Force Measurement on the GLAST Delta II Flight

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301-286-9940

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JPL

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Agenda

- Flight Force Measurement (FFM) Background
- Team Members
- GLAST Mission Overview
- Methodology Development
- Ground Test Validation
- Flight Data
- Coupled Loads Simulation (VCLA & Reconstruction)
- Basedrive Simulation
- Findings
- Summary and Conclusions

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Flight Force Measurement - Background

- Purpose: To measure interface forces at the spacecraft separation plane during the launch of the GLAST spacecraft
- Method: Mount strain gages on Delta II 6915 Payload Adapter Fitting (PAF)
- Calibrate instrumented PAF during dynamic and static ground testing
- Goals
  - *Develop and validate strain based methods for measuring interface forces*
  - *Develop special flight instrumentation (SFI) package for the GLAST flight*
  - *Acquire strain and acceleration measurements during flight*
  - *Perform post-flight data processing and evaluation*
- From the NESC Proposal: "This work attempts to address two critical technical questions:
  - *Is flight correlation and reconstruction with acceleration measurements sufficient?*
  - *How much can the loads and therefore design/qualification requirements be reduced by having force measurements?"*

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FFM Background (Cont.)

- NESC call for discipline enhancing proposals – June 2006
- Proposal accepted by NESC – October 2006
- Methodology development – October 2006 – Sept 2007
- Ground Testing w/ TPAF – Sept 2007 through July 2008
- SFI CDR – January 2008
- Installation of instrumentation on flight PAF – April 2008
- GLAST Flight – June 2008
- Data Processing – July 2008 to Present
- Final NESC Report – July 2009 (projected)

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Team Members

Name	Position/TDT Affiliation	Center/Contractor
Core Team		
Daniel Kaufman	Lead/Ground Testing and Analysis	GSFC
Curtis Larsen	NASA Technical Fellow for Loads and Dynamics	JSC
Scott Gordon	Lead/Ground Testing and Analysis	GSFC
Dan Worth	Dynamic Testing	GSFC
Isam Yunis[1]	Flight Implementation and Analysis	KSC
Chris Gerace	Flight Implementation and Analysis	KSC
Teresa Kinney	Flight Implementation and Analysis	KSC
Paul Rapacz	Analysis	JPL
Dennis Kern	Ground Testing and Analysis	JPL
William Haile	Analysis and Test	ATK
Michael Fendya[3]	Analysis and Test	ATK
Ayman Abdallah[2]	Flight Implementation and Analysis	KSC
Timothy Fogarty	Flight Implementation and Analysis	Analex Corporation
Terry Scharton	Consultant	JPL (Retired)
Administrative Support		
Chris Johansen	MTSO Program Analyst	LaRC
Linda Burgess	Planning and Control Analyst	ATK, LaRC
Pam Sparks	Project Coordinator	ATK, LaRC
Tina Dunn[4]	Project Coordinator	ATK, LaRC
Christina Cooper	Technical Writer	ATK, LaRC

1. Isam Yunis (KSC) moved to LaRC in 2007 leaving Chris Gerace as KSC lead for the effort.
2. Ayman Abdallah (KSC) was added to the Core Team list in 2008
3. Mike Fendya (ATK) was added to the Core team in 2007 to mid 2008 when he left ATK.
4. Pam Sparks replaced Tina Marie Dunn as Project Coordinator in 2008

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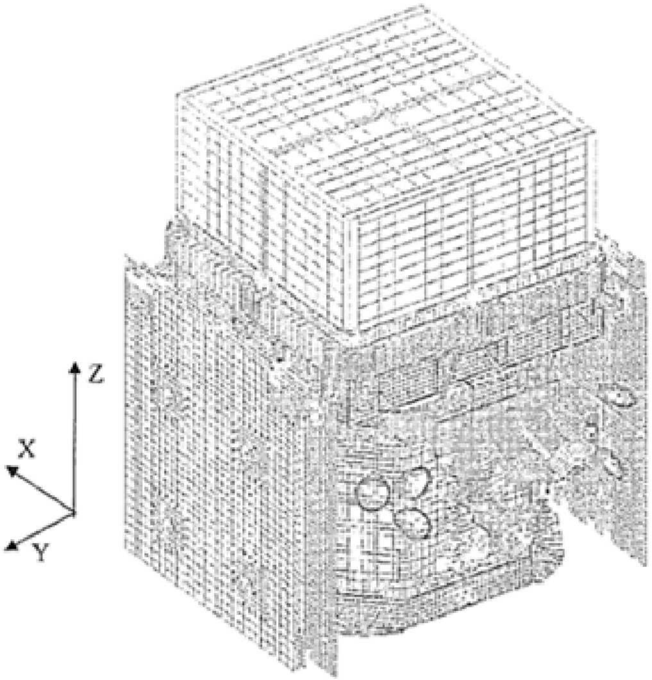
GLAST Spacecraft



- Gamma-Ray Large Area Space Telescope (GLAST)
- Joint DOE and NASA Mission
- High-energy gamma-ray observatory designed for making observations of celestial gamma-ray sources
- Total Launch Weight Including PAF = 9646 lbs

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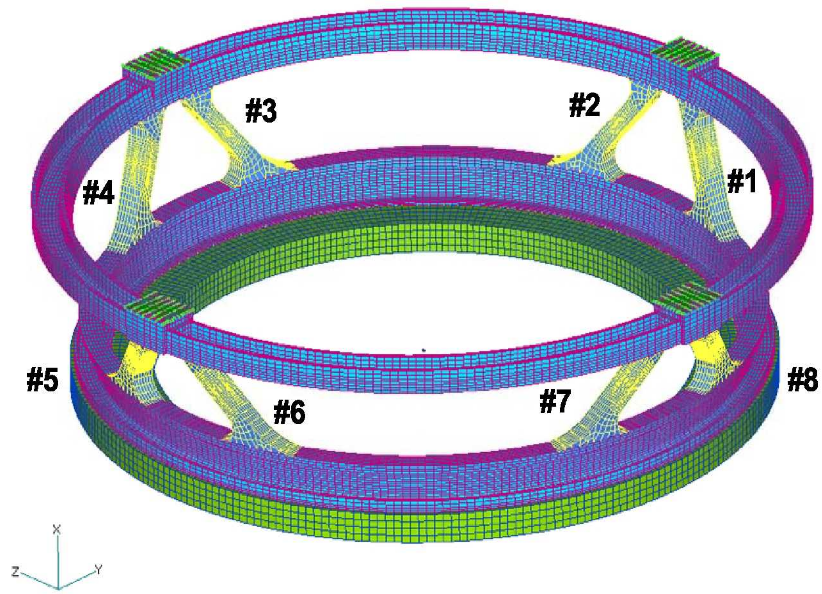
6915 Payload Adapter Fitting (PAF)



- Diameter at separation plane = 69", Overall height = 15"
- Spacecraft attaches at 4 mounting locations with explosive bolts
- Truss type PAF = 4 legs = 8 struts
- Overall weight = 190 lbs

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FFM Methodology

- Two methods were developed to convert strain to force at the separation plane
  - *Finite element method (FEM) which relies on the stiffness matrix of the PAF model to relate measured strain to force*
  - *Summed Force Method (SFM) which resolves the strains into strut forces and then uses the PAF geometry to sum the forces at the separation plane*

- **FEM Method**

$$\underset{(6xt)}{[F_o]} = \underset{(6x24)}{[R_p]^T}\underset{(24x24)}{[K_{pp}]}\underset{(24x64)}{[G_p]^{-1}}\ \underset{(64xt)}{[\varepsilon(t)]}$$

Where

$[G_p]$ = displacement to strain transform ($[\delta_p]=[G_p][\varepsilon]$)

$[K_{pp}]$ = PAF stiffness matrix

$[R_p]$ = Rigid body transform to calculate centerline force

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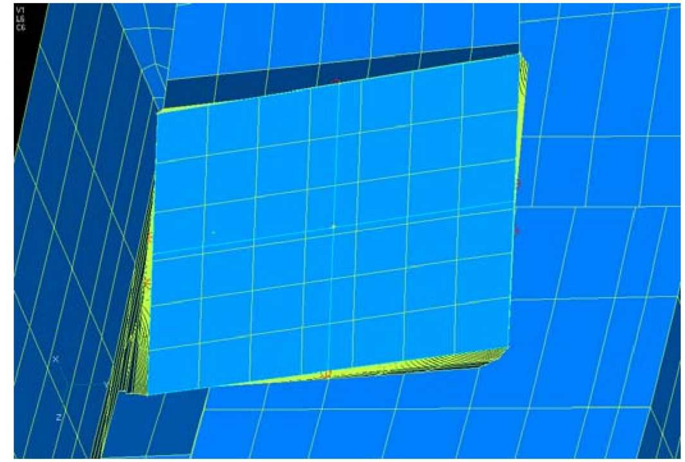
FFM Methodology - Cont

Cross-Section of Strut Geometry



- <u>Summed Force Method (SFM)</u>

$$[F_o] = [S] \quad [C]^{-1} \, [\varepsilon(t)]$$

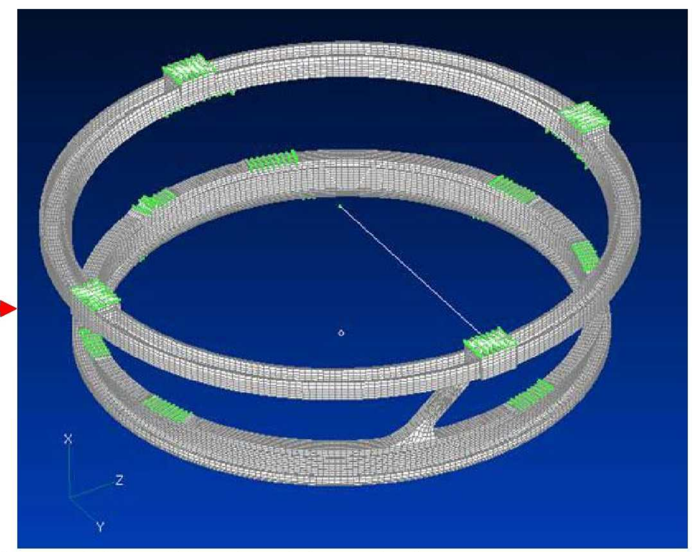
(6xt) (6x48) (48x64) (64xt)

Where

[C] = Strain to strut Force Transform ($[\varepsilon]=[C]*[F]$)

[S] = Summing matrix based on PAF geometry

Single Strut PAF Model Used to Derive Coefficients of Matrix C



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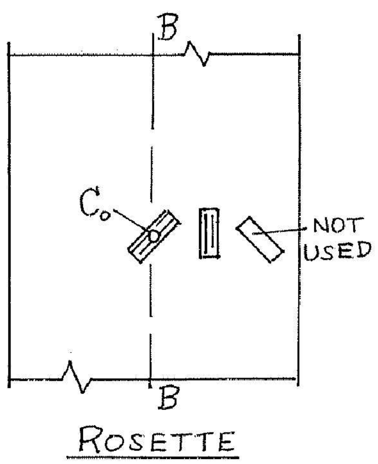
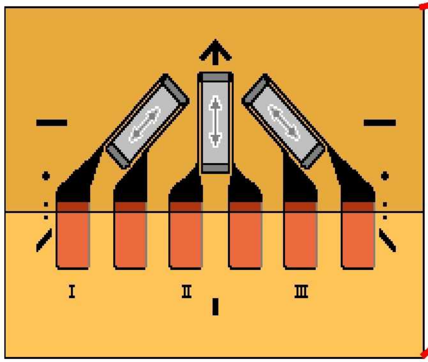
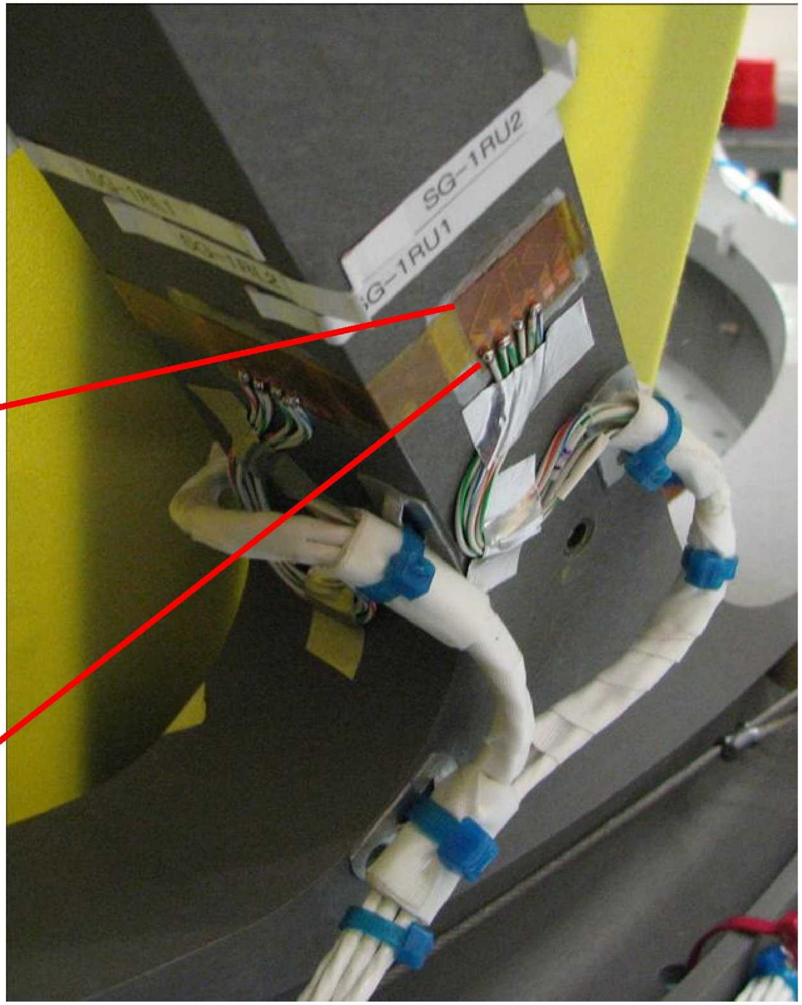
Strain Gages and Placement

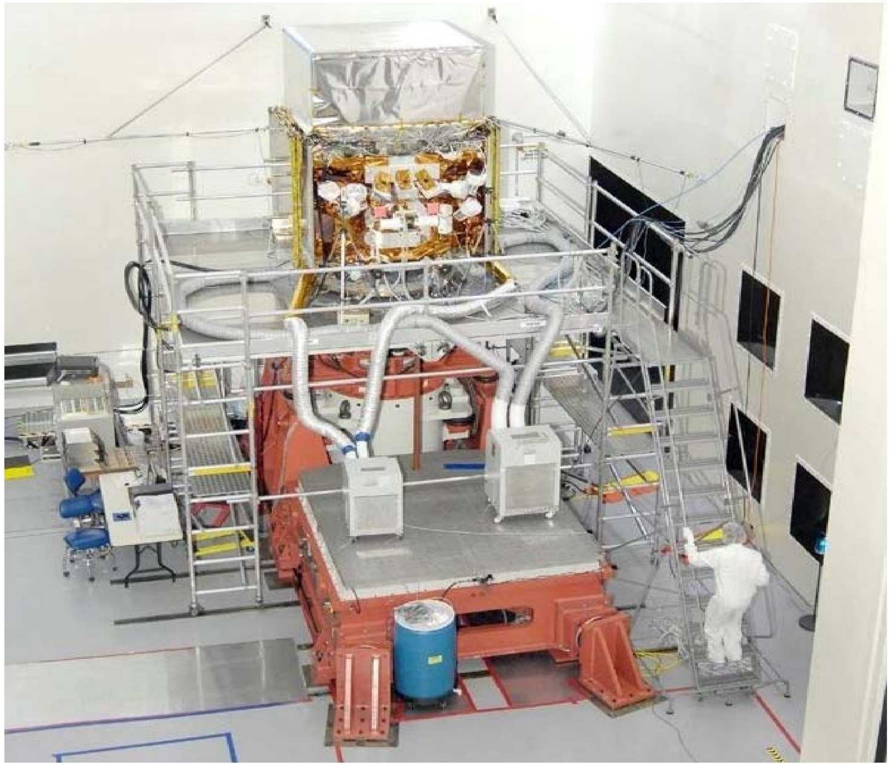
- 64 strain gages (8 per leg) = 32 Rosettes
- Type: Rosette Vishay CEA-13-250UR-35
- Only 45-degree (I) and axial (II) gages used from the rosette
- Gage placed at middle of strut
- 45-degree gage at centerline and axial parallel to strut long axis but slightly offset from centerline



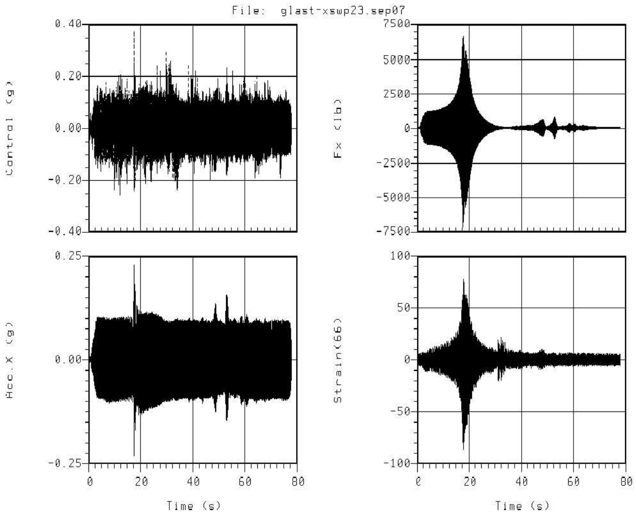




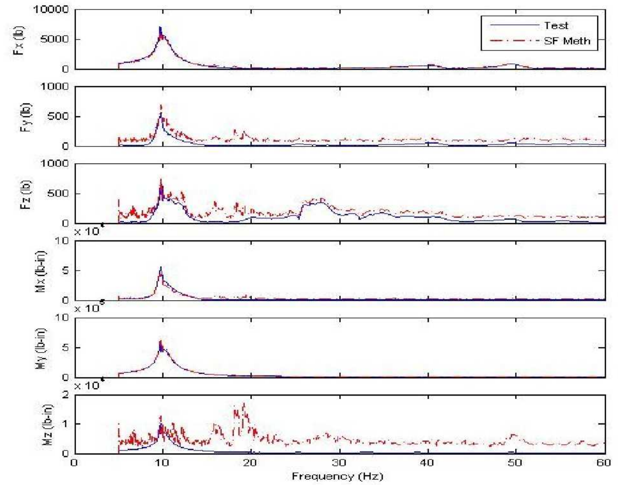
GLAST Sine Vibration Testing



Sine Vibe Test Data

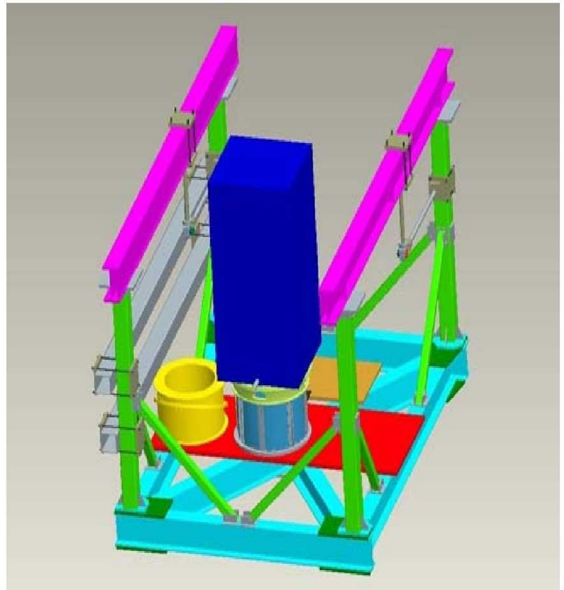


Test Forces vs SFM Results



- GLAST sine test performed – September 2007
- Instrumented TPAF along with force gauges
- Demonstrated ability to predict dynamic forces at the spacecraft interface with PAF

Ground Testing - Static



- Static testing performed using test PAF plus XTE spacecraft Simulator
- Spacecraft Simulator used as load application fixture
- Several loading conditions applied
- Testing performed on rigid fixture and flexible cylinder to understand impact of boundary conditions

TPAF Static Test Load Cases

Test Run	Load Axis	Load Point	Approx. Max Pull (lb)	Max at PAF-XTE I/F Mx (in-lb)	My, Mz (in-lb)	Max Strain Ax. (μ)	Shear (μ)	Notes
1/1A	Axial +X +X	 8159 8160	 +7200 +7200	0	99,200	**185**	89	XTE weight = 5157 lb
2	Bending +X -X	 8159 8160	 +4500 -4500	0	**384,700**	150	69	
3	Axial -X -X	 8159 8160	 **-6000** **-6000**	0	82,700	154	74	XTE weight = 5157 lb
3A/B	Axial/ Bending -X	 8159	 -6000	0	256,500	185	92	3B uses 1/4" strain gages
4	Bending -X +X	 8159 8160	 -4500 +4500	0	**384,700**	150	69	
5	Shear +Y +Y	 8159 8160	 **+3000** **+3000**	0	123,750	121	49	
5A/B	Shear/ Torsion +Y	 8159	 +3000	128,250	20,700	95	63	5B uses 1/4" strain gages
6	Torsion +Y -Y	 8159 8160	 +540 -540	**46,200**	0	15	6	50% rule ignored b/c of low level
7	Shear -Y -Y	 8159 8160	 **-3000** **-3000**	0	123,750	126	49	
8	Torsion -Y +Y	 8159 8160	 -540 +540	**46,200**	0	15	6	50% rule ignored b/c of low level
9	Combo +X +X +Y +Y	 8159 8160 8159 8160	 5570 1286 1428 1428	0	183,200	**185**	67	Combine runs 1,2,5 scaled down x 0.476
10	Combo -X -X -Y -Y	 8159 8160 8159 8160	 -5260 -750 -1500 -1500	0	-192,600	**184**	66	Combine runs 3,4,7 scaled down x 0.501

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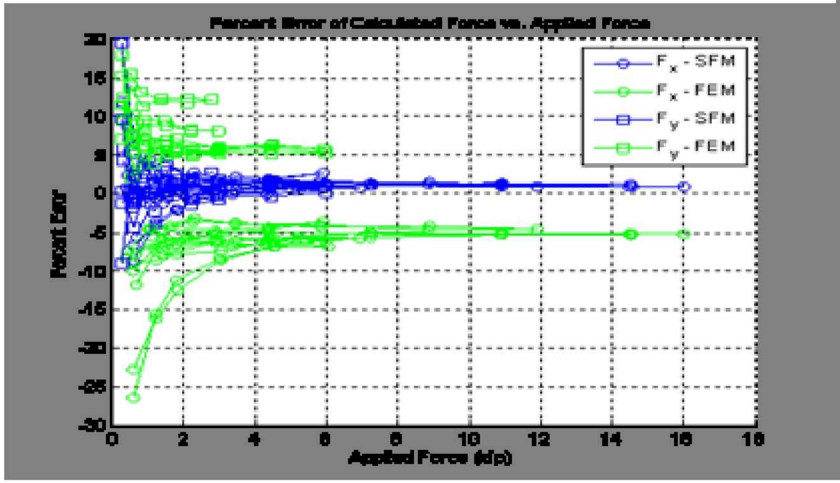
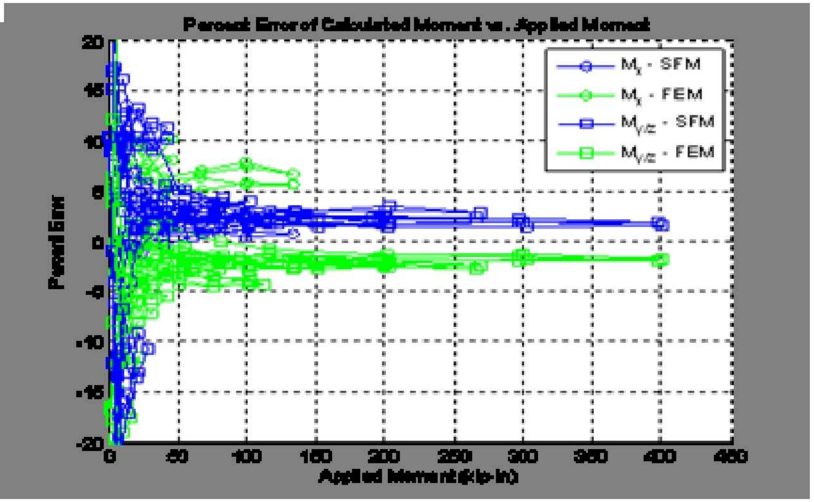
Ground Testing (Cont.)



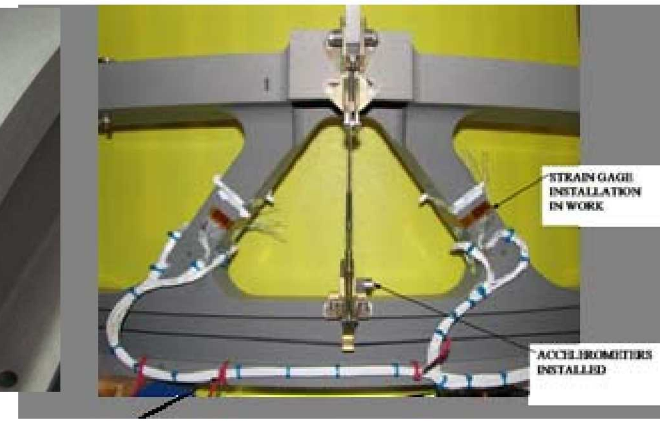


- Percent Error calculated as function of applied force based on static test measurement
- Goal was to be able to calculate forces within 10%
- Table at right shows the guidelines developed based on static testing

	Maximum Desired Error	Min. Predicted Force		Min. Predicted Moment		Method of Solution
		Axial (lb)	Lateral (lb)	Bending (lb-in)	Torsion (lb-in)	
On a Rigid Base	10%	500 500	500 2800	25,000 25,000	25,000 30,000	SFM FEM
	5%	800 11,000	800 6000	40,000 45,000	30,000 50,000	SFM FEM
On a Flexible Base	10%	500 3500	500 4000	45,000 45,000	15,000 30,000	SFM FEM
	5%	2500 N.A.	1800 N.A.	45,000 70,000	20,000 N.A.	SFM FEM

GLAST Special Flight Instrumentation (SFI)

- Strain Gage Info
  - Number: 64 gages (32 Rosettes)
  - Type: Rosette Vishay CEA-13-250UR-350
  - Range: +/-2400 $\mu\varepsilon$
  - Resolution: 2400/212-1 = 1.2 $\mu\varepsilon$ from 12 bit words in the flight data downlink
  - Filtering: DC coupled, 250 Hz Cutoff
- Accelerometer Info
  - 12 Accelerometers (4 Tri-Axial)
  - Mounted to base ring of PAF
  - Aligned to thrust, tangential, and radial axes of vehicle
  - Filtering: AC Coupled, 250 Hz Cutoff
- Sample Rate = 1000 Hz
- Data telemetered to ground stations during flight



GLAST Flight Overview

- GLAST Mission (Delta 333) launched June 11, 2008
- Launch from CCAFS (SLC 17B)
- Delta II 7920H-10C
- First flight of the Delta II heavy configuration with the 10’ composite fairing
- “All dynamic environments were normal and similar to previous comparable Delta II missions” – ULA Post-Flight Report

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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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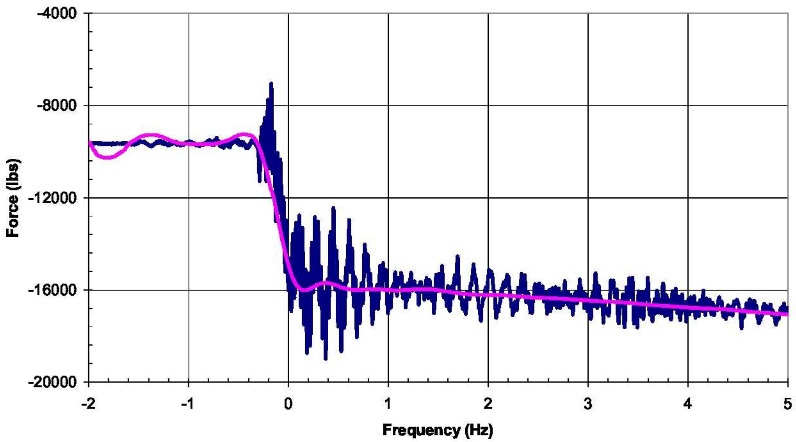
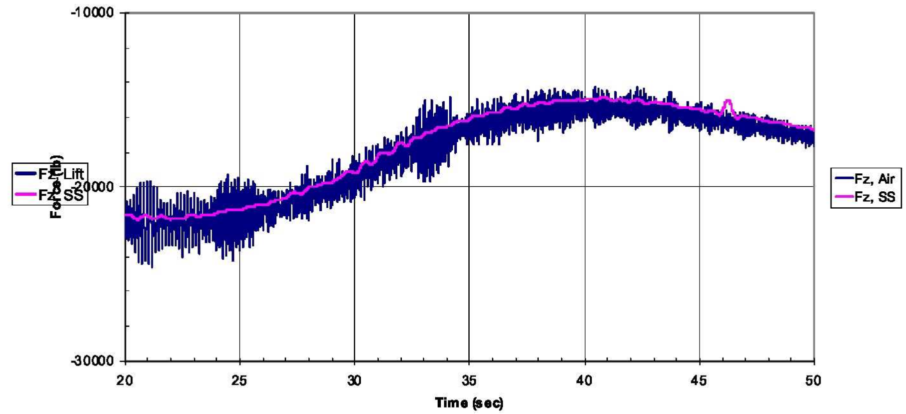
Flight Data (Liftoff, Airloads, MECO)

Liftoff Thrust Forces

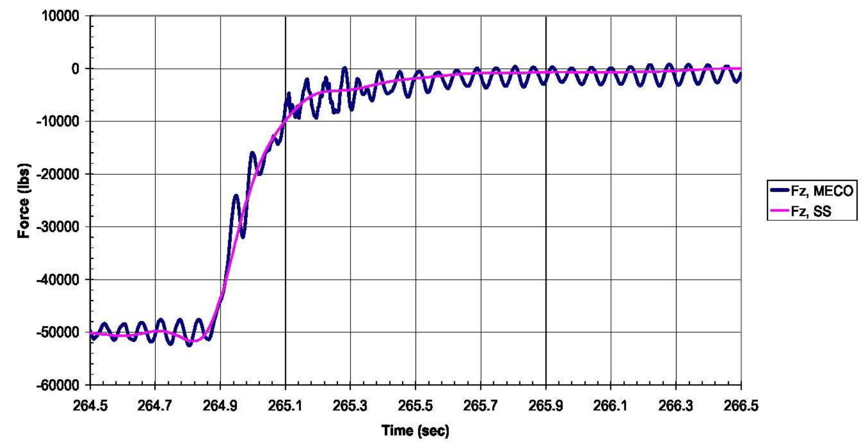


Airloads Thrust Forces



- Excellent agreement between measured forces and steady-state accelerations
- SFM method used as baseline for comparisons with analytical predictions based on ground test results

MECO Thrust Forces



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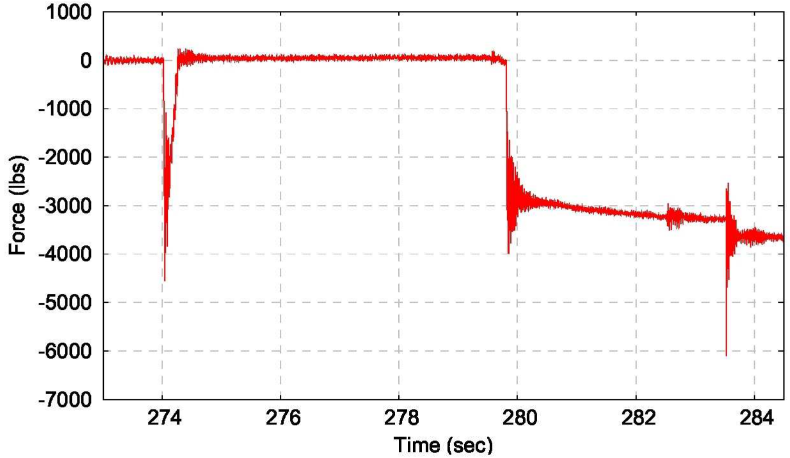
Flight Data – Other Events

SFM Max Forces – Other Events

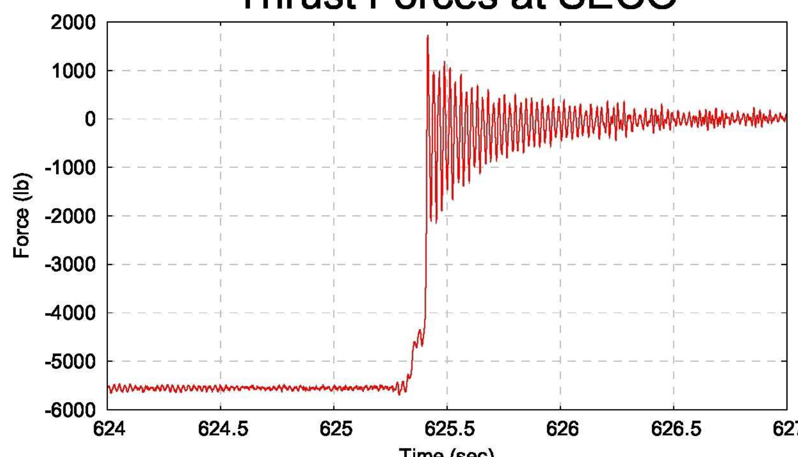
Event	Fx (lbs)	Fy (lbs)	Fz (lbs)	Mx (in-lbs)	My (in-lbs)	Mz (in-lbs)
S1Sep	168.40	490.85	4556.70	53763.00	9785.30	6948.70
S1Ign	423.56	364.41	3993.20	9229.30	11289.00	10160.00
Fair Sep	399.89	443.73	6104.00	20683.00	22543.00	30752.00
SECO	175.00	125.25	5693.40	12971.00	14513.00	5108.40
Max	423.56	490.85	6104.00	53763.00	22543.00	30752.00

- Examined forces for S1/2 Sep, S2 Ignition and Fairing Separation
- These events are not typically considered as spacecraft design drivers
- No CLA or other simulation typically performed for these events
- Measured SFM data shows that interface forces are enveloped by liftoff and airloads events

Thrust Forces S1/2 Sep, S2 Ign, Fairing Sep



Thrust Forces at SECO



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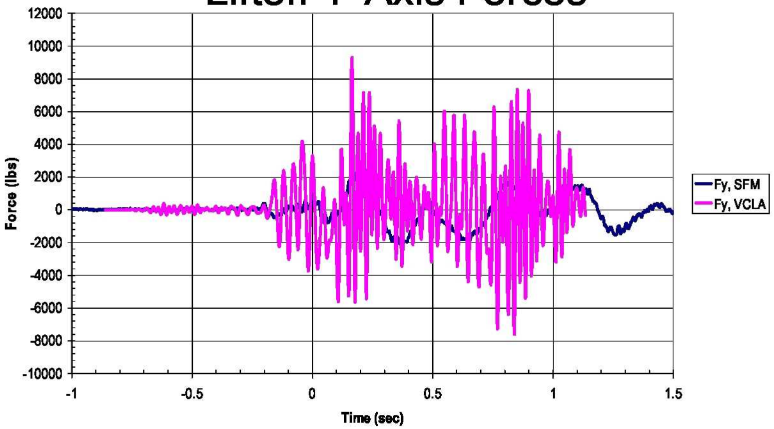
VCLA Comparison

Liftoff Y-Axis Forces



- Difficult to make comparison to VCLA with single flight
- Lateral forces and bending moments show higher % overprediction as compared with acceleration results
- For reference, VCLA results should overpredict by 100% for an average (mean) flight.
- Significant underprediction of the torsional moment needs further investigation

Liftoff VCLA vs SFI

	X (g)	Y (g)	Z (g)	Rx (rad/sec^2)	Ry (rad/sec^2)	Rz (rad/sec^2)
VCLA	0.757	1.5	2.243	5.064	3.357	1.549
SFI	0.285	0.401	2.034	4.437	2.545	1.464
	166%	274%	10%	14%	32%	6%
	Fx (lbs)	Fy (lbs)	Fz (lbs)	Mx (in-lbs)	My (in-lbs)	Mz (in-lbs)
VCLA	5477	9454.6	22887.9	385609	328252	25808
SFI	1121	2321	19004	140658	67612	22984
	389%	307%	20%	174%	385%	12%

Overprediction vs Acceleration

Airloads VCLA vs SFI

	X (g)	Y (g)	Z (g)	Rx (rad/sec^2)	Ry (rad/sec^2)	Rz (rad/sec^2)
VCLA	1.532	1.588	2.691	4.205	4.277	2.136
SFI	0.600	0.706	2.518	2.854	3.412	8.833
	155%	125%	7%	47%	25%	-76%
	Fx (lbs)	Fy (lbs)	Fz (lbs)	Mx (in-lbs)	My (in-lbs)	Mz (in-lbs)
VCLA	12078	12017	26060	766193	765807	46662
SFI	4597	4695	24582	288019	358479	247629
	163%	156%	6%	166%	114%	-81%

Significant Underprediction

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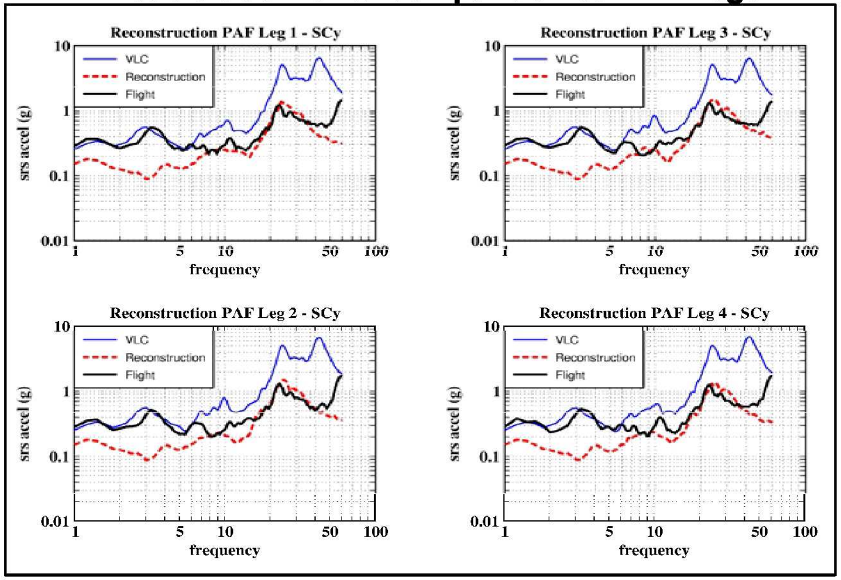
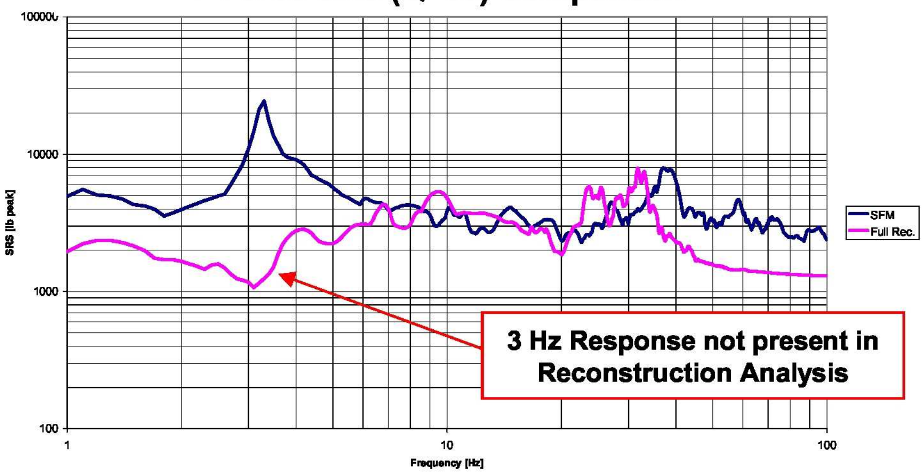
Liftoff Flight Reconstruction

- Full flight reconstruction could be performed for liftoff only
- Forcing functions and damping modified to provide match with measured SFI accelerations
- Reduction in overpressure forces resulted in underprediction of 3Hz vehicle bending mode
- Flight reconstruction for liftoff underpredicted maximum shear and bending moment
- Thrust forces showed good agreement
- Results of this activity were inconclusive

Y Acceleration SRS Comparison at PAF Legs



Y Force SRS (Q=50) Comparison



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Basedrive Simulation

- Transient basedrive simulation performed using measured SFI accelerations
- The data from the 4 triax accelerometers (12 channels) was used to calculate the average centerline acceleration (3 translations and 3 rotations) at the base of the PAF
- Two different models used for the basedrive analysis
  - *VCLA model with 2% constant damping*
  - *Correlated model and damping schedule from the GLAST sine test*
- Interface forces from acceleration basedrive compared to the measured flight forces using the SFM
- Provide comparison between acceleration based methods and measured forces

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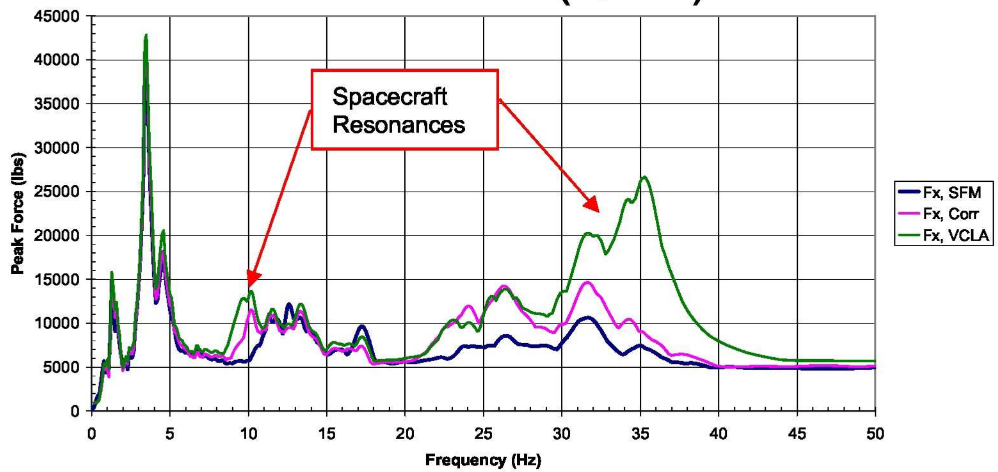
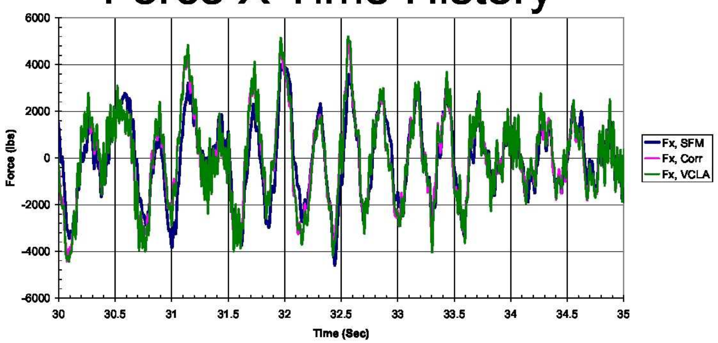
Basedrive Analysis - Airloads

- Basedrive overpredicts lateral forces
- SRS of forces shows overpredictions occur at resonant frequencies of the spacecraft
- Bending moments were underpredicted due to poor modeling of rotational inertia
- Modeling and damping differences had significant effect on basedrive results

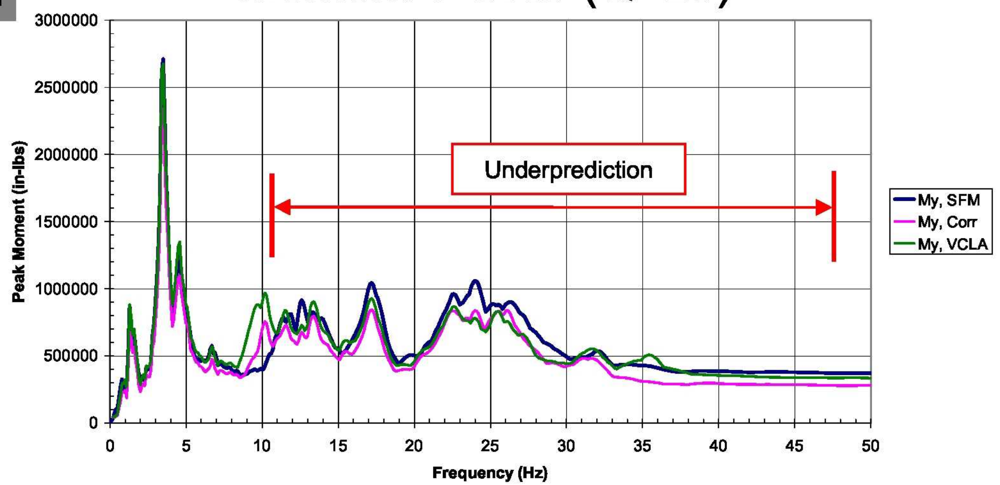
Force X SRS (Q=20)



Force X Time History



Moment Y SRS (Q=20)



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Basedrive Analysis – Airloads (Cont.)

Absolute Maximum Forces (Unfiltered)

Method	Maximum Fx (lb)	Time sec	Maximum Fy (lb)	Time sec	Maximum Fz (lb)	Time sec	Maximum Mx (in-lb)	Time sec	Maximum My (in-lb)	Time sec	Maximum Mz (in-lb)	Time sec
SFM	4596.51	32.444	4694.86	32.115	24581.83	21.19	288019.16	29.015	358478.65	32.443	247628.57	33.214
% Error	±5%		±5%		±5%		±5%		±5%		±5%	
Correlated	5029.94	32.568	4723.49	32.261	24335.43	21.191	262093.31	32.243	268588.37	32.555	237891.58	33.217
% Diff	**9.4%**		0.6%		-1.0%		**-9.0%**		**-25.1%**		-3.9%	
VCLA	5206.22	32.563	5228.49	32.259	24261.18	21.198	322407.42	32.244	324101.88	31.978	264057.74	33.216
% Diff	**13.3%**		**11.4%**		-1.3%		**11.9%**		**-9.6%**		**6.6%**	

Absolute Maximum Forces (Filtered 5 – 150 Hz)

Method	Maximum Fx (lb)	Time sec	Maximum Fy (lb)	Time sec	Maximum Fz (lb)	Time sec	Maximum Mx (in-lb)	Time sec	Maximum My (in-lb)	Time sec	Maximum Mz (in-lb)	Time sec
SFM	1407.76	35.178	1496.85	39.621	2539.51	21.19	167836.8	37.93	141576.73	35.929	250252.2	33.214
% Error	±10%		±10%		±10%		±5%		±5%		±5%	
Correlated	1916.74	38.89	2050.91	26.258	2650.33	33.027	119096.76	38.765	112120.24	35.929	241083.64	33.217
% Diff	**36.2%**		**37.0%**		4.4%		**-29.0%**		**-20.8%**		-3.7%	
VCLA	2379.18	41.976	2194.1	37.482	2858.07	24.683	152503.5	37.932	128209.27	33.317	267236.96	33.216
% Diff	**69.0%**		**46.6%**		**12.5%**		**-9.1%**		**-9.4%**		**6.8%**	

Overprediction

Underprediction

- Filtering to remove rigid body loads increases overprediction
- Poor modeling of the rotational inertias results in moment underprediction

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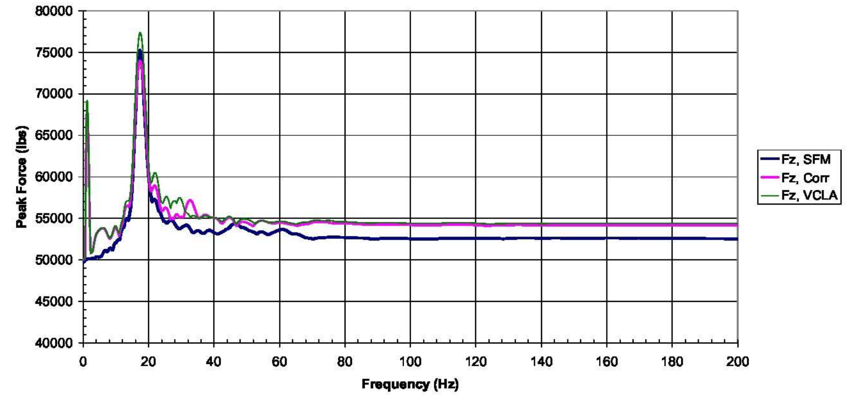
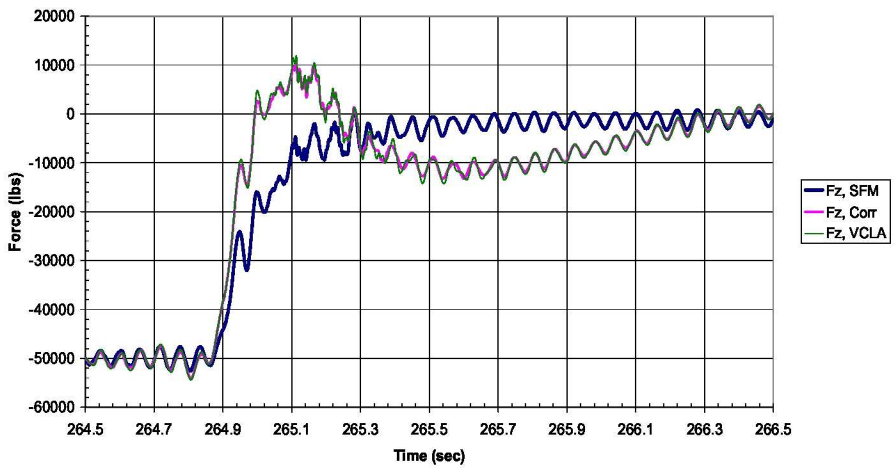
Basedrive Analysis – MECO Transient

- MECO Transient event occurs just after engine shutdown
- Acceleration basedrive overpredicts interface forces for MECO Transient
- Overprediction occurs at resonant frequencies of the spacecraft

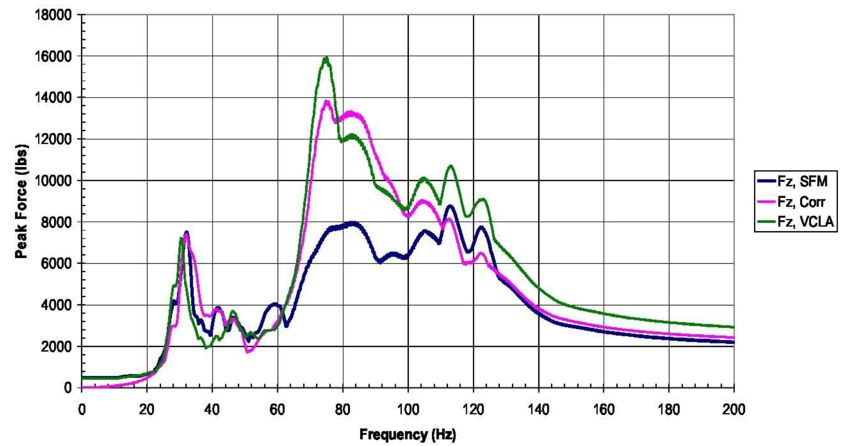
MECO Fz SRS (Q=20)



MECO Transient Thrust Force (Fz)



MECO Fz SRS (Q=20)
(Filtered 30 – 150 Hz)



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Basedrive Analysis – MECO Transient (Cont.)

MECO Forces (Unfiltered)

Method	Maximum Fx (lb)	Time sec	Maximum Fy (lb)	Time sec	Maximum Fz (lb)	Time sec	Maximum Mx (in-lb)	Time sec	Maximum My (in-lb)	Time sec	Maximum Mz (in-lb)	Time sec
SFM	494.7	265.24	394.41	265.578	52520.47	264.804	26326.62	265.446	26941.25	265.259	18947.03	265.173
% Error	>±10%		>±10%		±5%		>±10%		>±10%		±10%	
Correlated	544.98	265.39	691.39	265.582	54125.55	264.807	42111.49	265.584	27202	265.396	22642.73	265.177
% Diff	10.2%		**75.3%**		3.1%		**60.0%**		1.0%		**19.5%**	
VCLA	737.33	265.39	958.86	265.312	54352.45	264.807	51953.62	265.585	41739.43	265.4	23233	265.178
% Diff	**49.0%**		**143.1%**		3.5%		**97.3%**		**54.9%**		**22.6%**	

MECO Forces (Filtered 60 – 150 Hz)

Method	Maximum Fx (lb)	Time sec	Maximum Fy (lb)	Time sec	Maximum Fz (lb)	Time sec	Maximum Mx (in-lb)	Time sec	Maximum My (in-lb)	Time sec	Maximum Mz (in-lb)	Time sec
SFM	185.31	265.13	313.4	265.239	1449.43	265.12	3375.54	265.208	3998.98	265.245	9358.77	265.167
% Error	>±10%		>±10%		±10%		>±10%		>±10%		>±10%	
Correlated	288.38	265.29	441.93	265.25	1853.3	265.143	5640.21	265.24	9675.11	265.238	8451.97	265.177
% Diff	**55.6%**		**41.0%**		**27.9%**		**67.1%**		**141.9%**		**-9.7%**	
VCLA	412.48	265.29	646.11	265.255	1882.36	265.119	4362.05	265.242	6345.4	265.261	10212.26	265.184
% Diff	**122.6%**		**106.2%**		**29.9%**		**29.2%**		**58.7%**		**9.1%**	

- MECO Transient basedrive overpredicts interface forces
- Knowledge of interface forces could be used to improve flight predictions

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Some Key Findings

- PAF geometry makes strain-based force measurement difficult
- SFM more robust than FEM based on analysis and ground testing
- Flight thrust axis forces showed good agreement with steady-state acceleration
- Maximum flight forces and moments at S/C interface bounded by liftoff and airloads events
- Overprediction of measured flight loads by VCLA was higher than expected for shear and bending moments
- VCLA underpredicted torsional moment during airloads by a factor of 5
- Ability to perform flight reconstruction CLA is limited
- Acceleration basedrive analysis overpredicted shear forces typically at fixed-base spacecraft resonances
- Basedrive analysis underpredicted the bending moments due to poor modeling of rotational inertia

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Summary/Conclusions

- Measurement of forces on the GLAST mission was successful
- Identified two areas of further investigation regarding CLA
  - *Larger than expected overprediction of liftoff shear force and lateral bending moments as compared with acceleration results*
  - *Significant underprediction of torsional moment*
- Identified conservatisms in basedrive analysis using measured accelerations
- Where do we go next:
  - *Database of flight force measurements could be used to improve the accuracy of CLA predictions (LV and SC)*
  - *Database of flight force measurements could be used to improve basedrive analysis as an early design tool*
- Difficult to draw definitive conclusions with only one flight

Let's get more flight force data!!!!!

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