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An overview of Brigham Young University's participation in NASA's CarpetDIEM campaign

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This paper summarizes Brigham Young University's (BYU) participation in NASA's 2019 sonic boom data collection campaign in California, USA. Dubbed "Carpet Determination In Entirety Measurement" (CarpetDIEM) Phase I, the program was designed to measure conventional cruise booms across a widespread time-synchronous array, at the site where initial acoustical testing of the X-59 low-boom supersonic aircraft is planned. BYU deployed a total of 11 portable data acquisition systems across 10 nautical miles and tested a variety of microphone and data acquisition configurations. This paper describes both technical and logistical lessons learned at CarpetDIEM Phase I that can help with future X-59 test design including acquisition hardware comparison and local measurement effects, including turbulence.

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1. INTRODUCTION

With the upcoming initial flights of NASA's X-59 Quiet SuperSonic Technology (QueSST) aircraft, various field measurement campaigns have been undertaken to prepare for community testing of a shaped, low-amplitude sonic boom (i.e., a "low-boom") aircraft. This paper serves as an overview of Brigham Young University's (BYU) participation in one such campaign, the NASA Carpet Determination in Entirety Measurement (CarpetDIEM). Because CarpetDIEM occurred at the site of the first planned X-59 sonic boom measurements, this overview and initial results may impact future X-59 testing.

BYU's CarpetDIEM measurements built upon another NASA sonic boom measurement program that BYU was involved in, the Quiet Supersonic Flights 2018 (QSF18).[1] Although QSF18 was a much larger program that employed both objective measurements and subjective assessment of low-booms from F-18 dive maneuvers off Galveston Island, Texas, BYU's role was limited to deploying four measurements stations. These stations were primarily designed to test different combinations of data acquisition modules and microphones and to field-test a custom weather-robust ground-plate system for outdoor microphone measurements. This system, nicknamed at BYU the Compact Outdoor Unit for Ground-Based Acoustical Recordings, or COUGAR,[2] acquired high fidelity acoustic data during significant precipitation and wind. BYU also investigated the effects of microphone configurations on sonic boom metrics and found that microphones at elevated receiver locations tended to underestimate sonic boom metrics by several decibels. However, due to the complexity of the low-boom dive maneuver, local atmospheric profile, and measurement environment, the QSF18 boom signal-to-noise ratios were lower than expected and a decision was made to test some of the QSF18 findings as part of the CarpetDIEM objectives. Key objectives for BYU at CarpetDIEM included:

- Verify findings from QSF18 regarding the effect of elevated microphones on sonic boom metrics[2] in a quieter ambient environment.
- Field a total of eleven time-synced stations across approximately 10 nautical miles (NM) to help study boom carpet width.
- Learn important logistics regarding testing in this region, which is proposed for initial X-59 testing.
- Field test the next iteration of the COUGAR: the COUGARxt (xt stands for an "extra thick" windscreen and an "extra thin" ground plate).
- Examine sonic boom variability over short distances and investigate the relevance of local measurement arrays for understanding measurement uncertainty.

This paper includes an overview of the measurement set up and logistics behind testing in this region, as well as some preliminary analysis that serves as data validation. Further analysis and results are forthcoming.

2. STATIONS

A. STATION INFORMATION

The eleven stations deployed by BYU were designed to be rapidly deployable, weather robust, and capable of high-fidelity sonic boom measurement. BYU tested an improved data acquisition system dubbed Portable Unit for Measuring Acoustics (PUMA), which contained National Instruments data acquisition (DAQ) chassis and modules, tablet computers, and a portable charging bank. Ten equipped PUMA systems were outfitted with the base configuration of an NI 9250 low-noise input module and a GRAS 47AC low-frequency response microphone in a COUGAR microphone configuration. The only station of the eleven BYU stations without the base configuration was located at site 36, which was nominally below the flight track, and deployed a linear array of seven microphones perpendicular to the flight track to measure effects of turbulence. All PUMAs were equipped with a Masterclock GPS-500 time clock for time synchronizing the recordings across stations using the IRIG-B protocol, as well as Kestrel 4000-series Bluetooth-enabled meteorological instrumentation. Figure 1 shows an example of a base setup with PUMA data acquisition hardware, tripod-mounted weather station, and a COUGAR microphone configuration.

In addition to the basic configuration, four of the ten stations were also outfitted with configuration comparisons. Two of these stations included comparisons between COUGAR, Elevated, and Ground-Board microphone configurations (as shown in Figure 1), and the other two compared the revised and improved COUGARxt configuration with the original COUGAR. These configurations at the four stations were tested with different microphones and DAQ cards than those used in the basic configuration.

Figure 1. Example BYU Stations. Left: A base configuration station with data acquisition system (PUMA), tripod-mounted weather station, and COUGAR microphone configuration. Right: A microphone configuration comparison station with two COUGAR (left and top), one Elevated (bottom), and one Ground-Board configuration (right).

B. LOCATIONS

The CarpetDIEM campaign took place on Bureau of Land Management land to the east of California's Edwards Air Force Base and near Kramer Junction. There were 23 supersonic passes of an F/A-18C aircraft that took place from July 31 to August 6, 2019. Potential measurement sites for future X-59 testing were numbered 1-54, with 54 being located at the southern end of the array. The full CarpetDIEM array, manned by NASA, Volpe, and BYU, was limited to around 17 manned stations per day located between sites 20 to 54; the focus for this paper will be further limited to the BYU-manned stations. These eleven stations contained one PUMA each and covered essentially the southern half of the boom carpet, ranging from sites 32 to 54 (shown in Figure 2), and spanned 10 nautical miles. BYU's PUMAs moved between site numbers each day to specific sites determined by NASA, based on meteorological data and predictions each morning. Several site numbers were not used and are not shown in Figure 2. A summary of PUMA locations and configurations is given below in Table 1.

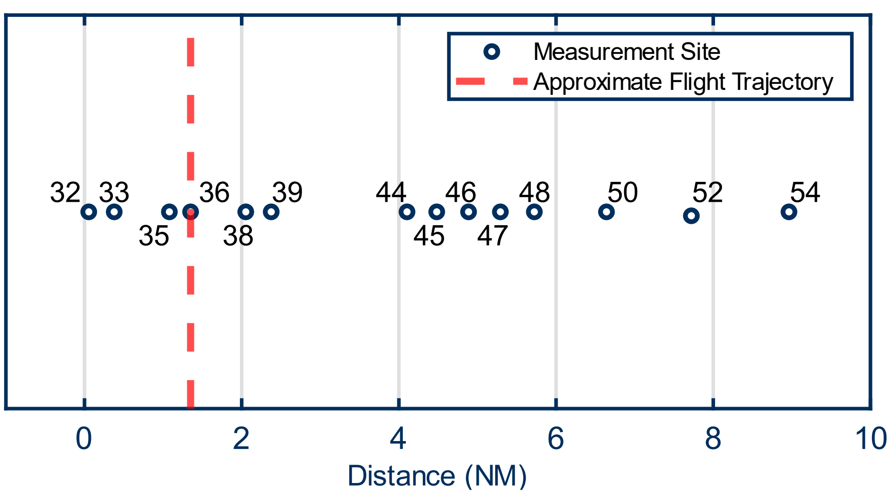

Figure 2. BYU Array Measurement Sites, where the flight track (shown in red) was perpendicular to the array over site 36. The span of the BYU portion of the array is approximately 10 NM.

Table 1. Summary of BYU PUMA configurations

PUMA/Station #	Sites	# Microphones	Configuration
1	32, 33	4	**COUGAR Base Configuration**
			COUGAR/Ground-Board/Elevated Comparison
2	36	7	**Linear Microphone Array**
3	38, 39	1	**COUGAR Base Configuration**
4	44	4	**COUGAR Base Configuration**
			COUGAR/Ground-Board/Elevated Comparison
5	43	1	**COUGAR Base Configuration**
6	45	3	**COUGAR Base Configuration**
			COUGAR/COUGARxt Comparison
7	46, 47	1	**COUGAR Base Configuration**
8	47, 48	3	**COUGAR Base Configuration**
			COUGAR/COUGARxt Comparison
9	50 ,54	1	**COUGAR Base Configuration**
10	50, 54	1	**COUGAR Base Configuration**
11	32, 35, 52	1	**COUGAR Base Configuration**

C. CAMPAIGN LOGISTICS

One of the most important components of the measurement campaign was practicing measurement logistics prior to initial X-59 testing. With stations spread over several miles and involving as many as eight people, BYU also learned many important logistical lessons with regard to testing in this region. These include lessons regarding data acquisition, transportation, and communications.

Regarding data acquisition, the test was overwhelmingly successful; 98% of possible boom events were recorded, mostly using peak-amplitude triggering. Relatively low winds and conventional booms allowed us to set the peak trigger level relatively high, 105-110 dB, with few false triggers due to wind. Two main data acquisition challenges occurred. One cause was the high temperatures in the area which resulted in the overheating and failure of a computer in a PUMA case. Temperatures measured in the field were as low as 22 degrees Celsius in the morning and as high as 42 degrees Celsius in the afternoon. Reflective shields placed around the PUMA cases and hockey puck-sized pieces of dry ice in the cases were sufficient to keep temperatures cool. The use of ruggedized PCs instead of the tablet-style Surface Pros and Surface Gos should also solve this problem in the future. Additionally, because of data security concerns, data were required to be directly recorded to Apricorn 120GB Aegis Secure Key 3.0 256-Bit AES XTS Encrypted flash drives that had been previously approved by NASA, rather than being stored on the internal solid-state drive. In two cases, data that had been confirmed to have been recorded mysteriously disappeared off the drives. Data recovery efforts post-campaign were unsuccessful. This kind of drive will not be used in the future.

Transportation proved to be one of the more difficult challenges of making measurements in the area. Before arrival in the field, briefings suggested terrain was traversable by two-wheel drive road vehicles. However, in practice, it was found that much of the terrain BYU was responsible for staffing contained roads that were difficult to traverse, even with four-wheel drive pickup trucks (pickup trucks used were too heavy, did not have enough clearance, and lacked off-road tires, which contributed to them struggling on challenging terrain). High-clearance vehicles such as off-road designed sport utility vehicles with four-wheel drive or midsize four-wheel drive trucks equipped with off-road tires would be optimal. However, almost no vehicles fitting these descriptions were available for rent, either from Victorville or even the Los Angeles International Airport. Throughout the test campaign as the roads were trafficked more and more, the road conditions further deteriorated until sections of road became nearly impassable. An additional lesson involves getting vehicles unstuck because four-wheel drive is not infallible. First, all vehicles should be equipped with shovels and traction mats. Second, trying to push out stuck vehicles in full sun in the desert without gloves is nearly impossible. Quality work gloves are recommended. Finally, having a heavy-duty vehicle with a winch on hand was invaluable.

Campaign communications also proved to be a challenge. Both cellular networks and LMR (Land Mobile Radio) systems did not provide adequate communication links at every point along the array. There were limitations with both personal cellphones and NASA-provided phones. Better communication systems in future testing would provide a logistical improvement. One possibility is installing a repeater tower for the LMR in the hill around site 45 and elsewhere as needed.

3. EFFECT OF ELEVATED MICROPHONE CONFIGURATIONS

Microphone configuration comparisons between COUGAR, Elevated, and Ground-Board setups were done at two stations near the flight track, PUMA 1 and PUMA 4 (see Table 1). The comparison setup, as seen in Figure 1, had all microphones placed within several meters of each other. Figure 3 shows an example waveform from PUMA 4 with all four microphone configurations plotted together, one of which is the base configuration and is plotted in black. Due to the microphones' proximity and choice of plotting scale, the waveforms look nearly identical.

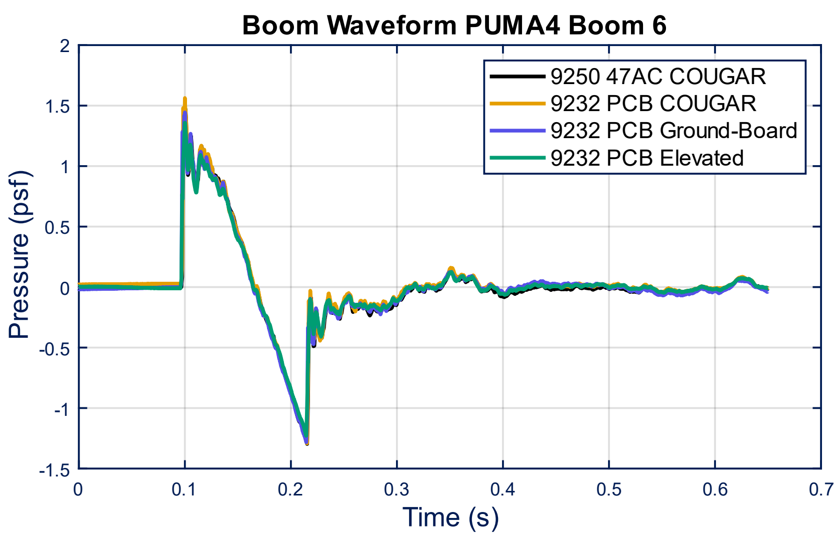

Figure 3. Boom 6 Waveform at Site 44. Average Windspeed of 4.6 m/s (10 mph). (See Figure 6-6 in Ref. 2)

While the time waveforms of each boom look similar, spectral comparisons demonstrate that setups featuring thicker windscreens and microphones closer to the ground provide the greatest wind noise rejection. Figure 4 demonstrates this wind noise rejection between configurations during a 60 second period of ambient wind noise with wind speeds approaching 5 m/s. All timeseries have been zero-padded with two seconds on either side to smooth low frequency levels in the spectra. The COUGAR configurations have the lowest amount of wind noise present, followed by the Ground-Board configuration and finally the Elevated configuration with the most wind noise. This result matches prior observations during QSF18 as well as other experiments dealing with wind noise.[3]

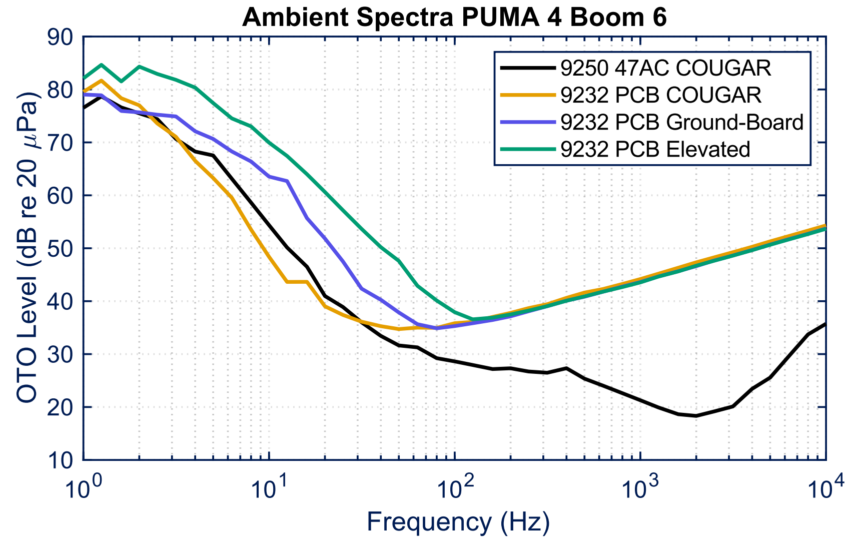

Figure 4. Boom 6 ambient spectra at Site 44, where there was an average wind speed of 4.6 m/s (10 mph). The relative wind noise rejection of the different setups is visible among lower frequencies.

Wind noise rejection has a significant effect on the SNR of the booms. Figure 5 shows the one-third octave SNR of Boom 6 relative to the ambient spectra immediately preceding the boom. COUGAR provides the highest SNR especially within the 2 to 100 Hz range. Comparing the three setups that used a PCB microphone at 10 Hz, COUGAR provides an additional 15 dB of SNR over the Ground-Board configuration, and 20 dB over the Elevated configuration. For quiet booms, this added increase in SNR due to wind noise rejection would provide an increased effective measurement bandwidth.

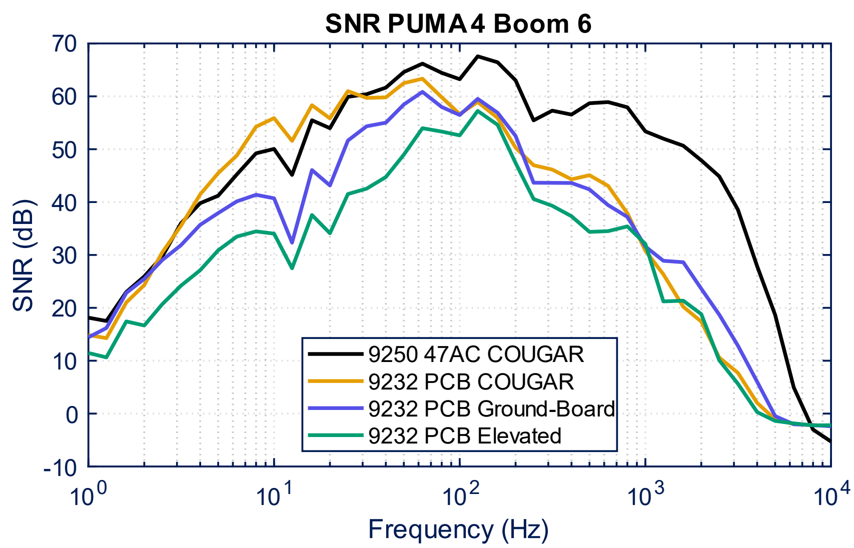

Figure 5. Boom 6 signal to noise (ambient) ratio at Site 44. Average wind speed of 4.6 m/s (10 mph).

Figure 6 contains the spectra of Ground-Board and Elevated configurations relative to COUGAR, demonstrating that Ground-Board and COUGAR are acoustically similar (to within $\pm$ 2 dB at all frequencies) when averaged over all booms (right), even if some booms have differences (left, differences above 1 kHz). This demonstration also shows that the Elevated configuration creates challenges with large losses approaching -8 dB at frequencies between 100 and 1000 Hz when averaged over all booms (right). Some booms exhibit even larger nulls than 8 dB (left). In comparison to the QSF18 results, the nulls are deeper (due to a harder surface and a greater signal to noise ratio), and peak at a slightly lower frequency (due to the angle of incidence being greater relative to grazing).

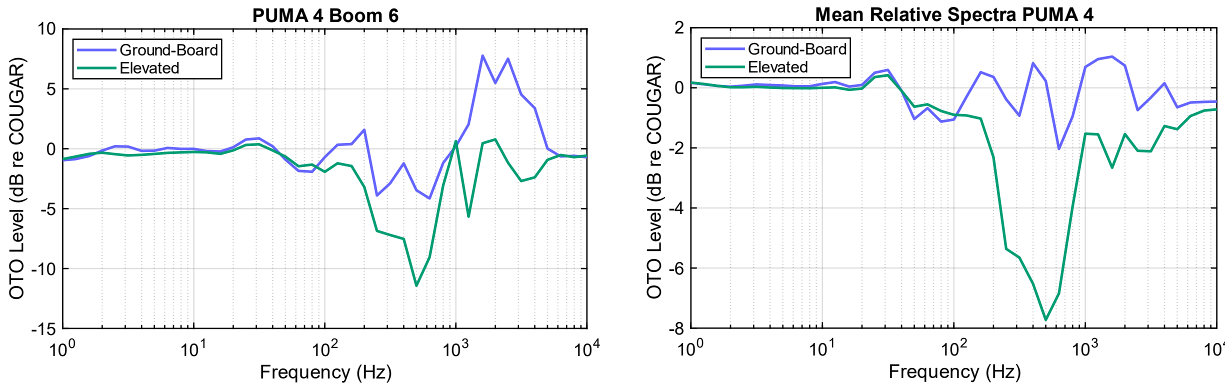

Figure 6. Left: Ground-Board and Elevated relative to COUGAR for PUMA 4, Boom 6. The characteristic losses of Elevated between 100 and 1000 Hz are apparent. Right: Mean relative spectra for PUMA 4 relative to COUGAR across all booms.

An analysis of the candidate sonic boom metrics[4] confirms the acoustic similarity between COUGAR setups, similarity between Ground-Board and COUGAR, and also the impact of the Elevated microphone configuration. ZSEL is not a candidate sonic boom metric for future supersonic aircraft noise certification standards but has been included in the analysis for completeness. Table 2 shows the mean differences between setups at PUMA 4 relative to one of the two COUGAR setups. In this case, the NI 9232/PCB 378A07 COUGAR setup was chosen as the baseline to provide for maximum consistency with the Ground-Board and Elevated channels – the DAQ channel and microphone type were identical across the three setups. However, the two COUGAR setups were also quite similar. In comparing Ground-Board and COUGAR, all metrics are within 0.3 dB of each other. However, the 2.1 dB underestimation of the Perceived Level (PL)[5] by the Elevated setup is greater than for QSF18, where the underestimation was about 1 dB.[6] Some metric differences exceed 2 dB, with the greatest difference in the A-weighted SEL of 3.4 dB. The Indoor Sonic Boom Annoyance Predictor (ISBAP) uses PL as part of its calculation, and thus behaves similarly to PL. In summary, a microphone raised off the ground – by causing an interference null at several hundred hertz – will result in a significant (> 1 dB) underestimation of most sonic boom metrics.

Table 2 Mean differences in metrics for PUMA 4 in dB re NI 9232 COUGAR.

	PL	ZSEL	ASEL	BSEL	DSEL	ESEL	ISBAP
NI 9250 47AC COUGAR	-0.5	-0.1	-0.03	-0.2	-0.1	-0.1	-0.6
NI 9232 COUGAR	-	-	-	-	-	-	-
NI 9232 Ground-Board	**-0.04**	**0.06**	**-0.2**	**-0.3**	**-0.2**	**-0.2**	**-0.02**
NI 9232 Elevated	**-2.1**	**-0.03**	**-3.4**	**-1.4**	**-1.3**	**-2.2**	**-0.8**

4. COUGAR VS. COUGARXT

While COUGAR provides excellent wind noise rejection in a weather-robust package, some improvements have been completed after laboratory measurements and analysis of QSF18 data.[7] This new iteration, which modifies the plate material and thickness along with the windscreen thickness (while keeping the same overall height for transportability) is referred to as COUGARxt (where the "xt" refers both to the "extra thick" windscreen and the "extra thin" plate). The extra thick windscreen provides additional wind noise rejection while the extra thin plate reduces plate effects.

CarpetDIEM provided a unique opportunity to test COUGAR and COUGARxt. Both were tested at three different sites– 45 (PUMA 6), 47 (PUMA 8), and 48 (PUMA 8), see Table 1. Figure 7 shows the comparison setup at site 45 (PUMA 6) with two COUGAR configurations, with one being the base configuration, and one COUGARxt. Figure 8 demonstrates the acoustic similarity between COUGARxt and COUGAR, where both configurations had the same DAQ and microphone (NI 9232, GRAS 46AO). Comparing relative spectra across all booms., the one-third octave levels are within ±1 dB up to 1 kHz. Beyond that, noise floor variability prevents meaningful comparison. The extra thick windscreen and extra thin plates do not appear to adversely affect data collection.

Figure 7. Comparison station setup at site 45 between COUGAR (top and middle) and COUGARxt (bottom).

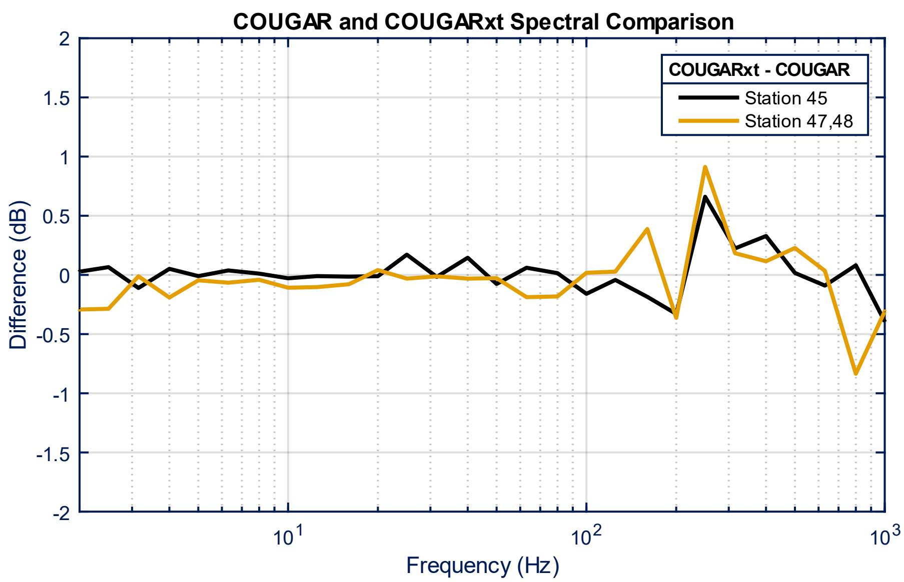

Figure 8. Average difference between COUGARxt and COUGAR over all recorded booms at site 45 (PUMA 6), 47 (PUMA 8) and 48 (PUMA 8). Sites 47 and 48 are paired together because the instrumentation was at site 47 for the first two days and at 48 for the final day. Data are only shown to 1 kHz because several booms reached the noise floor shortly after 1kHz.

5. MICROPHONE ARRAY RESULTS

A. COMPLETE BYU ARRAY

Figure 9 shows the recorded waveforms across the complete BYU array (11 manned stations between sites 32 and 54) for Boom 10. The COUGAR base configuration is used for each site, except for site 36, which didn't have the base configuration, so the center mic of the turbulence array is used instead. Arranged with equal spacing according to site number for ease of visualization, the center of the flight path was nominally at site 36. Differences in waveform shape and amplitude are apparent across stations, with a noticeable attenuation towards the southern edge of the array (labeled as sites 47, 50, and 54) where the boom arrived 15 seconds later than at station 32. Further investigation into meteorological and terrain conditions may yield information on the variations in waveforms across the array. However, one important point is noted: site 54, which was the south end of the array and was predicted to be in the shadow zone, recorded all booms. Thus, the southern edge of the boom carpet could not be determined.

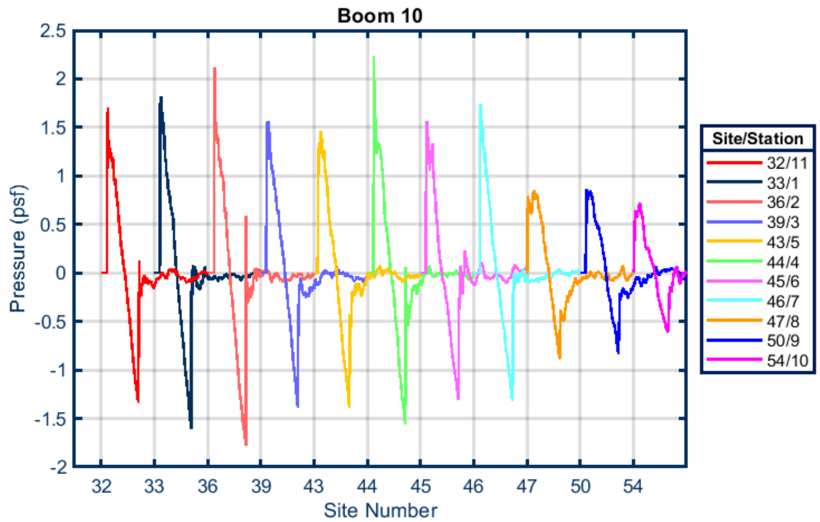

Figure 9. Example of Boom 10 across all 11 BYU array stations, with one station for each site. Waveforms at each site are plotted with equal spacing for ease of visualization. The time spacing between sites 32 and 54 is approximately 15 seconds. (See Figure 6-3 in Ref. 2)

Bow shock arrival times across the array are observed to relate to the distance from the center of the flight path. Figure 10 shows the arrival time of booms across the BYU stations, as a function of site number, for Boom 10, relative to the center of the array. These arrival times qualitatively fit what would be expected with the hyperbolic shape of the boom carpet but suggest that the effective center of the array for this case is somewhere between sites 33 and 36. Future quantitative analysis is merited, given that factors such as aircraft speed, altitude, trajectory and meteorological conditions may affect the arrival times of the booms.

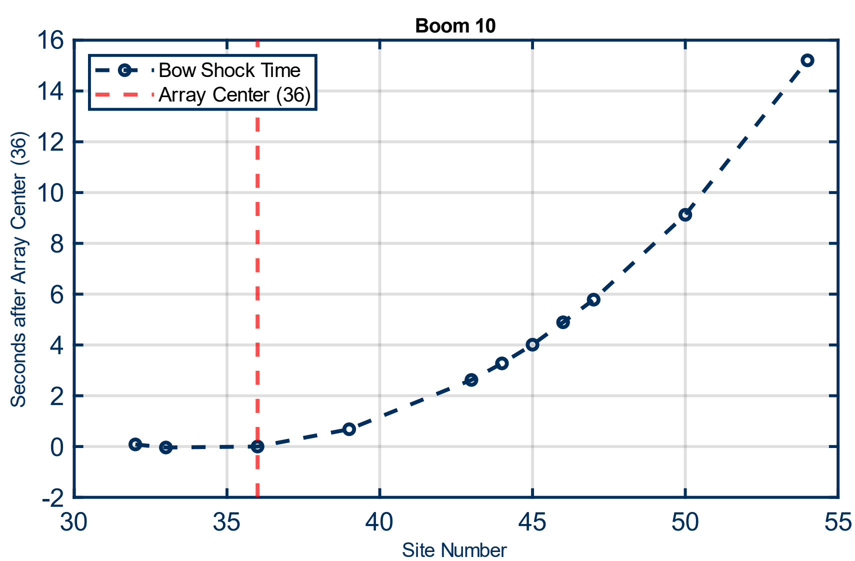

Figure 10. Arrival times of Boom 10 relative to center station at site 36.

Figure 11 shows the PL for three of the booms as a function of site number, with site 36 being the center of the array and site 54 being the predicted edge of the boom carpet. Due to increased propagation distance and properties of the aircraft near-field signature at off-track angles, booms farther away from the array center tended to be significantly quieter. Variability in PL is also a subject of further future analysis, especially in parts of the array that were near geological features such as mountains.

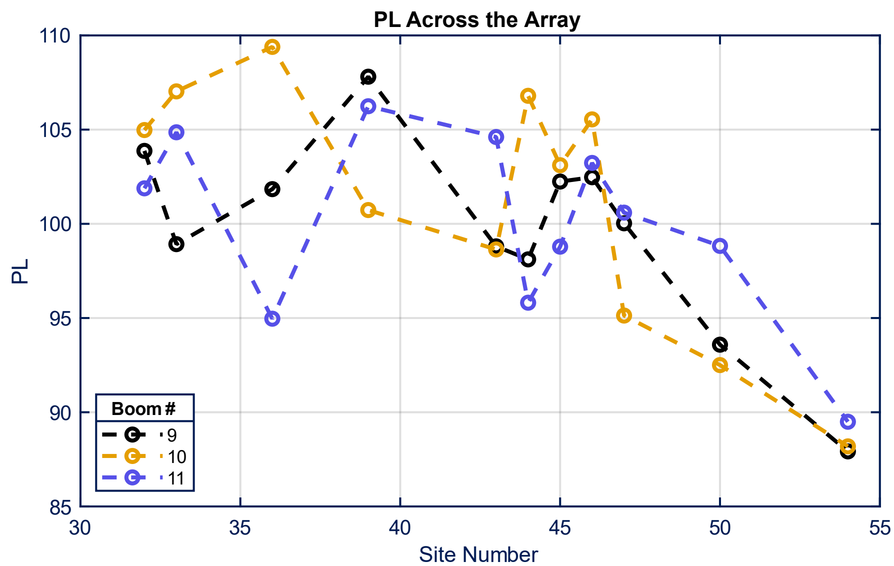

Figure 11. PL across the BYU sites 32-54, spanning a total of 10 NM. An overall trend of decreasing PL away from the array center at site 36 is noticeable, along with variability of PL at each site for each boom.

B. TURBULENCE ARRAY

One notable issue that causes difficulty in developing standardized measurement methods for supersonic aircraft certification and for associated community testing is atmospheric turbulence.[8] To investigate the possible local variation of sonic boom properties (e.g., due to atmospheric turbulence) in the vicinity of a measurement site at CarpetDIEM, a linear microphone array was deployed at one site at the center of the anticipated flight path (site 36). The linear array consisted of seven microphones in COUGARxt configurations, running roughly North to South and perpendicular to the anticipated flight paths of the aircraft, as demonstrated in Figure 12. The PUMA was placed near the center microphone, and microphones were located 15 m (50 ft), 30 m (100 ft) and 61 m (200 ft) to the North and South of the center microphone. Because the quantity of free-field microphones of a given type were limited, two different microphone models were utilized in the array: PCB 378A07 microphones at the center and both locations 15 m (50 ft) from the center, and GRAS 40AE microphones at the remaining four locations at 30 and 61 m (100 and 200 ft). For the highest-amplitude booms, the ~50 mV/Pa sensitivities of the GRAS 40AE microphones resulted in occasional peak clipping of the bow shock; signals exceeded the 5 V maximum input range of the data acquisition hardware when peak acoustic pressures were greater than ~100 Pa (~2.1 psf). This should not be an issue for measurement of quiet-boom aircraft.

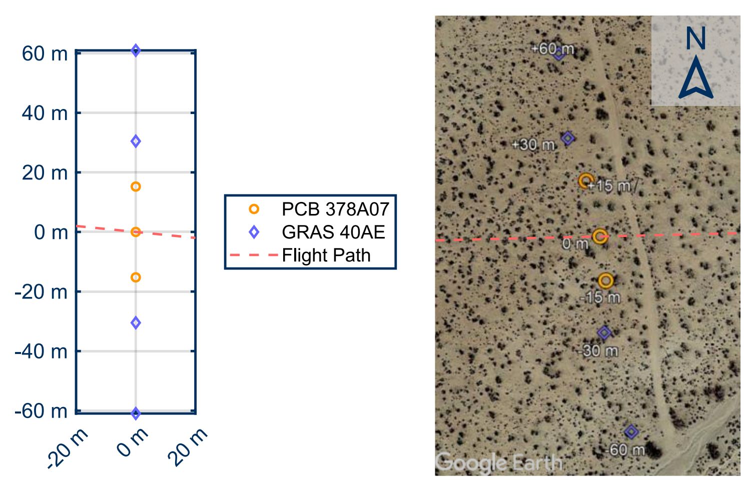

Figure 12. Turbulence array layout. Dashed lines on both figures represent the anticipated center of the flightpath.

Key to the interpretation of array measurements are local meteorological data, which affect associated turbulence. These data were measured and recorded by a portable weather station located at the center microphone at a height of 1.5 m (5 ft). The weather station recorded meteorological data for five out of the six flights. These data include wind speed and direction, barometric pressure, temperature, and humidity. The highest average wind speeds of the test series occurred around Boom 14, with an average wind speed of 3.5 m/s (7.8 mph).

Differences in recordings due to meteorological effects across the array are apparent in Figure 13, which demonstrates these differences observed in the waveforms for Boom 14. These differences would not be expected if the weather were calm, as all mics were close to the flight track and the aircraft was nominally flying a steady trajectory. Arrival times differed slightly between microphones, as expected, although the ordering can be unintuitive. The recorded waveforms also exhibit differences in amplitude, especially in the bow and tail shock areas. Microphones south of the center microphone [-15, -30, -61 m (-50, -100, -200 ft)] all exhibit a more peaked bow shock, greater in amplitude than the center and north microphones by approximately 24 Pa (0.5 psf).

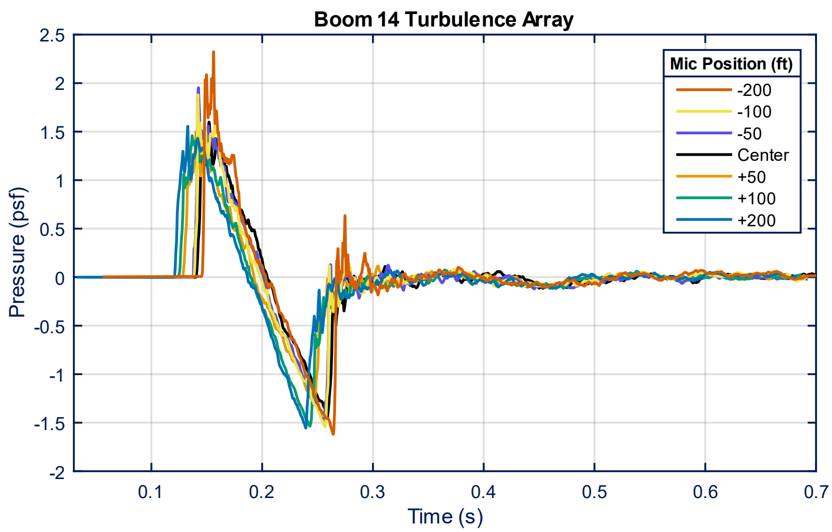

Figure 13. Boom 14 recorded at the turbulence microphone array (site 36) in an average wind speed of 3.5 m/s. (See Figure 6-15 in Ref. 2)

Spectral variations also are present between boom recordings across the turbulence array. Figure 14 shows the one-third octave spectra across the array for Boom 14. These variations start at about 10 Hz, presenting an approximate spread of 10 dB across frequencies from 20 to 1000 Hz. Generally, spectral levels at lower frequencies in the infrasound regime ($f < 10$ Hz) are consistent across all microphones.

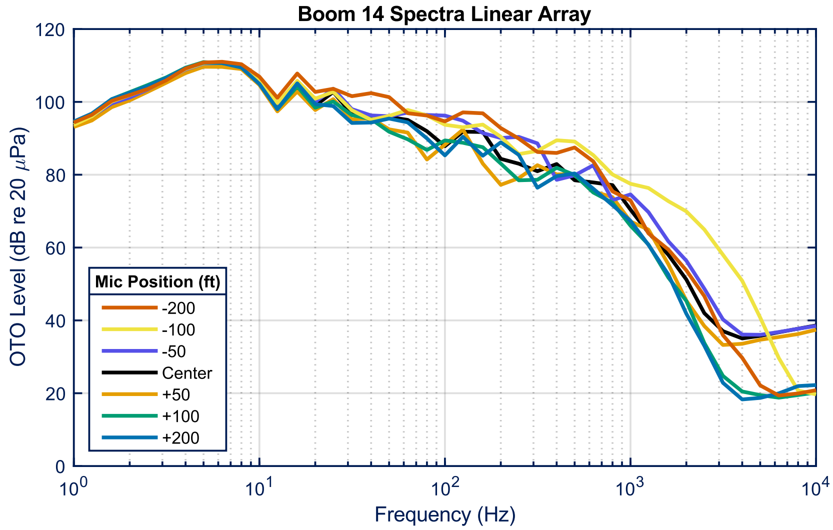

Figure 14. One-third octave spectra of Boom 14 recorded across the turbulence microphone array (site 36). (See Figure 6-16 in Ref. 2)

The PLs for two typical booms, Booms 4 and 14 are shown in Figure 15. Both booms occurred on days with peak temperatures above 40 degrees Celsius. For Boom 14, there is an 8+ dB difference in PL between microphones across the array. For Boom 4, the maximum difference is 11+ dB over 46 m (150 ft). This result indicates a large relative uncertainty in a single measurement at one location due to turbulence. This kind of uncertainty qualitatively matches the kinds of spatial variation seen by Stout and Sparrow [9] and Sparrow *et al*.[10]

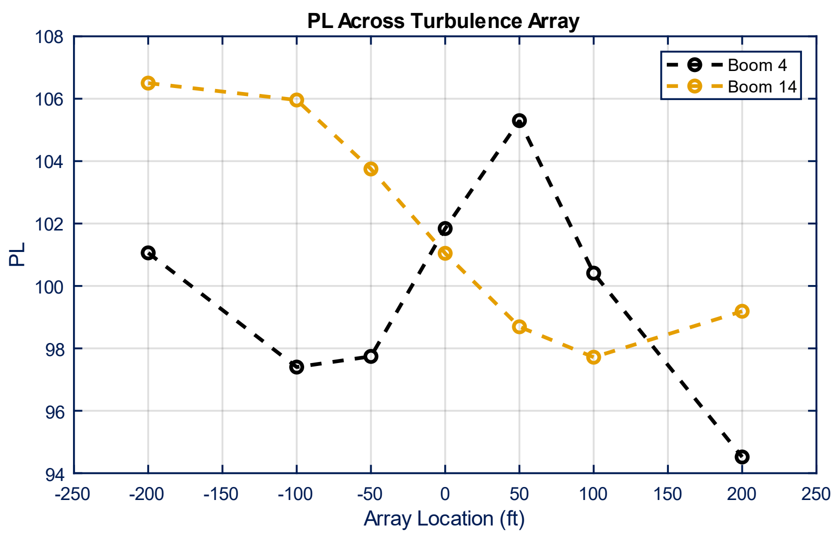

Figure 15. Perceived Level (PL) values across the turbulence microphone array for Boom 4. (See Figures 6-17 & 6-18 in Ref. 2)

6. CONCLUSION/DISCUSSION

The pre-X-59 CarpetDIEM flight test was a success for BYU and for the larger team with NASA and Volpe. The combination of PUMA and COUGAR proved to be an effective system for sonic boom measurements. Ground interference nulls from the elevated microphone configurations seen at QSF18 and in the laboratory were again observed in the field at CarpetDIEM, causing an underprediction of sonic boom metrics of up to 3.4 dB. The COUGARxt configuration was found to behave acoustically similar to COUGAR in the field, at least up to 1 kHz. Large differences in PL up to 11 dB were also observed over the span of the 122 m-long turbulence array, indicating that atmospheric turbulence can have large impacts on sonic boom metrics.

Further investigation into the linear array could provide more detailed estimations of uncertainty in data. The observations from the linear array demonstrate the need for uncertainty quantification in sonic boom measurements. In future testing, using a similar local array could provide models to predict the measurement uncertainty of an array-based measurement similar to CarpetDIEM.

This dataset acquired by BYU is valuable because of the clean waveforms, quiet ambient environment, and consistent flight trajectories. High-fidelity, time-synced sonic boom data will be extremely useful in further investigation into sonic boom variability, the impact of microphone configurations, and local measurement array designs, all of which will impact future X-59 testing in this same area. Logistical lessons learned during this campaign will also be of great help when an even larger-scale X-59 test is conducted under similar conditions.

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