10.3 Vibration and Dynamic Environment

The SOFIA 747-SP aircraft exhibits a low level of vibration characteristic of large jet aircraft. In addition, the instrument assembly mounted on the TA flange is isolated from the airframe vibrations during observing integration periods by the telescope Vibration Isolation Subsystem (VIS). The most severe vibration environment an instrument will experience is when the telescope assembly is caged and braked, which occurs during aircraft taxi, takeoff, landing, and maximum reverse thrust events. Caging and braking the telescope is a safety measure for the telescope assembly and aircraft that happens to result in a more severe vibration environment for instruments during these three specific phases of a flight.

In-flight vibration measurements have been made using a triaxial accelerometer during various phases of typical flights at the telescope flange with the telescope in caged and braked, locally and inertially stabilized and tracking configurations. Measurements were also taken at the Counterweight Rack (CWR), PI rack, on the SI Shipping Assembly in the SOFIA cargo bay, and on the aircraft floor seat track in the vicinity of the telescope "pit" and aft MCCS rack. These are provided within the captioned figures in this section as representative of the worst-case vibration environmental conditions to which instruments will be routinely subjected in flight.

10.3.1 Quasi-Steady Load Factors

Measurements taken at the aft seat track indicate that continuous accelerations during turns can be as high as 1.2g in Z for several minutes; shorter transients of 1.7g in Z due to turbulence (one "bump"), and even 3g in the Y (lateral) axis during takeoff have also been measured, however these are generally too short in duration to be considered quasi-steady load factors, and better quantified with the vibration characterization in subsection 10.3.2.

Table 10.3.1-1 presents 1 Hz flight dynamic load factor and angle data acquired during 9 flights of a Spring 2011 observing campaign, broken down by flight phase. Note that while these measurements capture airframe rather than TA-mounted dynamics, the load factors are quasi-steady and will be fairly representative of load factors for TA- and CWR-mounted SI equipment, in aircraft coordinates. The Max Nz value recorded for each flight is highlighted in blue text.

Figures 10.3.1-1 and 10.3.1-2 present these data graphically. Table 10.3.1-2 is a composite summary of the Min / Max values from this suite of 9 flights, also broken down by flight phase. Note that these 1 Hz data indicate that turbulence events during the cruise phase (i.e., during observations) yield higher load factors than runway taxi and even ascent operations, and confirms that lateral loads remain generally quite small.

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Table 10.3.1-1: Flight Acceleration Data (1 Hz) by Flight Phases

Flight Data by Flight Phase, 1 Hz										
Flight	Phase	Alt A	Alt B	Nz	Ny	Nx	Pitch	Nxyz	Nxy	Nxyz Angle
54	Taxi	2275	2236	1.19	-0.07	0.22	-2.0	1.20	0.22	13.3
	Takeoff	2275	37503	**1.27**	-0.07	0.29	18.6	1.29	0.29	17.3
	Cruise	37506	43050	1.19	0.08	0.08	3.9	1.19	0.09	5.2
	Descent	43045	2280	**1.27**	0.10	-0.16	7.3	1.28	0.17	-9.8
55	Taxi									
	Takeoff	2924	38004	0.91	-0.03	0.27	13.4	1.09	0.27	14.8
	Cruise	38010	42912	0.83	0.06	0.07	3.6	1.17	0.07	4.1
	Descent	42896	2511	**1.28**	0.10	0.20	7.9	1.28	0.20	11.3
56	Taxi	2569	2537	0.85	0.07	0.22	-2.1	1.11	0.22	13.0
	Takeoff	2569	38001	0.82	0.07	0.28	15.8	1.18	0.29	15.9
	Cruise	37998	41023	0.84	-0.05	0.08	4.0	1.14	0.08	4.7
	Descent									
57	Taxi	2448	2413	**1.23**	-0.07	0.22	-2.1	1.25	0.22	12.8
	Takeoff	2448	37930	1.23	-0.07	0.28	16.1	1.25	0.28	16.7
	Cruise	37933	43041	1.16	-0.04	0.07	4.4	1.16	0.07	4.2
	Descent	43022	2454	0.78	-0.10	-0.18	8.8	1.19	0.18	-10.6
58	Taxi	2537	2539	1.18	-0.06	0.23	-2.0	1.20	0.23	13.1
	Takeoff	2537	38003	**1.19**	-0.06	0.32	14.1	1.21	0.33	17.3
	Cruise	38006	41037	1.17	0.03	0.08	3.9	1.17	0.08	4.3
	Descent									
59	Taxi	2462	2460	0.86	-0.10	0.25	-2.1	1.14	0.25	13.7
	Takeoff	2462	37004	**1.33**	-0.10	0.30	16.9	1.36	0.30	16.0
	Cruise	37007	43017	1.21	-0.06	0.09	4.9	1.21	0.09	5.4
	Descent	43008	2508	1.20	-0.07	-0.22	7.5	1.20	0.22	-12.1
60	Taxi	2486	2447	1.29	-0.10	0.22	-2.0	1.30	0.22	13.5
	Takeoff	2486	38008	1.29	-0.10	0.32	15.3	1.30	0.32	17.6
	Cruise	38008	42950	**1.52**	-0.05	0.08	6.3	1.52	0.08	4.6
	Descent	42946	2479	1.25	0.13	-0.19	8.1	1.26	0.19	-11.6
62	Taxi	2468	2436	**0.78**	-0.09	0.22	-2.0	1.23	0.22	12.7
	Takeoff	2468	38050	0.78	0.21	0.35	13.8	1.26	0.41	18.9
	Cruise	38054	43050	0.74	-0.07	0.08	4.2	1.21	0.09	5.1
	Descent	43049	2414	0.75	-0.11	-0.16	7.0	1.18	0.16	-9.6
63	Taxi	2625	2575	1.15	-0.10	0.21	-2.0	1.01	0.22	12.9
	Takeoff	2625	38863	0.79	-0.10	0.29	14.1	1.21	0.29	15.3
	Cruise	38863	43101	**1.22**	0.05	0.10	6.3	1.23	0.10	5.8
	Descent	43089	2553	1.22	-0.07	-0.17	7.5	1.22	0.17	-9.7

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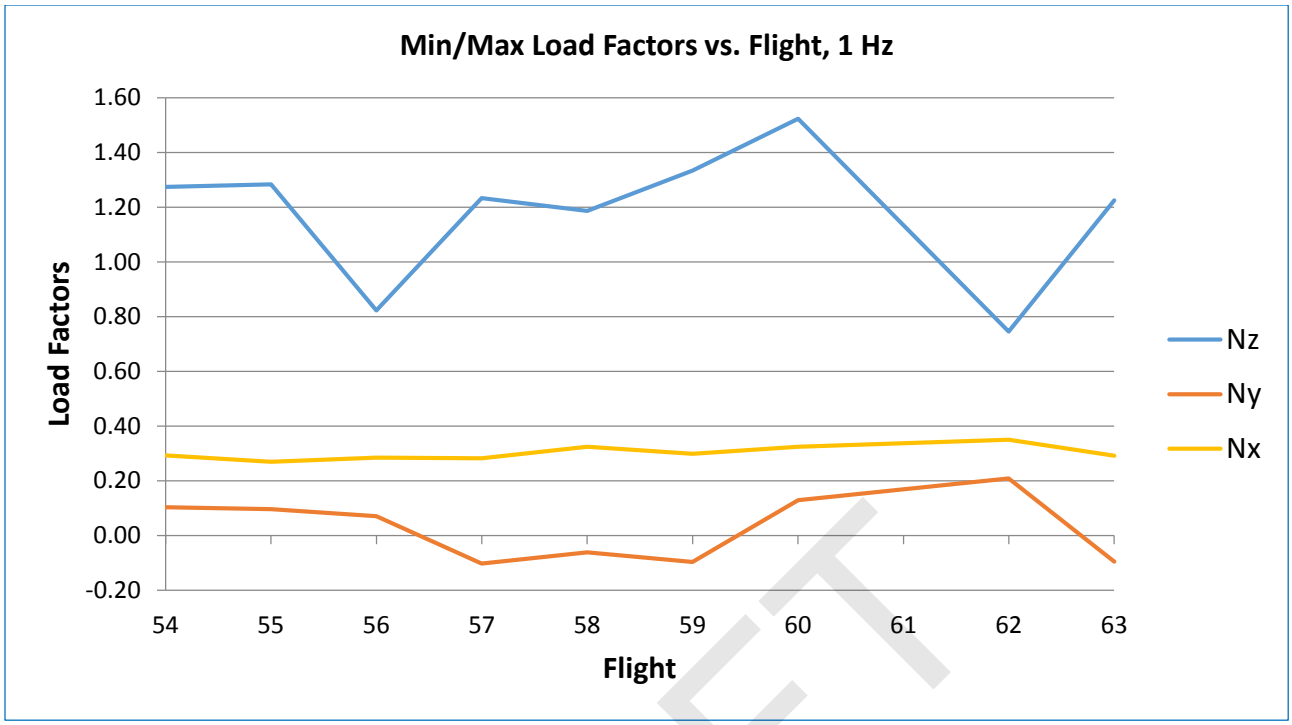

Figure 10.3.1-1: Graphical Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz)

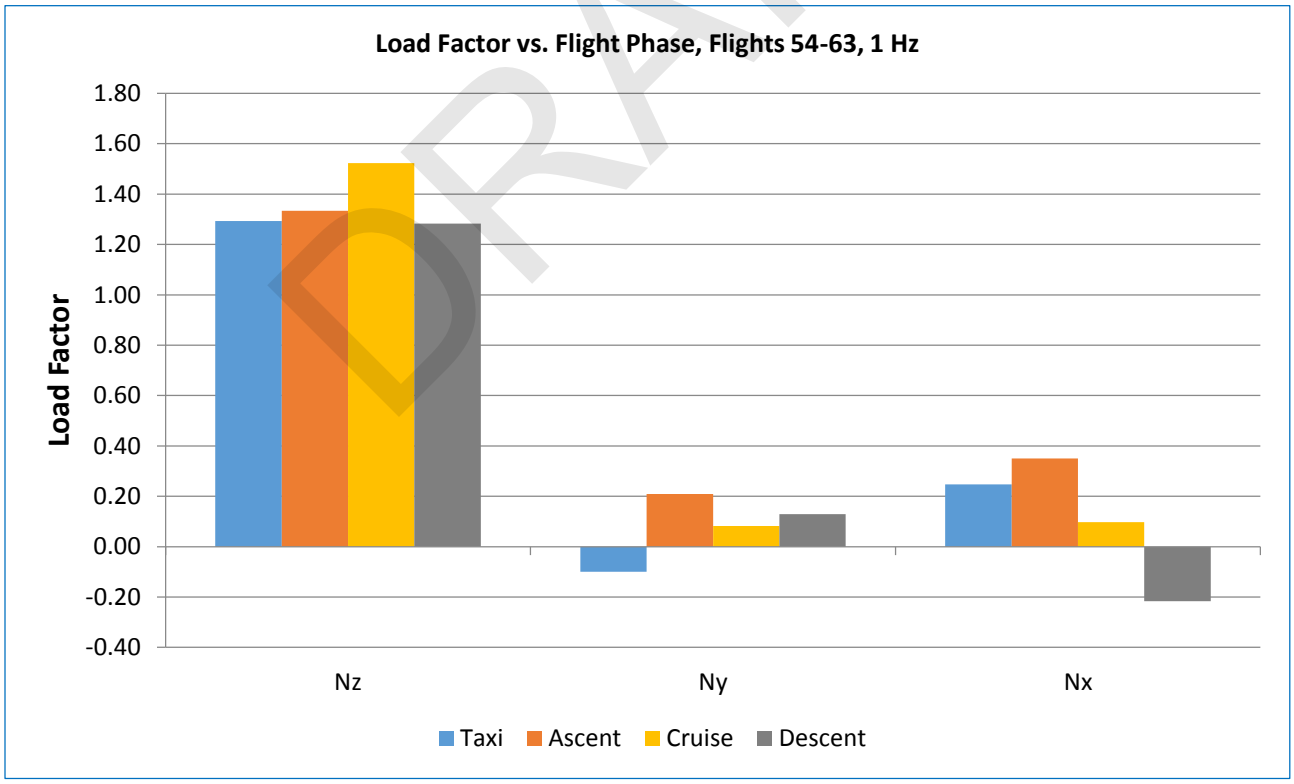

Figure 10.3.1-2: Graphical Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz) broken down by Flight Phase

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Table 10.3.1-2: Summary of Flight 54 through 63 Min / Max Accelerations (1 Hz) broken down by Flight Phase

Flight 54-63 Min / Max Values by Flight Phase, 1 Hz							
	Nz	Ny	Nx	Pitch	Nxyz	Nxy	Nxyz Angle
Taxi	1.29	-0.10	0.25	-2.10	1.30	0.25	13.70
Ascent	1.33	0.21	0.35	**18.63**	1.36	0.41	**18.90**
Cruise	**1.52**	0.08	0.10	6.30	**1.52**	0.10	5.84
Descent	1.28	0.13	-0.22	8.83	1.28	0.22	-12.06

10.3.2 Vibrations

In addition to the quasi-steady dynamic load factor measurements characterized above, a triaxial accelerometer head and "tattletale" vibration logger were flown on multiple SOFIA missions in order to characterize the vibration environment in three SI equipment locations: the TA IMF / SI Flange, a PI Rack, and a CWR. Earlier measurements have also been made with the accelerometer head mounted to seat track at the aft portion of the SOFIA main deck (near the TA pit), an aft MCCS rack, an upper bay of the MD Console, and the TA Balancing Plate Assembly (BPA), behind the CWR mounting location.

Detailed reports from each of these flights were produced by the AFRC Instrumentation group, and are available from the SOFIA SI Development group upon request. These reports generally include a summary of the data logger start and stop times, with a description of the flight phase and any notable conditions (e.g., turbulence, climb to new FL, etc.), and a variety of plots for the Longitudinal (X), Lateral (Y), and Normal (Z) axes: PSD plots (and corresponding composite G_{rms} levels) for the worst-case vibration levels encountered during the flight, time-series plot of Min / Max load factors, and time-series plot of G_{rms} vibration levels.

In addition to the primarily graphical information presented in the aforementioned summary reports and excerpted in the subsections below), the SOFIA SI Development group also has files that capture numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz, as measured in level cruise at the TA IMF / SI Flange during 2 SOFIA flights. These data will also be made available upon request to support analyses by SI development teams (e.g., propagation to SI cryostat cold plate, optical bench, and focal plane).

Rather than attempt to include all of these charts and summaries in this document, we have opted to "cherry pick" a subset of these that are representative of both typical / nominal operating conditions in the three (3) SI equipment locations aboard SOFIA, as well as for routine events such as turbulence, landings and high-speed ground maneuvers, etc.

The authors would like to thank Phil Hamory of AFRC-RD for providing and operating the accelerometer and tattletale recorder, as well as the post-flight processing and reporting of the vibration data. We would also like to thank Tim Krall of AFRC-OE for his assistance with integration of the hardware and coordination with the Instrumentation group to obtain these measurements.

10.3.2.1 Aft Seat Track

The triaxial accelerometer head was placed in the Brownline seat track on the starboard side of the aft main deck, just forward of the R/H CLA Disconnect Panel U2 during SOFIA Flight 55 (take-off on 5/5/2011). The worst-case vibrations during this flight were observed during the take-off phase. Figure 10.3.2.1-1 shows the time history of the G levels recorded by the accelerometer during this phase.

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It is worth noting that the +3 G lateral axis load factor picked up by this accelerometer and recorder is a very short-lived transient (< 1 millisecond) and as a result is not represented in the 1 Hz flight data set reported for the take-off phase from this same flight in the quasi-steady load factors section 10.3.1, above.

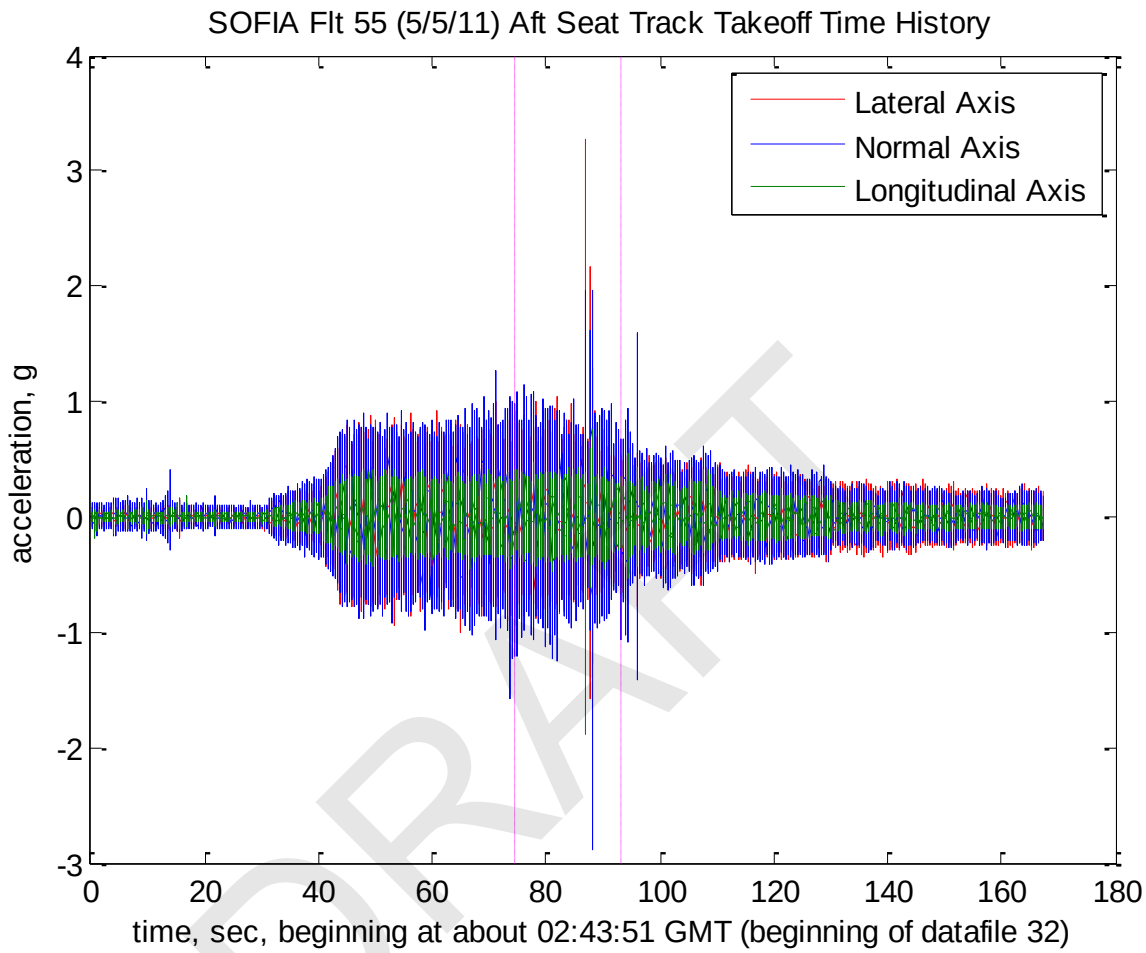

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Figure 10.3.2.1-1: Time history of loads measured at aft seat track on SOFIA main deck during take-off flight phase

The dashed vertical lines define the start and end of datafile 36, which is the 18.6 second period which includes the worst-case loads. Figure 10.3.2.1-2 shows the Power Spectral Density (PSD) content of the vibrations measured in each axis during this 18.6 second period.

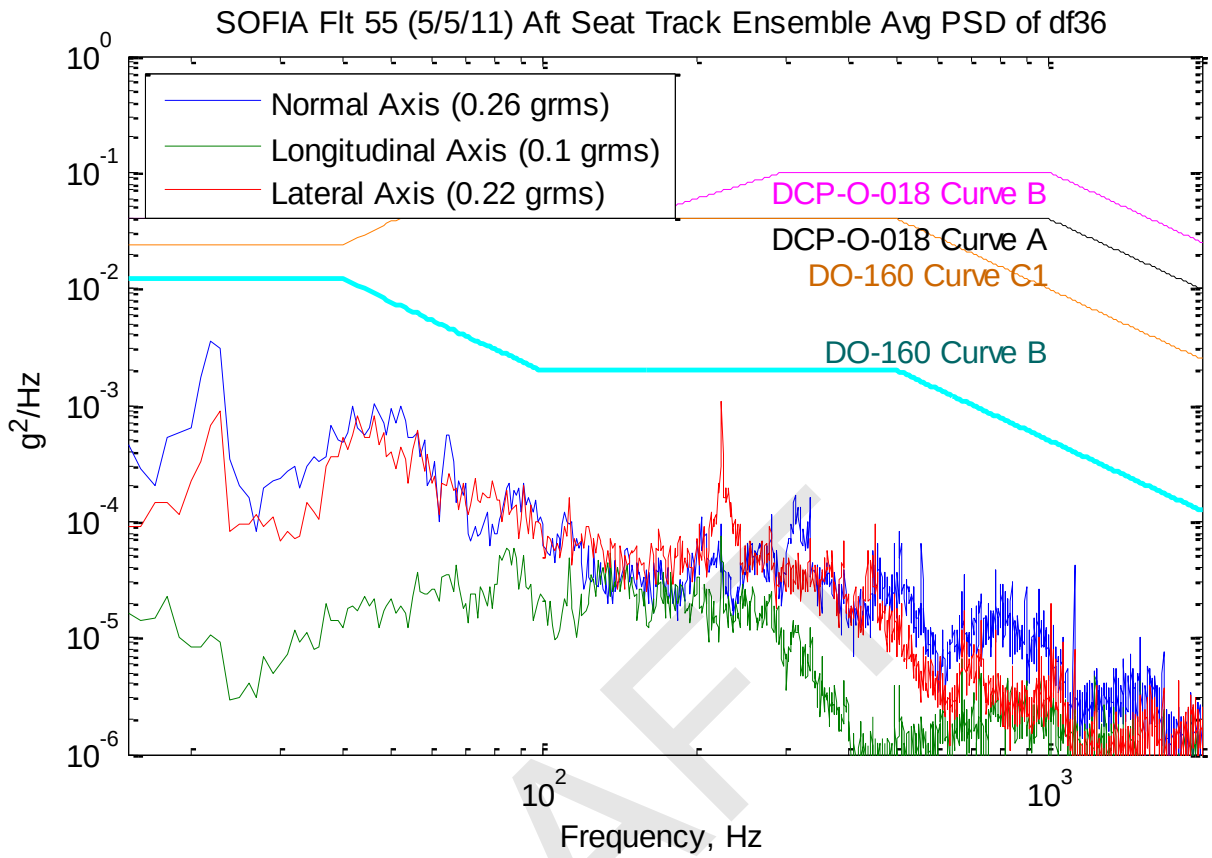

Figure 10.3.2.1-2: PSD of vibrations measured at aft seat track on SOFIA main deck during worst-case 18.6 seconds of take-off flight phase

Note that even measurements obtained from this non-isolated location of the SOFIA airframe during worst-case take-off flight phase exhibit low composite vibration levels of 0.1 G_{rms} in the Longitudinal (X) axis, 0.22 G_{rms} in the Lateral (Y) axis, and 0.26 G_{rms} in the Normal (Z) axis.

As expected, the vibrations recorded during observations in level flight at 38,000 ft, as shown in Figure 10.3.2.1-3, below, are even lower, with composite vibration levels of 0.06 G_{rms} in the Longitudinal (X) axis, 0.13 G_{rms} in the Lateral (Y) axis, and 0.18 G_{rms} in the Normal (Z) axis.

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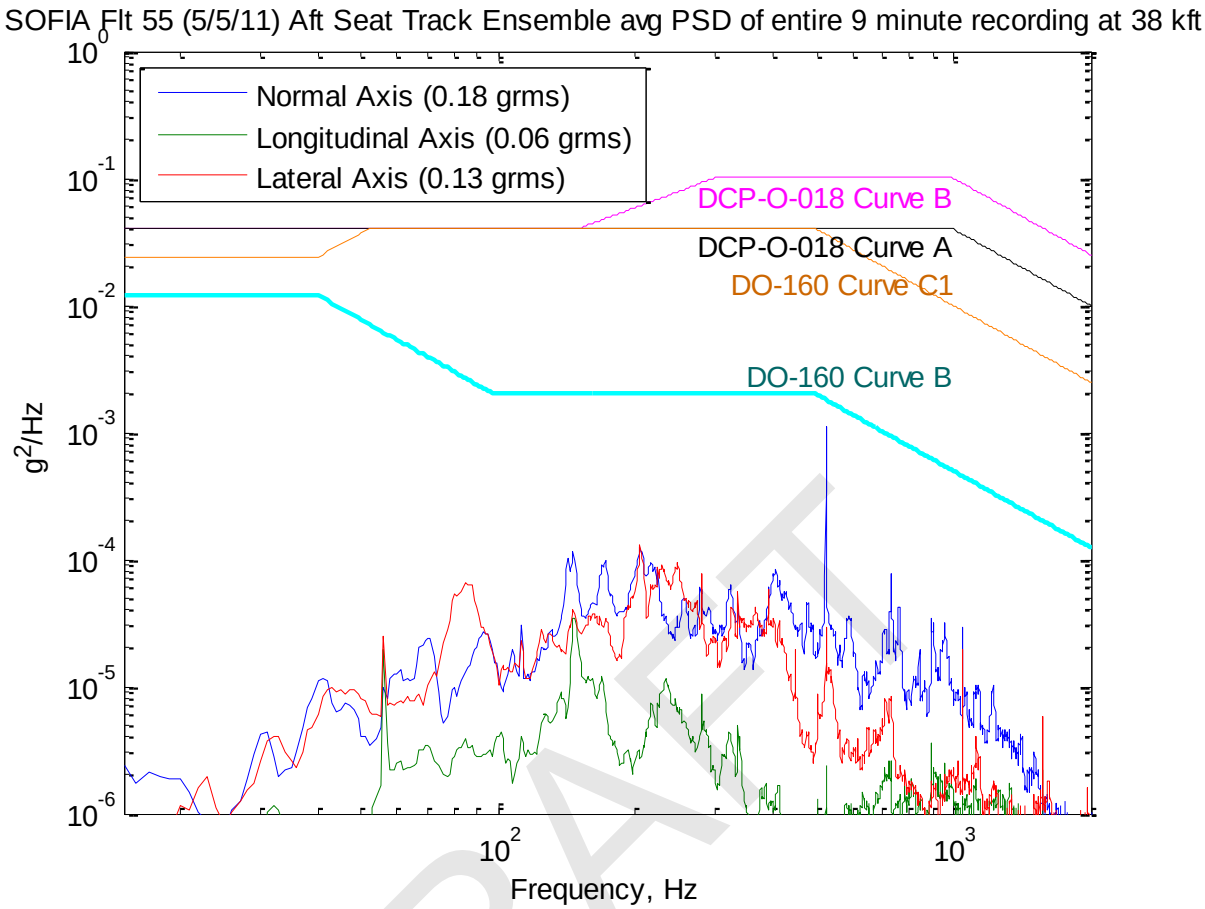

Figure 10.3.2.1-3: PSD of vibrations measured at aft seat track on SOFIA main deck during 9 minutes of recording in level flight at 38,000 ft.

Finally, measurements made during the descent flight phase, shown below in Figure 10.3.2.1-4, exhibit slightly higher vibration levels in the Longitudinal (X) axis, while the vibration levels in the Lateral (Y) and Normal (Z) axes are slightly lower.

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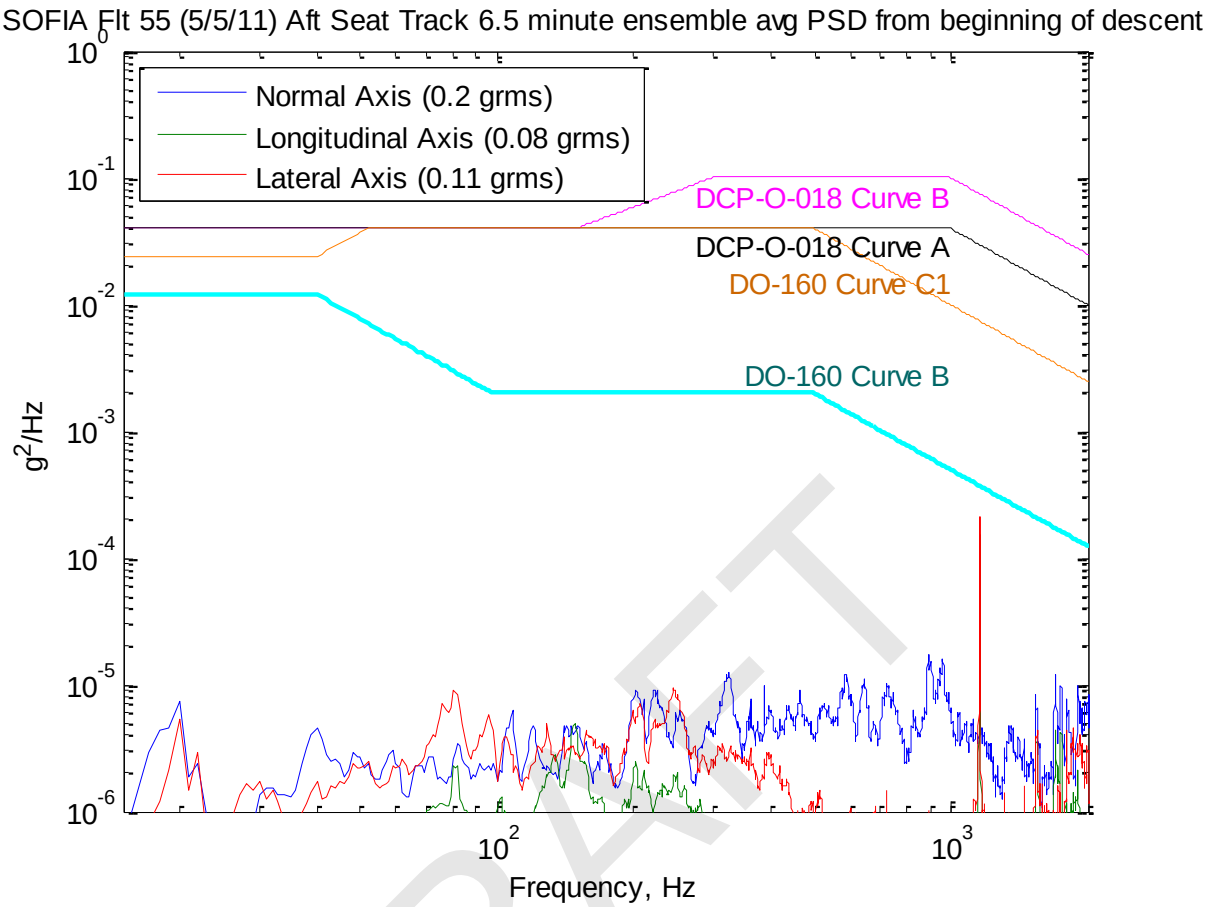

Figure 10.3.2.1-4: PSD of vibrations measured at aft seat track on SOFIA main deck during 6.5 minutes of recording starting with descent from observing altitude

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10.3.2.2 TA IMF / SI Flange (FORCAST)

Vibration measurements made at the TA IMF / SI Flange are expected to be of most interest to SI developers, as this is the structure to which the SI assembly, with the SI cryostat, optics, and focal plane detectors are rigidly mounted. Accordingly, measurements using the accelerometer and "tattletale" datalogger were made over 6 SOFIA flights, resulting in a very rich dataset.

In the interest of keeping this section concise and on point, we are publishing herein just a fairly tidy subset of these measurements, with a focus on those that characterize both typical / nominal operating conditions, as well as routine bumps and "knocks" that should be anticipated due to the dynamic nature of this observatory.

For these measurements, the triaxial accelerometer head was affixed to the "top" of the TA IMF, just aft of the FORCAST SI flange. See Figure 10.3.2.2-1 for an overview and detailed view of the accelerometer placement.

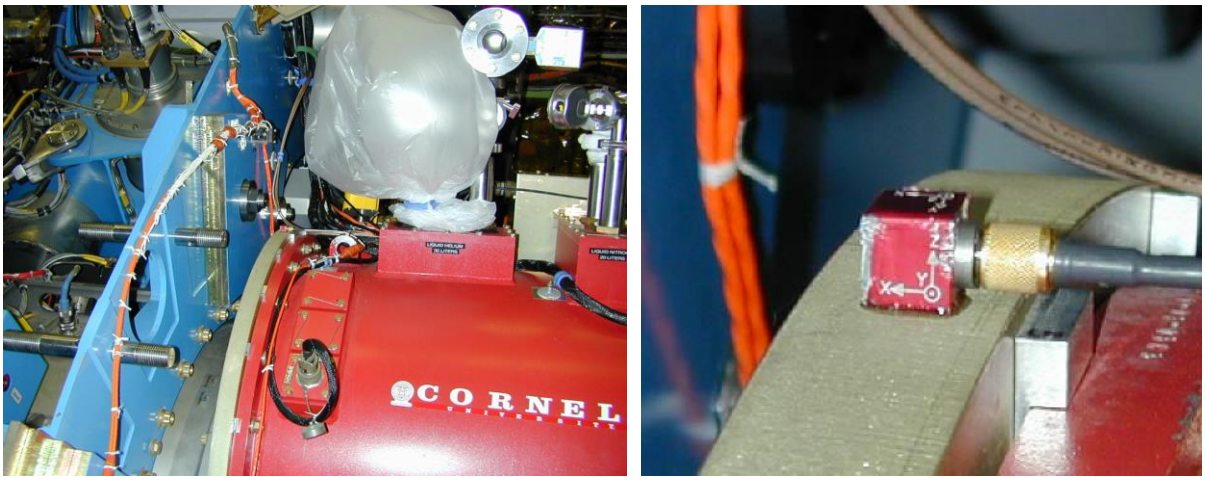

Figure 10.3.2.2-1: Overview and detailed view of the placement of the triaxial accelerometer head on "top" of the TA IMF, just aft of the FORCAST SI flange (red)

Note that these for measurements, the reported Aircraft Longitudinal, Lateral and Normal coordinate axes (X, Y, Z) should be interpreted as representing the corresponding TA coordinate axes u, v, w, due to the rotation of the TA w/ respect to the airframe in the Elevation (EL), and to a lesser extent, the Line of Sight (LOS) and Cross-Elevation (XEL) axes.

For SOFIA Flight 56 (take-off on 5/10/2011), the datafile with the worst-case composite G_{rms} levels was recorded during take-off (see Figure 10.3.2.2-2), while the datafile with the largest amplitude PSD component was recorded during ground taxi operations (see Figure 10.3.2.2-3).

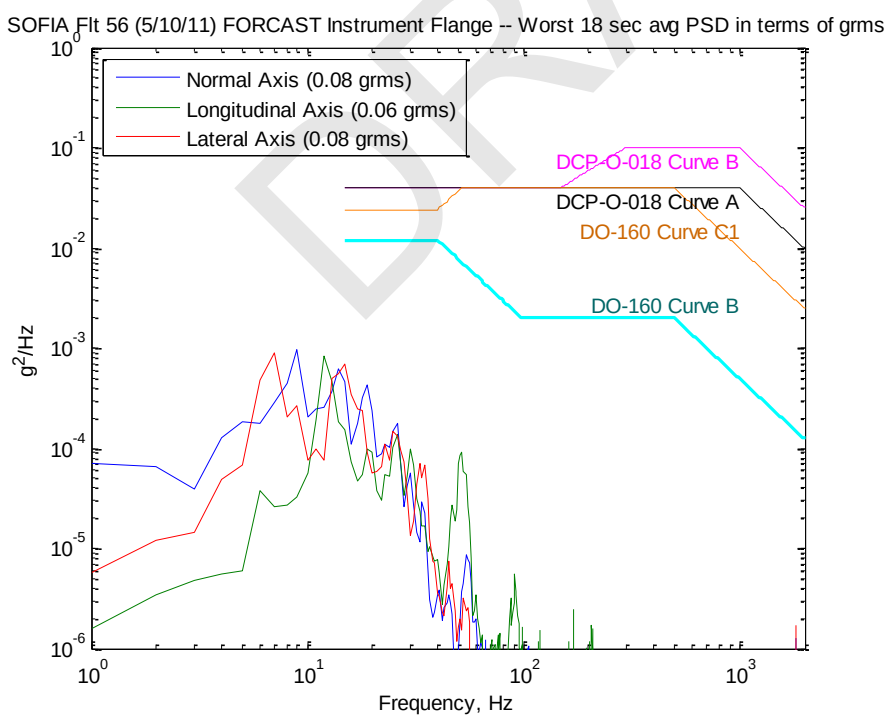

Figure 10.3.2.2-2: PSD of datafile reflecting worst-case composite G_{rms} vibration levels (take-off)

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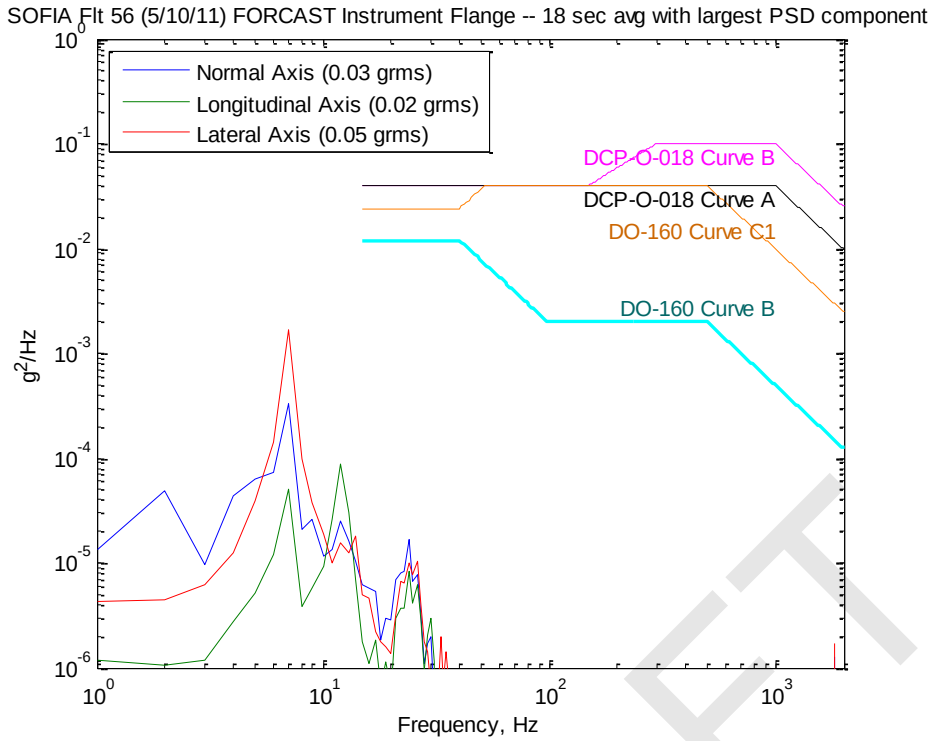

Figure 10.3.2.2-3: PSD of datafile reflecting largest amplitude PSD component (taxi)

To characterize a good range of flight conditions, we have selected and presented 3 datasets, below (these also represent the flight segments for which we have available the numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz from the datalogger).

Figure 10.3.2.2-4 represents the PSD averaged over a 7 minute segment acquired during level flight at 38,000 ft., with light turbulence and the TA uncaged / unbraked and on the vibration isolation system, but in inertial stabilization mode (not tracking an object).

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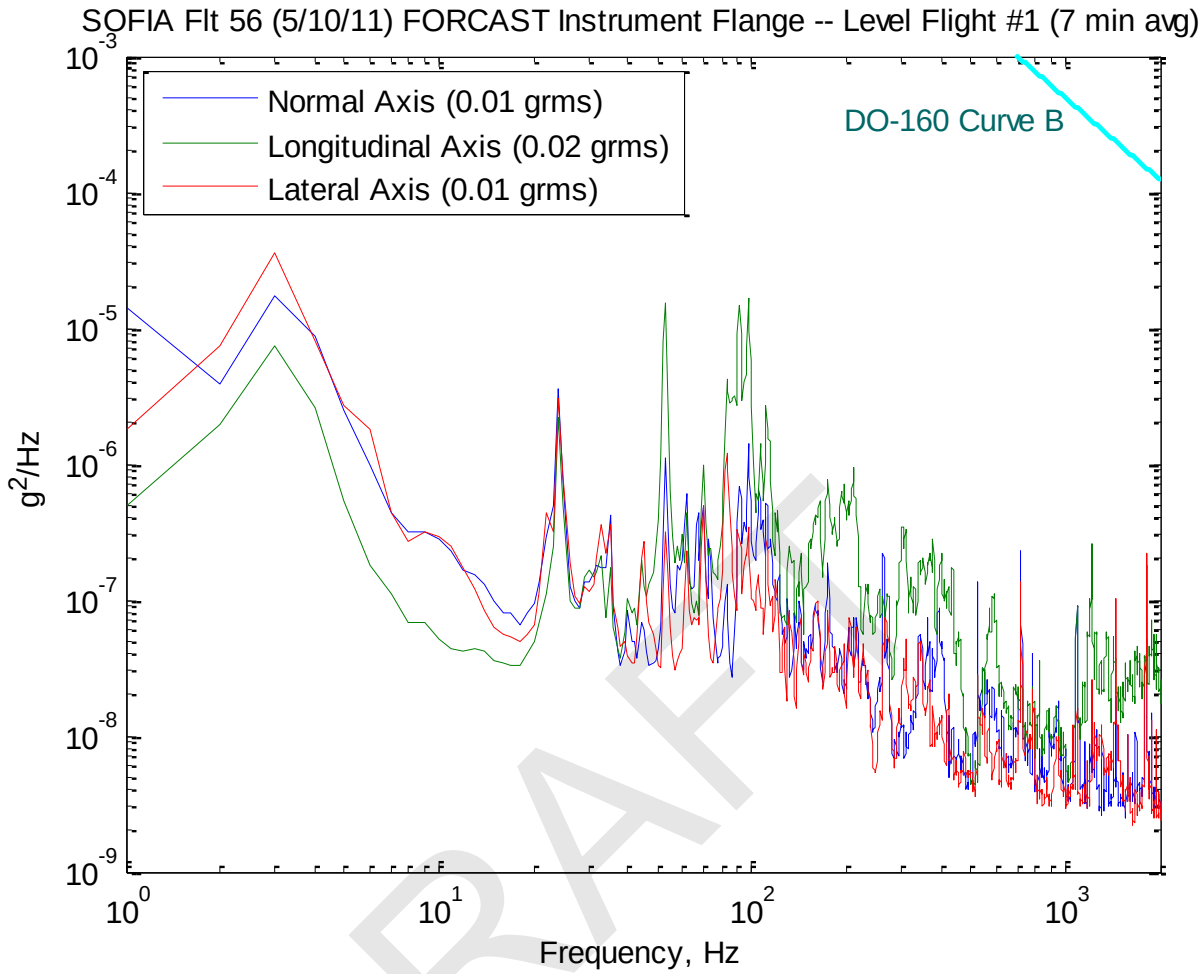

Figure 10.3.2.2-4: PSD of 7 minute datafile recorded in level flight at FL380 in light chop turbulence with TA uncaged / unbraked and in inertial stabilization mode (not tracking)

Figure 10.3.2.2-5 is the PSD from an 8 minute segment, also in level flight at 38,000 ft., but in smooth air and with the TA now tracking an object.

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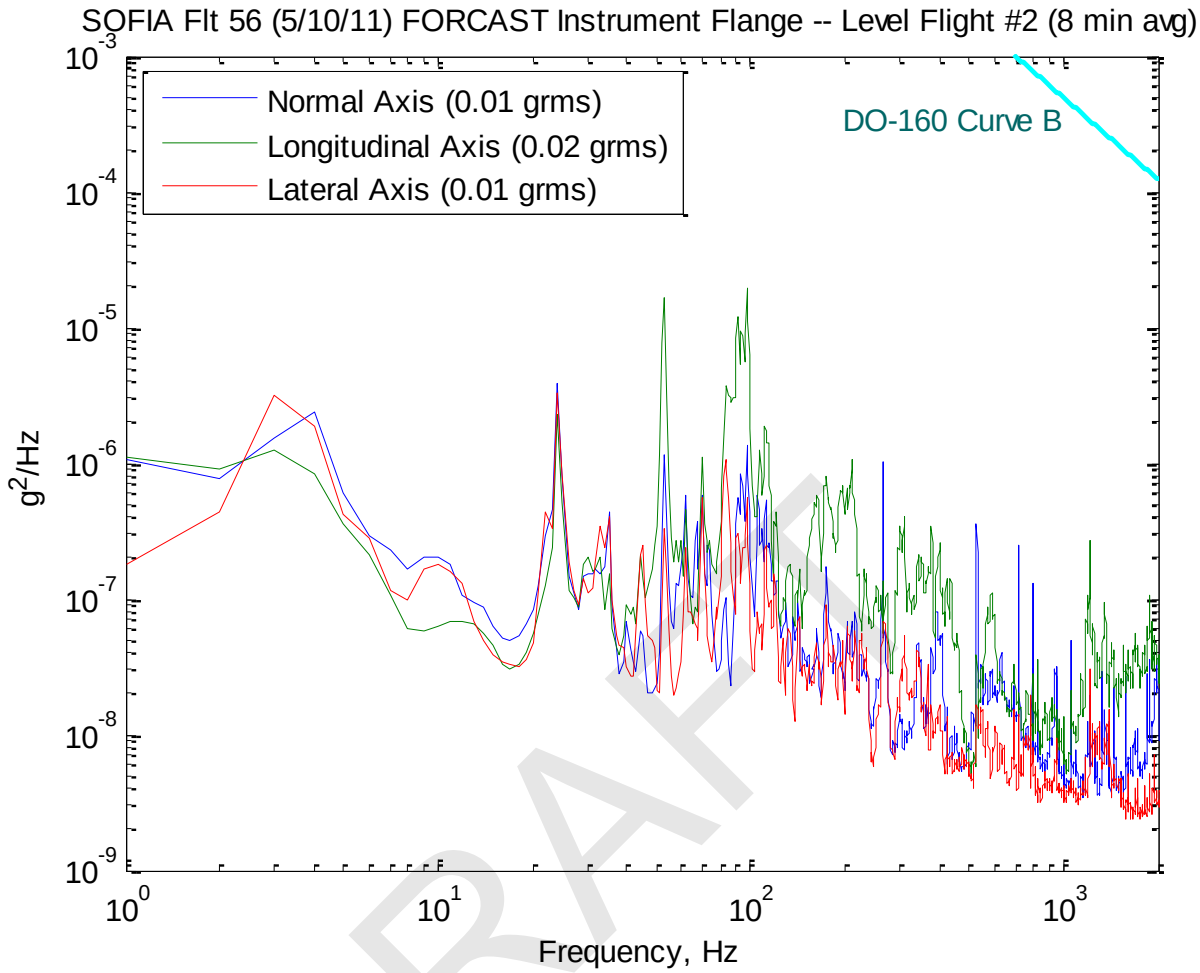

Figure 10.3.2.2-5: PSD of 8 minute datafile recorded in level flight at FL380 in smooth air with TA uncaged / unbraked and tracking object

Figure 10.3.2.2-6 is from SOFIA Flight 59 (take-off on 5/20/2011), and represents the PSD from a 4.3 minute segment acquired in level flight at 43,000 ft., in moderate turbulence with the TA uncaged / unbraked. As expected the low frequency content is a bit enhanced here due to the moderate turbulence.

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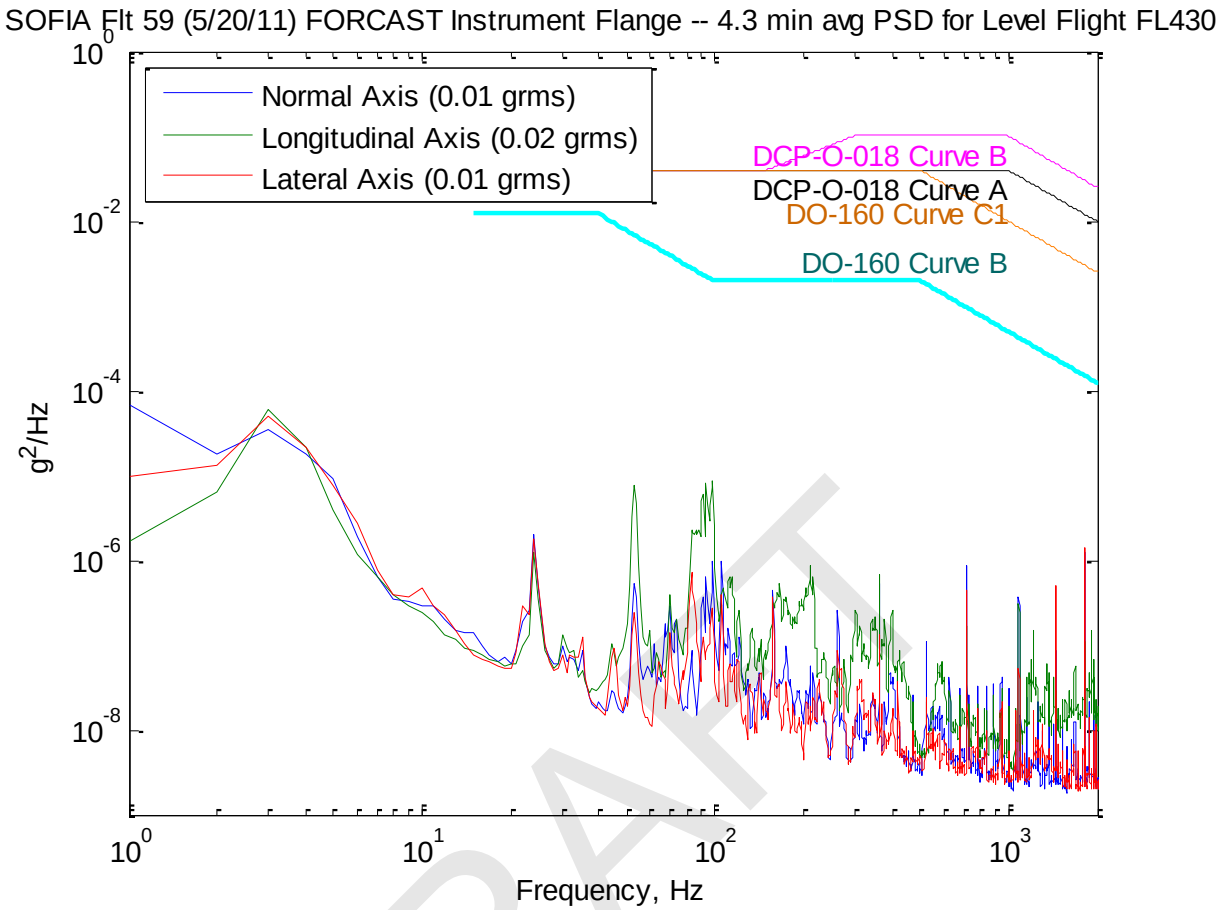

Figure 10.3.2.2-5: PSD of 4.3 minute datafile recorded in level flight at FL430 in moderate turbulence with TA uncaged / unbraked

As you can see, the SOFIA TA provides a fairly smooth ride to the SI during typical observing conditions, with these data providing some insight into certain frequency ranges where natural frequencies should be avoided to ensure these are not excited by transmitted vibrations.

10.3.2.3 PI Rack

To obtain vibration measurements representative of the PI Rack, the triaxial accelerometer head was attached to the aft center post of the Aux PI Rack, and the datalogger was operated during SOFIA Flight 64 (take-off on 6/7/2011). The worst-case vibrations for this location were observed during the landing phase. Figure 10.3.2.3-1 shows the PSD of the data file including this largest PSD component.

Though the vibration levels are still relatively low, the Lateral (Y) axis does reflect a largest frequency component “spike” at 19 Hz.

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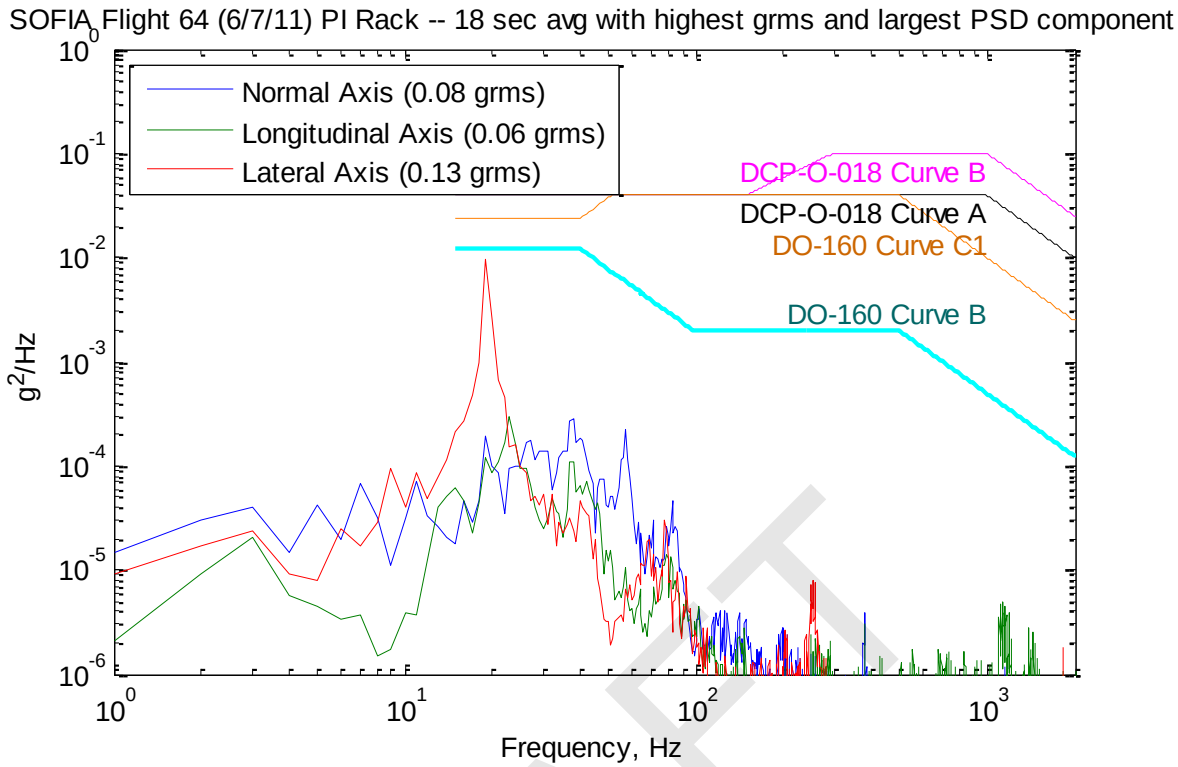

Figure 10.3.2.3-1: PSD of vibrations measured at aft center post of Aux PI Rack during landing

10.3.2.4 Counterweight Rack (CWR)

To obtain vibration measurements representative of the CWR, the triaxial accelerometer head was attached to one of the fore-aft equipment mounting extrusions in the CWR, and the datalogger was operated during SOFIA Flight 66 (take-off on 6/22/2011). The worst-case vibrations for this location were observed during the take-off phase. Figure 10.3.2.4-1 shows the PSD of the data file including this largest PSD component.

Note that these are correctly reported using the TA coordinate axes u, v, w, in lieu of Aircraft coordinate axes X, Y, Z.

The vibration levels measured here are somewhat higher than those recorded in the Aux PI Rack during landing, with the largest frequency component “spike” at 22 Hz.

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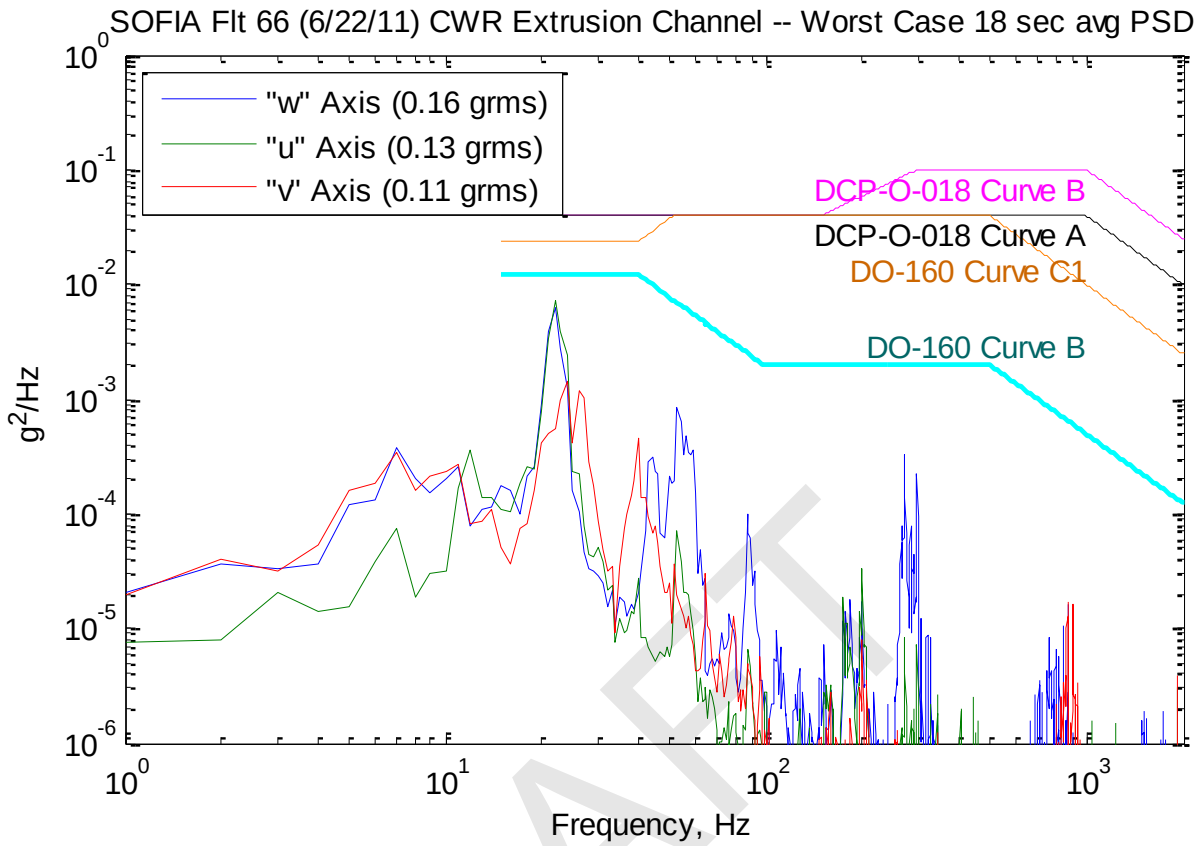

Figure 10.3.2.4-1: PSD of vibrations measured in CWR during take-off (worst-case)

Figure 10.3.2.4-2 presents the vibrational PSD measured in this same CWR location in flight, over a 12.5 minute period spanning cruise at 40,000 ft. and climb to 41,000 ft. with the TA caged and braked and the URD closed, with some measurements continuing with the TA uncaged and unbraked with the URD open. Note that while these PSD levels may appear to be similar to those from the worst-case take-off phase, the low end of the g^2/Hz scale is 2 orders of magnitude lower, and the composite G_{rms} values are also significantly lower.

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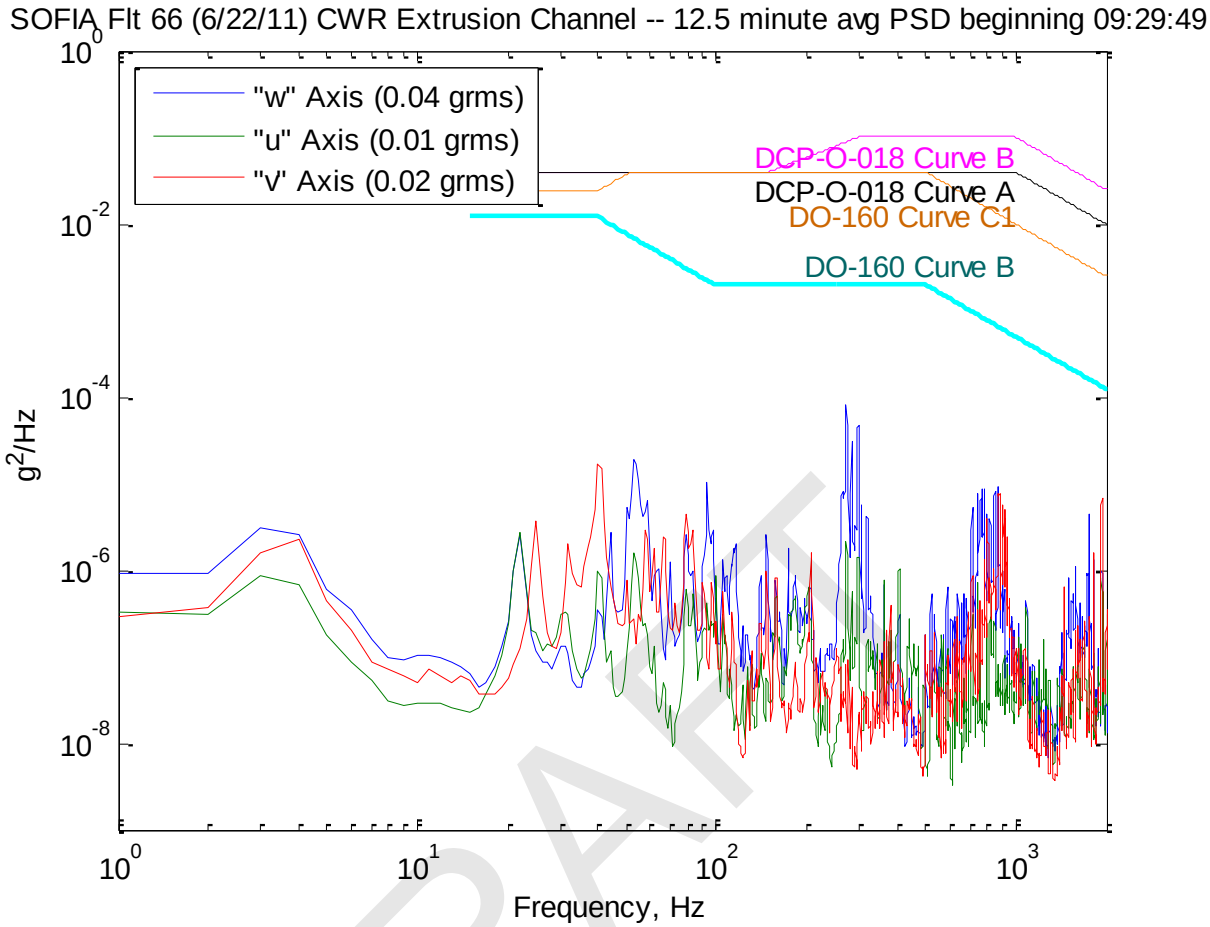

Figure 10.3.2.4-2: PSD of vibrations measured in CWR during 12.5 minute period during level flight at FL400 and climbout to FL410

As previously mentioned, the PSDs excerpted in this section are just intended to be exemplar of the range of vibration environmental conditions; the SOFIA SI Development group has a set of reports spanning 13 flights (9 from May ~ June 2011 period are presented in a comprehensive and consistent format, and will be made available to SI developers along with the accompanying numeric frequency-domain 3 axis average vibration PSDs from 1 to 2000 Hz files).

10.3.2.5 SI Shipping Assembly

To support the SI transportation logistics associated with multi-instrument deployments, the SOFIA program has developed two (2) SI Shipping Assemblies, shock-mounted and vibration-isolated structures that allow SIs to be transported in the SOFIA cargo bay, structurally supported solely via the SI mounting flange, for a very flight-like ride. This provides a convenient, low-risk, and cost-effective alternative to commercial freight shipment.

That said, the isolators used for these assemblies are known to be not particularly effective at attenuating lower frequency vibrations, such as those typically associated with inflight turbulence, and also exhibit natural frequencies in the 5 ~ 15 Hz range that can lead to amplification (resonance) with excitation frequencies.

A series of vibration measurements using triaxial accelerometer heads and vibration loggers were conducted on flights 208 and 211 in May 2015 to characterize the vibration and load environment for SIs being transported using this SI Shipping Assembly. During these flights, an SI mass dummy was supported on the SI Shipping Assembly in the cargo hold, and both the isolated and unisolated structures of the SI Shipping Assembly were instrumented with triaxial accelerometers. Simultaneous measurements were also acquired using a third triax accelerometer placed on the flange of the SI on the telescope (GREAT on Flight 208, and FORCAST on Flight 211) resulting in side-by-side comparisons of the vibrations during the various phases and dynamic events considered representative of a mission.

These measurements have been collected and published within SOF-NASA-REP-SE07-2165, *SOFIA SI Shipping Assembly Structure Dynamic Analysis*, so rather than attempting to excerpt and summarize these here, we invite interested parties to reference this analysis report.

It is worth mentioning that the vibration environment for SIs installed in the cargo bay are dependent on the orientation of the SI Shipping Assembly, and to a lesser extent, the specific location of the Shipping Assembly's pallet, and which tie-down "uplocks" are engaged.

10.3.2.6 Contextual comparison of measured vibrations with DCP-O-018B Environmental Acceptance Test levels

It is worthwhile to consider these typical SOFIA flight vibration measurements in the context of the environmental acceptance test levels that per DCP-O-018B are generally required of observatory mission system developments aboard SOFIA.

Partly because of the relatively "benign" shirtsleeve environment of SOFIA's pressurized jetliner cabin, SE01-2028 stops short of requiring that SOFIA SIs be subjected to vibration and/or "thermo-vac" environmental acceptance testing (commonly known as "Shake & Bake") in favor of a risk-tailored approach in which SOFIA environmental conditions are published so that SI developers may make informed assessments and decisions to optimize mission success criteria.

The figures showing vibration energy PSDs in previous subsections include several curves that define environmental acceptance vibration test levels from both DCP-O-018 and DO-160. However, these figures do not yet include Curve PA (1.55 G_{rms}), which was only available for NASA Transport Category V research aircraft via a Center Waiver process prior to Aug. 2014 when DCP-O-018B was released.

Figure 10.3.2.6-1 presents Z-axis vibration data PSD levels recorded over several flights, with an overlay of the applicable 1.55 G_{rms} Curve PA levels.

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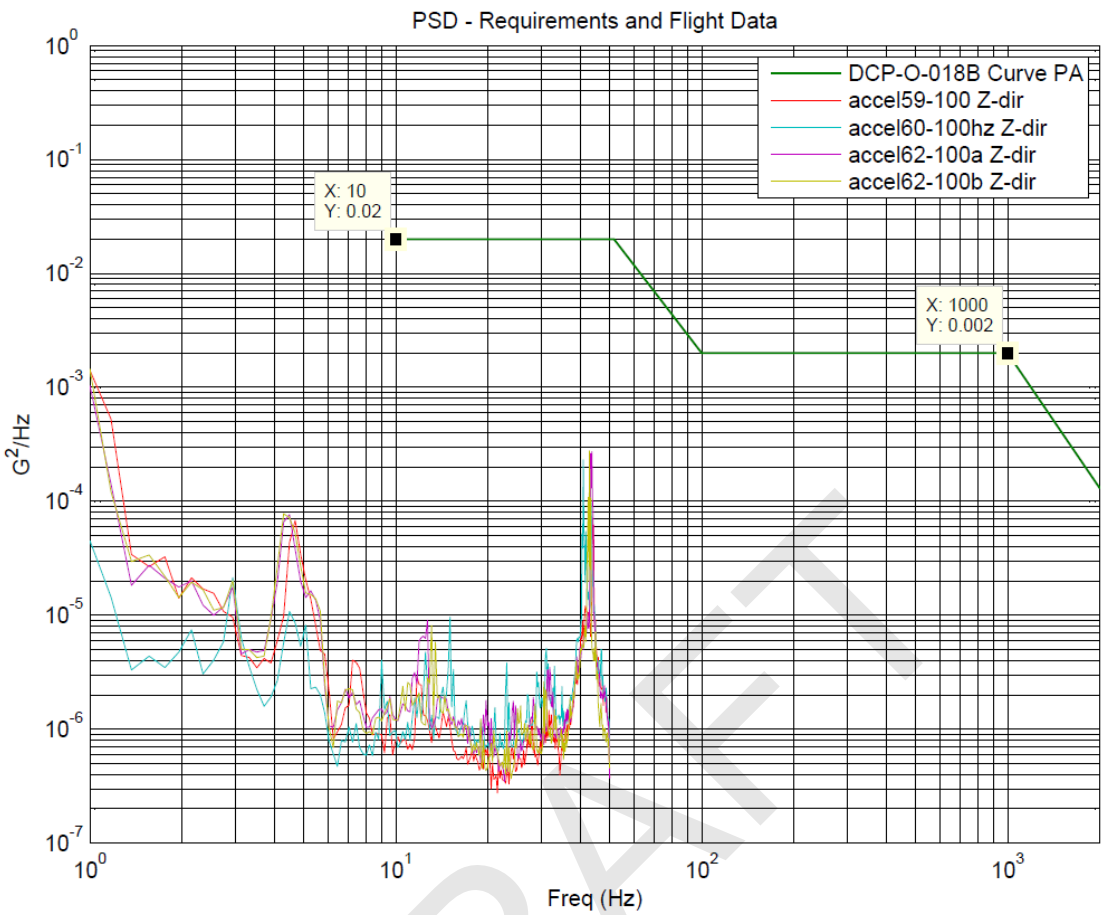

Figure 10.3.2.6-1: Typical Z-axis Vibrational PSDs with Overlay of DCP-O-018B Curve PA Environmental Acceptance Vibration Level

DCP-O-018B does include mass loading reduction factor provisions that allow for attenuation of the environmental acceptance test levels for heavier items of equipment (e.g., a typical SOFIA Science Instrument). For example, environmental acceptance vibration test levels for an assembly that weighs 160 lb or more are reduced from 1.55 G_{rms} to 0.78 G_{rms}, as depicted in Table 10.3.2.6-1 and Figure 10.3.2.6-2, below.

Table 10.3.2.6-1: DCP-O-018B Mass Loading Reduction Factor for Equipment weighing 160 lb or more

Test Curve Break Points						**G_{rms}**
Hz	**10**	**31**	**100**	**500**	**2000**	
Curve PA	0.02	0.02	0.002	0.002	0.00013	1.55
Curve PA, 160 lb	0.005	0.005	0.0005	0.0005	0.000033	0.78

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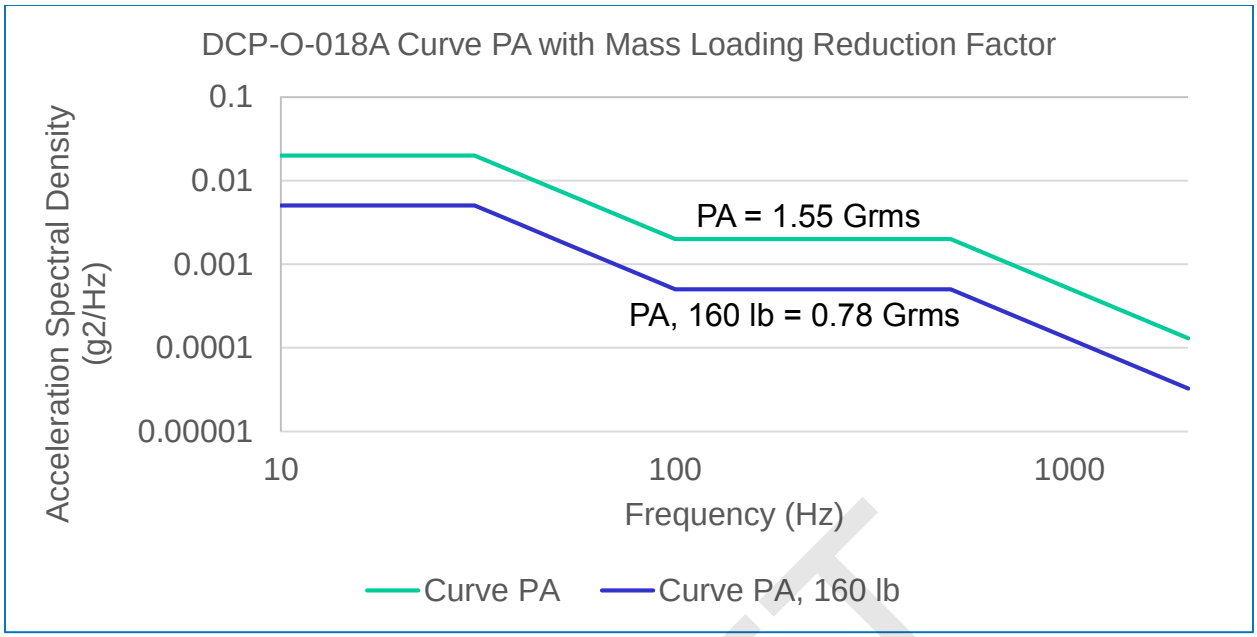

Figure 10.3.2.6-2: Typical Z-axis Vibrational PSDs with DCP-O-018B Curve PA Environmental Acceptance Level Overlay

It should be noted that even the attenuated 0.78 G_{rms} composite vibration level using this Mass Loading Reduction Factor is significantly higher than any of the measured environment vibration levels to which SOFIA SI equipment is subjected aboard SOFIA.

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