

LSS REFERENCE PLATFORM CONTROL

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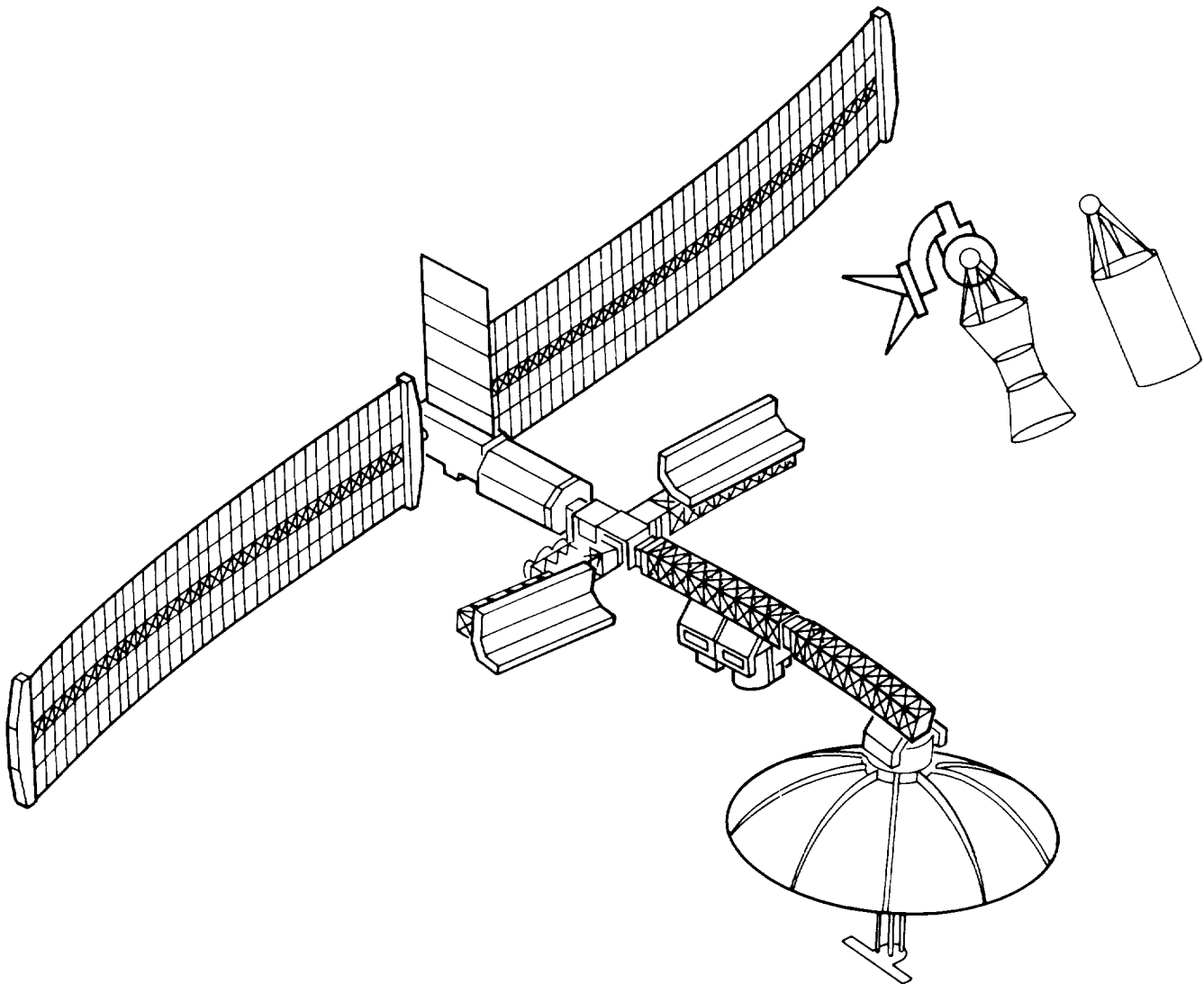
## FY'81 LSS PLATFORM CONTROL OBJECTIVES

The long range objective of this task is to develop basic technology in the design, mechanization, and analysis of control systems for large flexible space structures. The focus of the FY'81 platform control effort was on the pointing control problems associated with multiple independently controlled experiment packages operating simultaneously on a single platform. All of the FY'81 objectives stated below were accomplished. Particular emphasis was placed on obtaining a quantitative comparison of controller performance with and without base motion compensation.

- DEVELOP FREQUENCY DOMAIN DESIGN CAPABILITY FOR MULTIVARIABLE SYSTEMS
- DEVELOP THREE DIMENSIONAL STRUCTURAL/CONTROL MODELS
- INCORPORATE BASE MOTION COMPENSATION INTO CONTROLLER DESIGN
- QUANTIFY CAPABILITIES AND LIMITATIONS OF CONTROLLERS

## LSS PLATFORM CONFIGURATION

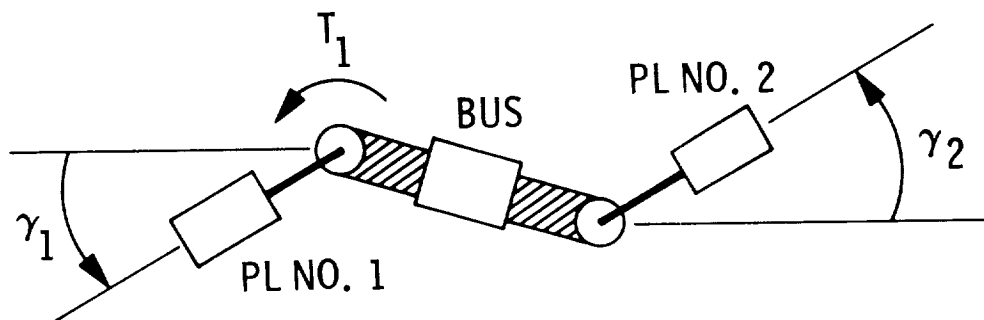
The LSS platform consists of solar panels, a central bus (with associated power, telemetry, and control systems), and platform arms with mounting pads on which various experiments can be attached. The actual configuration for the platform arms might vary widely depending on experiment requirements for physical separation and viewing angles. The tip to tip dimension of the solar panels is approximately 100 meters, and the total weight of the system is between 10 and 20,000 Kg.



## POINTING CONTROL PROBLEMS

Operation of multiple independent control systems on a single platform presents a major problem when high performance is required. The figure below illustrates the basic mechanism of payload controller interaction. A torque at payload 1 (PL No. 1) results in a rotation of the platform bus, which in turn causes a pointing error to result for payload 2. The magnitude of the disturbance caused by a torque applied by payload 1 depends primarily on the bus inertia and the geometry. It has been found from previous studies that conventional rate plus position control systems fail to meet performance requirements as a result of this interaction.

- PAYLOAD POINTING STABILITY IS DEGRADED BY CONTROLLER INTERACTION
- CONTROLLER INTERACTION EXISTS FOR RIGID SPACECRAFT AND IS AGGRAVATED BY FLEXIBILITY



- CONVENTIONAL RATE PLUS POSITION CONTROLLERS DO NOT MEET PERFORMANCE REQUIREMENTS

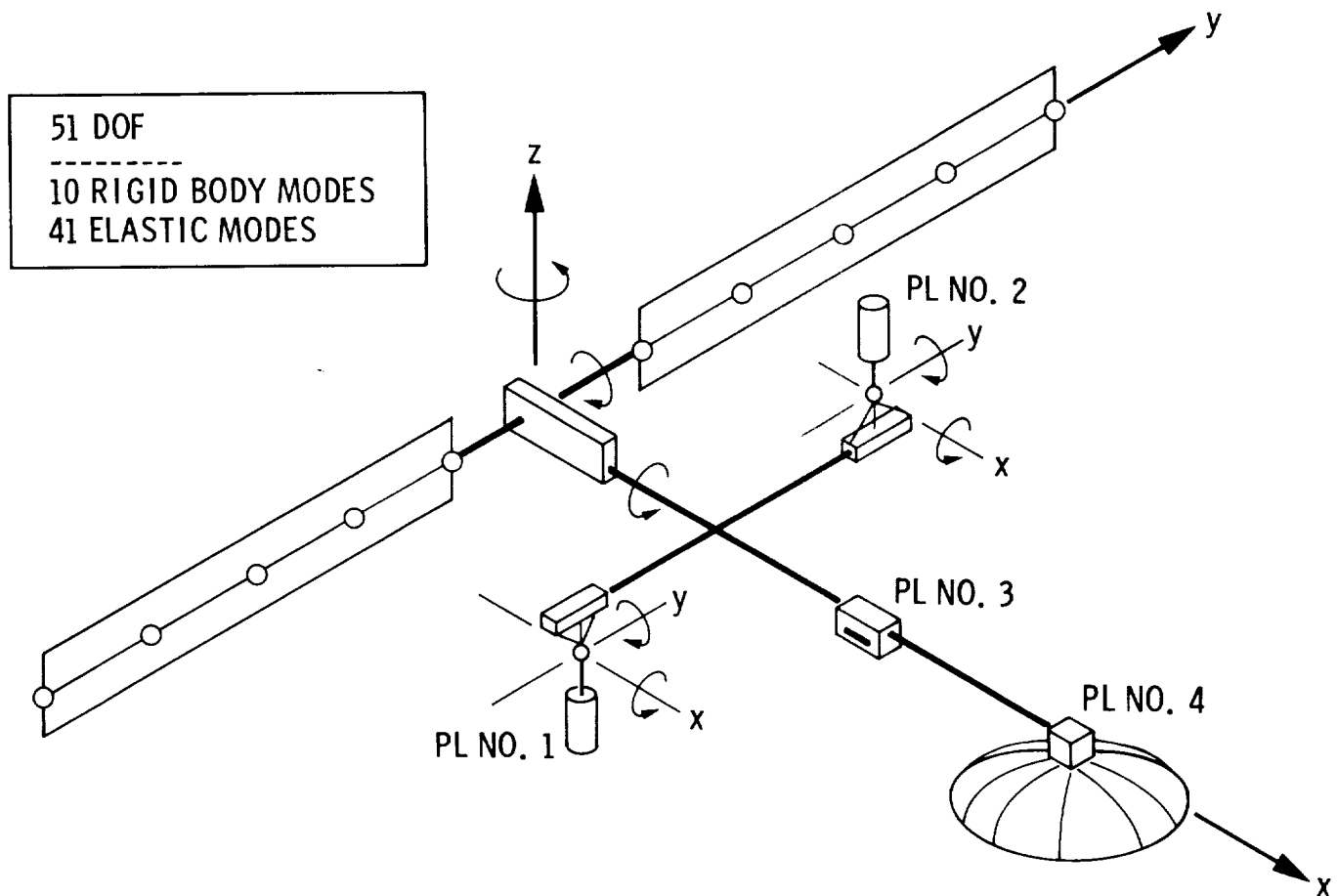
## POINTING CONTROL PROBLEMS (continued)

Control system design is complicated by large shifts in structural parameters which occur as a result of variations in the number and location of experiments mounted on the platform. Structural vibration frequencies in the controller bandwidth further complicate the design problem. The most difficult type of flexibility to design for is one which occurs between the gimbal actuator and the payload sensor. In this case, since the actuator and sensor are not colocated, phase shifts between an applied torque and the resulting angular acceleration at the sensor location can occur. These phase shifts can result in control system instabilities if not properly accounted for.

- CONTROLLER DESIGN IS COMPLICATED BY LARGE VARIATIONS OF STRUCTURAL PARAMETERS AND BY VIBRATION FREQUENCIES WITHIN THE CONTROLLER BANDWIDTH
- STRUCTURAL FLEXIBILITY BETWEEN ACTUATORS AND SENSORS PRESENTS SPECIAL DESIGN PROBLEMS AND MAY RESULT IN CONTROLLER INSTABILITY IF NOT PROPERLY ACCOUNTED FOR

## LSS PLATFORM MODEL

The three-dimensional structural model used for this study is shown below. It's relative simplicity allows the effects of structural parameter variations to be investigated cost effectively, yet it has sufficient completeness to account for the generic characteristics of a platform. Payloads 1 and 2 are attached to their pallets with two-degree-of-freedom pointing mounts. Payloads 3 and 4 are rigidly attached to their pallets. Two variations of this basic configuration are considered. The first has a rigid element between the two axis hinge and the payload interface for payload 2, and the second has an elastic element in this same location. These variations will be called rigid pointing mount and elastic pointing mount configurations respectively.



## CONTROL SYSTEM DESIGN APPROACH

The control system design follows the steps outlined below. Once a controller configuration has been selected the most important modes of the structural model are selected. This selection takes into account the combined characteristics of the controller and structural model and is described later. Next, compensation and preliminary controller gains are selected based on Single-Input, Single-Output root locus design methods. The controller gains are adjusted using Multi-Input, Multi-Output root locus methods. Finally, performance is verified using dynamic simulations.

- SELECT CONTROLLER CONFIGURATION
- PERFORM MODEL REDUCTION TO SELECT MOST SIGNIFICANT STRUCTURAL MODES
- SELECT COMPENSATION TO STABILIZE SELECTED MODES USING SISO ROOT LOCUS METHODS
- SELECT CONTROLLER GAINS TO PROVIDE DESIRED BANDWIDTH USING MIMO ROOT LOCUS METHODS
- PERFORM SIMULATIONS TO DETERMINE SYSTEM PERFORMANCE

## FREQUENCY DOMAIN DESIGN FEATURES

Single Input-Single Output (SISO) frequency domain approaches can be used to obtain controller designs which are relatively insensitive to parameter errors and model truncation. Also, many engineers prefer frequency domain approaches because of their directness and intuitive appeal. The Multi-Input, Multi-Output (MIMO) root locus approach developed for the LSS platform is robust and retains the appeal of SISO frequency domain approaches.

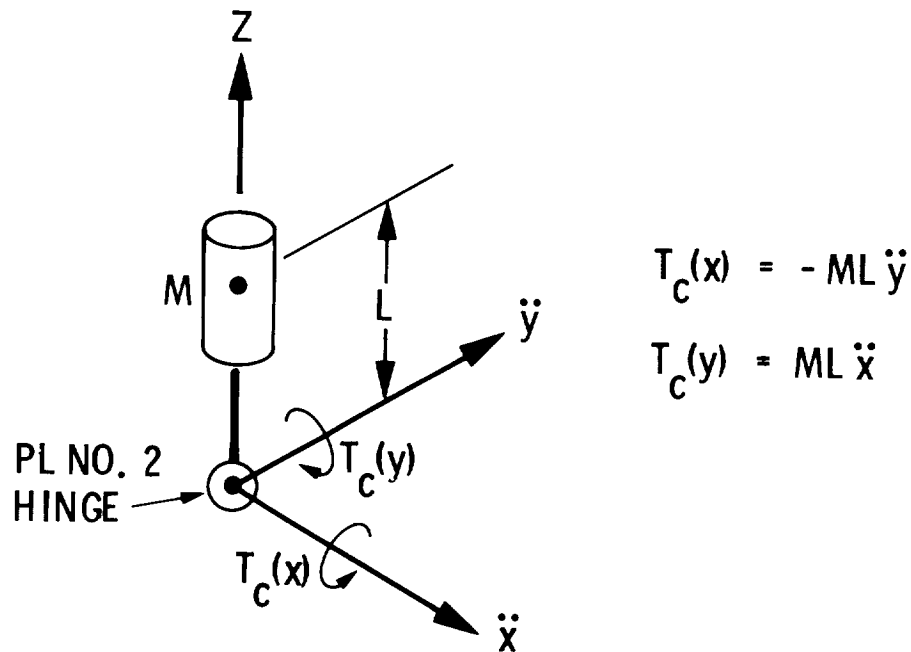
- STANDARD (SISO) FREQUENCY DOMAIN DESIGNS ARE ROBUST IN PRESENCE OF:
  - PARAMETER ERRORS
  - MODEL TRUNCATION
- SISO FREQUENCY DOMAIN APPROACHES HAVE DIRECTNESS AND INTUITIVE APPEAL
- MIMO FREQUENCY DOMAIN METHODS HAVE BEEN DEVELOPED FOR LSS PLATFORM WHICH RETAIN DESIRABLE FEATURES OF SISO DESIGNS



## BASE MOTION COMPENSATION

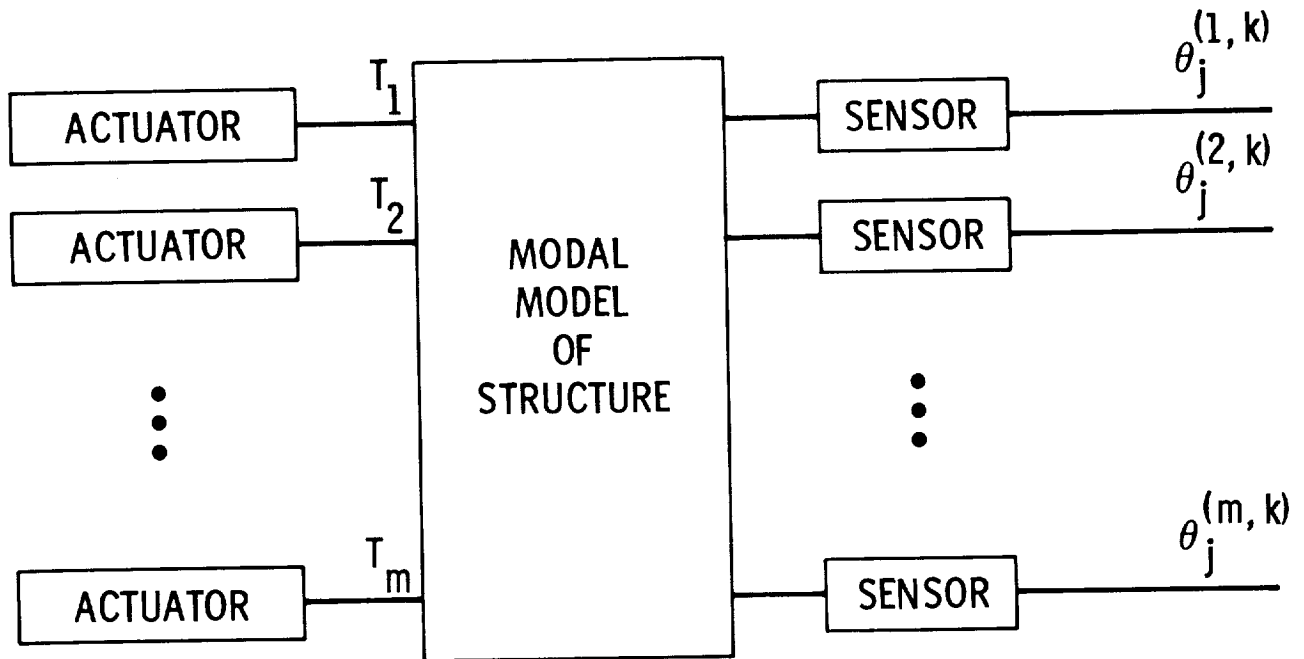
This study investigates the use of base motion compensation to reduce the interaction between payloads. The basic operation may be explained with the help of the figure below. The acceleration of the payload hinge point (or base) is measured and used to apply a corrective torque ( $T_c$ ). For an acceleration along the y axis, an x-axis torque is applied proportional to  $ML\ddot{y}$ . A similar y axis torque is applied for x axis accelerations.

Base motion compensation is being implemented on two major pointing systems under development for shuttle application. These are the Annular Suspension Pointing System (ASPS) under development by Sperry Flight Systems Division and the Instrument Pointing System (IPS) being developed by Dornier System. The study which follows is intended to identify generic limitations of pointing systems of this type, when operating in the LSS platform environment, without consideration of the detailed characteristics of a specific configuration.



# MODEL REDUCTION METHOD

A reduced order model of the structure is desired for control system design. The method used for this study chooses those modes which have the greatest effect on sensor outputs based on step actuator inputs. Maximum actuator torques are used as determined from system specifications. The resulting open loop response of the sensors are normalized using specification values for these outputs. Modal influence coefficients are found for each mode which represent the maximum normalized responses over all actuator and sensor pairs.

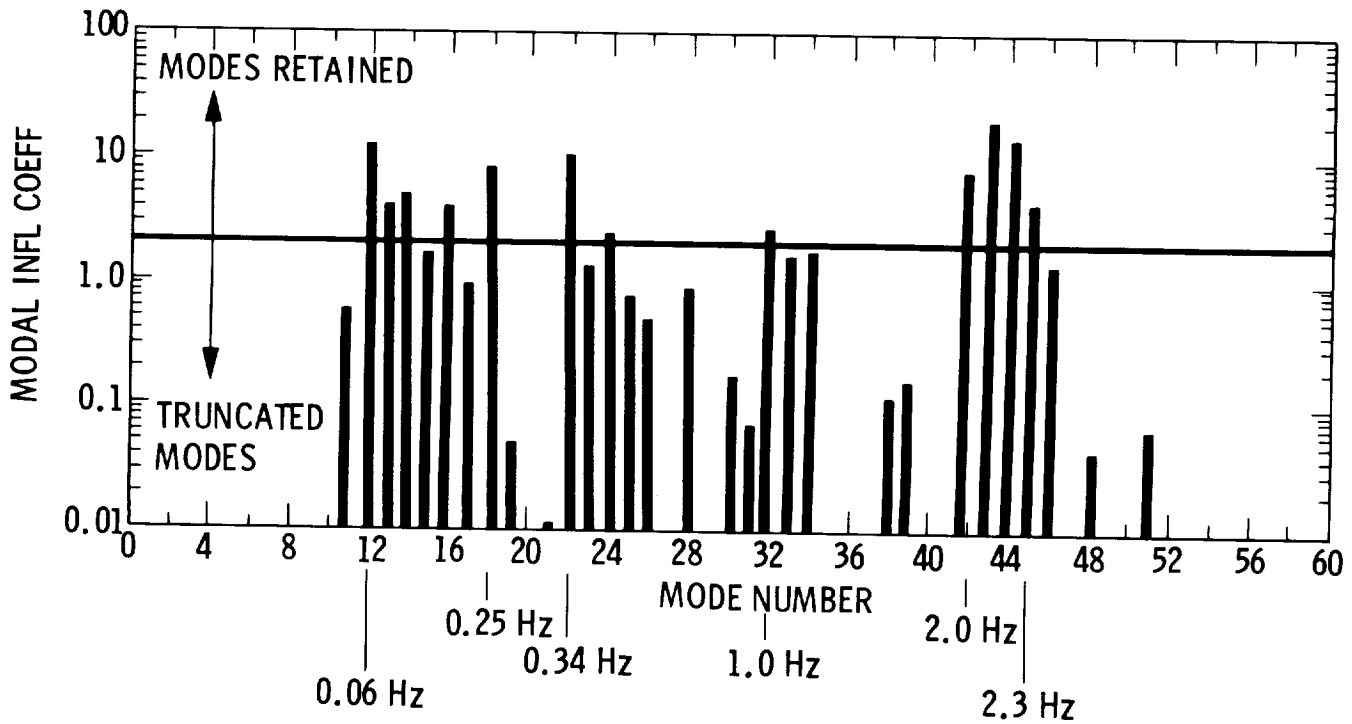


## MODAL INFLUENCE COEFFICIENT

$$\bar{\theta}_j = \text{MAX}_{i,k} \left[ \theta_j^{(i,k)} / Q^{(i)} \right]$$

# MODEL REDUCTION RESULTS (Flexible Pointing Mount)

Model reduction results for the LSS platform are shown below. The model has 51 modes, 41 of which are elastic. Influence coefficients are shown for each of the elastic modes. The 12 most important elastic modes have frequencies between 0.06 and 2.3 Hz. The lower frequency modes (12 through 18) are dominated by solar panel bending. The intermediate frequency modes (22 through 32) include cross arm and trailing arm torsion and bending. The higher frequency modes (42 through 45) are associated with elasticity of the pointing mount.

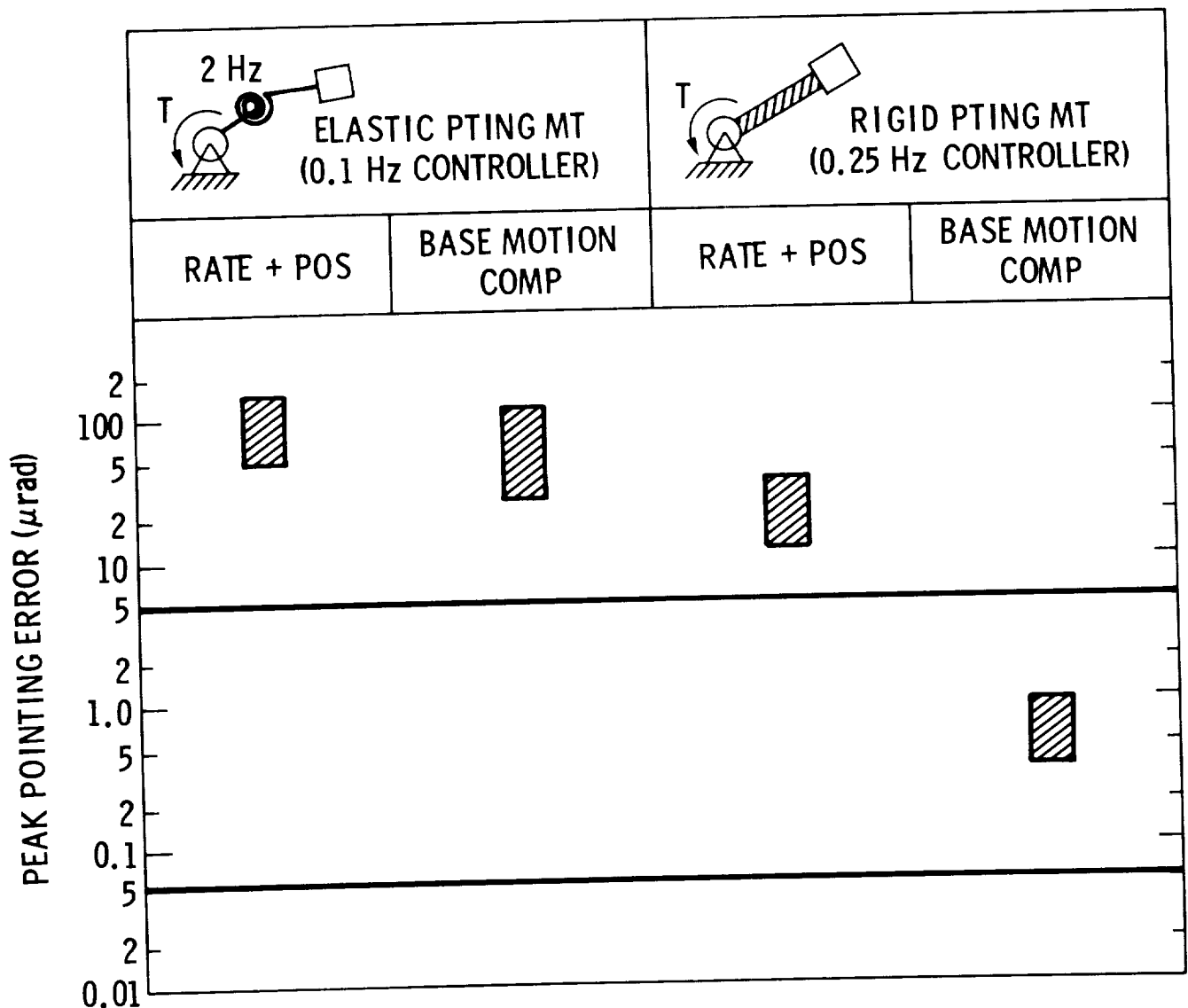


# PAYLOAD CONTROLLER PERFORMANCE

Peak pointing errors for payload No. 2 as a result of a 5 degree slew by payload No. 1 are given in the figure below. The slew torque used was 20 N-m. For the rigid pointing mount a 0.25 Hz bandwidth controller was used. The range of pointing errors resulting from x and y axis slews was from 10 to 30  $\mu$ rad for the rate plus position controller. Base motion compensation reduced these errors by more than an order of magnitude to between 0.3 and 1.0  $\mu$ rad. A 16 Hz bandwidth accelerometer was used.

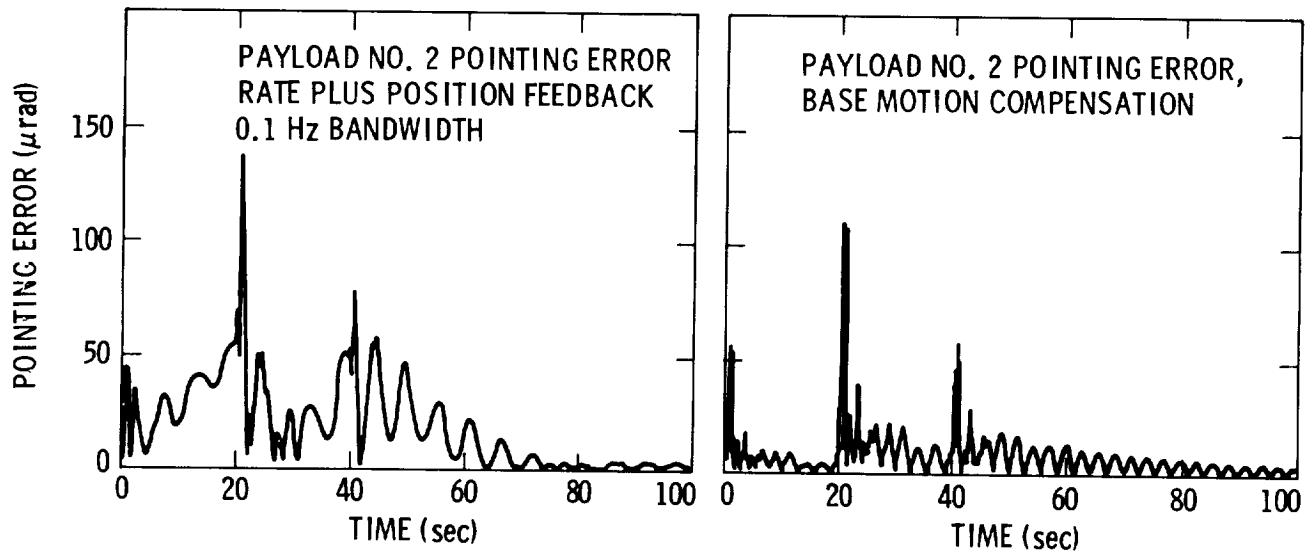
For the elastic pointing mount it was necessary to reduce controller bandwidth to 0.1 Hz to achieve stability. Pointing errors were between 50 and 150  $\mu$ rad. Base motion compensation reduced the peak errors only slightly for this case.

Many user requirements are in the range of 0.05 to 5  $\mu$ rad. Only the controller using base motion compensation and operating with a rigid pointing mount achieved performance in this range.



PAYLOAD CONTROLLER PERFORMANCE  
(Elastic Pointing Mount)

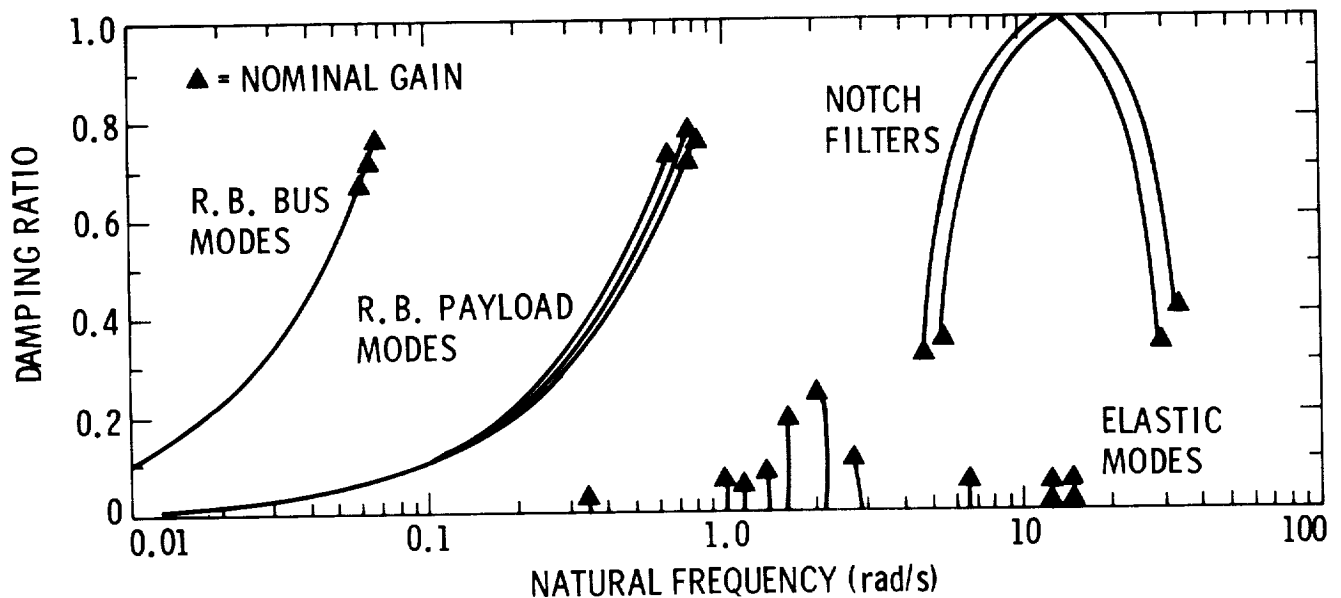
Representative simulation results are shown below for the elastic pointing mount. Results shown are for a 5 degree y axis slew of payload No. 1. The slew torque profile was a +20 N-m step at time zero followed by -20 N-m at 20 seconds with the slew ending at 40 seconds. Although the peak errors for the rate plus position and base motion compensation controllers are fairly similar, the average pointing errors for the base motion compensation controller are less by a factor of 2 or 3 for the first 60 seconds. Notice, however, that low damping of the mode at 1.1 rad/s (.18 Hz) for the base motion compensation run results in poorer performance than the rate plus position controller after about 70 seconds.



MIMO ROOT LOCUS RESULTS  
RATE PLUS POSITION CONTROLLER

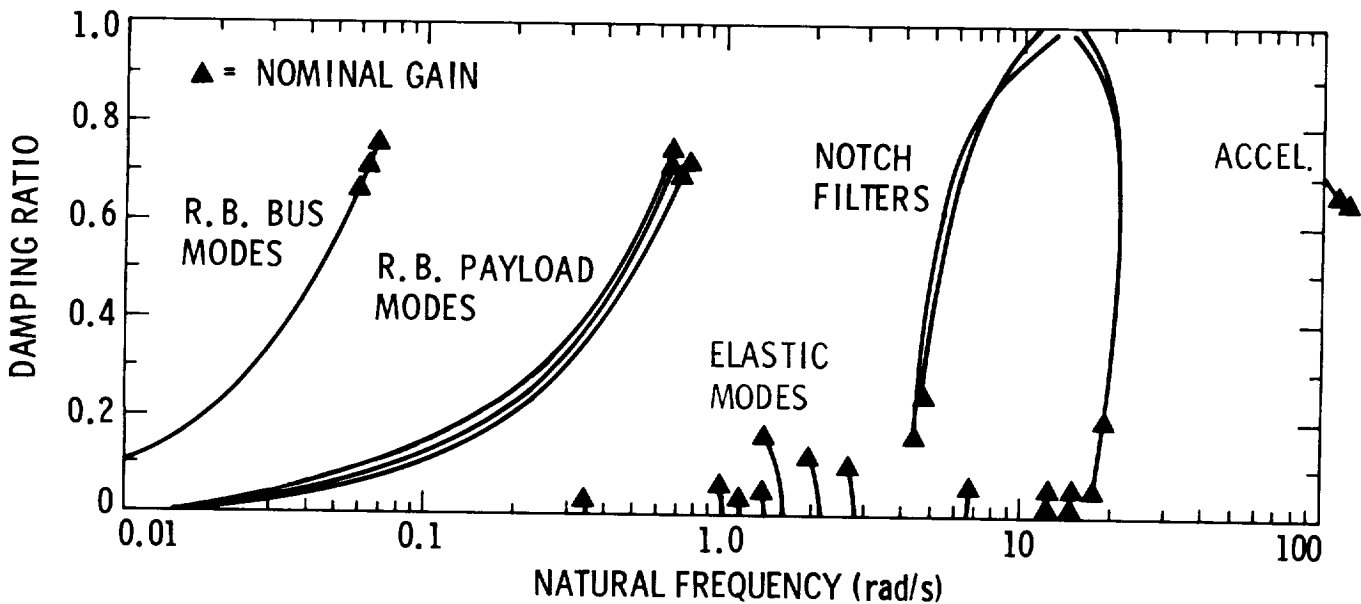
Multi-Input, Multi-Output (MIMO) root locus results are shown below for the rate plus position controller. These results include 7 rigid body (zero frequency) rotational modes and 12 elastic modes. In both cases, compensation consists of two double notch filters one double notch set at 2.0 Hz the other at 2.3 Hz. These filters are used to prevent the elastic modes of the pointing mount from causing instability.

For nominal gain, the 3 rigid body rotational modes of the bus are placed at natural frequencies of .06 to .07 rad/s with damping near 0.7. The 4 rigid body rotational modes of the payloads are placed between 0.6 and 0.9 rad/s with similar damping. Damping for the 12 elastic modes is increased from 0.5% with zero gain to values between 1.5% and 24% at nominal gain.



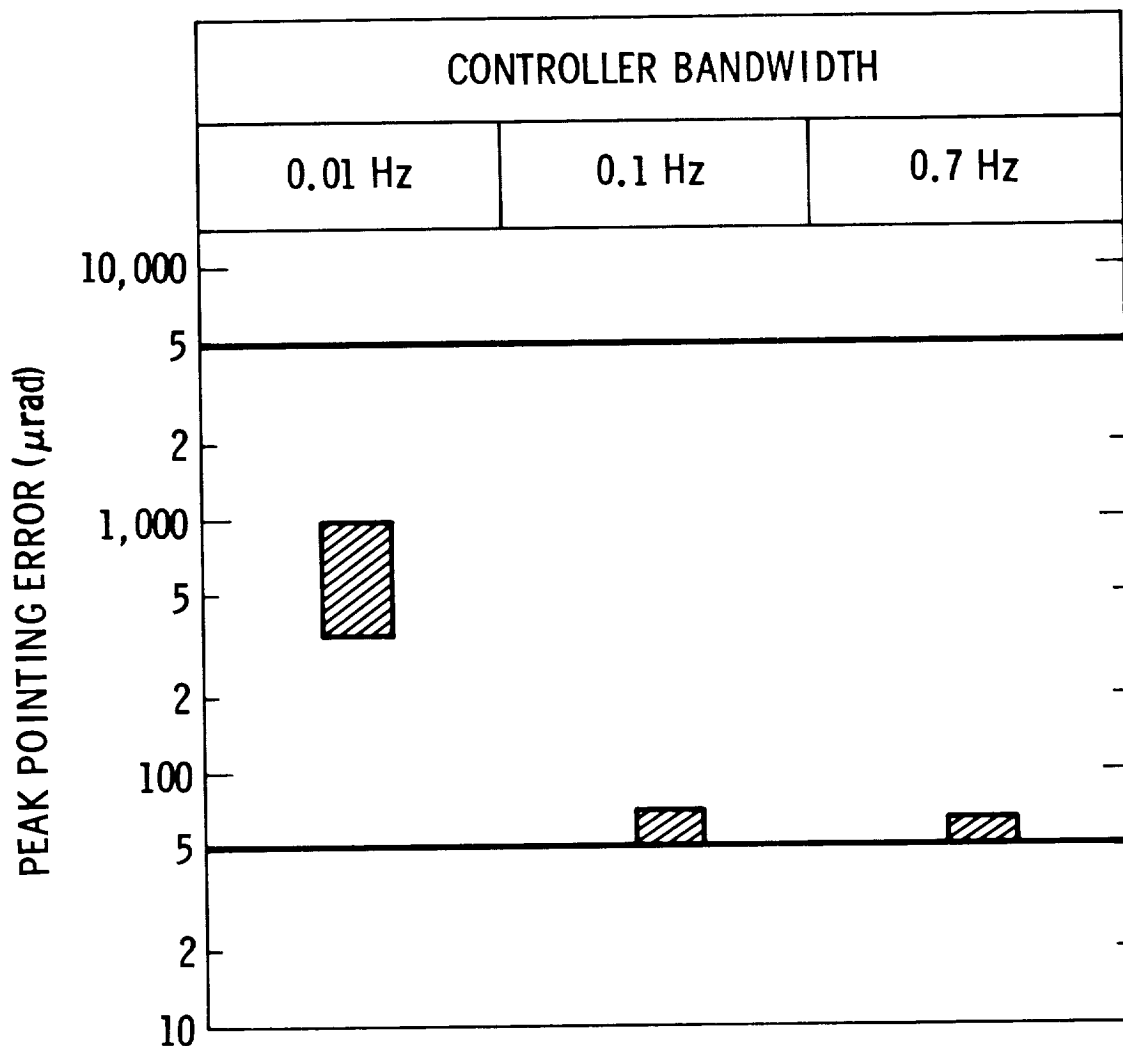
# MIMO ROOT LOCUS RESULTS BASE MOTION COMPENSATION CONTROLLER

MIMO root locus results for the controller using base motion compensation are similar to those for the rate plus position controller. Damping of the elastic modes is somewhat less however, especially at frequencies of 1.1 rad/s, 1.3 rad/s, and 1.9 rad/s where damping is reduced by a factor of 2. The loci associated with the notch filter poles exhibit less damping at nominal gain and this implies the system has a smaller stability margin since these loci are the first to go unstable as gain is increased. Another fact, not illustrated by these root loci, is that this controller is quite sensitive to errors in placement of the notch filter. The rate plus position controller is much more robust in this aspect.



## BUS CONTROLLER PERFORMANCE

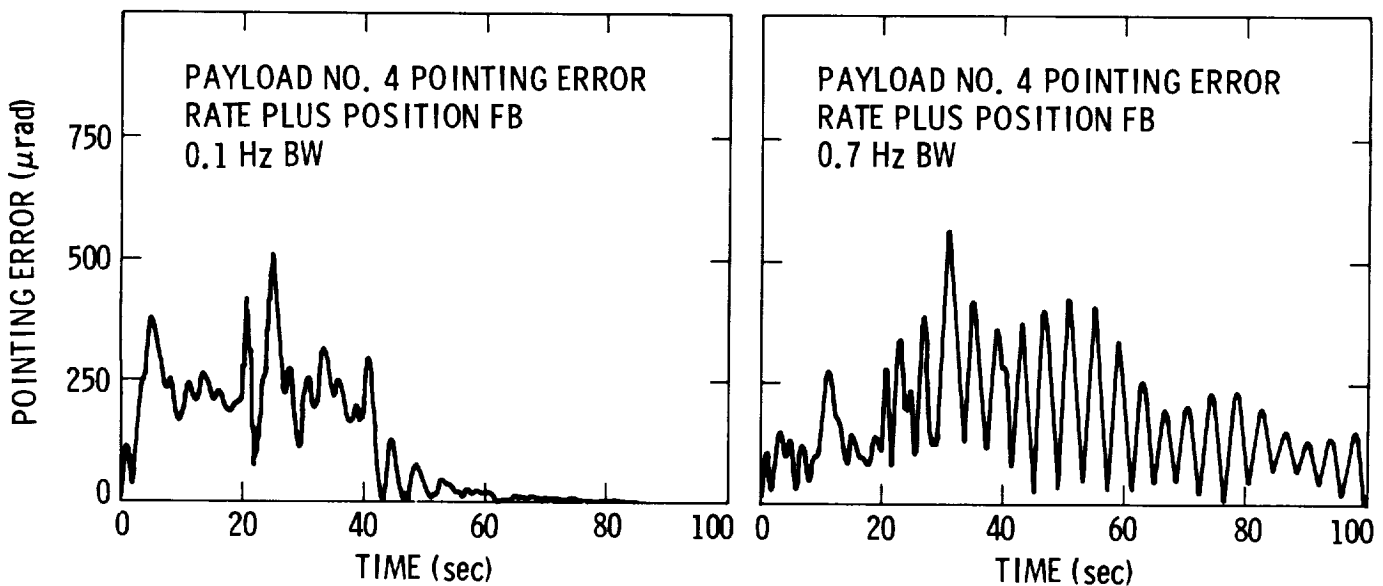
Peak pointing errors for payload No. 4 as a result of a 5 degree slew by payload No. 1 are given in the figure below. The slew torque used was 20 N-m. For a bus controller bandwidth of 0.01 Hz, the range of pointing errors resulting from x and y axis slews was 350 to 1000  $\mu$ rad. A 0.1 Hz bandwidth controller reduced this error by an order of magnitude, but further increases in bandwidth did not provide corresponding reductions in pointing error.





BUS CONTROLLER PERFORMANCE  
(Rigid Pointing Mount)

Representative simulation results are shown below. Pointing errors are for payload No. 4. The slew profile for payload No. 1 was a +20 N-m step at time zero followed by -20 N-m at 20 seconds with the slew ending at 40 seconds. The peak errors for the 0.1 and 0.7 Hz controllers are similar, however, damping of the 0.1 Hz controller after the end of the slew is superior to the 0.7 Hz controller. These results show that spacecraft flexibility places a limit on the performance which can be expected from a bus controller.



## SUMMARY

In summary, it has been found that base motion compensation can be very effective when used with rigid pointing mounts. Pointing errors of less than  $1 \mu\text{rad/s}$  can be achieved. However, the effectiveness of base motion compensation is severely limited when there are flexible elements between the pointing mount actuator and the payload sensor. Bus controller performance is also limited by spacecraft flexibility.

- BASE MOTION COMPENSATION IS EFFECTIVE WHEN USED WITH RIGID POINTING MOUNTS

16 Hz ACCELEROMETER 0.25 Hz CONTROLLER	>	0.3 TO $1.0 \mu\text{rad}$ POINTING ERROR
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- FLEXIBILITY BETWEEN POINTING MOUNT ACTUATOR AND PAYLOAD SENSOR LIMITS EFFECTIVENESS OF BASE MOTION COMPENSATION

2 Hz FLEXIBILITY 0.1 Hz CONTROLLER	>	30 TO $150 \mu\text{rad}$ POINTING ERROR
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- BUS CONTROLLER PERFORMANCE IS ALSO LIMITED BY SPACECRAFT FLEXIBILITY

0.1 Hz CONTROLLER 0.7 Hz CONTROLLER	>	50 TO $80 \mu\text{rad}$ POINTING ERROR
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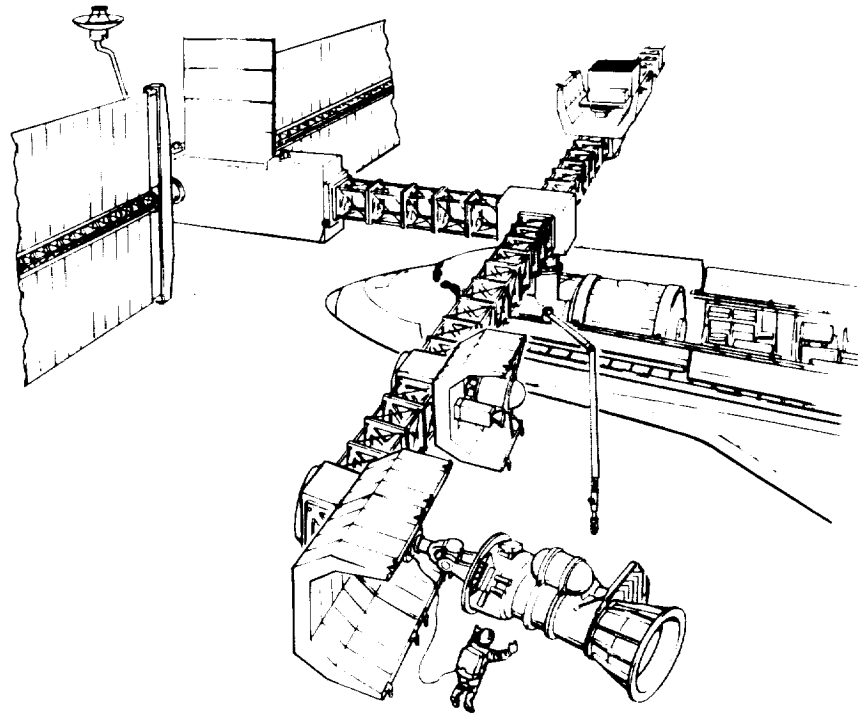
## FUTURE WORK

Future work will be performed to determine the effect of man/shuttle disturbances on payload pointing. These disturbances will occur during periods of time when the shuttle is berthed to the LSS platform and will include man push off forces and shuttle thruster firings. Techniques for improving pointing mount disturbance isolation will be examined to include sensor output blending and optimized compensation parameters.

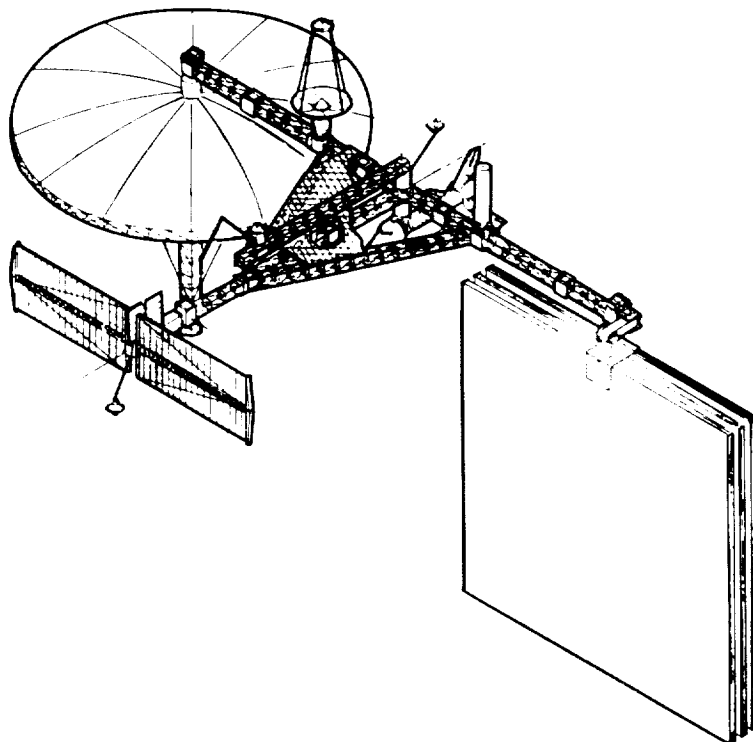
A variety of platform and payload configurations will be examined. These configurations will include advanced platforms having large flexible payloads (e.g. 100 meter antenna systems) and others intended for manned applications. Payload controller performance will be examined for each major configuration. Payload controller performance will also be determined as a function of platform and pointing mount stiffness.

- EXAMINE SENSITIVITY OF CONTROLLER PERFORMANCE TO DISTURBANCES CAUSED BY MAN/SHUTTLE INTERFACE
- DEVELOP IMPROVED METHODS FOR DISTURBANCE ISOLATION
- ESTABLISH CONTROLLER PERFORMANCE LIMITS FOR A VARIETY OF PLATFORM AND PAYLOAD CONFIGURATIONS
  - LARGE FLEXIBLE PAYLOADS
  - MANNED SPACE STATIONS
- DEVELOP CONTROLLERS TOLERANT OF CONFIGURATION CHANGES AND PARAMETER ERRORS

## BERTHED ORBITING CONFIGURATION



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