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Land- and Aircraft Carrier-Based F-35C Jet Blast Deflector Noise Testing

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Measurements of the noise generated by supersonic, impinging jets from full scale, high performance tactical aircraft engines are discussed. The supersonic jet studied is the exhaust from an F-35C, the Naval variant of the Joint Strike Fighter currently undergoing System Design and Development in the United States. The jet impinges on a Jet Blast Deflector – a surface angled behind the aircraft to deflect the exhaust up and away from personnel and other aircraft on the deck of an aircraft carrier. Data from land-based measurements with a large microphone array are compared with measurements from a limited array on the deck of an aircraft carrier.

I. Introduction

The high speed jet flows produced by modern high performance military aircraft engines generate high amplitude noise. These high noise levels are of increasing concern to the United States' military because of the hearing loss and other physiological impacts to personnel who work in close proximity to the aircraft. The concern is greatest for those personnel who work on the flight decks of aircraft carriers, where overall sound pressure levels (OASPL) can exceed 140 decibels. One measure of the financial impact of high noise levels is the cost of hearing loss benefits paid to United States military veterans. The rising costs associated with these claims in recent years are highlighted in reference.[1] Engineers developing the F-35C aircraft are required to define the flight deck noise environment due to operation of the aircraft. This requirement is driven by the need to develop advanced hearing protection systems for flight deck crew members, and thereby reduce hearing loss claims within the United States Department of Veterans Affairs.

The aircraft carrier flight deck noise environment is very complex, due to jet impingement on the carrier's Jet Blast Deflector (JBD); reflections from the flight deck, carrier island and other structures; ambient wind over the carrier deck; multiple simultaneous aircraft operations; and other factors. Two recent noise tests have been completed in order to develop models for the flight deck noise environment due to F-35C aircraft carrier launch operations. The first of these tests took place on land, at Joint Base McGuire-Dix-Lakehurst (JBMDL), NJ in June-July, 2011. The goal of this test was to define the noise field in the immediate vicinity of an F-35C / JBD system. The second F-35C / JBD test took place at sea, on the flight deck of the USS Dwight D. Eisenhower (CVN 69) during October, 2015. The goal of the second test was to validate the data obtained at JBMDL in an actual flight deck environment.

This paper describes the results of these F-35C noise tests. The following sections provide a description of the F-35C aircraft, and the aircraft carrier flight deck. Then, each of the JBD noise tests is described in detail, including various benefits and detriments in testing at each of the locations. This is followed by a comparison of the data recorded during the two tests, and discussion of preliminary conclusions. The paper will conclude with a discussion of possible future work.

II. F-35C Aircraft

The F-35C is the naval variant of the Joint Strike Fighter program. (The F-35A and F-35B are designed for conventional takeoff and landing – CTOL, and short takeoff, vertical landing – STOVL, respectively.) It is designed for operations from the United States' Nimitz class aircraft carriers, using steam-driven catapults

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for launch, and arrested recovery via a tail hook and steel cable pendants on the flight deck of the aircraft carrier. The aircraft employs one *Pratt & Whitney* F-135-PW-100 engine capable of producing 25000 lb_f of thrust at military power and 40000 lb_f with full afterburner augmentation. The aircraft empty weight is 34800 lb_f. It is in the 70000 lb_f maximum weight class.[2] A three-view image of the F-35C is shown in Figure 1.[3]

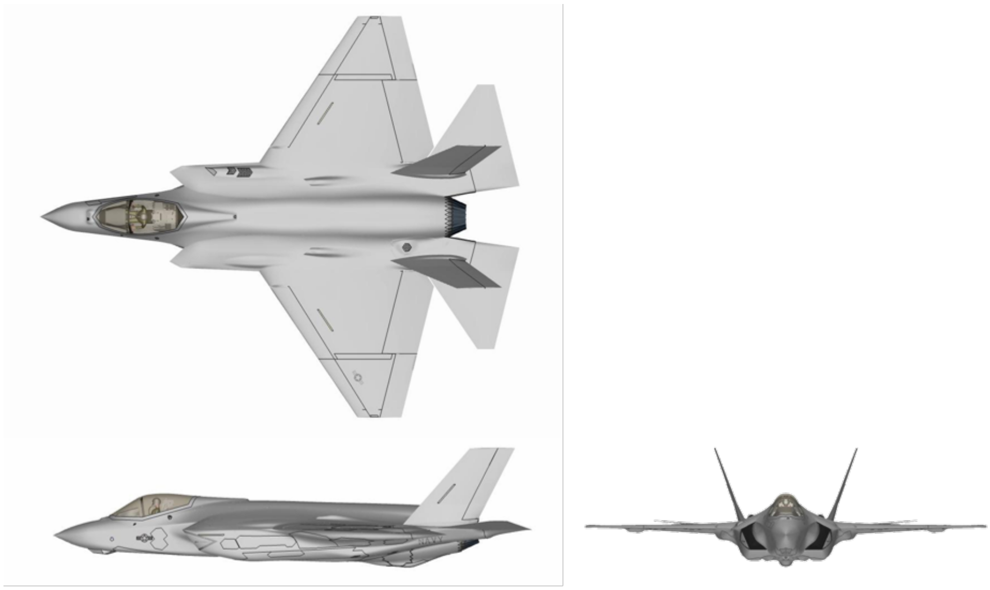

Figure 1. F-35C Configuration Three-View

III. Aircraft Carrier Flight Deck

The Nimitz class aircraft carrier is the largest ship in the United States Navy fleet. The flight deck is 1092 feet long and 252 feet wide, providing 4.5 acres of space for fixed wing aircraft and helicopter operations. Two nuclear reactors drive four propellers to give the carrier speeds in excess of 30 knots. Total crew, including ships company, the air wing and other personnel is approximately 5000. The carrier holds a mix of approximately 60 fixed wing aircraft and helicopters.[4] Figure 2 provides a representation of the flight deck. Evident in the figure are the four catapults. Each of the catapults is 302 feet long, and is capable of accelerating a 48000 lb_f aircraft from zero to 143 knots in two seconds.[4] A seawater-cooled, steel JBD is located aft of each catapult. The JBDs are normally stowed flush with the flight deck surface. When an aircraft is positioned on the catapult prior to launch, the JBD is raised to an angle of 50 degrees. When fully raised, the JBDs are 10.7 feet high. The JBDs behind Catapults 1, 2 and 3 are 36 feet wide; the JBD behind Catapult 4 is 24 feet wide. Before launching, each aircraft will run its engine(s) at full power for 15-30 seconds while system checks are performed by the pilot and flight deck crew. The JBD serves to deflect the resultant high speed, high temperature exhaust jet up and away from the flight deck, personnel, equipment and other aircraft. This significantly alters the noise radiated by the exhaust jet. Note that each of JBD / catapult combination has a unique orientation and separation distance. The goal of the tests described in the paper is to quantify the noise field from each JBD / aircraft combination.

IV. Land-Based Tests

The land-based tests took place at Joint Base McGuire-Dix-Lakehurst (JBMDL), NJ in June-July, 2011. JBMDL has a JBD installed within a concrete apron for use in carrier-based aircraft development. 81 *Brüel & Kjær* 1/4 inch pressure field microphones were placed in the near field of the aircraft / JBD system during F-35C engine runs at idle, military and afterburner power. The aircraft was positioned in front of the JBD at distances and orientations which correspond to the catapult / JBD separation distances and orientations on an aircraft carrier flight deck. 62 of the microphones were mounted on tripods, with the diaphragms four feet

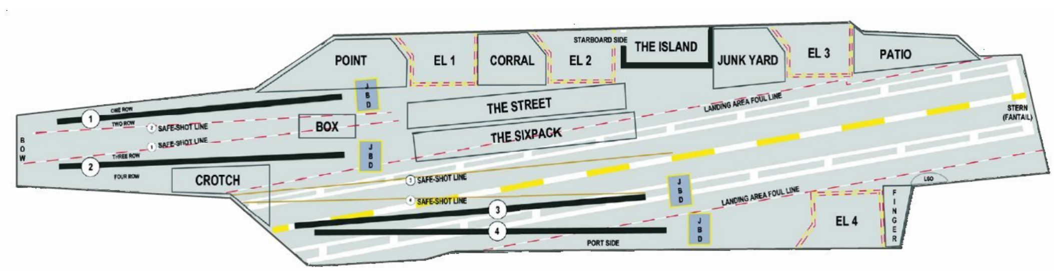

Figure 2. Representation of an aircraft carrier flight deck. Approximate scale.

above the surface. Six microphones were secured to the ground, to capture ground interaction effects, and 13 were mounted on the surface of the aircraft, to assist in quantification of sonic fatigue and structural dynamics assessments. Tripod-mounted microphones located in areas of high outwash, due to jet impingement on the JBD, were fitted with nose cones to reduce the effects of flow noise. These microphones were oriented with the noise cones pointed at the jet impingement location on the JBD, while the microphones with standard protective grids were oriented with the diaphragm normal to the impingement location on the JBD.

The aircraft / JBD test environment at JBMDL is shown in Figure 3. Evident in the figure is the array of 62 near field microphones on the port side of the aircraft. Outwash and thermal instrumentation is also shown to the side and behind the JBD. Multiple ground surface types – concrete, asphalt, grass and steel plating (behind the aircraft), are also shown. These varying surfaces, along with a drainage ditch with standing water beyond the microphone array, instrumentation trailers and other vehicles near the aircraft, and trees behind and to the right of the aircraft may have compromised the measurements. Winds were generally light (less than six knots) during the testing.

Figure 3. Aircraft / JBD test environment at Joint Base McGuire-Dix-Lakehurst.

The microphone signals were digitally recorded on a *Brüel & Kjær Pulse* recording system with a sample rate of 32768 Hz on all channels. Each microphone was calibrated with a *Brüel & Kjær* model 4228 piston-phone before and after each testing day. Piston-phone levels were compensated for the effects of humidity. Recorded signals were digitally post-processed into one-third octave band power spectra for each microphone and each test point using ANSI compliant digital Butterworth band-pass filters centered at the nominal band center frequencies from 10 Hz to 10 kHz.[5] The resulting spectra were corrected for the effects of atmospheric absorption,[6] and microphone frequency response.[7] The JBMDL, "Lakehurst," test captured the near field noise environment around an isolated aircraft / JBD system, at very low wind conditions.

V. Aircraft Carrier-Based Tests

The second F-35C / JBD test took place at sea, on the flight deck of the USS Dwight D. Eisenhower (CVN 69) during F-35C "Developmental Test II," (DT-II) in October, 2015. An array of six *Brüel & Kjær* 1/4 inch pressure field microphones were mounted on tripods four feet above the flight deck near Catapult 1 on the forward, starboard side of the Eisenhower. The tripods were secured to pad-eyes in the deck of the ship. The microphones were used to capture the noise generated by F-35C launches from all four catapults, as well as arrested recoveries and "touch and go" operations in the landing area. Each of the microphones was fitted with a nose cone to reduce the effect of the "wind over deck" due to atmospheric wind and the forward motion of the aircraft carrier. The microphones were oriented with the nose cones pointing down the ship's longitudinal axis so that they pointed into the prevailing wind. Outwash due to the exhaust jet impinging on the JBD was not observed at the microphone locations during DT-II. Wind over deck varied between 15-40 knots during DT-II.

The DT-II microphone tripods are shown in Figure 4. Catapult 1 on the Eisenhower is also evident on the left side of the image, approximately 50 feet from the line of six microphones. Note also that the tractor in the figure was not in that position during F-35C launches or recoveries. Figure 5 shows a close-up view of the system used to attach the tripods to flight deck pad-eyes. Also evident in these figures is the anti-skid coating on the flight deck. This coating is used to increase traction on the flight deck. The acoustical effect of this coating on the flight deck is unknown at this time.

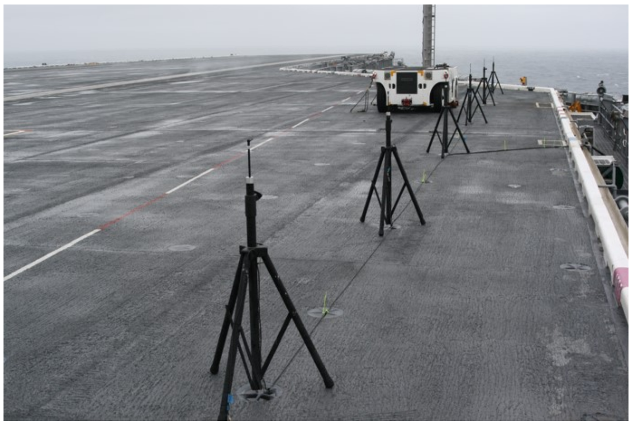

Figure 4. Microphone tripods mounted at "the Point" on the Eisenhower.

As in the Lakehurst tests, the microphone signals were digitally recorded on a *Brüel & Kjær Pulse* recording system with a sample rate of 65536 Hz on all channels. Each microphone was calibrated with a *Brüel & Kjær* model 4228 piston-phone before and after each testing day. Piston-phone levels were compensated for the effects of humidity. The microphones were removed and stored below deck after each test day to protect them from the salt air environment. Recorded signals were digitally post-processed into one-third octave band power spectra for each microphone and each aircraft launch test point. The resulting spectra were corrected for microphone frequency response. However, the effects of atmospheric absorption have not been corrected in DT-II data. The Eisenhower DT-II test captured a portion of the flight deck noise environment for relevant operational conditions.

In addition to the tripod-mounted microphones, 10 portable microphone / recorder measurement systems developed by the U.S. Air Force Research Laboratory were employed during the test. These portable systems allowed the test team to measure noise at specific locations in the aircraft near field and far field which correspond to crew member positions during flight operations. The fixed and portable microphone systems are shown in Figure 6, which was taken on the Eisenhower during an afterburner launch on Catapult 1. One of the portable systems is shown in the traditional "final checker" location just aft of the aircraft's wingtip. The fixed microphone array is also visible in the background, approximately eight feet from the edge of the flight deck. Data from the portable microphone systems will be used to validate the fixed microphones, quantify noise at specific crew member work locations, and correlate data measured during the two tests. This correlation is difficult to achieve, due to the vastly different environmental conditions experienced during the two tests. Data from the portable microphone systems are being processed, and results will be related in follow-on publications.

Figure 5. Microphone tripod attachment to flight deck pad-eye.

VI. Results

VI.A. Land-Based Test

The data recorded during the land-based test at JBMDL were processed as discussed above. Figure 7 shows contours of OASPL in the near field of an F-35C / JBD combination for a catapult-JBD distance of 67 feet, 4 inches, and the catapult normal to the JBD. This configuration corresponds closely to that of Catapult 2 on a Nimitz class carrier. (The nominal orientation for Catapult 2 is 1.9 degrees left of normal.) The engine was set to military power. One-third octave spectra were averaged over eight test points (264 seconds of data) to calculate OASPL for each of the tripod-mounted microphones in the near field. The contours were generated with the Kriging[8] algorithm in *Tecplot.*®Figure 8 shows the contours from Figure 7 overlaid on a sketch of an aircraft carrier flight deck. The limited extent of the Lakehurst microphone array is evident in the figure. The tripod-mounted microphones from the carrier-based test are also shown in the figure, on the opposite (starboard) side of the aircraft from the Lakehurst array. The lower right portion of 8 shows the locations of the tripod-mounted microphones from the carrier-based test mirrored to the port side of the aircraft. The sound field will be assumed to be symmetric about the JBD, and spherical spreading will be assumed valid, in order to compare the results of the land-based and carrier-based tests. These assumptions will be discussed in greater detail below.

Figure 6. Portable (foreground, aft of wingtip), and fixed (background, on tripods) microphone systems employed on DT-II.

Figure 9 shows eight one-third octave band spectra, corresponding to the eight land-based test points used to generate Figure 7. The spectra were generated for the microphone located 21 feet forward of the JBD hinge line, and 80 feet laterally from the JBD centerline. Considerable variability exists between the test points – as much as 8 dB near the spectral peak. However, seven of the spectra have much lower variability, around 4 dB at the peak. This moderate amount of variability increases the confidence that the land-based test adequately captured the near field F-35 / JBD noise environment. Figure 10 shows contours of A-weighted Sound Level (L_A) in the near field of an F-35C / JBD combination for a catapult-JBD distance of 57 feet, 9 inches, and the catapult oriented 5 degrees to the left of normal to the JBD. This configuration corresponds closely to that of Catapult 1 on a Nimitz class carrier. (The nominal orientation for Catapult 1 is 5.22 degrees left of normal.) In this case, the engine was set to afterburner power. One-third octave spectra were averaged over eight test points (284 seconds of data) and A-weighted[9] to calculate L_A for each of the tripod-mounted microphones in the near field. Note the different character of the contours, when compared with Figure 7. This is due to the closer aircraft-JBD separation, different aircraft orientation, and higher power setting. Figure 11 shows the contours from Figure 10 overlaid on a sketch of an aircraft carrier flight deck. The limited extent of the Lakehurst microphone array is again evident. The tripod-mounted microphones from the carrier-based test are again shown in the figure, opposite Lakehurst array. The lower right portion of 11 shows the locations of the tripod-mounted microphones from the carrier-based test mirrored to the port side of the aircraft. In the discussion below, the sound field will be assumed to be symmetric about the JBD, despite the obvious bias in the aircraft orientation, in order to compare the results of the land-based and carrier-based tests. Figure 12 shows eight one-third octave band spectra, corresponding to the eight land-based test points used to generate Figure 10. The spectra were generated for the microphone located 10 feet forward of the JBD hinge line, and 50 feet laterally from the JBD centerline. The variability is much lower in this case – about 2 dB. This provides more confidence that the land-based test adequately captured the near field F-35 / JBD noise environment.

VI.B. Carrier-Based Test

Data recorded during the carrier-based test were processed in an analogous fashion to those recorded during the land-based test. However, contours were not generated in this case due to the linear array of six

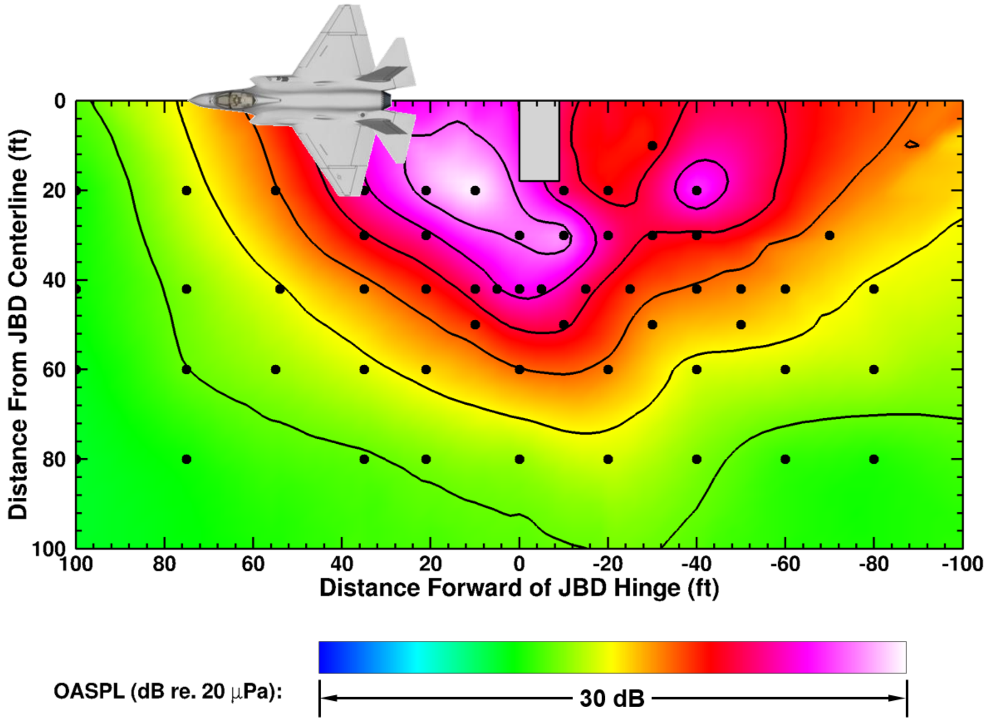

Figure 7. Military power OASPL contours in the near field of Catapult 2. Black circles denote microphone locations.

microphones employed. Figure 13 shows 15 one-third octave band spectra, generated with data from 15 military power launches from Catapult 2 during the ship-based test. Only data recorded during the military power run-up, prior to launch, were processed. That is, the transient signals generated as the throttle was increased, and as the aircraft moved down the catapult, were not processed. The spectra were generated for the microphone located 19.1 feet forward of the JBD hinge line, and 125 feet laterally from the Catapult 2 JBD centerline. The variability is quite low – about 4 dB. This is noteworthy due to the significant variations in atmospheric conditions and winds experienced during DT-II.

Figure 14 shows 12 one-third octave band spectra, generated with data from 12 afterburner power launches from Catapult 1 during the ship-based test. As noted above, only data recorded during the afterburner power run-up were processed. The spectra were generated for the microphone located 8.33 feet forward of the JBD hinge line, and 50 feet laterally from the Catapult 1 JBD centerline. The variability is again quite low – about 4 dB.

VI.C. Comparison: Land-Based to Carrier-Based

As mentioned above, the land-based and carrier-based tests employed microphone arrays on opposite sides of the F-35C / JBD system. Additionally, the land-based microphone array did not extend as far laterally from Catapult 2 as the carrier-based microphone array (80 feet vs. 125 feet). However, qualitative comparisons can be made if the sound fields are assumed symmetric about the JBD, and if spherical spreading is assumed.

Figure 15 shows a comparison of one-third octave spectra for military power operations from Catapult 2. In Figure 15, the dashed black line represents the spectrum at the microphone located 21 feet forward and 80 feet laterally from the center of the JBD hinge line in the land-based test. This spectrum was calculated by averaging the eight spectra in Figure 9. The blue line in Figure 15 represents the the spectrum at the microphone located 19.1 feet forward and 125 feet laterally from the center of the JBD hinge line in the carrier-based test. This spectrum was calculated by averaging the 15 spectra in Figure 13. The gray line in Figure 15 represents an adjustment to the spectrum recorded in the land-based test, to more closely match the spectrum recorded at 125 feet laterally during the carrier-based test. The adjustment assumes spherical spreading, i.e. $SPL_{adj} = SPL - 20\log_{10}(125/80)$. The spectra from the two tests compare reasonably, especially when considering that the data from the carrier-based test have not been corrected for

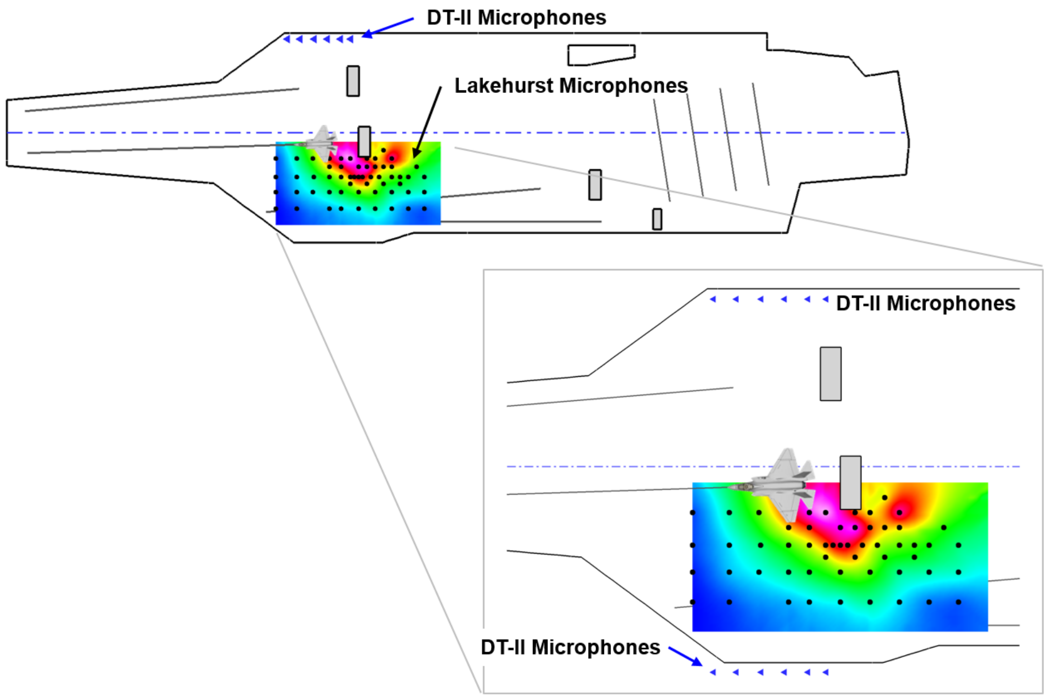

Figure 8. Catapult 2 Military power OASPL contours overlaid on a sketch of an aircraft carrier flight deck. Black circles denote land-based microphone locations. Blue triangles denote carrier-based microphones.

the effects of atmospheric absorption or winds. Figure 16 shows a comparison of one-third octave spectra for afterburner power operations from Catapult 1. In Figure 16, the black line represents the spectrum at the microphone located 10 feet forward and 50 feet laterally from the center of the JBD hinge line in the land-based test. This spectrum was calculated by averaging the eight spectra in Figure 12. The blue line in Figure 15 represents the the spectrum at the microphone located 8.33 feet forward and 50 feet laterally from the center of the JBD hinge line in the carrier-based test. This spectrum was calculated by averaging the 12 spectra in Figure 14. The spectra from the two tests do not compare well, largely due to the asymmetric nature of the sound field generated by the jet impinging on the Catapult 1 JBD.

VII. Conclusions

The data recorded during the land-based and carrier-based tests discussed above will help define the noise field on the deck of an aircraft carrier due to F-35C operations. However, many gaps remain. The microphone arrays in the land-based test had limited coverage, when compared with the extensive area of an aircraft carrier flight deck. There is also very limited overlap between the land-based and carrier-based arrays. The sound fields generated by exhaust jets impinging on jet blast deflectors are not symmetric for Catapult 1, and presumably Catapult 3, which has geometry similar to that of Catapult 1.

Thus, a comprehensive, dedicated, land-based F-35C / JBD test may be warranted. Such a test could employ an extensive microphone array to capture both sides of the JBD, for all four catapult / JBD orientations, and also cover the full extent of the flight deck. The test could be conducted in a more homogeneous acoustical environment, such as the Rogers dry lake bed at Edwards Air Force Base in California. Known weather conditions and a controlled environment (no reflecting structures or equipment in the vicinity of the test) allow for high quality data.

A detailed acoustical model of the impinging jet acoustical field is needed. Such a model provides the only means of defining noise exposure at all locations on the flight deck. A detailed model can also provide requirements for the development of hearing protection devices issued to flight personnel. A comprehensive impinging jet model could also help define noise exposures in work and living spaces below the flight deck on an aircraft carrier.

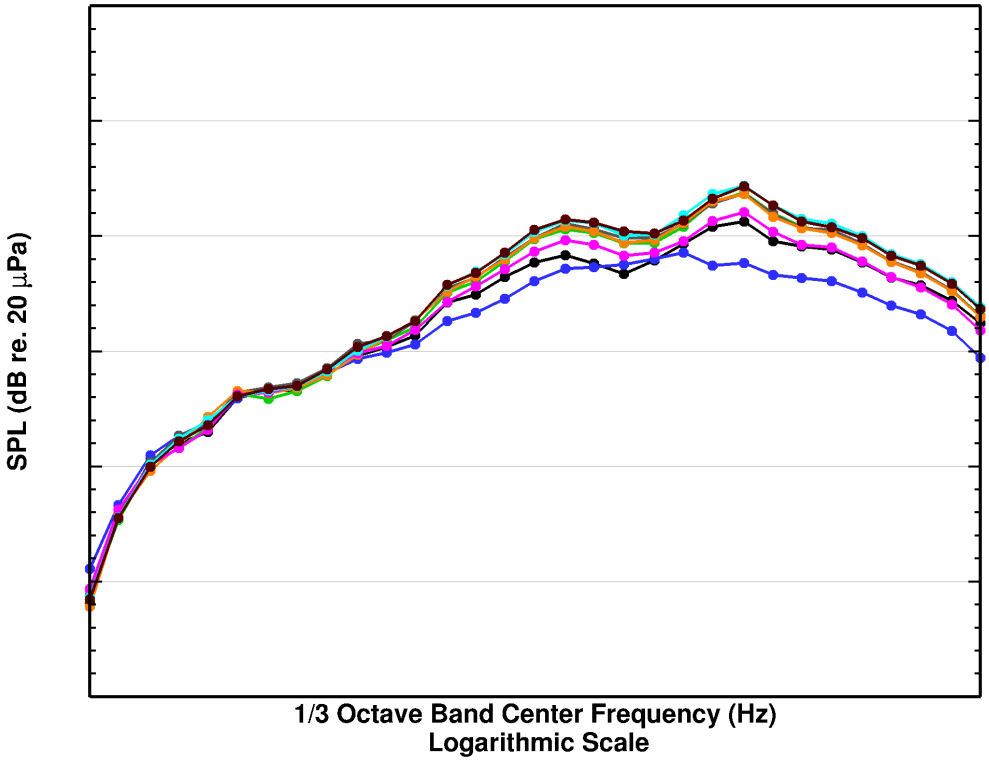

Figure 9. Catapult 2 Military power one-third octave band spectra for the microphone located at $(x, y) = (21.0, 80.0)$. Distances are measured in feet, and are referenced to the center of the JBD hinge line.

VIII. Future Work

Future work will involve further processing of data from both tests, to include corrections for atmospheric absorption, ground or deck reflection and winds. The land-based test data will be used to develop a flight deck noise model for launch operations from all four catapults, as well as arrested recoveries. Data from the carrier-based test, both fixed and portable microphones, will be used to validate the model.

Acknowledgments

A large group of dedicated engineers from several organizations participated in, or facilitated, the tests described in this paper. It is a pleasure to work with them, and to acknowledge their contributions here:

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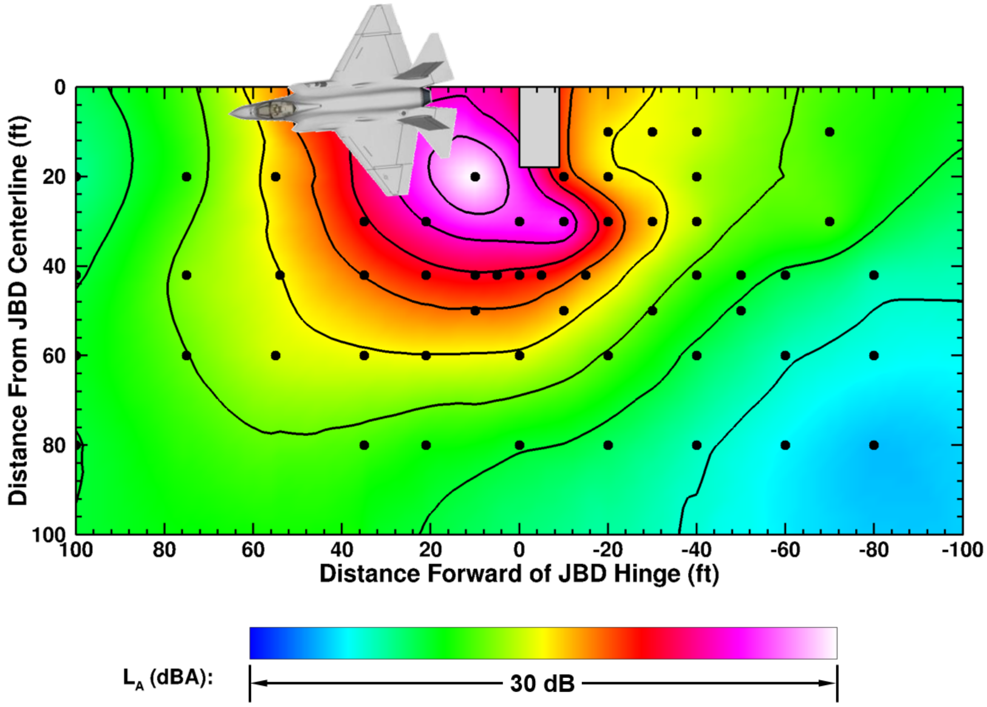

Figure 10. Afterburner power L_A contours in the near field of Catapult 1. Black circles denote microphone locations.

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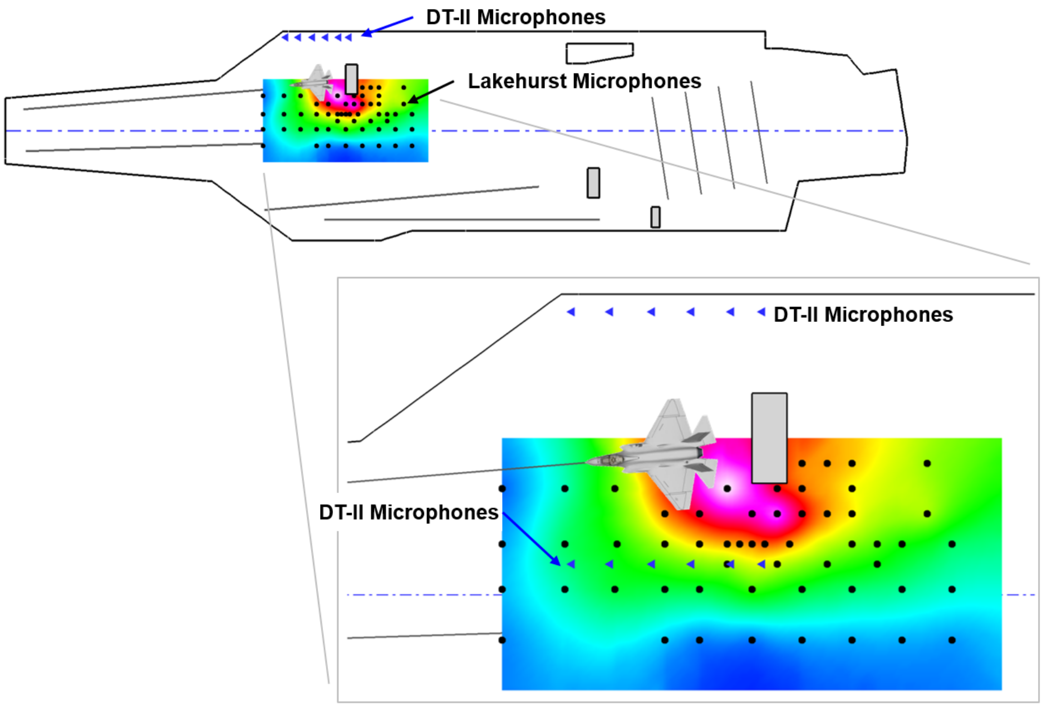

Figure 11. Land-based Catapult 1 Afterburner power L_A contours overlaid on a sketch of an aircraft carrier flight deck. Black circles denote land-based microphone locations. Blue triangles denote carrier-based microphones.

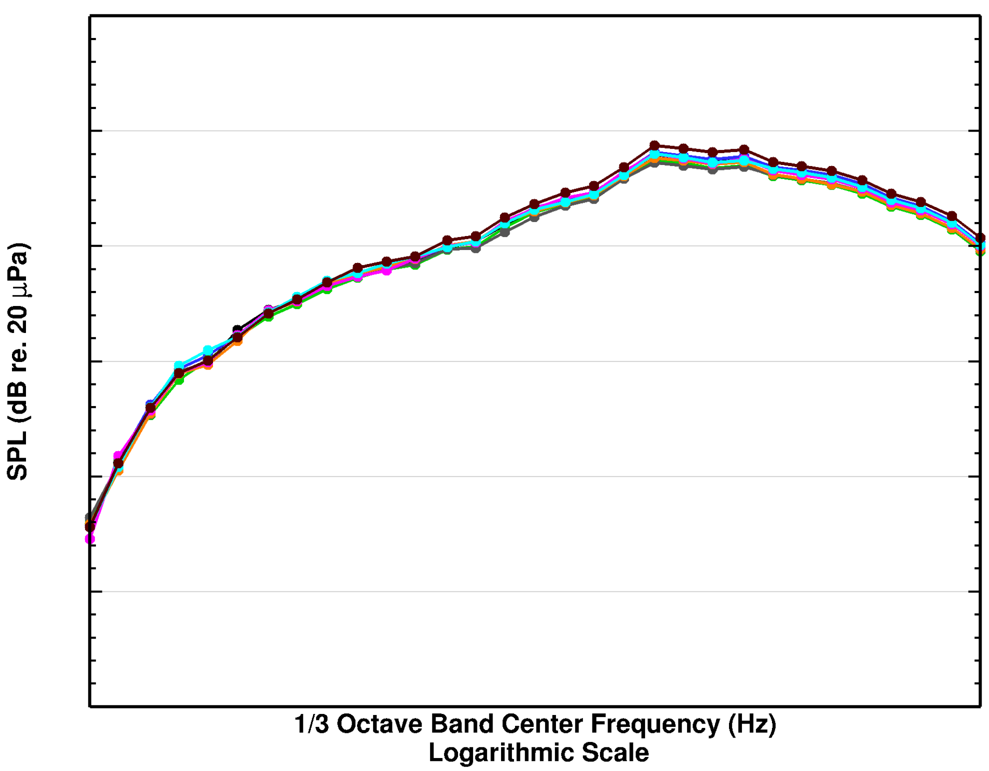

Figure 12. Land-based Catapult 1 Afterburner power one-third octave band spectra for the microphone located at $(x, y) = (10.0, 50.0)$. Distances are measured in feet, and are referenced to the center of the JBD hinge line.

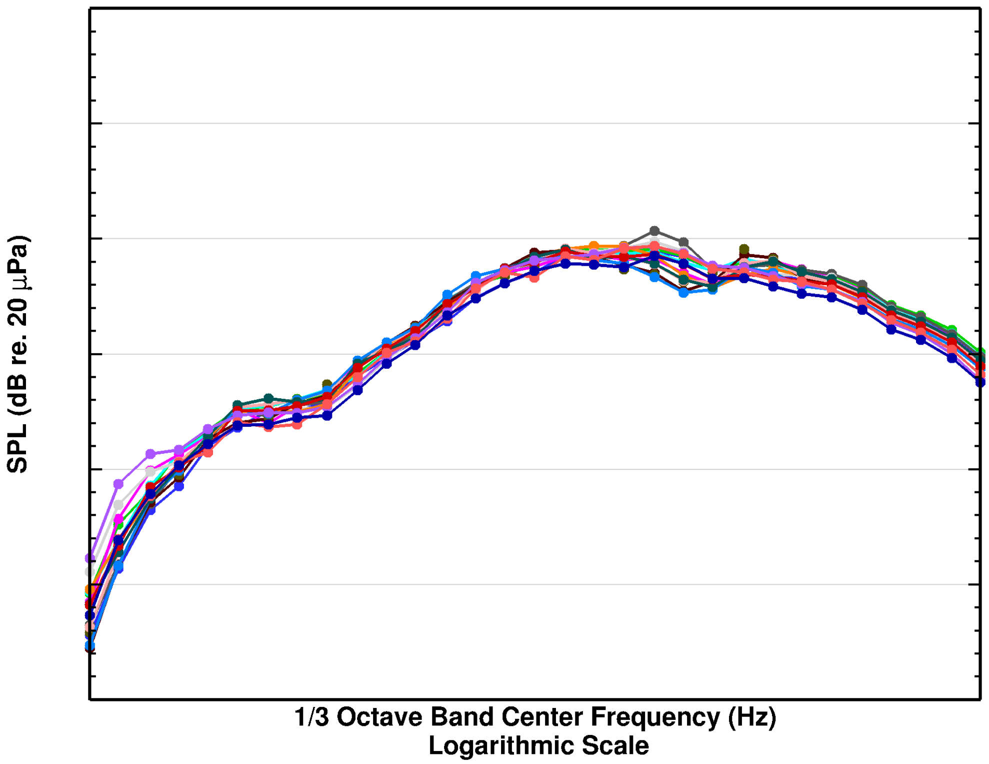

Figure 13. Carrier-based Catapult 2 military power one-third octave band spectra for the microphone located at $(x, y) = (19.1, 125.0)$. Distances are measured in feet, and are referenced to the center of the JBD hinge line.

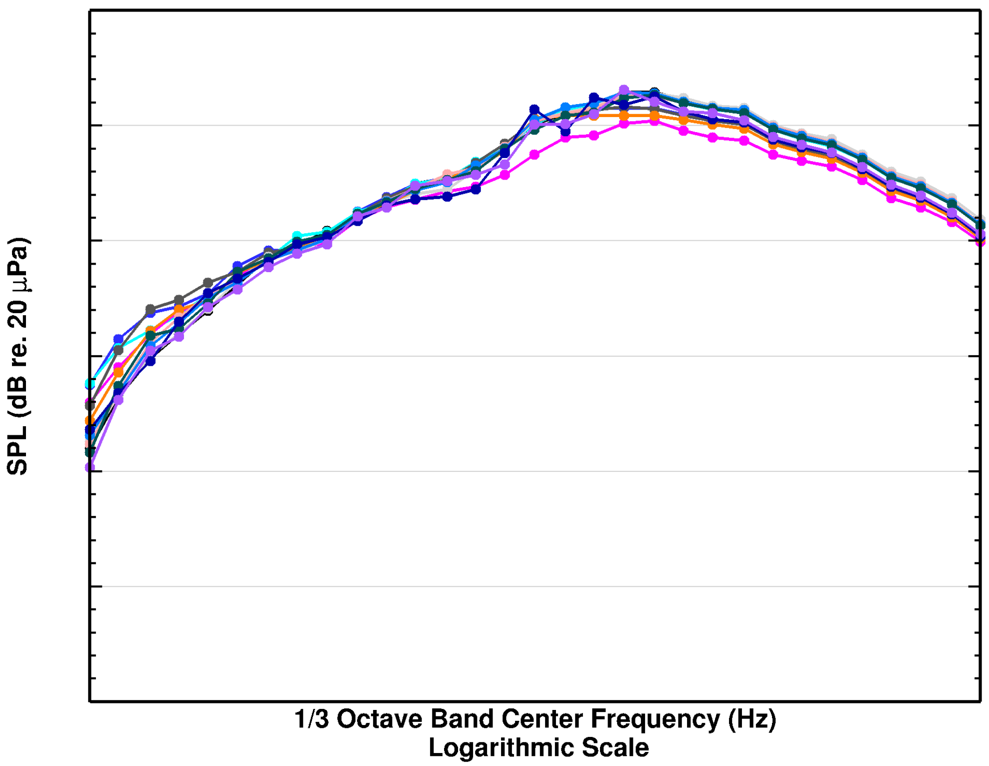

Figure 14. Carrier-based Catapult 1 afterburner power one-third octave band spectra for the microphone located at $(x, y) = (8.33, 50.0)$. Distances are measured in feet, and are referenced to the center of the JBD hinge line.

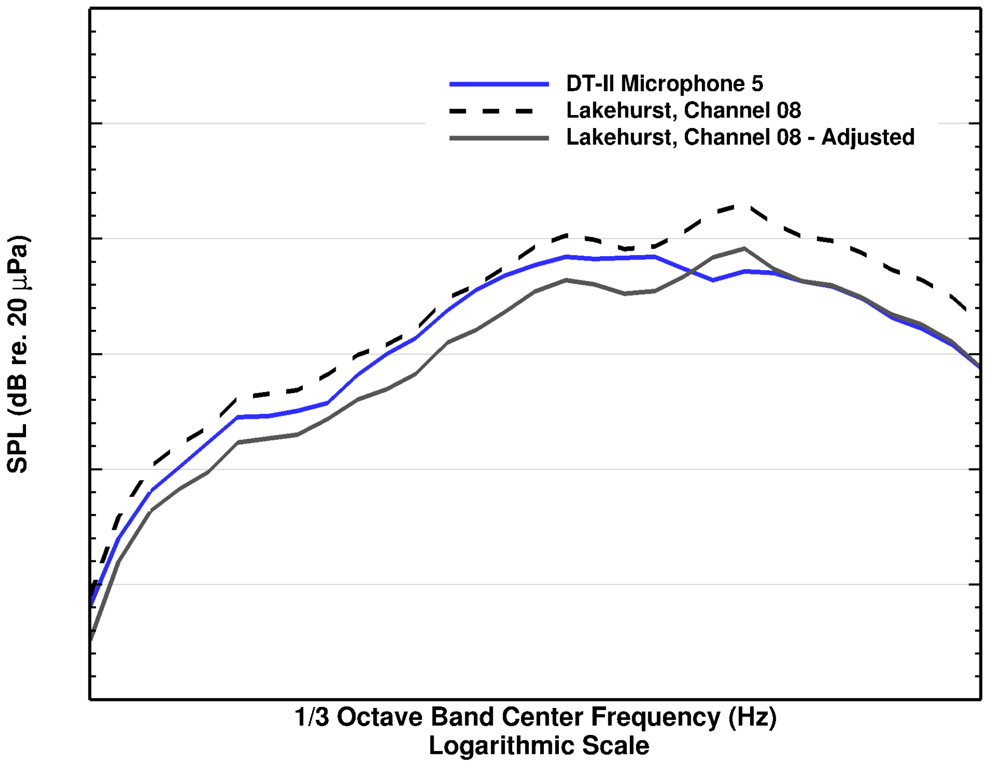

Figure 15. Comparison of land-based and carrier-based Catapult 2 military power one-third octave band spectra for the land-based microphone located at $(x, y) = (21.0', 80.0')$, and the carrier-based microphone at $(x, y) = (19.1', 125.0')$.

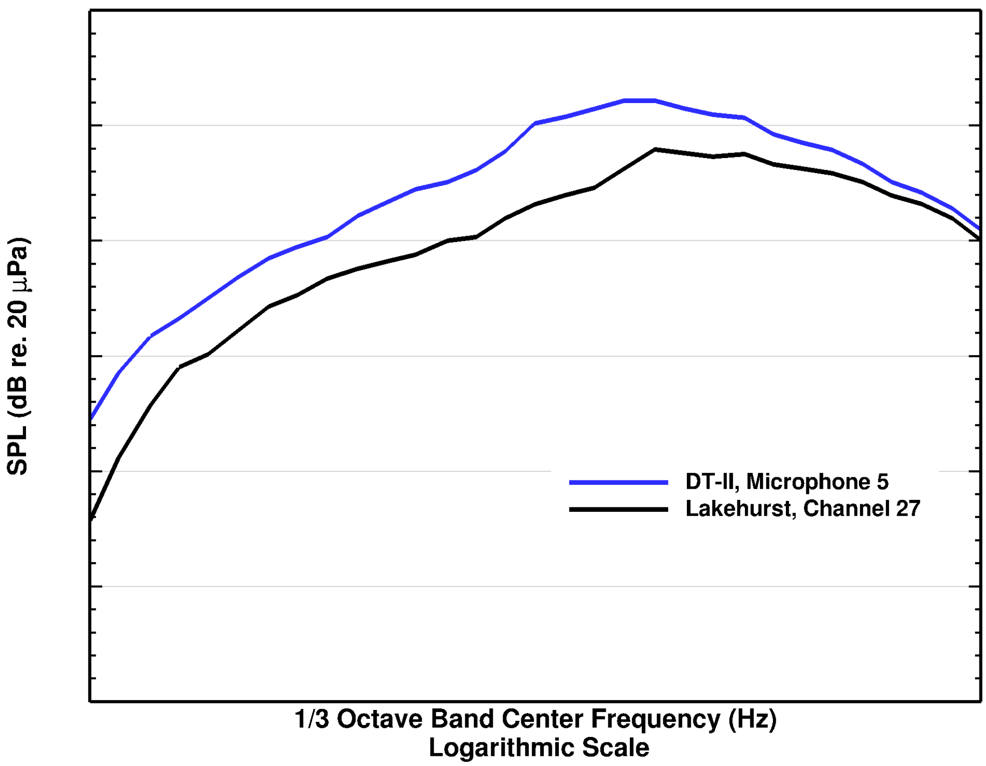

Figure 16. Comparison of land-based and carrier-based Catapult 1 afterburner power one-third octave band spectra for the land-based microphone located at $(x, y) = (10.0', 50.0')$, and the carrier-based microphone at $(x, y) = (8.3', 50.0')$.