SI Shipping Assembly Structure Dynamic Analysis

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SI Shipping Assembly Structure Dynamic Analysis

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Revision History

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-	5/4/2015	Initial draft release for review and comment.	

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SI Shipping Assembly Structure Dynamic Analysis

1. PURPOSE

This report presents the SI shipping assembly (Figure 1) structure analysis. This document will be used as a Verification and Validation method for compliance with the SI shipping assembly requirements as specified in SE01-2084 document. The SI shipping assembly will be installed in SOFIA cargo bay and will be used to support the 2nd Science Instrument (FORCAS/GREAT) shipment to New Zealand.

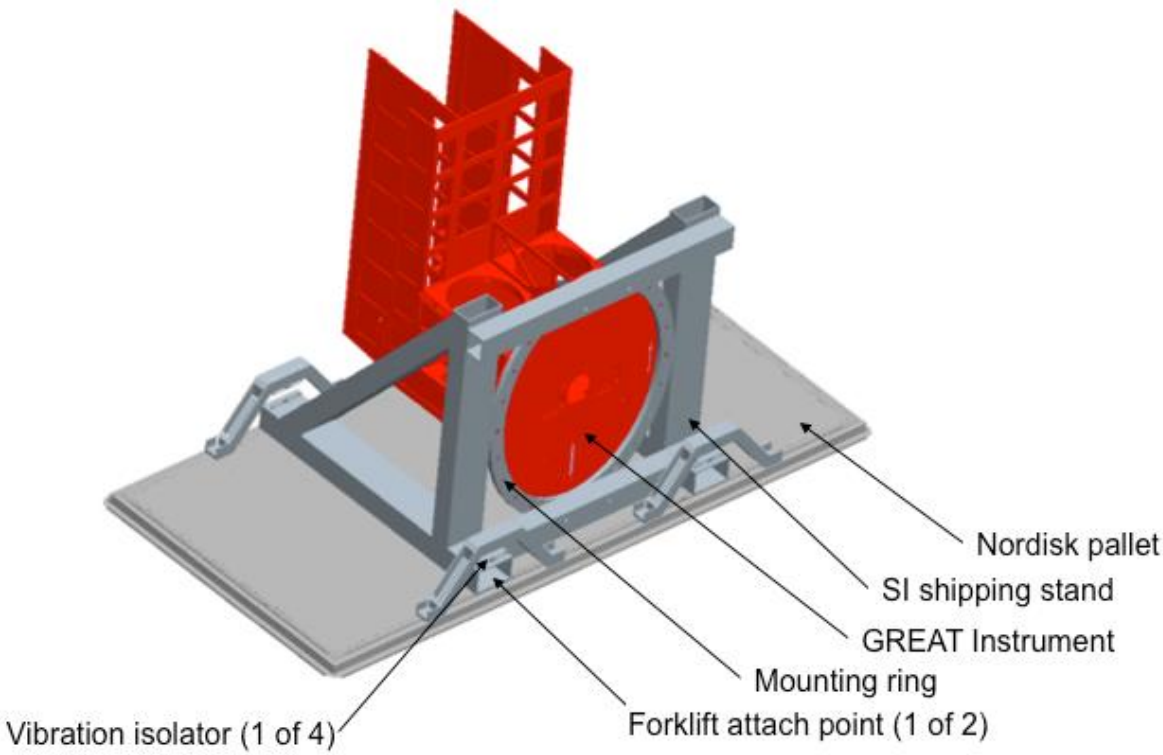


Figure 1: SI Shipping Assembly

Figure 1 shows that the SI shipping assembly consists of, for example, the following elements:

- Nordisk pallet
- SI shipping stand
- Mounting Ring Forklift attach point
- Vibration isolator

1.1. Scope

The higher accelerations already measured at the Science Instrument (SI) stations on the TA for a particular frequency over the range of 1 Hz to about 2000 Hz are typically equal or higher than those estimated for the "payload" side of the SI shipping assembly in the cargo bay. So

assuming that an SI on the TA has already flown these without concern, an SI on the cargo bay shipping assembly shouldn't be worse. These SI on TA accelerations are also similar to those measured on nearby fuselage bulkhead structure during the SOFIA envelope expansion landings.

Consideration is also included for the estimated amplification (worst case resonance) at the suspended natural frequency of isolators/shipping assembly substructure/GREAT sized SI, as well as for frequencies lower and a little higher which would have transmissibility roll off. The summary comparison also holds true for the higher frequencies than the roll off when the isolator damping begins to reduce accelerations.

Concerns were expressed as to whether the SI shipping assembly located in the SOFIA cargo bay would experience excessive aircraft vibrations on the vibration isolated SI side ("payload") for a GREAT sized SI. An independent assessment was performed for the SI shipping assembly vibrational estimates.

Information reviewed began with the presentation in the SI shipping assembly design review. Additional flight data excerpted from Phil Hamory's "SOFIA TA Vibration Data" report, "Additional Info About Spikes in Vibration Report for SOFIA Cargo Bay" (Flt 191, 2/3/15), SOF-DA-ICD-SE03-037 Rev. 1.1 titled Worst Case Loading and then also the vibrational isolator information from the Isolation Dynamics Corporation web site. Discussions on the subject took place with Glen Crampton (SOFIA Static Structures) and Natalie Spivey (AFRC Structural Dynamics).

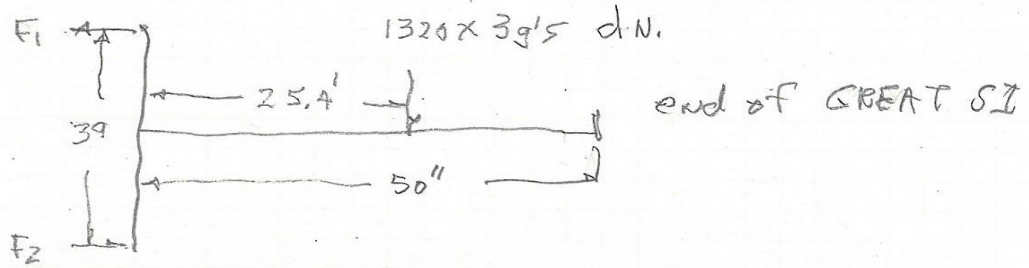
2. SI SHIPPING ASSEMBLY STRUCTURE ANALYSIS

2.1. SI Shipping Fixture Deflection

The following presents the SI shipping fixture deflection analysis:

SI Shipping Fixture Deflections

13 Apr 15
GHK



$$F_1 = \frac{1320 \times 3 \times 25.4}{39} = 2580 \text{ lb}$$

@ F_1

$$\delta = \frac{W l^3}{48EI} = \frac{2580\,(50)^3}{48 \cdot 10 \times 10^6 \times 104}$$

length of upper beam

$$= .0065 \text{ IN}$$

$$\delta \text{ @ end of GREAT} \approx .0065 \times \frac{50}{19.5} = \underline{.0166 \text{ in}}$$

deflection due to stand with GREAT as rigid body

2.2. SI Shipping Fixture (FORCAST Version) Structure Analysis

SI Shipping Fixture	Analysis		3/20/15		N/R		forcast version									
	Applied Load lbs															
Load Case	X	Y	Z	R1	R2	R3	R4	Stress B1	Stress B2	Stress F1	Stress F2	Allowable	MS B1	MS B2	MS F1	MS F2
								psi	psi	psi	psi	Stress psi				
4.7 g's down			6204	2704	2704	3610	2594	644	644	11181	8036	42000	64.23	64.23	2.76	4.23
1.7 g's up			2244	978	978	1306	938	233	233	4044	2907	42000	179.34	179.34	9.39	13.45
1.3 g's fwd + 1.5 g's dn	1716		1980	863	2137	1152	828	205	509	3568	2565	42000	203.39	81.53	10.77	15.38
.9 g's side + 1.5 g's dn		1188	1980	863	863	1152	828	205	205	3568	2565	42000	203.39	203.39	10.77	15.38
.75 g's rearward + 1.5 g's dn	990		1980	863	2500	1152	828	205	595	3568	2565	42000	203.39	69.55	10.77	15.38
					4x4 side wall stress											
				W	Ra	Mmax	Stress	MS								
				901	169	489.5	22591	0.86								
				Weld Stress			Beam 1									
				R1/2	area	stress	Allowable	MS								
							stress psi									
				1352	1.41	956.3	15120	14.81								

Table 1: Structure Analysis (FORCAST Version)

2.3. SI Shipping Fixture (GREAT Version) Structure Analysis

SI Shipping Fixture	Analysis		3/20/15		N/R		GREAT Version									
	Applied Load lbs															
Load Case	X	Y	Z	R1	R2	R3	R4	Stress B1	Stress B2	Stress F1	Stress F2	Allowable	MS B1	MS B2	MS F1	MS F2
								psi	psi	psi	psi	Stress psi				
4.7 g's down			6204	4041	4041	2640	3564	962	962	8176	11041	42000	42.66	42.66	4.14	2.80
1.7 g's up			2244	1461	1461	955	1289	348	348	2957	3994	42000	119.70	119.70	13.20	9.52
1.3 g's fwd + 1.5 g's dn	1716		1980	1290	2137	842	1138	307	509	2609	3524	42000	135.79	81.53	15.10	10.92
.9 g's side + 1.5 g's dn		1188	1980	1290	1290	842	1138	307	307	2609	3524	42000	135.79	135.79	15.10	10.92
.75 g's rearward + 1.5 g's dn	990		1980	1290	2500	842	1138	307	595	2609	3524	42000	135.79	69.55	15.10	10.92
					4x4 side wall Stress											
				W	Ra	Mmax	Stress	MS								
				2020	1010	947	24243	0.73								
				Weld Stress			Beam 1									
				R1/2	area	stress	Allowable	MS								
							stress psi									
				2020	1.41	1429	15120	9.58								

Table 2: Structure Analysis (GREAT Version)

2.4. Vibration Isolation System Structure Dynamic Analysis

Isolation of the suspended SI on the shipping assembly in the SOFIA cargo bay is to use four spring/dampers (model M16A-325-06 from Isolation Dynamics Corporation).

Independent calculations were made to access the vibration isolators used on the shipping assembly. The primary reason for this is that in the SI shipping assembly design review several of the equations presented were not familiar with those historically used by the structural dynamics group.

Damping of the cargo bay vibration will begin at just above the undamped natural frequency of the suspended system and damping will increase as vibrational frequencies increase. At the undamped natural frequency of the suspended system, cargo bay vibration amplitude will be increased (resonance or maximum transmissibility). For the reported hardware damping ratio of 0.2, this resonance amplitude (transmissibility) is increased by about 2.69 (close to the presentation approximate 2.5 value) and then transmissibility rolls off to 1.0 at about 1.4 times the undamped natural frequency. The transmissibility rolls off to a factor of about 1 at zero frequency for all damping ratios. These roll offs agree with the presentation.

The use of Fd (Hz), or damped frequency, in the presentation was confusing since its use in free vibration is described by equation (1) below and would be 0.98 of the undamped natural frequency and not 1.4 (for the reported damping ratio of 0.2). Although 1.4 times the undamped natural frequency is the frequency where transmissibility is 1.0 as mentioned above. The undamped natural frequency is Fn (Hz).

Fd = Fn X sqrt (1 – (damping ratio**2)) (1)

To find the undamped natural frequency, Fn (Hz), of the individual isolators, we would use equation (2) below which didn't appear similar to the one used in the presentation. Kv (vibration) or Ks (shock) are the spring rates of the isolator to be used, in lbf/in., using the manufacturer's web page. M is the mass supported by the isolator. The mass uses weight (lbf) / g (in./sec.**2). With four isolators, weight would be ¼ of the total suspended weight (1000 lbf GREAT + 360 lbf shipping assembly structure) assuming they are equally loaded at 340 lbf each. Acceleration in g's is converted from ft/sec.**2 to in/sec.**2 by multiplying by 12.

Fn = (1 / (2π)) X sqrt (K / M) K can be Kv or Ks (2)

The manufacturer's isolator data spring rates vary somewhat with load and direction. The curve appears fairly linear for lower loads such as for the ones above and below 340 lbf. Linear interpolation of the tabulated vibrational spring rates was used to estimate a deflection for 340 lbf. The vibrational spring rates, Kv, were calculated using equation (3), per deflection, x, and load (weight), F. The shock spring rates, Ks, are used as listed with no load/deflection variations.

Kv = F (lbf) / x (in.) (3)

Spring stiffness used for loads and directions of motion and the undamped natural frequencies calculated using equation (2) and the isolator data sheet.

Isolator Load Condition Direction	Flight Data Equivalent Direction	Vibration		Shock	
		Spring Stiffness (lbf/in.)	Undamped Natural Frequency (Hz)	Spring Stiffness (lbf/in.)	Undamped Natural Frequency (Hz)
Compression	Vertical, Normal	4497	11.37	2025	7.63
Tension	Vertical, Normal	4703	11.63	4950	11.93
Shear or Roll	Lateral, Longitudinal	872	5.01	1200	5.88
45 deg. Compression/Roll	Lateral, Longitudinal	2313	8.16	940	5.20
45 deg. Tension/Roll	Lateral, Longitudinal	2833	9.03	3150	9.52

Table 3: Isolator Directional Variations, Spring Rates and Undamped Natural Frequencies (Maximum Resonance/Transmissibility)

3. VIBRATION DATA FLIGHT ANALYSIS

3.1. Flight 191 -2/3/2015

Data from flight 191, 2/3/2015 has been used as the source for this analysis. The accelerations were compared between the SI on the shipping assembly in the cargo bay and the SI on the TA. The shipping assembly with a GREAT sized SI mass used amplified resonance and roll off (transmissibility) factors, based on the frequencies in table 3 and the accelerations measured in the cargo bay. The SI on TA flight data also used accelerations at these resonance frequencies for comparison. The highest levels of flight data acceleration that were outside of these resonance frequencies were also included.

Cargo bay landing was considered to be the worst case compared to takeoff. To have a wider

spread of variability, the SI on TA flight data used cases of taxi, takeoff, a typical and a worst case landing. These are shown for vertical (normal) and lateral directions on figure 2; the SI/Shipping Assembly in the cargo bay accelerations in red are generally in the middle of the SI/TA cases over the frequency range shown. Where the SI/Shipping Assembly amplitudes begin to decrease in the higher frequency range shown is where the damping of isolators begins to have a lowering effect of acceleration. The upper range of SI on TA accelerations shown in figure 2 are very similar to those observed at fuselage bulkheads during SOFIA envelope expansion landings.

The longitudinal directions in figure 2 are not shown since they usually had the lowest amplitude of the three but in the few cases where they were elevated, they were similar to vertical and lateral amplitudes. For the SI on the TA flight data that were given in u (longitudinal, v (tangential) and w (radial), vertical and lateral components were calculated for comparison.

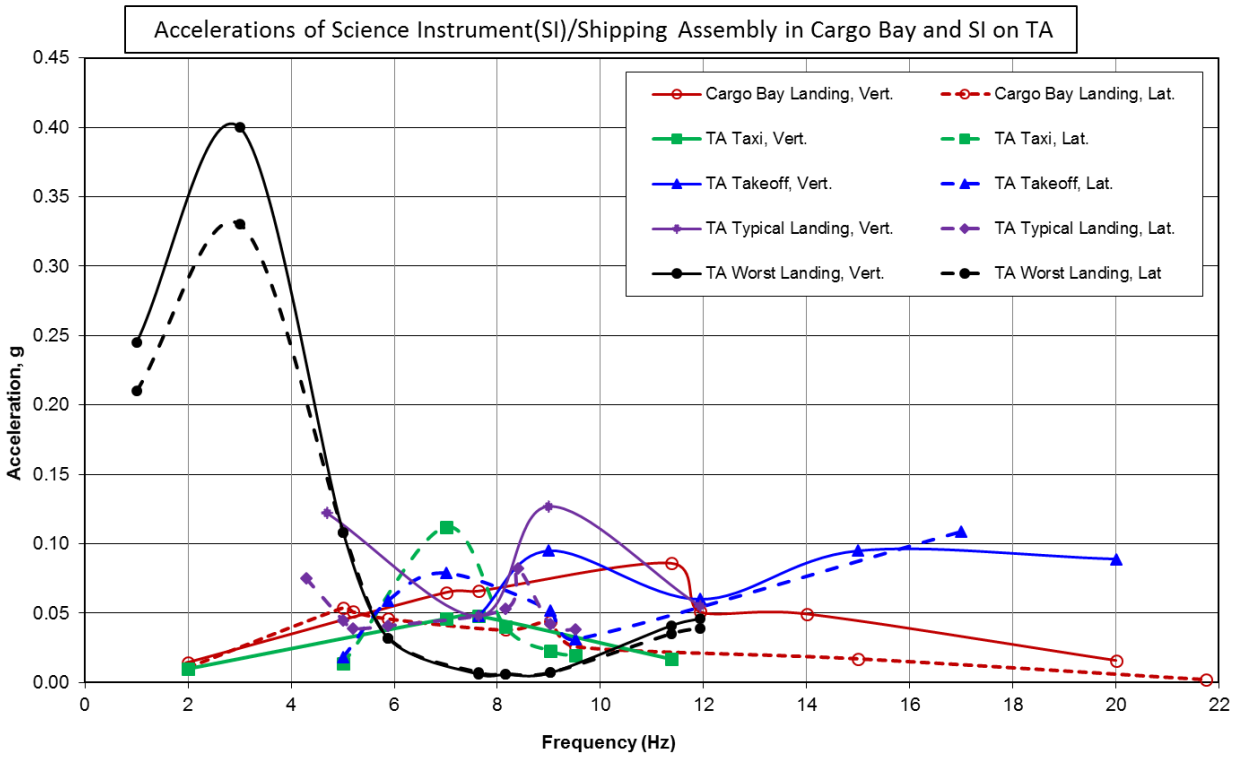


Figure 2: Data comparison between Cargo bay and SI on TA

3.1.1. Conclusion

Estimates of the SI/Shipping Assembly accelerations in the SOFIA cargo bay were performed and flight data comparisons were made to those of the SI on TA. Resonance/amplifying effects of the vibration isolators in the shipping assembly that were included should have accelerations similar to those of the SI on the TA that have been previously observed in flight.

3.2. Flight 208 & 211, vibration data analysis with SI Dummy Installed

This section presents the vibration data analysis with the SI dummy installed at the SI shipping fixture in the cargo bay.

To be clear up front: this report is about Flight 211 where the GREAT shipping fixture (shown below) was "fully locked down." This is in contrast to Flight 208 for which PSDs of the landing were produced even though, in that flight, the shipping fixture was secure but not fully locked down.

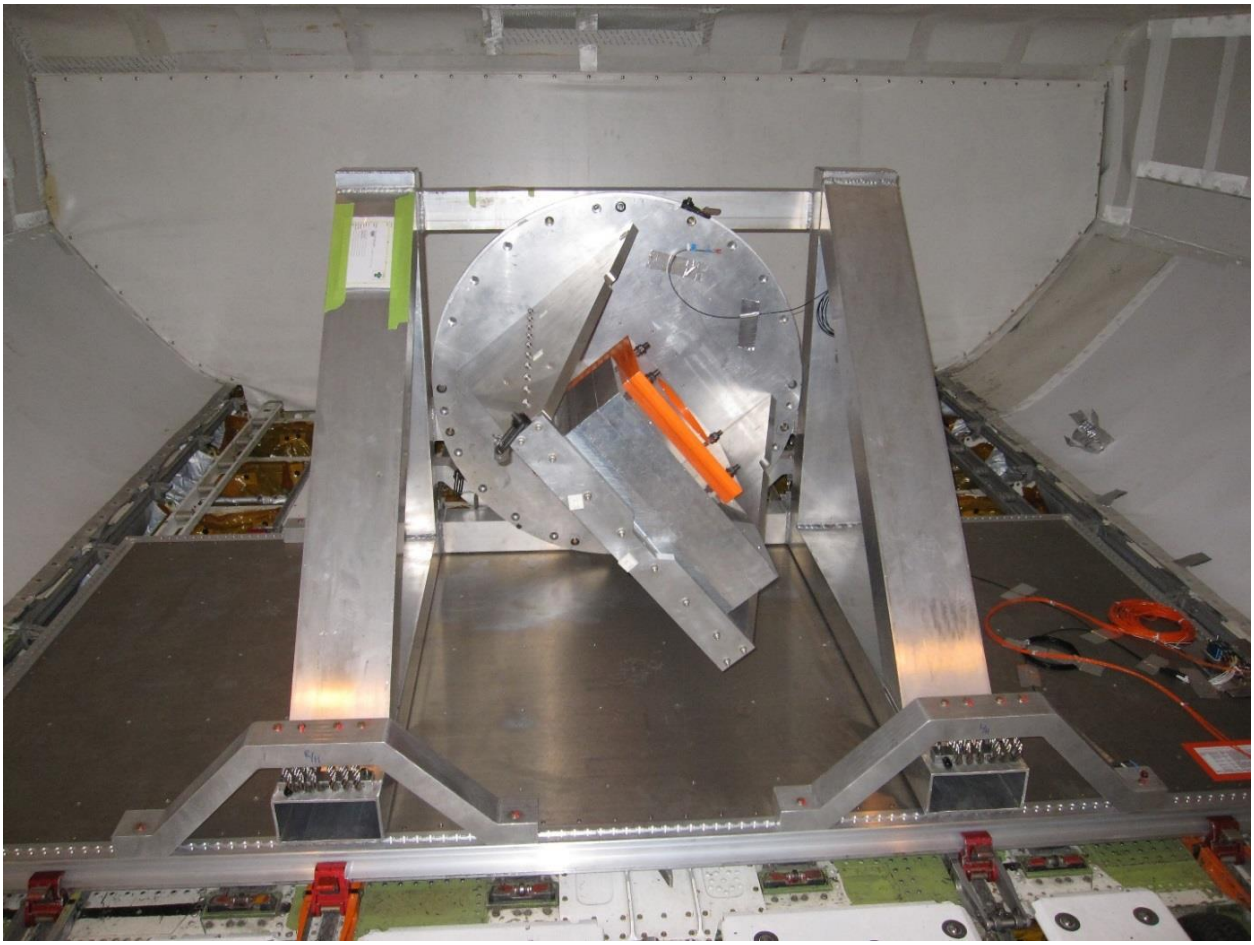


Figure 3: SI Shipping Fixture

Triax A is on the isolated structure. Triax B is not isolated. Note: the photo above was taken before the rubber shims shown below were installed.

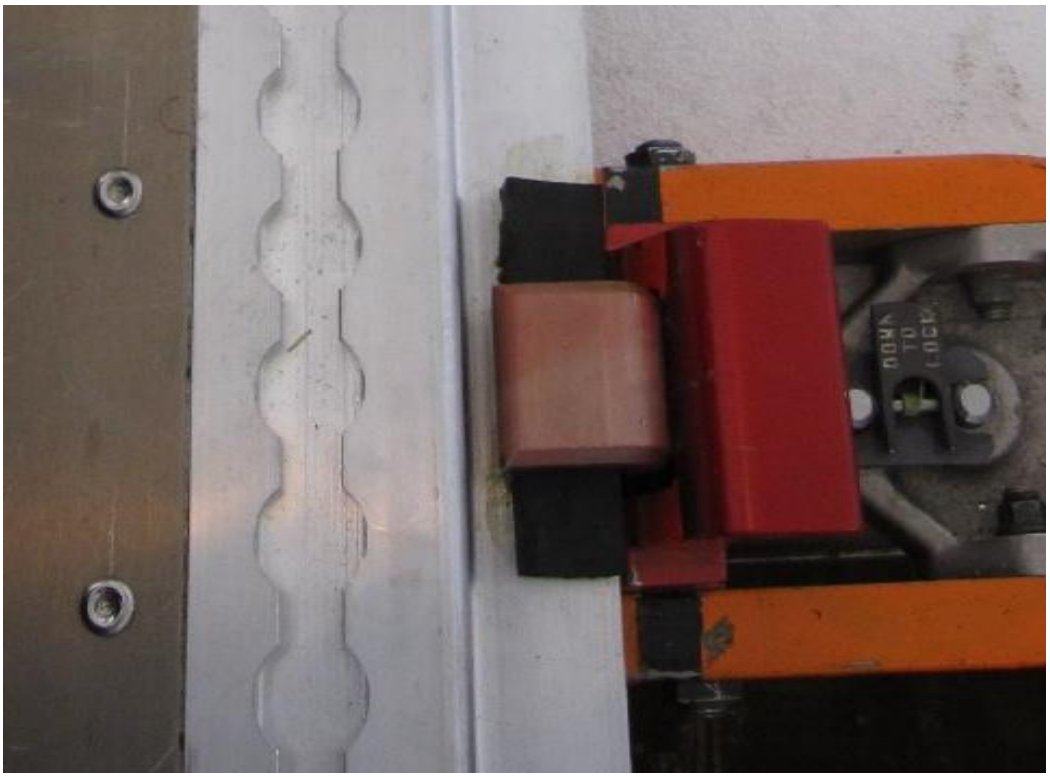


Figure 4: Rubber Shims Installed

3.2.1. Introduction

Normally, I would start a report like this with a summary statement and the worst case PSD. Then I would provide an overview of the whole flight and highlight significant parts of the flight. In this report, I'll be going backwards, so to speak, starting with a comparison of the landing in order to carryover from what was provided for Flt 208. Then I'll provide more general info about Flt 211.

3.2.2. Landing

On the next two pages, Figures 5 and 6 show isolated data while Figures 7 and 8 show unisolated data. Figure 5 is a 30 sec ensemble average PSD for the landing from Flt 211. Figure 6 is the 30 sec ensemble average PSD provided earlier for Flt 208. The two PSDs are very similar though the peak amplitudes for Flt 211 are smaller and the grms values are slightly smaller as well.

3.2.3. Takeoff

Figure 9 shows the 30 sec ensemble average PSD for the isolated shipping fixture. Figure 10 shows the 30 sec ensemble average PSD for the unisolated structure. Figures 11, 12, and 13 show the same data but plot the isolated and unisolated responses together one axis at a time. Figures 14 and 15 show the takeoff time history, and Figure 14 shows the 30 sec portion used for the PSDs. (The same portion is used for Fig 15 but the vertical dotted lines were not included in the plot.)

3.2.4. Overview of the whole flight

The next set of figures provide overview information for the whole flight. Data was recorded in four parts: (a) takeoff; (b) at altitude; (c) again at altitude; and (d) descent, landing, and taxi. Gaps are included in some of the plots to show the distinction between recording portions.

The roughly two hours of flight data was analyzed in 30 second segments. Figures 16 and 17 show the grms values for each segment. Figure 16 shows it for the isolated structure, and Figure 17 shows it for the unisolated structure. From these plots we see that the largest average power is seen during takeoff and landing (no surprise). Interestingly enough, taxi appears to be a bit rougher for the isolated structure than the unisolated structure. Elsewhere, the isolation is a benefit.

Figures 18 and 19 shows the minimum and maximum g levels from each 30 second segment. The unisolated structure sees more gs (again, no surprise).

Figure 20 and 21 provide yet another view of what's going on. For each 30 second segment, an ensemble average PSD was computed. The maximum amplitude seen in the PSD for each segment is plotted. It's the isolated structure that has the highest peak. It occurred at takeoff and the actual PSD is given in Figure 9.

3.2.5. Comparison with telescope assembly data

The FORCAST instrument was attached to the telescope assembly for Flt 211 and a triaxial accelerometer was mounted on it as well. See Figure 22 - because of the way the data is divided up in the Tattletale, analysis segments for this data are 18 seconds long. (I have reason to believe that in most cases the differences between 18 and 30 sec analysis segments are minor.) Figure 23 is a PSD of the takeoff, and Figure 24 is a PSD of the landing. Figure 25 shows the grms values for each analysis segment. (Note: Figures 25, 26, and 27 don't show the gaps that Figure 16 and others show.) Figure 26 shows the min and max g levels seen for each analysis segment. Figure 27 shows the max PSD amplitude for each segment.

In the same way GREAT data from Flt 208 is shown after that even though it was a different flight.

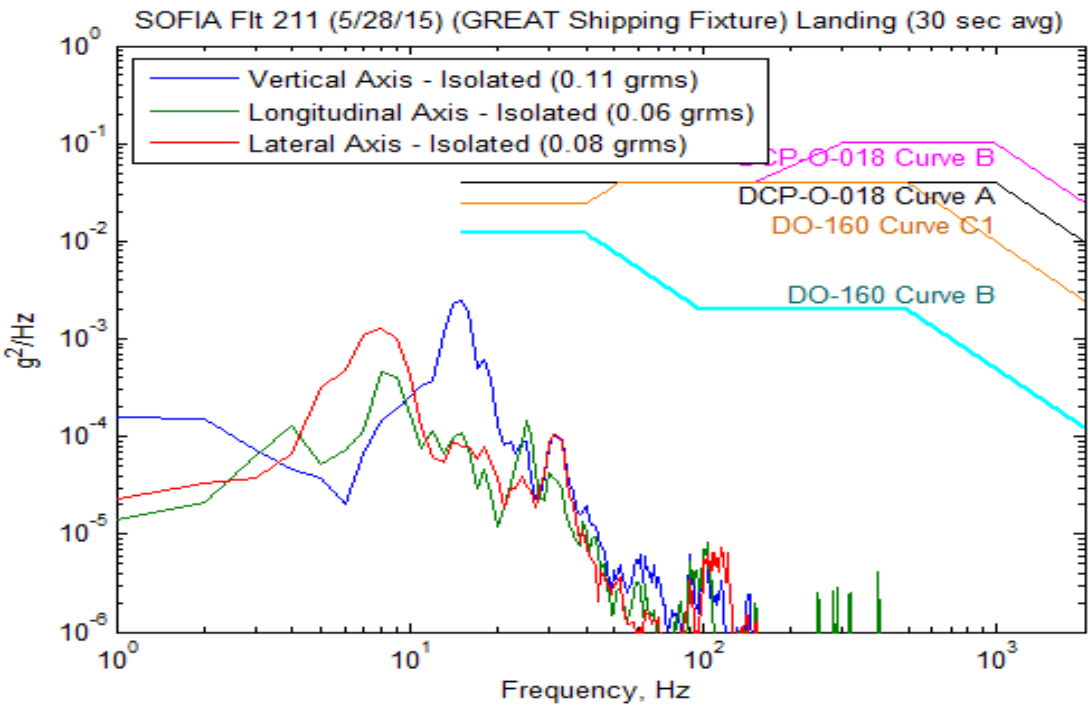


Figure 5: GREAT Shipping Fixture – Landing 30sec

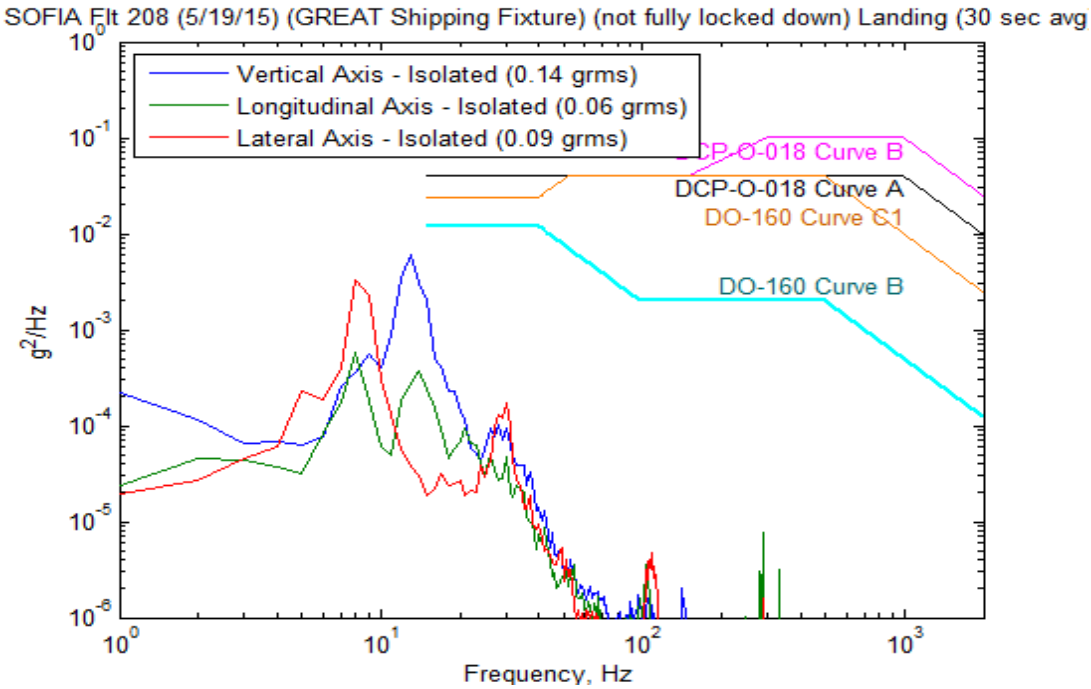


Figure 6: GREAT Shipping Fixture-not fully locked down landing 30 sec

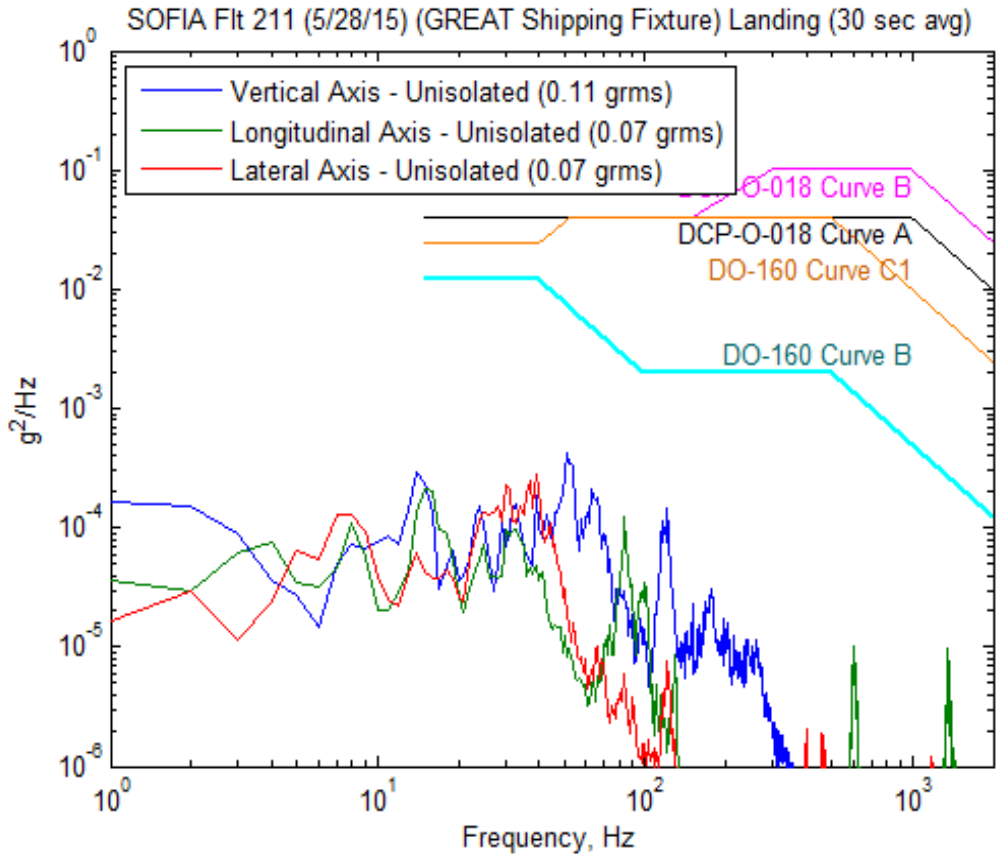


Figure 7: GREAT Shipping Fixture – Landing 30 sec

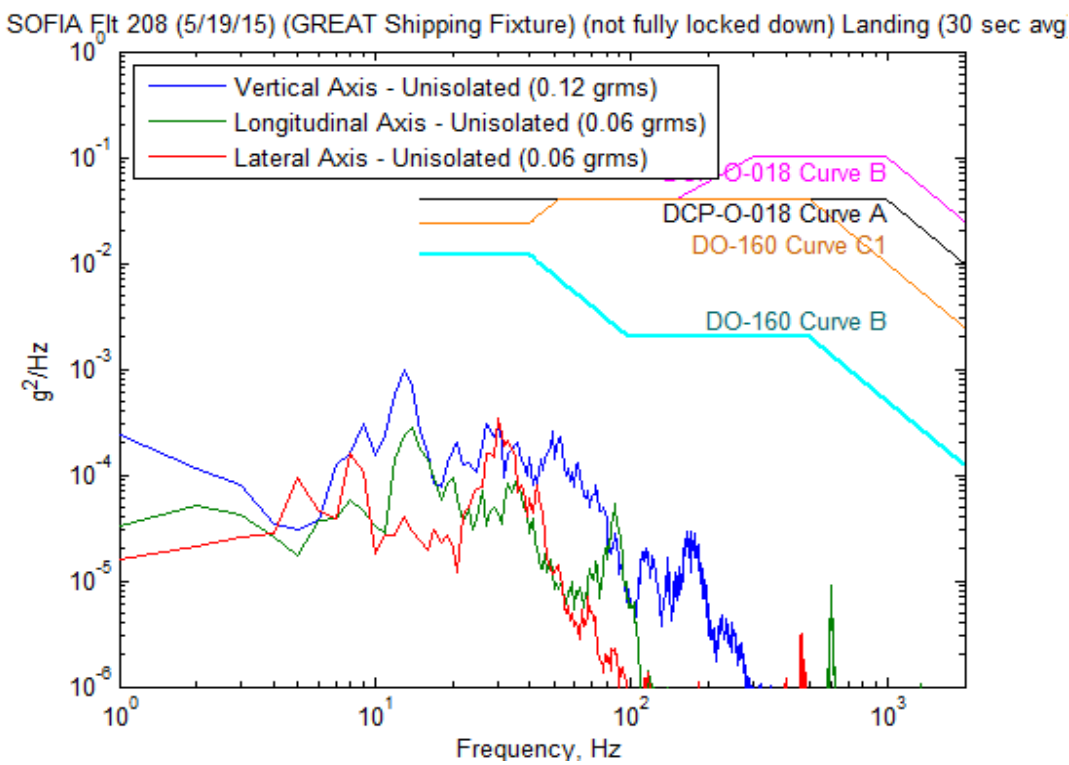


Figure 8: GREAT Shipping Fixture not fully locked down - landing 30 sec

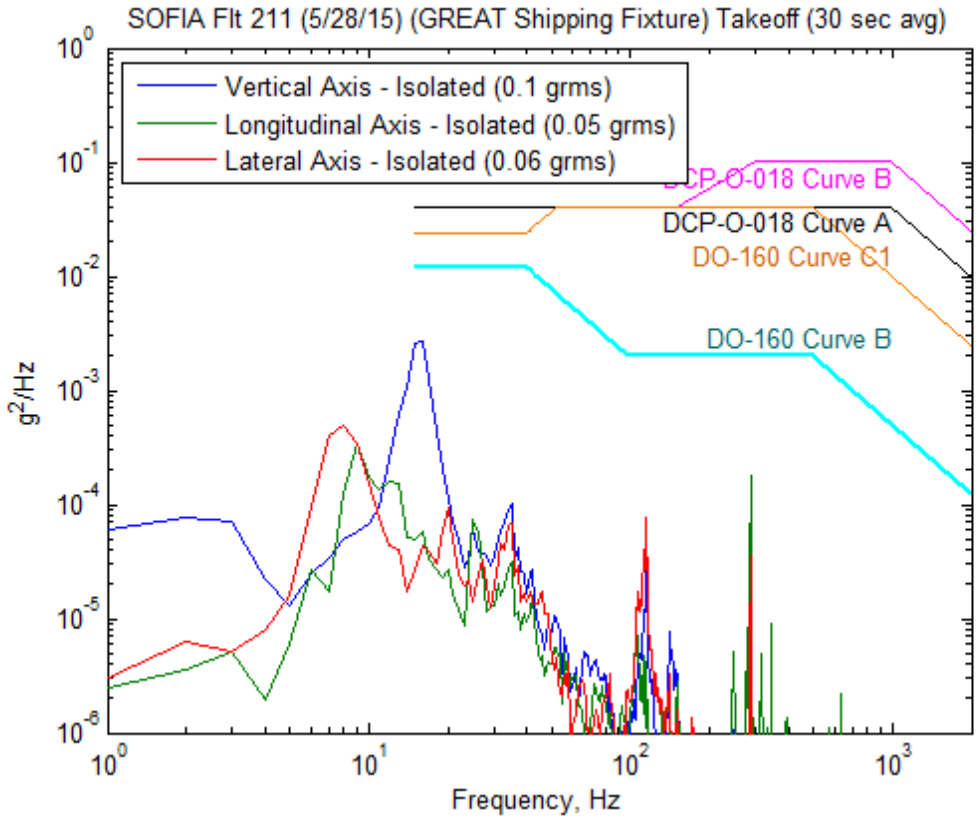


Figure 9: GREAT Shipping Fixture T/O 30 sec

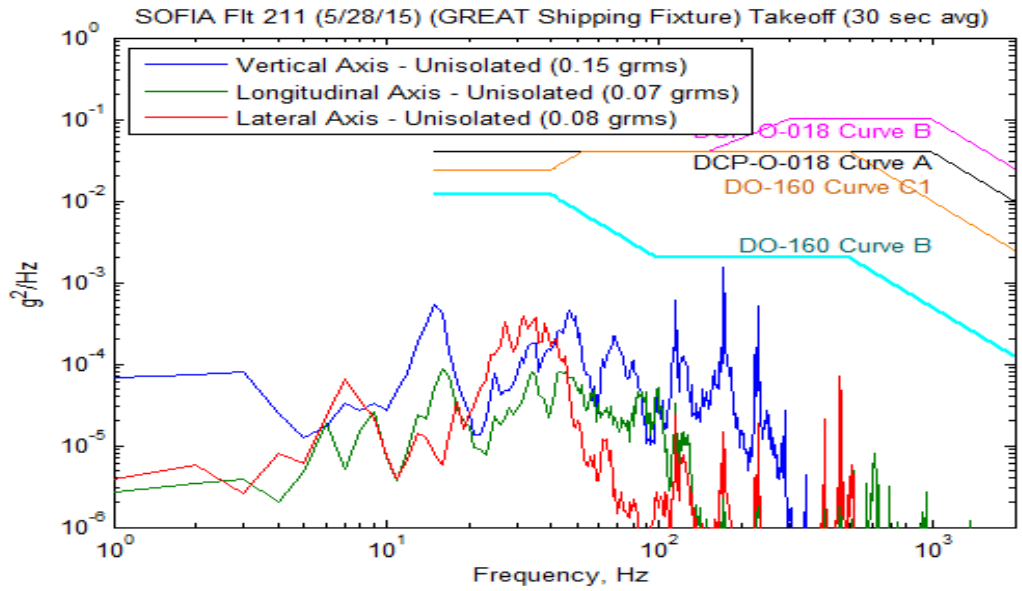


Figure 10: GREAT Shipping Fixture T/O 30 sec

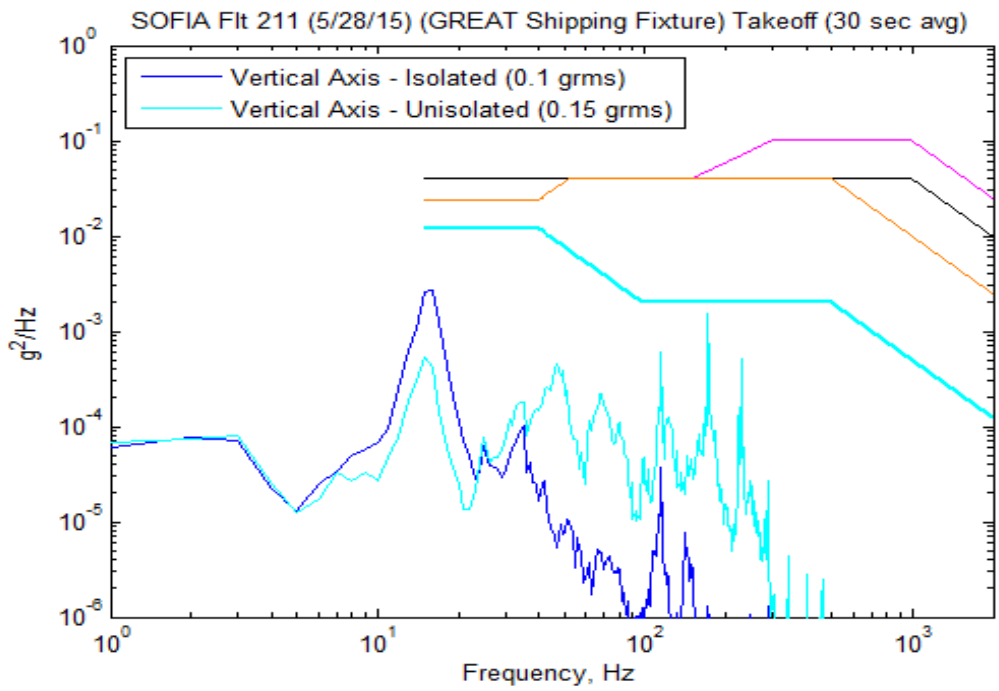


Figure 11:GREAT Shipping Fixture T/O 30 sec

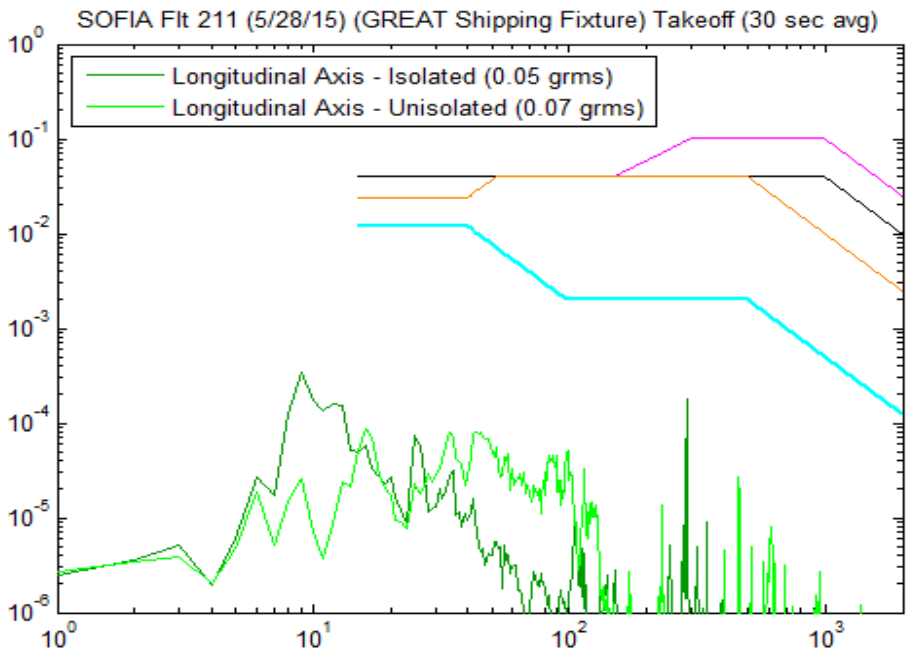


Figure 12: GREAT Shipping Fixture T/O 30 sec

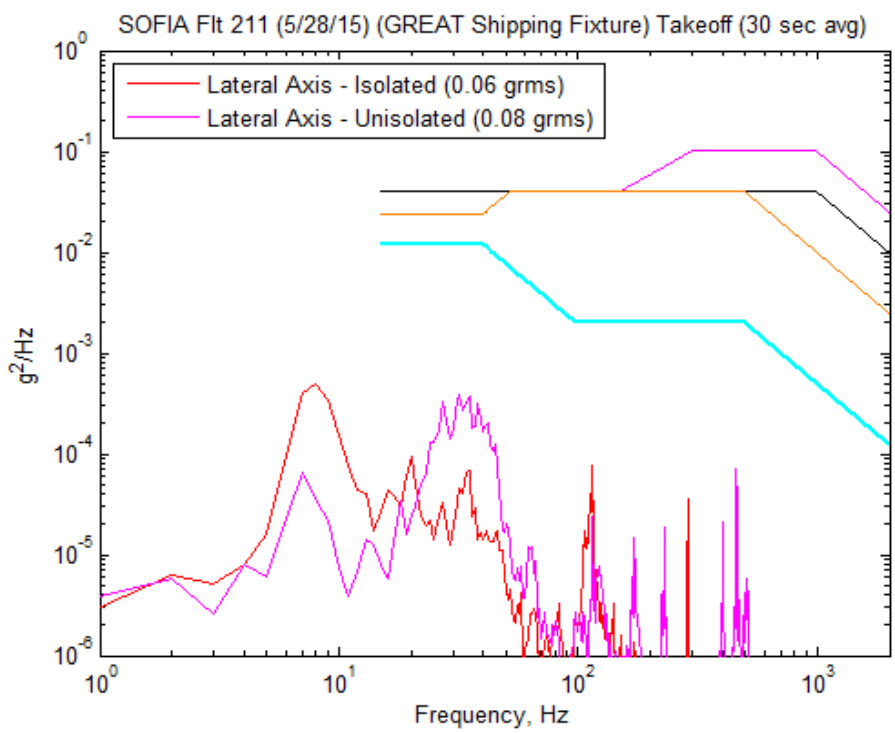


Figure 13: GREAT Shipping Fixture T/O 30 sec

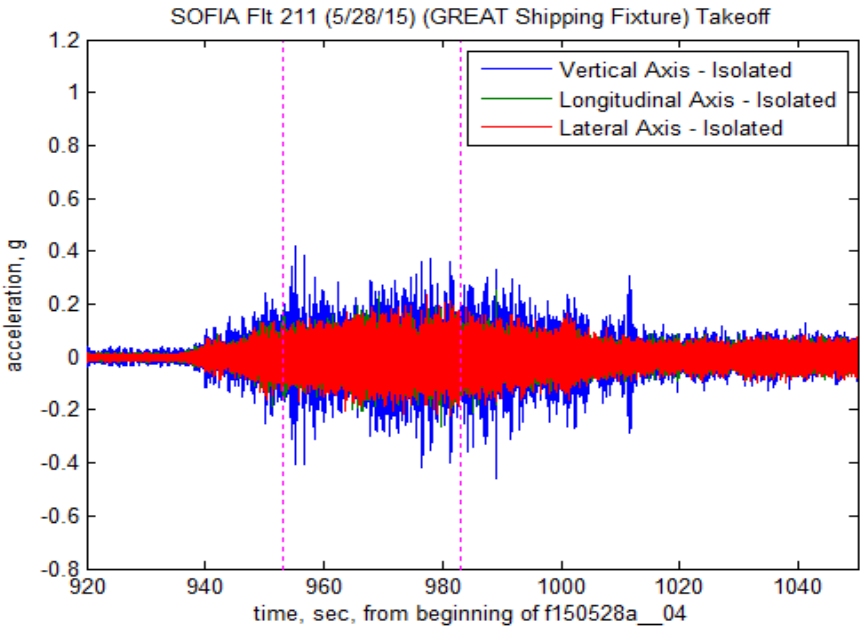


Figure 14: GREAT Shipping Fixture T/O (Isolated)

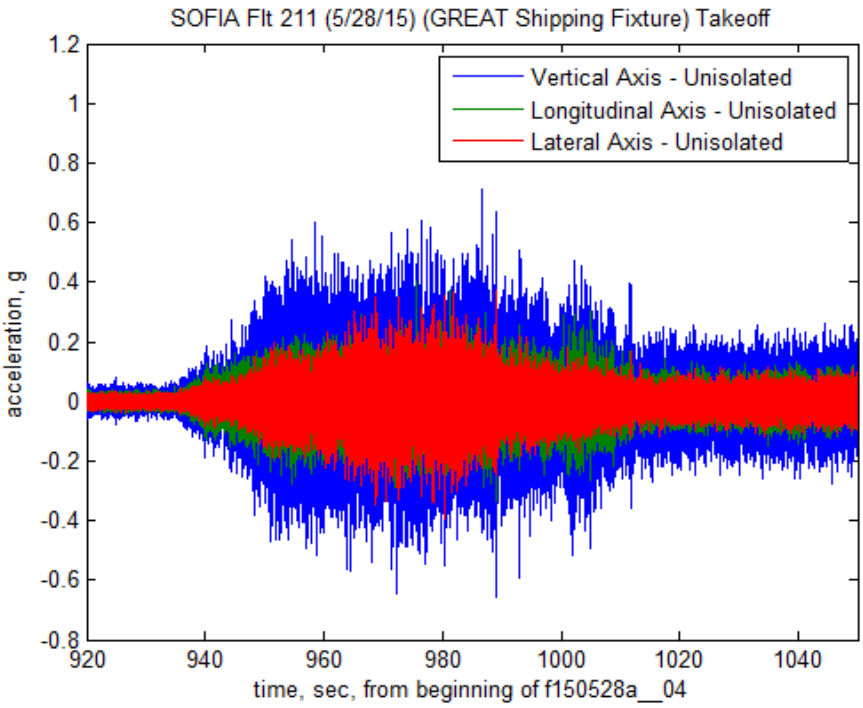


Figure 15: GREAT Shipping Fixture T/O (Unisolated)

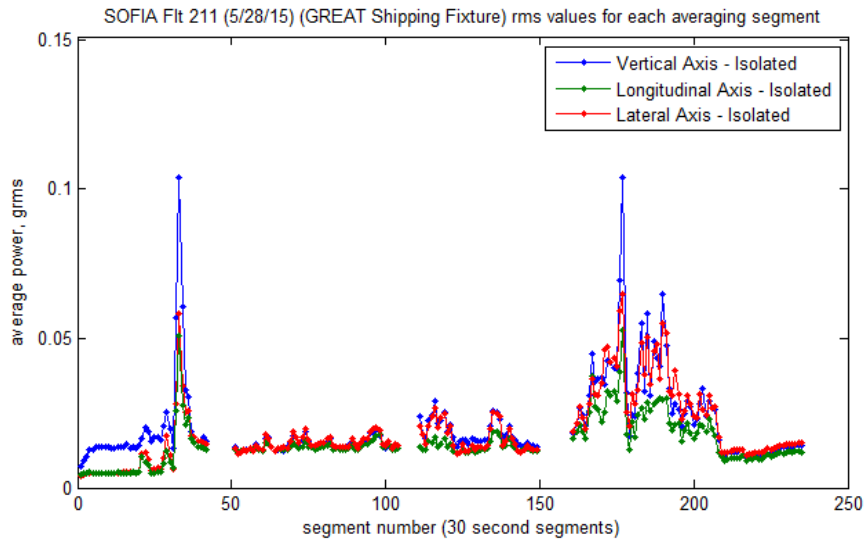


Figure 16: GREAT Shipping Fixture rms (Isolated)

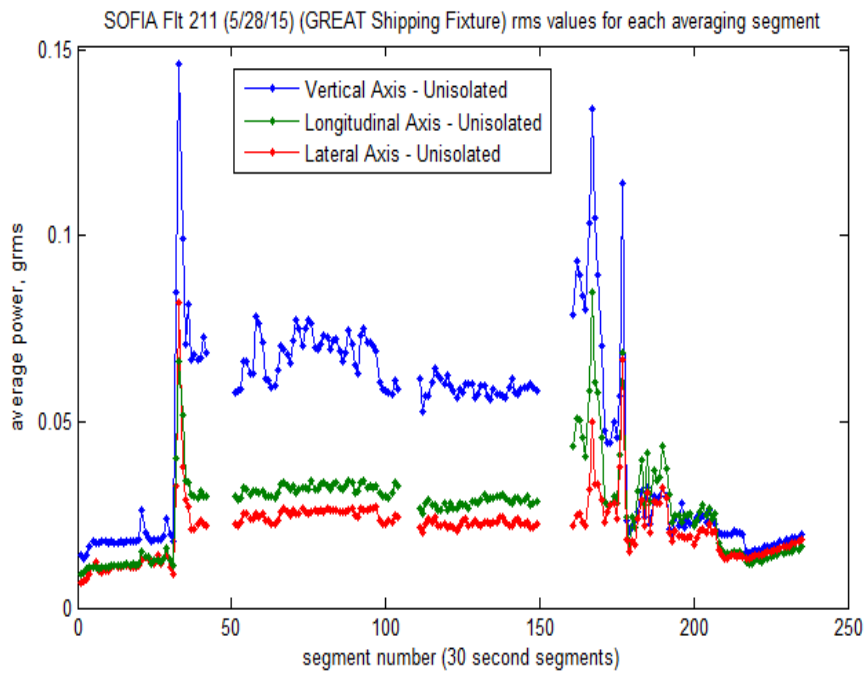


Figure 17: GREAT Shipping Fixture rms (Unisolated)

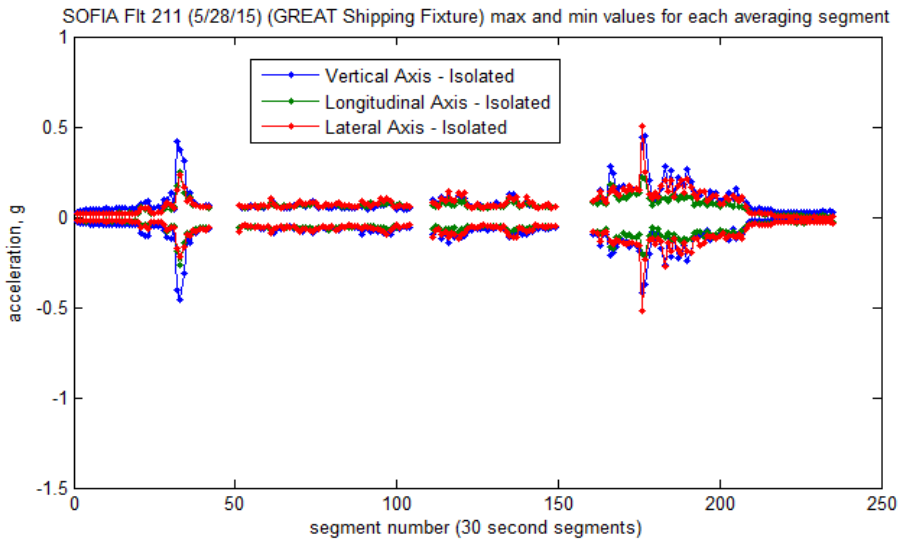


Figure 18: GREAT Shipping Fixture max and min values (Isolated)

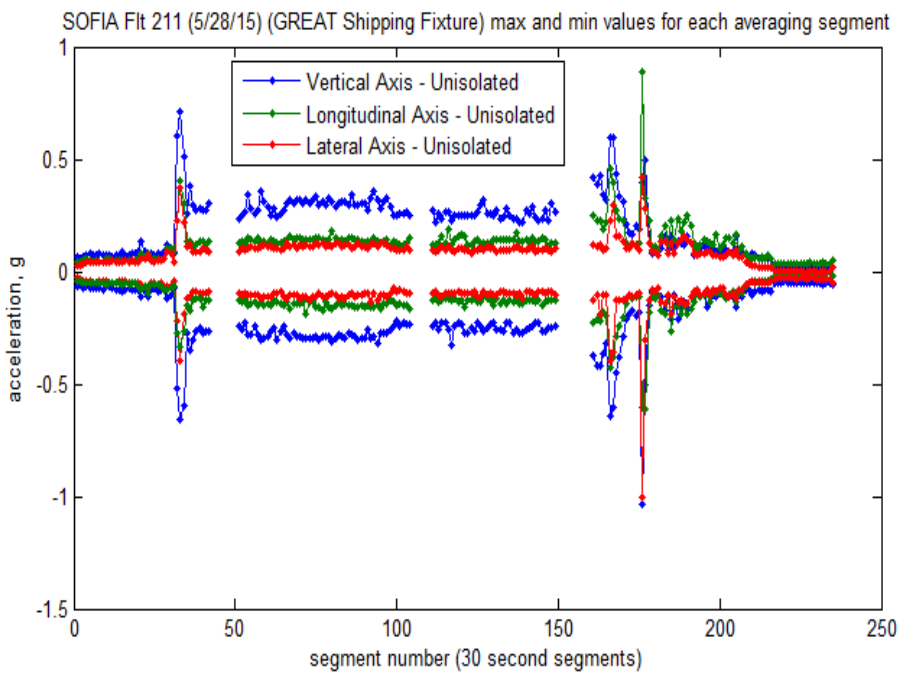


Figure 19: GREAT Shipping Fixture max and min values (Unisolated)

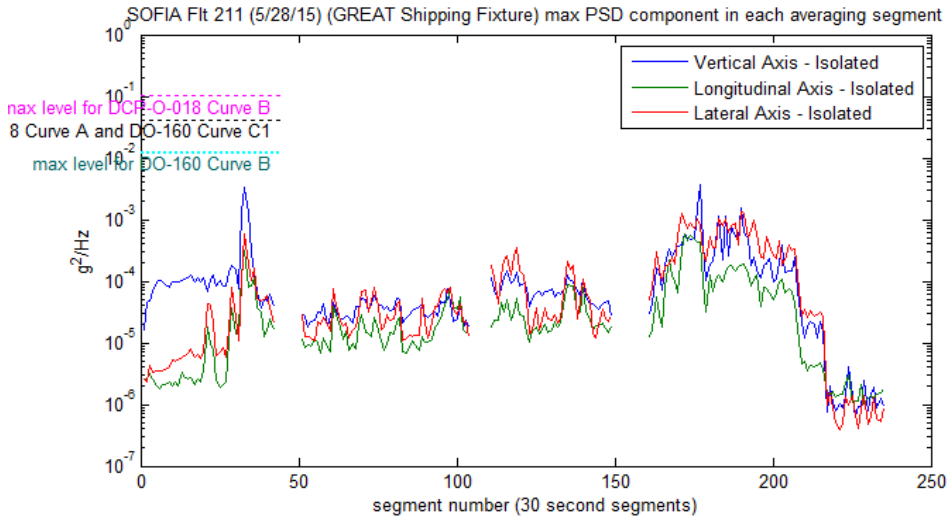


Figure 20: GREAT Shipping Fixture max PSD (Isolated)

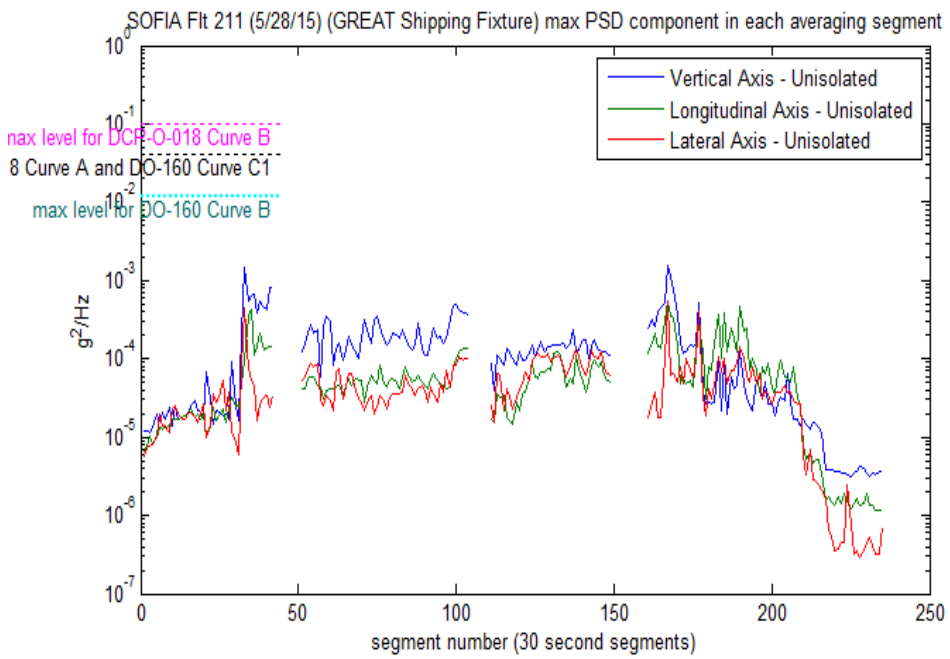


Figure 21: GREAT Shipping Fixture max PSD (Unisolated)

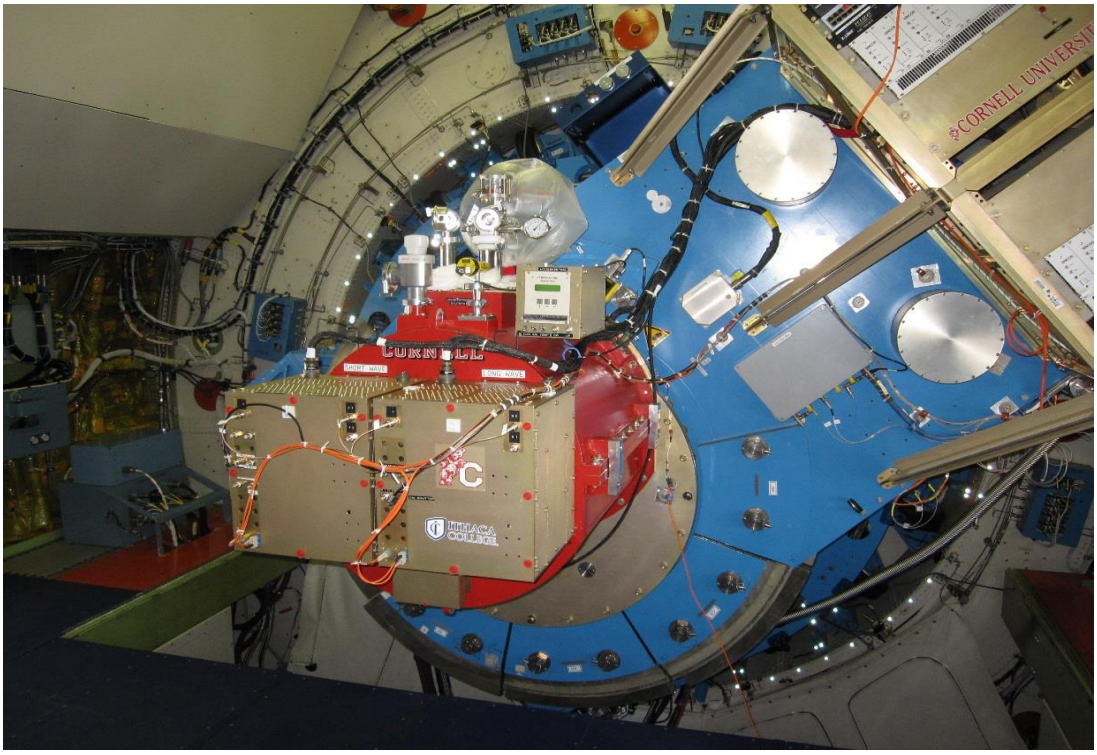


Figure 22: FORCAST on FLT#211

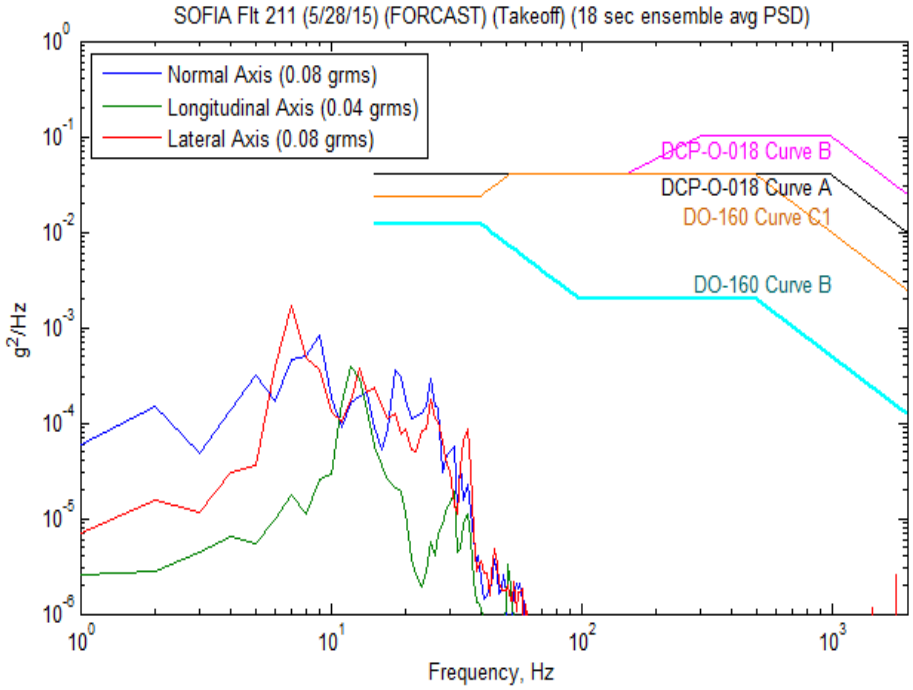


Figure 23: FORCAST T/O 18 sec

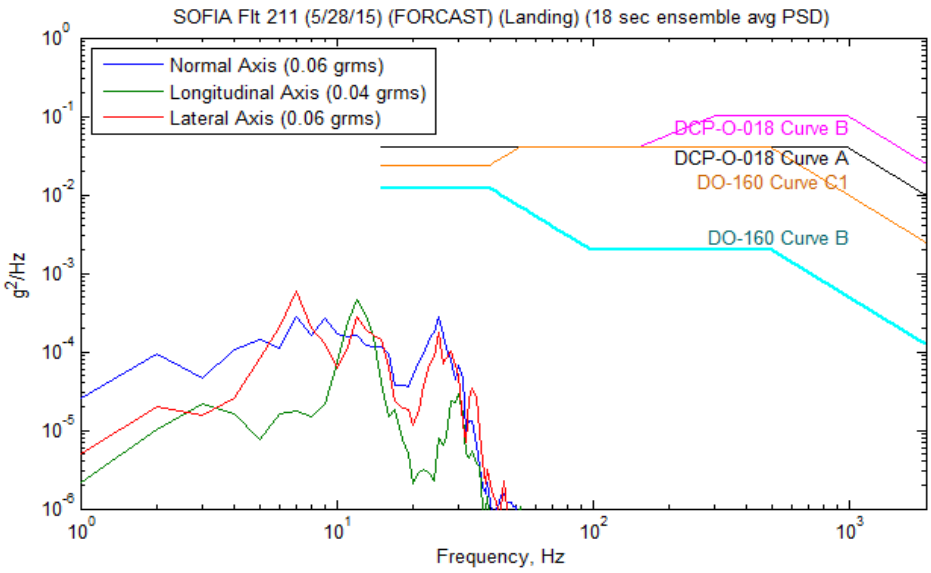


Figure 24: FORCAST Landing 18 sec

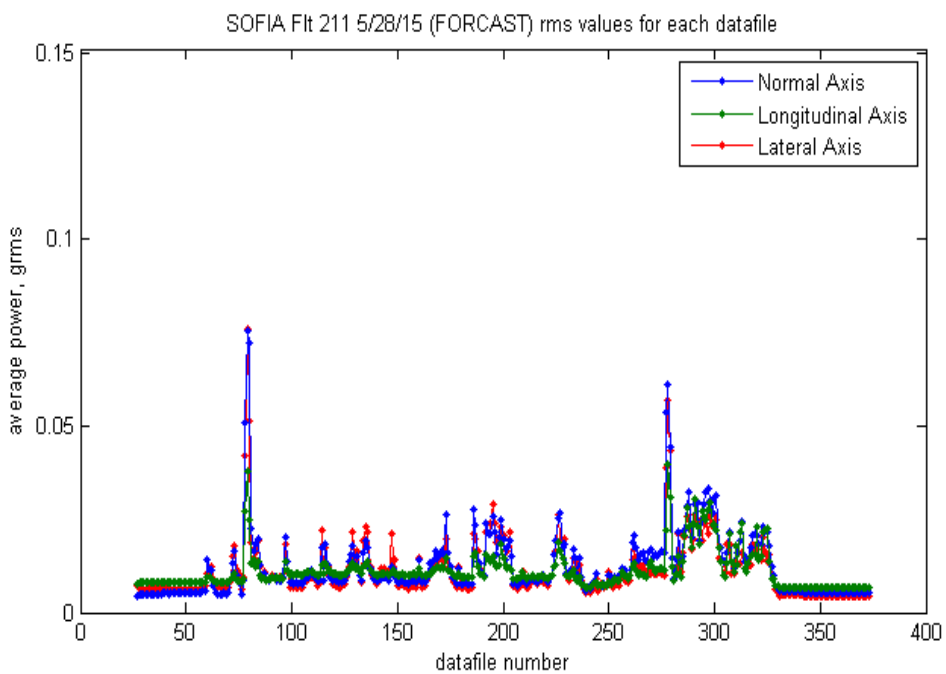


Figure 25: FORCAST rms values

Takeoff and climb was from datafile 27 – 96. Data at altitude was from datafile 97 – 185 and from 186 – 252. Descent, landing, and taxi was from datafile 252 – 373.

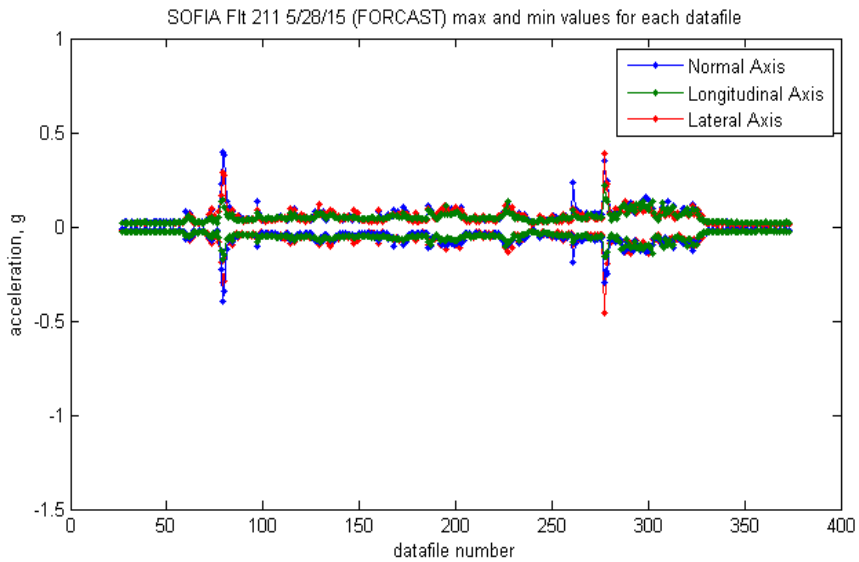


Figure 26: FLT211 FORCAST max and min values

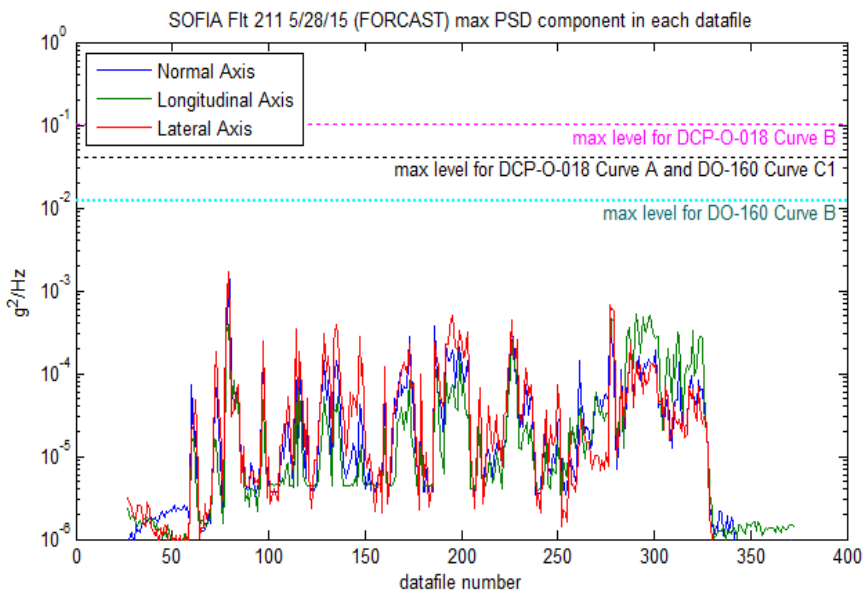


Figure 27: FLT 211 FORCAST max PSD

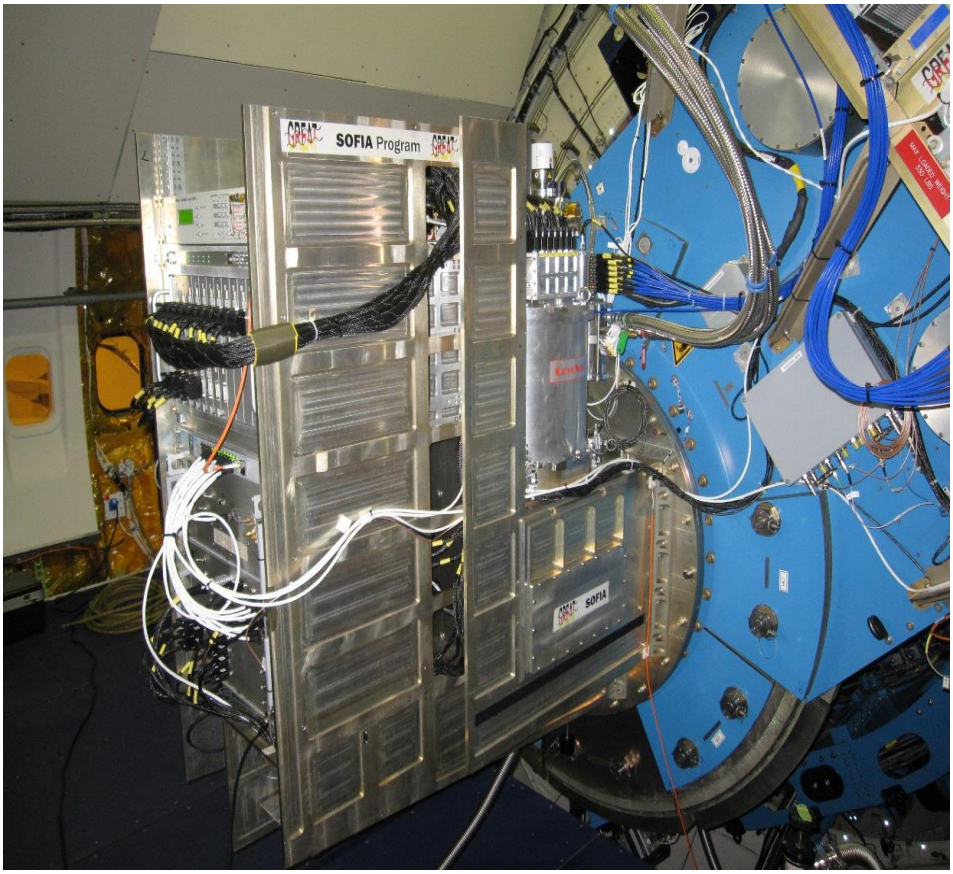


Figure 28GREAT on FLlt 208

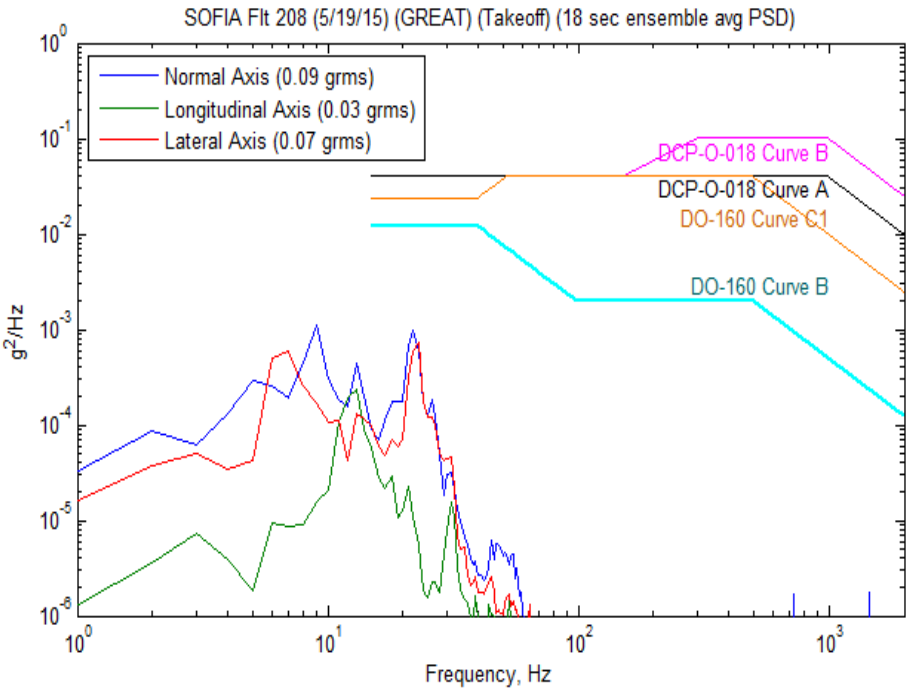


Figure 29: Flt 208 GREAT T/O 18 sec

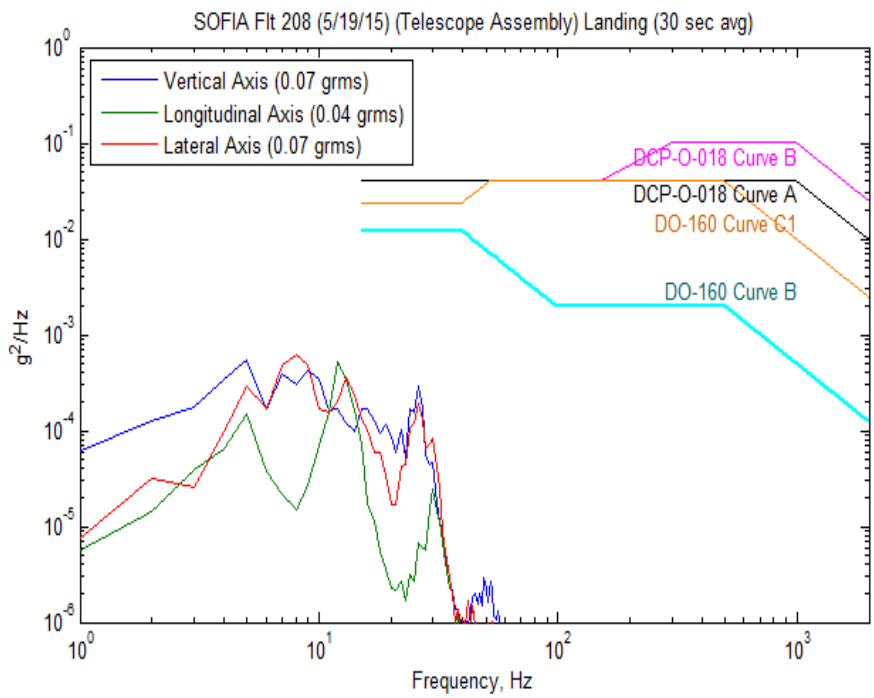


Figure 30: Flt 208 TA Assembly landing 30 sec

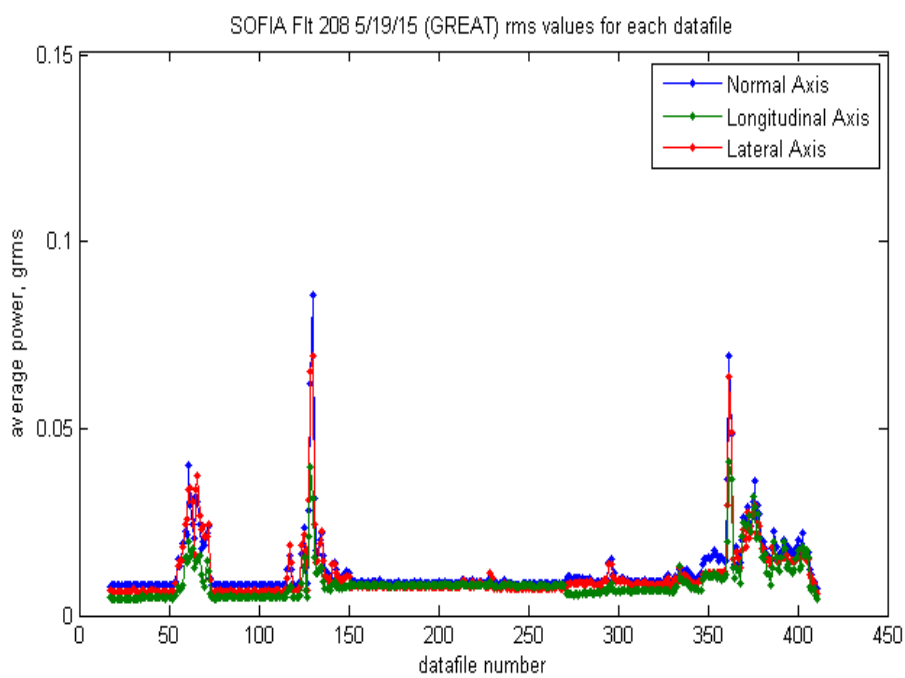


Figure 31: Flt 208 GREAT rms values

Taxi and takeoff took place during datafiles 17 – 150. SOFIA was at altitude during datafiles 151 – 270. Descent, landing, and taxi were in datafiles 271 – 411. Note: it appears from comparison with Figure 25 that GREAT has a quieter ride at altitude than FORCAST does. Compare also Figure 32 with Figure 27.

4. CONCLUSION

This analysis presents the vibration data for the SOFIA cargo bay with/without the vibration isolators on the mass dummy that represents the weight of GREAT and FORCAST. The vibration data also compared the TA flange vibration data with GREAT (Flt 208) and FORCAST (Flt 211) installed. The data shows that the vibrations environment of the SI shipping fixture with the vibration isolators meets the TA specifications as defined in the ICD TA-SI-02.