Prediction of acoustic environments from horizontal rocket firings

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Abstract

In recent years, advances in research and engineering have led to more powerful launch vehicles which yield acoustic environments potentially destructive to the vehicle or surrounding structures. Therefore, it has become increasingly important to be able to predict the acoustic environments created by these vehicles in order to avoid structural and/or component failure. The current industry standard technique for predicting launch-induced acoustic environments was developed by Eldred in the early 1970's. Recent work has shown Eldred's technique to be inaccurate for current state-of-the-art launch vehicles. Due to the high cost of full-scale and even sub-scale rocket experiments, very little rocket noise data is available. Much of the work thought to be applicable to rocket noise has been done with heated jets.

A model to predict the acoustic environment due to a launch vehicle in the far-field was created. This was done using five sets of horizontally fired rocket data, obtained between 2008 and 2012. Through scaling analysis, it is shown that liquid and solid rocket motors exhibit similar spectra at similar amplitudes. This model is accurate for these five data sets within 5 dB of the measured data.

Introduction and Background

- Method to predict acoustic environments due to rocket launches is necessary

- Previously proposed models
  - Eldred NASA SP8072: inaccurate
  - Tam 2-source model: rocket noise seems to exhibit Mach wave radiation and fine scale turbulence but the method used for jets to determine the shape/levels of each does not work for rockets

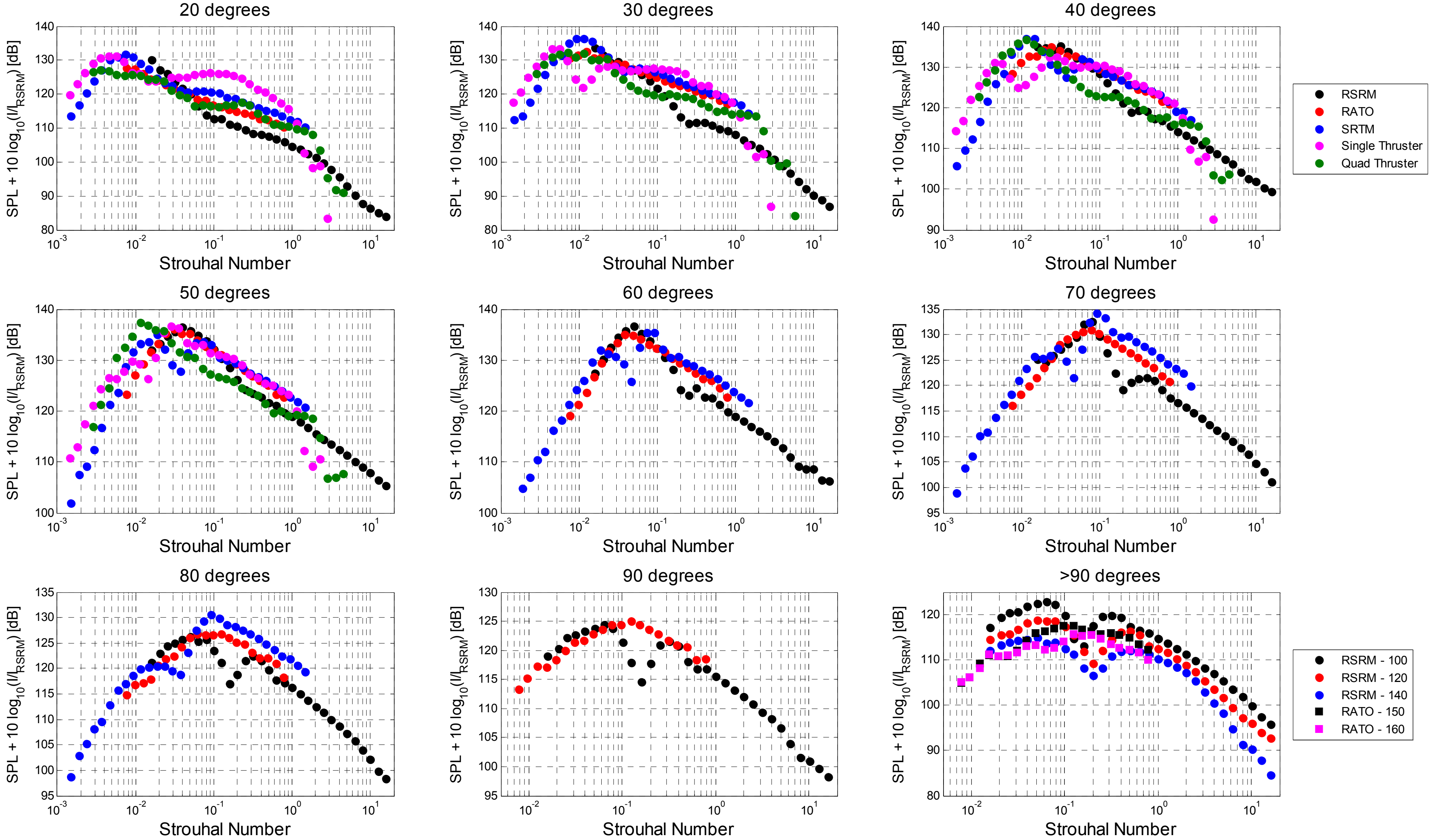
- Take the two-source model proposed by Tam and fit new similarity curves for rockets
  - “Directional” source (Source A) is dominant below 80°
  - “Broadband” source (Source B) is dominant at and above 80°

General Method

- Five sets of data were used in the creation of this model
  - Reusable Solid Rocket Motor (RSRM)
  - Solid Rocket Test Motor (SRTM)
  - Rocket-Assisted Take-Off motor (RATO)
  - Single Thruster
  - Quad Thruster

- Scale five sets of rocket data
  - In frequency via Strouhal number
  - In amplitude using intensity scaling
    - $\frac{I_2}{I_1} = \frac{\eta_2}{\eta_1}\frac{\dot{m}_2}{\dot{m}_1}\left(\frac{V_2}{V_1}\right)^2\left(\frac{R_1}{R_2}\right)^2$
    - Scaled the four "subscale" rockets to RSRM

Non-Dimensionalized/Scaled Data



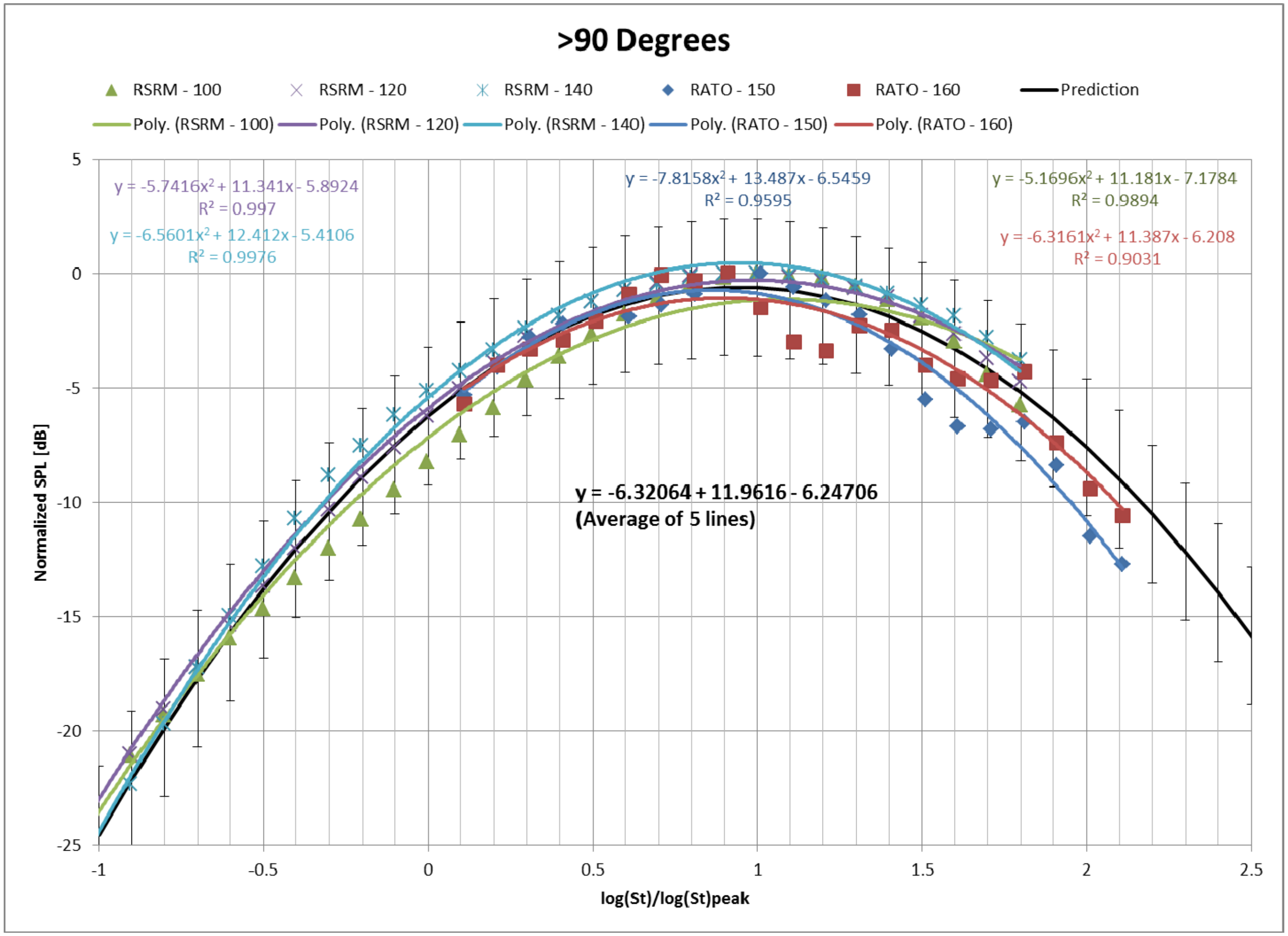
Peak Frequency

- The frequency at which the maximum SPL occurs shifts as receiver angle changes
- Equation to determine where this peak is:
  - $$\begin{cases} LSt_{peak} = 0.020272 * \theta - 2.5843 & \theta \leq 90 \\ LSt_{peak} = -1 & \theta > 90 \end{cases}$$
  - $$f_{peak} = 10^{LSt_{peak}} * \frac{v}{D}$$

Frequency [Hz]	Strouhal Number (RSRM)	$log(St)$	$\frac{log(St)}{log(St_{peak})}$
10	0.0159	-1.79	1.139
100	0.159	-0.79	0.5029
1000	1.59	0.201	-0.1279
10000	15.9	1.201	-0.7646

Source B Turbulence

- Receiver angles > 90°



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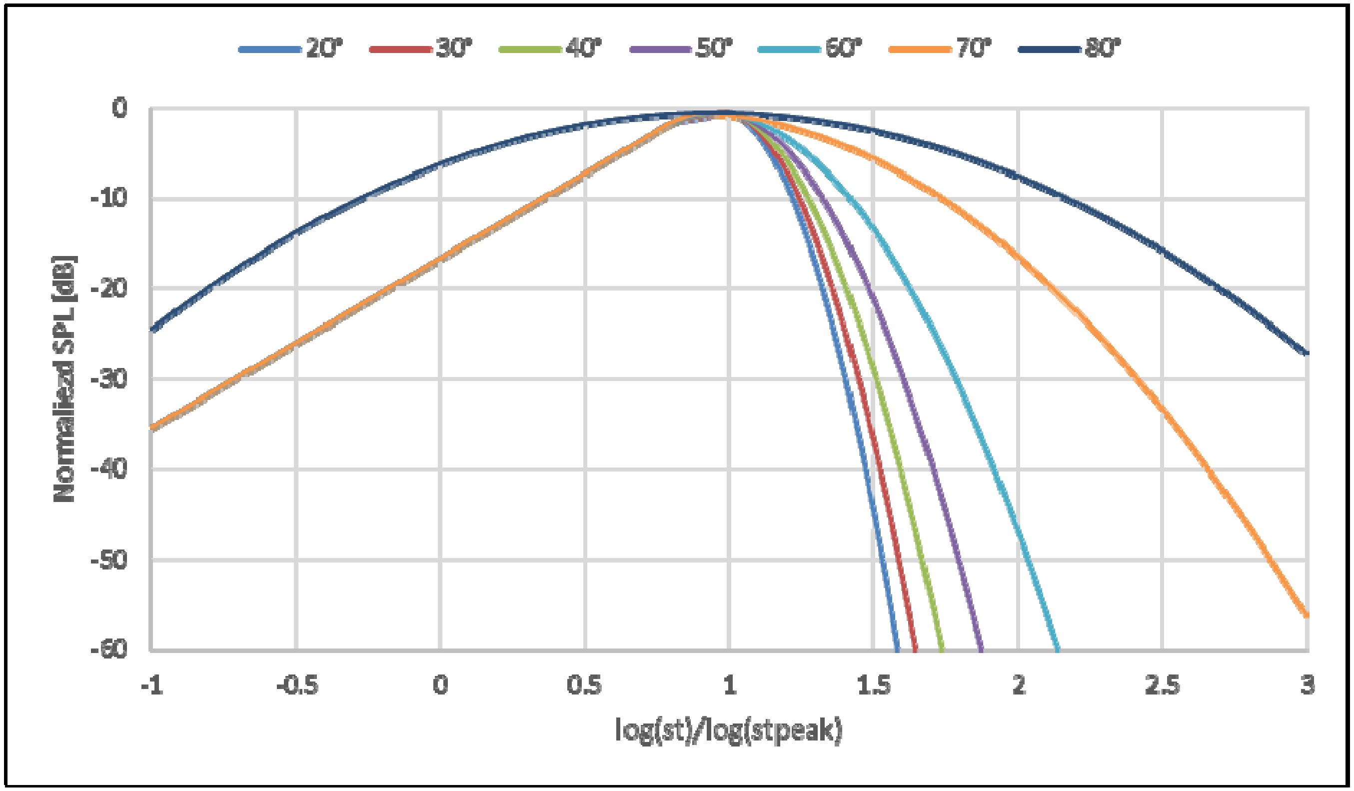
Source A Turbulence

- Can be approximated as a line at higher frequencies and parabola at lower frequencies
- Line has approximately the same slope for all receiver angles
- Parabola has different coefficients depending on receiver angle



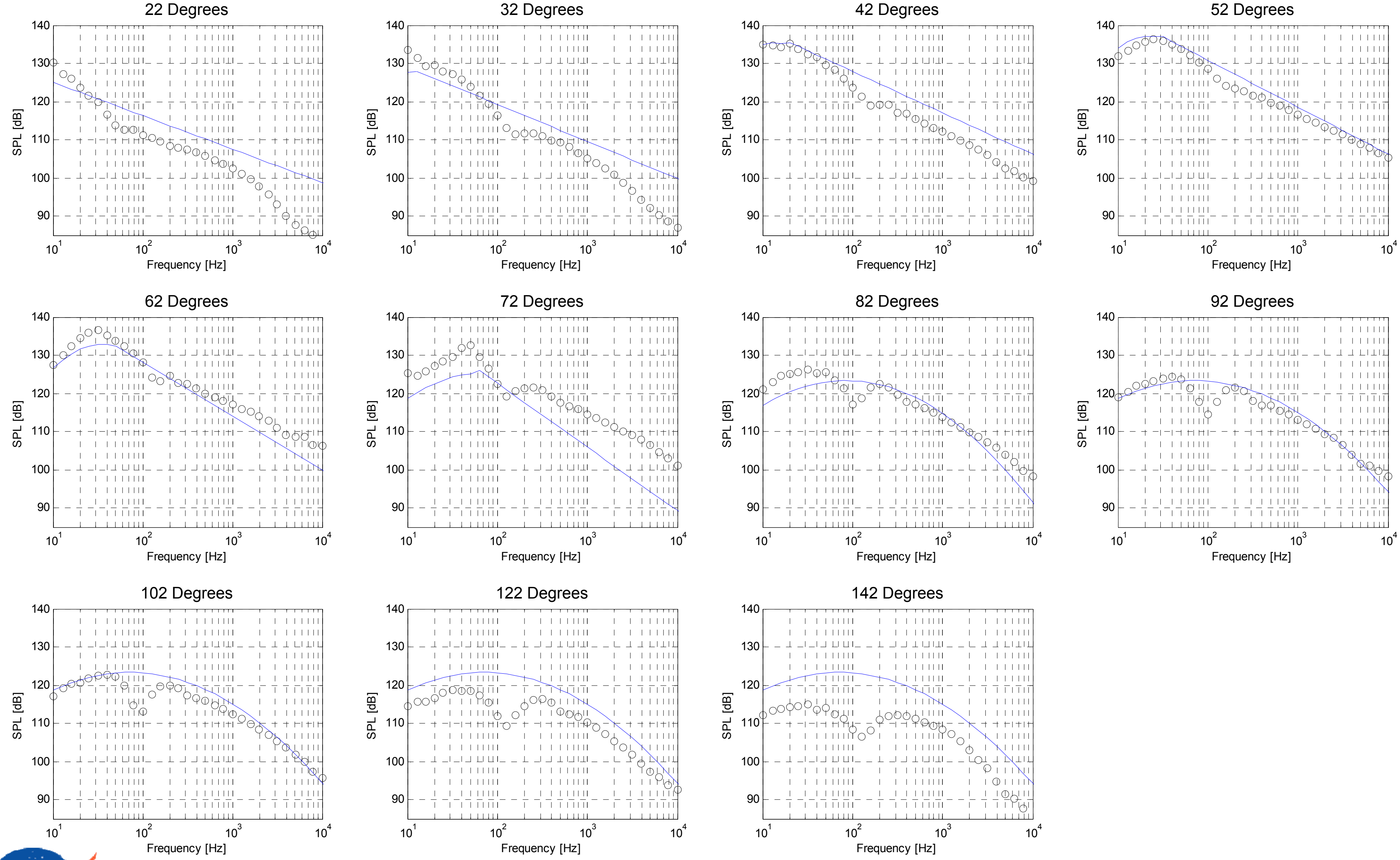
Scaling

- To bring the predicted curve up to the SPL of the measured data:
  - Acoustic power (from 8072)
    - $W_{OA} = \frac{1}{2}\,\eta\,\dot{m}\,v^2$
    - $PWL_{OA} = 10\log\left(\frac{W_{OA}}{10^{-12}}\right)$
  - Reduce Source B based on receiver angle and mass flow rate
  - Alter Source A by receiver angle, exit diameter, and mass flow rate
  - $$A = \begin{cases} PWL_{OA} * \cos(\theta_{max} - \theta) + 20\log\left(\frac{1}{D_e}\right) - 2.5\log(\dot{m}) & \theta < 80 \\ -1000 & \theta \geq 80 \end{cases}$$
  - $$B = \begin{cases} 0 & \theta < 80 \\ PWL_{OA} - \frac{\theta - 80}{5} - 10\log(\dot{m}) & \theta \geq 80 \end{cases}$$

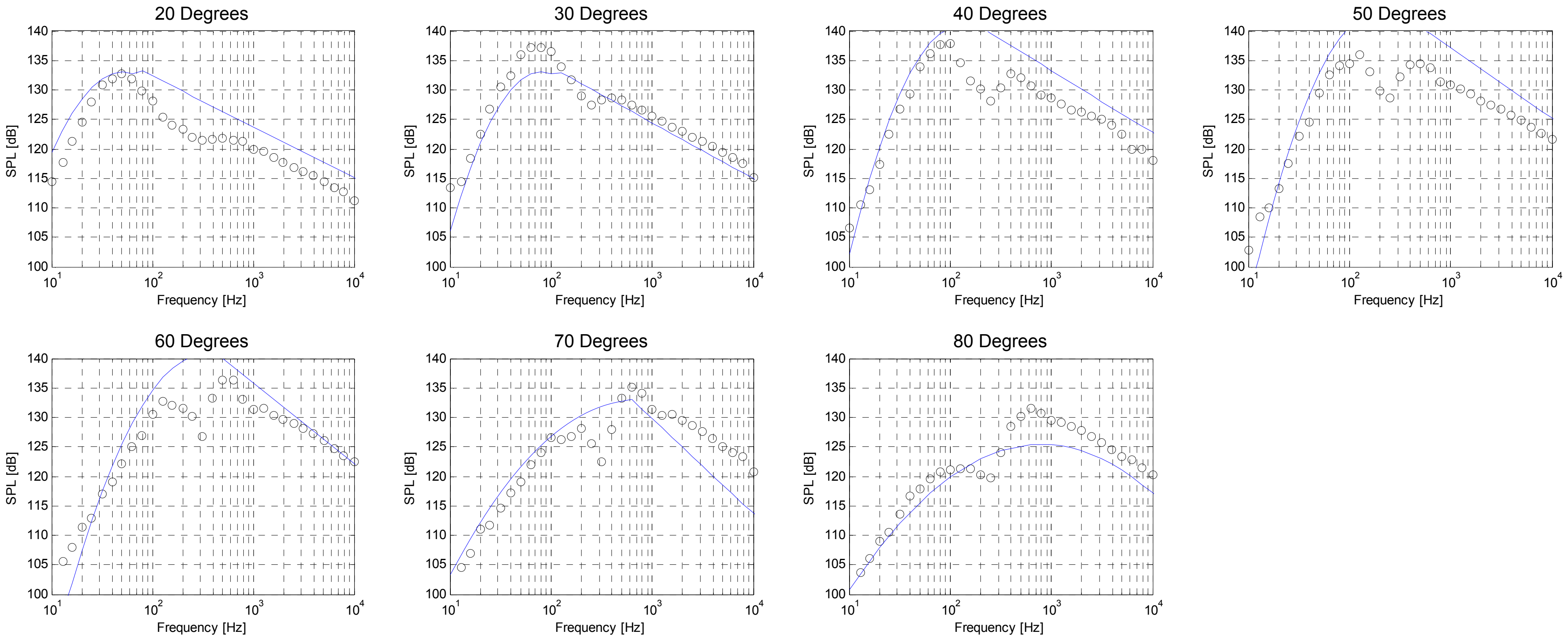
Final Model

Step 1	Calculate peak frequency	$\begin{cases} LSt_{peak} = 0.020272 * \theta - 2.5843 & \theta \leq 90 \\ LSt_{peak} = -1 & \theta > 90 \end{cases}$
Step 2	Calculate Acoustic Power	$W_{OA} = \frac{1}{2}\,\eta\,\dot{m}\,v^2$
Step 3	Calculate Sound Power Level	$PWL = 10\log\left(\frac{W_{OA}}{10^{-12}}\right)$
Step 4	Calculate coefficients for Source A and Source B	See previous slide
Step 5	Create spectra for Source A and Source B	$SB = -6.32064 * \left(\frac{\log(St)}{\log(St)_{peak}}\right)^2 + 11.9616 * \left(\frac{\log(St)}{\log(St)_{peak}}\right) - 6.24706$ $SA = \begin{cases} 18.74767 * \left(\frac{\log(St)}{\log(St)_{peak}}\right) - 16.6977 \\ a * \left(\frac{\log(St)}{\log(St)_{peak}}\right)^2 + b * \left(\frac{\log(St)}{\log(St)_{peak}}\right) + c \end{cases}$ $a = 2.9476 * \theta - 218.45$ $b = -5.7794 * \theta + 425.29$ $c = 2.8234 * \theta - 207.14$
Step 6	Logarithmic addition	$C = 10^{\frac{SB+B}{10}}, \qquad D = 10^{\frac{SA+A}{10}}$
Step 7	Total SPL Calculation	$SPL_{TOTAL} = 10\log(C + D) - 20\log\left(\frac{R}{D_e}\right)$

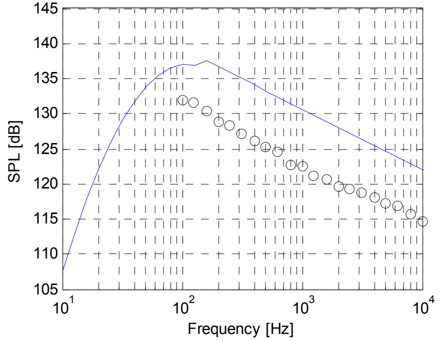
Individual Results - RSRM

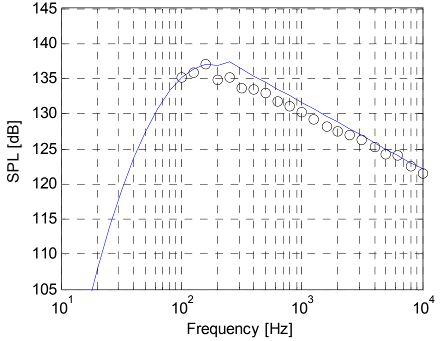


Individual Results - SRTM



Individual Results - RATO


20 Degrees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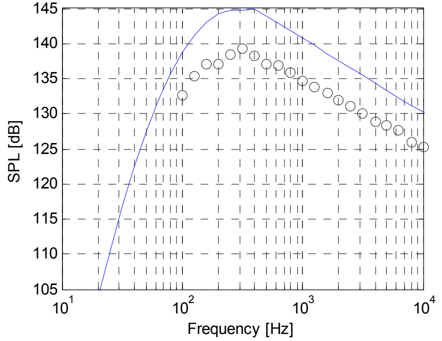
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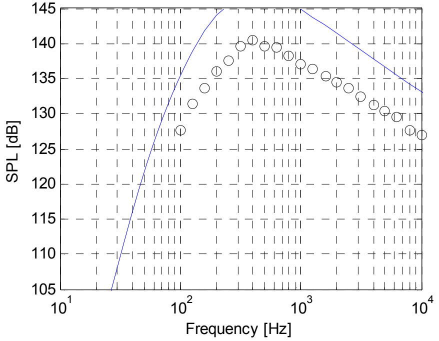
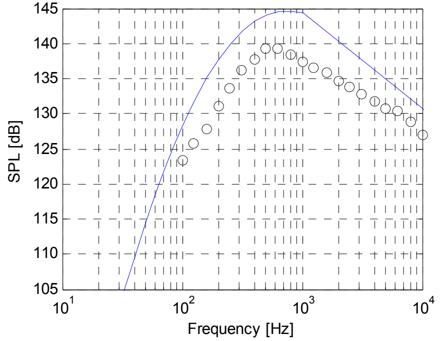
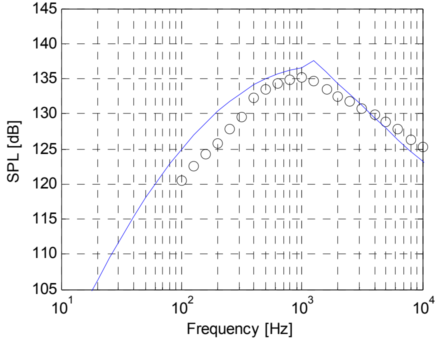
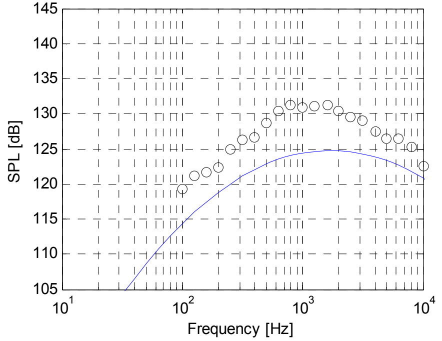
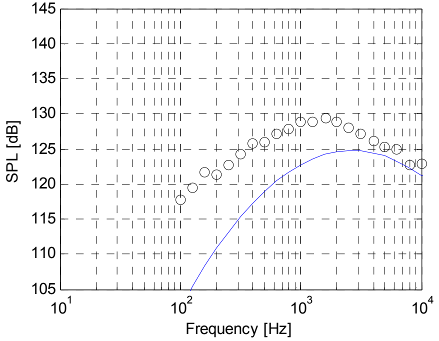
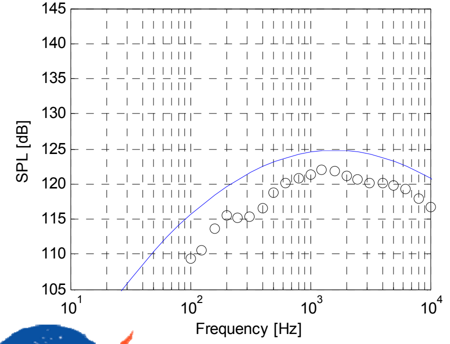

50 Degrees

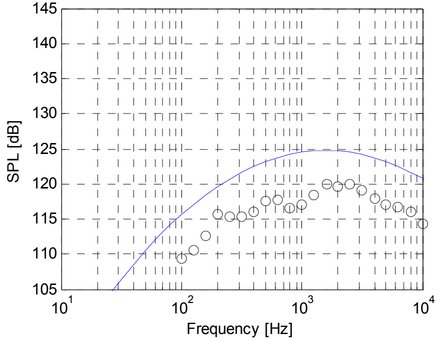

60 Degrees


70 Degrees

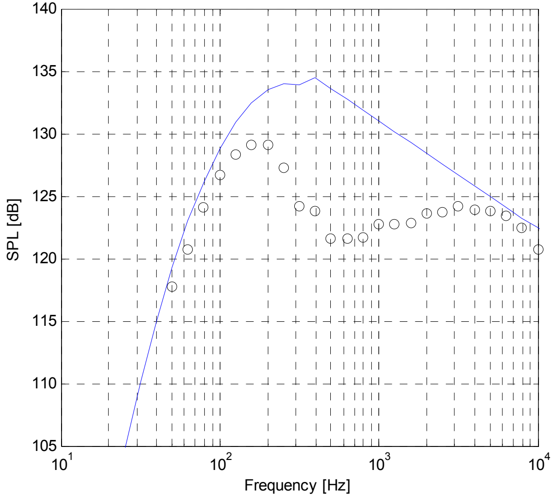

80 Degrees


90 Degrees


150 Degrees


160 Degrees

Individual Results – Single Thruster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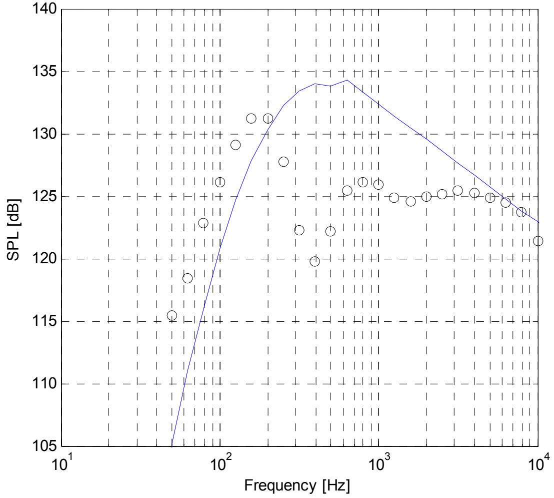
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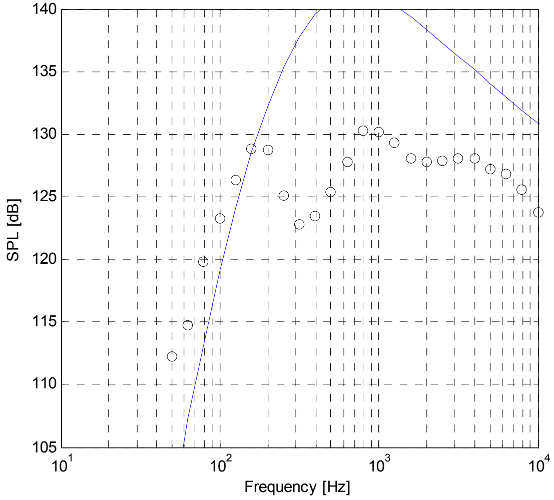
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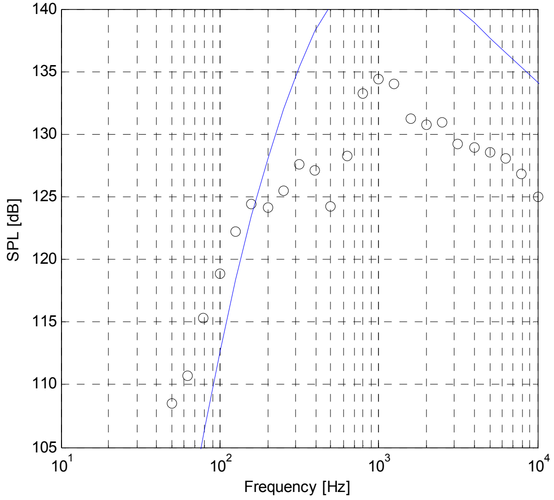
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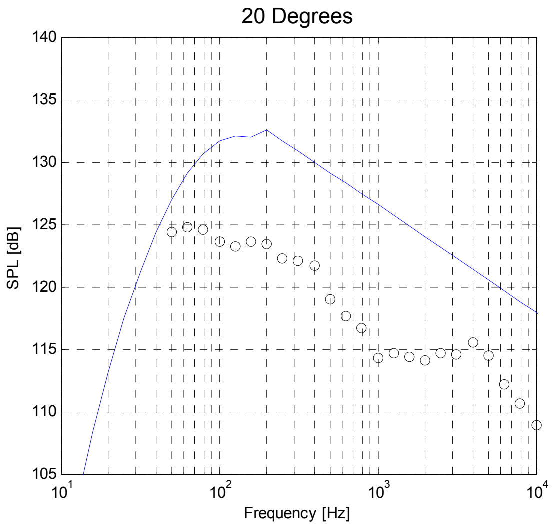
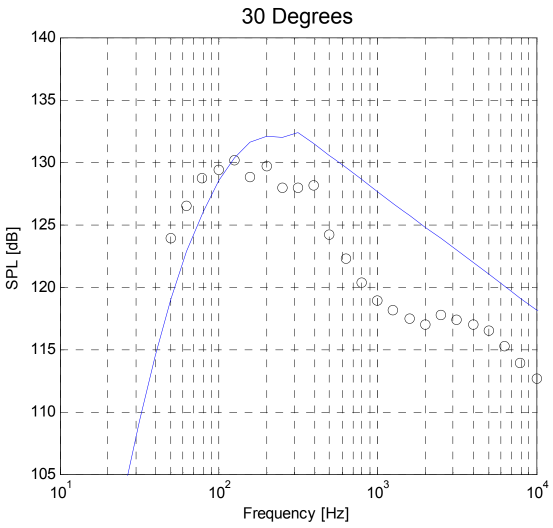
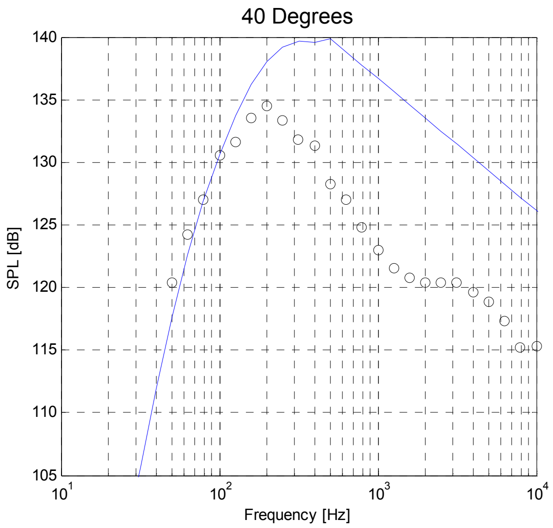
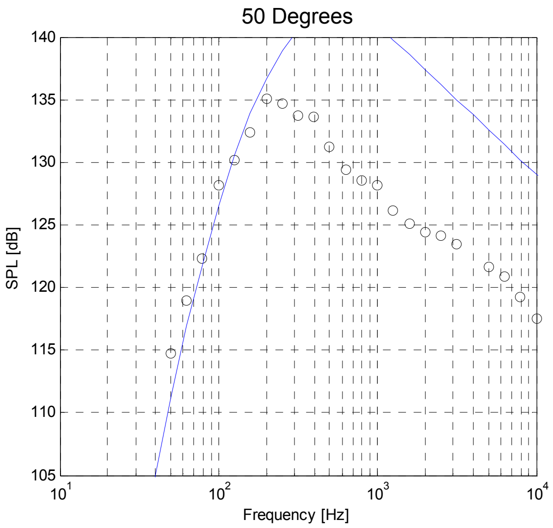
Individual Results – Quad Thruster


20 Degrees


30 Degrees


40 Degrees


50 Degrees

Conclusions and Future Work

- Model predicts rocket noise decently
  - Within 5% for the most part
- Liquids may not be able to use the same model

- Try to predict noise for other rockets not used in this study
- Investigate a combination of CFD and propagation methods to predict far field acoustics

BACKUP SLIDES

Engine Parameters

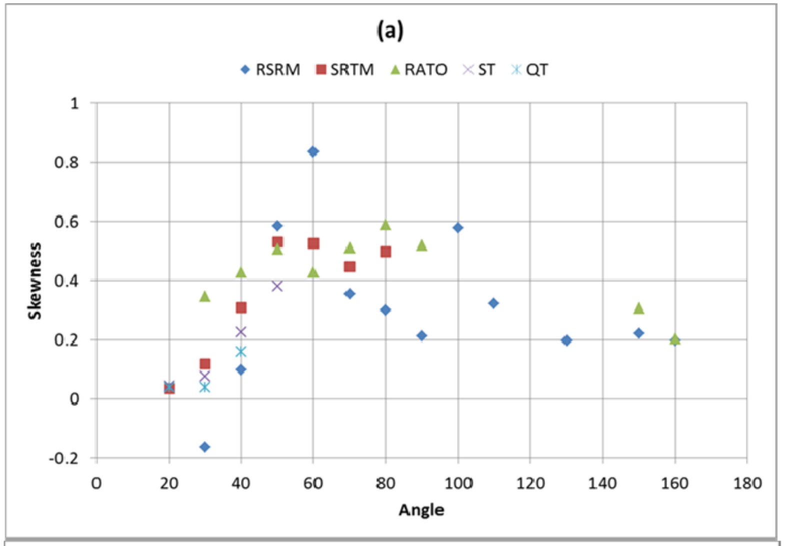
	RATO	SRTM	RSRM	Thruster	4-Thruster
			SI Units		
D_e (m)	0.194	0.35	3.8	0.115	0.23
V_e (m/s)	2500	2360	2379	4029	4029
η (%)	0.6	0.523	0.375	0.2	0.2
$\dot{m}$ (kg/s)	17.8	33	4557	1.58	6.31
R (m)	15.6	28	310	9.2	18.4
Thrust (kN)	44.5	77.9	10,841	6.4	22.7
ΔSPL	-4.35	-0.86	0	2.21	2.21
			Imperial Units		
D_e (ft)	0.64 (7.68”)	1.15	12.5	0.3765 (4.5”)	0.753 (9”)
V_e (ft/s)	8200	7740	7800	13,191	13,191
η (%)	0.6	0.375	0.53	0.2	0.2
$\dot{m}$ (lbm/s)	39.3	72.6	13,500	3.47	13.89
R (ft)	51.2	91.8	1000	30.16	60.3
Thrust (lbf)	9,868	17,508	3,310,000	1430	5100
ΔSPL	-4.35	-0.86	0	2.21	2.21

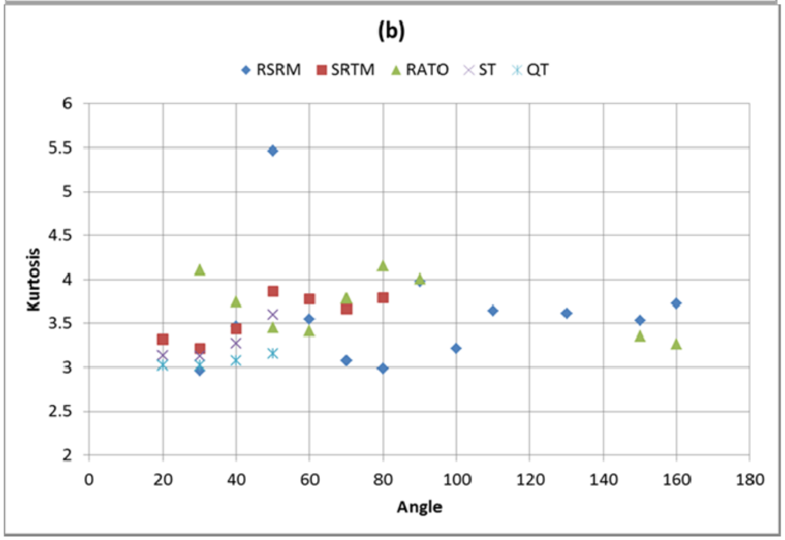
Directivity

- Must find a way to scale SPL based on receiver location
- Investigate skewness and kurtosis of the pressure-time history and the derivative of the pressure-time history
  - Statistical analysis of these time histories may help to determine direction of maximum non-linear propagation
  - Derivative of pressure-time history is a better metric

Directivity

$p(t)$





$$\frac{dp}{dt}$$