Crest Factor Analyses Of Launch Vehicle Noise

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Abstract

As some of the loudest machines made by mankind, the sound produced by rockets can have catastrophic results on the vehicle payload and its environment surrounding the launchpad. Because of this, it is vital for acousticians to understand the noise environment produced by rockets during launch. One tool that is used to ensure that acousticians have the requisite equipment when performing noise measurements is the Crest Factor. The Crest Factor is a measure of the relationship between the max and mean pressures, and as such is a useful measurement tool for determining the difference between where the majority of the pressure occurs and where the max pressure occurs. This information is useful in determining which equipment to use in order to minimize clipping. To better assist with the equipment planning for future rocket launch noise measurements, this study was performed to analyze the behaviors of the Crest Factor vs Distance, Time, and the range that Crest Factors can fall in. It is concluded that the Crest Factor measured during rocket launches does not have any discernible relationship with distance and that the Crest Factor occurs at either the ignition or the maximum pressure, and falls in the range of 11-20 dB.

Crest Factor Analyses of Launch Vehicle Noise

Throughout recent history, rockets have captured humanity's imagination with their ability to escape Earth's atmosphere and explore the heavens. As the main instrument responsible for such accomplishments as the Space Race, the Apollo missions, the Mars Rovers, and the International Space Station, rockets have been a key part of many scientific accomplishments in the last century. However, one vital element of rocket launches has gone relatively unstudied since the early Apollo missions. This is the field of rocket acoustics, which is the study of the acoustic pressure produced during a rocket launch. This realm of acoustics was well studied during the Apollo missions, but then went relatively unstudied from the late 1970s -2008, which is a large portion of the lifespan of rockets (see Fig. 1). However as the number of rocket launches per year has increased since 2008, the study of rocket acoustics has begun again with renewed interest.

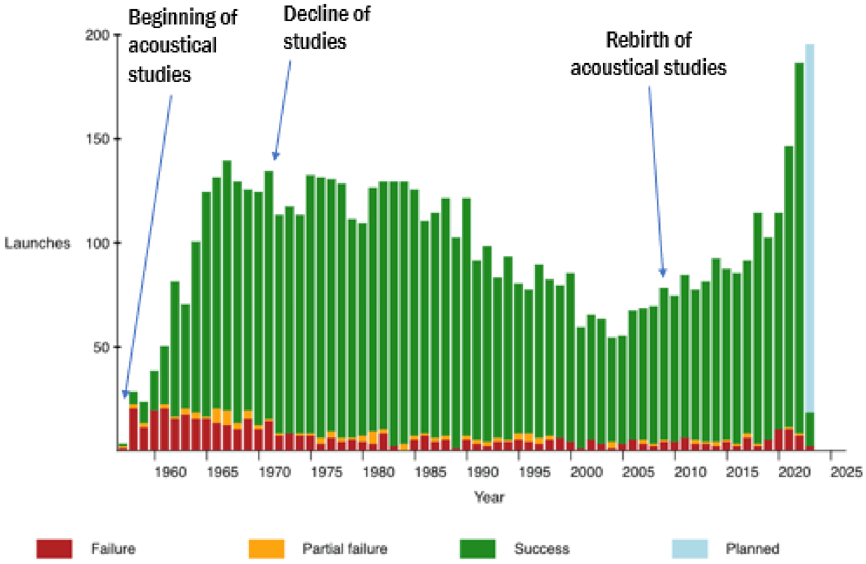
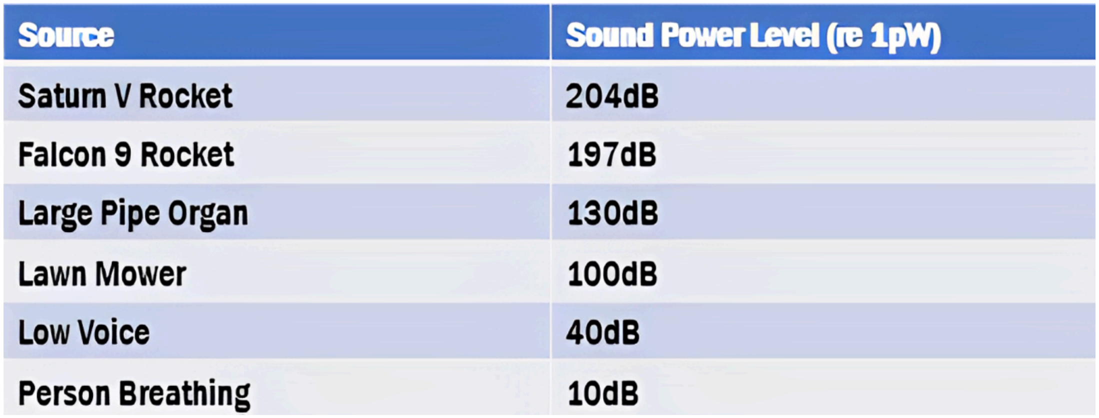


Fig 1: The number of rocket launches per year from 1957-2023

As the number of rockets per year has increased, the importance of understanding the sound produced by those rockets has become ever more important. The Saturn V rocket was measured at 203 dB (199.5 MW) of sound power (Gee et al, 2022). Even relatively smaller rockets like the Falcon 9 can reach up to 197 dB of sound power. With the low frequency and high amplitude of the acoustical waves produced by rockets, rocket noise can travel for miles. In fact, the sound pressure level over three miles from the Artemis 1 rocket launch pad is approximately the same as the sound of a chainsaw (Mack, 2023). For further context, Fig. 2 compares some common sound power levels with that of two rockets. It is important to note that each increase of 10 dB is ten times the sound power. So, from the table below the sound power produced by the large pipe organ is one thousand times higher than the sound power from a lawn mower.



Source	Sound Power Level (re 1pW)
Saturn V Rocket	204dB
Falcon 9 Rocket	197dB
Large Pipe Organ	130dB
Lawn Mower	100dB
Low Voice	40dB
Person Breathing	10dB

Fig 2: Comparison of Sound Power Levels of several common noise sources

The high acoustic pressures created during launch can be detrimental to the vehicle payload. A study by the NASA Kennedy Space Center recently reported that "vibration/acoustic launch environment was estimated to account for 30 to 60 percent of the first-day space failures" (Caimi, et al). Additionally, another study about "lessons learned" suggested the implementation of an acoustical noise requirement. This study found that "in the absence of an acoustic noise requirement for spacecraft design and test, critical hardware that would likely survive other mission phases may fail when exposed to the mechanical stresses of launch" ("Acoustic Noise Requirement"). These mechanical stresses are caused by the vast range of frequencies that the launch vehicle is exposed to during the launch environment. This range of 20-10,000 Hz can cause extreme strains on components of the rocket that will lead to failure. This arises when the frequencies induce vibrations in the rocket's components, potentially leading to catastrophic consequences for large flat panels that may undergo significant displacement due to vibration. This environment can also cause damage in such ways as causing broken solder joints, loosening fasteners, and cracking structural members ("Acoustic Noise Requirements"). Additionally, this broad range of frequencies can have severe effects on the surrounding infrastructure and environments, including the local wildlife. A recent example of this is shown below in Fig 3, as a flock of disoriented birds fly in the midst of the the launch of the SpaceX launch vehicle Starship.

Fig 3: A flock of birds flying near the launch of the SpaceX vehicle Starship. While it is unknown the precise reason why the birds are there, experts surmise it may have been caused in part by the acoustical environment of the launch (Urrutia, 2023).

Because of the dangers that the acoustical environment poses to the launch vehicle and the surrounding region, it becomes necessary to develop a better understanding of rocket noise. Since methods to correctly predict the noise from first principles have not been developed yet, measurements are key to understanding the acoustic environment. . However, with rocket launches one common struggle for acousticians is clipping. Microphones only have certain ranges of frequency and amplitude that they are able to measure accurately. Once the noise signal exceeds that range, then the pressure waveform “clips” or does not record any of the higher values and simply records the maximum of the microphones range (See Fig 3).

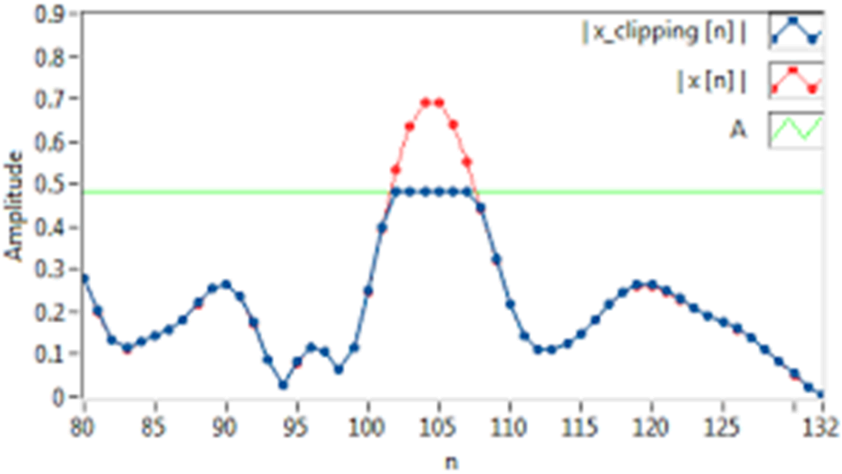
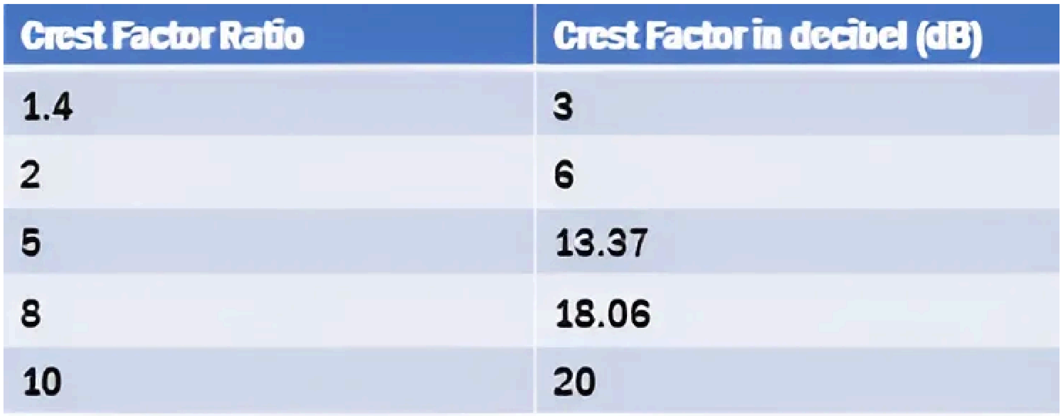


Fig 4: A visual demonstration of clipping. The green line represents the maximum of the microphones range. The red values are those that are not recorded because they exceeded the microphones limit.

One tool that is commonly used to minimize the likelihood of clipping is the Crest Factor (CF). The Crest Factor is defined as the ratio of the Peak Pressure and the Mean Pressure of the waveform. Due to the nature of the decibels (ie a logarithmic scale), this can also be demonstrated as the difference between the peak dB and the rms overall sound pressure level (OASPL) of the noise source. If the trends of the Crest Factor can be better understood, then acousticians can more confidently select equipment to use to ensure accurate data collection. Previous studies of the Crest Factor in aeronautics have been performed, but there are very few that have explored the behavior of the Crest Factor in depth. One such study that has been conducted was on the behavior of jet noise, where it was discovered that jet noise had a maximum Crest Factor of approximately 20dB (Gee, et al., 2013). Another such study was performed by McInerny where she calculated crest factors based on time periods of maximum levels (McInerny, 1996).



Crest Factor Ratio	Crest Factor in decibel (dB)
1.4	3
2	6
5	13.37
8	18.06
10	20

Fig 5: Table showing the relationship between common CF ratios and their counterparts in dB. McInerny1 calculated crest factors based on time periods of maximum levels in an analysis of several space vehicle launches.

The above table serves to assist in providing further context in comparisons between CF in pressure and decibel. A CF ratio of 1.4 or 3dB is the CF value of a sine wave, while a CF of 8 or 18.06 dB is demonstrative of a sawtooth wave. Additionally, if a CF has a pressure ratio of 10 or 20 dB then the peak pressure is 10 times larger than the RMS pressure.

Methods

As part of this project data were collected from the Northrop Grumman Antares NG-19 rocket launch. The process used to gather data at this launch is fairly indicative of the other launches, and so only the Antares launch will be discussed in how data were collected. At this launch, a configuration of seven microphones, consisting mostly of GRAS ¼” 46 BG, GRAS 46 BD, and GRAS 146 AE microphones, were placed in two concentric circles (see Fig 5). These microphones have a bandwidth of 3.15 Hz - 70 kHz and a maximum peak pressure level of 180 dB. The microphones were connected to data acquisition cards, and a Cincozee monitorless computer where the data were stored. In order to protect the microphones readings from wind noise the microphones were placed inside foam wind caps (See Fig 6). These stations were given the title of "Pumas".

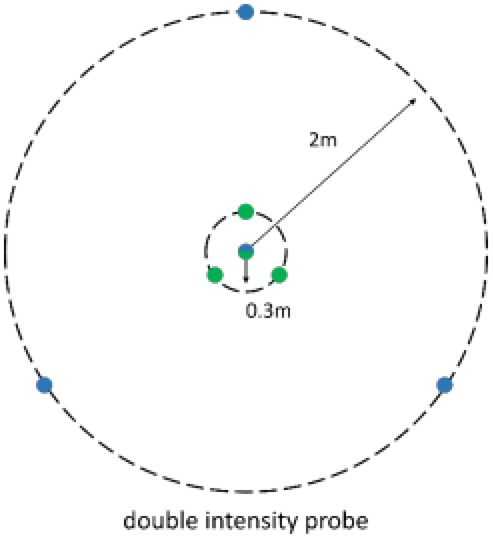


Fig 6: The configuration of microphones (shown as blue or green dots) used to measure noise during the Antares launch

Fig 7: The configuration and appearance of the microphones (only the wind screens are visible). The configuration is established to "point" directly at the rocket.

In order to measure the acoustic intensity from all sides and from a variety of distances, these microphone configurations were established in various locations (see Fig. 7). These locations were deliberately chosen in collaboration with Northrop Grumman and NASA in order to provide the most accurate and complete set of data. These locations were also chosen to ensure the protection of the equipment and to ensure that the equipment would be out of the way for the final steps of preparing the launch.

Figure 8: Map showing the locations of each of the microphone stations (Pumas) that collected data at the Antares 230 NG-19 rocket launch

Analyses

For this report, two analyses were performed. The first analysis that was performed was to determine at what point during the waveform the Crest Factor occurred. The second of which was an analysis in which the single value Crest Factor was found for a variety of statistically significant values and plotted against distance. This analysis was performed with the hypothesis that the Crest Factor would have an inverse relationship with distance and would decrease as distance increased.

Analysis I: Crest Factor vs Time

After the above calculations and analyses were performed, another set of analyses were conducted in order to more fully understand the behavior of the Crest Factor. This analysis was performed on the data collected from the Antares 230 NG-19 launch. In this analysis the running CF was plotted against time in the attempt of establishing when the Crest Factor occurred during the launch process. In order to accomplish this, the CF was calculated over 1 second time blocks. This running value was then compared with the pressure waveform of the launch measured by that channel in order to determine when in the launch process the maximum Crest Factor occurred. The hypothesis behind this analysis was that the maximum Crest Factor would occur at either ignition or the peak overall pressure of the pressure waveform. As part of this analysis histograms were also made of the pressure waveforms in order to assure that they behaved in a Gaussian fashion.

The results from this analysis consistently behaved in a few key ways. Because of this, not every result from all 20+ channels that were analyzed will be included in this report. However, the results that are included below will be indicative of the larger results that were obtained. It is possible that these results would also be indicative of the larger subset of rockets, however this analysis was only performed on the Antares 230 NG-19 rocket.

Puma 5 Channel 1

The first subset of results that occurred from this analysis will be represented by Puma 5 Ch 1. In this analysis it was found that the maximum Crest Factor was 18.4 dB and the minimum was 7.9 dB. After comparisons with the pressure waveform it was observed that the maximum Crest Factor occurred at approximately the same time as ignition. Additionally, the minimum Crest Factor occurred near the end of the pressure waveform. In the plot of the running Crest Factor, it can be observed that a large spike in the Crest Factor occurred at approximately 190 seconds. However, this spike is not relevant for this study in that it occurs over a minute before ignition and this study is only interested in the acoustical outputs that occur after ignition. All subsequent discussion will ignore this spike. Additionally, histogram analysis showed that at ignition, the pressure waveform was nearly perfectly Gaussian. At the time of the minimum Crest Factor, the pressure waveform was markedly less Gaussian but still had a general Gaussian form.

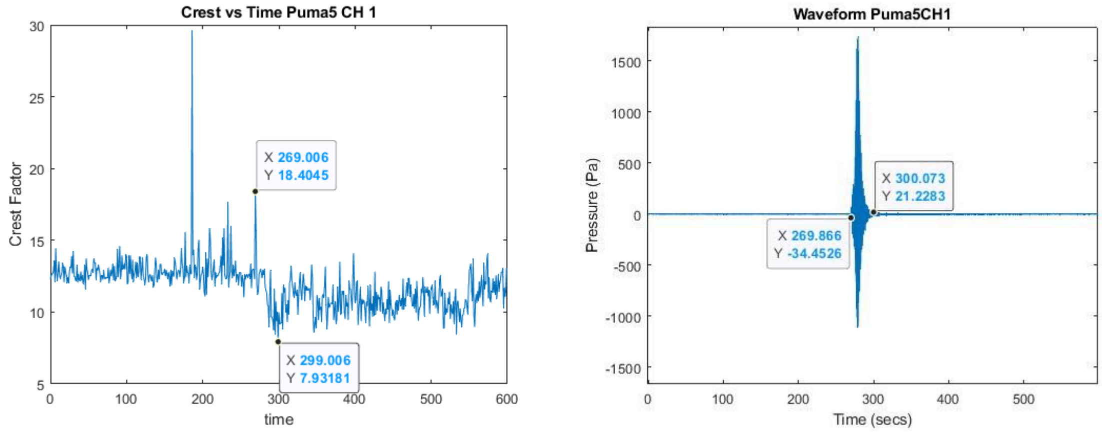
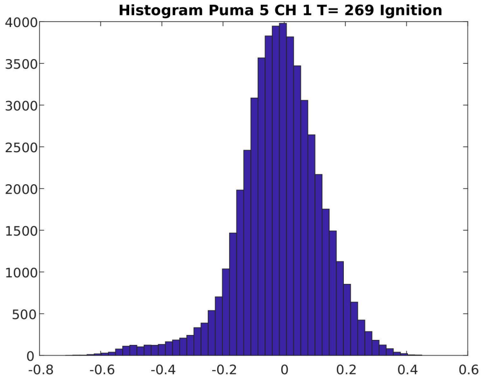
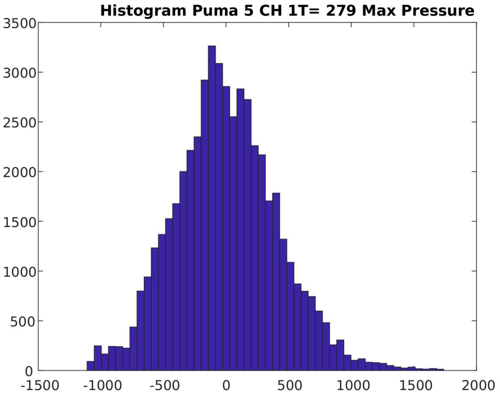


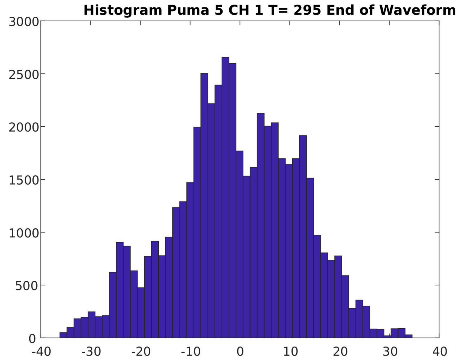
Fig 9 and 10: The running Crest Factor (dB) vs Time (s) (left) and the overall Pressure Waveform (right) of Puma 5 Channel 1. Notable moments such as ignition, max pressure, and the end of the pressure waveform are marked on the graphs for ease of comparison.

Histogram Analyses

In addition to analyzing the running Crest Factor and the pressure waveform, histograms of the pressure waveform were created to further analyze the pressure response of the Antares launch vehicle at notable moments during the launch. Since histogram analyses behaved similarly across stations, only histogram analysis of Puma 5 has been included. In Figs 11-13, histograms can be seen for the one second interval of launch, max pressure, and the end of the pressure waveform. Each waveform behaved in a Gaussian manner, meaning that the pressure waveform was fairly well distributed from minimum to maximum pressure. A point of note, randomly generated white noise is perfectly Gaussian. So the pressure at these points behave in a similar fashion to white noise.







Figs 11-13: Histograms of the Ignition, Max Pressure, and End of Waveform. The ignition has nearly perfectly Gaussian distribution, with the Max Pressure and End of Waveform being markedly less.

Puma 3 Channel 1

In comparison to Puma 5, Puma 3 behaved similarly but slightly differently. In Puma 5, the maximum Crest Factor occurred during ignition, with a minimum occurring at the end of the pressure waveform. In contrast, Puma 3 recorded a maximum Crest Factor of 21.3 dB near the end of the pressure waveform. The second highest CF occurred during ignition. With the exception of these two events, the Crest Factor seems to fall between 10-15 dB. Notably, this is what the values oscillated between before ignition. Again, a large spike in CF occurs at approximately 190 seconds. However, this value occurs before ignition and so is of no use for this study.

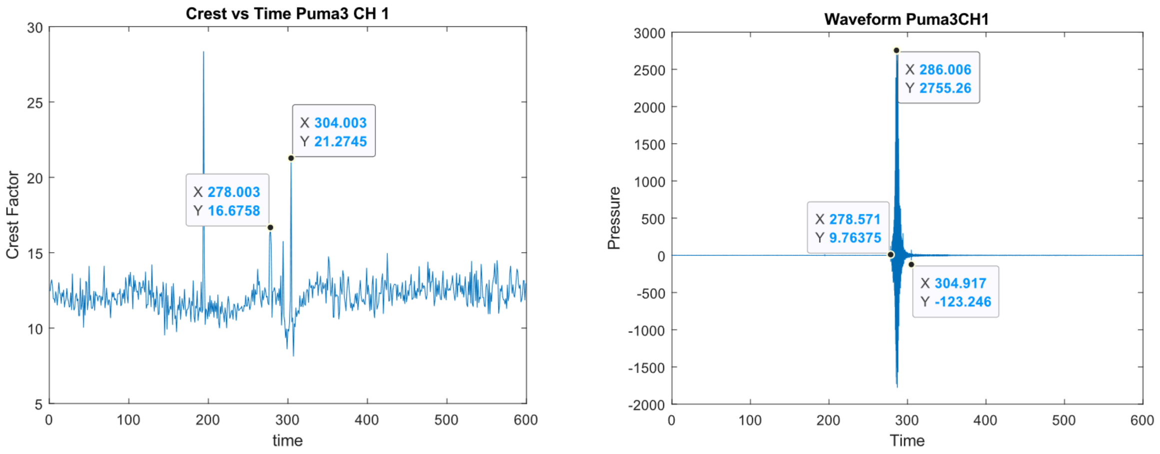
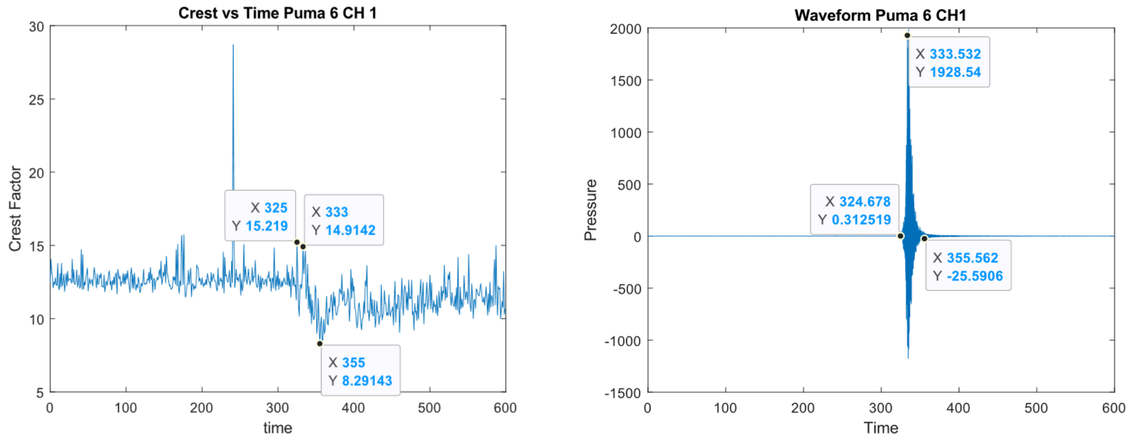


Fig 14 and 15: The running Crest Factor (dB) vs Time (s) (left) and the overall Pressure Waveform (right) of Puma 5 Channel 1. Notable moments such as ignition, max pressure, and the end of the pressure waveform are marked on the graphs for ease of comparison.

Puma 6 Channel 1

Lastly, those results that did not behave similarly to Puma 3 or Puma 5 can be represented by Puma 6. At Pumas 3 and Puma 5, there was a clear cut maximum occurring at either the ignition or the end of the pressure waveform. At Puma 6 the Crest Factor behaved in a way that was much closer to the original hypothesis. In these results, there was no clear single maximum as both the time of ignition and the time of maximum pressure were maximums (after ignition) and only varied by 0.3 dB. Additionally, in these results the Crest Factor reached a minimum at approximately the time that the pressure waveform caused by the launch is diminished.



Figs 16 and 17: Graphs showing the Crest Factor (dB) vs Time (s) and Pressure Waveform (Pa) vs Time (s) for Puma 6 Ch 1. Important moments are marked for ease of comparison

Analysis II: Crest Factor vs Distance:

The second analysis that was performed was an analysis that compared the Crest Factor against the distance from the launch in terms of meters and effective diameters. Effective diameters is a unit of measurement used by Gee et al (2022) to establish a way to compare various size rockets. Since the overall power produced by a rocket is directly correlated to the size of the rocket's diameter, the power from the rocket can be normalized across a variety of launch vehicles using this methodology. This allows us to discover trends across a variety of rockets.

Another aspect of this analysis that makes it unique is that the Crest Factor was calculated for a variety of statistically significant values. Specifically, the 90, 95, 99, 99.9, 99.99, 99.999, 99.9999 and 100% values were calculated. The reasoning behind this decision was that outliers can easily influence the value of the Crest Factor. By taking a variety of statistically significant values, the top 10, 5, 1, .1, .01, .001, .0001 percent of values were omitted to provide for a more accurate representation of the data and eliminate potential skew caused by outliers. In other words, it may be inconsequential if a small number of data point clips.

Each of the following plots data were collected by the BYU Rocket Acoustics team. Data were collected from a variety of launch vehicles including the Falcon 9, Atlas V, Delta IV Heavy, Firefly, and SLS launches. Many of these launch vehicles had data collected from multiple launches. The Crest Factor for each of these statistical values was calculated for each channel of each station of all of these launches. For this analysis nearly 1000 CF values were calculated from over 140 different channels and 10 different launches. This was performed with data collected from 5 different launch vehicles.

100% Crest Factor

In figure 8, shown below, the calculated values of the single valued Crest Factor with 100% of the data taken into account to calculate the Crest Factor. The figure contains a logarithmic scale for the x-axis based on meters. The unit of measurement for the y-axis is in dB. For this percentage, the results fell in the range of 11-19 dB with a slight negative correlation between CF and distance.

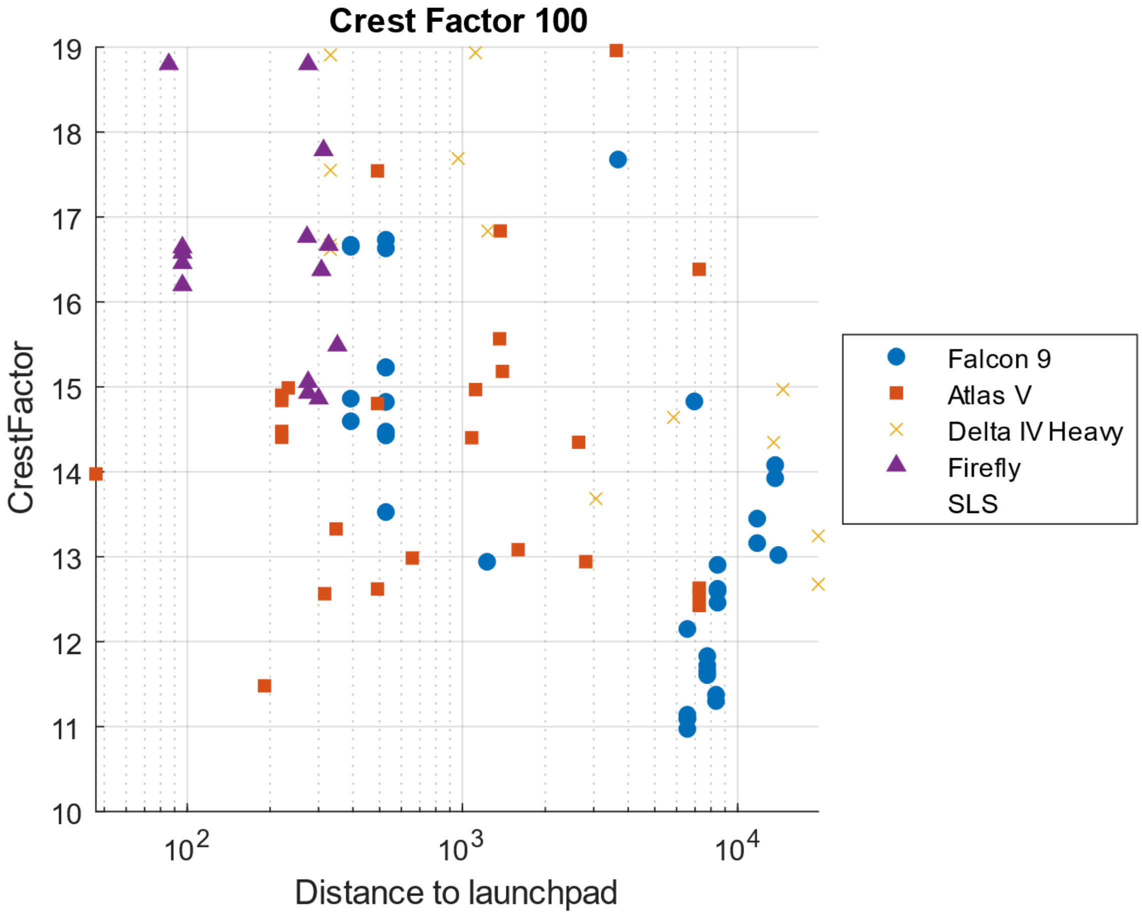


Fig 18: 100 % Crest Factor (dB) plotted against distance (meters) from the launchpad. Data points fell between 11-19 dB.

99.9999% Crest Factor

The figure below (Fig. 9) shows the values for the 99.9999% Crest Factor. The Crest Factor was evaluated using all of the data except for the top .0001%. With most measurements being performed with a sampling frequency of 102400 samples per second, this measurement accounts for all of the data besides about the top ten values of every second. After observation, the 100% and 99.9999% CF are nearly identical with values falling between 11-19 dB.

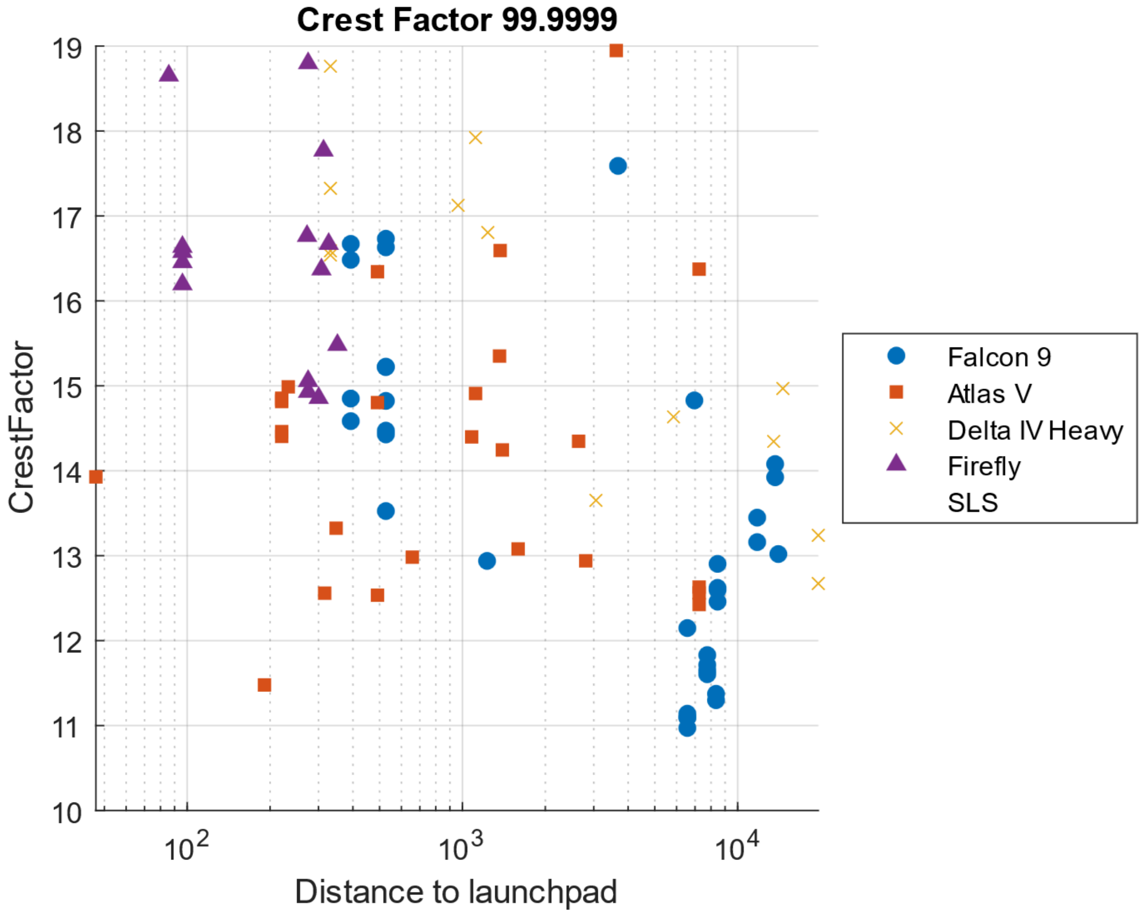


Figure 19: 99.9999% Crest Factor (dB) vs Distance to launchpad (meters). Values fell between 11-19 dB.

99.999% Crest Factor

The figure below shows the 99.999% Crest Factor. At this value differences begin to show from the 100% Crest Factor. The data points become more concentrated together and the highest values are slightly lower than before. For this percentage, a data set having a sampling frequency of 102400 would lose approximately the top 102 samples (per second). At this percentage value, the CF begins to decrease. The CF for this percentage falls in the range of 11-18 dB.

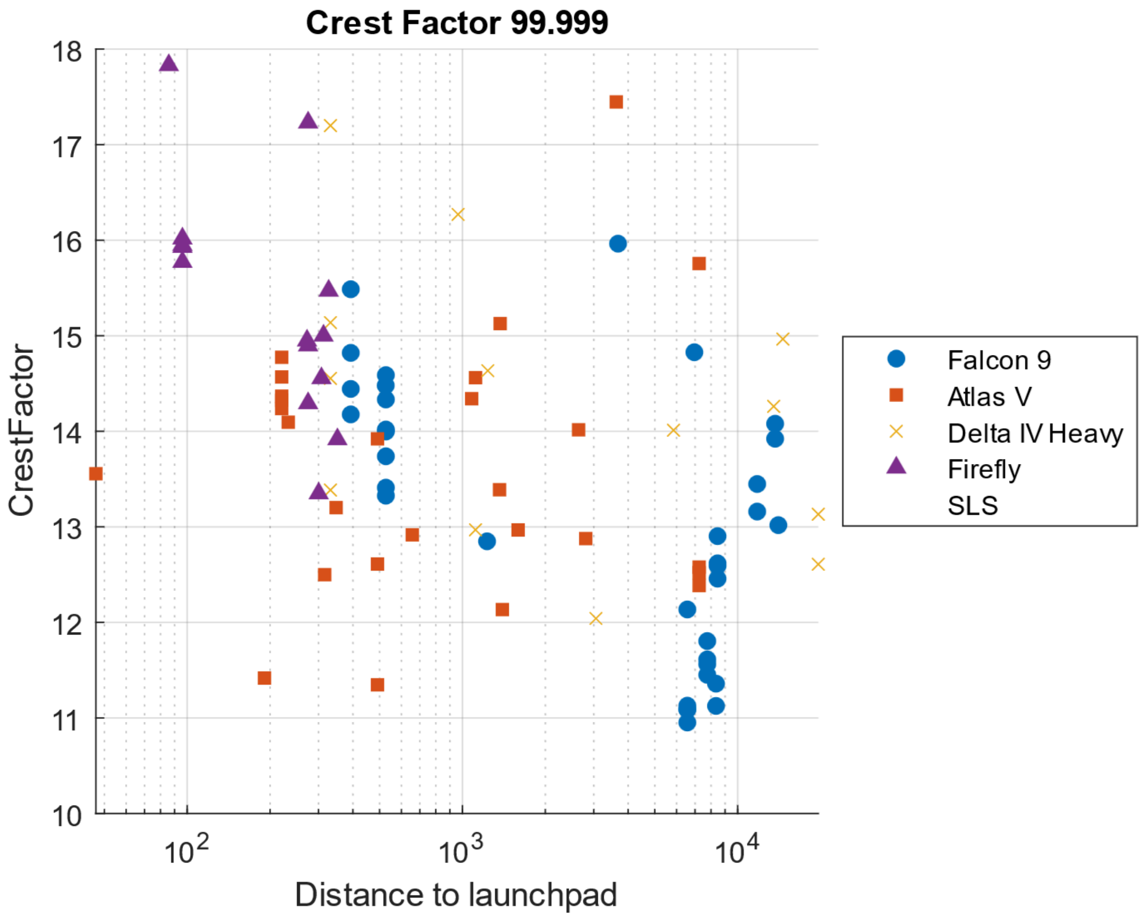


Fig 20: 99.999% Crest Factor (dB) vs Distance to launchpad (meters). Values fell between 10-18 dB.

Crest Factor 99.99%

Figure 11 shows the 99.99% Crest Factor. At this percentage approximately 1024 samples of the highest values are omitted. At this value a negative logarithmic correlation between distance and Crest Factor begins to be slightly visible. Again as the CF % decreases, the values become smaller and closer together. For this value the values fall between the range of 10.5-15.5 dB. At first glance at this value, the values of the Firefly launch vehicle and parts of the data of the Falcon 9 seem to present a negative correlation. However, the Atlas V values and the rest of the Falcon 9 values do not show this same trend.

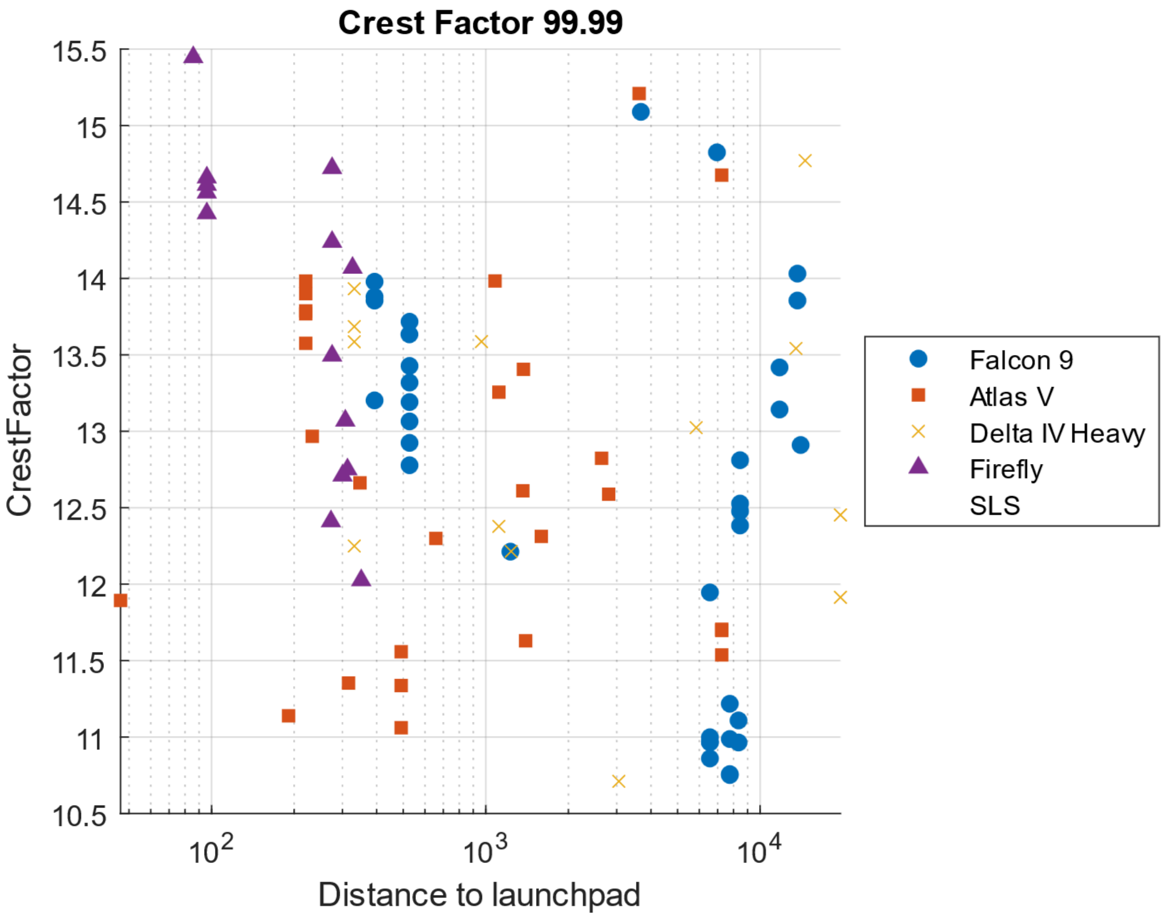


Fig 21: Graph showing the 99.99% CF vs Distance (meters). Values fall in the range of 10.5 dB-15.5 dB.

Crest Factor 99.9%

Figure 12 below shows the 99.9% Crest Factor. With this percentage 10240 of the highest samples are omitted. This shows a dramatic decrease in the values of the Crest Factors, with most of the values settling between 10-12 dB. Analyses for smaller percentages were performed, but so much of the value of the Crest Factor was lost that the data becomes irrelevant.

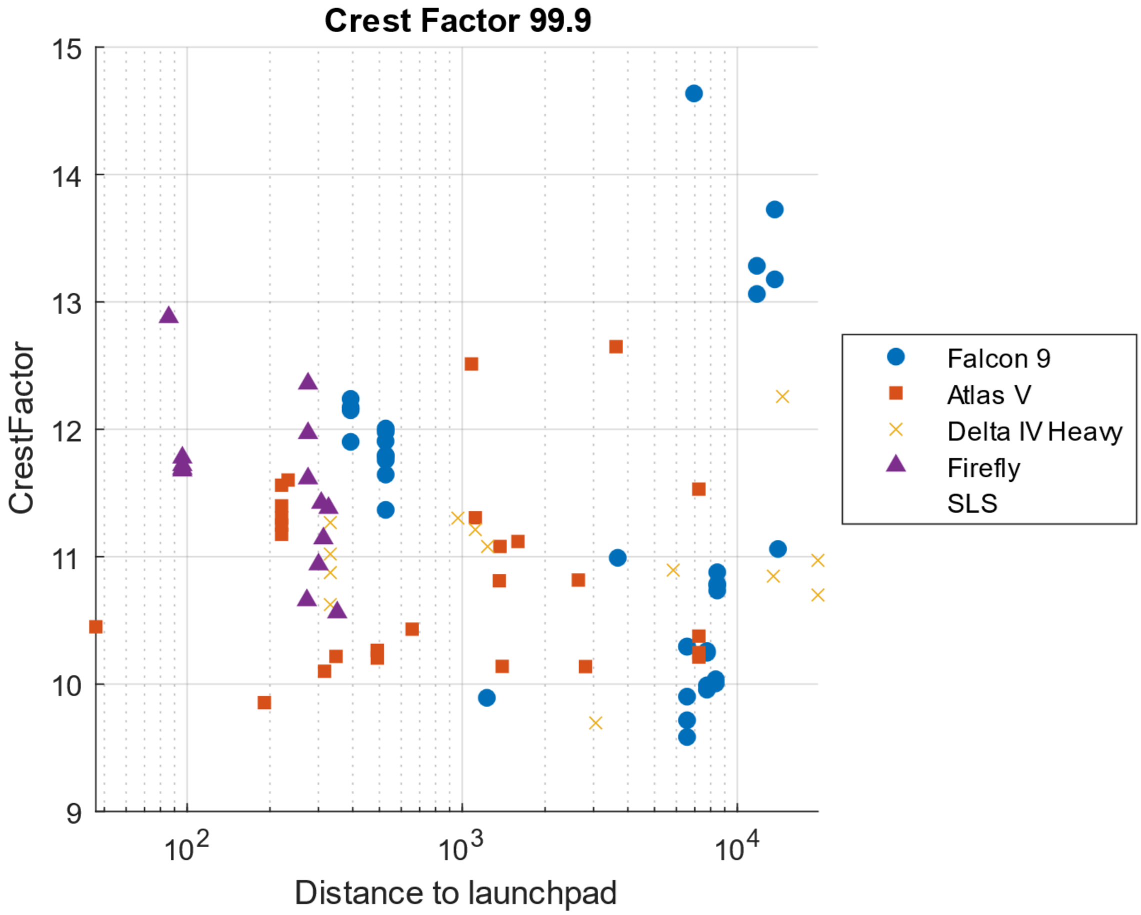


Fig 22: Graph showing the 99.9% CF vs Distance (meters)

Further CF vs Distance Analyses

In addition to plotting the CF vs distance in meters and on a logarithmic scale, several other graphs were produced with the data available in the attempt to find correlation. These graphs included nonlogarithmic scales, separating points based off of sample rates and using effective diameters instead of meters. For many of these graphs, multiple percentages were tested. However, only the 100 CF will be shown as they were fairly indicative of the correlation for those circumstances. The graphs of each of these analyses are below.

Nonlogarithmic Distance vs. 100% CF

The below figure is a graph of the Crest Factor vs Distance in meters on a nonlogarithmic scale. This method of analysis is not effective because most of the data occurs between 0-2000 meters, but since some measurements were taken at a much farther distance the plot becomes congested near the left axis. However, with values ranging from 13-19 dB for the same distances, this congestion shows the lack of noticeable correlation between distance and the Crest Factor.

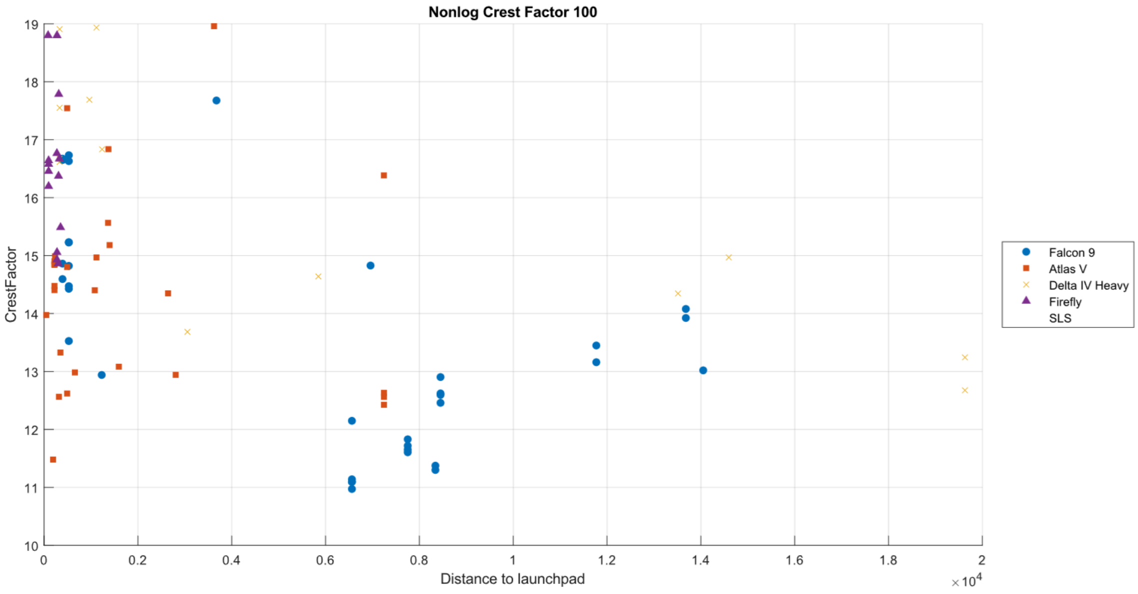


Fig 23: Crest Factor vs. Distance on a NonLogarithmic Scale

Sampling Frequency

Additionally, plots were created that separated data based on the sampling frequency that was used. All of the points were collected at either 102400 or 51200 Hz sampling frequencies. Fig 14 and Fig 15 below are the graphs of the Crest Factor vs distance in meters for the 102400 and 51200 frequencies.

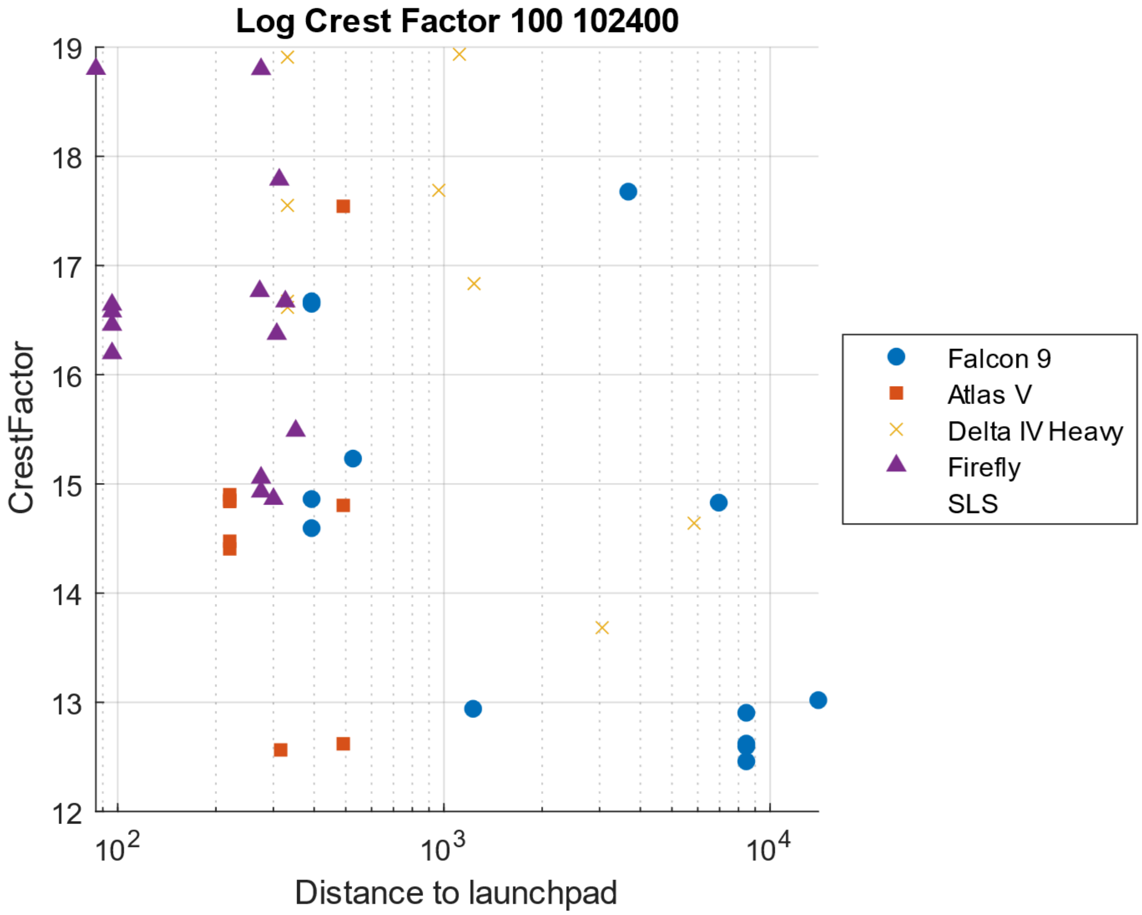


Fig 24: 100% CF of data points with sampling rate of 102400 Hz

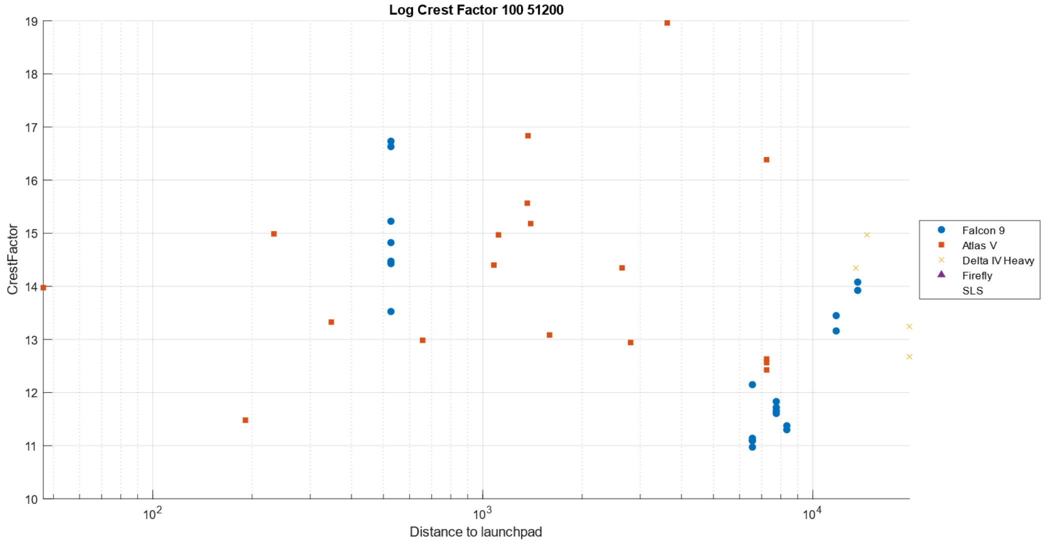


Fig 25: 100% CF of the data points with a sampling rate of 51200

Effective Diameters

As mentioned above, a common way to normalize the power produced by a rocket and thus the distances from the rocket is the effective diameter. Since the acoustic power of a rocket is directly correlated to the mass flow rate (and therefore diameter) of the rocket, it is oftentimes more efficient to use effective diameters in place of meters. The effective diameter is merely the distance in meters a measurement location is from the time of the launch divided by the diameter of the rocket. However, analysis of effective diameters showed no more correlation with distance than regular units of measurement. The reasons for the lack of perceived correlation are unknown, but may include considerations such as varied propagation effects due to differing times and locations when the vehicles were launched. Also, this study did not take any nonlinear behaviors into account and thus these may be the cause of the lack of perceived correlation.

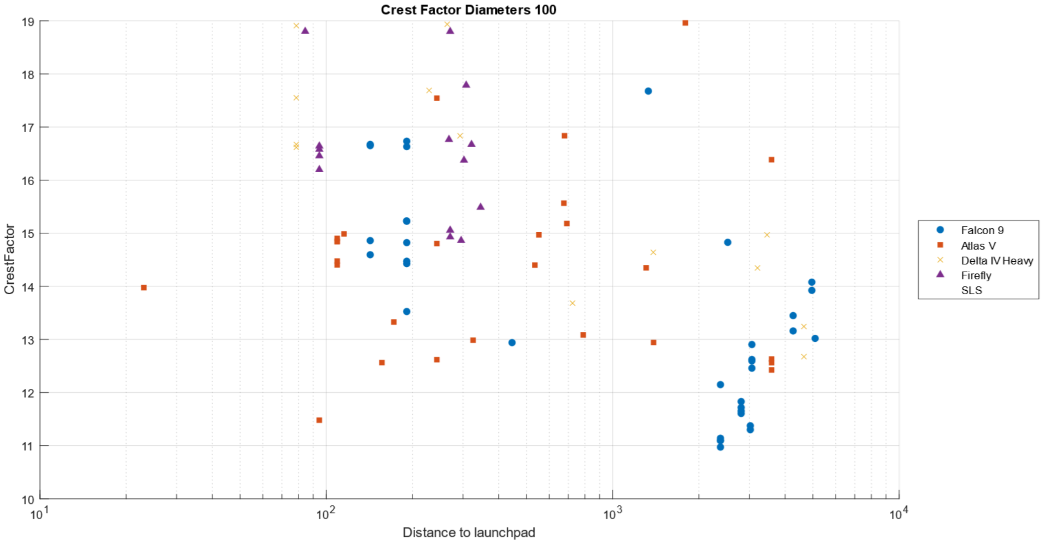


Fig 26: 100% Crest Factor measured against effective diameters

Conclusions

From the analyses performed above it becomes apparent that the behavior of the Crest Factor of a rocket launch is something that cannot easily be predicted. After analyses comparing the Crest Factor of different statistically significant values to distance from the launch there was no observable correlation linearly or logarithmically, against meters or effective diameters, and regardless of sampling frequency. However, this analysis still provided useful data. The 100% Crest Factor fell in the range of 10-19 dB, with each of the successively smaller percentage CFs having a smaller range until the 99.9% Crest Factor which fell in the range of 9-15dB.

Additionally, the additional comparisons showed the complexity of the behaviors of the Crest Factor. As Crest Factor vs Time analyses were performed it was found that the maximum Crest Factor did not occur consistently in one occasion. Rather, it occurred at either the ignition, maximum pressure, or the end of the waveform. On some occasions, these different results would occur at the same location making it hard to believe that Crest Factor is a result that is determinant on the distance from the launch pad. Regardless, this analysis still provided important information regarding the Crest Factor in that it showed that during the majority of the launch the CF varies across a distance of approximately 5 dB. It's only in a few rare moments that the Crest Factor breaks from this range. This information is useful for future acousticians as they plan for launches, as they can know what range the upper fifty percent of anticipated data will fall in. This will allow for more accurate planning, in order to minimize the likelihood of microphone clipping and increase the likelihood that data is collected in such a manner as to meet the parameters of the experiment.

Although the correlation between the Crest Factor and distance was not discovered, there remains room for further studies on this matter. In this study, the relationship between the Crest Factor of the entire waveform was calculated and plotted against distance. Further studies may take the running 1 second time block maximum values and plot them against distance and find different results. Additionally, further study is warranted to determine what causes the maximum Crest Factor to occur at either the ignition, max pressure, or end of the waveform.

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