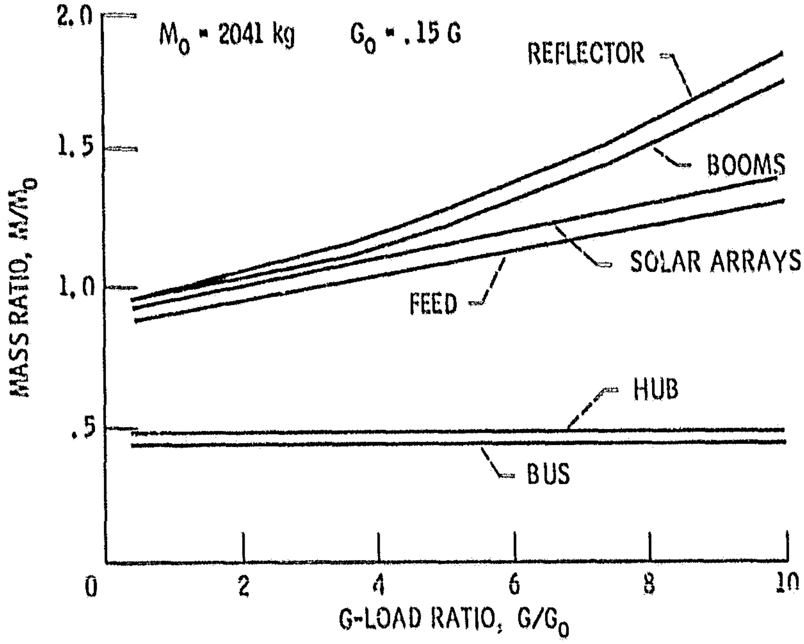

Figure 7. - Effect of G-load on mass; 25 meter warp rib.

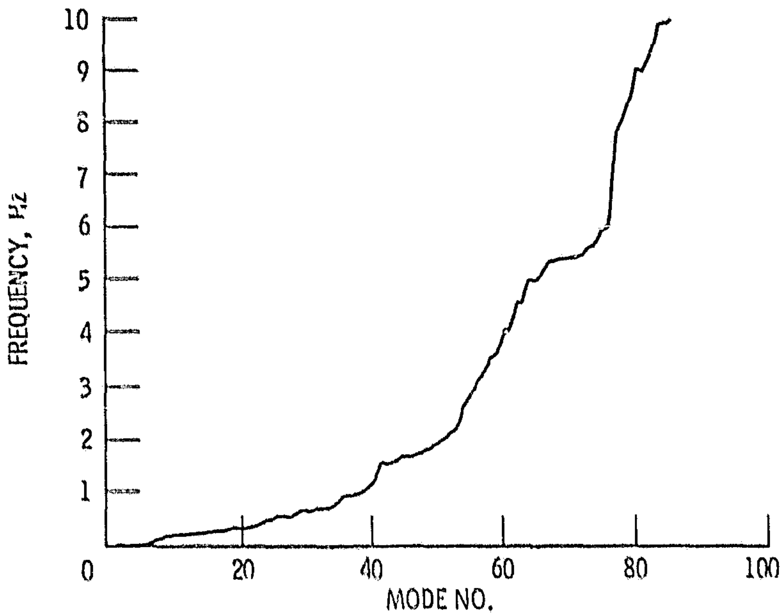

Figure 8. - Wrap rib antenna mode map.

Figure 9. - NASTRAN input assumptions.

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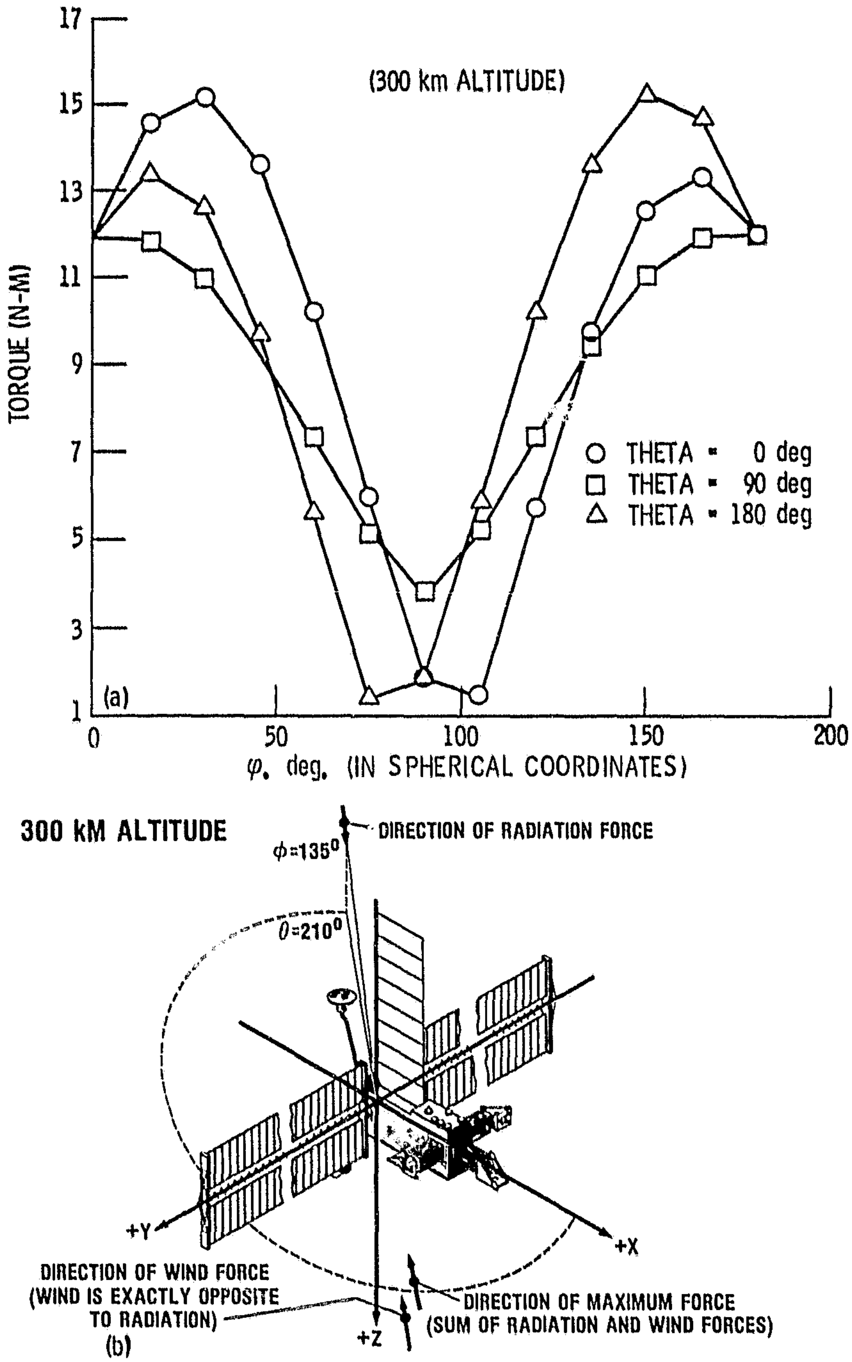


(a) Sum of aerodynamic, radiation and gravity gradient torques.
(b) Spherical coordinate reference angles.

Figure 10. - Environmental torques acting on the SASP (12.5 kW).

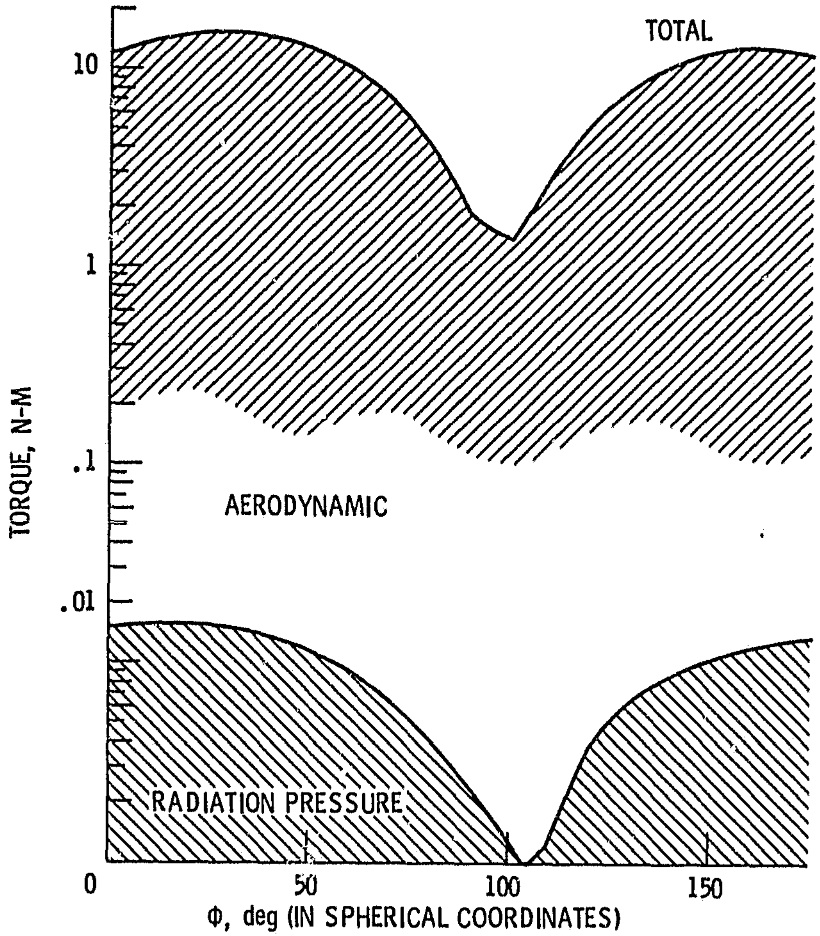


Figure 11. - Sum of torques acting upon SASP (12.5 kw) AT 300 KM ALTITUDE; THETA = 0^{0}.

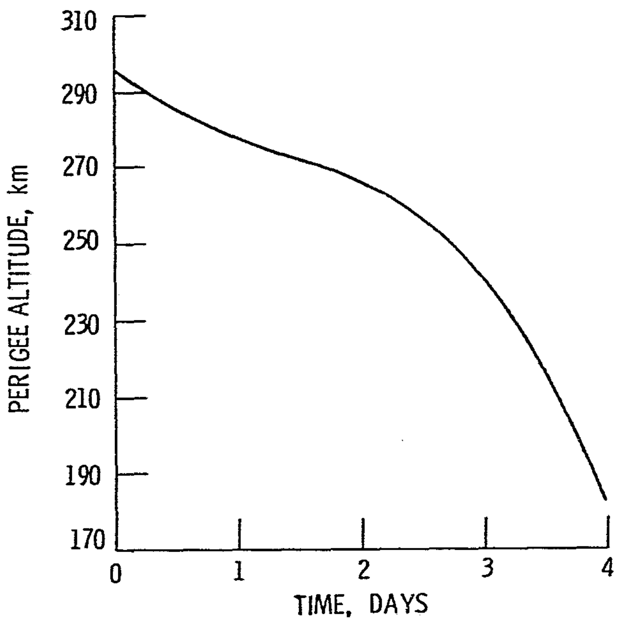


Figure 12. - Altitude decay rate for 12.5 kW SASP at initial 300 km orbit and NASA neutral atmosphere.

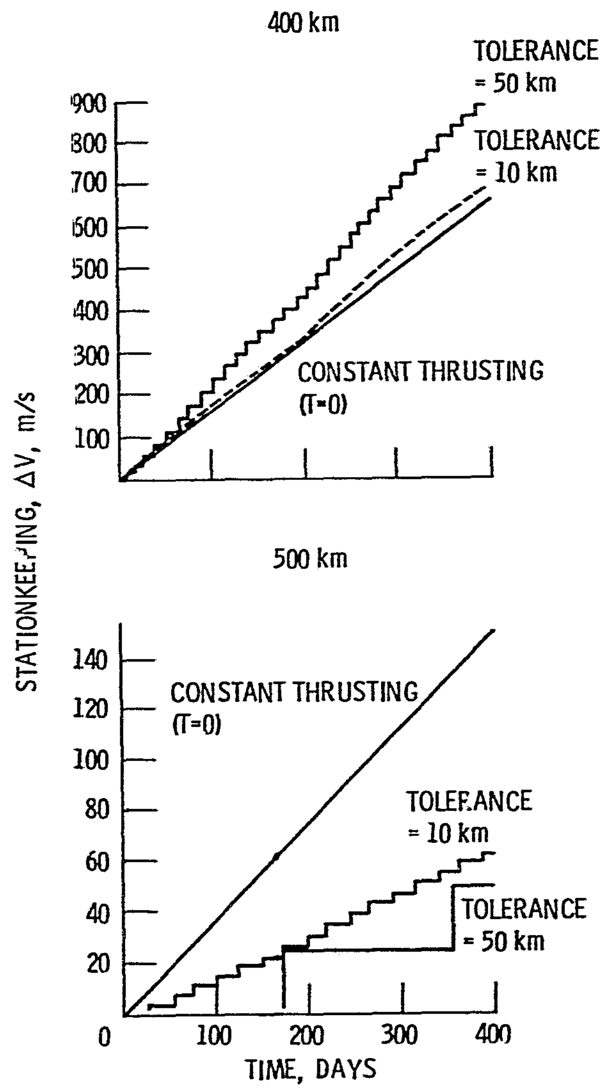


Figure 13. - Effects of LEO stationkeeping for different altitude tolerances.

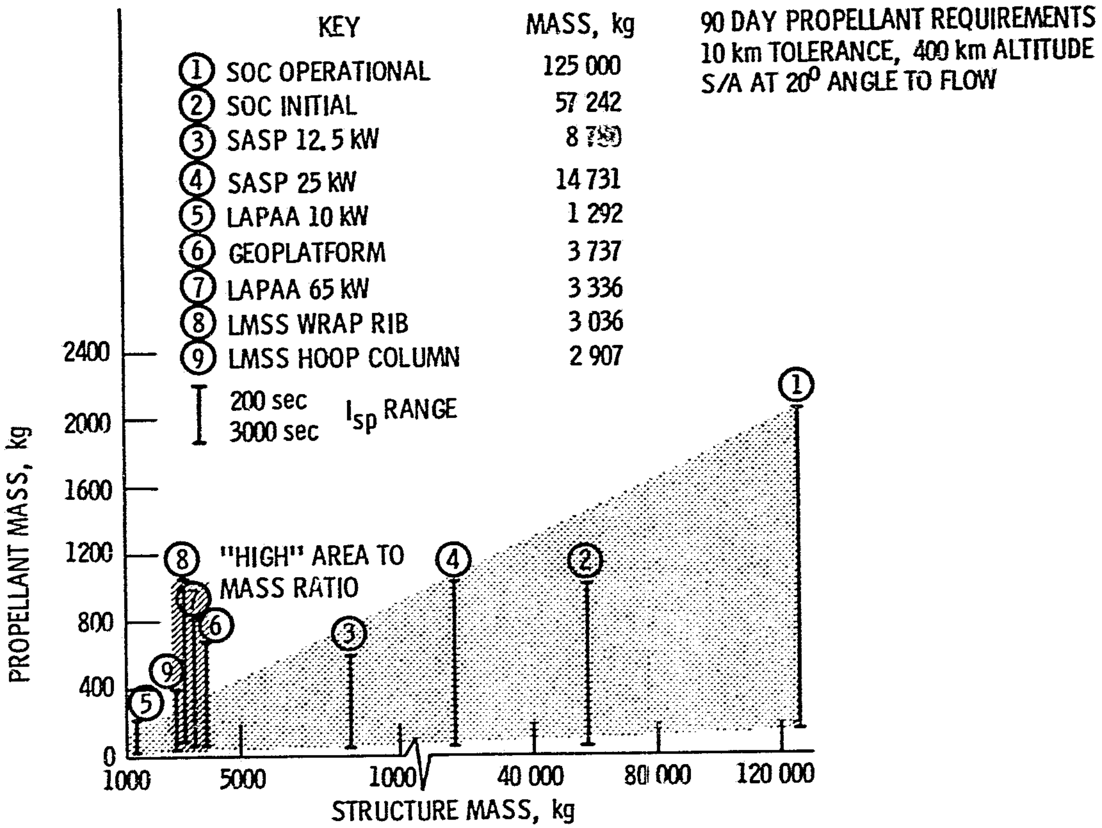
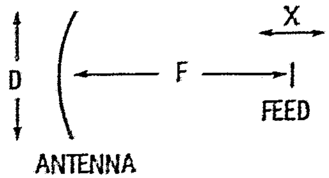


Figure 14. - LEO stationkeeping propellant requirements.

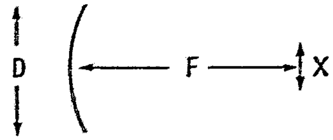
DESPACING



DEFINITION: ΔLONGITUDINAL DISTANCE BETWEEN FEED & ANTENNA

IMPACT: PHASE ERROR AND GAIN LOSS & BROADENING OF BEAM

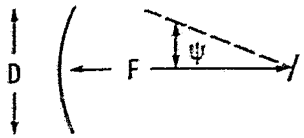
DECENTER



DEFINITION: ΔLATITUDINAL DISTANCE FEED/ANTENNA

IMPACT: POINTING LOSS; NO GAIN LOSS UNLESS ΔX GETS LARGER THAN THE BEAMWIDTH

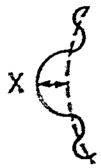
TILT



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 15. - Defocusing definitions.

DEFOCUSING FOR LARGE APERTURE PHASED ARRAY

CONDITIONS	DECENTER, m	DESPACE, m	TILT, rad
6.96 N/THRUSTER NO THRUSTER MASS	.0211	.0000	.0006
	.0612	.0001	.0069
6.96 N/THRUSTER WITH THRUSTER MASS	.0639	.0001	.0077
2.0 N/THRUSTER WITH THRUSTER MASS	.0072	.0000	.0000
	.0193	.0000	.0022

DEFOCUSING FOR HOOP COLMN LAND MOBILE SATELLITE SYSTEM

CONDITIONS	DECENTER, m	DESPACE, m	TILT, rad
30.0 N/THRUSTER NO THRUSTER MASS	.6263	.0025	.0069
	.4383	.0000	.0057
30.0 N/THRUSTER WITH THRUSTER MASS	.5368	.0016	.0069
	.4342	.0000	.0056
2.0 N/THRUSTER WITH THRUSTER MASS	.0357	.0001	.0005
	.0291	.0000	.0004

DEFOCUSING FOR WRAP RIB LAND MOBILE SATELLITE SYSTEM

CONDITIONS	DECENTER, m	DESPACE, m	TILT, rad
8.12 N/THRUSTER NO THRUSTER MASS	.1130	.0007	.1939
	.0097	.0018	.0653
8.12 N/THRUSTER WITH THRUSTER MASS	.1162	.0006	.2323
2.0 N/THRUSTER WITH THRUSTER MASS	.0286	.0002	.1941
	.0087	.0008	.0633

10% POWER LOSS

DEFOCUSING FOR GEOSTATIONARY PLATFORM

CONDITIONS	UHF ANTENNA			PETA ANTENNA		
	DECENTER, m	DESPACE, m	TILT, rad	DECENTER, m	DESPACE, m	TILT, rad
7.2 N/THRUSTER NO THRUSTER MASS	.0043	.0001	.0541	.0016	.0048	.0001
	.0030	.0024	.0002	.0084	.0107	.0006
7.2 N/THRUSTER WITH THRUSTER MASS	.0038	.0020	.0002	.0083	.0099	.0006
2.0 N/THRUSTER WITH THRUSTER MASS	.0012	.0000	.0001	.0004	.0014	.0000
	.0011	.0006	.0001	.0023	.0027	.0002

10% POWER LOSS

Figure 16. - APS/LSS interactions results; deflections in meters.