Prediction of Spacecraft Vibration Using Acceleration and Force Envelopes

Scott Gordon and Daniel Kaufman, NASA Goddard Space Flight Center; Dennis Kern, Jet Propulsion Laboratory; and Terry Scharton, Consultant

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JPL

AEROSPACE

Overview

- **Objective:** To investigate the use of envelopes of flight acceleration and force data to conduct basedrive vibration analyses of spacecraft designs

- **Data:** GLAST spacecraft test and flight data from Flight Force Measurement study conducted by NASA Goddard Space Flight Center (GSFC) and sponsored by NASA Engineering and Safety Center (NESC)

- **Basic Concepts:**
  - Frequency domain basedrive analyses of spacecraft
  - Use envelopes of flight acceleration and force data
  - Acceleration envelope is input and force envelope provides limiting/notching
  - Obtain flight force data to complement existing acceleration databases
  - Development of methods of normalizing and extrapolating force data to accommodate flight-to-flight and spacecraft differences (future work)

- **Flight Data Disclaimer:**

> FLIGHT DATA AND ENVIRONMENTS CONTAINED HEREIN ARE PROVIDED FOR ILLUSTRATIVE PURPOSES ONLY AND ARE SPECIFIC TO THE GLAST MISSION. THEY ARE NOT INTENDED FOR USE WITH OTHER SPACECRAFT.

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Outline

- Overview

- Section I: Introduction

- Section II: Comparison of GLAST sine vibration test specifications and responses with flight acceleration and force data

- Section III: Use of envelopes of GLAST acceleration data with force limits from NASA 7004B handbook

- Section IV: Use of envelopes of both flight acceleration and force data

- Section V: MECO Transient Analysis

- Conclusions

- Suggestions for Future Investigation

- Backup Charts

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Section I: Introduction

- Flight Measurements of GLAST Accelerations and Forces

- Why Use Envelopes Instead of Actual Flight Data?

- Examples of Flight Data Time Histories and PSD's

- Methods of Characterizing Frequency Response --Liftoff X-axis (see backup charts for other axes and aeroloads)
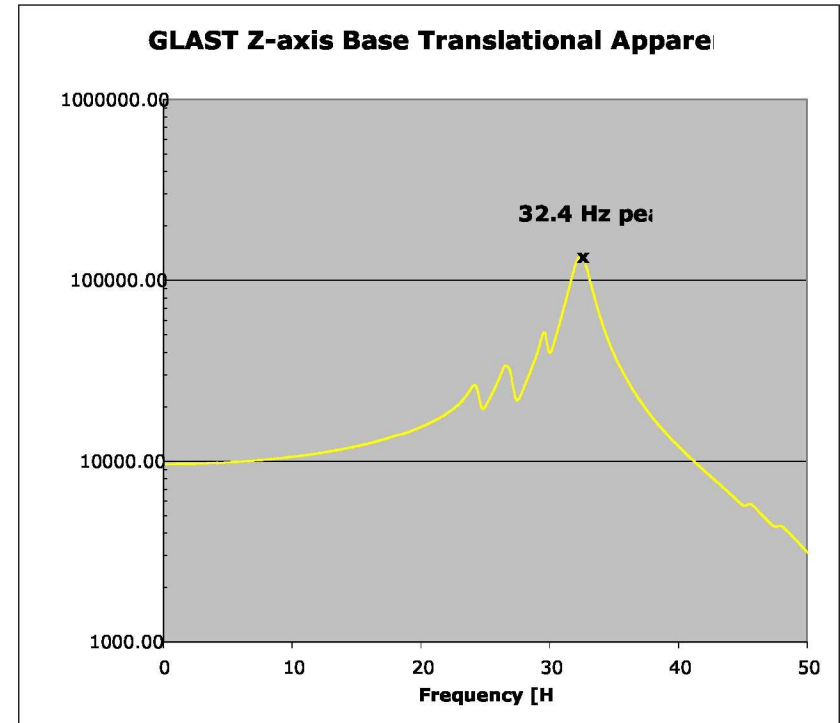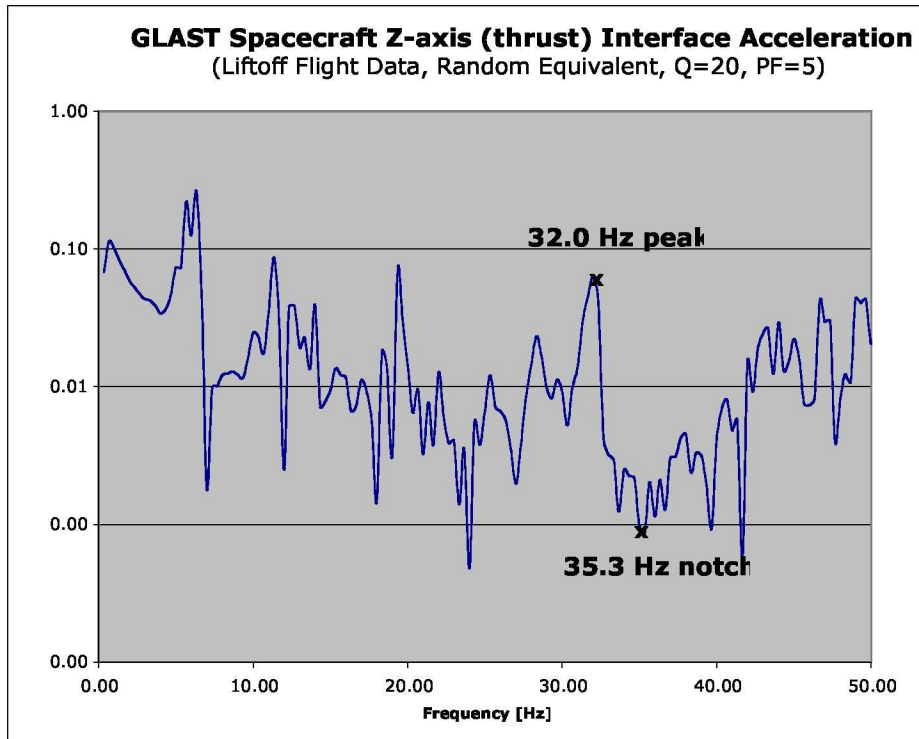
- Comparison of SRS and Random Equivalent

# Flight Measurements of GLAST Spacecraft Accelerations and Forces
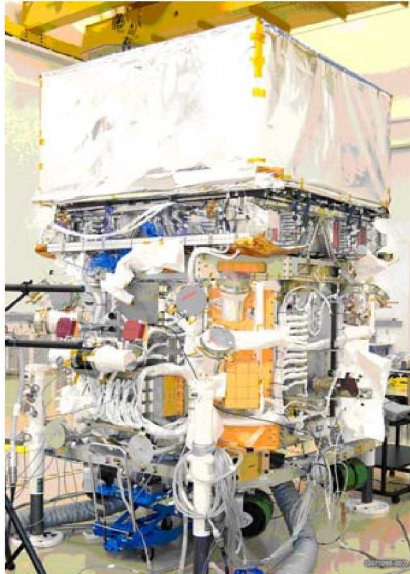
- The GLAST spacecraft (left photo) flight interface acceleration data presented herein were measured with four triaxial accelerometers mounted on the base ring of the Payload Adapter Fitting (right photo)

- The GLAST spacecraft flight base force data presented herein were measured with 64 strain gages mounted on the Payload Adapter Fitting using the Summed Force Method (see companion presentation by Scott Gordon at this workshop)

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Why Use Envelopes for Base Drive Analyses
Instead of Actual Flight Data

GLAST Spacecraft Z-axis (thrust) Interface Acceleration
(Liftoff Flight Data, Random Equivalent, Q=20, PF=5)

32.0 Hz peak

35.3 Hz notch

Frequency [Hz]

GLAST Z-axis Base Translational Appare

32.4 Hz pea

Frequency [H
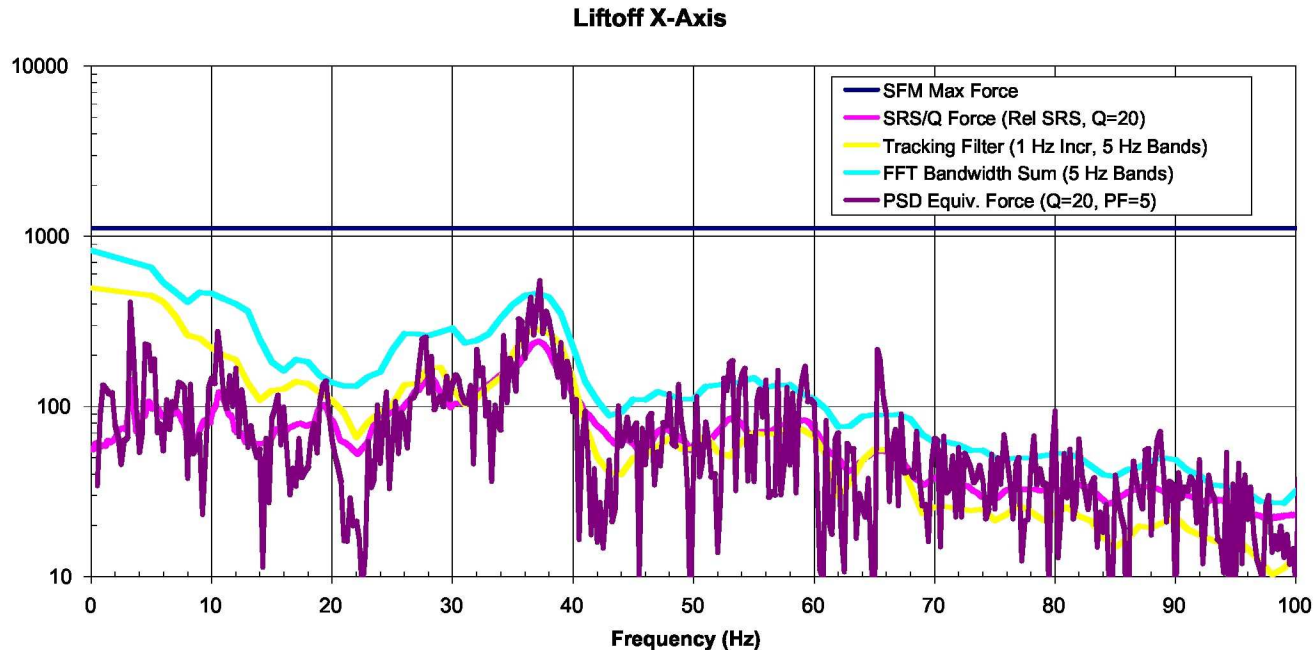
- Spacecraft and launch vehicle configurations change from flight to flight (envelopes must consider flight-to-flight and configuration variations)

- Notches are at different frequencies in flight and in fixed-base configurations (compare plots of the z-axis spacecraft interface acceleration measured in flight with the spacecraft z-axis apparent mass measured in the spacecraft vibration test)

Examples of Flight Data Time Histories and PSD's
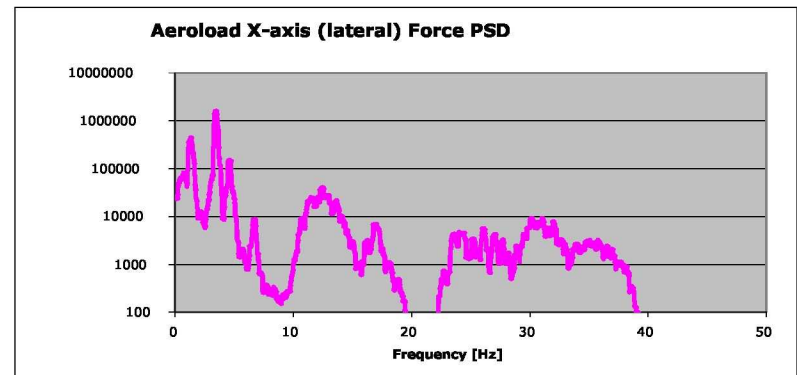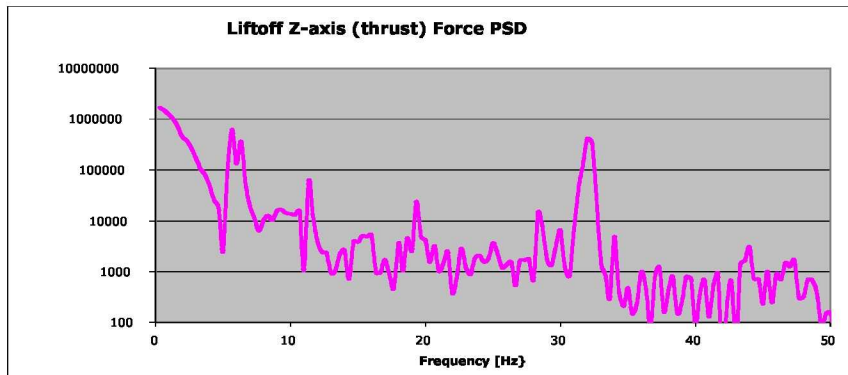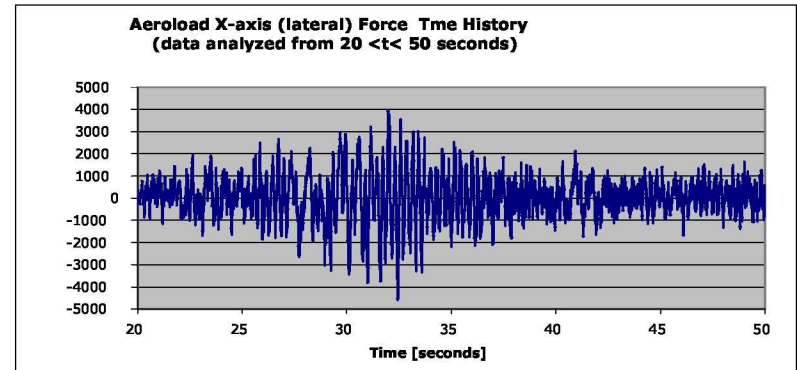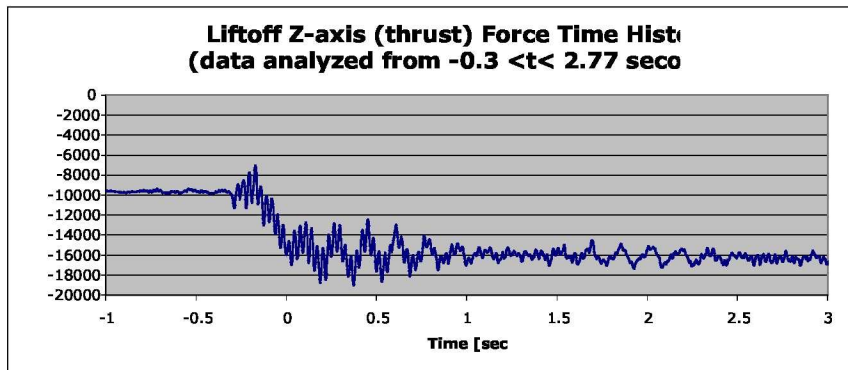
- Flight data sampled at 1000 Hz and low-pass filtered at 250 Hz
- Octave open source software used for FFT analysis, with no windowing, and no averaging of records (T=3 seconds for liftoff, T = 30 seconds for aeroloads, and T = 2 seconds for MECO transient)

Methods of Characterizing Frequency Response

Liftoff X-Axis

Legend:
- SFM Max Force
- SRS/Q Force (Rel SRS, Q=20)
- Tracking Filter (1 Hz Incr, 5 Hz Bands)
- FFT Bandwidth Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

X-axis: Frequency (Hz)

- Different methods evaluated to convert measured force time histories to the frequency domain (SRS/Q, Tracking Filter, FFT Sum, Random Equivalent)

- All methods dependent on parameters selected for processing

- Can under predict peak time domain load
    - *Peak load in time domain is summation of loads with different frequency content*
    - *Averaging techniques will smooth over peaks*

- All the methods investigated give more or less similar frequency dependence

Comparison of SRS and Random Equivalent

GLAST Spacecraft X-axis (lateral) Base Accelerat (Liftoff Flight Data)

Legend:
— Random Equivalent, (Q=20, PF=5
— SRS/20, (Q=20)

Y-axis: 1, 0.1, 0.01, 0.001
X-axis (Frequency [Hz]): 0, 20, 40, 60, 80, 100

GLAST Spacecraft Z-axis (thrust) Base Accelera (Liftoff Flight Data)

Legend:
— Random Equivalent, (Q=20, PF
— SRS/Q, (Q=20)

Y-axis: 1.00E+00, 1.00E-01, 1.00E-02, 1.00E-03
X-axis (Frequency [H): 0.00, 10.00, 20.00, 30.00, 40.00, 50.00, 60.00
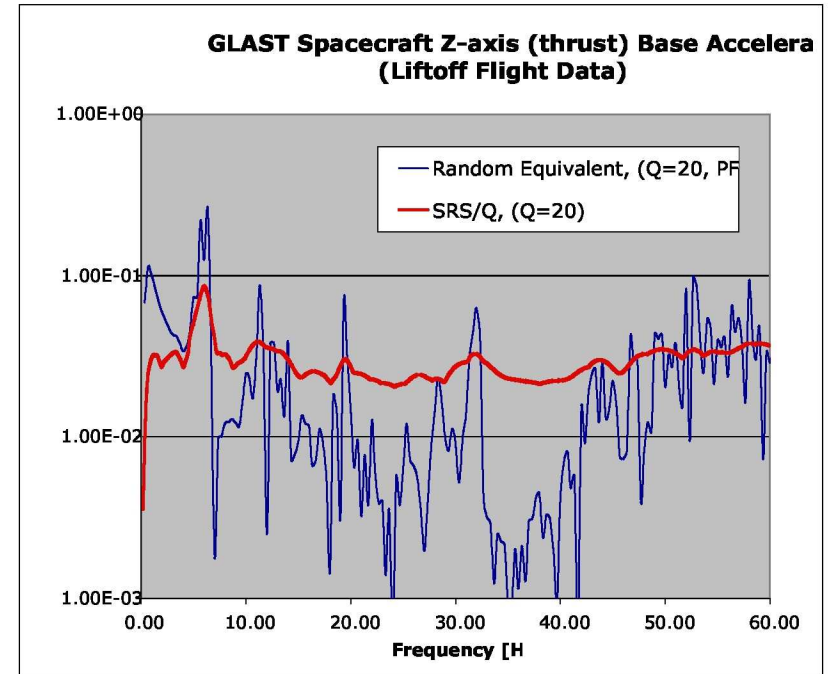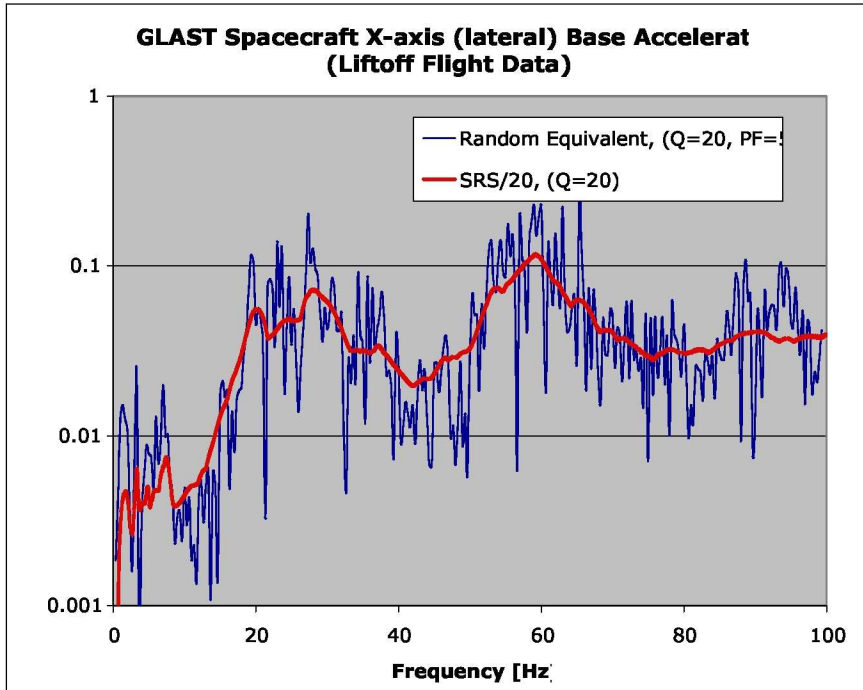
- Random Equivalent equates the amplitude of a sine input to that of a resonance peak in a random input: $PF * [(\pi/2)*Freq*PSD/Q]^{0.5}$ (this differs from Mile's Eq. by Q^2)

- For lateral axis liftoff acceleration SRS/20 is average of Random Equivalent, but for thrust axis liftoff, SRS/20 is biased up by DC and low frequency input

- SRS/Q is questionable in the case of forces at the spacecraft base

# Section II: Comparison of GLAST Sine Vibration Test Input and Response with Flight Data

- GLAST Spacecraft X-axis (lateral) Interface Acceleration

- GLAST X-axis (Lateral) Base Apparent Mass

- GLAST Spacecraft X-axis (lateral) Base Force

- GLAST Spacecraft Z-axis (thrust) Interface Acceleration (backup)

- GLAST Z-axis (Thrust) Base Apparent Mass (backup)

- GLAST Z-axis (Thrust) Base Force (backup)

GLAST Spacecraft X-axis (lateral) Interface Acceleration

- GLAST Sine Test
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroloads (Random Eqivalent, Q=20, PF=5)
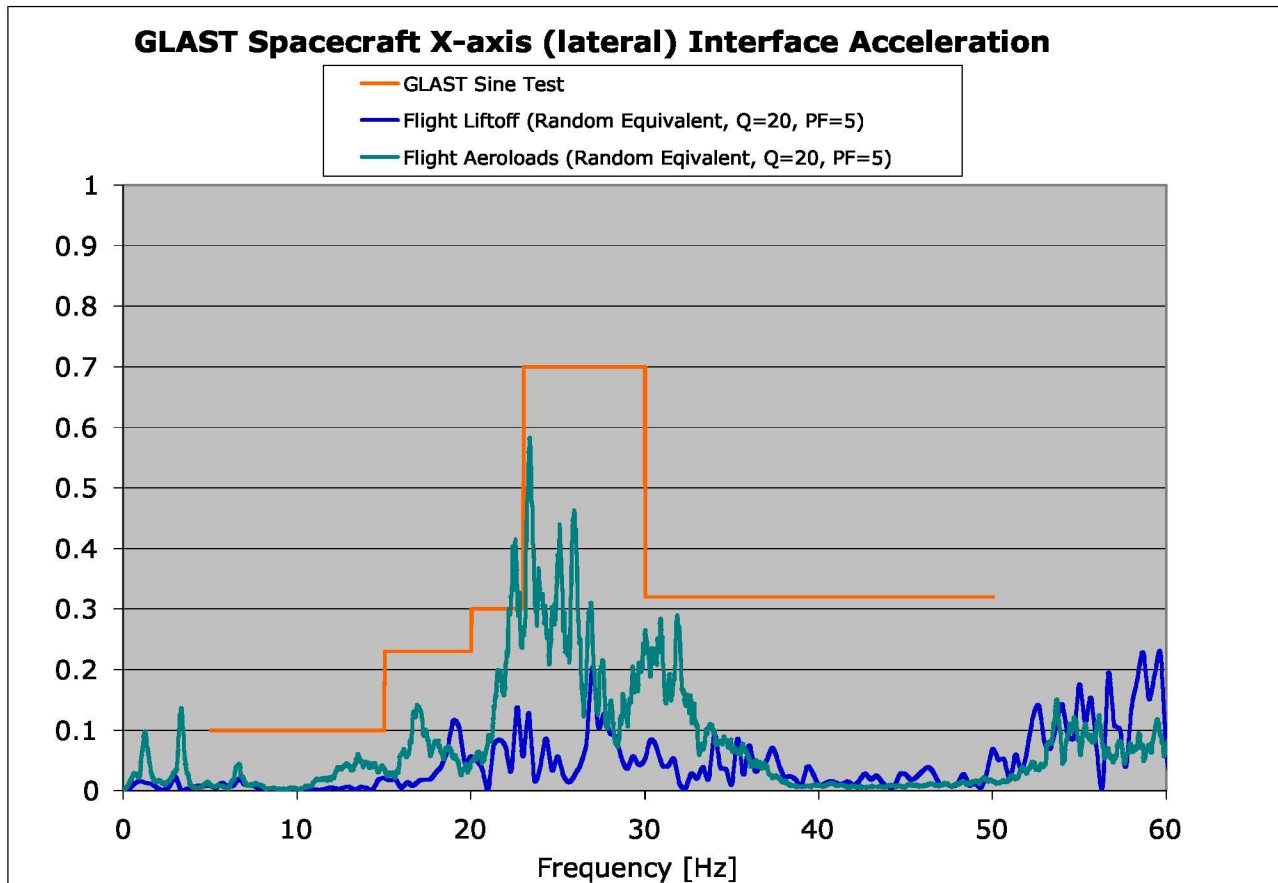
- Sine vibration test input was tailored with FEA to not exceed CLA
- The x-axis interface acceleration data measured for liftoff and aeroloads are comparable to the input acceleration in the GLAST sine vibration test
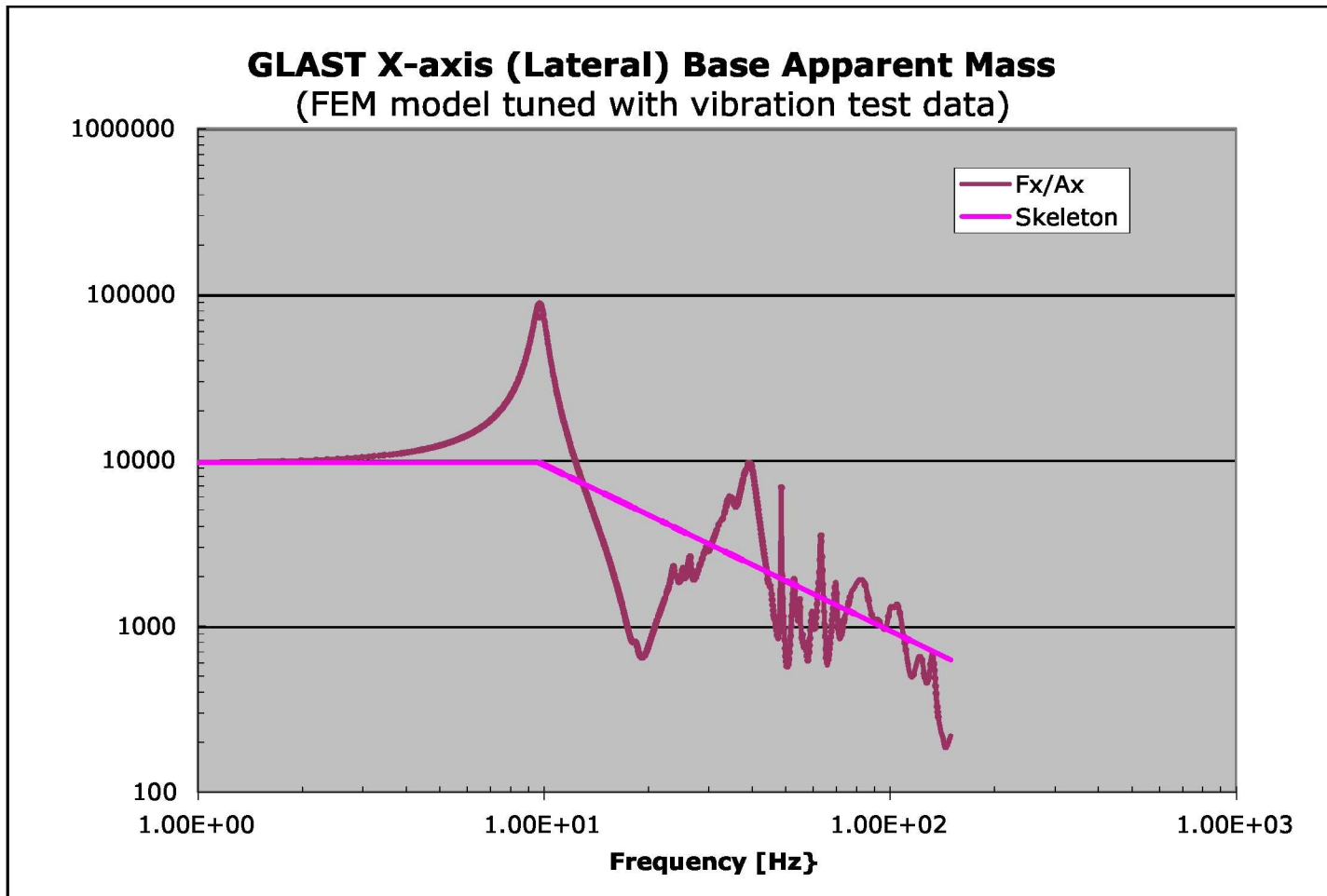
GLAST X-axis (Lateral) Base Apparent Mass
(FEM model tuned with vibration test data)

- The apparent mass is used to calculate the base reaction force resulting from an acceleration input at the spacecraft base

- The skeleton is used to derive force limit specifications (NASA HDBK 7004B)

GLAST Spacecraft X-axis (lateral) Base Force
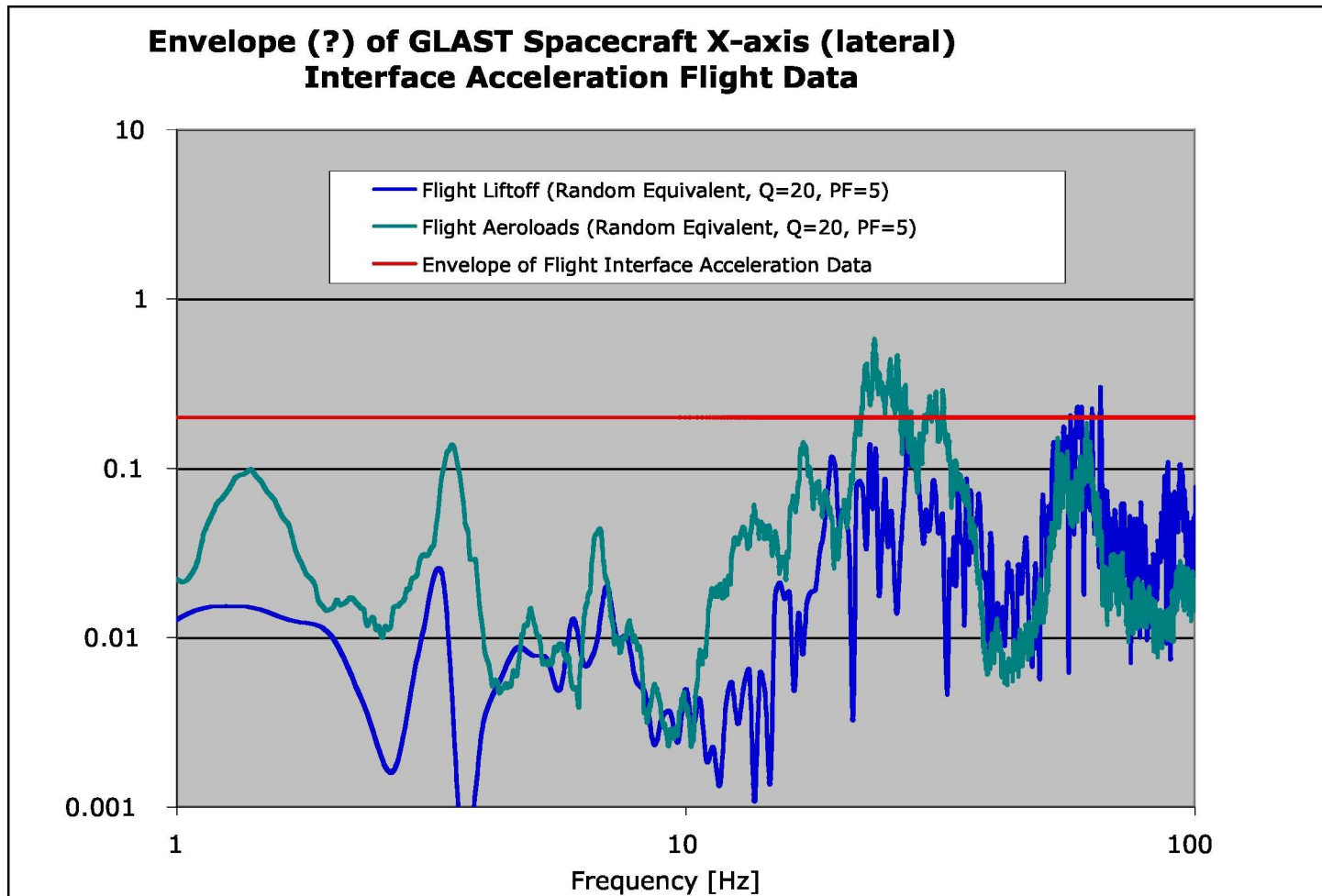(calculated by multipying input acceleration by apparent mass)

Legend:
- Users Guide Input with Handbook Force Limit
- GLAST Sine Test (tailored not to exceed CLA)
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroloads (Random Equivalent, Q=20, PF=5)

X-axis: Frequency [Hz]
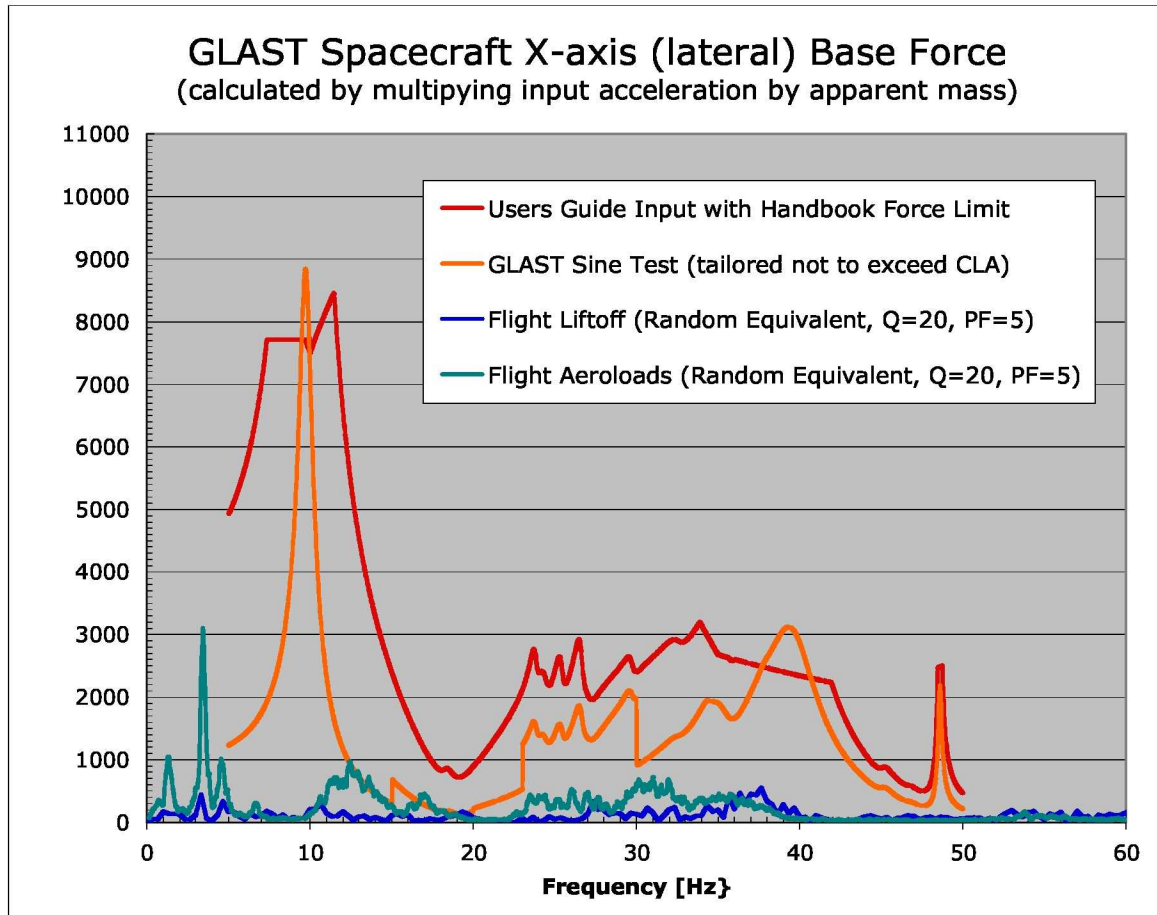
- Force derived from Delta II Users Guide acceleration input and NASA 7004B Handbook force limit is close to that in sine test based on CLA
- Base force data measured in flight are less than in the sine vibration test
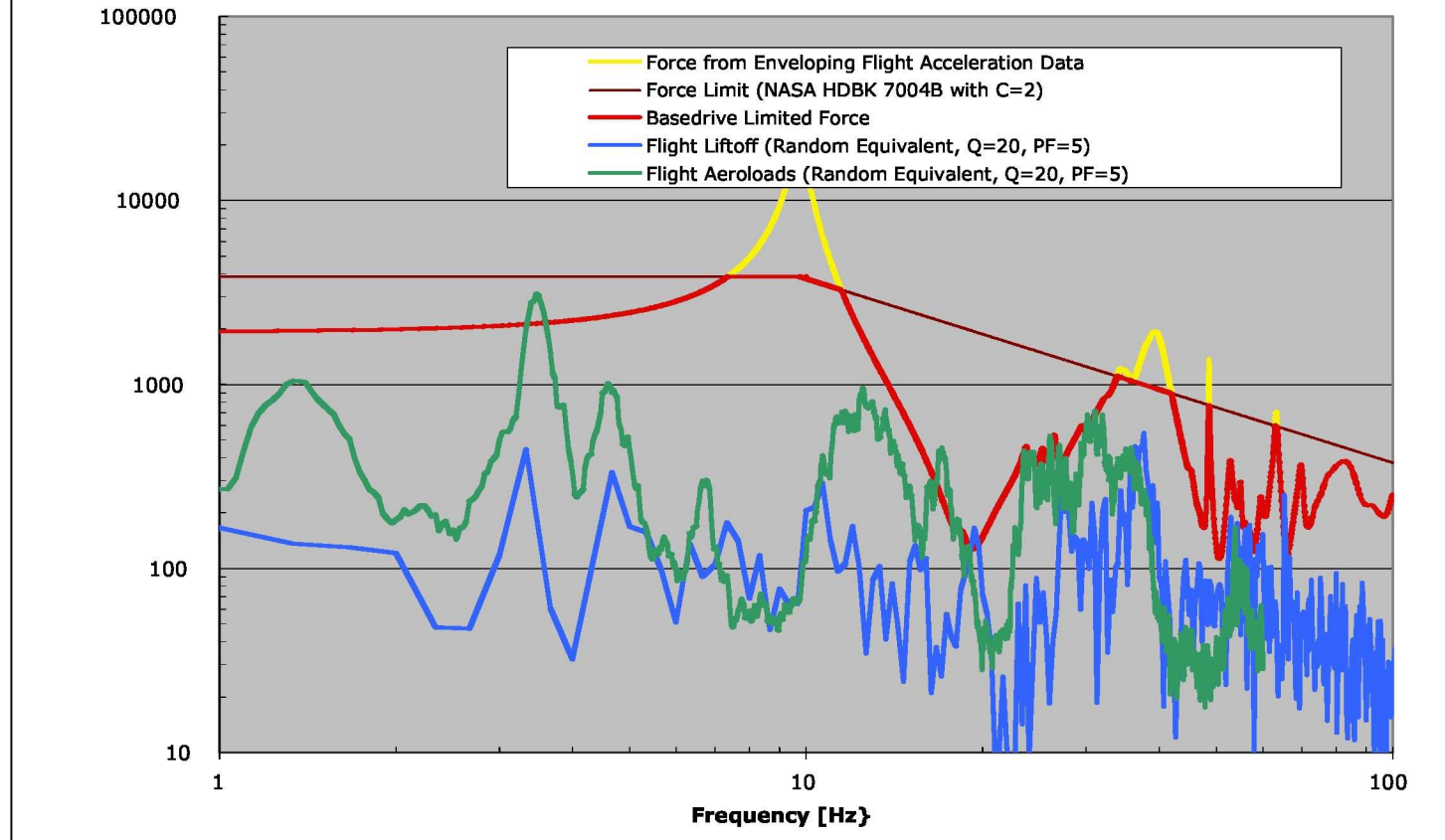
Section III: Use of Envelopes of GLAST Acceleration Data with 7004B Force Limits

- Envelope (?) of GLAST Spacecraft X-axis (lateral) Interface Acceleration Flight Data

- Basedrive Analysis of GLAST Spacecraft X-axis Base Force Using Envelope of Flight Acceleration Data and Force limit from NASA 7004B Handbook

- Envelope (?) of GLAST Spacecraft Z-axis (thrust) Interface Acceleration Flight Data (backup)

- Basedrive Analysis of GLAST Spacecraft Z-axis Base Force Using Envelope of Flight Acceleration Data and Force limit from NASA 7004B Handbook (backup)

Envelope (?) of GLAST Spacecraft X-axis (lateral) Interface Acceleration Flight Data

Legend:
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroloads (Random Eqivalent, Q=20, PF=5)
- Envelope of Flight Interface Acceleration Data

Frequency [Hz]

- Crude envelope of flight acceleration data is input to basedrive model
- Envelope over data below 10 Hz, and below data above 22 Hz

Basedrive Analysis of GLAST Spacecraft X-axis Base Force Using Envelope of Flight Acceleration Data and Force limit from NASA 7004B Handbook

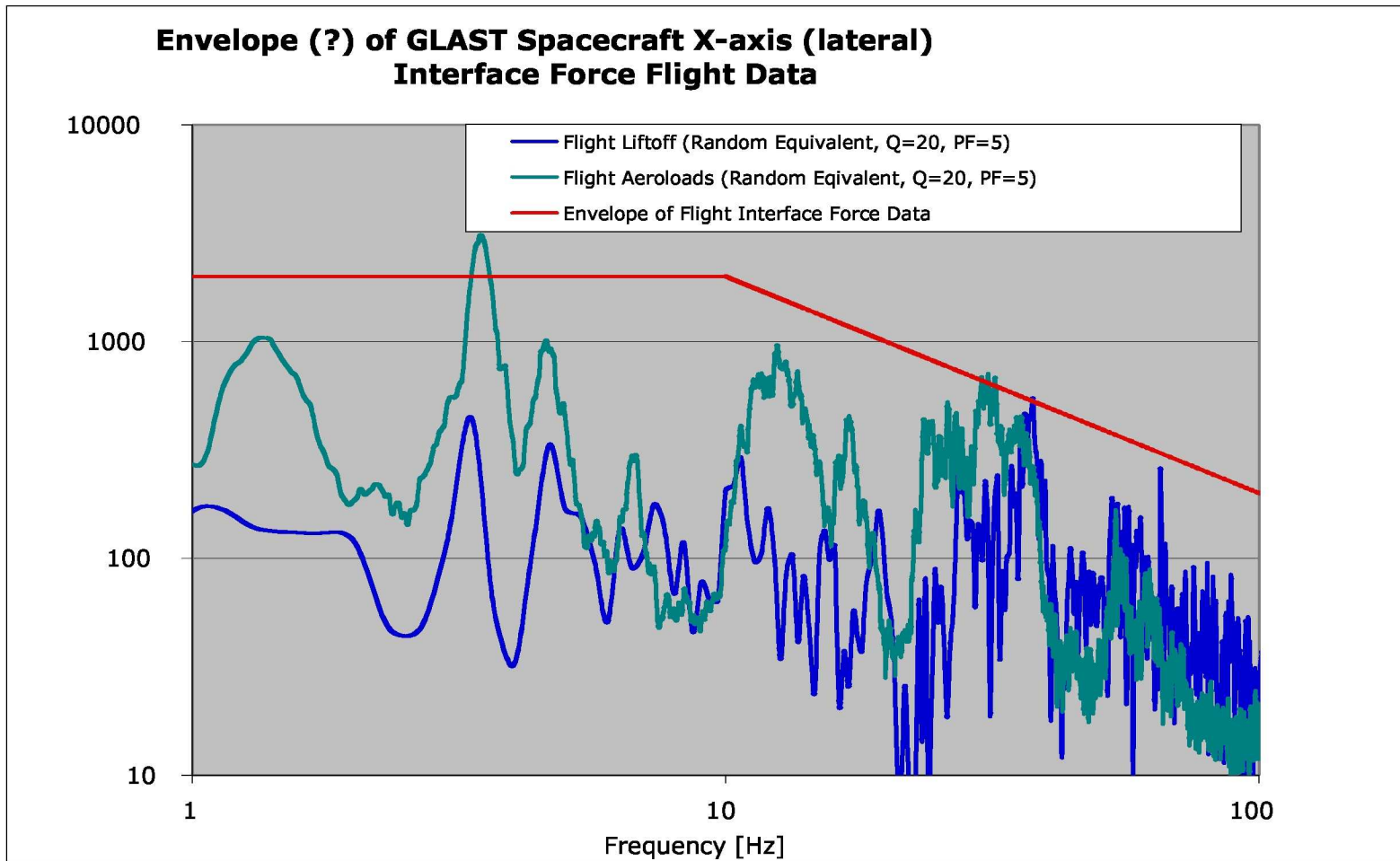- **Basedrive Force at 10 Hz S/C resonance exceeds flight force at 3.5 Hz L/V mode**
- **Basedrive force is higher than the flight force above 22 Hz, even though the acceleration envelope is below the flight acceleration**

Section IV: Use of Envelopes of Both Flight Acceleration and Force Data

- Envelope (?) of GLAST Spacecraft X-axis (lateral) Interface Force Flight Data

- Basedrive Analysis of GLAST Spacecraft X-axis Base Force Using Envelopes of Both Flight Acceleration and Force Data

- Envelope (?) of GLAST Spacecraft Z-axis (thrust) Interface Force Flight Data (backup)

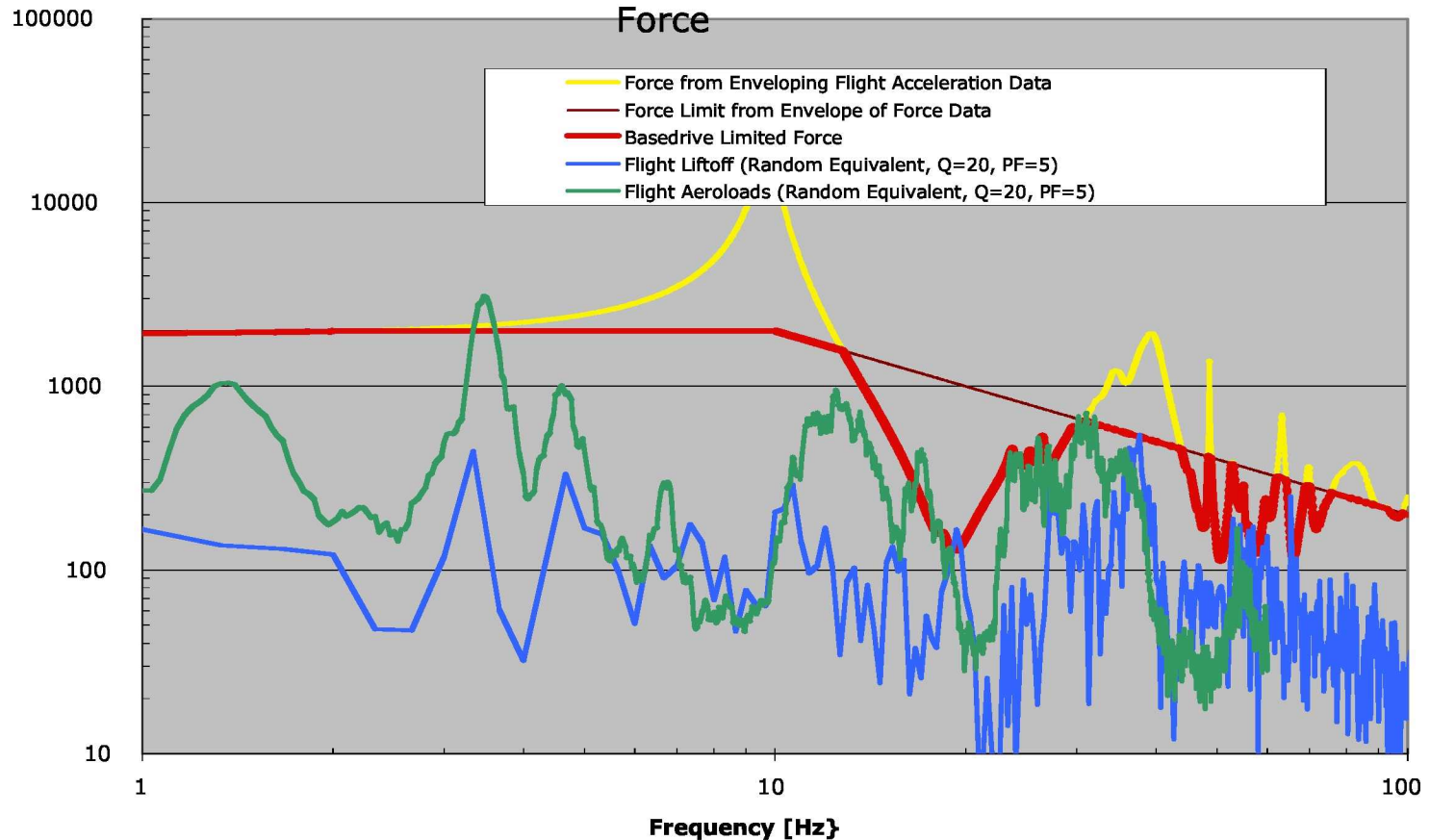- Basedrive Analysis of GLAST Spacecraft Z-axis Base Force Using Envelopes of Both Flight Acceleration and Force Data (backup)

Envelope (?) of GLAST Spacecraft X-axis (lateral) Interface Force Flight Data

Legend:
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroloads (Random Eqivalent, Q=20, PF=5)
- Envelope of Flight Interface Force Data

X-axis: Frequency [Hz]

- When deriving the force limit by enveloping flight force data, it is important to keep the envelope flat out to the fundamental resonance frequency of the new spacecraft

Basedrive Analysis of GLAST Spacecraft X-axis Base Force Using Envelopes of Flight Acceleration and Force

Legend:
- Force from Enveloping Flight Acceleration Data
- Force Limit from Envelope of Force Data
- Basedrive Limited Force
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
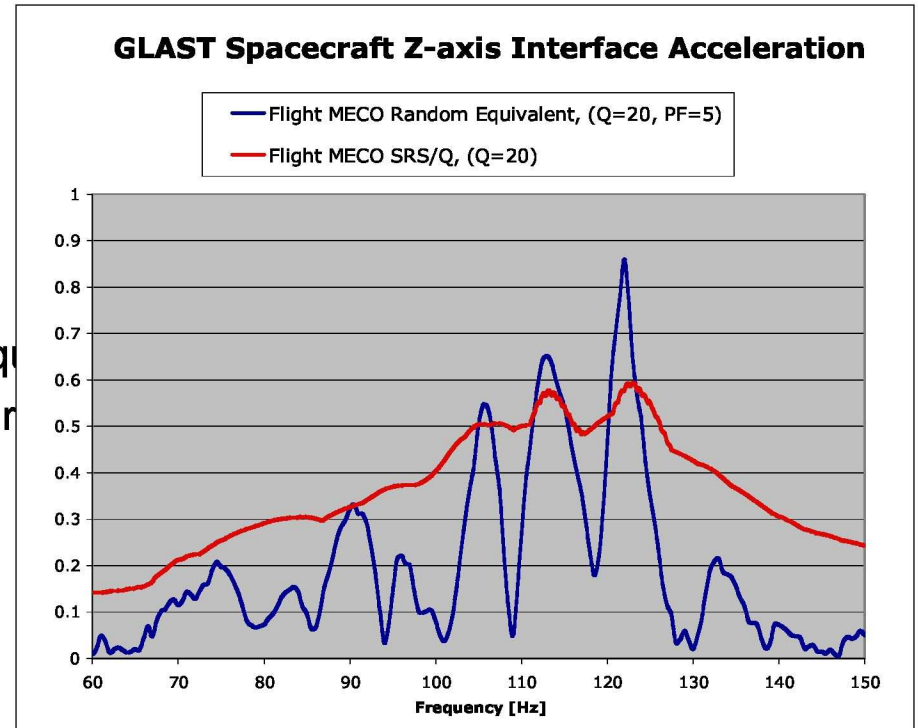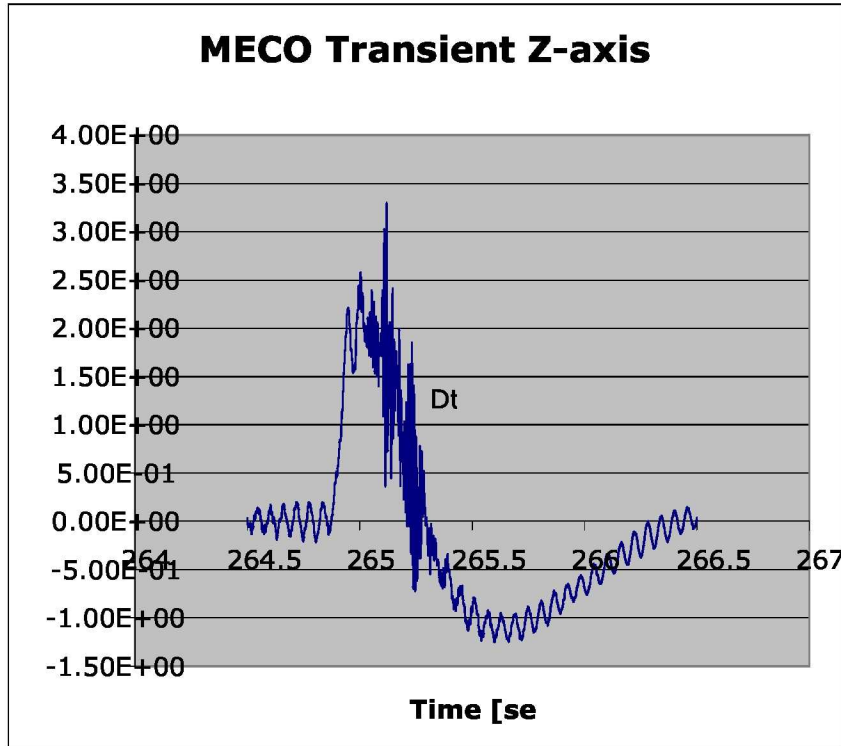- Flight Aeroloads (Random Equivalent, Q=20, PF=5)

- As one might expect, a basedrive analysis using envelopes of both the flight acceleration and forces provides a relatively accurate prediction of the flight forces

Section V: MECO Transient Analysis

- MECO Transient Z-axis (thrust) Acceleration

- MECO Transient Z-axis (thrust) Force

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MECO Transient Z-axis (thrust) Acceleration

MECO Transient Z-axis

GLAST Spacecraft Z-axis Interface Acceleration

- Flight MECO Random Equivalent, (Q=20, PF=5)
- Flight MECO SRS/Q, (Q=20)

- MECO acceleration in 60 to 150 Hz frequency regime is less than 1 G
- SRS/20 and Random Equivalent agree reasonably well from 60 to 150 Hz

MECO Transient Z-axis (thrust) Force

MECO Transient Z-ax

GLAST Spacecraft Z-axis Dynamic (total - st Base Force
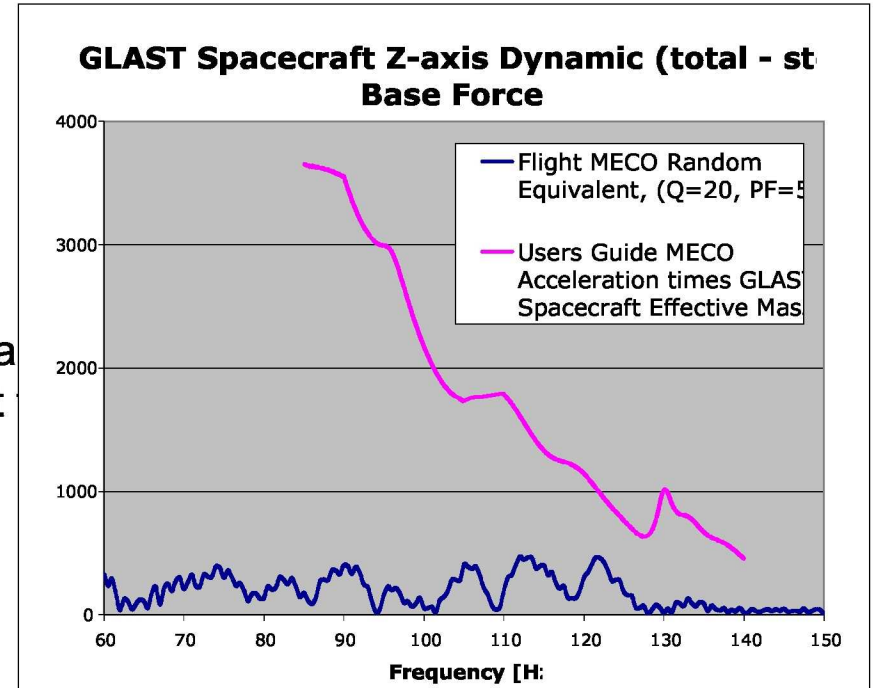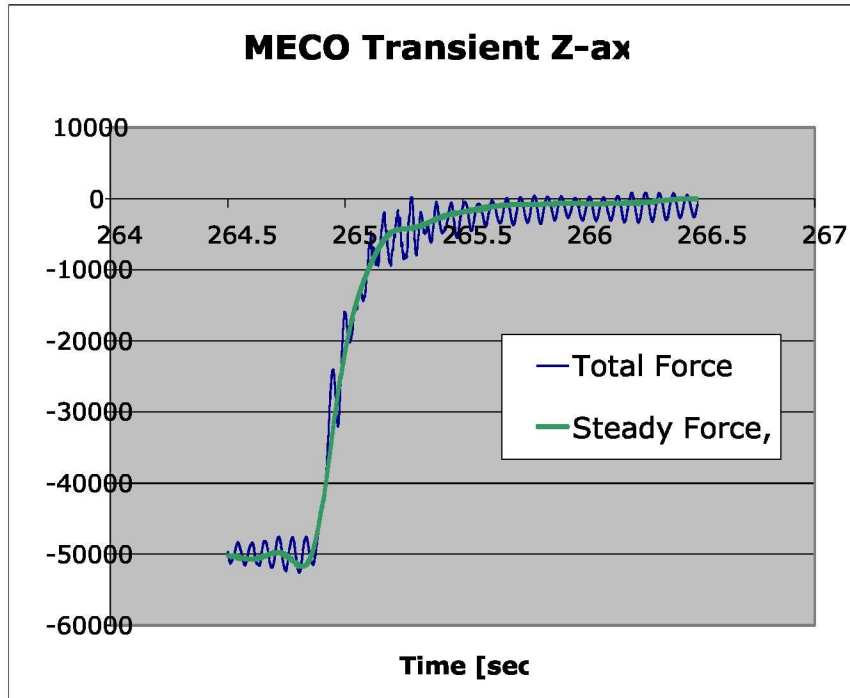
- Steady force, computed by multiplying DC acceleration by the weight of the spacecraft, was subtracted from total to get the dynamic force
- Flight force data is below force predicted with User's Guide Specification, but the latter does not include the effects of limiting and notching

Conclusions (1)

- Basedrive analyses, using envelopes of flight acceleration and force databases, have the potential to improve the prediction of spacecraft design loads

- Envelopes of flight data are preferred inputs for basedrive analyses because:
  - *Enveloping can accommodate flight-to-flight configurations changes*
  - *notches are at different frequencies in flight and fixed-base configurations.*

- When enveloping the low-frequency peaks in flight force data, it is important to extend the envelopes out to include the fundamental resonance frequencies of the new spacecraft

- FFT and most other frequency analysis methods under estimate peaks in time history, because they:
  - *average over the record length, and*
  - *don't combine responses at different frequencies.*

- SRS are not ideal for launch vehicle transient analysis because:
  - *the SRS is biased up by DC and low-frequency input, and*
  - *SRS/Q is questionable for spacecraft base forces.*

Conclusions (2)

- The base forces in the GLAST X- and Z-axis sine vibration tests were similar to those derived using generic inputs (from users guide and handbook), but the base forces in the sine test were generally greater than the flight data.

- Basedrive analyses using envelopes of flight acceleration data provided more accurate predictions of the base force than generic inputs, and as expected, using envelopes of both the flight acceleration and force provided even more accurate predictions

- The GLAST spacecraft interface accelerations and forces measured during the MECO transient were relatively low in the 60 to 150 Hz regime.

- One may expect the flight forces measured at the base of various spacecraft to be more dependent on the mass, frequencies, etc. of the spacecraft than are the corresponding interface acceleration data, which may depend more on the launch vehicle configuration

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Suggestions for Future Investigation

- **Obtain more flight force data** for a range of launch vehicle and spacecraft configurations

- **Improve methods of frequency analysis** of flight data for purpose of defining transient and sine sweep inputs for basedrive analyses and vibration tests (The PSD works well for random data.)

- **Develop methodology for enveloping** flight force data, and techniques for normalizing the data prior to enveloping and for extrapolating the data after enveloping to accommodate flight-to-flight and spacecraft variations

- Extend the study of basedrive analysis using envelopes of interface acceleration and force data to include the **calculation of spacecraft equipment responses**
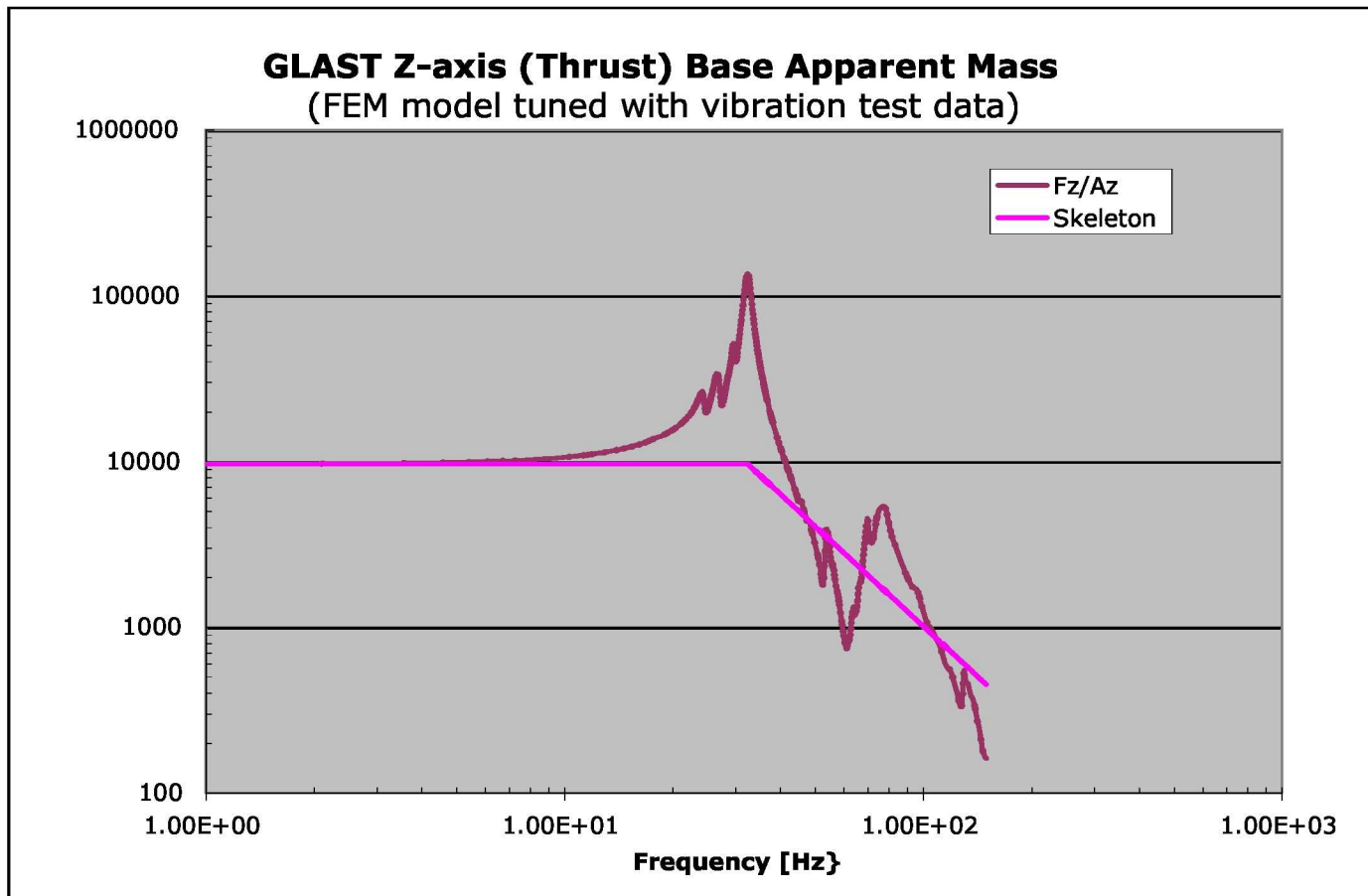
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Backup Charts

GLAST Spacecraft Z-axis (thrust) Interface Acceleration
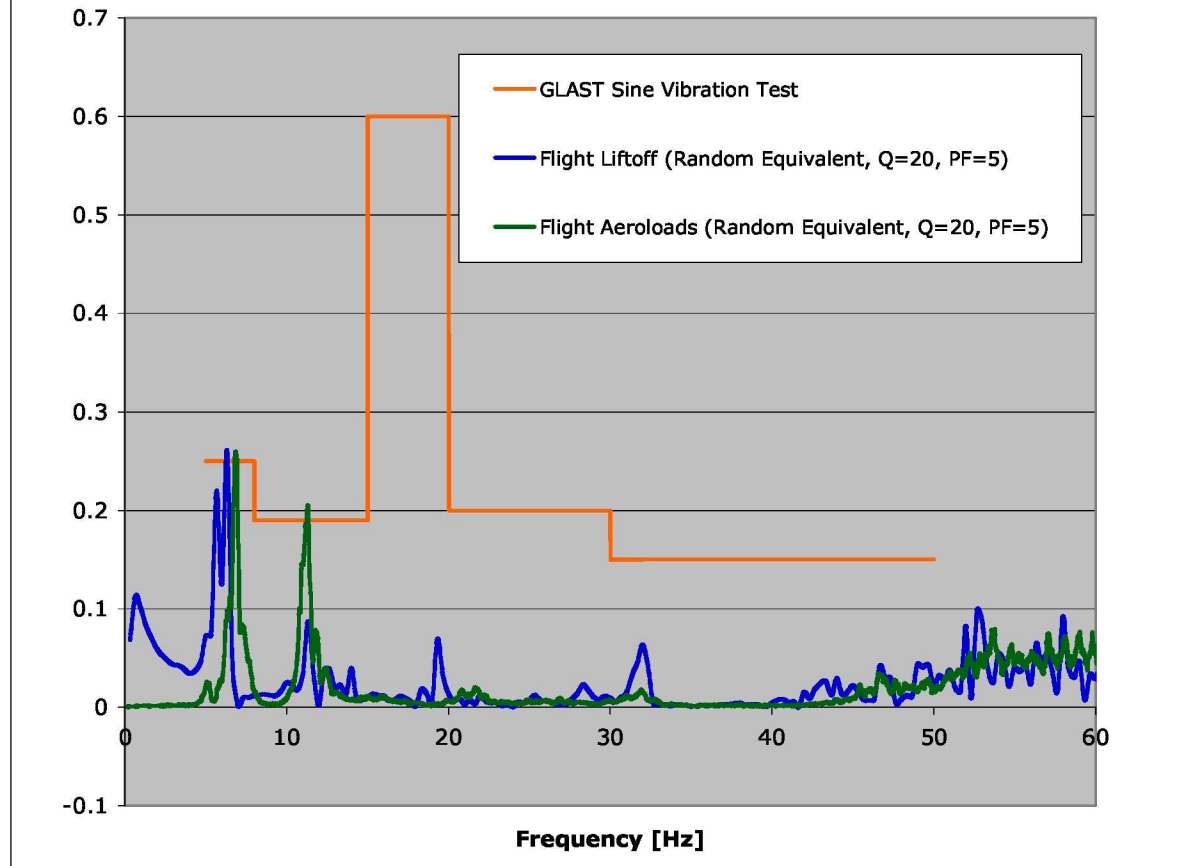
- Sine test input was, as in x-axis test, tailored with FEA to not exceed CLA
- The z-axis interface acceleration data measured for liftoff and aeroloads are generally less than the input acceleration in the GLAST sine vibration test

GLAST Z-axis (Thrust) Base Apparent Mass
(FEM model tuned with vibration test data)

- The apparent mass is used to calculate the base reaction force resulting from an acceleration input at the spacecraft base
- The skeleton is used to derive force limit specifications (NASA HDBK 7004B)

GLAST Z-axis (Thrust) Base Forces
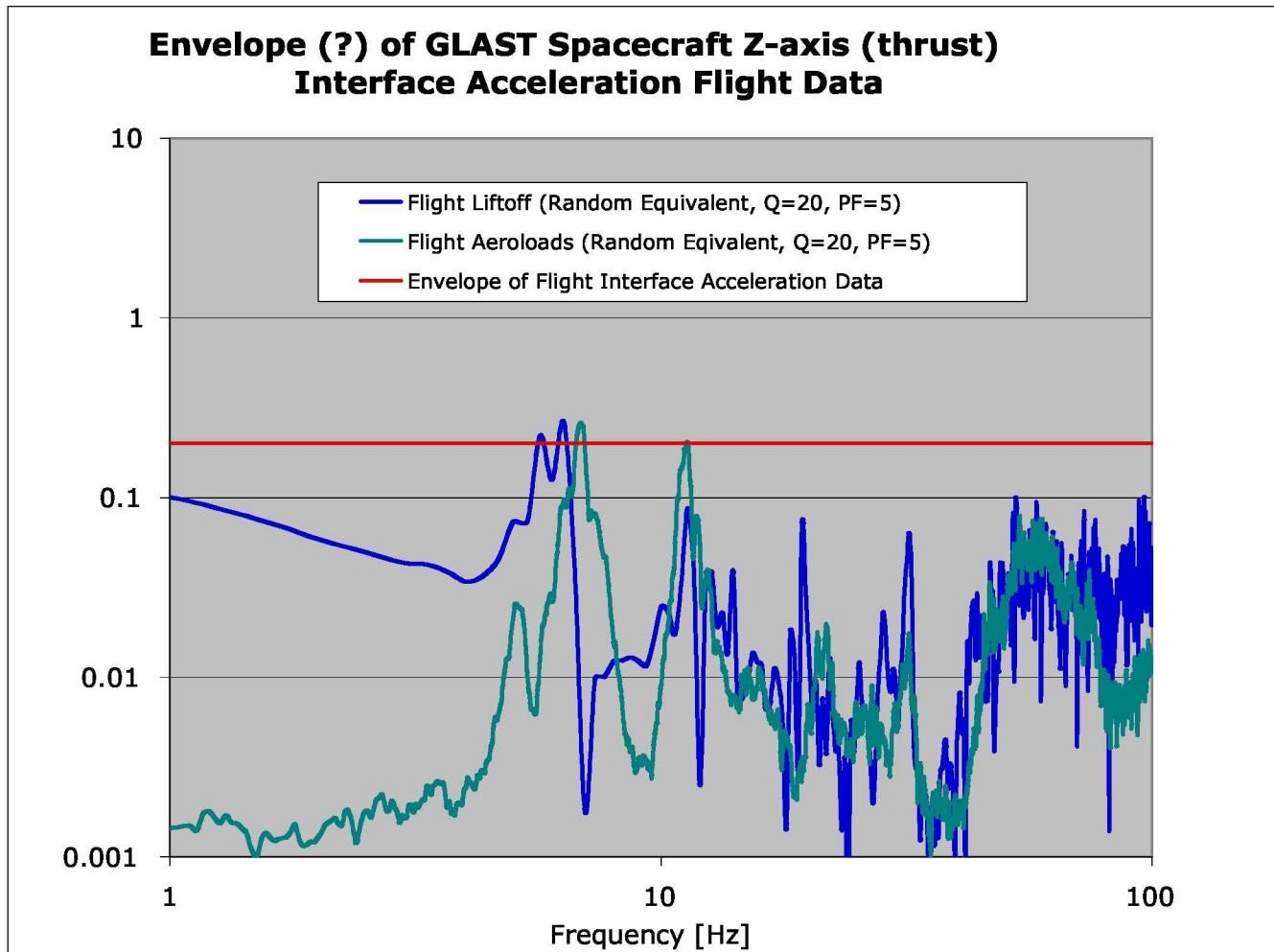(calculated by multipying input acceleration by apparent mass)

Legend:
- Delta II Users Guide Input with C=2 Force Limit (NASA HDBK 7004B)
- GLAST Full-Level Sine Test (Input Tailored with FEM Analysis)
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroload (Random Equivalent, Q=20, PF=5)

Y-axis: 0, 10000, 20000, 30000
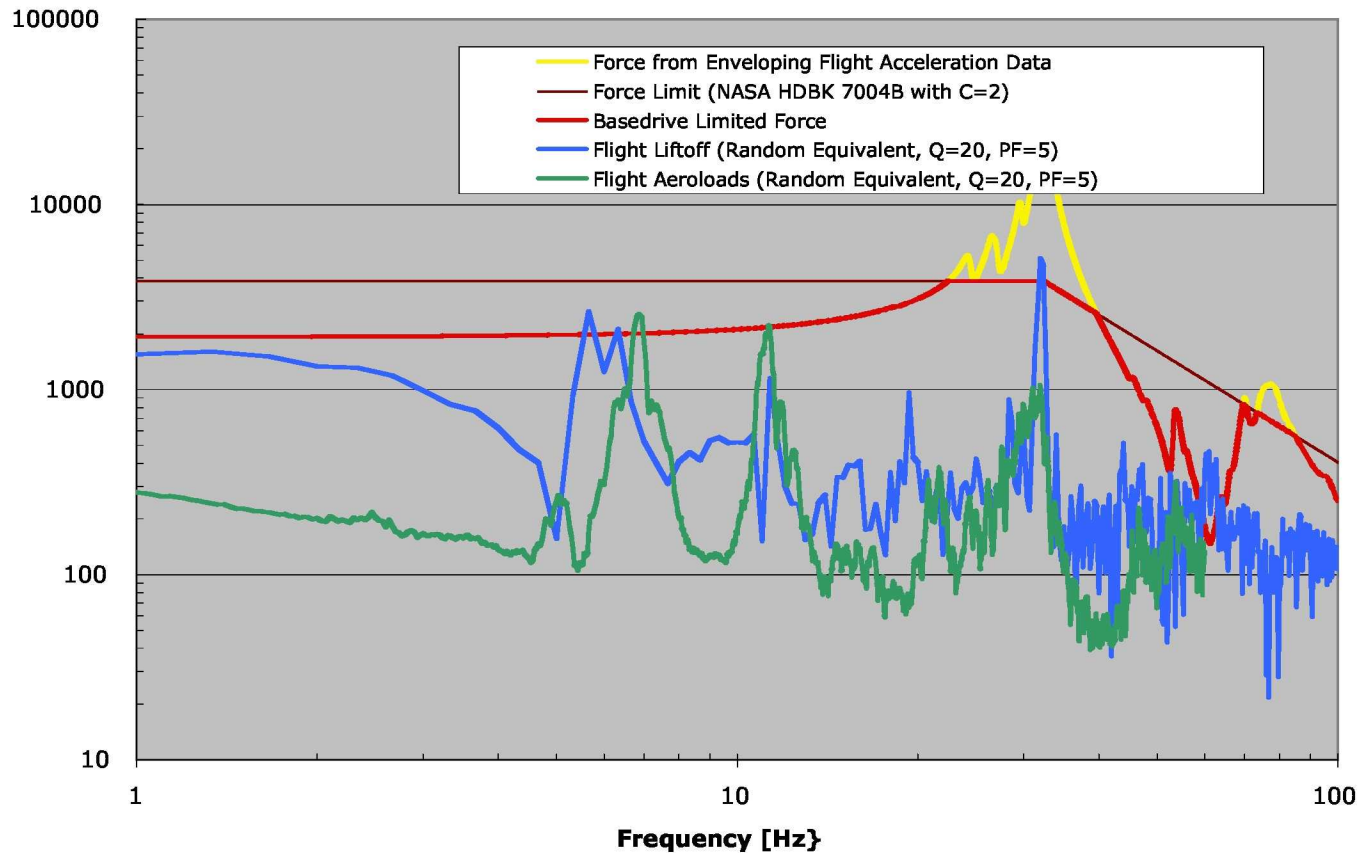X-axis: Frequency [Hz}, 0, 10, 20, 30, 40, 50, 60
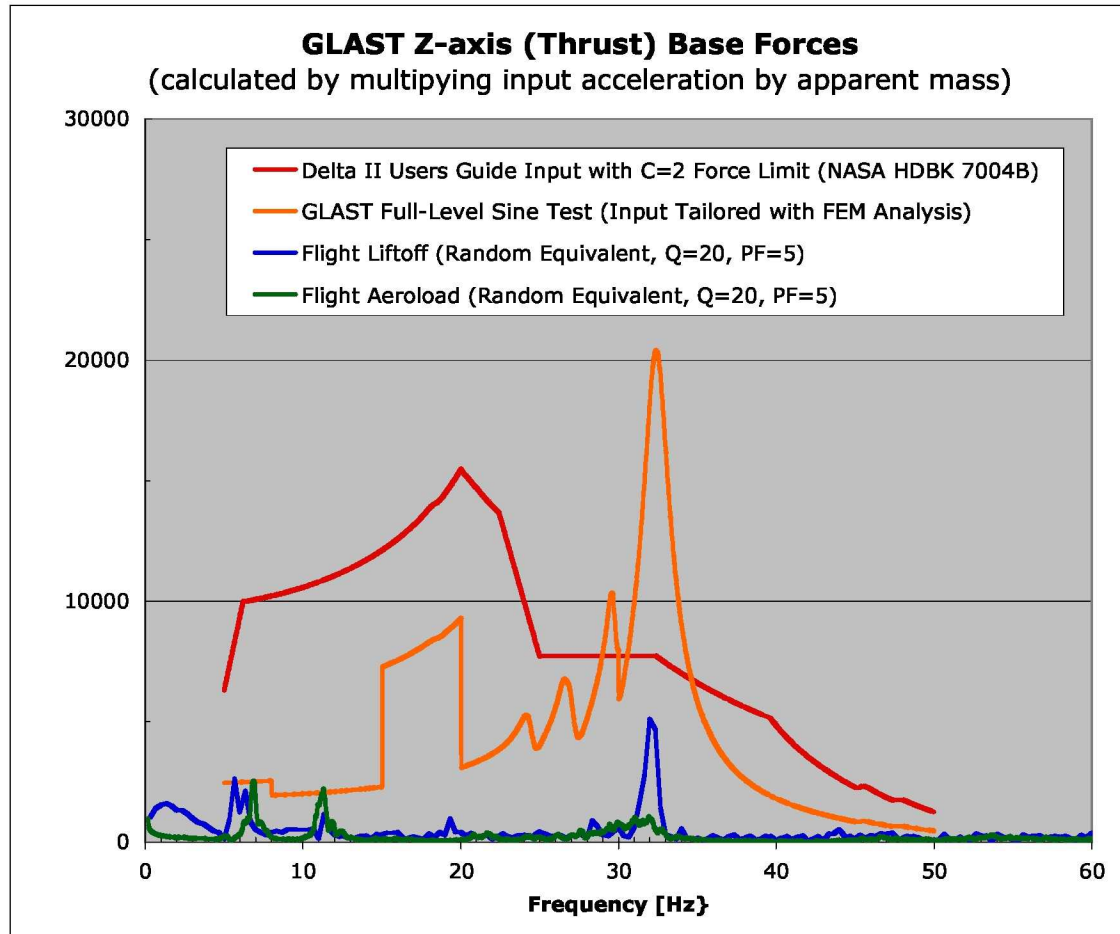
- Force derived from Users Guide and 7004B Handbook are comparable in magnitude but peak at different frequencies, which reflects large difference between launch vehicle and spacecraft axial resonance frequencies
- As in x-axis, the inflight force data are less than in the sine test

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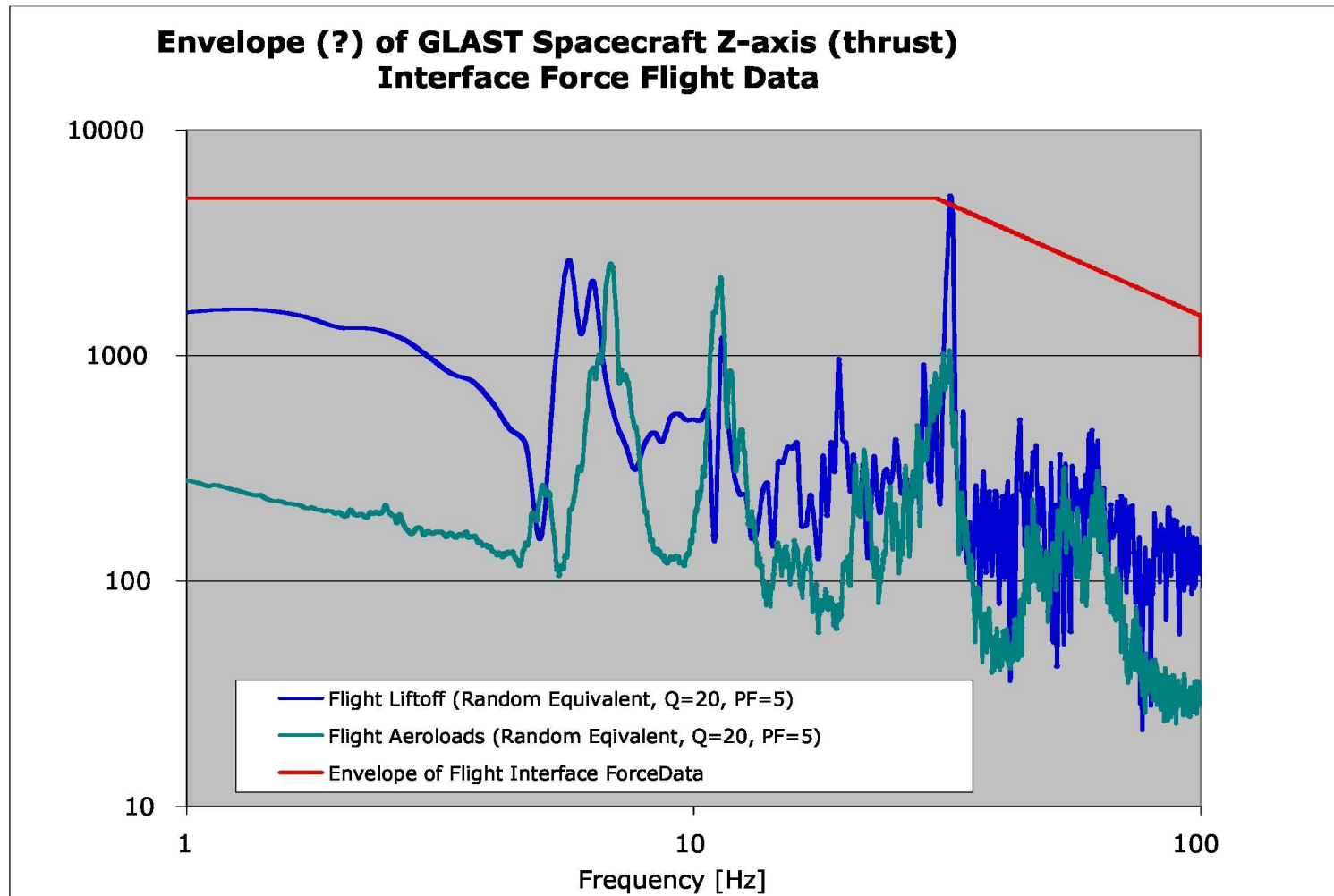Envelope (?) of GLAST Spacecraft Z-axis (thrust) Interface Acceleration Flight Data

- Crude envelope of flight acceleration data is input to basedrive model
- Envelope is over data above 10 Hz

Basedrive Analysis of GLAST Spacecraft Z-axis Base
Force Using Envelope of Flight Acceleration Data and
Force limit from NASA 7004B Handbook

Legend:
- Force from Enveloping Flight Acceleration Data
- Force Limit (NASA HDBK 7004B with C=2)
- Basedrive Limited Force
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
- Flight Aeroloads (Random Equivalent, Q=20, PF=5)

Frequency [Hz}
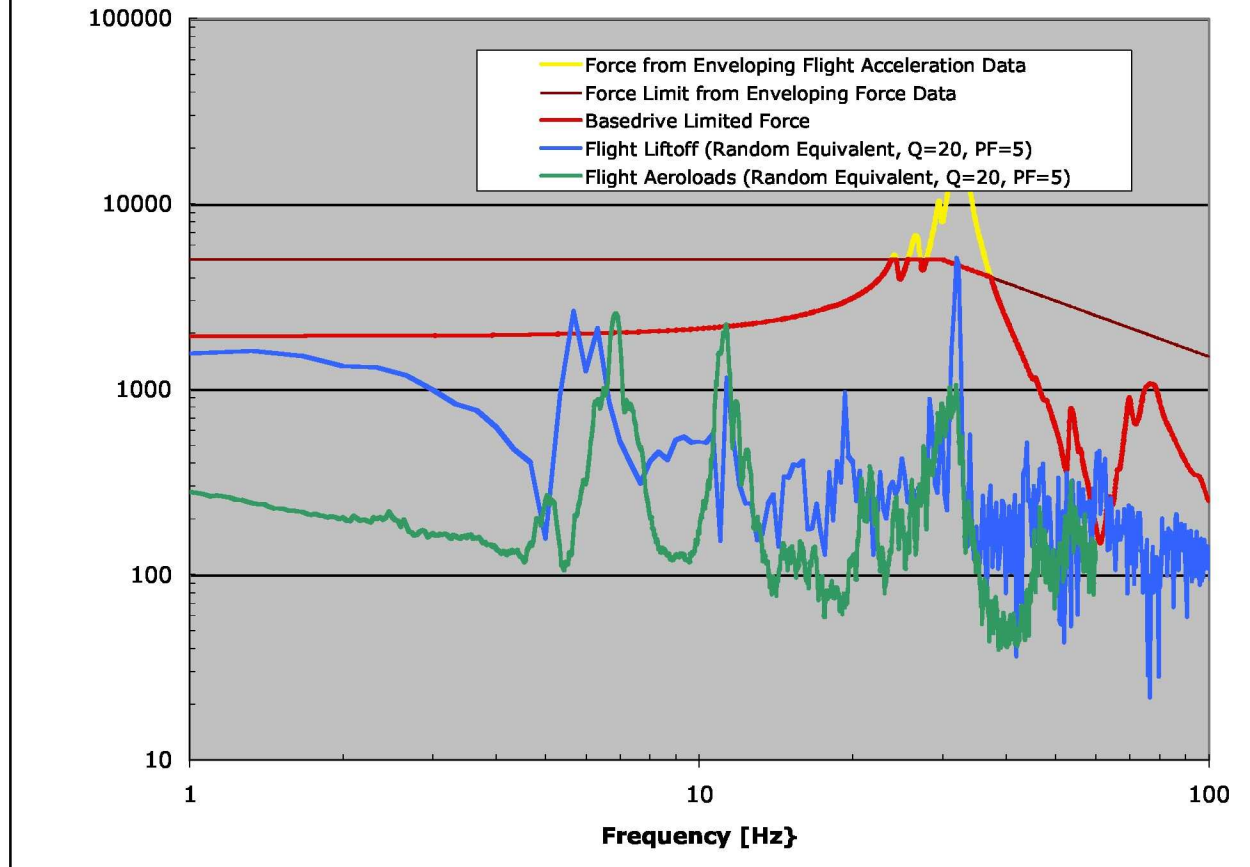
- **Basedrive force is good envelope of flight data below and at 33 Hz thrust axis resonance, but over data above 33 Hz**

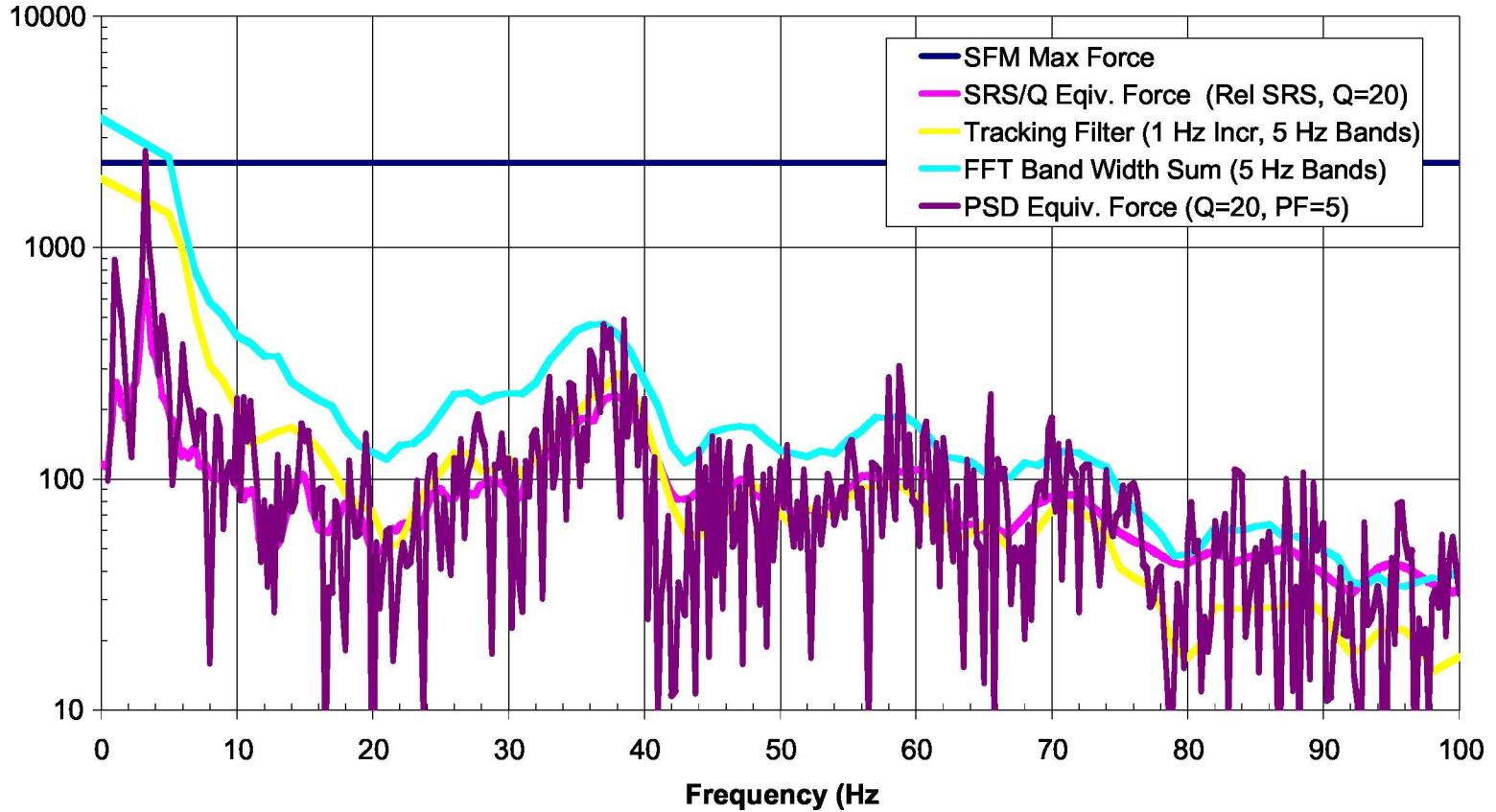Envelope (?) of GLAST Spacecraft Z-axis (thrust) Interface Force Flight Data

- When deriving the force limit by enveloping flight force data, it is important to keep the envelope flat out to the fundamental resonance frequency of the new spacecraft

Basedrive Analysis of GLAST Spacecraft Z-axis Base Force Using Envelopes of Flight Acceleration and Force

Legend:
- Force from Enveloping Flight Acceleration Data
- Force Limit from Enveloping Force Data
- Basedrive Limited Force
- Flight Liftoff (Random Equivalent, Q=20, PF=5)
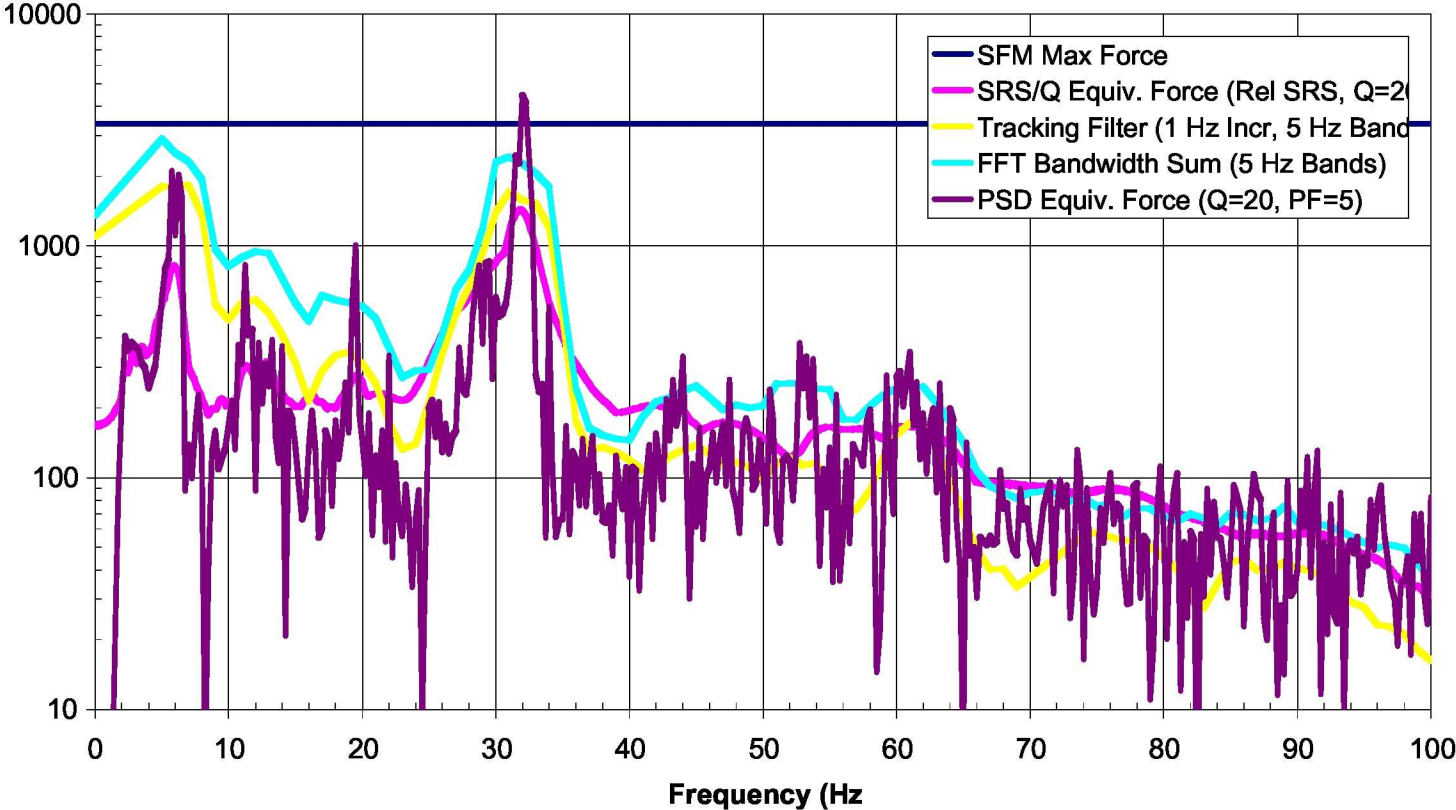- Flight Aeroloads (Random Equivalent, Q=20, PF=5)

Frequency [Hz}

- As one might expect, a basedrive analysis using envelopes of both the flight acceleration and forces provides a relatively accurate prediction of the flight forces

Liftoff Y-Axis

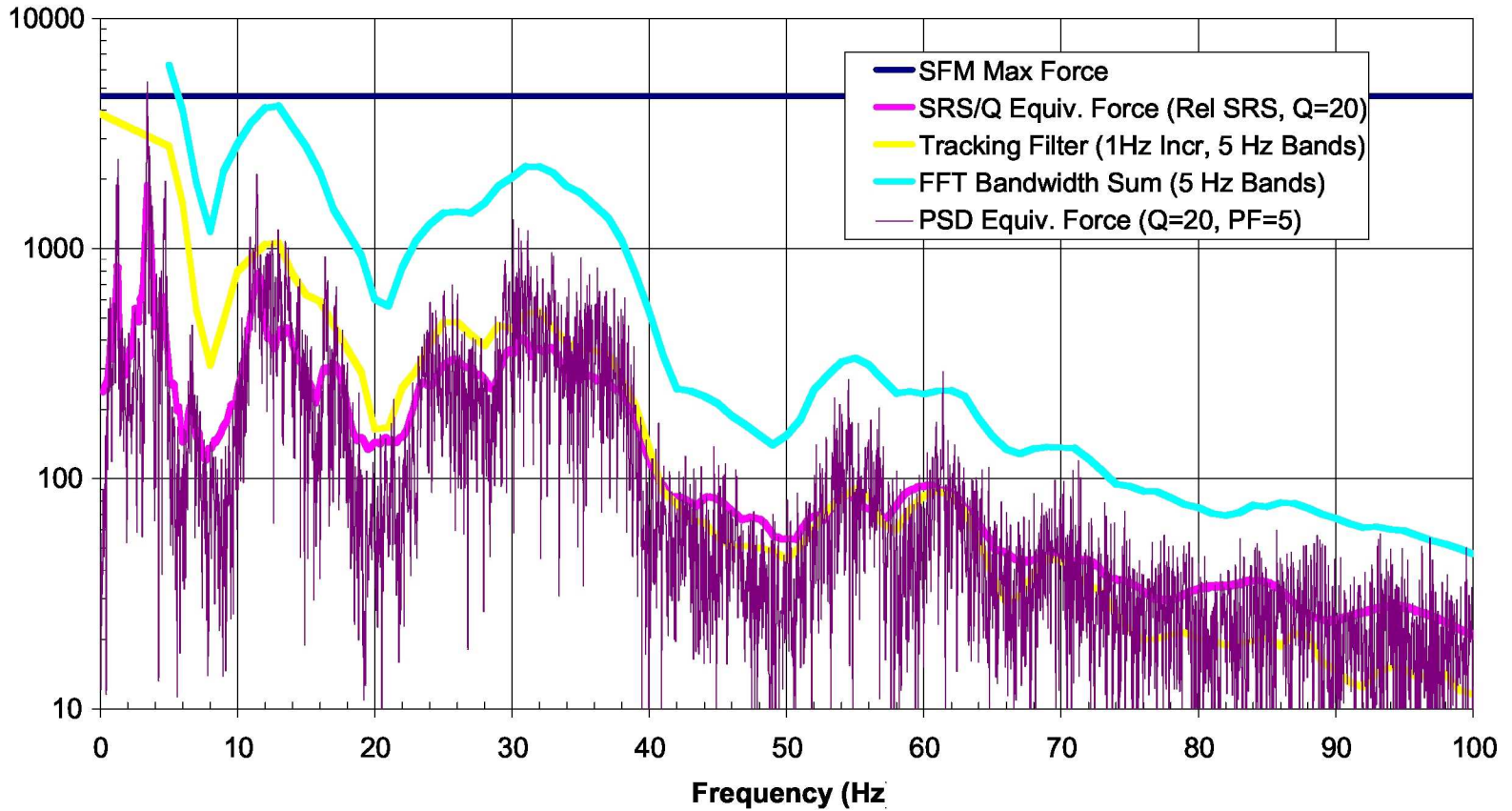

Legend:
- SFM Max Force
- SRS/Q Eqiv. Force (Rel SRS, Q=20)
- Tracking Filter (1 Hz Incr, 5 Hz Bands)
- FFT Band Width Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

X-axis: Frequency (Hz
Y-axis: 10, 100, 1000, 10000

Liftoff Z-Axis

Legend:
- SFM Max Force
- SRS/Q Equiv. Force (Rel SRS, Q=20)
- Tracking Filter (1 Hz Incr, 5 Hz Band)
- FFT Bandwidth Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

Y-axis: 10000 to 10
X-axis: Frequency (Hz), 0 to 100

Airloads X-Axis

Legend:
- SFM Max Force
- SRS/Q Equiv. Force (Rel SRS, Q=20)
- Tracking Filter (1Hz Incr, 5 Hz Bands)
- FFT Bandwidth Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

Frequency (Hz)

Airloads Y-Axis

Legend:
- SFM Max Force
- SRS/Q Equiv. Force (Rel SRS, Q=20)
- Tracking Filter (1 Hz Incr, 5 Hz Bands)
- FFT Bandwidth Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

Frequency (Hz)

Airloads Z-Axis

Legend:
- SFM Max Force
- SRS/Q Equiv. Force (Rel SRS, Q=20
- Tracking Filter (1 Hz Incr, 5 Hz Bands
- FFT Bandwidth Sum (5 Hz Bands)
- PSD Equiv. Force (Q=20, PF=5)

X-axis: Frequency (Hz

GLAST Spacecraft Base X-axis (lateral) Apparent Mass
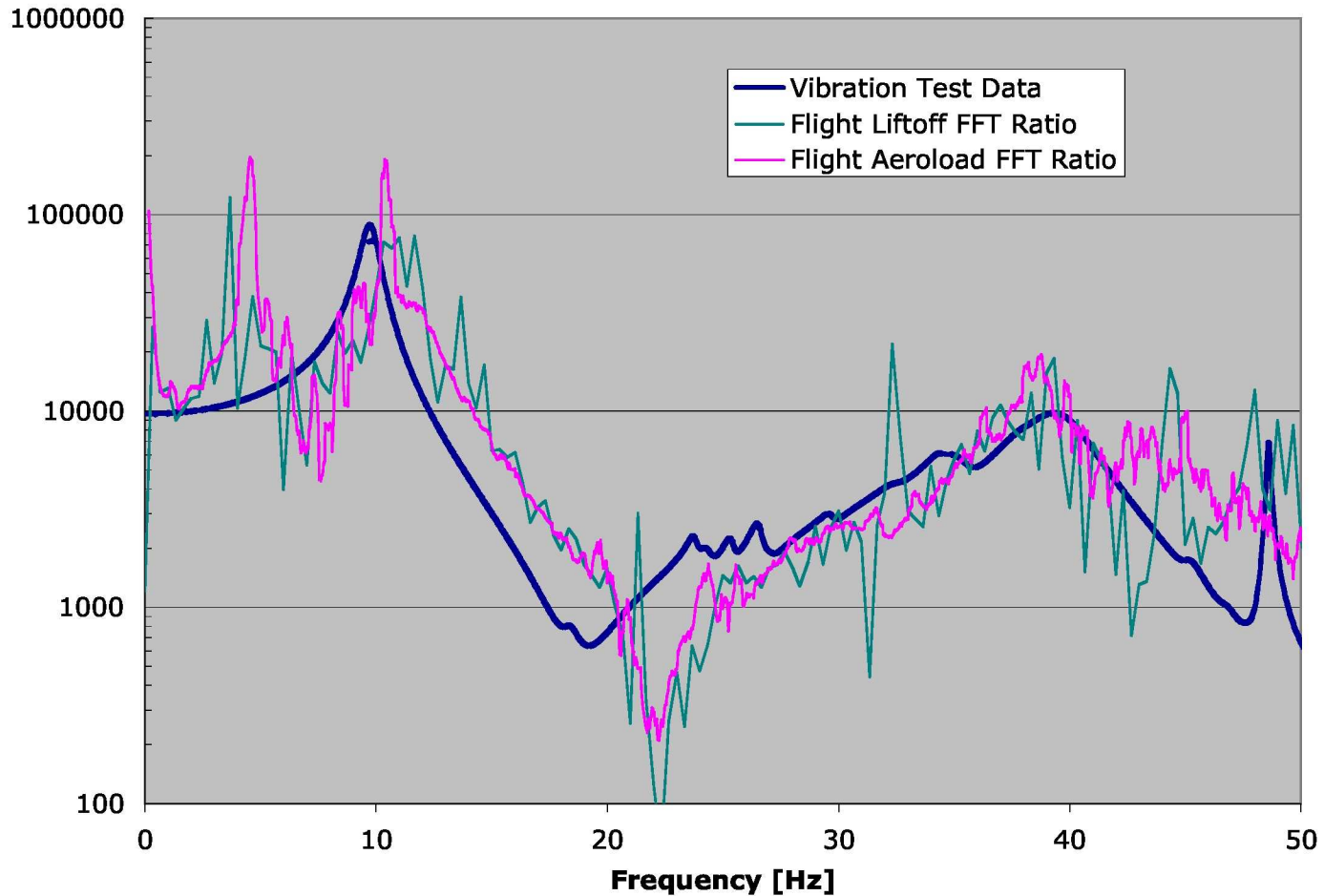
GLAST Spacecraft Base Z-axis (thrust) Apparent Mass

Legend:
- Vibration Test Data
- Flight Liftoff FFT Ratio
- Flight Aeroload FFT Ratio
- Flight MECO FFT Ratio

Frequency [Hz]