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Acoustical measurements during a static firing of the Space Launch System solid rocket motor

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Acoustical measurements were made in the very far field during a recent test firing of the five-segment QM-1 Space Launch System solid rocket motor at Orbital ATK. Data were taken using 6.35 mm and 12.7 mm type-1 microphones at three far-field locations to the sideline and aft of the nozzle at a range of 650-800 nozzle diameters. The experiment setup, including the appreciable terrain changes, is first discussed. Spectral and autocorrelation analyses highlight the variation of the noise with respect to observation angle. In addition, high-frequency spectral characteristics and waveform statistics are evidence of the significant nonlinear propagation over the propagation range. Terrain effects and data stationarity during the firing are discussed. This dataset is compared to measurements of other solid rocket motors at closer and farther ranges, including the GEM-60 and the four-segment Shuttle Reusable Solid Rocket Motor.

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1. INTRODUCTION

The Space Launch System (SLS) represents the future of NASA-based deep space exploration. A new booster, based on the Space Shuttle Solid Rocket Booster but with 15% more thrust, will be integral to deep space missions. This 5-segment booster has a length of 177 ft, a diameter of 12 ft, and provides 3.6 million pounds thrust during the burn time of 126 seconds. Before the SLS begins operations, the unique acoustic environment associated with the new five-segment rocket motor needs to be understood. A preliminary measurement of the spatial variation in sound levels from the first of these new rocket boosters, known as Qualification Motor-1 (QM-1), was obtained in March 2015. A horizontal, static firing test took place at Orbital ATK near Brigham City, Utah, and was open to the public behind a fence at a safe distance. This test environment gave students and faculty from nearby Brigham Young University the opportunity to measure and analyze the noise from QM-1 at three far-field locations.

The analyses presented in this proceedings paper show a preliminary characterization of the far-field characteristics of the noise from QM-1. After the basic measurement setup is explained, waveforms are shown from each measurement location, along with a running 0.5-s OASPL. Spectra are presented and then decomposed into contributions from fine-scale and large-scale turbulence. Cross-correlations and coherence are compared between the different measurement locations. The waveforms are inspected for evidence of nonlinear propagation using the derivative skewness metric, and then results are compared with similar rocket tests.

2. MEASUREMENT SETUP

The measurement took place at the Orbital ATK firing grounds near Brigham City, Utah. Measurement locations were confined to public viewing areas along a roadside more than 2 km from the rocket nozzle, at angles of 70°, 90°, and 120° relative to the nozzle centerline. Due to local topography, a large hill obscured direct line of sight between the 70° measurement location and the rocket itself.

Figure 1. Locations of the three measurement stations relative to the rocket nozzle.

Each measurement station had a total of four elevated free-field microphones, two ½” microphones and two ¼” microphones. These microphones were mounted on a tripod 12’ in the air, as shown in Figure 2. Each measurement station was equipped with an independent data acquisition system. The 70° station was equipped with a National Instruments PXI with a 4462 card which sampled at 204.8 kHz, while the other two stations each had a simpler National Instruments USB-9233 DAQ housed in a single-slot bus-powered chassis and recording at a 50 kHz sampling rate.

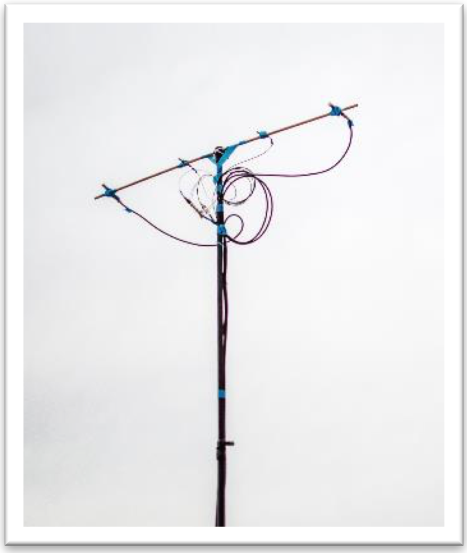

Figure 2. An example of the measurement stations, with two ¼” microphones and two ½” microphones elevated 12’ above the ground.

3. ANALYSIS

A. WAVEFORM ANALYSIS

Before analyzing the properties of the rocket motor noise, questions regarding the consistency of the 126 sec long firing need to be addressed. The waveforms are plotted, along with the running 0.5 s OASPL, in Figure 3. The first feature of note is the ignition overpressure, most visible at 120° (lower), but also visible at 90° (middle). Unfortunately, due to technical difficulties the initial few seconds of the firing were not recorded at 70°. After the initial overpressure, occasional outliers in pressure are seen, but they have a minimal effect on the running OASPL, which stays within roughly 5 dB over the course of the measurement. While the 70° station would normally be expected to experience the largest OASPL, in this case the nearby hill provided shielding, thus the OASPL is higher at 90°. The time-averaged OASPLs from the three measurement locations are 110, 119, and 113 dB at 70°, 90°, and 120°, respectively.

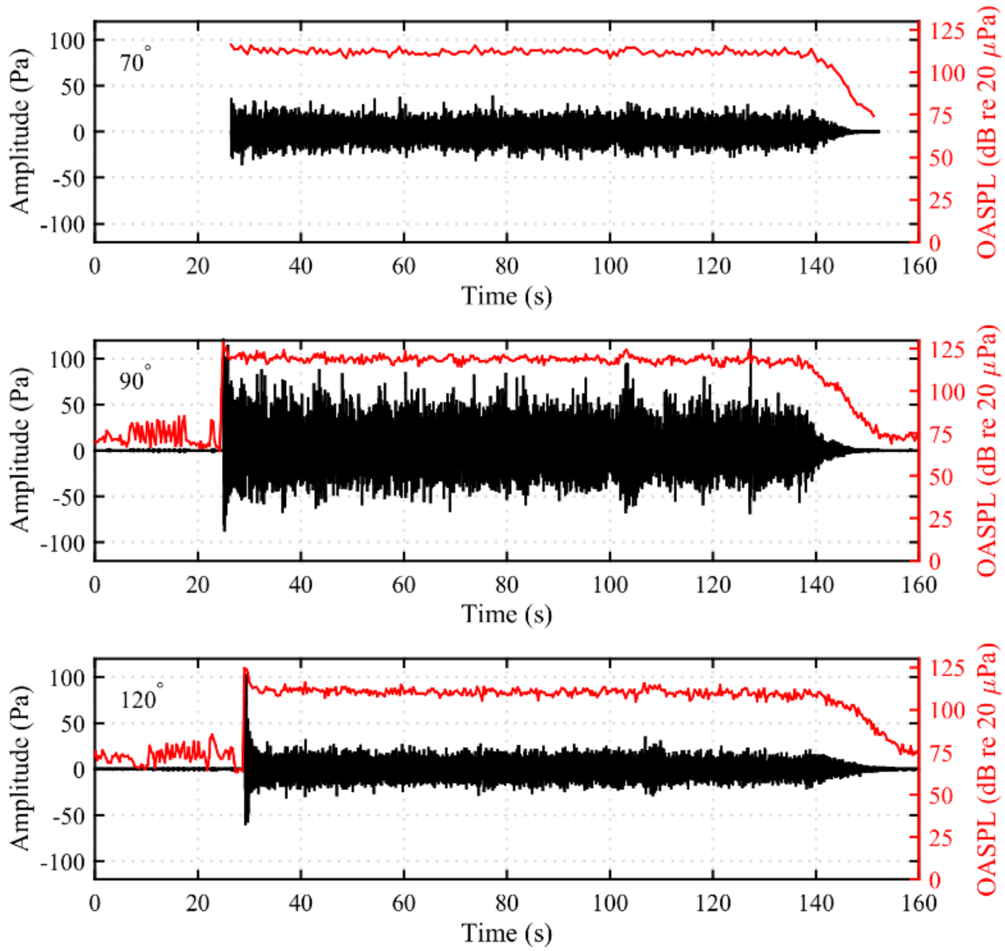

Figure 3. Waveforms from the entire 126 s firing duration of the rocket at each measurement location, plotted with the 0.5 s running OASPL. An overpressure is seen at 90° (middle) and 120°(lower) but was not recorded at the 70° location (top).

B. SPECTRAL ANALYSIS

While the time-domain features visible in Figure 3 yield the measured levels, additional information is gained by viewing the associated spectra, shown in Figure 4. As expected from the previous discussion, the 90° spectral levels are higher level than the two other locations, while the 70° and 120° spectra are similar in level. The low peak frequency, indicative of the large nozzle, at 90° is between 10-20 Hz, while the peak frequency for the other two locations is 5-7 Hz. Also present at all three locations is evidence of ground reflections, causing the dip at roughly 30, 80, and 120 Hz at the 70° and 90° locations. One more important spectral feature is the presence of high-frequency energy (greater than 1 kHz) at locations more than 2 km away. For comparison, linear absorption would predict more than 100 dB of attenuation at this distance at 4 kHz, which would have pushed the high-frequency levels well into the noise floor. Nonlinear propagation is believed to be responsible for the high-frequency energy measured far from the rocket motor [1, 2].

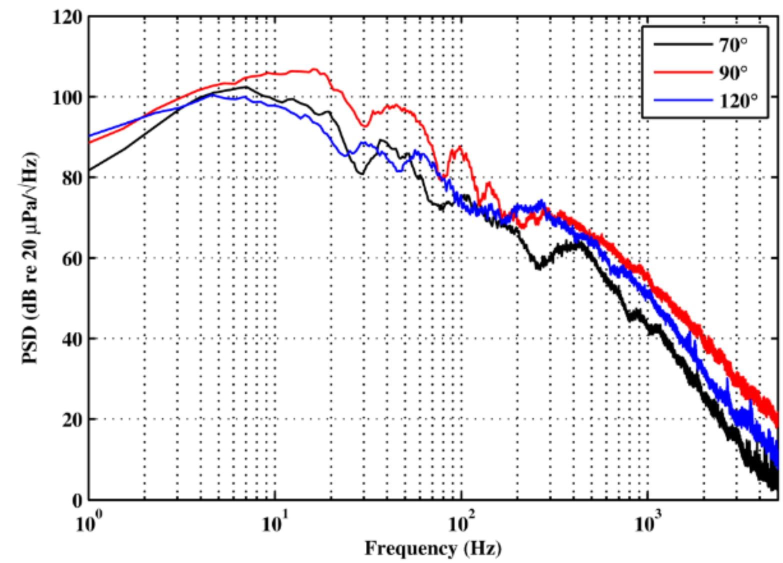

Figure 4. Spectra from the three waveforms shown in Figure 3.

C. SIMILARITY SPECTRA

Even though the QM-1 spectra have evidence of ground reflections, the overall spectral shape can be compared to similarity spectra for the two-source model of turbulent mixing noise [3]. Far-field data from a variety of cold and heated laboratory-scale jets were used to develop two similarity spectra that match the primary features of the noise from the fine and large-scale turbulent structures [4, 5]. The large-scale similarity (LSS) spectrum was reported to fit at angles closer to the centerline. The fine scale similarity (FSS) spectrum matched the radiated spectra at larger angles. In addition, it was proposed that the turbulent mixing noise at any radiation angle is a sum of LSS and FSS spectra. Agreement between the similarity spectra and measured jet noise spectra has been shown for laboratory-scale jets [6-8], and for high-power engines installed in military aircraft [9, 10], with a few exceptions. Comparisons between the similarity and QM-1 spectra (shown in Figure 5) follow expected trends. The general shapes of the spectra at 70° and 90° follow the LSS spectrum up to approximately 1 kHz, except for the low frequencies at 70°. This low frequency discrepancy has also been seen in high-power military aircraft noise in and near the direction of maximum sound radiation [9, 10]. The measured rolloff above 1 kHz is likely due to atmospheric absorption, which Viswanathan pointed out was not explicitly included in the LSS/FSS fits, but is also complicated by the additional impact of nonlinear propagation. At 120°, the overall spectral shape is best approximated by a combination of the LSS and FSS spectrum, but we also point out that only FSS phenomena have been previously reported in the jet noise literature in the forward direction. The measured spectral shape may be due to other causes, but then again, the relatively high convective Mach number for this motor will push the peak directivity angle (dominated by LSS radiation) to be somewhere between 65 and 70° [11]. Thus, it is possible that LSS contributions may appear in the forward direction, although further study is needed. For now, we simply note that the radiation appears more LSS-like at all three angles.

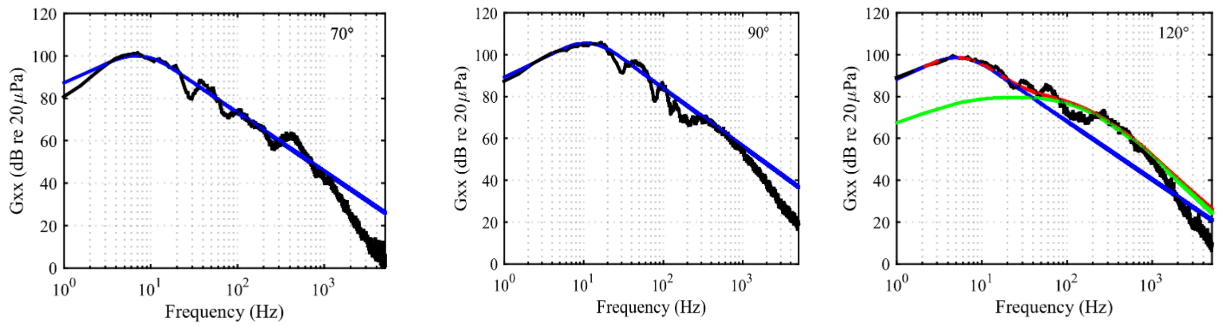

Figure 5. Similarity spectra from the spectra at each measurement location. Fine-scale contributions are seen only at the 120° location.

D. CROSS CORRELATION

Though the sound at all measurement locations radiates from the rocket plume, there is not necessarily a coherent relationship (i.e. a constant phase difference) between two points in the field. Correlation and coherence has been used to illustrate the fine-scale and large-scale nature of jet noise sources [12-16]. Figure 6(a) shows the cross-correlation between the 70° waveform with itself (the autocorrelation) and waveforms from the other two measurement locations. A high value in the cross-correlation would imply a time delay between similar signals arriving at the two measurement locations, corresponding to a longer path to one of the microphones. Lack of a definite peak in the cross-correlation indicates the two microphones are seeing different noise signals. In Figure 6(a), there is a small peak in the cross-correlation between 70° and 90°, but very little correlation is seen between 70° and 120°. If we look at the coherence shown in Figure 6(b), which is high when the Fourier spectra have a constant relative phase relationship, there is significant low-frequency coherence between 70° and 90°, and much lower coherence between both of those locations and 120°. This result indicates that there is some coherence in noise radiated closer to the nozzle centerline that is not well correlated with radiation at larger angles, similar to the case of jet noise [14, 16]. This result also suggests that although the measured spectra at the three angles are most consistent with noise radiated from large-scale structures, they are relatively incoherent, except around and below the peak-frequency region.

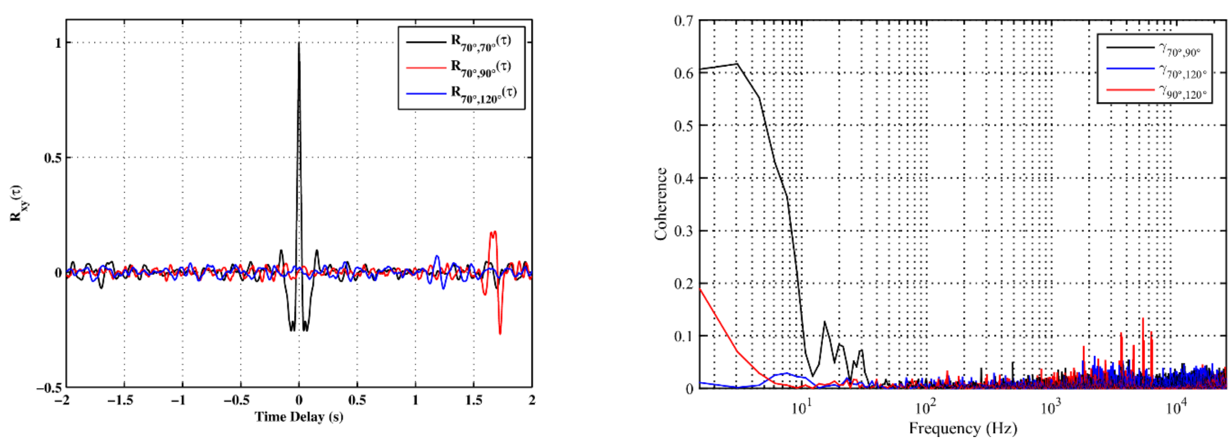

Figure 6. Cross-correlation and coherence plots.

E. NONLINEARITY

The levels associated with rocket noise induce nonlinear propagation.[1, 17] As discussed earlier, in the frequency domain this results in an anomalous amount of high-frequency energy at large distances from the source. In the time domain, nonlinear propagation is associated with steepening of the waveform. While there are many metrics that have attempted to quantify this behavior, one of the most useful is the skewness of the first time derivative of the waveform (referred to as derivative skewness), which expresses the amount of asymmetry in the distribution of derivative values.[18-20] As waves steepen and shocks form, large positive derivative values emerge, much larger than any negative derivatives present in the noise, producing an asymmetric distribution. In jet noise, a waveform with a derivative skewness value of 5 is considered to contain significant shocks.[20] The derivative skewness of each of the microphones is shown in Figure 7, with multiple plot markers at each measurement angle due to the four microphones present at each location. At these measurement distances, shocks have largely thickened, as evidenced by the fairly low derivative skewness values. The spectral roll-off above 1 kHz in Figure 4 is also indicative of significant high-frequency energy loss, whereas waveforms with many thin shocks would have spectra with a f^{-2} slope. Though the positive derivative skewness at 70° and 90° does suggest that the waveforms are still steepened, there are likely few if any significant shocks within the waveforms. However, in the case of the 70° location (which should be near the peak radiation direction) it could be that significant shocks are present in the unobstructed noise field, but the large hill disrupts the waveform's impulsive nature.

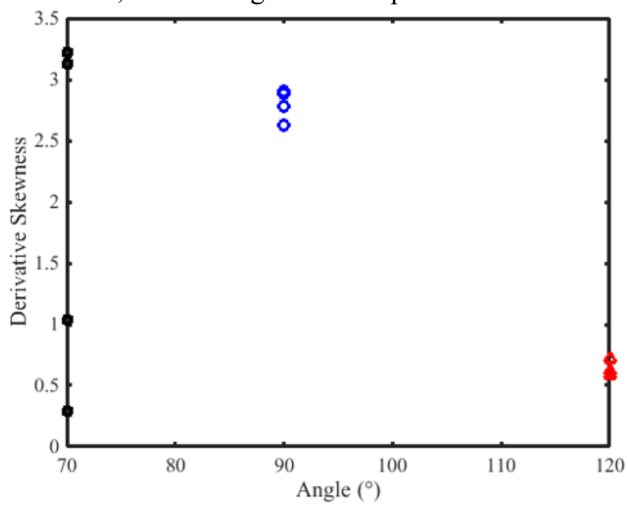

Figure 7. Derivative skewness plots.

4. COMPARISON WITH SIMILAR MEASUREMENTS

While the dataset presented here is unique in many ways, it can still be compared in meaningful ways with prior rocket experiments. Here, comparisons are made with OASPL, measured spectra, and derivative skewness.

A. OASPL

The OASPL is likely the most robust comparison that can be made between rocket measurements. While there is some uncertainty associated with propagation over the large distances and terrain affects associated with these measurements, OASPL is expected to be similar to previous rocket data. One set of measurements from the RSRM that the SLS booster is based on showed the OASPL as a function of angle [17]. The levels reported, at a distance of 80 diameters, are 128, 134, and 140 dB at 120, 90, and 70° respectively. Corrected for the larger distance (677-808D_j) and the slightly larger thrust of the SLS booster, expected levels would be 110, 116, and 121 dB at the measurement locations in this paper. Aside from the 70° measurement location, which is well below the expected level due to the obstructing hill, the QM-1 measurements are roughly 3 dB higher than could be expected from the RSRM measurements. Similar comparisons with other rocket measurements [11, 21] show that the OASPL at the 90° and 120° measurement locations are within 3 dB of expected behavior.

B. SPECTRAL COMPARISON

One example in the literature of spectra from a rocket motor is from McInerny and Olcmen[1]. The spectra from the QM-1 measurement are shown in Figure 8(a) while those from five measurement sites near a Titan IV during liftoff are shown in Figure 8(b). Those same spectra, corrected for spherical spreading to better illustrate propagation effects, are shown in Figure 8(c). Measurement sites A-E were located 0.95, 2.3, 3.94, 6.69 and 15.2 km away from the site of a rocket launch. As the rocket is not in a fixed location, there is not a defined angle for each microphone, but the spectra shown are taken from the peak OASPL, at an angle of roughly 60°. The spectrum from the Site A measurement peaks between 10 and 20 Hz at a value of 123 dB re 20μPa/Hz, while at site B the peak occurs at 113 dB. In the Titan IV measurements, nonlinear propagation and shock formation cause the slope of the PSD to decay as $1/f^2$ (approximately 20 dB/decade) in the high-frequency regime, causing high-frequency energy, even past 10 kHz, at extreme distances from the rocket. The QM-1 spectral levels past 1 kHz decay more rapidly than the $1/f^2$ slope. In the case of the Titan IV measurement, the vertical launch meant that the loudest section of each waveform was when the microphone was located in the peak directivity of the rocket, while the microphones in the QM-1 test were either not located in the peak radiation angles or obstructed. Thus, while some features agree between the two measurements, others do not line up because of differences in radiation angles, terrain effects, and differences between the rockets themselves.

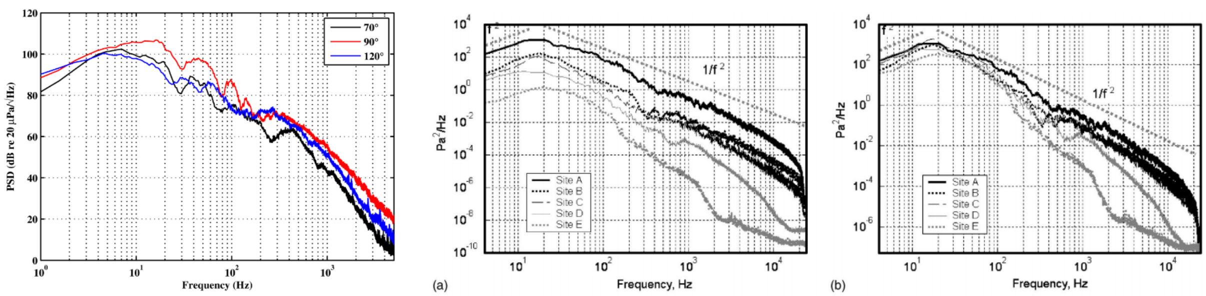

Figure 8. Comparison of spectra (a) from the QM-1 test with the (b) raw and (c) corrected Titan IV far-field spectra [1].

C. NONLINEARITY COMPARISON

The derivative skewness of the sound field produced by a reusable solid rocket motor (RSRM) for the SLS was calculated by Gee *et al.*[17] This measurement shows high derivative skewness at nearly all angles, and especially in the peak directivity lobe of the rocket, with values reaching over 40 at a distance of 80 nozzle diameters, or 310 m. This high derivative skewness is indicative of significant shocks. However, it is difficult to extrapolate the high derivative skewness values in the mid field, as shown in Figure 1, to the far-field locations shown for the QM-1. However, some trends do hold between the two measurements, such as the derivative skewness being noticeably higher closer to the nozzle centerline. Future measurements should ensure that the path to far-field locations is not obstructed to more accurately capture shock behavior and enable comparison with other experiments.

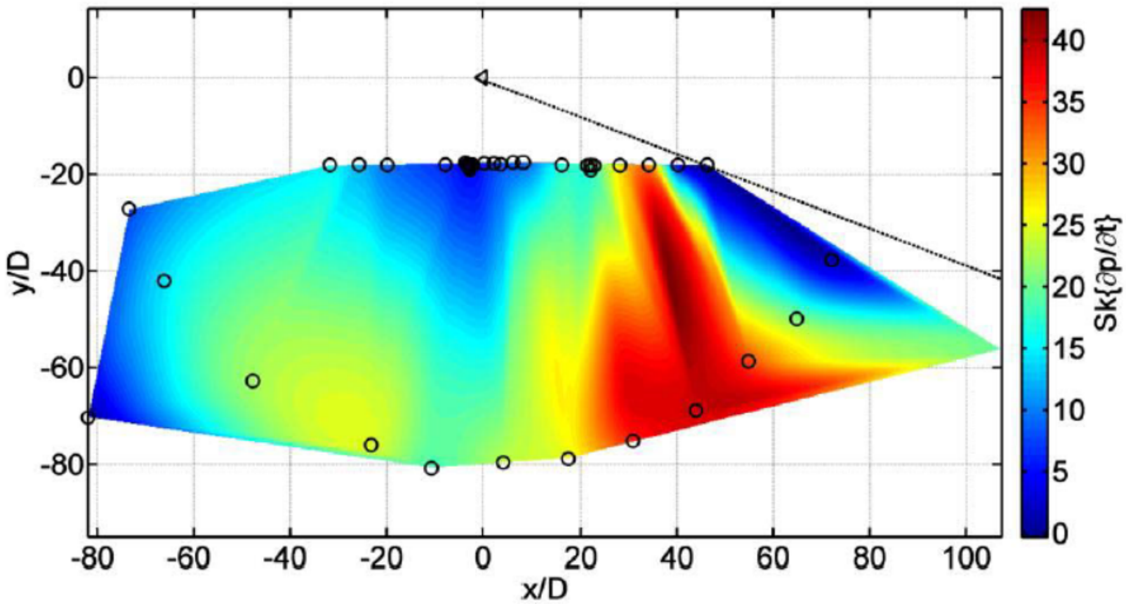

Figure 9. Derivative skewness values near the RSRM to be used in the SLS from Gee et al. [17].

5. CONCLUSIONS

The far-field noise of a solid rocket booster has been shown for 3 measurement locations more than 2 km from the source. Levels at this distance are still very high, near 100 dB at all three locations throughout the entire 126 second burn time. Spectra calculated from the waveforms show a peak frequency near 10 Hz, significantly lower than other measurements, with the presence of high-frequency energy at large distances suggesting nonlinear propagation. A similarity spectra decomposition shows that the majority of the noise can be attributed to large-scale turbulent structures at both the 70° and 90° locations, while at 120° there is evidence of both large-scale and fine-scale structures. Between the 70° and 90° measurements, there is considerable low-frequency coherence, but coherence is significantly less at high frequencies. Also there is negligible coherence between the 120° measurement and the other two. The derivative skewness values at 70° and 90° suggest steepened waveforms, but not the presence of significant shocks at these long distances. Some trends from the spectra and the derivative skewness compare favorably with other measurements, but non-ideal measurement locations and terrain make more direct comparisons impossible. Future far-field measurements, for example on the upcoming QM-2 test, can focus on more measurement locations and a direct line of sight between locations and the rocket plume, ensuring an unobstructed noise field to obtain the cleanest measurements possible.

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