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Correcting for ground reflections when measuring overall sound power level and acoustic radiation efficiency of rocket launches

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Historically the radiation efficiency of a rocket plume has been assumed to be 0.5%, but recent measurements have thrown this into some doubt. Determining the sound power level of a rocket is the first step in characterizing its radiation efficiency. Because the sound radiation from a launch vehicle is anisotropic, well-calibrated ground measurement stations are used, along with trajectory data, to obtain sound power. Historically, the effect of ground reflections appears largely to have been neglected in the literature, despite the potential to inflate overall power levels (OAPWL) and therefore radiation efficiency. This study investigates the likely effect of a finite-impedance ground on spectra, overall sound pressure levels (OASPL), and power levels. A single-parameter ground reflection model is used to obtain an estimate for change in OASPL for a model spectrum based on measured space vehicle launches. When the correction is applied to the OAPWL it produces in a nearly 3dB level reduction, therefore reducing the radiation efficiency by a factor of two. This indicates the probability that the radiation efficiency assumed for rockets in the past is too high.

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1. INTRODUCTION

The proper modeling of rocket noise is becoming increasingly important as the number of launches increases.[1] The noise needs to be understood both from community noise and environmental impact perspectives. Most computer models assume a free-space source and take reflections and ground effects into account in the propagation code. This means that in order to ensure the accuracy of that model, it is important that measurements that go into developing that source model need to have any measurement artifacts of the ground removed from them.

Two parameters that are commonly extracted from the measurements are the overall power level of the rocket (OAPWL), which is the source power in decibels, and the radiation efficiency, the ratio of the acoustic power to the plume mechanical power. Based on work that was done in the 1950s and 1960s, it has been commonly assumed that the radiation efficiency of a rocket is about 0.5%.[1–6] So the total acoustical radiation power can be estimated by multiplying the known mechanical power of the rocket by 0.5%. However, if the measurements on which that assumption were based didn't take ground effects into account, that number may be in error. The historical literature is often unclear on whether ground effects have been included in their analysis. Most say nothing about it at all, but others say that it is included, but no details are given.

One interesting outlier in Figure 3 of NASA's SP-8072 report[4] with regard to radiation efficiency is a measurement made on a vertically (upward) fired rocket.[7] That measurement showed a radiation efficiency of less than 0.2%. This is possibly because all the microphones were high on towers, far from the ground, and so ground effects would be minimized. This implies that perhaps this lower value would be a more accurate measure of the radiation efficiency of rockets.

Sections 2 and 3 of this paper discuss the model used to account for the ground effects and then how to calculate the sound power of a rocket from the data taken during a launch. Section 4 discusses the spectrum of a rocket launch vehicle and the effect of the ground reflections on what is measured. Section 5 applies these results to two bounding cases, a small rocket, the Firefly Alpha, and a large rocket, the Delta IV Heavy. Section 6 discusses the implcations of these measurements on the total sound power and radiation efficiency of rockets.

2. GROUND REFLECTION EFFECTS

The basic geometry of our model is shown in Figure 1. The measured signal is the coherent sum of a wave directly from the source and a wave that is reflected off the ground. The reflected wave is modeled as if it came from an image source located at the same distance below the ground as the actual source is above the ground. The reflected wave is shifted both in its magnitude and its phase, depending on the properties of the ground.

This basic model of ground effects was used by Embleton et al. in 1983.[8] It is a single parameter model, using an effective flow resistivity, that incorporates the effect of other parameters as well, such as tortuosity and porosity. In general, when an outdoor launch is recorded the detailed ground characteristics around the measurement site is not well known, and so those other parameters are not very useful. The effective flow resistivity is measured using rayls. Following Embleton, in this paper we will cite values using cgs rayls. Table 1 shows the value of the effective flow resistivity for several types of ground.

The simplest case is for infinitely hard ground. At low frequencies there will be pressure doubling, causing the acoustic power level to increase by 6 dB. At higher frequencies there will be destructive interference because of the difference in the path length. This is illustrated by the orange curve in Figure 2. In that calculation the microphone was 1.25 m above the ground, causing the interference nulls above 1 kHz.

To avoid the problem with these interference nulls, we make our measurements at ground level, with microphones spaced one-half the microphone diameter above a hard ground plate. The blue line in Fig. 2

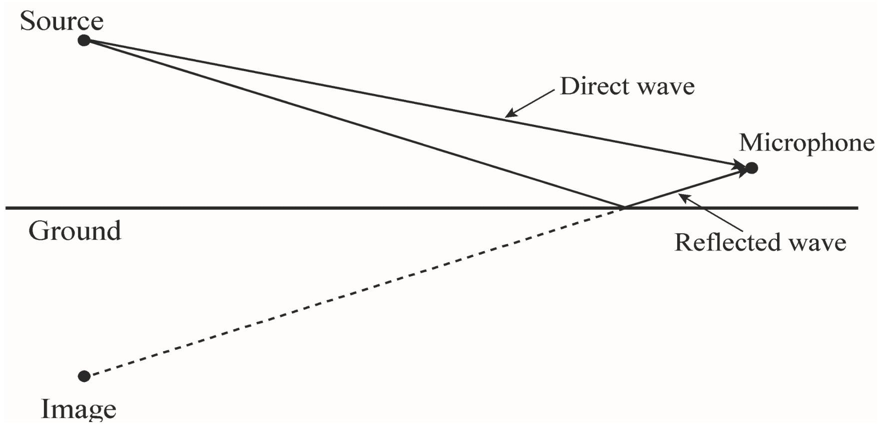

Figure 1: The geometry of the model showing the source of the ground effects. The sound from the source interferes with ground reflections, which are modeled as an image source below the ground. The magnitude and phase of the reflected wave is modeled using the relations from Embleton's paper.

shows the result for this configuration for a 1/2 inch microphone, spaced roughly 3 mm above the ground plate. While there is still an effect at higher frequencies, it is much smaller up to 10 kHz.

Figure 3 shows the effect of the ground reflections on a source located at an angle of 25° above the horizonatal at a distance of about 3000 m, as function of frequency. There are a number of different values of σ plotted, ranging from very soft, 20 cgs rayls (3" thick fresh snow), to relatively hard, 8000 cgs rayls (rain packed dirt). The effect of reflections for all surfaces equal to or harder than a grassy surface ($\sigma = 200$) is to add 6 dB to the signal (pressure doubling) at frequencies below about 50 Hz, and then have the effect to decrease as the frequency increases. The start of that roll-off moves upward as σ increases.

3. ESTIMATING THE TOTAL SOUND POWER OF A ROCKET

Because the acoustic radiation from a rocket is highly anisotropic it is necessary to have measurements at many different angles relative to the plume of the rocket. For a single-engine rocket we expect the radiation to be axially symmetric around the plume. Since a launched rocket moves relative to a motionless microphone, we are able to map out the distribution of the acoustic radiation as the rocket rises, subject to knowledge of the rocket trajectory, and the assumptions that engine properties remain constant during the

Table 1: Typical values of the the effective flow resistivity. σ, for various types of ground.

Ground type	**σ (cgs rayls)**
Soft Snow (3" thick)	20
Forest floor	80
Grass	200
Soft Dirt	800
Hard dirt	2000
Rain packed dirt	8000
Cured and painted concrete	$10^5 - 10^6$

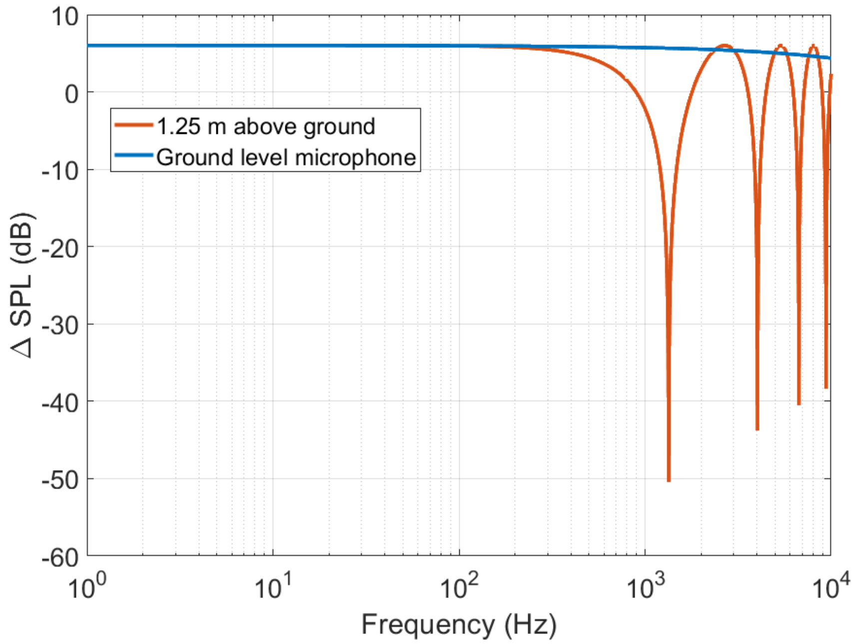

Figure 2: The effect of ground reflections due to infinitely hard ground vs. frequency. The y-axis shows the change in sound level, in dB. The orange curve is for a microphone located 1.25 m above the ground and the black curve is for a microphone located 3 mm above the ground. The presence of interference nulls in the spectrum is clearly visible on the orange curve, but are shifted to much higher frequencies on the black curve.

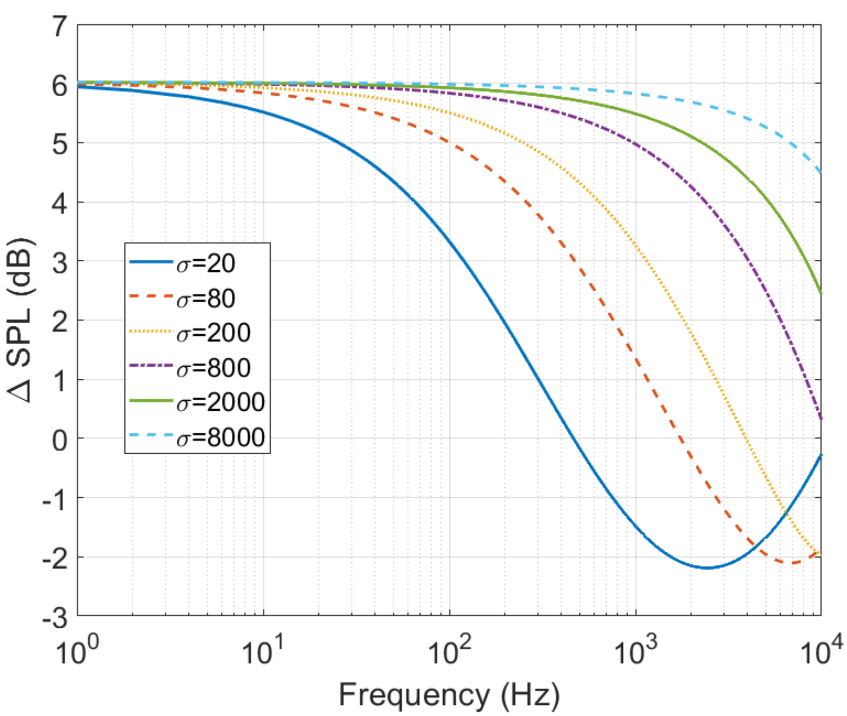

Figure 3: The effect of ground reflections as a function of frequency for a number of different values of the effective flow resistivity, σ. The source is at an angle of 25° above the horizontal and a distance of about 3000 m away. The micophone is 3 mm above the ground.

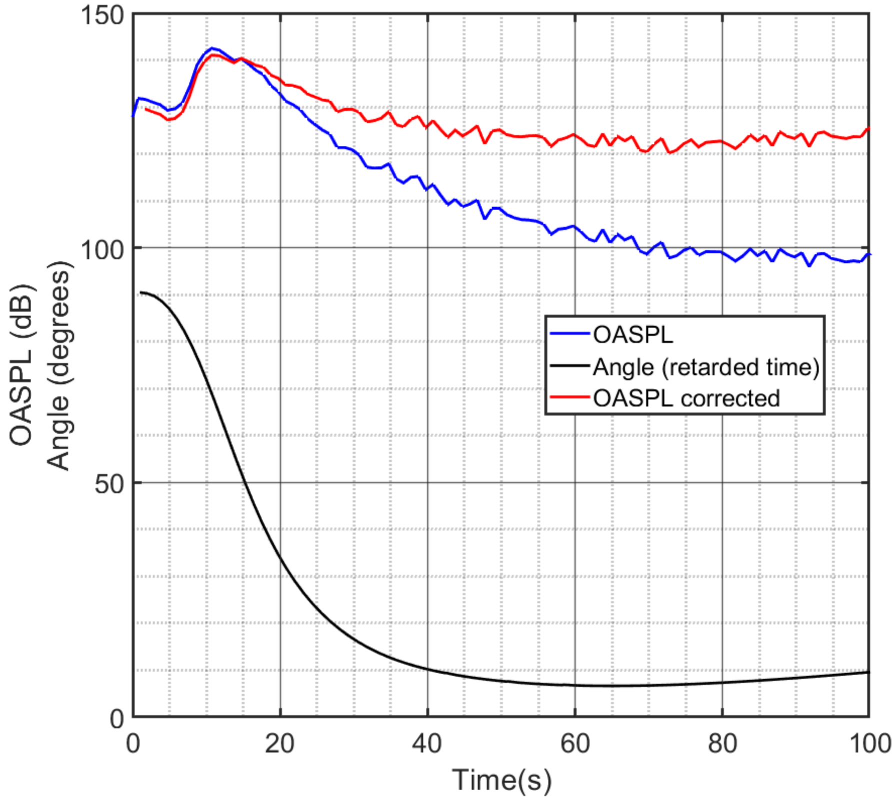

Figure 4: Data used to calculate the total sound power level of a rocket. The 1-second OASPL is shown in the blue curve. Using the trajectory data it is possible to correct for spherical spreading to a distance of 100 effective nozzle diameters, shown in the red curve. The angle of the receiving station relative to the plume can also be calculated at all times and is plotted in the black line, corrected for propagation delay.

ascent, and that spherical spreading applies.

A typical calculation is shown in Figure 4. The one-second OASPL (blue line) is calculated from the data recorded at a given station. Using trajectory data of the rocket, the distance to the rocket and angle of the station relative to the plume direction can be calculated at each time. The OASPL can be corrected for spherical spreading to a constant distance, usually 100 nozzle diameters (red line). Taking the propagation delay into account, the angle relative to the plume can also be calculated at each observation time (black line). Note that there is a dropoff of between 10 and 20 dB between the OASPL at the peak directivity angle and that at both higher and lower angles. This means that there is very little contribution to the total power from angles far from the peak directivity. There is rarely an opportunity to get data at angles much greater than 90° on a rocket launch, but static-fire data from rocket engines shows that there is a negligible contribution to the total power from those angles.[9,10] The integral over all angles produces the total sound power of the rocket.

4. CORRECTION FOR GROUND EFFECTS

The measurements discussed in the previous section are made without correction for ground effects, which means that the calculation is inaccurate. Since the gound effects are frequency dependent, we need to take the spectrum of the rocket noise into account when calculating that correction.

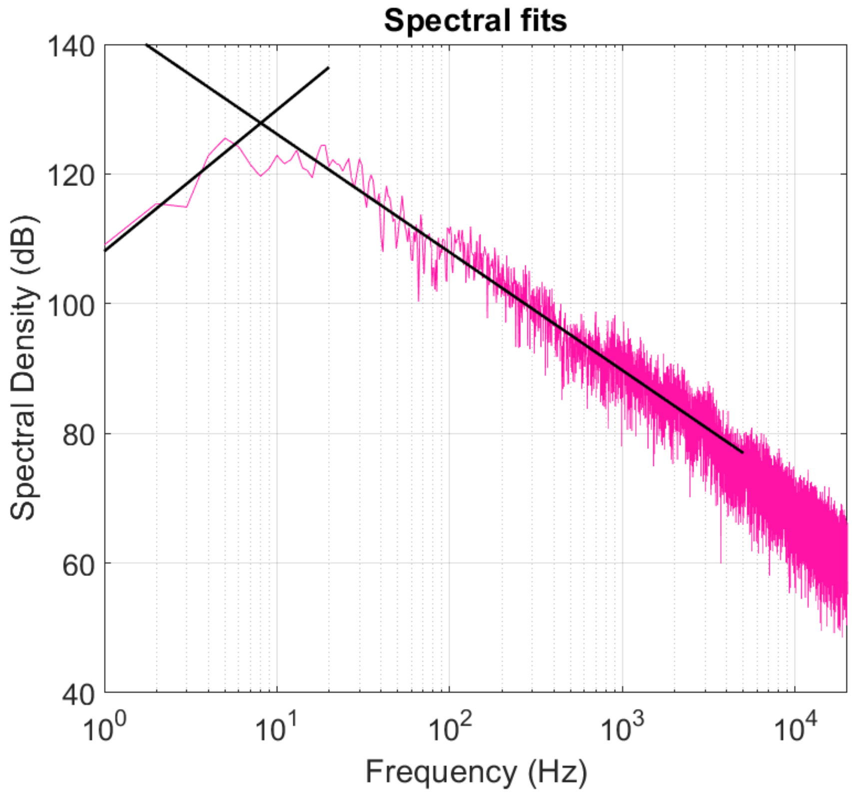

Figure 5: The spectrum of a launch vehicle is modeled as two power-law based lines that meet at the peak of the spectrum. The slope of the high-frequency line is -20 dB/decade, characteristic of nonlinear shock formation and propagation. The lower-frequency line has a slope that varies from 10-25 dB/decade, depending on the measurement. This spectrum is from a Delta IV Heavy launch and shows a spectral peak at about 8 Hz.

A. MODEL SPECTRA

Figure 5 shows a typical spectrum taken from a Delta IV Heavy launch.[11] A reasonable approximation to the spectrum is found to be two lines that intersect at the frequency of the peak of the spectrum. The high-frequency line is found by doing a least-squares fit to the high-frequency side of the spectrum. This line always has a slope very close to -20 dB/decade, which is characteristic of shock formation and propagation.[1,12] The low-frequency line is also found from a least-squares fit to the spectrum. It has a slope that can vary from 10 to 25 dB/decade, depending on the measurement. This uncertainty in slope doesn't affect the results of our calculation significantly, because all of the ground effects typically occur at much higher frequencies. The OASPL is found by integrating the spectrum over frequency. The model spectrum has the same OASPL as the experimental spectrum to within a fraction of a decibel.

B. INCLUDING THE GROUND EFFECTS

The correction for ground reflections is applied to the model spectrum by first integrating the spectrum to get the measured OASPL. The correction from Embleton's model is then added to the model spectrum and that new spectrum is integrated to get the corrected OASPL. The original OASPL is subtracted from the corrected OASPL to get the size of the correction, which we will call δ.

Figure 6 shows this procedure applied to two model spectra. Part (A) has a spectrum that peaks at 10 Hz and is measured over ground which has a σ of 800 cgs rayls (typical of soft dirt). When the correction

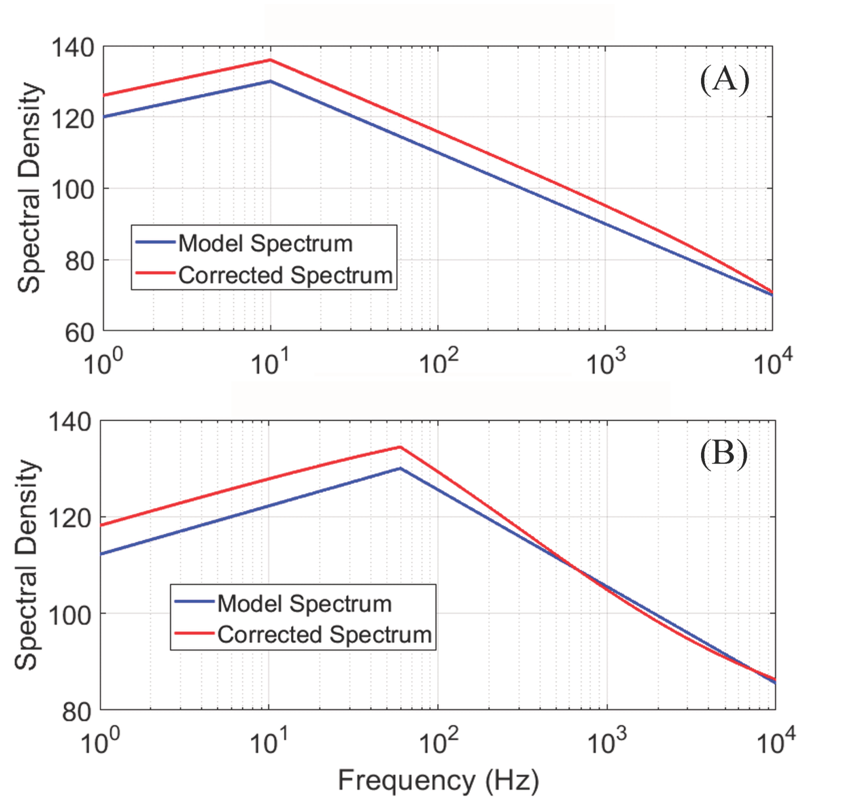

***Figure 6:* Part (A) shows the effect of ground reflections on a spectrum that peaks at 10 Hz and is over soft dirt, which has $\sigma = 800$ cgs rayls. The integrated effect of the correction on these data is 5.95 dB. Part (B) shows the same thing for a spectrum that peaks at 60 Hz and is over snowy ground, with $\sigma = 20$ cgs rayls. The integrated effect for this spectrum is 3.75 dB.**

procedure is applied to this spectrum, it produces a δ of 5.95 dB. Part (B) of the plot shows the effect of a spectrum that peaks at 60 Hz and is measured over extremely soft, snowy ground with a σ of 20 cgs rayls. The combination of higher peak frequency and very soft ground makes the integrated effect much smaller. In this case $\delta = 3.75$ dB. In general, both a higher peak frequency and softer ground create a larger deviation from a 6 dB pressure doubling.

5. APPLICATION OF THIS MODEL TO DIFFERENT ROCKETS

To better understand the effect of the ground on launch measurements, we consider two bounding cases, a Delta IV Heavy rocket and a Firefly Alpha rocket. The Delta IV Heavy is the third most powerful rocket in current use,[11] after the SpaceX Falcon Heavy and Nasa's Space Launch System.[13,14] The parameters of its engines are shown in Table 2. The Firefly Alpha is a small rocket, typical of the generation of small-lift rockets being developed by multiple companies throughout the world. Its parameters are also shown in Table 2. Note the higher frequencies produced by the smaller rocket. This is typical of rocket noise - larger rockets, with larger nozzles, produce turbulence with longer length scales and therefore lower frequencies.

Figure 7 part (A) shows the results of the ground effects calculation for a Firefly Alpha rocket at different angles above the horizon for different values of σ. These curves are made for a peak frequency of 60 Hz,

Table 2: Parameters of the engines of the rockets used in this study.

Parameter	Delta IV Heavy	Firefly Alpha
Thrust	9.3 MN (2.13 million lbs)	0.61 MN (0.14 million lbs)
Effective nozzle diameter	8.8 m	1.0 m
Frequency at peak directivity	10-30 Hz	40-60 Hz

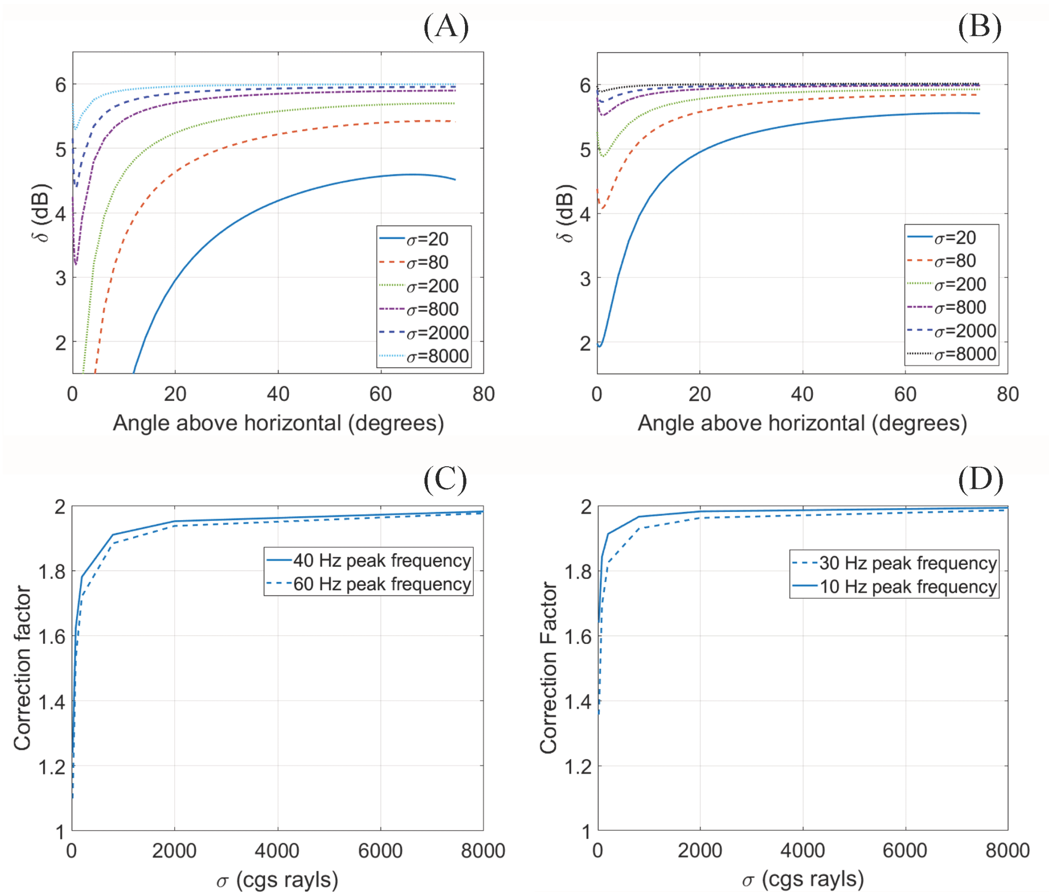

Figure 7: Part (A) shows the change in SPL, δ, as a function of the angle above the horizon for a rocket with a peak frequency of 60 Hz, like the Firefly Alpha. The different curves are drawn for different values of the effective flow resistivity, σ. Part (B) shows δ as a function of the angle above the horizon for a rocket with a peak frequency of 10 Hz, like the Delta IV Heavy. Again, the different curves are drawn for different values of the effective flow resistivity. Part (C) gives the correction factor that should be applied to the total rocket power based on the measured power as a function σ for a rocket such as Firefly Alpha. The two curves show the correction factor based on the maximum and minimum peak frequencies of that rocket at peak directivity. Part (D) shows a similar plot for the Delta IV Heavy rocket.

which is the highest peak frequency when this rocket is near peak directivity, between 20 and 30 degrees above the horizontal. Part (B) of this plot shows a similar set of curves for the Delta IV Heavy rocket with a peak frequency of 10 Hz, which is the lowest peak frequency for this rocket during the time when it is at peak directivity. Almost all current rockets should fall between these two bounding cases.

We can use these curves to calculate the correction factor that needs to be used to get the correct free-source sound power from the measured sound power. The correction factor is obtained by calculating

$$C = \frac{10^{(\delta/10)}}{2}, \tag{1}$$

where δ is the quantity we have just calculated. The factor of 2 in the denominator is needed because the integration is only over the upper hemisphere rather than the whole sphere. C is the factor that we divide our power estimate by to correct for the pressure increase caused by the ground reflection. Mathematically we say

$$W_{\mathrm{OA\,free-source}} = \frac{W_{\mathrm{OA\,meas}}}{C}, \tag{2}$$

Where W_{OA} is the overall acoustic power of the rocket. Therefore a δ of 6 dB will give a correction factor of 2, and the free-source power is half of what is measured.

Figure 7 part (C) shows the value of the correction factor, C, calculated using the value of δ averaged between 20 and 30 degrees. These are the angles of peak directivity where the bulk of the measured power comes from. This is plotted as a function of σ, for the Firefly Alpha rocket. There are two curves that correspond to the maximum and minimum peak frequencies that occur during that time period. The values of C range from 1.9 to 2 for all values of σ above about 800 rayls (grass). Part (D) shows the same calculation for the Delta IV Heavy. Because of the lower frequencies involved (due to the greater thrust of the rocket) the values are all much closer to 2 than for the Firefly Alpha. Given the uncertainties involved, a value of 2 can be considered accurate for all types of ground for this rocket, except for the very softest ground.

6. IMPLICATIONS OF THESE CALCULATIONS

Over moderately hard ground for both rockets δ ranged from 5.7 to 6.0 in the region of peak directivity. This corresponds to a factor of 1.8 to 2.0 overestimate in the power. Historical results have shown a radiation efficiency of about 0.5%, but information on how, or if, ground effects were accounted for is spotty; some papers say they did account for ground effects, but do not say how. Others make no mention of the ground at all. We have made recent measurement on several rockets, such as the Falcon 9[15] and Delta IV Heavy[11] that seem to have acoustic efficiencies somewhat less that 0.5%, without accounting for ground effects. Since the acoustic power is likely to have been overestimated in the past, the true acoustic radiation efficiency is likely to be less than the historical 0.5% assumption, probably by a factor of about two. Incorporating these corrected source levels in propagation codes that include the ground effects will make them more accurate. Also, as we attempt to understand the energetics of noise production in rocket launches, it is important to accurately measure the total sound power of the rocket and take into account the effect of the ground on our measurements.

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