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Citation: [Proc. Mtgs. Acoust.](#) **29**, 045008 (2016); doi: 10.1121/2.0000727

View online: <https://doi.org/10.1121/2.0000727>

View Table of Contents: <http://asa.scitation.org/toc/pma/29/1>

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## 172nd Meeting of the Acoustical Society of America

Honolulu, Hawaii

28 November - 2 December 2016

### Physical Acoustics: Paper 2aPA10

## Acoustic measurements in the far field during QM-2 solid rocket motor static firing

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The five-segment Space Launch System solid rocket motor was recently tested at Orbital ATK. Far-field acoustical measurements were performed at angles between  $80^\circ$  and  $120^\circ$  relative to the rocket exhaust at a distance of roughly 2500 m from the rocket, approximately 800 nozzle diameters. The angular aperture allows for evaluating spatial variation in acoustic properties and a comparison with similar tests in the past, including the 2015 test of the same rocket motor. Although terrain variations introduce uncertainty, an approximate 10 dB change in level is seen throughout the aperture, consistent with previous studies. In addition, at low frequencies a high degree of correlation is seen. Near the peak radiation direction high levels of derivative skewness indicate significant shock content and crackle. This dataset also presents the opportunity to test a new method for processing acoustic vector intensity. [Thomas et al., JASA 137, 3366-3376 (2015)] Comparison with the traditional method shows an increase in usable bandwidth of more than an order of magnitude.



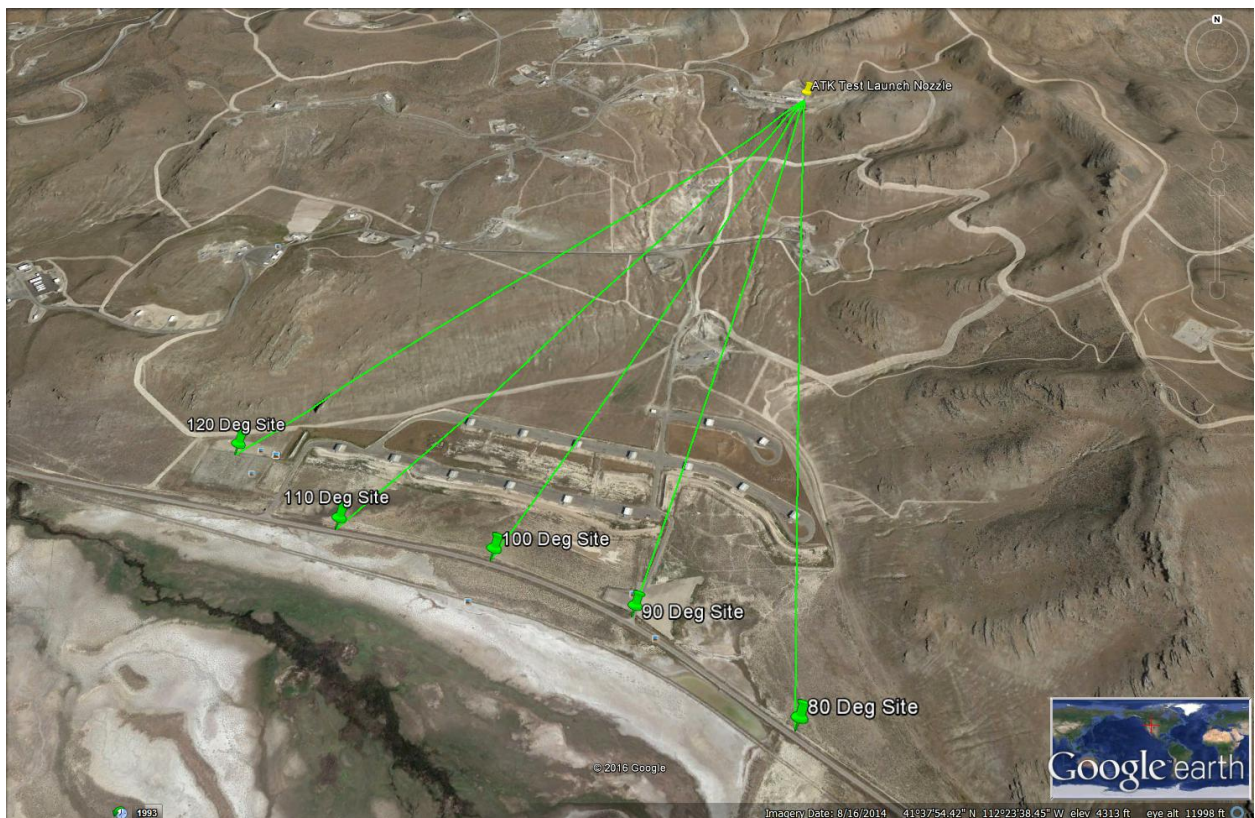
## 1. INTRODUCTION

The Space Launch System (SLS) represents the future of space exploration, leading the exploration into deep space. A new booster, based on the Space Shuttle Solid Rocket Booster but with 15% more thrust, will be integral to deep space missions. Before the SLS begins operations, the unique acoustic environment associated with the new five-segment rocket motor needs to be understood. Preliminary measurement of the spatial variation in sound levels for the SLS rocket boosters were obtained from horizontal, static firings of the first two qualification motors, QM-1 and QM-2. The QM-1 measurements and analyses were reported in Ref. [1]. In June 2016, a horizontal, static firing test of QM-2 took place at Orbital ATK near Brigham City, Utah, and was open to the public behind a fence at a safe distance.

The analyses presented in this proceedings paper show a preliminary characterization of the far-field characteristics of the noise from QM-2. After the basic measurement setup is explained, spectra are shown and far-field, high-frequency sound energy is shown as evidence of nonlinear propagation. Intensity calculations are compared between the traditional finite-difference method and the PAGE method.[2] The waveforms are inspected for evidence of nonlinear propagation using the derivative skewness metric, and then results are compared with the QM-1 measurement.[1]

## 2. MEASUREMENT SETUP

The measurement locations of the QM-2 rocket were chosen to be close to those of the earlier QM-1 measurements[1], but additional preparation time enabled more measurement stations. The QM-1 measurement had measurement stations at  $70^\circ$ ,  $90^\circ$ , and  $120^\circ$ , measured relative to the nozzle axis with  $0^\circ$  being along the nozzle centerline downstream of the nozzle. However, as the  $70^\circ$  measurement location during the QM-1 test had no direct line of sight to the rocket due to a large hill, the QM-2 test array extended only to  $80^\circ$ .



*Figure 1. Measurement locations relative to the rocket site.*

Measurement locations were limited to public viewing areas, over 2 km from the rocket itself. The distances to each measurement location from the rocket motor nozzle are given in Table 1; the shortest and longest measurement distances were within 0.24 km, or roughly 10%. At 80° the waveforms were sampled at 204.8 kHz using a National Instruments PXI with a 4498 card, while at all other stations they were sampled at 50 kHz using a National Instruments USB DAQ and a 9233 card.

**Table 1. Distances from the rocket nozzle to the measurement stations.**

Angle (°)	80	90	100	110	120
Distance (km)	2.64	2.45	2.40	2.54	2.54

These measurements were motivated by two main factors. The first goal was to complement and improve upon the previous QM-1 measurements in characterizing the far-field noise from the SLS rocket boosters. Second, an additional type of measurement was made to estimate the acoustic vector intensity of the rocket noise. Traditionally intensity calculations have not been possible at low frequencies because of the phase mismatch between microphones on standard intensity probes. A newer processing method, the phase and amplitude gradient estimator (PAGE), can extend the frequency bandwidth and allow microphones to be spaced farther apart. The QM-2 measurements provided the opportunity to use PAGE method on a low-frequency, broadband source. As such there were two types of measurement stations, those measuring only pressure and those with one-dimensional intensity probes.

The measurement locations with intensity setups (90° and 120°) each contained three phase-calibrated, ¼" G.R.A.S. pressure microphones. The microphones were oriented vertically and attached to a small PVC pipe, mounted on a tripod. (See Figure 2.). The three microphones are all in one straight line pointing towards to rocket motor, such that the one-dimensional intensity is estimated along the direction of propagation. As this is the extreme far-field of the source, the assumption that sound propagation is essentially planar across this three-microphone intensity probe is valid.



*Figure 2. Example of the intensity microphone setup at 120°, with the rocket exhaust pictured in the background.*

The measurement stations at 80°, 100°, and 110° consisted of one ¼" and one ½" G.R.A.S. microphone, both of which are free-field microphones. These microphones are mounted on a wooden dowel and attached to a tripod, but these microphones are both pointed horizontally towards the rocket motor, as in Figure 3.

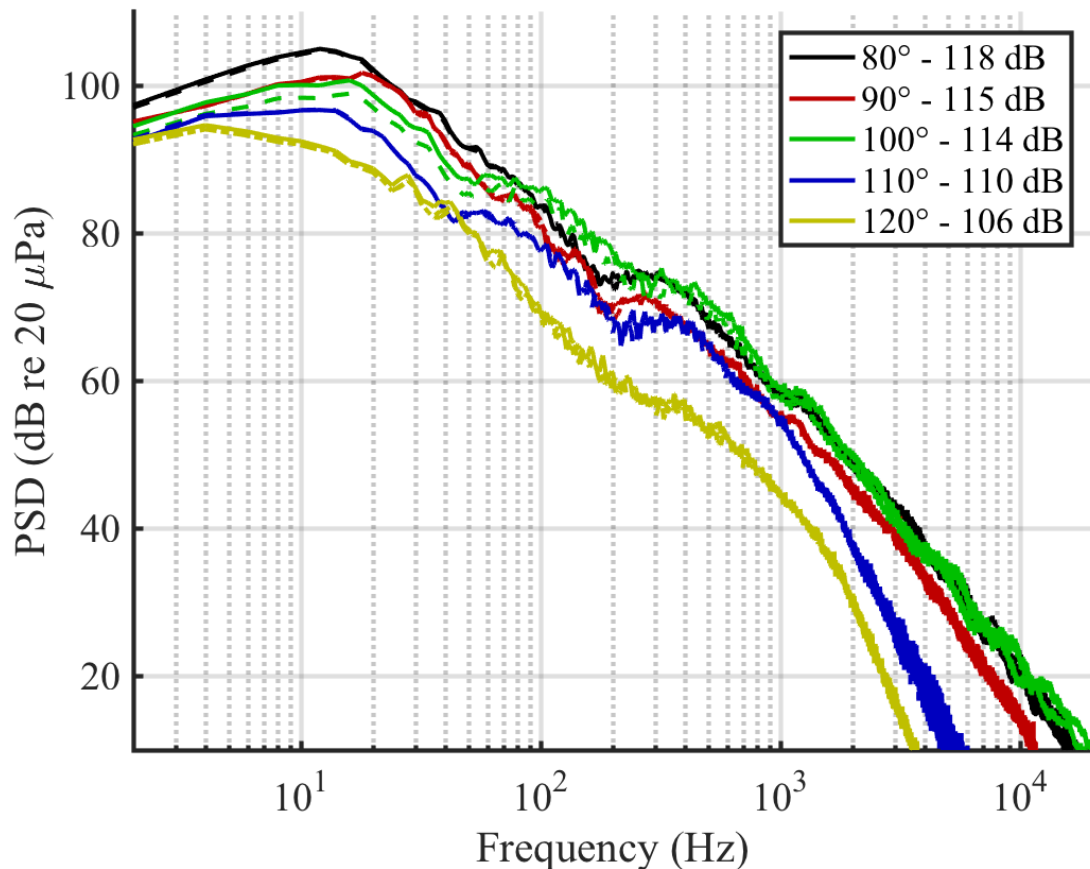


*Figure 3. An example of the pressure measurement setup, with both microphones pointed towards the source.*

### 3. ANALYSIS

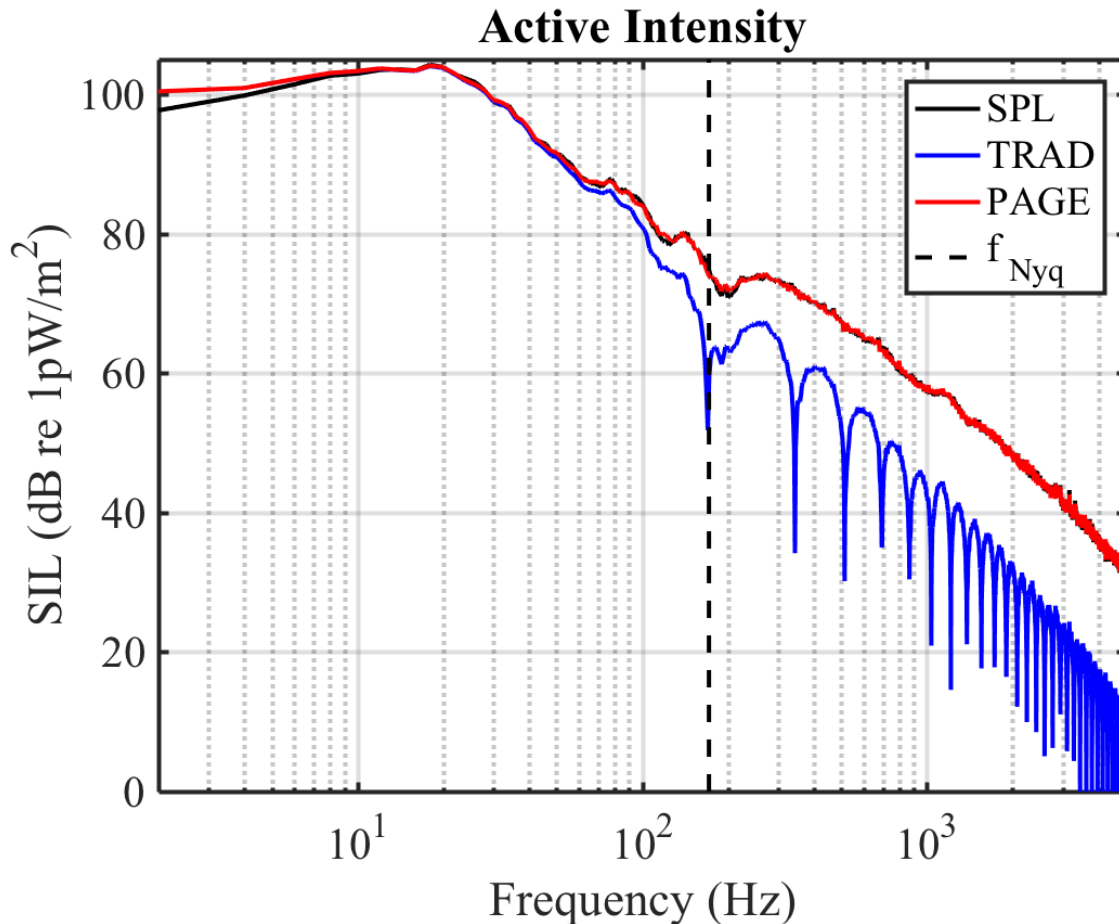
#### A. SPECTRA AND DIRECTIVITY

Jet and rocket noise have several identifying characteristics, including spectral shape and directivity[3]. The spectra of each microphone are shown in Figure 4. Each angle is plotted using a different color, with different line patterns showing the individual microphones. However, the close/indistinguishable differences between microphones at the same measurement location show the consistency between microphones, in particular for the intensity probe microphones at 90° and 120°. One interesting feature of the spectra is the change in relative frequency content. The peak frequency at 80° is at 15 Hz, but the peak frequency at 90° has shifted forward to 20 Hz, while the peak frequency shifts back to lower frequencies at 120°. Another point of interest is the presence of high-frequency energy, especially at 80°-100°. The high-frequency levels in these microphones are indicative of nonlinear propagation. Linear absorption would predict a loss of over 100 dB at 4 kHz over a distance of 2 km, with even greater losses at higher frequencies. The fact that high-frequency levels are still measureable points to the fact that nonlinear propagation is generating high-frequency content through waveform steepening. The legend also shows the average OASPL at each location, showing the overall directivity. The peak angle of directivity is expected around 75°, meaning that the microphones from 80-120° should experience drops in OASPL [4], which is indeed what is shown in the legend.



**Figure 4.** Power spectral density at each microphone, color-coded according to angle. Average OASPL at each location is shown in the legend.

As mentioned in the Measurement Setup section, microphones at 90° and 120° were phase-calibrated and aligned to calculate intensity along the far-field propagation radial. Using the PAGE method [2, 5, 6], which calculates intensity by taking separate gradients of the pressure and phase between microphones, the phase can be unwrapped and high-frequency intensity calculations can be performed even for large microphone spacing. (The large spacing is necessary to obtain accurate low frequency estimates.) Figure 5 shows the active sound intensity level (SIL) calculated using both the traditional finite-difference method for calculating intensity and the PAGE method. These are compared with the SPL, which should be identical to the SIL for a propagating wave. The SIL calculated using the traditional method begins to drop off as the spatial Nyquist frequency is approached, which for a total spacing of 1 m equates to roughly 170 Hz. Errors on the order of a few decibels are seen as low as 60 Hz, and beyond this point the SIL is severely underestimated using the traditional method. In contrast, the PAGE method extends the usable bandwidth for intensity calculations beyond the spatial Nyquist limit, with the SIL and SPL nearly overlaying each other up to 5 kHz, over an order of magnitude above the spatial Nyquist frequency, using the same microphone spacing as was used in the traditional calculation. This shows that when SIL calculations are needed, microphones can be spaced farther apart than the 1-2” spacing previously used and still achieve good bandwidth using the PAGE method.

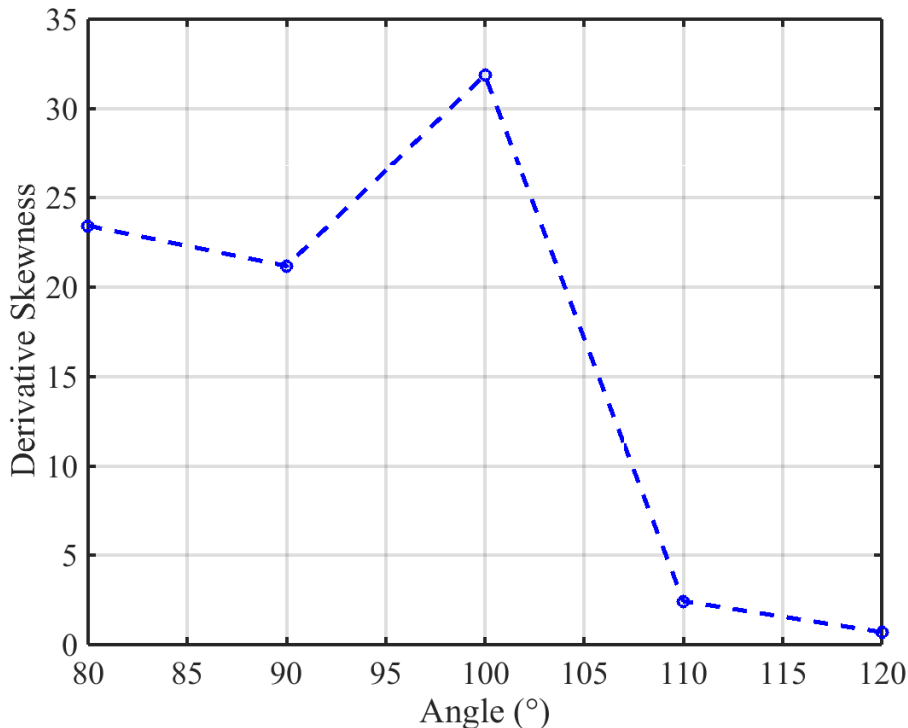


*Figure 5. Comparison of SPL with two methods of calculating SIL. The spatial Nyquist frequency is indicated by the dashed line*

## B. NONLINEARITY

The high-frequency content shown above suggests the influence of nonlinear propagation. While this influence is seen in the frequency domain as an anomalously large amount of high-frequency energy, in the time domain this is seen as a steepening of waveform and the formation of shocks. While several metrics have been used to show the shock content of a signal [7-11], in this paper the derivative skewness is shown. The skewness expresses an asymmetry in a distribution, and the large positive derivative associated with shocks result in a positive skewness. A threshold of  $Sk\{\partial p/\partial t\} \geq 5$  is typically indicative of significant shocks present in the waveform.[9] The derivative skewness at each of the measurement angles is shown in Figure 6. The measurement locations at 110° and 120° show very little derivative skewness, below the threshold of five, but the other three measurement locations show significant shock content. The large derivative skewness values indicate the significance of nonlinear propagation even at distances of over 2 km from the source, with similar values to those seen near the rocket [12].





**Figure 6.** Derivative skewness at each of the measurement stations.

#### 4. COMPARISON WITH QM-1 MEASUREMENTS

These measurements closely mirrored earlier measurements of the QM-1 rocket firing, enabling a comparison in similar measurement locations. The quantities compared in this section are spectra and nonlinearity indicators. The rocket booster is identical between the QM-1 and QM-2 measurements, although the rocket had a temperature of 90°F in the QM-1 test and was cooled down to 40°F for the QM-2 test.

The spectra, shown in the upper half of Figure 7, exhibit many similarities but also significant differences. While the 70° measurement point from the QM-1 measurements was not present in the QM-2 measurements due to an obstruction, the spectra at 90° peaks near 105 dB at roughly 15 Hz, a similar frequency but 4 dB lower than the QM-1 measurement. In both experiments the peak frequency shifts downwards in the downstream direction, though it is slightly lower in the QM-1 measurements at 120° than in the QM-2 measurements, and the OASPL at 120° is 7 dB lower in the QM-2 measurement. One interesting point is that the QM-2 measurements seem to have much smaller ground interference nulls. Without specific weather data, including wind profiles and a detailed topography, it is difficult to point to the reason why, but it is likely related to differences in weather conditions, as the QM-1 measurements were performed in March and the QM-2 measurements were performed in June.

A comparison of derivative skewness between the two measurements does not agree as well as the spectra, as shown in the lower half of Figure 7. While both measurements show an increase in derivative skewness in the downstream direction, the derivative skewness in the QM-2 measurement reaches values above 20 at 80°, 90°, and 100°, while the QM-1 measurements peak of  $Sk\{\partial p/\partial t\} = 3$  occurs at 90°. One possible explanation is the difference between a hot rocket and cold rocket, but since the levels and peak frequencies are similar between measurements, this is unlikely to affect shock formation. Another possible explanation is that, similar to the differences in spectra, atmospheric conditions changed the propagation medium enough to significantly alter shock formation between the two measurements.

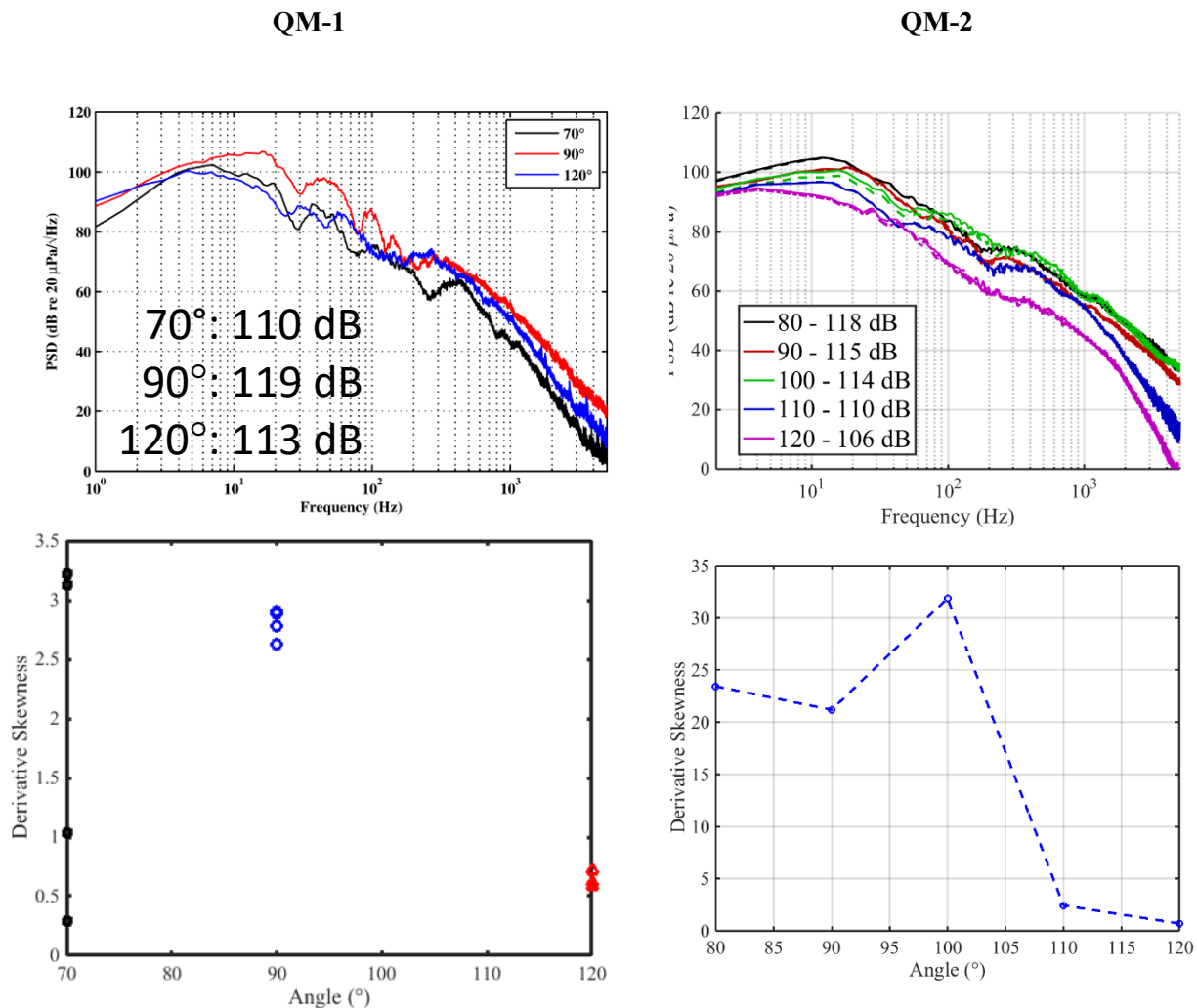


Figure 7. Comparison of spectra and derivative skewness between the QM-1 and QM-2 measurements.

## 5. CONCLUSIONS

The far-field acoustic environment during the QM-2 rocket firing has been measured and a basic analysis provided. Directivity likely peaks somewhere downstream of 80°, and OASPL increases as the angle decreases from 120° to 80°. The spectra show peak frequencies between 10 and 20 Hz between 80-110°, then a shift down to roughly 3 Hz at 120°. This behavior is the opposite of what is seen in jet noise, as the peak frequency is typically higher in the forward direction, but in line with the QM-1 measurements. Three-microphone intensity probes were used to estimate acoustic vector intensity in the radial direction. The PAGE method obtains good estimates of the intensity from 5-5000 Hz, a significant increase in bandwidth over traditional processing methods.

## ACKNOWLEDGMENTS

We would like to gratefully acknowledge the BYU Acoustics Research Group for assistance with organizing the measurements and equipment, as well as the students who helped with the measurements, including Caleb Goates, Jared Oliphant, Aaron Vaughn, and Daxton Hawks.

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