NASA Technical Memorandum 102703

Utilization of the Spacehab Module as a Microgravity Carrier

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Washito A. Sasamoto
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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

1.0 ABSTRACT

Spacehab, Incorporated has proposed the use of its mid-deck augmentation module as a near term microgravity test bed. The orbital flight dynamics and payload accommodation capabilities of a Space Shuttle with the Spacehab module (figure 1) were investigated to assess this proposal. It was found that the module will provide a 1 μG (32.2x10E-06 ft/sec^2) quasi-steady state environment for limited periods of time when the shuttle is actively controlled. A passively stable attitude will provide a 4μG environment for longer periods. Shuttle imposed constraints on the composite payload center of gravity, however, severely limit the possibilities for co-manifesting additional payloads. This report details the analysis leading to these conclusions.

2.0 INTRODUCTION

The opportunity to conduct experiments in a nearly acceleration-free environment promises to yield countless scientific and technological benefits. One goal of the Space Station Freedom Program will be to provide lab space that is subjected to a quasi-steady state acceleration of less than 1 μG (32.2x10E-06 ft/sec^2). Placing an experiment on Freedom will require a long term commitment. The Spacehab module, used as a short term microgravity facility, will provide scientists with the opportunity to refine processes to the point where accommodation on the Space Station would be economically feasible. The first launch of the Spacehab module is scheduled for September 1992, with at least 5 more in the following 2 years.

The Spacehab module was proposed in response to a growing backlog of Orbiter mid-deck type experiments. Of the 42 lockers on the orbiter an average of 7 are normally available for such experiments. By augmenting the orbiter mid-deck with an additional 1000 ft^3 of pressurized volume, the commercially developed Spacehab module will provide more flight opportunities to scientists. The baseline module can be configured to accommodate 79 mid-deck lockers, 1 double rack and 57 lockers, or 2 double racks and 45 lockers.

The components making up the Spacehab system are shown in figure 2. The module will be a truncated cylinder 10 ft long and 13.5 ft in diameter. Pressurized access from the orbiter will be provided by a tunnel adapter connected to a transition section. Reconfiguration of the removable Experiment Augmentation Plate will facilitate different missions. The system will occupy the first 220.76 in of the payload bay, leaving approximately 69% of the bay available for other payloads. The ability to co-manifest other payloads is one of the primary advertised advantages of the Spacehab system over Spacelab, which normally requires a dedicated flight.

The module, including support set, will weigh 6530 lbs. Payloads have been allocated 3000 lbs. An additional 280 lbs for the transition section and 690 lbs for the tunnel adapter kit bring the total to 10,500 lbs. This figure does not include shuttle chargeable items such as the

Standard Multiple Cargo Harness and orbiter/payload structural attachments which will increase the weight.

One potential future application of the module investigated in this study was its use as a combination resupply and docking system for man tended free flying spacecraft such as the currently proposed Commercially Developed Space Facility (CDSF). Figure 3 shows the CDSF mated to a Spacehab module. Docking would be facilitated by a berthing assembly mounted onto the module's Experiment Augmentation Plate. Spacehab would carry two double racks into orbit for changeout on the CDSF. Residual volume in the module could be used to accommodate additional experiments to be run concurrently.

3.0 MICROGRAVITY REQUIREMENTS

The acceleration level requirements used in this study were set forth by the Microgravity Science and Applications Division of the Space Station Office in the Naumann letter of February 24, 1988. The proposed requirements were stated in terms of the quasi-steady state residual g-vector:

> *This vector must be equal [to] or less than 10E-6 g in magnitude and fixed in direction to within +/- 5 degrees from the mean. Certain experiment modules ... must be aligned with this vector.*

It was recognized that 1μg would probably be unachievable above a certain frequency in a manned vehicle. Analysis indicated that experiments could tolerate higher g-levels for periodic accelerations at frequencies higher than .01 Hz. The resulting requirement follows.

> *Oscillatory accelerations are permissible at frequencies above .01 Hz provided their amplitudes in units of earth gravity are equal [to] or less than 10E-5 times the frequency in Hz.*

3.1 SOURCES OF MICROGRAVITY ACCELERATIONS

The accelerations affecting manned spacecraft can be separated into two categories: quasi-steady state and transient/oscillatory.

Accelerations which are continuous and slowly varying in nature are termed quasi-steady state. The components that make up the quasi-steady state sensed acceleration vector include gravity gradient, rotational, and drag induced effects (angular acceleration was assumed to be negligible). The gravity gradient component results from a difference in gravity force experienced at a point on an object by virtue of its separation from the object center of mass. Rotational acceleration is caused by the angular velocity of a rigid body. For the shuttle to maintain an earth oriented attitude it must rotate about the pitch axis once per orbit. Aerodynamic drag is due to atmospheric friction and acts in the opposite direction of the velocity vector. These components sum as in figure 4. Also in the figure are microgravity contours that represent regions that experience the same magnitude of sensed acceleration. Part of the difficulty of providing payloads with a 1 μG environment is that the envelope is typically about 5 meters high. Consequently the payload must be less than 2.5 meters along the Z axis from the spacecraft center of gravity to experience less than 1 μG.

Sinusoidal accelerations which may be described by discrete amplitudes and frequencies are defined as oscillatory; all other time varying accelerations are defined as transient. The oscillatory/transient accelerations considered in this study were crew translation, background machinery, and vernier thruster firing. Actual NASA flight experienced dynamic disturbances measured on previous STS microgravity missions are shown superimposed over the defined μG magnitude versus frequency requirement in figure 5. It can be seen that these disturbances generally fall outside of the acceptable limits. The dominant disturbances are vernier reaction control system (VRCS) thruster activity and crew activity The VRCS jets are nonthrottlable units designed to produce 25 lb of thrust which would cause a 36 μG acceleration if assumed to be applied at the spacecraft center of gravity. Jet activity must therefore be minimized. Crew activity, while being continuous, can be somewhat controlled. Sensitive experiments must be scheduled around periods of high crew activity.

3.2 ENVIRONMENTALLY INDUCED PERTURBATIONS

Gross dynamic effects need to be taken into account to insure that the +/- 5 degree μG direction requirement is not violated. There are a number of environmentally induced torques which affect spacecraft attitude. These include aerodynamic torques, gravity-gradient effects, solar pressure, and gyroscopic effects. In low earth orbit the first two tend to predominate. Aerodynamic torques are a function of frontal area with respect to the velocity vector for a given spacecraft and orbit. An unsymmetric frontal area normally results in an offset between the center of pressure and the center of gravity which gives rise to an aerodynamically induced torque. Gravity gradient effects manifest themselves in two ways. First they tend to align the spacecraft's axis of minimum mass moment of inertia with the gravity-gradient field (nadir/zenith). Additionally they align the axis of maximum mass moment of inertia with the axis perpendicular to the orbit plane (P.O.P.)

For each spacecraft and orbit combination there exists a Torque Equilibrium Attitude (TEA), which is defined as the attitude where the sum of the gravity gradient and aerodynamic torques is minimized on average. A spacecraft's TEA establishes the mean attitude from which the μG vector variation is measured.

4.0 SCOPE OF ANALYSIS

The analysis outlined in this report was conducted with mathematical models generated in the NASA/SDRC IDEAS[2] software package.Two configurations were studied: a module-only configuration of the spacehab module mounted in the payload bay; and a mated configuration in which a CDSF module was mated to a shuttle-based spacehab module. Rigid body control requirements and microgravity contours were calculated using the Articulating Rigid body Control Dynamics (ARCD) program. The module ATTitude PREdict (ATTPRED) was used to determine the orbital flight dynamics of the configurations. Both modules utilize a Jacchia 1970 atmosphere density model with input values provided by the Marshall Space-flight Center.

4.1 ASSUMPTIONS

For this study, it was assumed that both crew activity and background equipment noise could be minimized to meet the microgravity requirements. For crew activity this requires that the forces associated with normal duties be limited to 20 lbs. Since jet thruster force cannot be controlled it must be minimized. A drift rate of +/- 0.005 rad/sec was assumed for microgravity profile calculation.

4.2 ORIENTATIONS AND OPTIONS STUDIED

Three orthogonal orbiter orientations that were representative of earth oriented attitudes were studied for the Spacehab only configuration. The orbiter +Z axis, which points out of the payload bay, was aligned with the axes of the Local Vertical Local Horizontal (LVLH) coordinate system, where Z points towards earth, Y is perpendicular to the orbit plane, and X is along the velocity vector. A flight altitude of 220 nautical miles was chosen for all three attitudes. See figure 6.

Three different power generation options were studied for the mated configuration: 7kW and 10kW feathered solar arrays, and a 7kW sun tracking option. Each option was studied at the two proposed rendezvous attitudes: 174 and 202 nautical miles. See Figure 7.

5.0 RESULTS: SPACEHAB ONLY CONFIGURATION

The first attitude studied was an Earth oriented orbiter attitude with the body axis along the velocity vector (LVLH X axis) and the payload bay pointing away from earth. As shown in figure 8 this attitude will provide a pressurized workspace in which the sensed acceleration is less than 1 μG. The attitude, however, is not passively stable. Gravity gradient effects attempt to reorient the spacecraft so that the orbiter's axis of minimum inertia (body axis) is parallel to the LVLH Z axis. Since this pitching torque would cause the spacecraft to tumble in less than 1 orbit, active control is required to maintain the attitude. Figure 9 shows the spacecraft's attitude over the course of two orbits given a VRCS deadband of five degrees. The sharp peaks in the figure represent thruster firings. As thruster activity results in an unacceptable acceleration in the module; microgravity experimentation would be restricted to quiescent periods between firings. The periods between peaks are on the order of 30 minutes.

Most experiments require more than 30 minutes of run time. These can only be accommodated by a passively stable orientation that does not require VRCS control. As shown in figure 10 an orbiter with its body axis (minimum inertia) aligned with the LVLH Z axis and its payload bay (axis of maximum inertia) pointed perpendicular to the orbit plane is passively gravity gradient stable. Due to the vertical stabilizer, however, the projected area of the orbiter with respect to the velocity vector is not symmetric about the orbit plane. The resulting aerodynamic torques cause the orbiter to yaw about the LVLH Z axis until gravity gradient torques begin to predominate. Interplay between these two effects results in an oscillatory motion about the LVLH Z axis. This is shown in figure 11. Gravity-gradient effects dominate at the peaks while aerodynamic effects dominate at the troughs. If the orbiter is initially rotated 10 degrees about the LVLH Z axis, the oscillation amplitude is less than 8 degrees. But the sensed acceleration in the Spacehab module for this particular attitude is dominated by the gravity gradient term which points along the Z axis. So despite the yaw oscillation the sensed acceleration vector remains within +/- 5 degrees of the spacecraft's mean TEA over a full orbit. The drawback to this configuration is that it can only provide a 3 to 4 μG environment (figure 10).

The last attitude in which the orbiter's body axis is aligned with the LVLH Z axis and the payload bay points opposite the velocity vector (figure 12) is unstable. Gravity gradient effects will tend to align the axis of greatest mass moment of inertia (IXX) with the LVLH Y axis. An orbiter in an uncontrolled mode will consequently begin to yaw about the LVLH Z axis. It will continue to do so until aerodynamic torques begin to predominate as in the last case. The oscillation that results will be of a much greater amplitude due to the increased angular momentum associated with the gravity gradient induced roll. Figure 13 shows the attitude of an uncontrolled shuttle over 10 orbits. Although the sensed acceleration in the Spacehab module is again dominated by the gravity gradient term, the amplitude of the oscillation is such that the microgravity directional requirement is violated.

Consequently, there are two acceptable attitudes. The first attitude will meet both microgravity magnitude and direction requirements with active control, but will only do so for periods of about 30 minutes. The passively stable orientation fails to meet the microgravity magnitude requirement, but will satisfy the direction requirement despite an oscillatory motion.

5.1 MATED CONFIGURATION

An attitude with the orbiter nose pointed towards Earth and cargo bay pointed opposite the velocity vector proved to be passively gravity gradient stable for all three power generation options. This attitude is unstable for the Spacehab only configuration, but the additional mass of the CDSF and its gravity gradient boom change the inertia properties enough to make the new configurations gravity gradient stable. All three options possess similar microgravity profiles. Figure 14 shows the profile for the 10kW feathered option. In all cases both the CDSF and Spacehab fall within the 4 μG envelopes. The projected area of the mated spacecraft with respect to the velocity vector is symmetric about the orbit plane. The aerodynamic torques that do arise are consequently quite small. The oscillations of both feathered options are all on the order of +/- 1 degree as shown in figures 15 and 16. The articulating arrays for the 7kW sun tracking option do however cause a translation of the center of pressure along the Z axis (nadir/zenith). This gives rise to an oscillation much like that described for the passively stable Spacehab only configuration. As shown in figure 17 microgravity direction requirements are marginally met at 202 nautical miles. The requirements are violated at 174 nautical miles

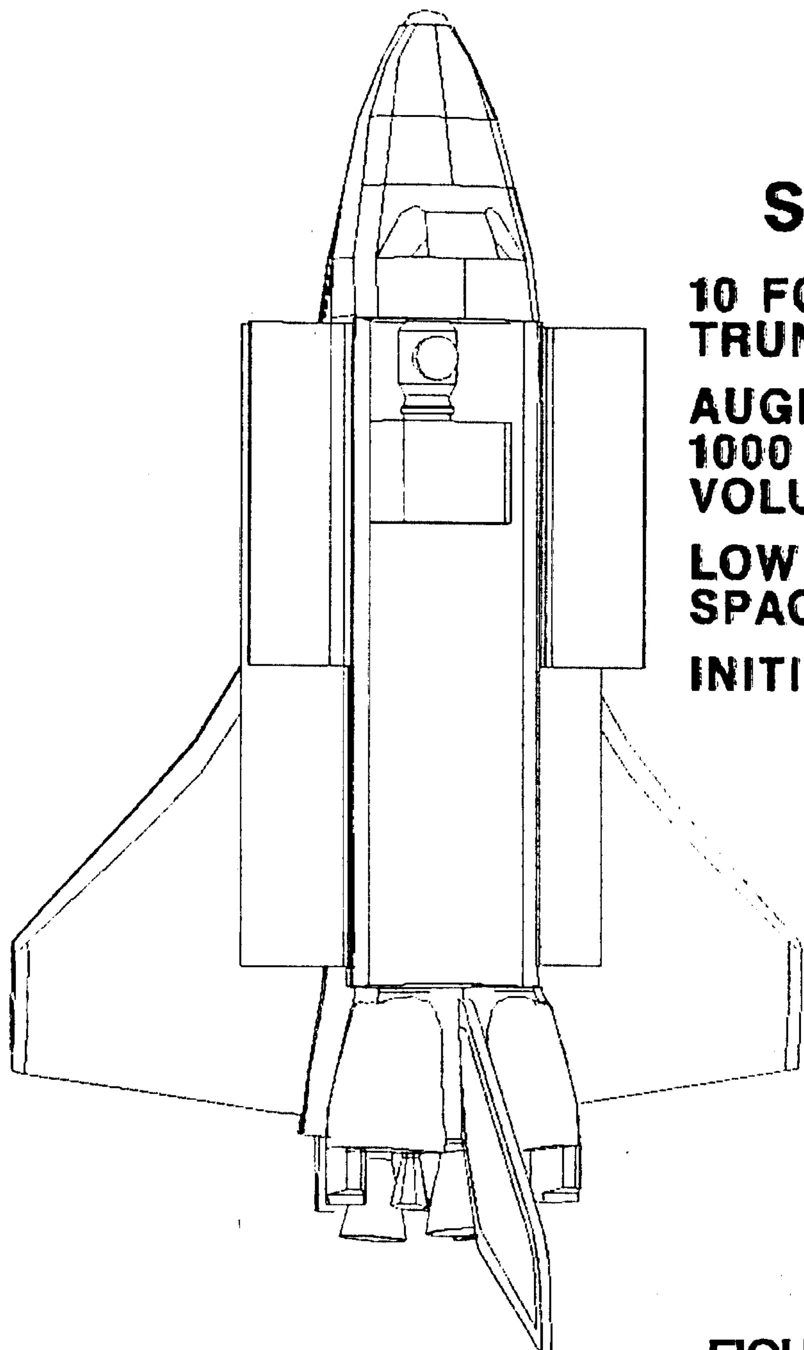
5.2 ORBITER CENTER OF GRAVITY RESTRAINTS

The composite x-axis center of gravity of the 10,500 lb Spacehab system is located at station 736" of the orbiter payload bay. This falls within the center of gravity envelope defined in revision I of the Space Shuttle Payload Accommodation Handbook (NSTS 00770 Volume XIV). This is to be expected given that Spacehab was designed under these constraints.

The shuttle center of gravity constraints, however, have been updated in revision J of Volume XIV in response to the Challenger accident. These new constraints reflect new orbiter launch and abort landing limitations. The Spacehab system fails to meet these constraints as shown in figure 18. The system is approximately 3700 lbs too heavy for the location it occupies in the payload bay. To meet the new center of gravity constraints, the composite center of gravity of all additional payloads must fall within the hatched area in the figure. Consequently, although over 69% of the payload bay is physically available for use, the bulk of any additional payloads must fall in the last 27% of the bay. This places a severe constraint on items co-manifested with Spacehab. Note also that a minimum of 5000 lbs of additional payload must be ballasted for the shuttle to land safely.

6.0 CONCLUSIONS

The results of this study indicate that Spacehab can be used as a microgravity carrier. For processes that must have a 1μG environment an actively controlled module only attitude can be used - but only for periods on the order of 30 minutes. Experiments that require more time to complete can only be conducted in a passively stable mode that offers a 4μG quasi-steady state environment. Since the sensed acceleration vector for these two attitudes is approximately 90 degrees apart, experiments sensitive to the mean acceleration vector direction must be configured for one or the other. No major problems were found with the use of the Spacehab module as a combination resupply and docking system. As long as rack change-out does not cause excessively large disturbances microgravity experiments can be carried out concurrently in a 4μG environment. The most formidable barrier to fully utilizing the module's capabilities arises from the requirement placed on co-manifested payloads by the new shuttle C.G. restraints.



SPACEHAB DEFINITION

- 10 FOOT LENGTH, 13.5 FOOT DIAMETER TRUNCATED CYLINDER
- AUGMENTS ORBITER MID-DECK WITH 1000 CUBIC FEET OF PRESSURIZED VOLUME
- LOW COST TO USER (COMPARED TO SPACELAB)
- INITIAL LAUNCH IN JUNE 1991

FIGURE 1

SPACEHAB SYSTEM COMPONENTS

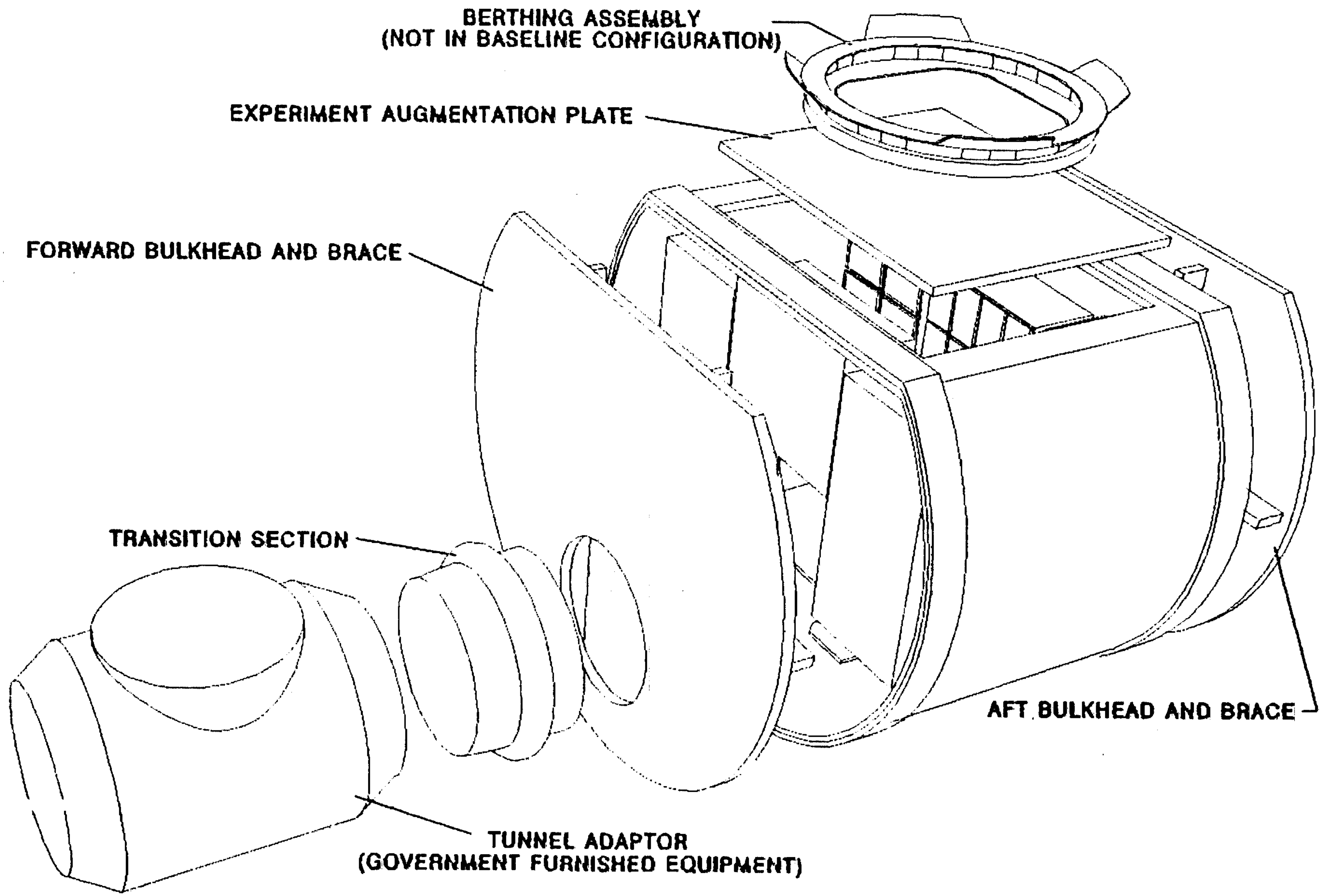


FIGURE 2

CDSF MATED TO SPACEHAB

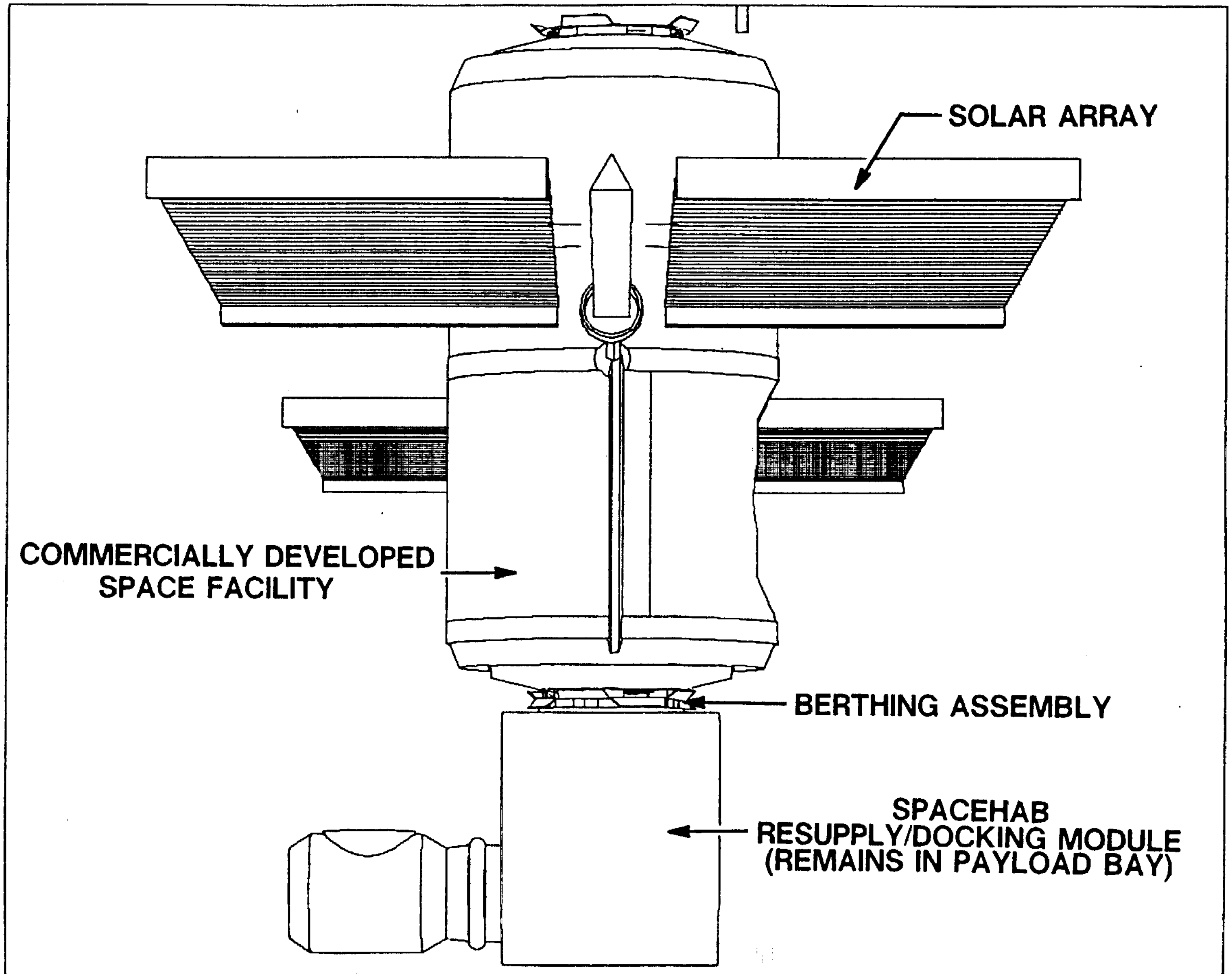
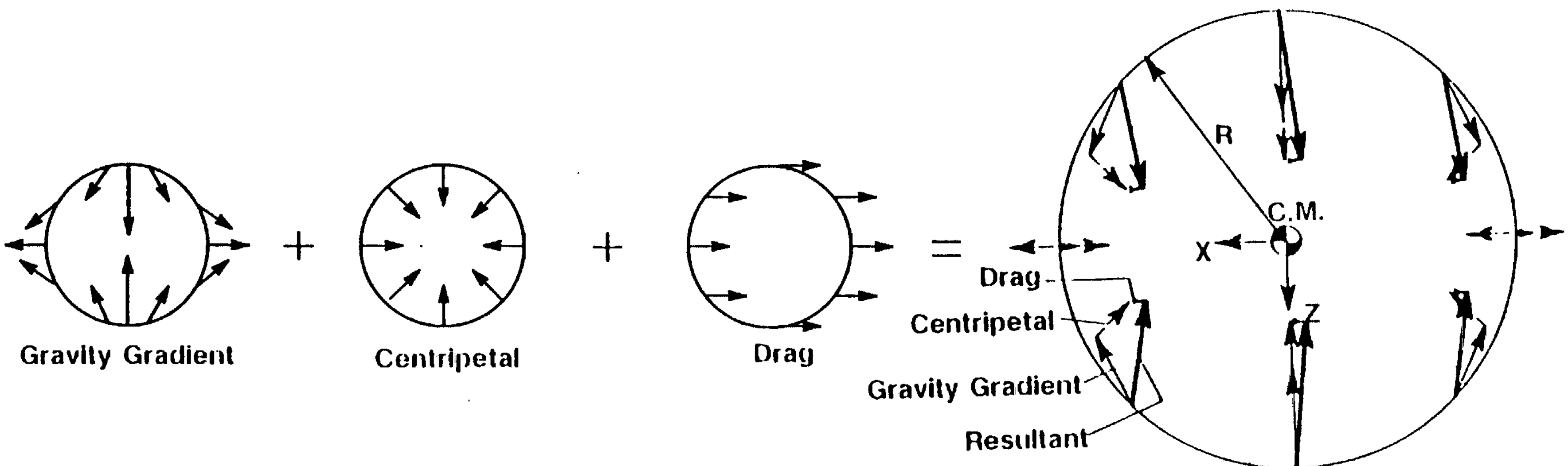
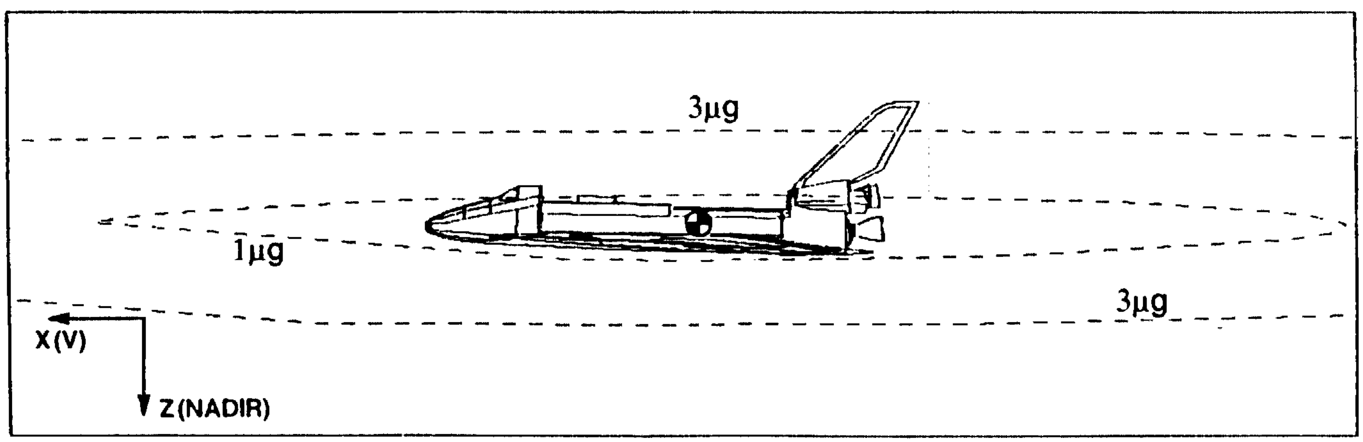


FIGURE 3

QUASI-STEADY STATE MICROGRAVITY



SENSED ACCELERATION COMPONENTS

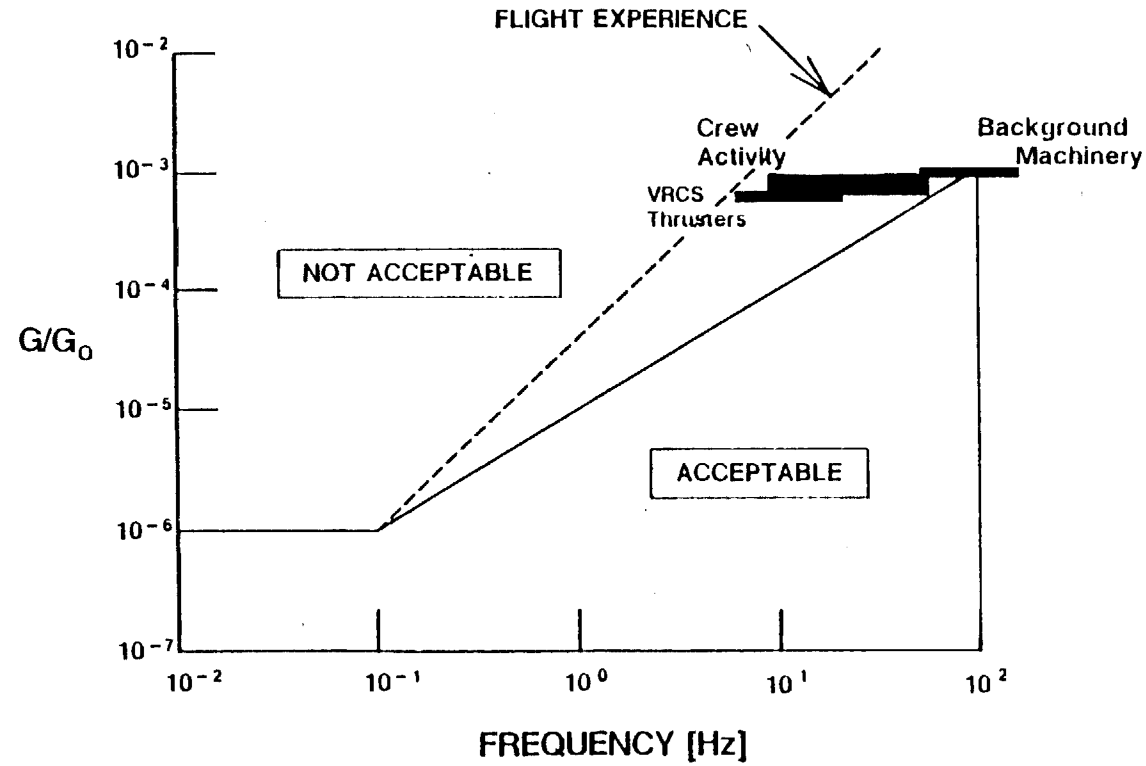


MICROGRAVITY CONTOURS

FIGURE 4

DYNAMIC MICROGRAVITY EXPERIMENT REQUIREMENTS

MAGNITUDE REQUIREMENT – 1 MICROGRAVITY STEADY STATE
FREQUENCY DEPENDENT FOR INDUCED VIBRATIONS



DIRECTIONAL REQUIREMENT – MAINTAIN SENSED ACCELERATION VECTOR TO WITHIN +/– 5 DEGREES

FIGURE 5

SPACEHAB MODULE ONLY ATTITUDES

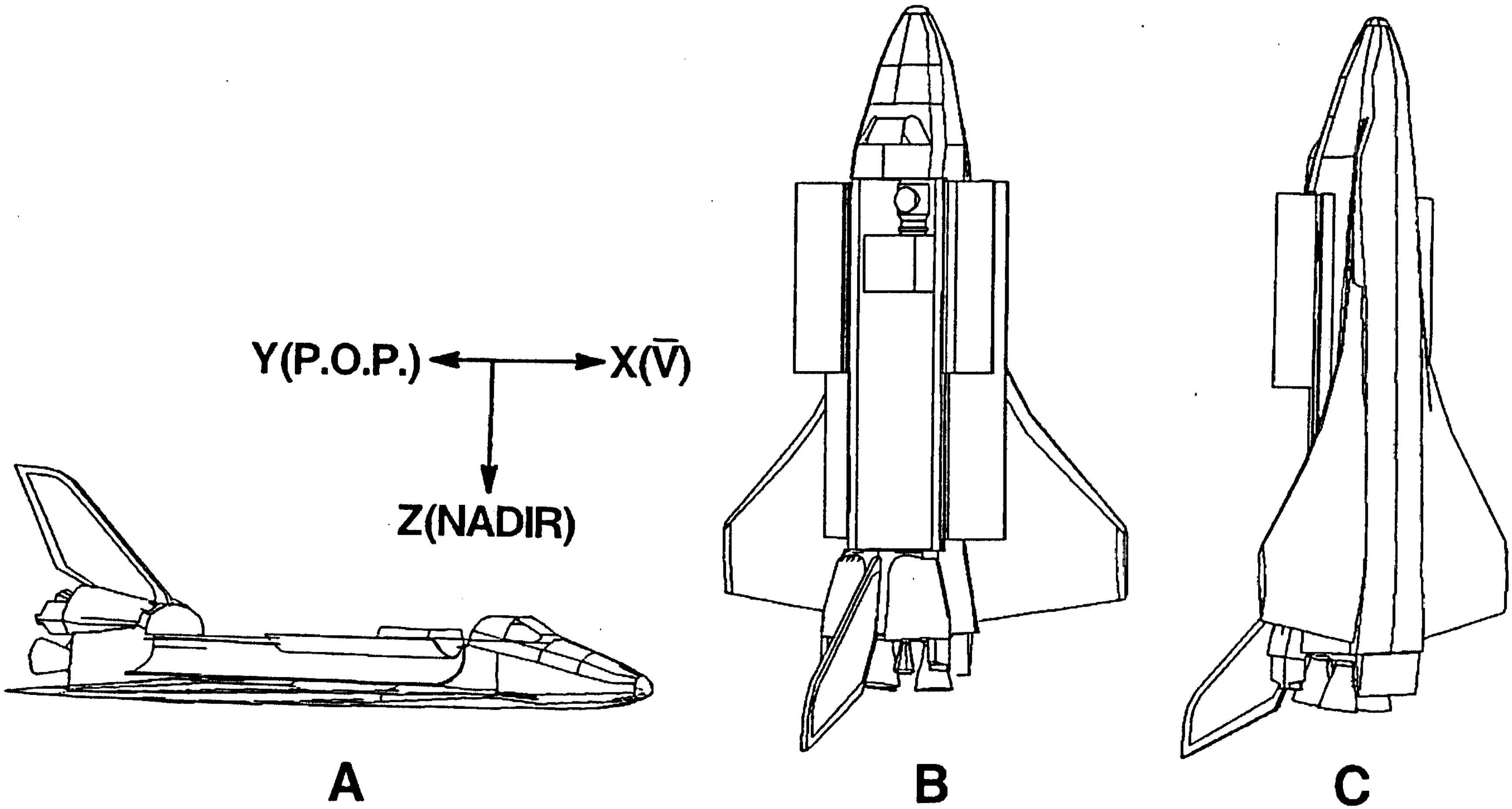
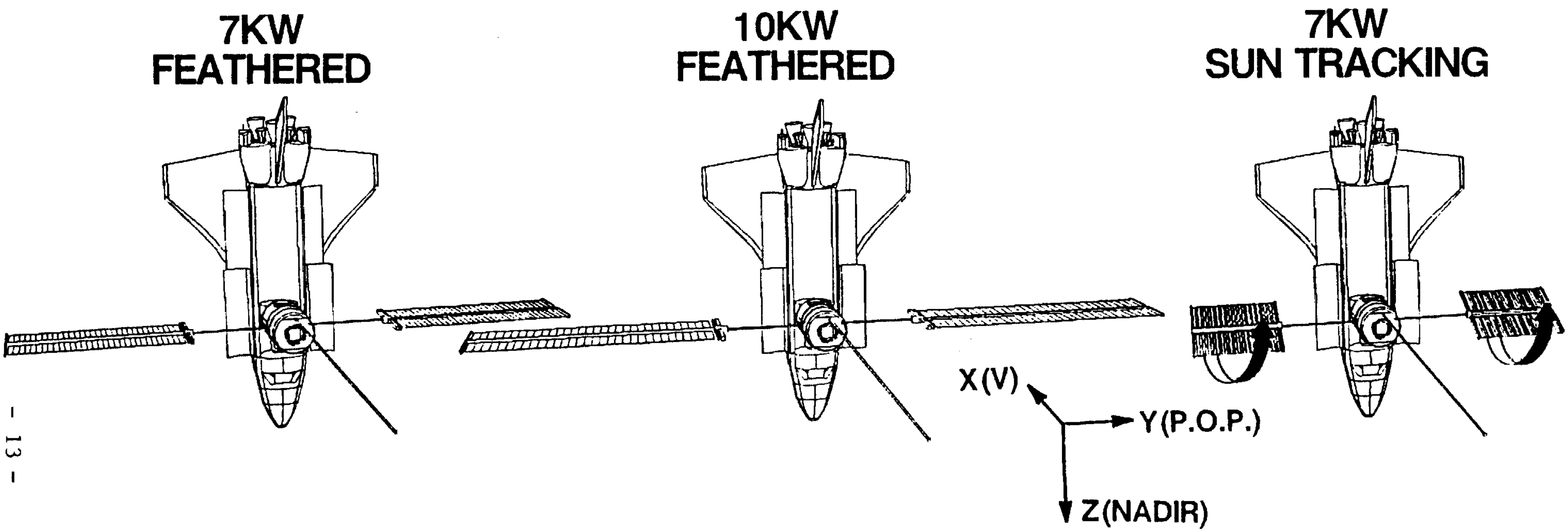


FIGURE 6

SOLAR ARRAY CONFIGURATIONS

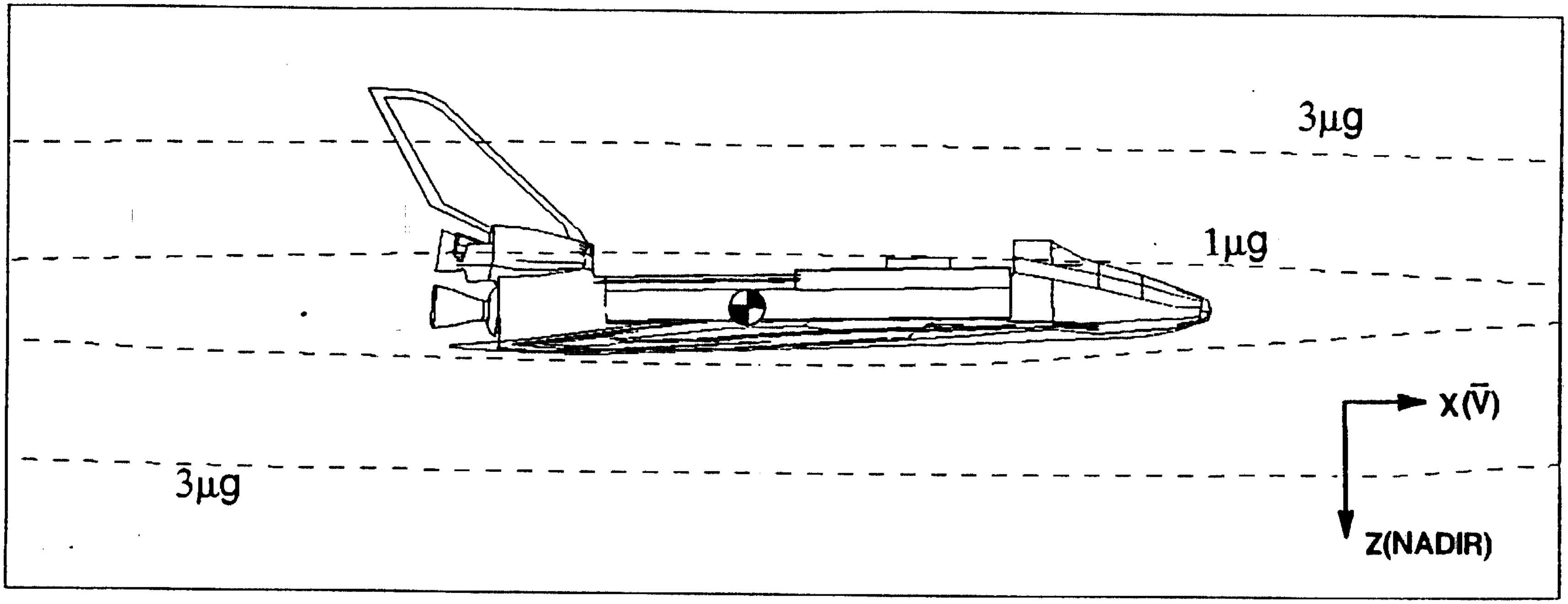


FEATHERED: ARRAYS ORIENTED WITH THEIR LARGEST AREA PERPENDICULAR TO V

SUN TRACKING: ARRAYS INERTIALLY POINTING TO SUN, ROTATING WITH RESPECT TO THE SPACECRAFT

FIGURE 7

ATTITUDE A MICROGRAVITY PROFILE



MASS MOMENT OF INERTIA
($lb\text{-}ft^2$)

IXX = 2.80E+07 IYY = 2.14E+08 IZZ =2.31E+08

FIGURE 8

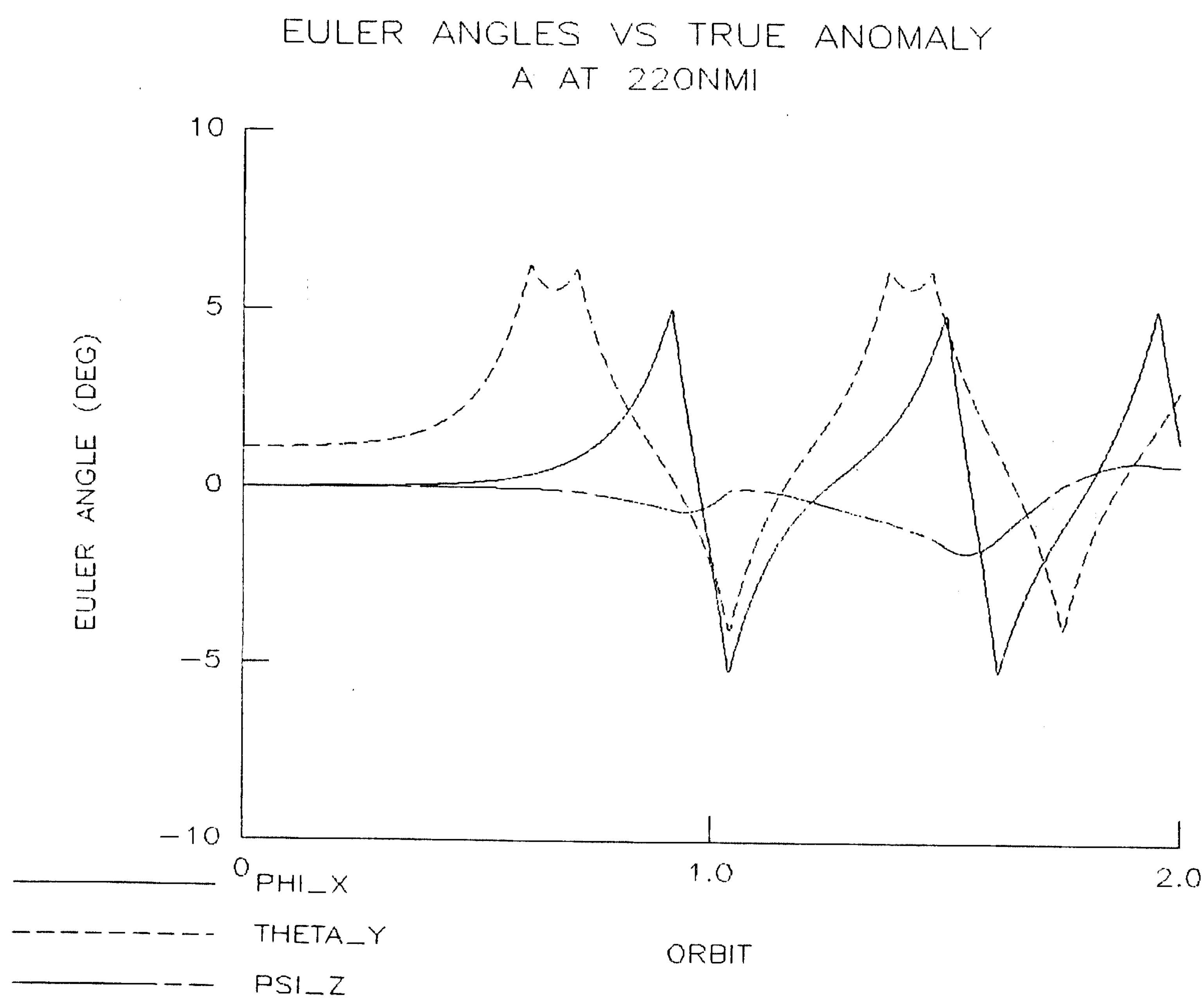
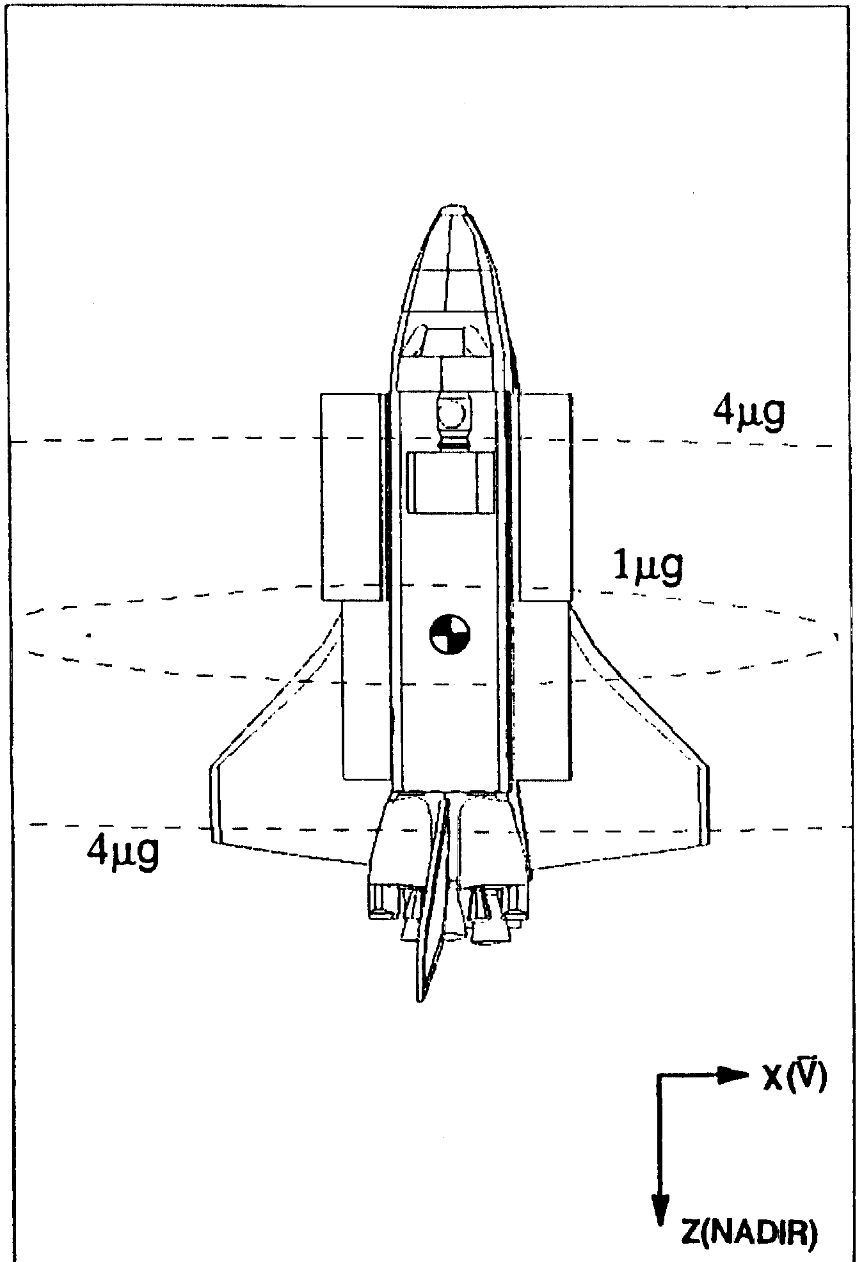

EULER ANGLES VS TRUE ANOMALY
A AT 220NMI
10
5
0
−5
−10
EULER ANGLE (DEG)
0
1.0
2.0
ORBIT
PHI_X
THETA_Y
PSI_Z

FIGURE 9

ATTITUDE B MICROGRAVITY PROFILE



MASS MOMENT OF INERTIA
($lb\text{-}ft^2$)

IXX = 2.15E+08

IYY = 2.31E+08

IZZ = 2.80E+07

FIGURE 10

EULER ANGLES VS TRUE ANOMALY
B AT 220NMI

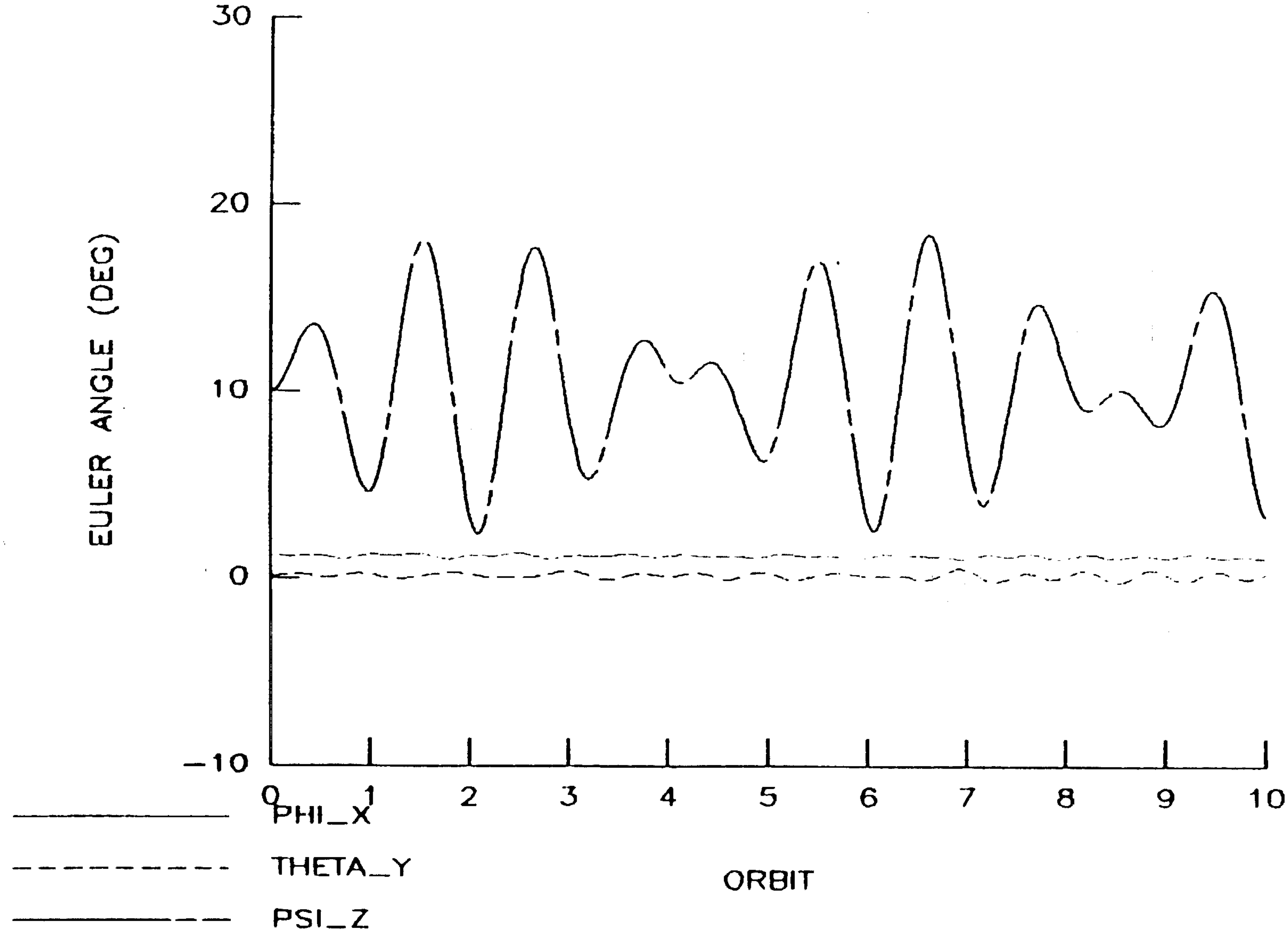
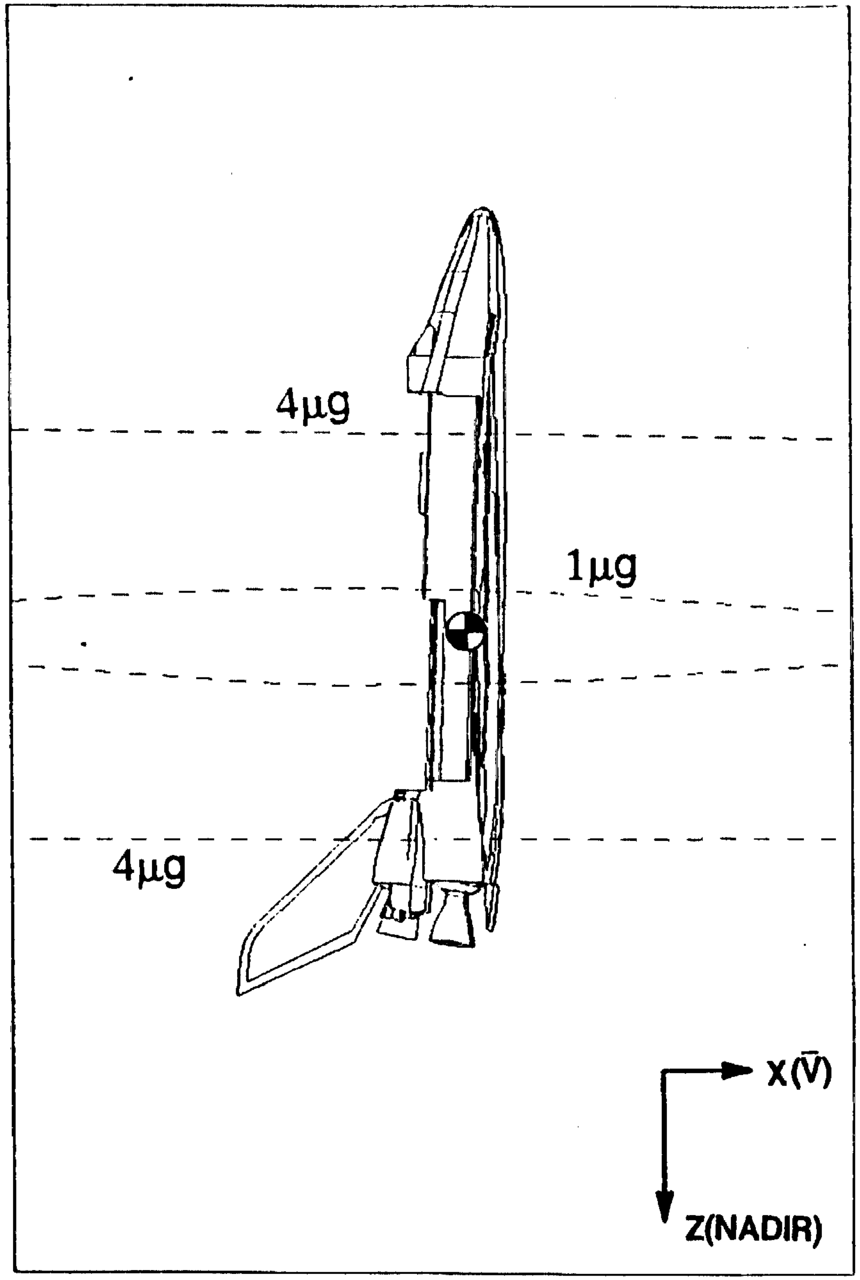


FIGURE 11

ATTITUDE C MICROGRAVITY PROFILE



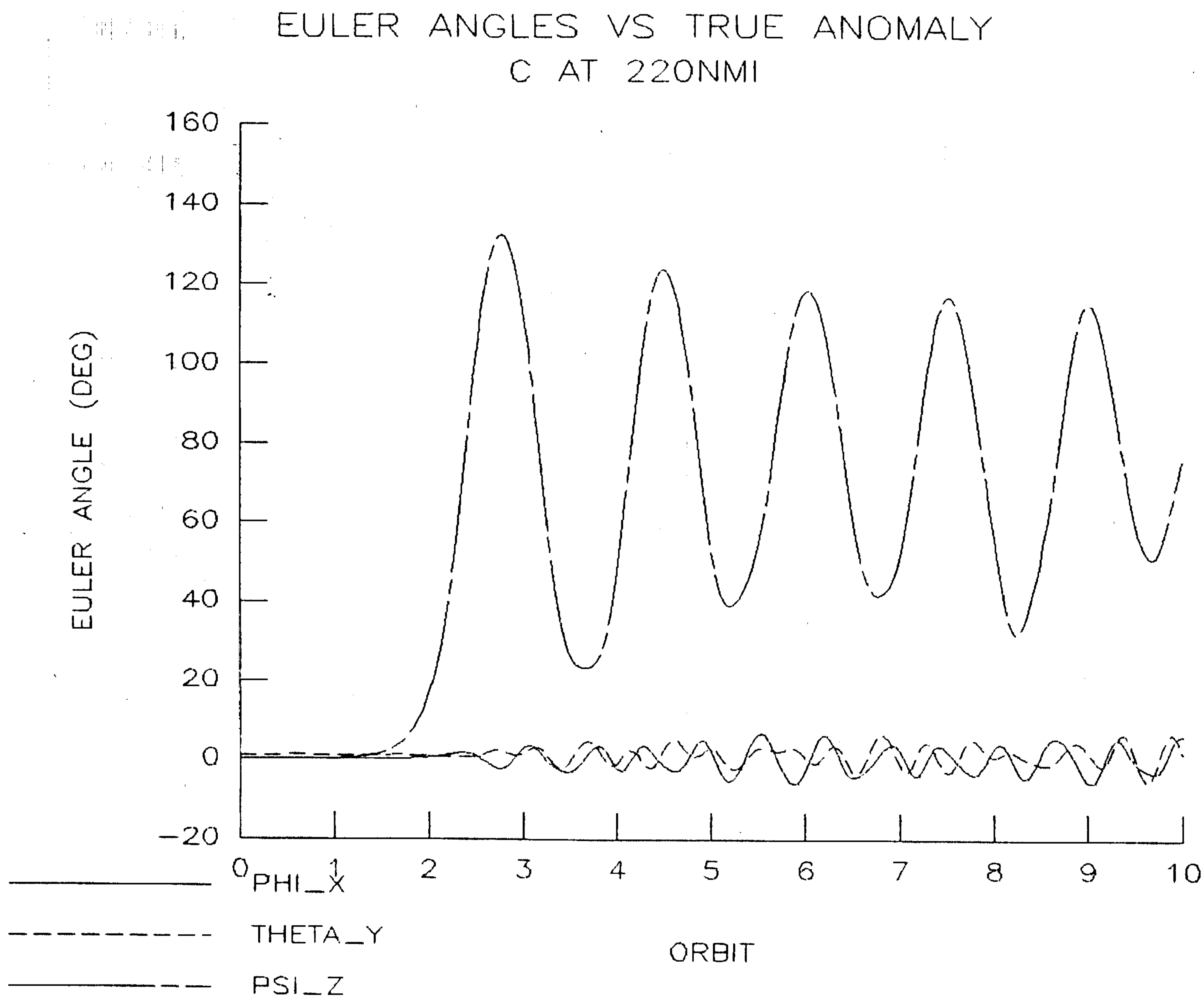
MASS MOMENT OF INERTIA
($lb\text{-}ft^2$)

IXX = 2.31E+08

IYY = 2.14E+08

IZZ = 2.83E+07

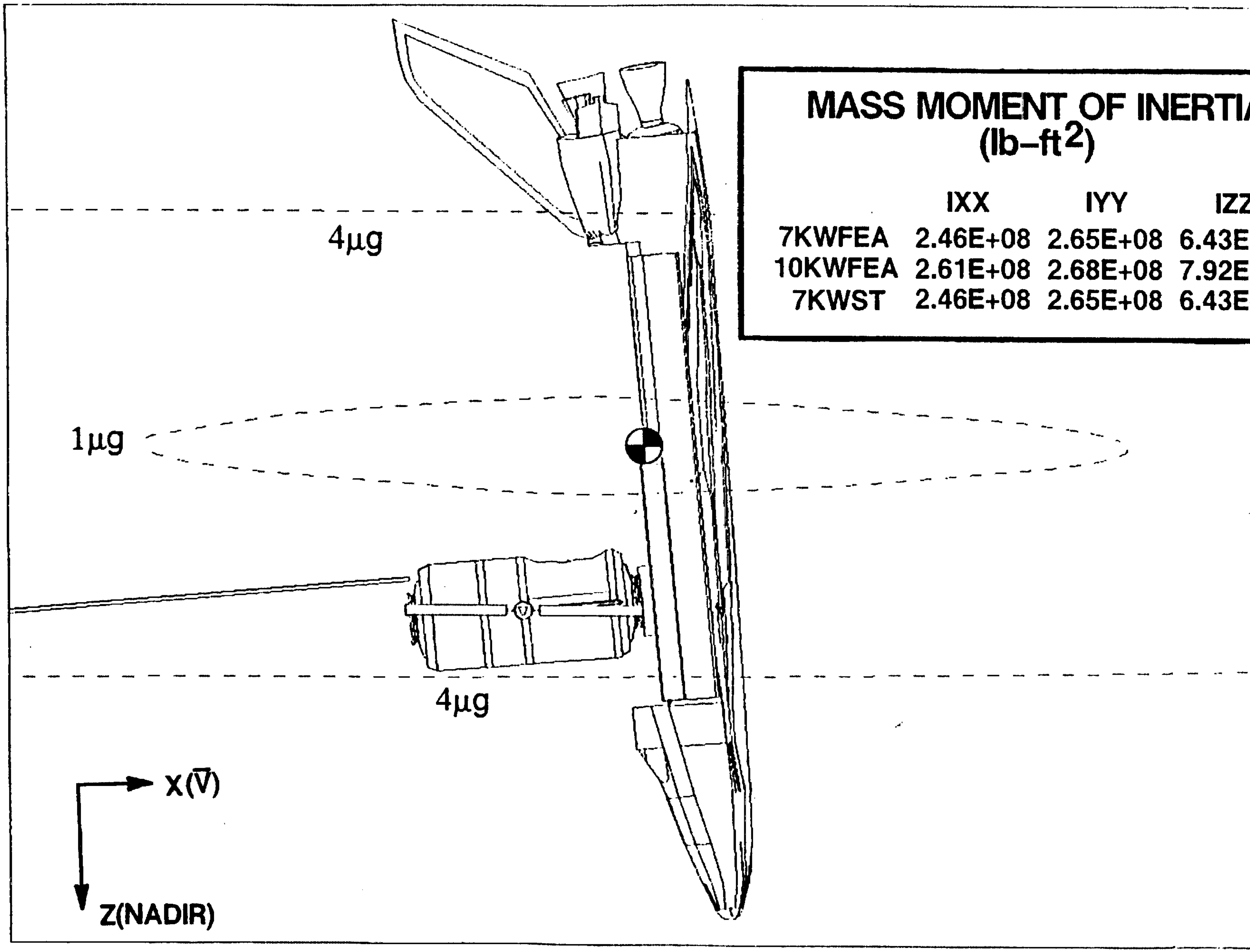
FIGURE 12



EULER ANGLES VS TRUE ANOMALY
C AT 220NMI
EULER ANGLE (DEG)
160
140
120
100
80
60
40
20
0
−20
0
1
2
3
4
5
6
7
8
9
10
ORBIT
PHI_X
THETA_Y
PSI_Z

FIGURE 13

MATED CONFIGURATION MICROGRAVITY PROFILE



MASS MOMENT OF INERTIA
(lb–ft^2)

	IXX	IYY	IZZ
7KWFEA	2.46E+08	2.65E+08	6.43E+07
10KWFEA	2.61E+08	2.68E+08	7.92E+07
7KWST	2.46E+08	2.65E+08	6.43E+07

FIGURE 14

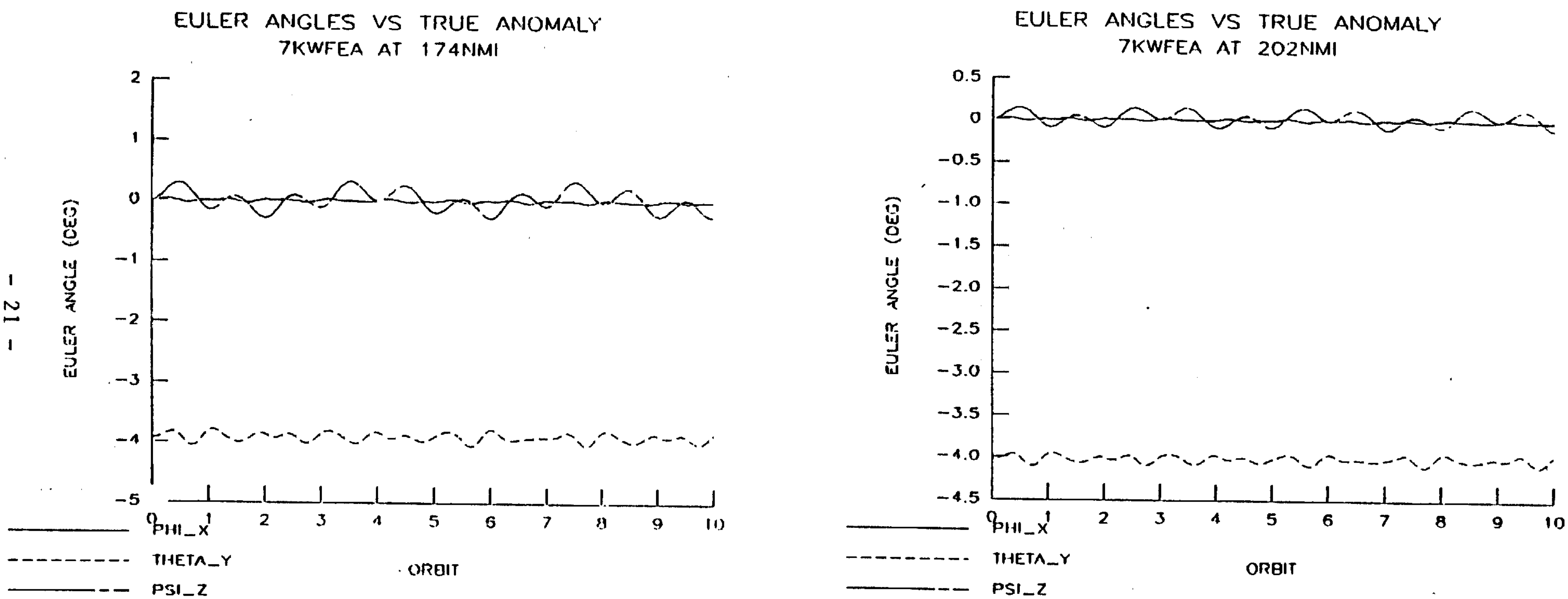

EULER ANGLES VS TRUE ANOMALY
7KWFEA AT 174NMI
EULER ANGLE (DEG)
2
1
0
-1
-2
-3
-4
-5
0
1
2
3
4
5
6
7
8
9
10
ORBIT
PHI_X
THETA_Y
PSI_Z
EULER ANGLES VS TRUE ANOMALY
7KWFEA AT 202NMI
EULER ANGLE (DEG)
0.5
0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
0
1
2
3
4
5
6
7
8
9
10
ORBIT
PHI_X
THETA_Y
PSI_Z

FIGURE 15

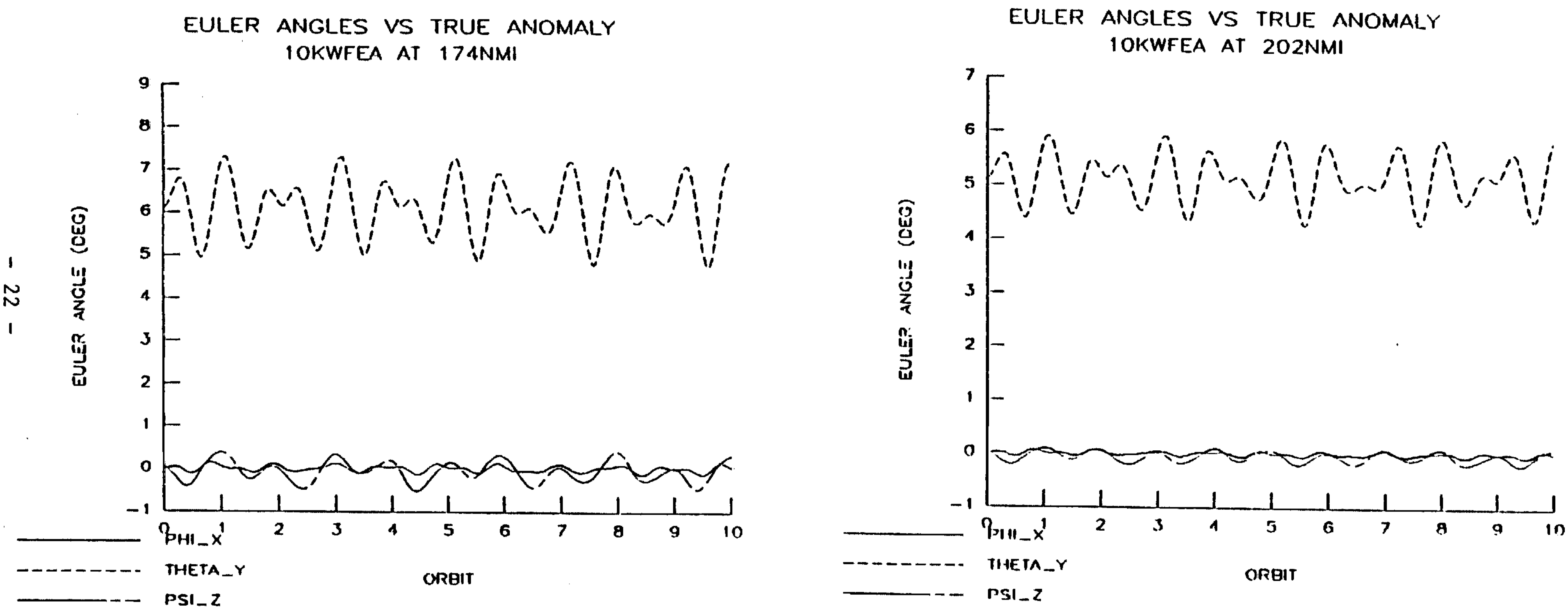

EULER ANGLES VS TRUE ANOMALY
10KWFEA AT 174NMI
EULER ANGLE (DEG)
ORBIT
PHI_X
THETA_Y
PSI_Z
EULER ANGLES VS TRUE ANOMALY
10KWFEA AT 202NMI
EULER ANGLE (DEG)
ORBIT
PHI_X
THETA_Y
PSI_Z

FIGURE 16

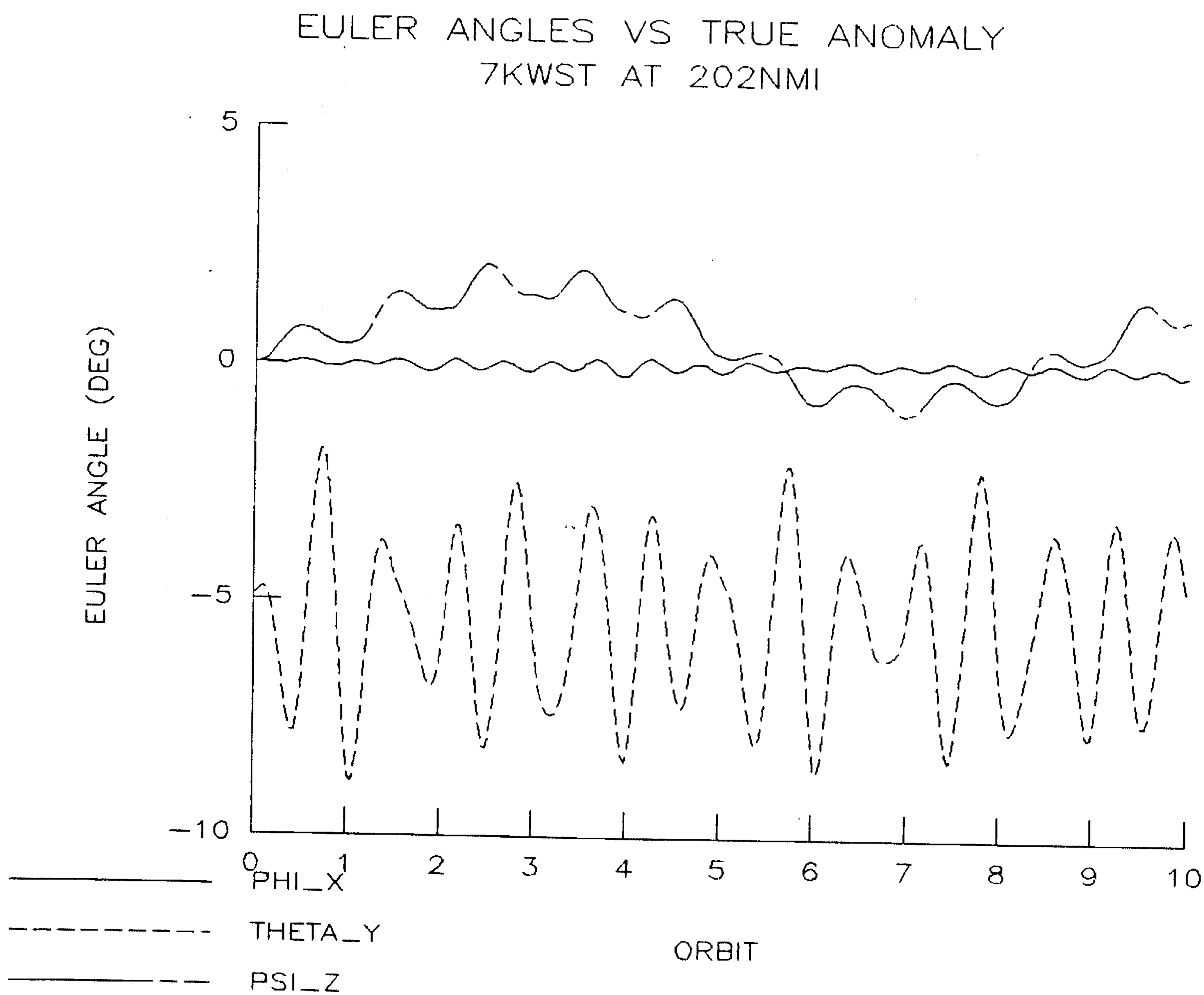
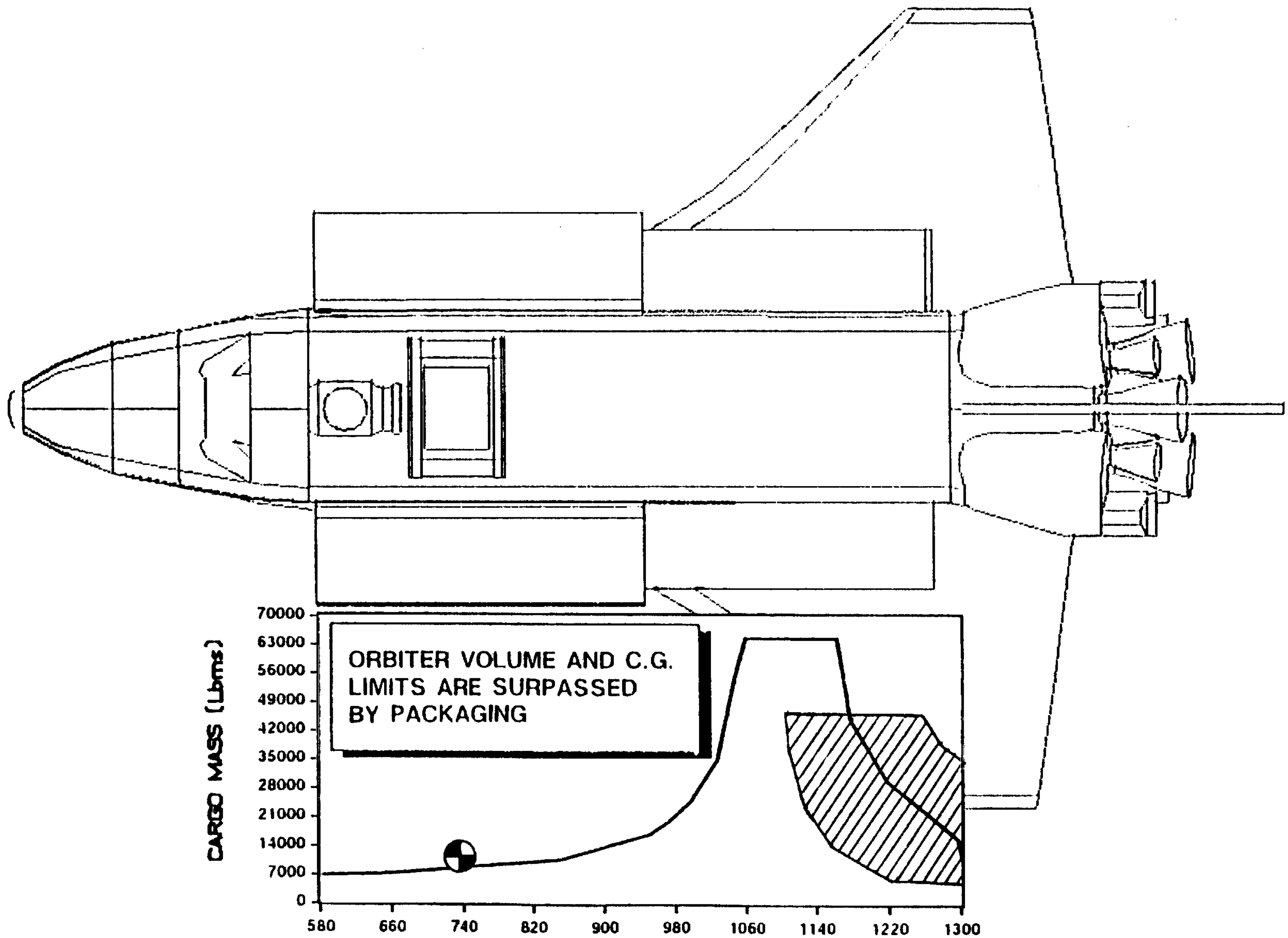

EULER ANGLES VS TRUE ANOMALY
7KWST AT 202NMI
EULER ANGLE (DEG)
5
0
−5
−10
0
1
2
3
4
5
6
7
8
9
10
ORBIT
PHI_X
THETA_Y
PSI_Z

FIGURE 17

X-AXIS C.G. LOCATION OF BASELINE CONFIGURATION



X-AXIS C.G. ENVELOPE FOR STS CARGO

FIGURE 18

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16. Abstract

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