

GALEX Telescope Vibration Response Reduction

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ABSTRACT

GALEX, Galaxy Evolution Explorer, is a space UV imaging and spectroscopic earth orbiting mission, which will map the history of star formation. In addition, GALEX will perform the first ultraviolet all-sky imaging survey and will launch in early 2003 on a Pegasus.

The GALEX Instrument, which consists of a Telescope, an optical wheel assembly, UV detectors, and support structure, was initially subjected to random vibration testing in October 2000. The Telescope secondary mirror exhibited a high dynamic amplification causing the peak response to far exceed design capability. In addition, the Telescope showed signs of misalignment after vibration testing. Although the testing included force limiting, the Telescope local lateral mode, which produced the high response, was unaffected by the force limiting due to the low mass of the secondary mirror. A manual 20 dB notch in the input was needed to maintain a peak response of the secondary mirror below the 30 g design capability. This notch was a lien against the qualification of the Instrument.

Numerous analytical studies were investigated to reduce the Telescope response in both the Instrument level and Spacecraft level tests. It was determined that by softening the Instrument support bipods and adding constrained layer damping, the Telescope secondary mirror response at the Instrument and Spacecraft level testing could be significantly reduced. The response reduction relied on aligning the global mode of the Spacecraft and the Instrument/Telescope local

modes such that force limiting would reduce the input at the base. The addition of the constrained layer damping on the Instrument support bipods was intended to further reduce the Telescope response.

The GALEX Instrument, with the new Instrument composite support bipods and constrained layer damping, was random vibration tested again in June 2001. As a result of the testing, the finite element model predicted analytical frequencies were verified. The Telescope secondary mirror experienced less than 30 g's peak lateral response using force limiting only. The Instrument was successfully qualified.

In January 2002, the GALEX Spacecraft was subjected to random vibration testing with force limiting. The finite element model correctly predicted the lateral frequencies and Telescope response. The Telescope secondary mirror experienced less than 20 g's peak response in the lateral directions. As a result, the GALEX Spacecraft was successfully tested to Protoflight vibration levels.

INTRODUCTION

The GALEX Spacecraft configuration is shown in Figure 1. The Instrument bipods support the TSP (Telescope Support Plate), which supports the entire GALEX optical Instrument. The Telescope Assembly weighs 70 lbs with the secondary mirror assembly weighing 10 lbs. The total weight of the Instrument supported on the bipods is 215 lbs and the Spacecraft weight is 640 lbs.

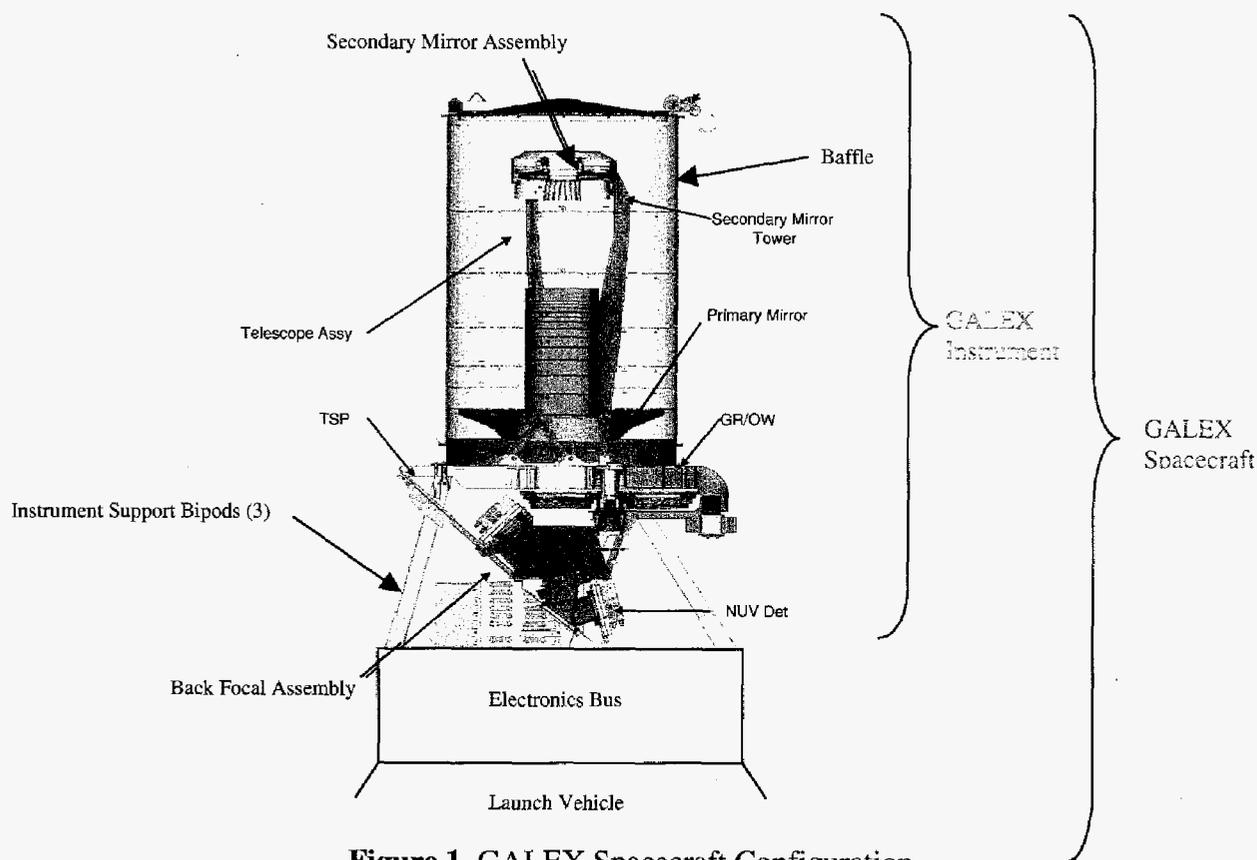


Figure 1 GALEX Spacecraft Configuration

The Pegasus vibration environment includes a peak in the acceleration spectral density specification to account for side to side motion during the drop of the Pegasus from the L1011 aircraft. The Instrument vibration levels are shown in Table 1. The X and Y axes refer to the lateral directions while the Z axis refers to the vertical direction.

Table 1 Instrument Vibration Input

X, Y Axes		Z Axis	
Freq (Hz)	ASD	Freq (Hz)	ASD
20-30	+9 dB/Oct	20-75	+9 dB/Oct
30-60	0.1 g ² /Hz	75-120	0.1 g ² /Hz
60-80	-10 dB/Oct	120-160	-10 dB/Oct
80-1000	0.04 g ² /Hz	160-1000	0.04 g ² /Hz
1000-2000	-12 dB/Oct	1000-2000	-12 dB/Oct
Overall	7.3 grms	Overall	7.4 grms
duration	75 sec	duration	75 sec

During Instrument random vibration testing in October 2000, the Telescope Assembly first lateral mode was 50 Hz, while the Instrument first bending mode was 80 Hz. Due to the low

effective mass of the Telescope secondary assembly local mode, force limiting at the base was unaffected. A 20 dB notch was required between 45 and 55 Hz in both lateral axes in order to maintain a peak g response at the secondary mirror assembly of less than 30 g's, leaving the Instrument with a lien against successful qualification testing.

ANALYTICAL METHODS

Force limiting is used to reduce the response of the test article at its resonances on the shaker to account for the response at the combined system resonances in the flight mounting configuration. Piezo-electric force transducers sandwiched between the shaker and the test article are used to automatically adjust the input acceleration according to a programmed force specification. Therefore, a significant effective mass will produce energy at the base to induce force limiting.

Several paths were analytically investigated to reduce the secondary mirror high response at the Spacecraft level. A few of the options studied are as follows:

- a tuned mass damper between the secondary mirror assembly and the top of the baffle cover
- a dampened spring system between the secondary mirror tower and the baffle structure
- a vibration isolation system on the Instrument or Spacecraft
- stiffness reduction with constrained layer damping of the Instrument support bipods.

The analysis employed the modal strain energy method, where the energy contributed per mode by an element set was recovered. A loss factor for the set as well as the system was calculated according to Equation 1.

$$\text{SE fraction} * \text{loss factor} + \text{remaining FEM} * \text{loss factor} = \text{total SE} * \text{system loss factor} \quad (\text{Eqn 1})$$

where FEM = finite element model
 SE = strain energy
 loss factor = critical damping
 = 2 * modal damping

For example, the set of Instrument bipods had a significant amount of strain energy which influence the global mode of the Spacecraft. The grouping of elements in this fashion was helpful in ascertaining the benefit of such components to the overall system modes. Therefore, in Equation 1 the term 'SE fraction' may refer to the Instrument bipods as a set while the 'remaining FEM' refers to the rest of the model elements. A critical damping on a mode by mode basis could then be calculated for use in the vibration analysis.

The use of this method provided knowledge as to the benefits of additional members or the contributions of existing members to the overall system damping.

The analysis proved that the Instrument bipod stiffness reduction combined with a constrained layer damping treatment was the optimal choice. This decision was based on schedule and cost by reducing the Telescope secondary response to acceptable levels without effecting already built optical hardware. The stiffness of the bipods was varied from the original stiffness of 262,000 lb/in to the new stiffness of 46,500 lb/in. This stiffness decrease resulted in two benefits: favorable modal combinations and increased damping.

The favorable modal contributions involved a 200 pound Instrument on a 200 pound Spacecraft electronics bus. By reducing the Instrument first bending mode to combine with the Telescope local bending mode, the Instrument on its own is amenable to force limiting. Combining the Instrument and the Spacecraft bus creates a first global bending mode less than the original 36 Hz. Again this mode due to its large effective mass is susceptible to force limiting. The reduction of the Spacecraft bending mode to a range between 30 and 35 Hz occurs at a frequency where the input is lower, which is an additional decrease in telescope response. Figure 2 shows the Spacecraft lateral X axis Protoflight random vibration input specification. The original Spacecraft bending mode frequency and the new frequency with the Instrument bipod stiffness reduction are illustrated.

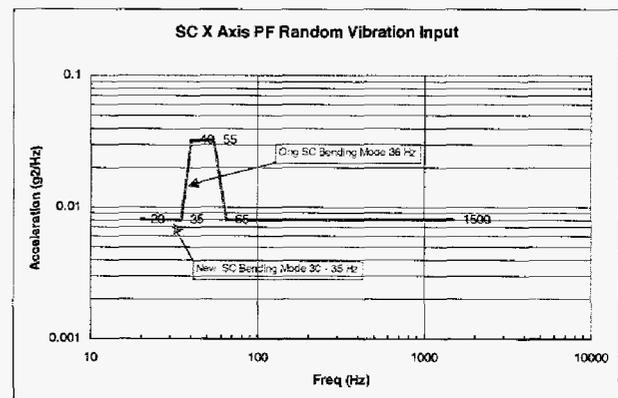


Figure 2 GALEX Spacecraft X axis Protoflight Random Vibration Input

The Telescope predicted secondary response decreased from 11.1 grms to 5.6 grms without force limiting and 8.5 grms to 4.2 grms with force limiting, as shown in Figure 3. Based upon these values, the reduction in Instrument bipod stiffness and input level drives the Telescope response significantly lower.

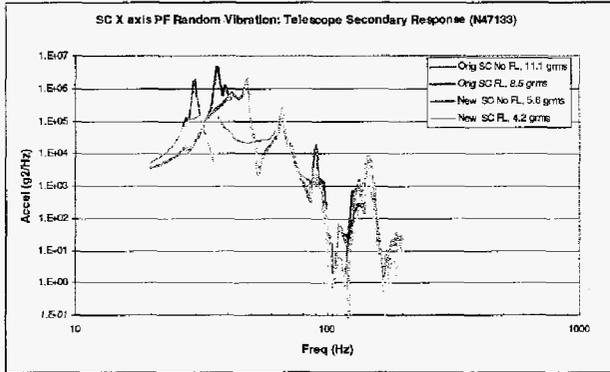


Figure 3 GALEX Spacecraft Telescope Secondary Predicted Response

BIPOD DESIGN APPROACH

Based upon acceptable Telescope secondary response from the random analysis performed at the Spacecraft level, bipod stiffness variations were determined to be 46,500 lb/in minimum and 66,400 lb/in maximum. The bipod material and wall thickness were determined using the minimum stiffness of 46,500 lb/in. A $\pm 45^\circ$ layup of Astroquartz produced an adequate Young's modulus. Tube testing showed the Young's modulus less than predicted and as a result, the wall thickness was increased. In order to achieve a 1.5 percent modal damping, CSA Engineering designed a constrained layer damping treatment consisting of aluminum 0.050 inch thick staves with 2 inches of 0.010 inch thick visco-elastic material at each tube end. A bipod with constrained layer damping is shown in Figure 4.

Test results showed the undamped single tube to have a stiffness of 59,400 lb/in and a loss factor of 0.45 percent. A tube with the constrained layer damping treatment showed a tube stiffness of 64,000 lb/in and a loss factor

of 9.6 percent at 70°F and 30 Hz.

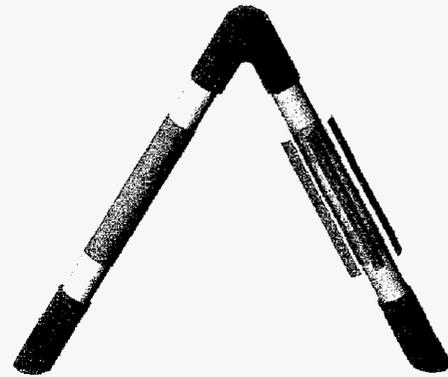


Figure 4 Bipod with Constrained Layer Damping

A tube stiffness of 72,000 lb/in was used in the revised analysis to account for colder temperatures and additional margin. The loss factor of 11 percent was used in the analyses. Figure 5 illustrates the predicted telescope secondary response using the Instrument bipod revised stiffness, and compares the results with and without force limiting as well as without the loss factor. Results indicate that the peak response occurs in a frequency range between 30 and 34 Hz. The Telescope secondary response without force limiting at the base is 5.5 grms, while with force limiting is 4.84 grms. The removal of the strut loss factor and force limiting, results in an increase in the secondary response to 6.48 grms. Assuming a worst case scenario of 4-sigma peak response, the Telescope secondary peak response is expected to be below the 30 g limit.

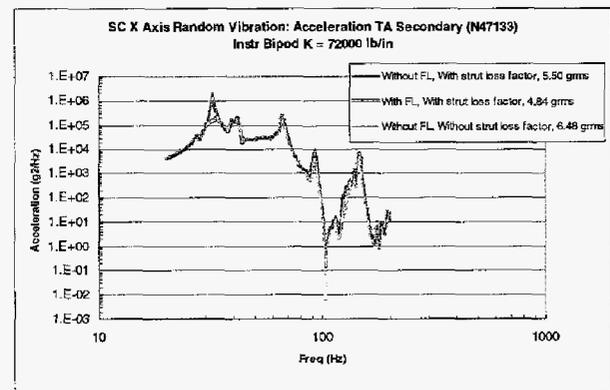


Figure 5 Secondary Predicted Response with Instrument Bipod Stiffness of 72,000 lb/in

INSTRUMENT RANDOM VIBRATION TEST

Pre-test analysis predicted a single mode at 45 Hz with enough effective mass for force limiting to reduce the input at the base as well as the Telescope secondary response. Figure 6 shows the force at the base predicted for the Instrument X axis lateral test. Figure 7 reflects the notch predicted in the input due to force limiting.

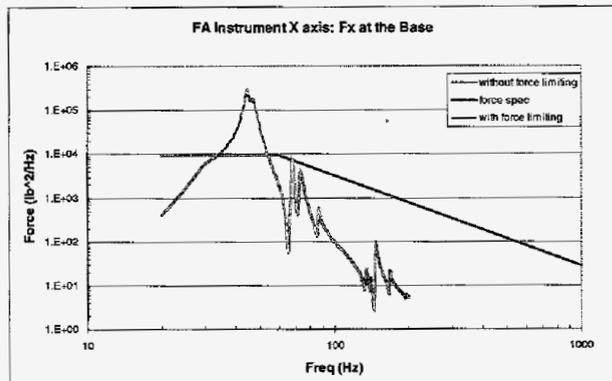


Figure 6 Instrument Predicted Force at the Base Response

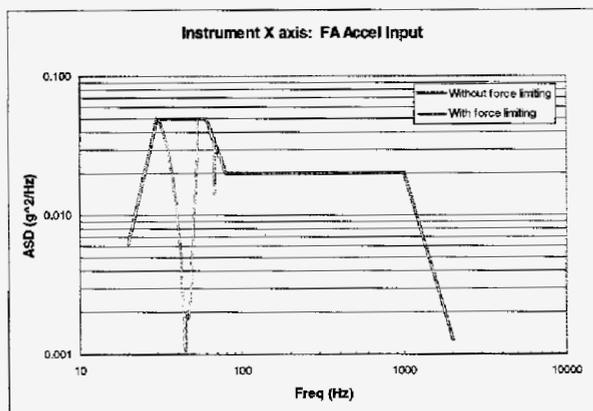


Figure 7 Instrument Acceleration Input with Predicted Notch

The actual Instrument random vibration testing, which was performed in June 2001, showed two modes at 45 and 55 Hz with large effective mass for force limiting to reduce the input by 6 dB. Figure 8 illustrates the effects of force limiting on the input acceleration, while Figure 9 reflects the two modes through the force at the base response.

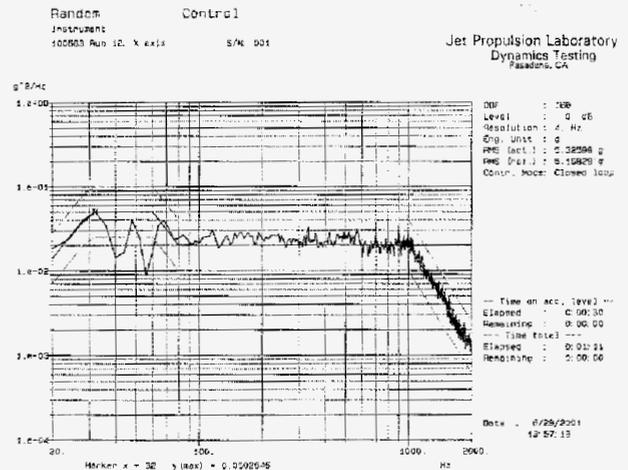


Figure 8 Instrument Acceleration Input with Actual Notch

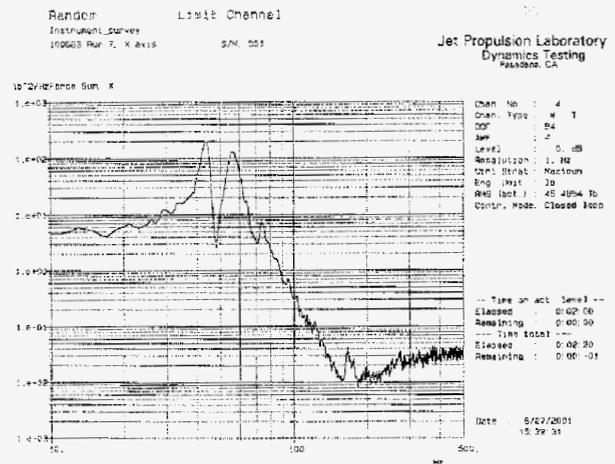


Figure 9 Instrument Actual Force at the Base

The Telescope secondary response was 10.1 grms with 29.1 g peak. Post-test alignment checks showed the Telescope to be acceptable. Figure 10 shows the Telescope secondary response. The actual effect of the constrained layer damping treatment on the struts may be attributed to the lower peak g response of the Telescope secondary assembly. The Instrument successfully passed random vibration testing and was deemed qualified.

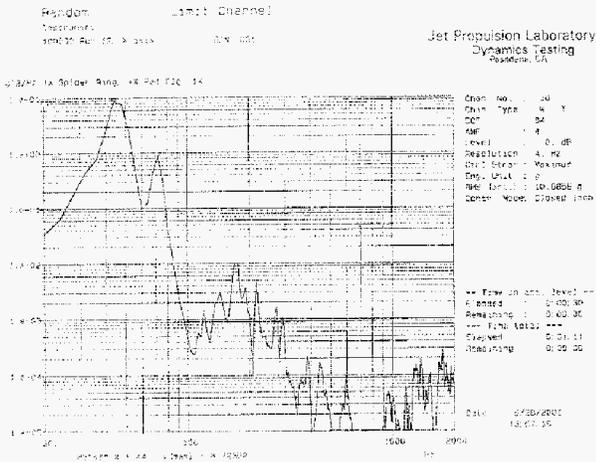


Figure 10 Telescope secondary response

FEM CORRELATION TO TEST RESULTS

The Instrument finite element model was correlated to Instrument level vibration test results. Once the correlation was completed, the single Instrument mode was eliminated and reflected the two modes at 43 and 53 Hz. The new Instrument model was incorporated into the Spacecraft model and the test predictions for the Spacecraft level random vibration testing was performed.

SPACECRAFT RANDOM VIBRATION TESTING

The Spacecraft level random vibration test predictions showed a first global bending mode at 33.5 Hz as shown in Figure 11.

The Telescope secondary response was estimated to be 6.14 grms without force limiting and 4.63 grms with force limiting as illustrated in Figure 12.

The Spacecraft level testing was conducted in January 2002. Results indicated that the frequency and Telescope response predictions were correct. The Spacecraft / Instrument/ Telescope first mode occurs at 33 Hz, as shown in Figure 13. The Telescope secondary response rms was as predicted. The actual

structure exhibited more damping which resulted in less force limiting than predicted.

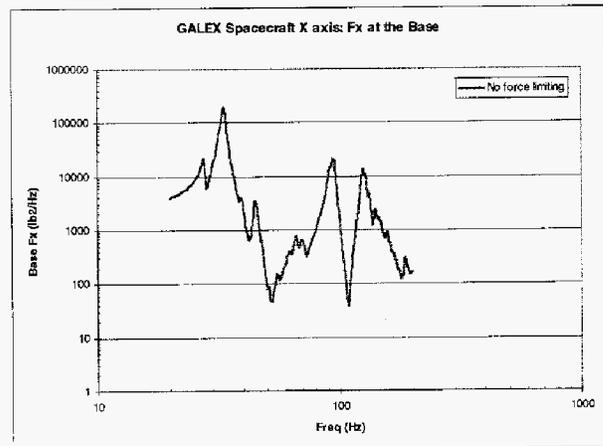


Figure 11 Spacecraft X Predicted Force at the Base

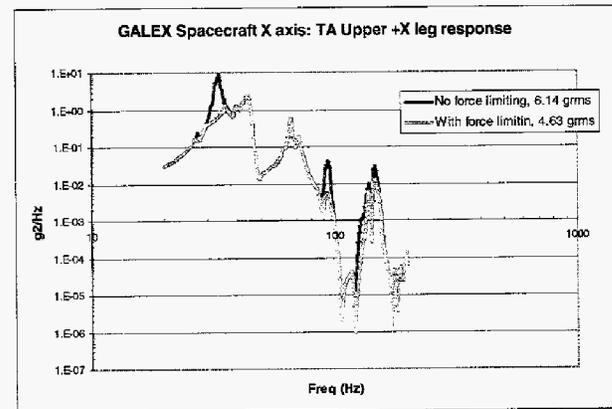


Figure 12 Telescope Predicted Response

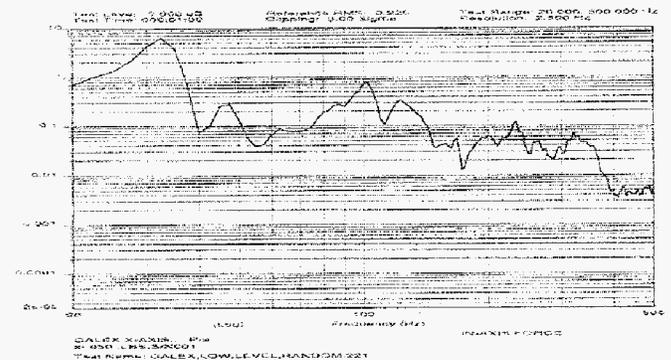


Figure 13 Spacecraft X Force at the Base

Figure 14 shows the Telescope response at full Protoflight level. The sharp peak, which was predicted, is relatively flat. The peak response was 19.6 g's.

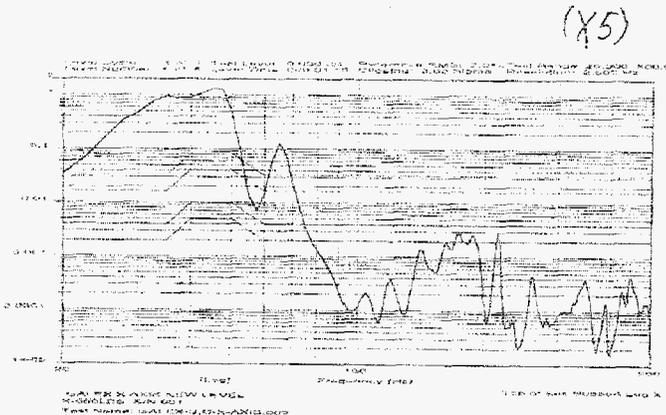


Figure 14 Telescope Secondary Response

The Telescope experienced less response during the Spacecraft testing as compared to Instrument vibration testing. The benefit of the Spacecraft bus provided more damping to the overall system. The Spacecraft successfully passed random vibration in three axes with force limiting.

CONCLUSION

For the GALEX Spacecraft, the unconventional method of combining modes as well as adding damping resulted in a qualified satellite. The method of lowering the Instrument bending mode to align with the Telescope local mode and thereby driving the overall Spacecraft mode to a lower frequency range in the input acceleration proved to be highly successful. The strain energy method distribution was highly useful in determining the optimal area to focus hardware modifications.

ACKNOWLEDGEMENTS

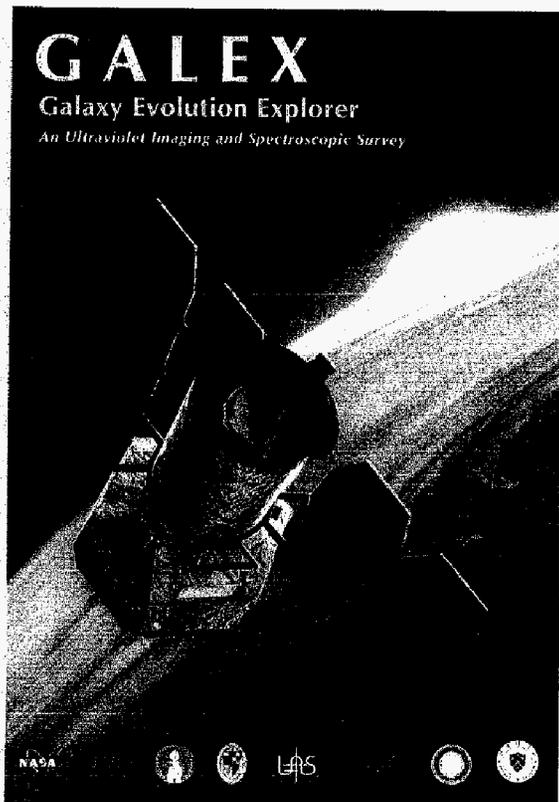
The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The GALEX Spacecraft is part of NASA's Small Explorer program. The support of James Fanson, Spacecraft Manager, and Amit Sen, Instrument Manager, is greatly appreciated. The contributions of Dr. Terry Scharon and Dr. Kung Chang for their analytical support is also appreciated. CSA Engineering of Mountain View, California provided their damping expertise.

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- T.D. Scharon, "Force Limited Vibration Testing Monograph" NASA Reference Publication RP-1403, May 1997.



Mapping the history of star formation in the universe



GALEX TELESCOPE VIBRATION RESPONSE REDUCTION

Michelle Coleman
December 11-13, 2002



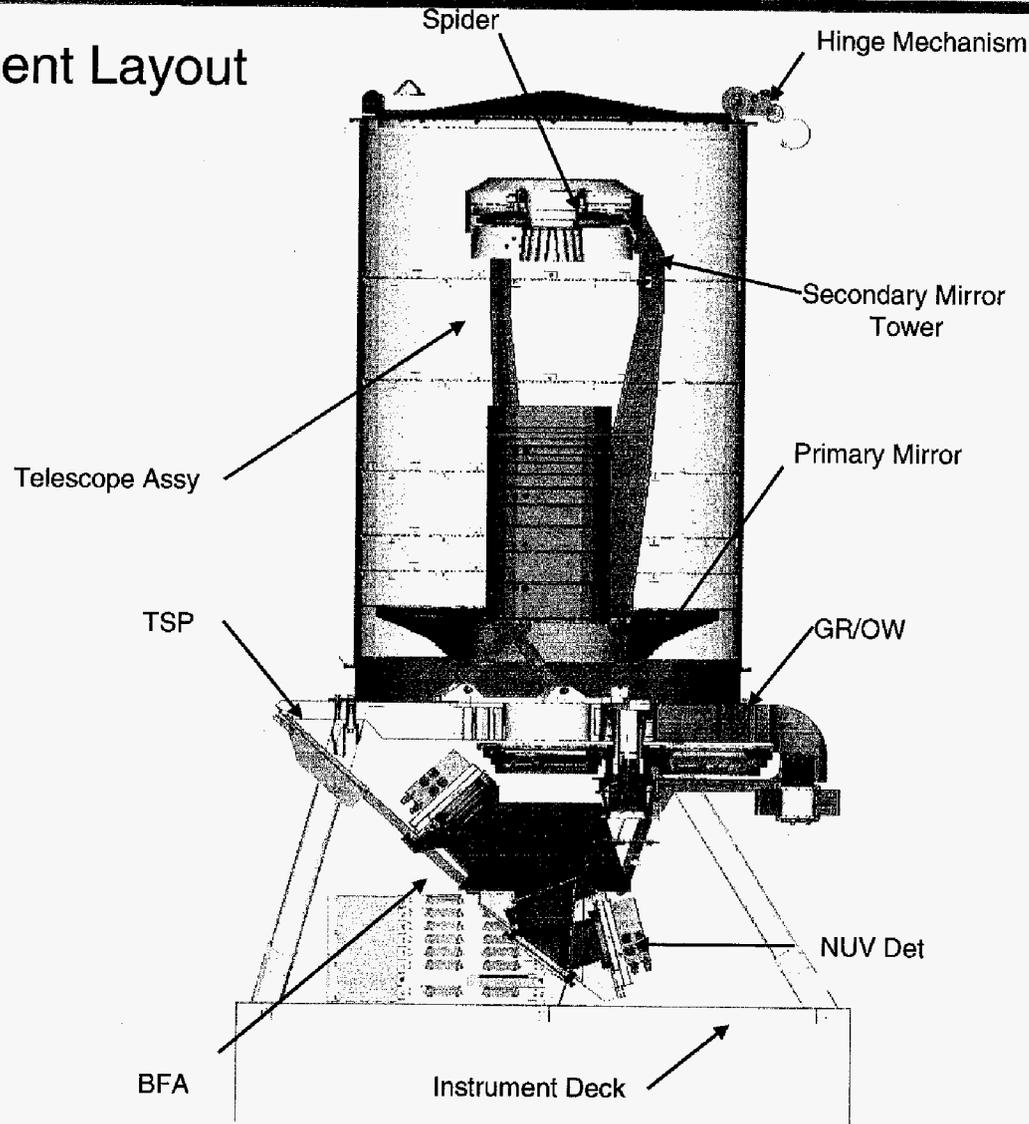
GALEX Telescope Vibration Response Reduction



- Overview
 - *Telescope Response Problem*
 - *Telescope Response Solution*
 - *Instrument Bipod Design Approach*
 - ◆ Stiffness Reduction
 - ◆ Damping
 - *Instrument Vibration Test Results*
 - *Spacecraft Vibration Test Results*

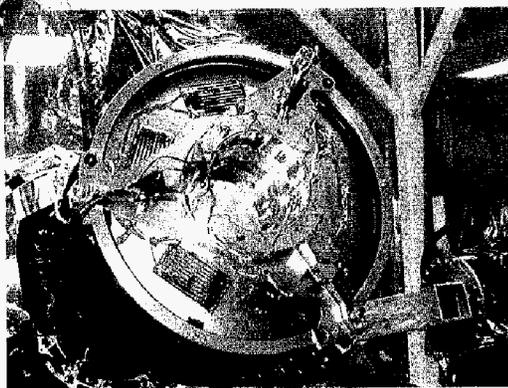
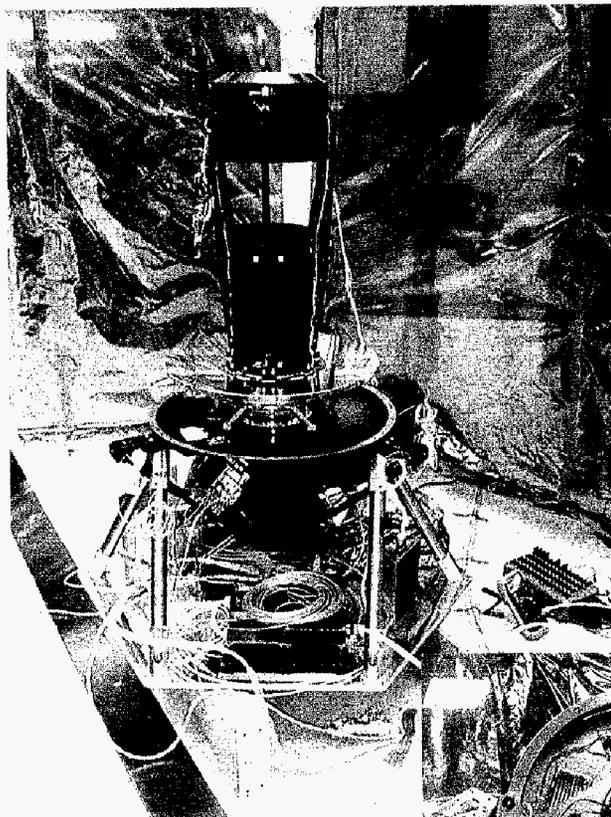
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- Instrument Layout





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- Telescope Response Problem
 - *During Instrument lateral vibration testing (10/00), the input was manually notched -20 dB from 45 to 55 Hz in addition to force limiting due to the TA secondary mirror assembly response above the misalignment g level (22 g) determined by static testing (8/00).*
 - ◆ Response at the Telescope secondary mirror showed a Q of 80+

X, Y Axes		Z Axis	
Freq (Hz)	ASD	Freq (Hz)	ASD
20-30	+9 dB/Oct	20-75	+9 dB/Oct
30-60	0.1 g ² /Hz	75-120	0.1 g ² /Hz
60-80	-10 dB/Oct	120-160	-10 dB/Oct
80-1000	0.04 g ² /Hz	160-1000	0.04 g ² /Hz
1000-2000	-12 dB/Oct	1000-2000	-12 dB/Oct
Overall	7.3 grms	Overall	7.4 grms
duration	75 sec	duration	75 sec

- *As a result, the Instrument was not qualified in the lateral axes.*



GALEX Telescope Vibration Response Reduction



- Telescope Response Solution
 - *Several Paths were investigated*
 - KSC re-analyzed Spacecraft vibration levels based on previous Pegasus flight data
 - *Analysis indicated that a -2 dB reduction in the X axis input acceleration from 0.16 g²/Hz to 0.10 g²/Hz was possible*
 - ◆ Design modifications to reduce the Telescope Secondary response levels
 - *Options investigated by analysis were*
 - tuned mass damper on Baffle cover
 - dampened spring system between Telescope and Baffle structures
 - Instrument Bipod stiffness reduction with constrained layer damping
 - Instrument vibration isolation system (CSA Engineering)
 - Spacecraft vibration isolation system (CSA Engineering)
 - *Instrument Bipod stiffness reduction was optimal choice (based on schedule and cost) by reducing the TA response to acceptable levels without effecting optical hardware and resulted in 2 benefits*
 - favorable modal combination
 - increased damping



GALEX Telescope Vibration Response Reduction



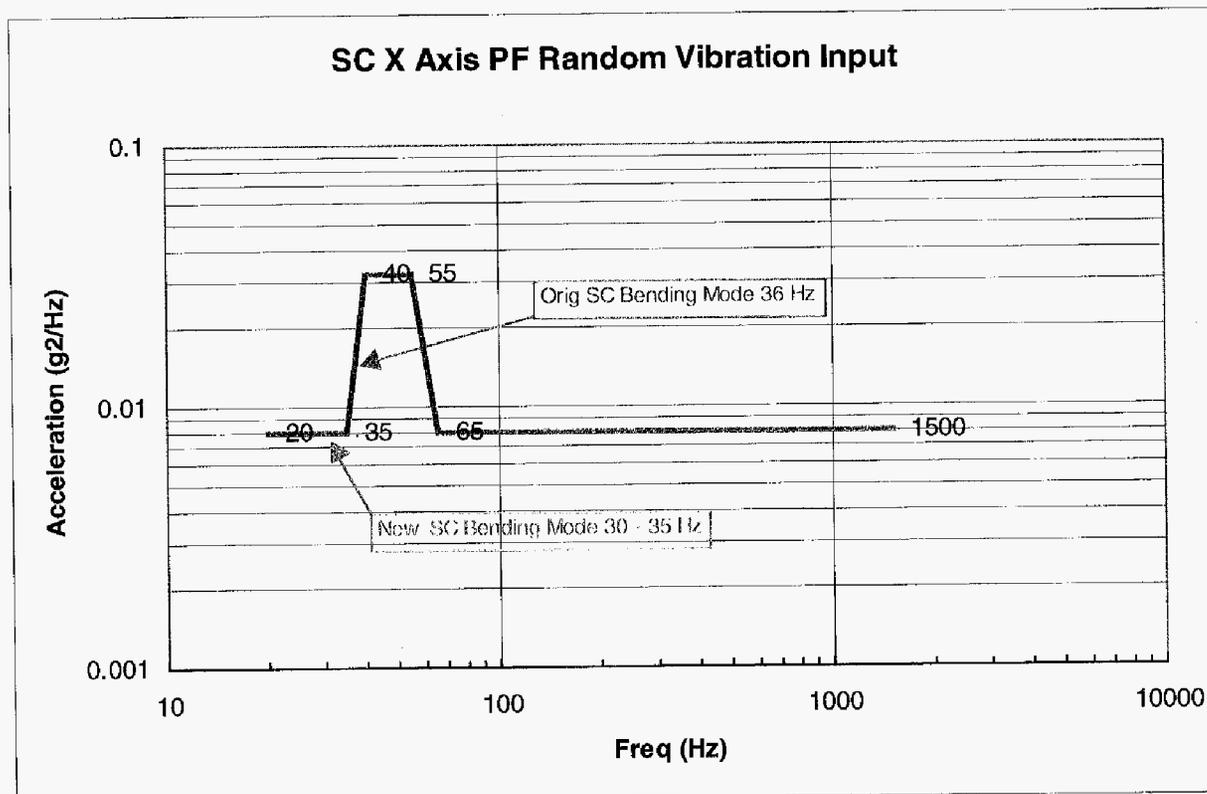
- Instrument Bipod Design Approach - Stiffness Reduction
 - *Favorable modal combinations*
 - ◆ *200 lb Instrument on a 200 lb Spacecraft bus*
 - ◆ *Critical local Telescope mode not susceptible to force limiting due to low effective mass*
 - *Vibration Analysis Assumptions*
 - ◆ *Spacecraft FEM with 1.5% modal damping for all modes*
 - ◆ *Stiffness of the bipods were varied from current 262,000 lb/in to 46,500 lb/in min*
 - *Method relies on changing the Instrument modal character*
 - ◆ *Instrument bending mode combines with the Telescope bending mode and drives the overall Spacecraft bending mode from 36 Hz to 30 Hz.*
 - ◆ *Reduced SC bending mode occurs at a frequency which is at the lower acceleration input level than previous SC bending frequency*
 - *Force limiting at the base further reduces input acceleration*
 - ◆ *Telescope secondary response decreased from 11.1 grms to 5.6 grms without force limiting and 8.5 grms to 4.2 grms with force limiting*



GALEX Telescope Vibration Response Reduction



- Instrument Bipod Design Approach - Stiffness Reduction

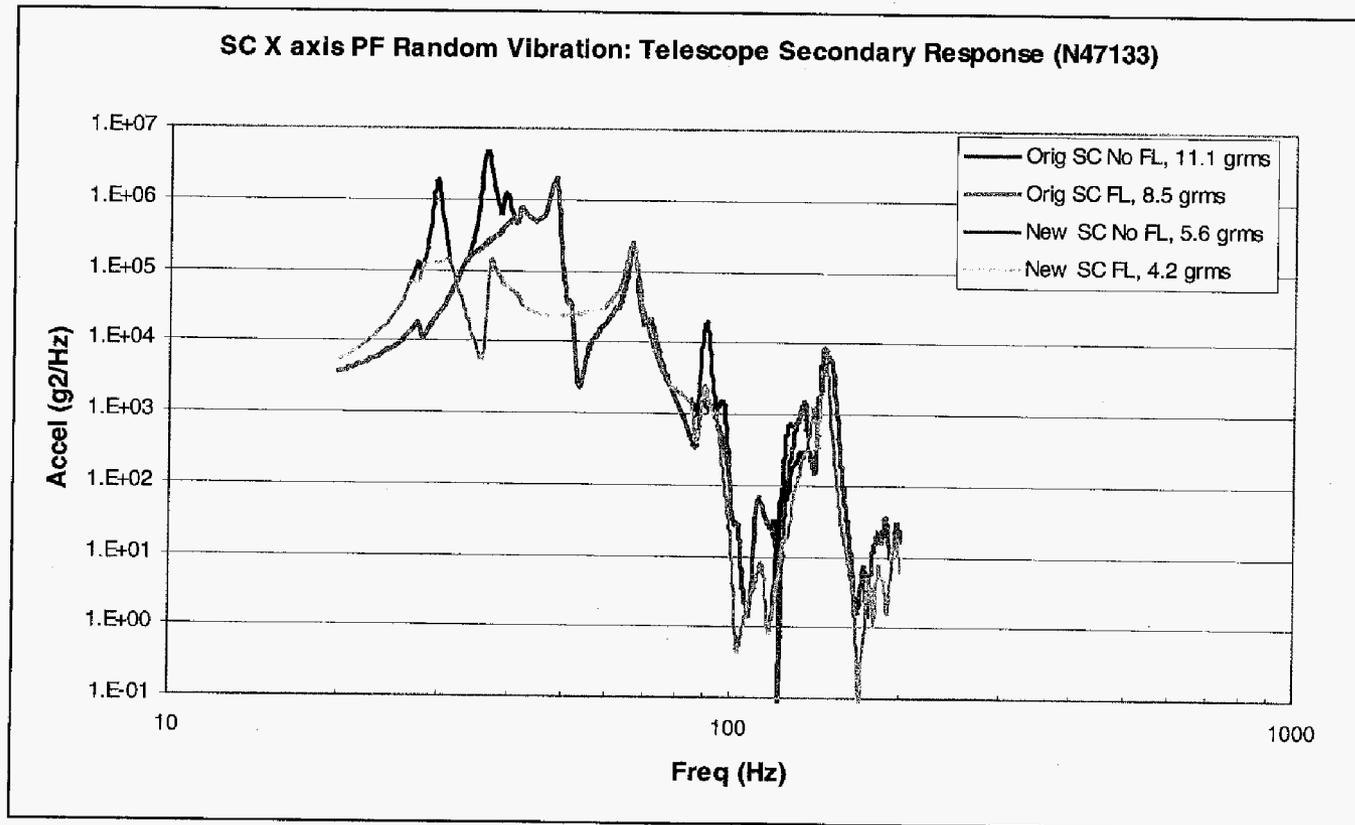




GALEX Telescope Vibration Response Reduction



- Instrument Bipod Design Approach - Stiffness Reduction





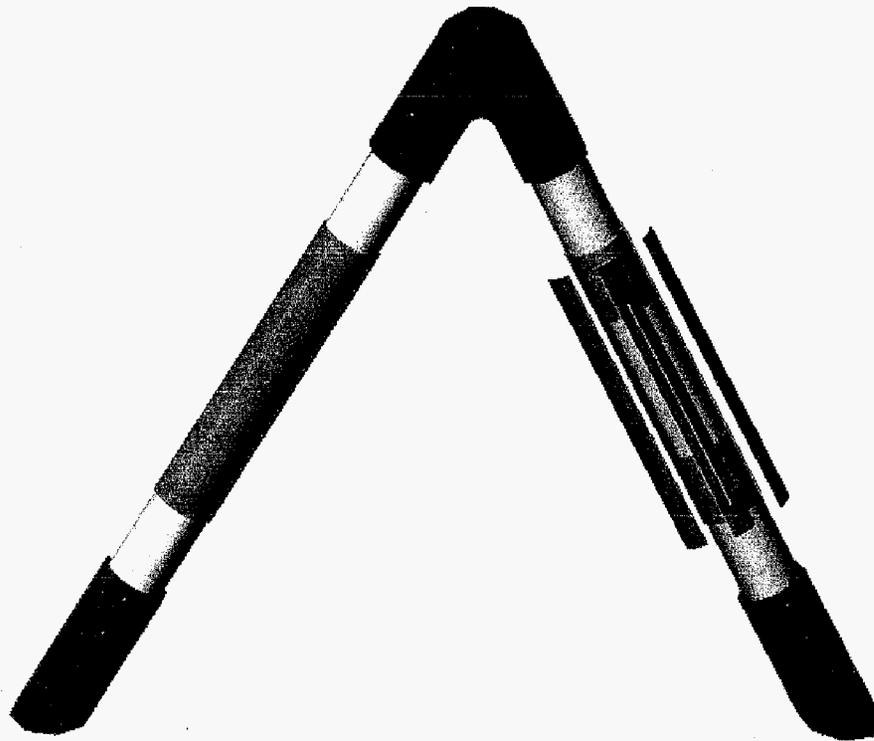
GALEX Telescope Vibration Response Reduction



- Instrument Bipod Design Approach - Stiffness Reduction
 - *Based upon acceptable TA secondary response from random vibration analysis, bipod stiffness variations were determined*
 - ◆ 46500 lb/in minimum
 - ◆ 66400 lb/in maximum
 - *Bipod material and wall thickness were determined using 46500 lb/in*
 - ◆ 1.5" OD drove the tube material to Fiberglass for acceptable wall thickness of 0.050" for handling and positive buckling margins
 - *Composite codes showed that Astroquartz II with ± 45 layup produced an acceptable Young's Modulus*
 - coupon plate test results (± 45 & 0, 90, ± 45 layups) showed Young's Modulus lower than composite code predictions
 - Tube (t=0.040" & 0.060") test for Young's Modulus (less than predicted) and tensile failure
 - Tube thickness was increased to 0.070", tested for Young's modulus and sent to CSA Engineering
 - ◆ Bipod fittings were changed from AL 7075 to Ti 6Al 4V for thermal compatibility with new fiberglass tubes and 8 mil bond line of 9394 epoxy
 - *Structural Integrity maintained*

GALEX Telescope Vibration Response Reduction

- Instrument Bipod Design Approach - Damping
 - *In order to achieve 1.5% modal damping, CSA Engineering designed a constrained layer damping treatment*
 - ◆ Eight Alum 0.050" thick staves, 0.010" thick 3M9473 2" at both ends of strut





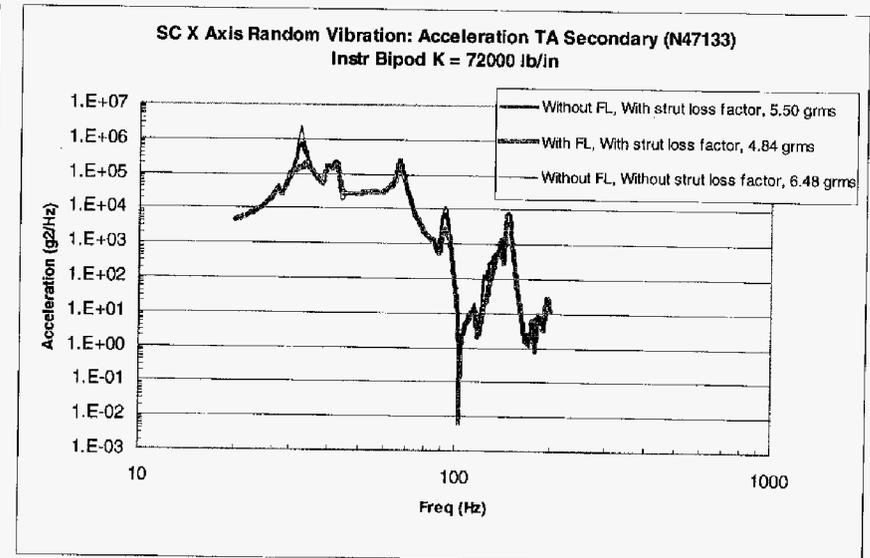
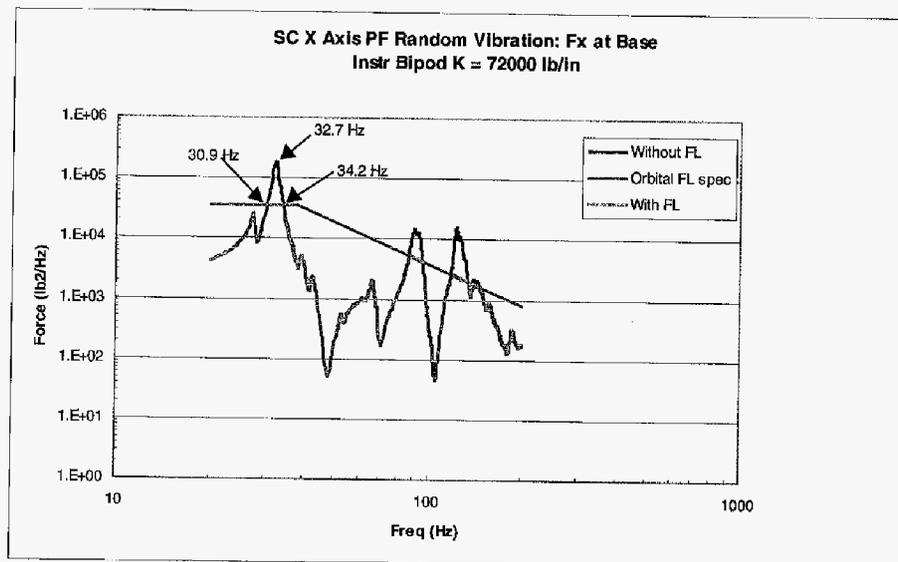
GALEX Telescope Vibration Response Reduction



- Instrument Bipod Design Approach - Damping
 - *CSA test tube results (1.35" ID, 14 plies Astroquartz II \pm 45 layup)*
 - ◆ undamped - tube stiffness 59400 lb/in, loss factor of 0.45%
 - ◆ damped - VEM (t=0.010") is temperature and frequency dependent
 - @70F and 30Hz
 - tube stiffness 64000 lb/in, loss factor 9.6%
 - @74.5F and 30 Hz
 - tube stiffness 62700 lb/in, loss factor 8.7%
 - *A tube stiffness of 72000 lb/in was used in the analysis to account for colder temperature and additional margin*

GALEX Telescope Vibration Response Reduction

- Instrument Bipod Design Approach - Damping
 - SC vibration analysis for 72000 lb/in strut with a loss factor of 0.11 resulted in a SC bending mode of 32.7 Hz and TA secondary response of 5.5 grms without force limiting and 4.8 grms with force limiting

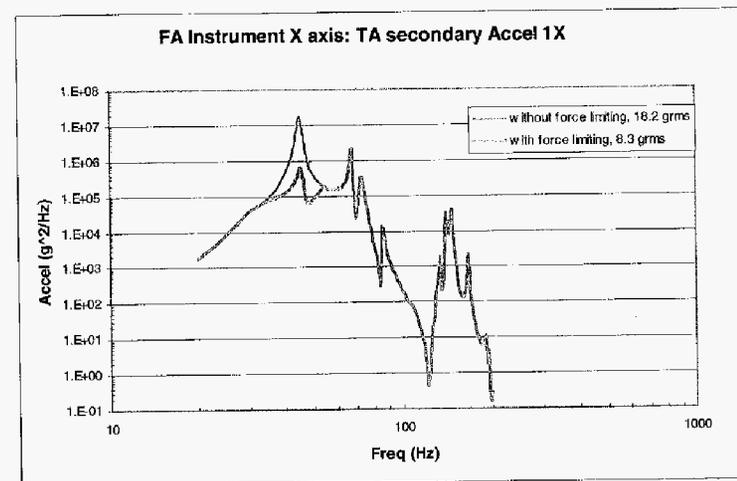
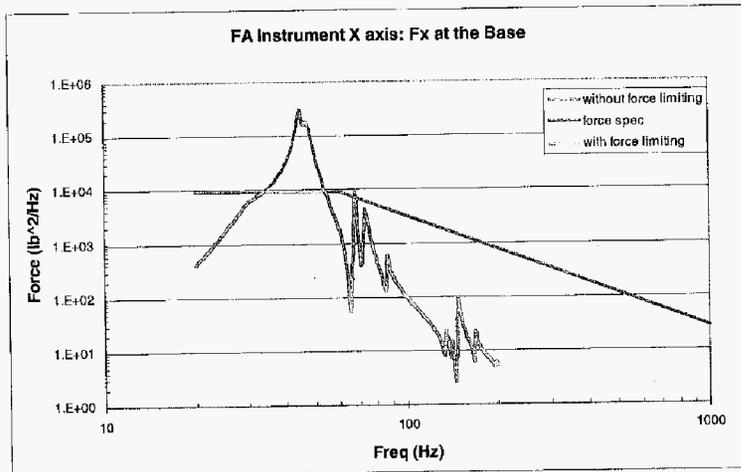
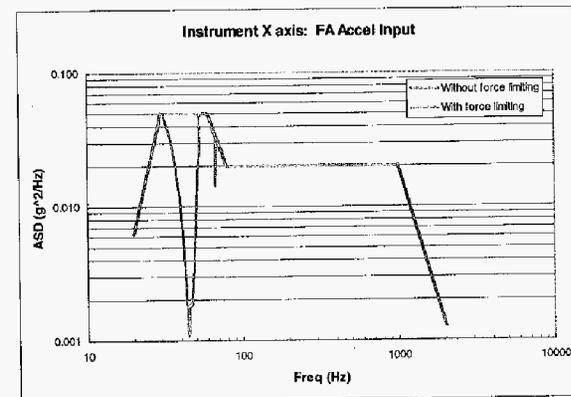




GALEX Telescope Vibration Response Reduction



- Instrument Random Vibration Test, June 2001 - Predictions
 - Analysis predicted a single mode at 45 Hz with enough effective mass for force limiting to reduce input and Telescope response

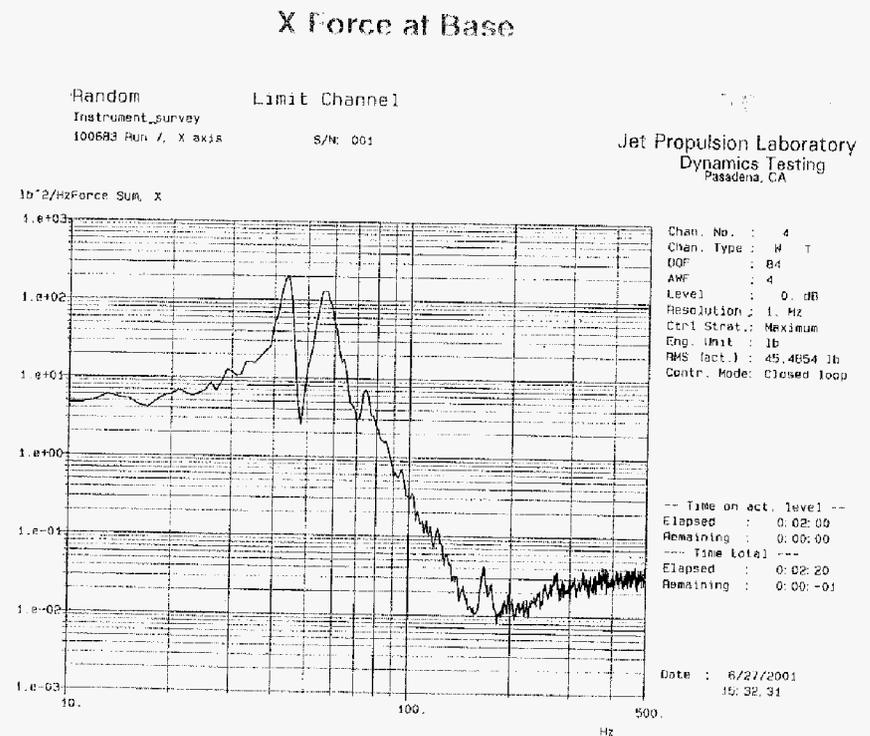
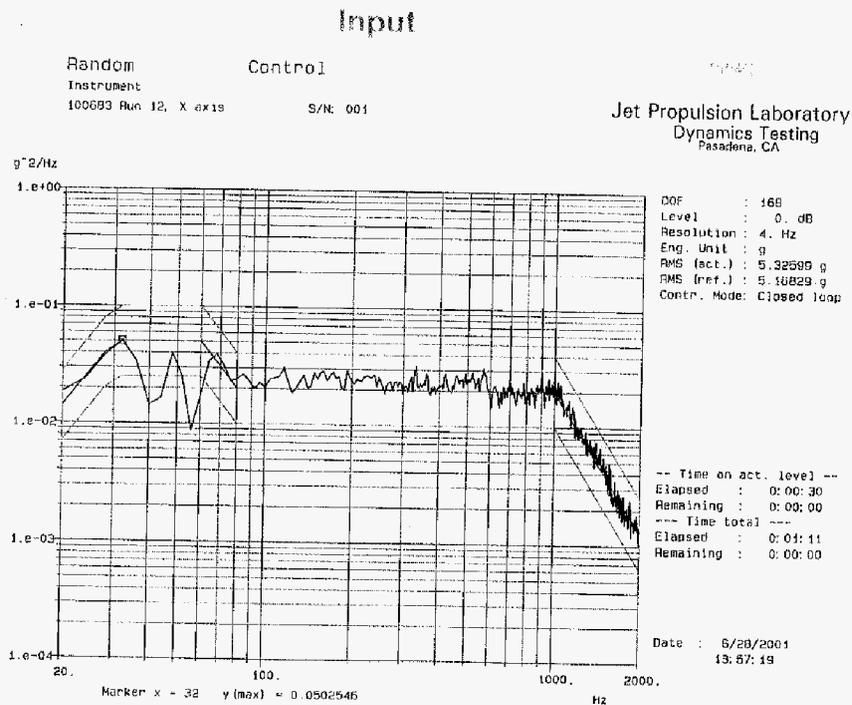




GALEX Telescope Vibration Response Reduction



- Instrument Random Vibration Test, June 2001 - Results
 - Two modes at 45 and 55 Hz with large effective mass for force limiting to reduce input by 6 dB.



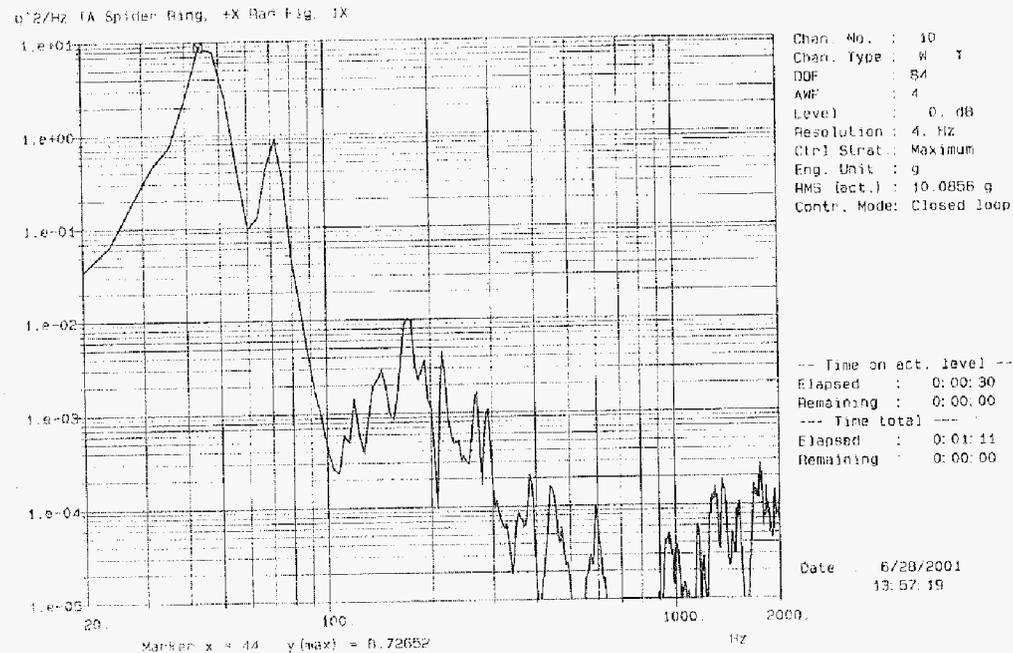


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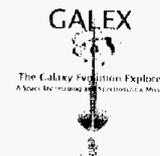


- Instrument Random Vibration Test, June 2001 - Results
 - Time histories: 29.1 g peak X axis, 21.4 g peak Y axis
 - Post-test misalignment showed acceptable

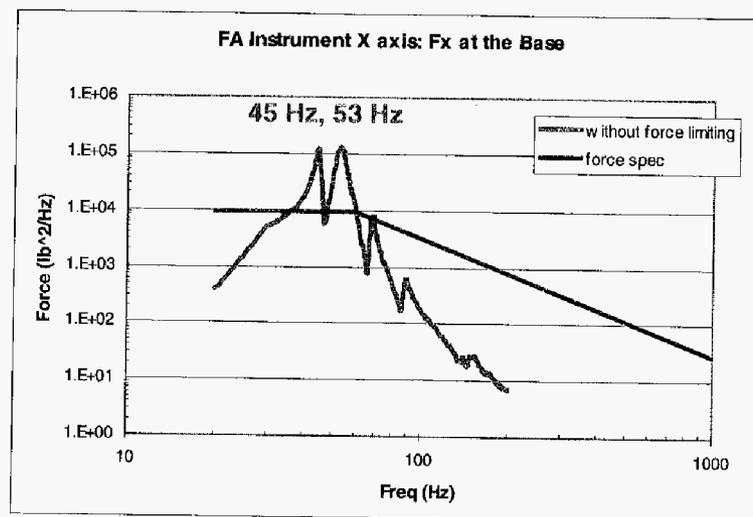
Telescope Response Random Instrument Limit Channel Jet Propulsion Laboratory
 100583 Run 12, X axis S/N: 001 Dynamics Testing
 Pasadena, CA



GALEX Telescope Vibration Response Reduction



- Instrument Random Vibration Test, June 2001 - Results
 - *Correlation of vibrate test results with Instrument finite element model*
 - ◆ calculated effective mass from test
 - ◆ single mode to two modes
 - *Adjusted bipod properties to obtain results similar to test*

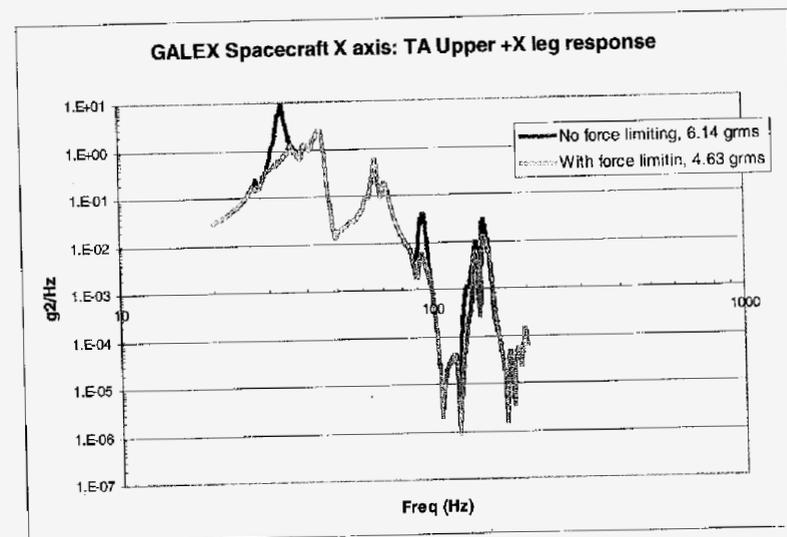
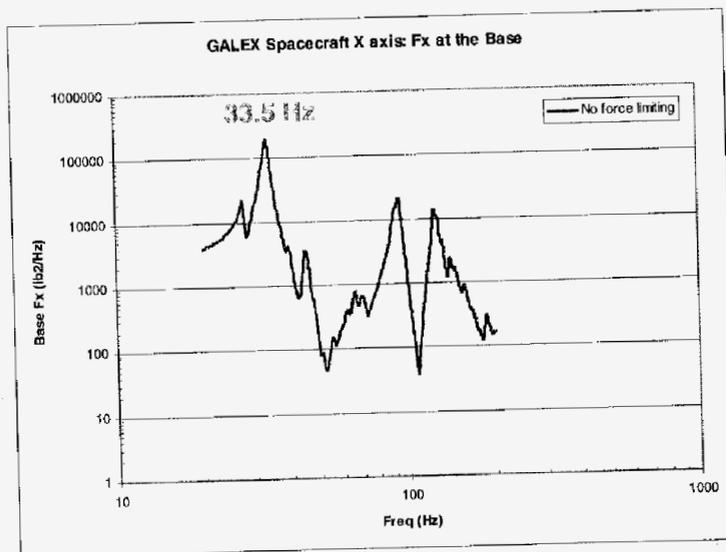




GALEX Telescope Vibration Response Reduction



- Spacecraft Random Vibration Test, January 2002 - Predictions
 - *Re-analyzed Spacecraft random analysis with updated Instrument FEM*



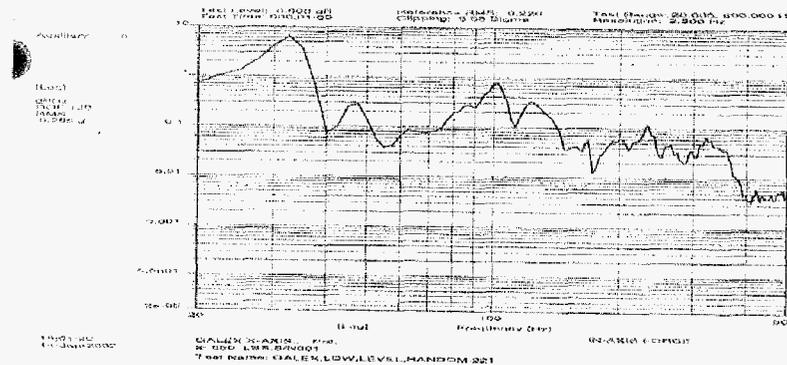


GALEX Telescope Vibration Response Reduction

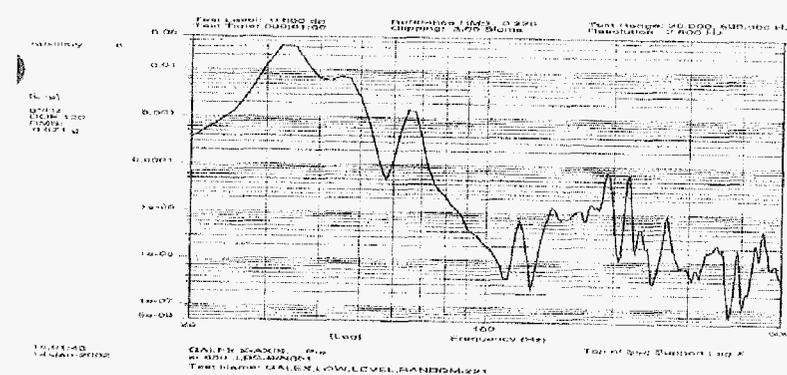


- Spacecraft Random Vibration Test, January 2002 - Results
 - *Frequency and Telescope response predictions correct*
 - ◆ Spacecraft / Instrument/ Telescope mode at ~33 Hz
 - ◆ Telescope response rms prediction
 - *Spacecraft provided additional damping*

Low level run: X Force at Base



Low level run: Telescope Response



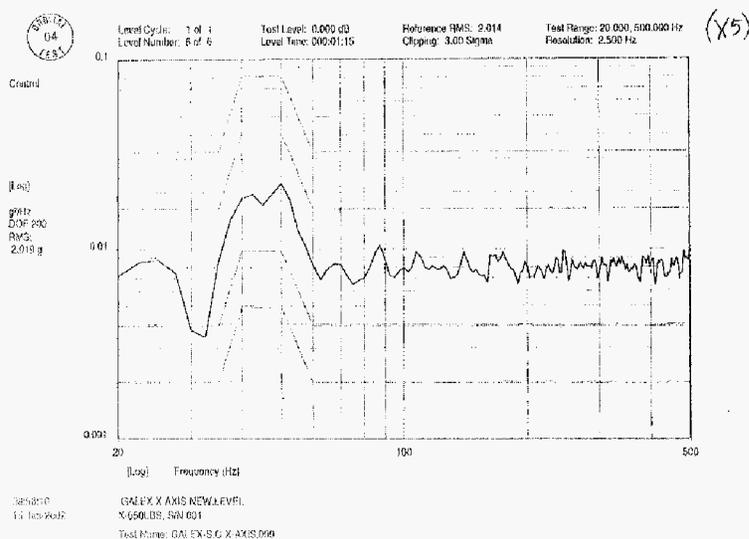


GALEX Telescope Vibration Response Reduction

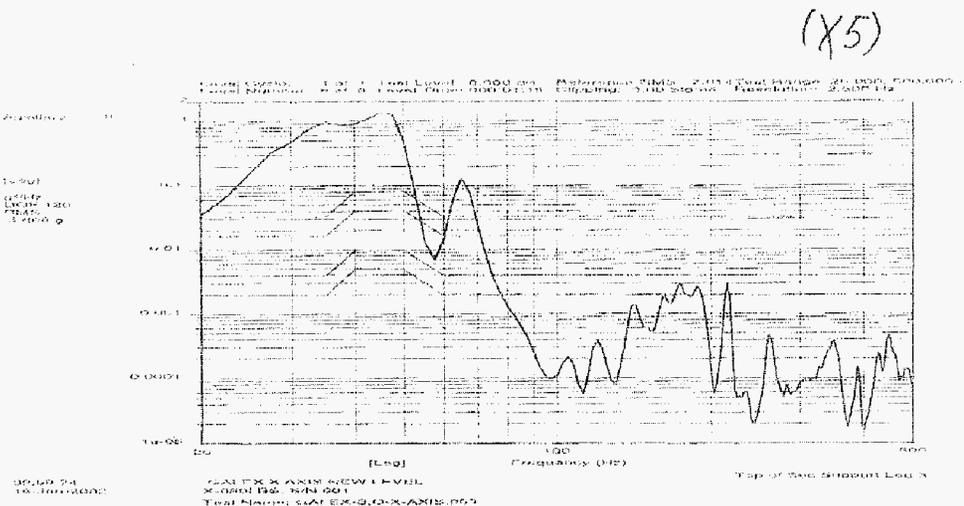


- Spacecraft Random Vibration Test, January 2002 - Results
 - *Time Histories: 17.4 g on leg extrapolated to 19.6 g peak at spider in X axis*

Full level run: X Force at Base



Full level run: Telescope Secondary leg Response



- *Spacecraft successfully completed random vibration testing with minimal force limiting*