

**VIBRATION ISOLATION VERSUS VIBRATION COMPENSATION  
ON MULTIPLE PAYLOAD PLATFORMS\***

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## Overview

There are many future science instruments with high performance pointing (sub microradian) requirements. To build a separate spacecraft for each payload is prohibitively expensive, especially as not all instruments need to be in space for a long duration. Putting multiple payloads on a single basebody that supplies power, communications, and orbit maintenance is cheaper, easier to service, and allows for the spacecraft bus to be reused as new instruments become available to replace old instruments.

Once several payloads are mounted together, the articulation of one may disturb another. The situation is even more extreme when the basebody serves multiple purposes, such as Space Station which has construction, satellite servicing, and man motion adding to the disturbance environment. The challenge then is to maintain high performance at low cost in a multiple payload environment.

### The Goal:

- Supply many future science instruments with high performance pointing (sub microradian).

### Options:

- Independent spacecraft for each payload - expensive.
- Multiple payloads on a single basebody - cheaper, easier to service, basebody reusable for several short duration payloads.

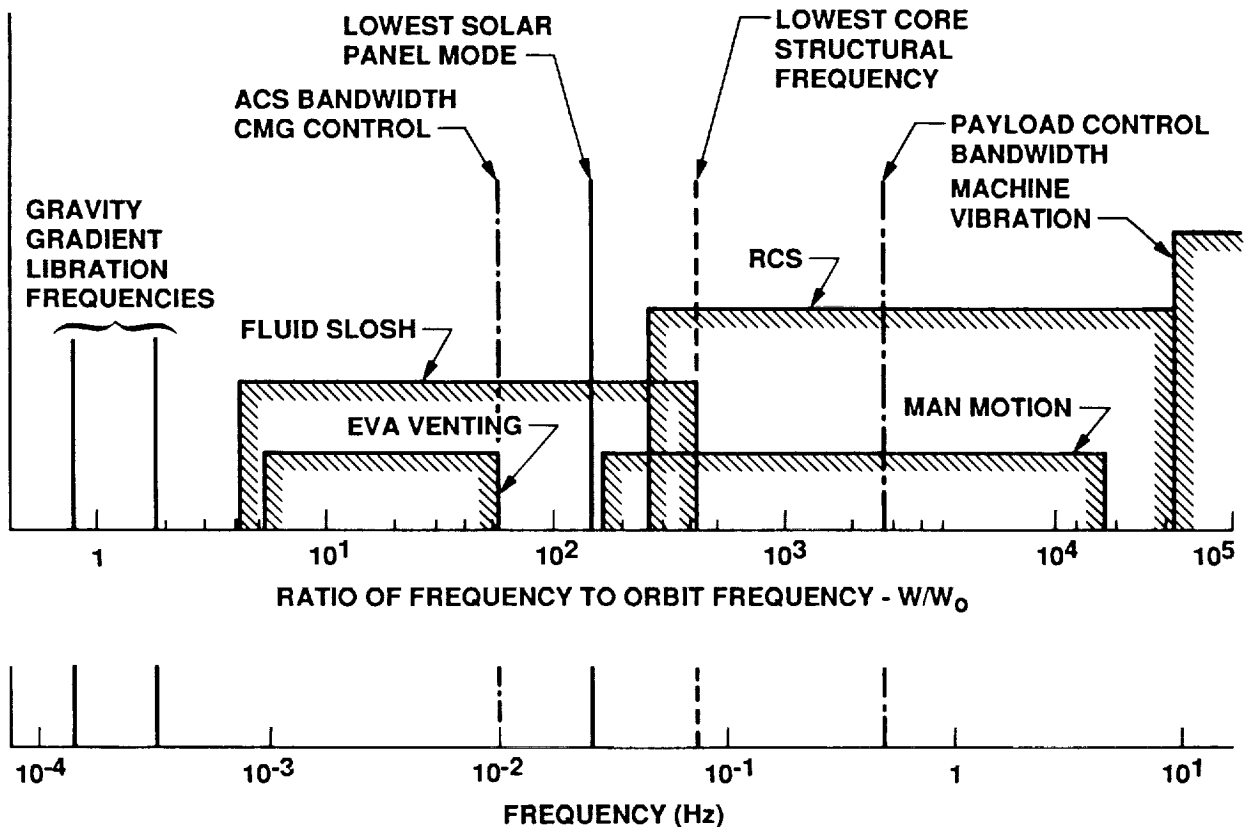
### The Problem:

- One payload can disturb another.
- Other activities create large disturbances - construction, satellite servicing, and man motion.

## Typical Disturbance Environment

Large, multi-function space platforms, especially manned systems, will have a variety of noise sources that can disturb pointing systems. The platform attitude control system (ACS) of such systems will be of low frequency, able to control only a few of the disturbances such as gravity gradient libration and the low frequency liquid slosh and gas venting. The reaction control system (RCS) can itself excite many of the platform structural modes. The RCS and various activities of the crew (such as push offs, landing, and treadmill walking) are likely to be the dominant noise sources, but vibrations from a variety of machines (pumps, the CMG's, and the washing machine) will also contribute heavily.

## SPACE STATION GENERIC INTERACTIONS



## Design Approaches

There are three main approaches to the multi-payload pointing problem: vibration suppression, vibration compensation, and vibration isolation. Vibration suppression consists of global reduction of spacecraft disturbances over the whole spacecraft. Examples of global suppression include the use of the spacecraft attitude control system to eliminate vibrations caused by predictable machine vibrations, or the addition of passive damper elements at strategic locations to reduce vibrations at structure resonances.

Vibration compensation consists of active compensation for local vibrations. An example of this is control of a payload gimbal system based on knowledge of the expected spacecraft dynamics, the disturbance sources, and global vibration knowledge. In this case the payload may point accurately even though the basebody vibrates at large amplitudes.

The idea of vibration isolation is not to control all spacecraft vibrations, but allow vibration only in certain places by isolating the noisy parts from the payloads that require precise pointing. The isolation can be done for each disturbance source individually, or for each payload, or "noisy" or "quiet" bus structures for compatible payloads can be built with isolation interfaces.

Three Main Approaches: Vibration Suppression, Vibration Compensation or Vibration Isolation:

- o Vibration Suppression:
  - Global Suppression of Spacecraft Disturbances
- o Vibration Compensation:
  - Active Compensation for Local Vibrations
- o Vibration Isolation:
  - Allow vibration only in certain places
- o These approaches are not mutually exclusive.

## Vibration Suppression

The possible sources of disturbances can of course be constrained in both amplitude and frequency so as not to disturb the basebody or other payloads.

The vibrations of a structure can be reduced by adding passive damping elements at strategic locations with large participation in the motion. Passive techniques include constrained layer damping, elastomeric or viscous damping at the joints. Active structural elements such as piezo-electric actuators may be used to improve damping performance.

Active disturbance suppression must utilize a wide variety of actuators to reduce vibrations induced by both internal and external torques and forces. A wide variety of centralized active control methods are available to handle this multi-input multi-output problem, ranging from LQG/LTR, and  $L_\infty$ ,  $H_\infty$  synthesis to methods specifically addressing disturbances such as disturbance accommodating control. A flight system will require substantial computational capability to implement a design of this type. All of these centralized techniques depend on detailed knowledge of the system dynamics. Since this is likely to change for large structures as they evolve, some kind of on board adaptation system such as system identification or adaptive control is necessary.

- Global Reduction of Spacecraft Disturbances
- Control by Requirements:
  - Constrain possible disturbance sources
  - Allocate allowable payload motion to certain spectral bands
- Passive:
  - Constrained layer damping
  - Elastomeric damping at joints
  - Viscous Damping
- Active:
  - Reaction wheels, thrusters, or CMG's
  - Proof mass actuators
  - Active structural elements
  - Centralized control design
  - Multi-input multi-output

## Vibration Compensation

Vibration compensation may be applied to existing hardware, such as hard mounted gimbal systems. Accurate knowledge of the basebody as well as the payload dynamics is required however, since the actuator torques between the two. Due to the rich disturbance spectrum, high performance compensation systems will use a more hardware based approach, consisting of a hierarchy of actuation and control bandwidths. An example is a gimbal system with a bandwidth in the neighborhood of 1 Hz, with a high bandwidth (100 Hz) fast steering mirror for line of sight stabilization. This kind of system is of course unique to a particular payload, though some design elements may be reusable.

A wide variety of centralized active control methods are available, as for vibration suppression. Substantial computational capability may be required, especially if a more modular, non-hierarchical approach is used.

### o Active Compensation for Local Spacecraft Disturbances

- Hard mounted gimbal system
- Fast steering mirrors
- Many control options:
  - o Centralized control design
  - o LQG/LTR
  - o  $L_\infty$ ,  $H_\infty$
  - o Disturbance accommodating control
  - o Need detailed system model
  - o System Identification
  - o Adaptive control

## Vibration Isolation

Vibration isolation is essentially a hardware based approach. An active or passive interface is built that is soft in the frequency range of the expected disturbances. This can be used either to keep a disturbance source isolated by itself, or to isolate a payload (or a group of commonly mounted payloads) from the general basebody motion caused by a variety of disturbances.

The isolation can be along single or multiple degrees of freedom, rotational or translational. For gimballed pointing, translational isolation is key, since if there are even small offsets of the mass center from the gimbal axis, then basebody translations may couple into substantial torques on the payload.

Passive isolators have a long history. One of the more promising common active isolators is active suspension for cars. Some examples of isolators for space based pointing are discussed below.

- o Allow vibration only in certain places

### Options:

- Active or passive isolator
- Local (isolate each payload separately) or bus systems (isolate a group together)
- Isolation along single or multiple degrees of freedom, rotational or translational

### Examples:

Automobile suspension, Honeywell Space Telescope reaction wheel mount, Honeywell magnetic suspension (VIPS), MMC Gimballflex, Ames KITE tether, JPL Reactuator on a soft mount, JPL SIRPNT concepts, various gravity gradiometer designs.

## Design Approaches - Tradeoffs

Vibration suppression must be considered in three parts. Disturbance requirements of some kind must be levied on all payloads. When the variety of payloads is large however, imposing constraints so that all payloads are undisturbed may impose severe constraints on science performance, and hence be unworkable. The passive techniques are simple to apply, but do require extensive hardware and have limited performance. The active techniques are very complex for both hardware and software. Substantial improvements in both design and implementation technology are required to make such an approach feasible.

Vibration compensation can consist of either complex hardware or software. The hierarchical hardware approach has been demonstrated in practice. Obtaining high performance in a modular, non-hierarchical way may require advanced hardware designs and new control technologies beyond the state of the art.

The vibration isolation approach, using hardware to decouple the payload from the noise source, requires much less knowledge of the basebody dynamics. While new hardware is required, it is easily adapted for a variety of payloads. Active methods promise high performance.

### o Vibration Suppression:

Control by Requirements: - Limits payload performance

Passive: - New hardware, simple implementation  
- Performance may be limited

Active: - Most complex, high performance hardware and software  
- May require extensive, accurate knowledge of the whole system

### o Vibration Compensation:

- May require complex software
- Requires accurate knowledge of the whole system
- No new hardware, but must have high performance

### o Vibration Isolation:

- Does not require extensive knowledge of the whole system
- Modular, easily adapted to different situations
- New hardware, but less strict performance requirements

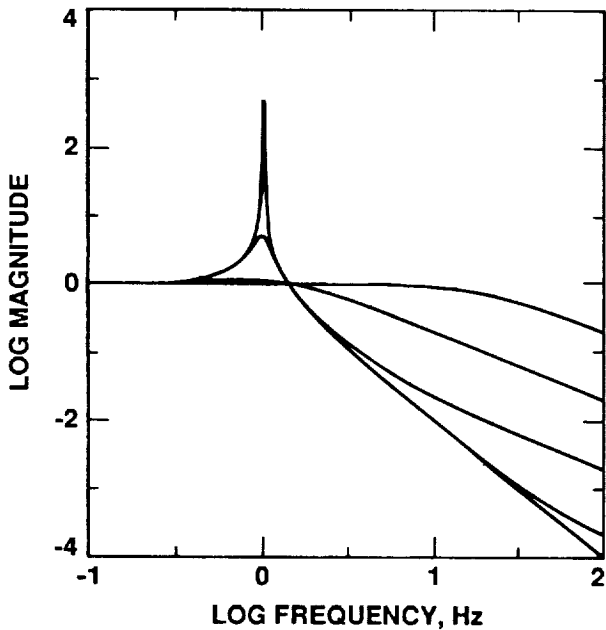
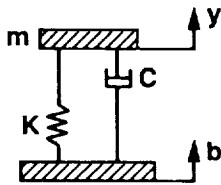


## Passive Isolation

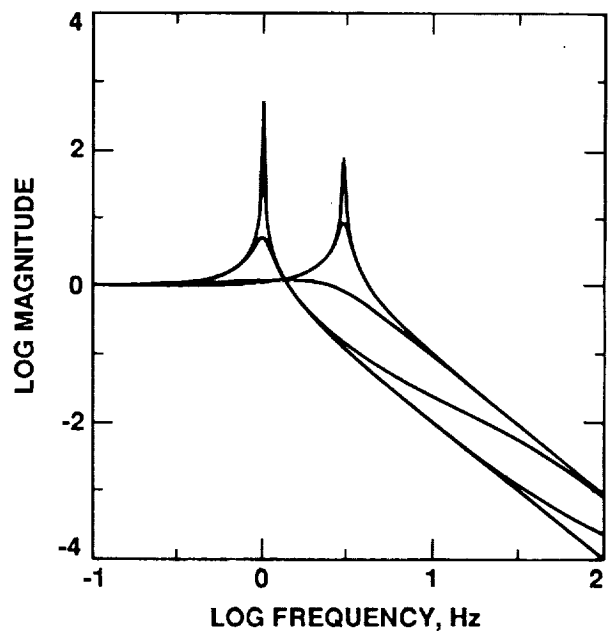
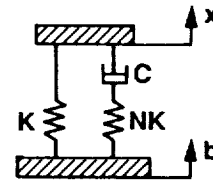
Examining the transfer function from base body motion to payload motion, at low frequency, the mount should support the payload for the required loads, so the transfer function should start at 1. At high frequency, ideally transmission should be 0. In between, at some frequency the transfer function should roll off. There remains the problem of resonance. Given a directly coupled damping mechanism, reducing the resonance (by increasing the damping  $c$ ) increases the high frequency response. This can be overcome by clever mount design, for example if the damping mechanism is elastically coupled, the resonance may be damped while maintaining second order rolloff behavior. In this case as  $c$  is increased, the resonance decreases to a minimum, and then increases at a higher frequency. The rolloff maintains a second order character.

### TRADEOFF BETWEEN LOW FREQUENCY STIFFNESS, DAMPING, HIGH FREQUENCY ISOLATION

DIRECTLY COUPLED DAMPING



ELASTICALLY COUPLED DAMPING



## Active Isolation

Active isolators allow much more design flexibility than passive systems. In first of the examples shown, the control adds damping only over a limited bandwidth:

$$u = - \left( \frac{\alpha}{s + \alpha} \right) c s (x_p - x_b).$$

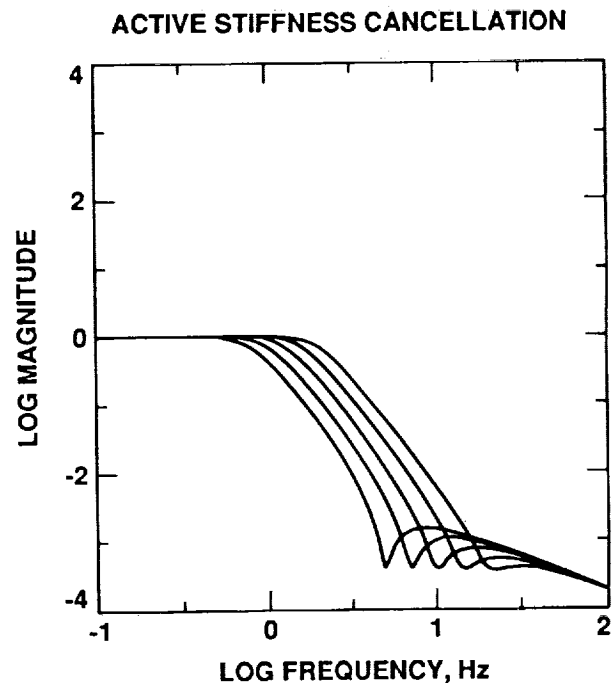
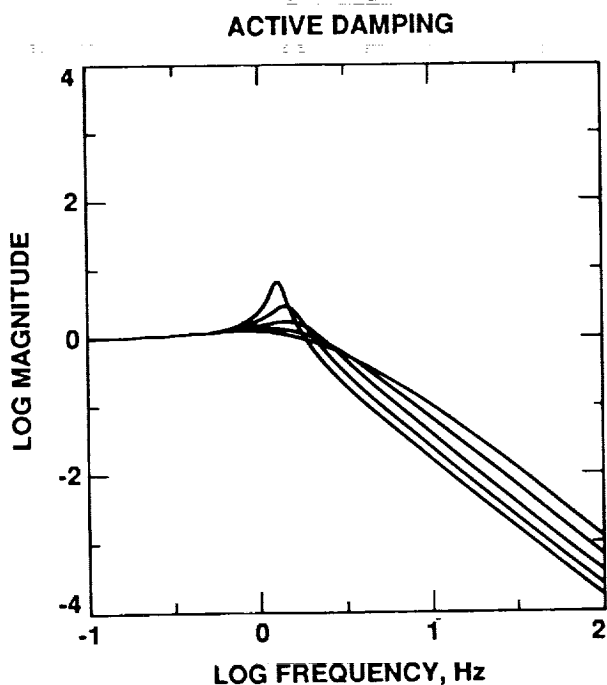
As  $\alpha$  is increased, past the natural frequency, the transfer function approaches the passive directly coupled damping case. The control can also cancel the stiffness over high frequencies:

$$u = \left( \frac{s}{s + \alpha} \right) k (x_p - x_b).$$

In this case, as  $\alpha$  is increased the disturbance rejection is performed at higher and higher frequencies.

The examples demonstrate some ways in which the frequency response can be tailored to the problem at hand. The spring/damping characteristics can even take on complex nonlinear behavior, for example the stiffness could be set to zero within a deadband, maintaining close to perfect isolation for a limited time. If certain disturbances are predictable, then disturbance compensation techniques can be incorporated into the isolator control to improve performance.

- MORE DESIGN VARIABILITY THAN PASSIVE SYSTEMS
  - FASTER THAN SECOND ORDER HIGH FREQUENCY ROLLOFF
  - NONLINEAR SPRING/DAMPING CHARACTERISTICS
  - CAN INCLUDE COMPENSATION FOR PREDICTABLE DISTURBANCES
  - CAN ADJUST ISOLATION PROPERTIES FOR DIFFERENT CONDITIONS

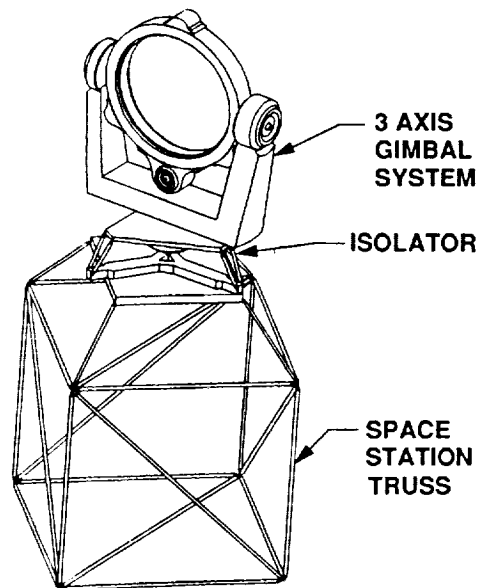


## Example Isolator Performance

### Passive Soft Mount with Reactuator

One vibration isolation system under study at JPL is a passive soft mount with a reactuator on top. The soft mount consists of 6 struts similar to those used by Honeywell for isolation of the Space Telescope reaction wheels, a passive hydraulic system. The reactuator, for each axis, consists of a powered gimbal system (with axis through the payload center of mass), with an additional motor driving a reaction wheel on the payload. There are thus two motors, one gimbal system, and one reaction wheel per axis. The gimbal motor is driven so as to cancel external torques such as bearing friction and cable windup. The reaction wheel is used for high bandwidth control of payload pointing. The control can be high bandwidth even if the basebody is not known, since the torque acts between the payload and the wheel, and only affects the basebody through the remaining bearing friction and cable torques not eliminated by the outer gimbal motor control.

- SPACE STATION BASED POINTING SYSTEM
- PASSIVE SOFT MOUNT - FLUID FOR DAMPING, 6 STRUTS FOR 6 DOF, EFFECTIVE ISOLATION FREQUENCY 0.02 Hz
- CENTER OF MASS MOUNTED GIMBAL
- TWO MOTORS PER AXIS:
  - LOW FREQUENCY CONTROL REACTS AGAINST SOFT MOUNT
  - HIGH FREQUENCY CONTROL REACTS AGAINST REACTION WHEEL



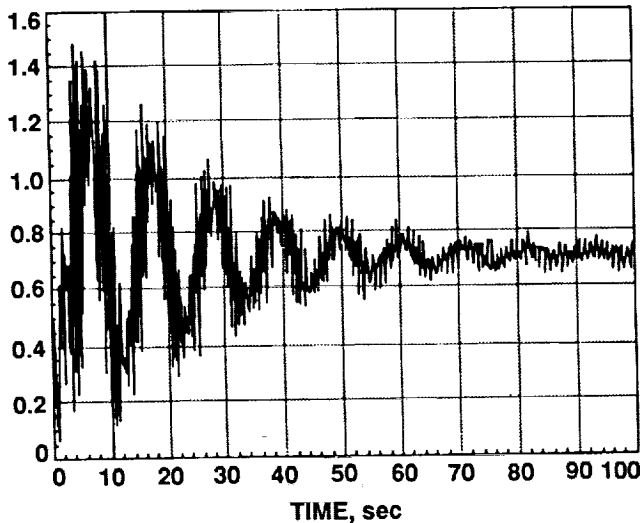
Example Isolator Performance  
Passive Soft Mount with Reactuator

Shown is the Solar Terrestrial Observatory and Solar Instrument Group (STO/SIG) payload on the block 1 Space Station. A hardmount direct drive system is compared to the reactuator on a soft mount. Both systems use gimbals with axes through the payload mass center. The comparison shows the substantial improvement obtained using isolation, even using the same controller.

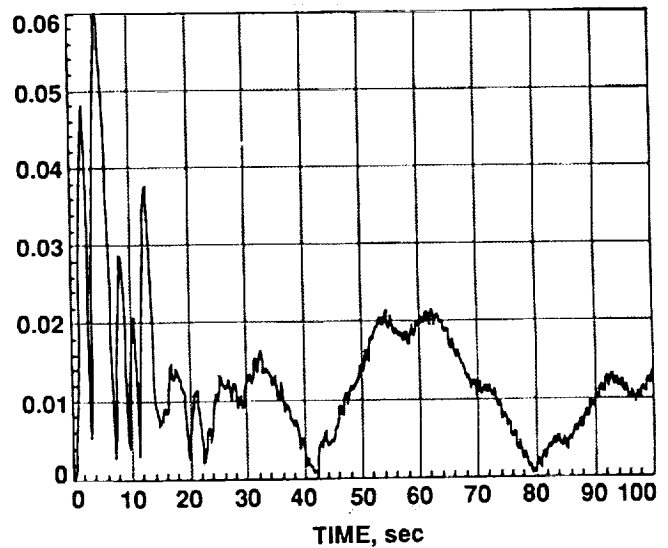
## HARDMOUNT vs ISOLATOR LINE OF SIGHT ERROR IN ARC-SECONDS

STO/SIG PAYLOAD 45 deg  
CONTROLLER: 0.5 Hz INNER 0.1 Hz OUTER 0.01 Hz CMG  
FRICTION: LINEAR SPRING OF 4 Nm / 206 arc-sec  
DISTURBANCE: 180 lb TREADMILL AT HAB FX TUNED TO 1.125 Hz REASONANCE

HARDMOUNT INTERFACE / DIRECT DRIVE MOTOR



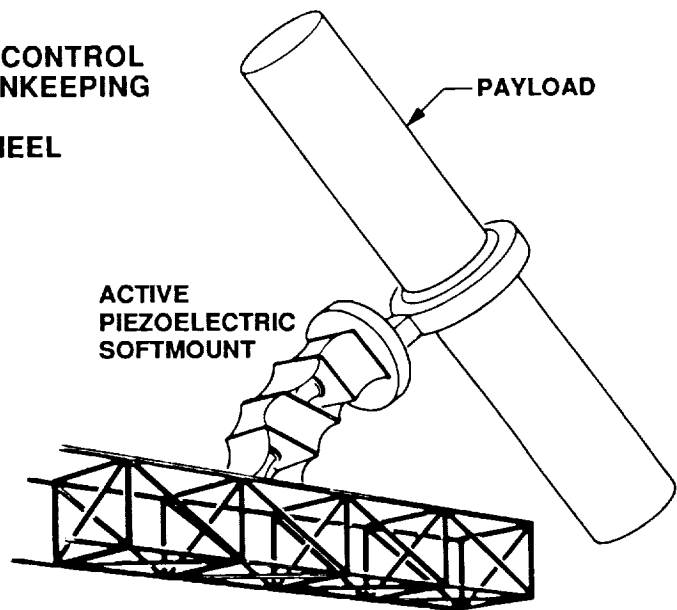
ISOLATOR INTERFACE / REACTIONLESS MOTOR



Example Isolator Performance  
Soft Mounted Inertially Reacting Pointing System (SIRPNT)

An advanced pointing system concept in development at JPL is SIRPNT. The mount is made of multilayered piezoelectric polymer  $PVF_2$ , which is very compliant, but the shape can be controlled (with low authority). A gimbal system is not needed as the polymer can undergo large deformations. While the mount performs vibration isolation and stationkeeping, the primary pointing control consists of reaction wheels (or small CMG's) on the payload itself.

- SPACE STATION BASED POINTING SYSTEM
- ACTIVE 6 DOF SOFT MOUNT - MULTILAYER PIEZOELECTRIC POLYMER (PVDF) CAPABLE OF LARGE DEFORMATION, EFFECTIVE ISOLATION FREQUENCY 0.002 Hz
- NO GIMBAL SYSTEM
  - LOW FREQUENCY SOFT MOUNT CONTROL TO DAMP RESONANCES, STATIONKEEPING
  - HIGH FREQUENCY REACTION WHEEL OR CMG CONTROL



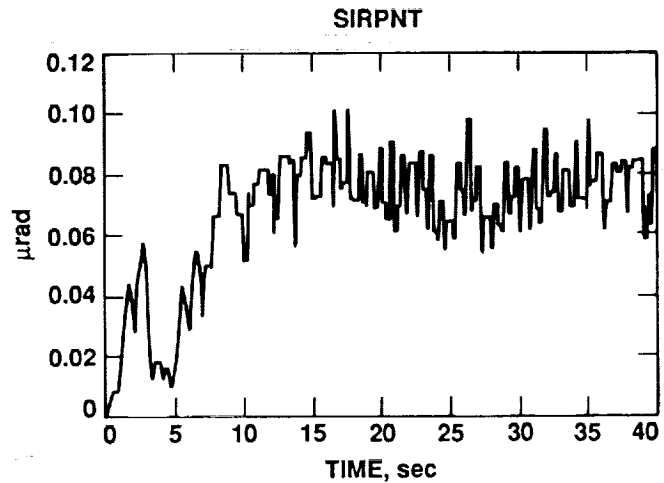
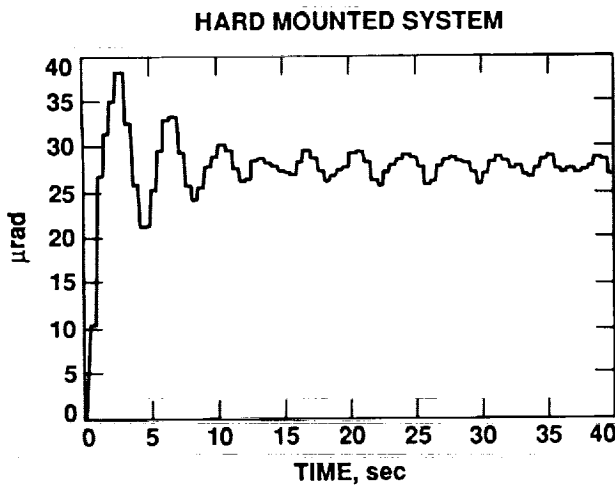
## Example Isolator Performance Soft Mounted Inertially Reacting Pointing System (SIRPNT)

Shown is a comparison of a hard mounted, mass center mounted gimbal system with a SIRPNT (with a 2.0 m mass center offset from the attach point). The basebody is the block 1 Space Station, with a treadmill disturbance. The payload is the High Resolution Solar Observatory (HRSO). Pointing stability is a measure of image "smear," the amount the image will be smeared given the instrument exposure time. The stability  $s(t)$  over time  $T$  is defined in terms of the pointing error  $e$  by:

$$s(t) = \max_{\tau < T} | e(t + \tau) - e(t) | .$$

The controller for the hardmount had a 0.5 Hz bandwidth, while the SIRPNT controller used a 2 Hz bandwidth.

### SPACE STATION POINTER STABILITY OVER 1 SECOND



## Plans for MPP Work at JPL

Work on Multiple Payload Platforms at JPL will concentrate on vibration isolation methods, building upon previous JPL work in the area of passive and active isolation. We will start with existing simulations, and integrate the isolation and pointing systems from the simulations onto a standard basebody. The basebody used will be the Langley Mission to Earth model, to complement the analytical and experimental work at LaRC. Other, new concepts for isolation systems will be considered for integration into this model. An expanded effort would examine in detail differences between vibration compensation, vibration suppression, and isolation for the MPP problem, but this is beyond the scope of the current effort.

- Concentrate on vibration isolation methods, including previous JPL efforts at passive and active isolation.
- Generate analytical testbed for examining various isolation and compensation designs.
- Complement the analytical and experimental work at LaRC.
- An expanded effort would examine in detail differences between vibration compensation, vibration suppression, and isolation for the MPP problem.

