Uncertainty Margins for SP-8072 Lift Off Acoustic Loads Estimation

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June 4–6, 2019

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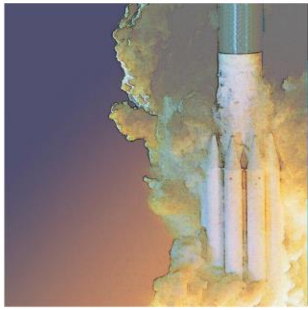
Assuring Mission Success

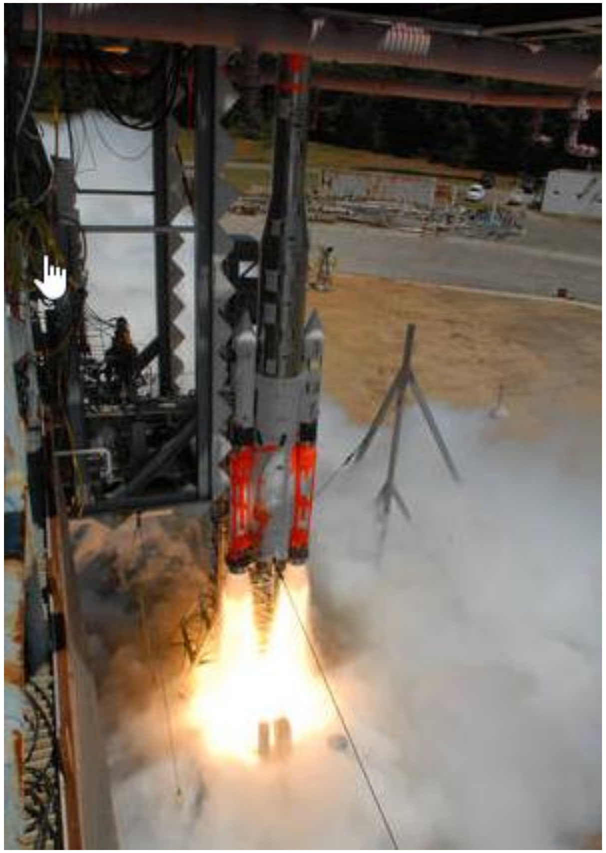


Outline

- **Motivation**
- SP-8072 Lift-off Acoustics Model
- Uncertainty Analysis
- Comparison with ASMAT, SMAT results

Motivation

- All launch vehicles need to define lift-off acoustic (LoA) loads
- Smaller / newer LV programs cannot afford model scale testing
- NASA ASMAT & SMAT tests provide valuable model validation data
- Model can be used to determine which tests will burn down uncertainty margins



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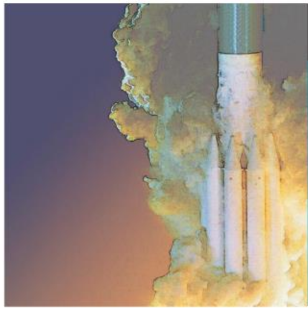

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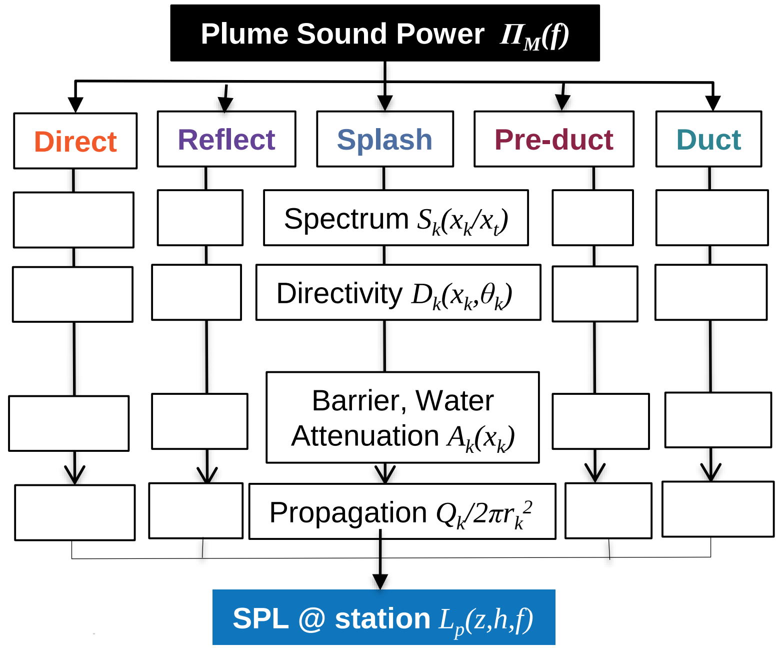
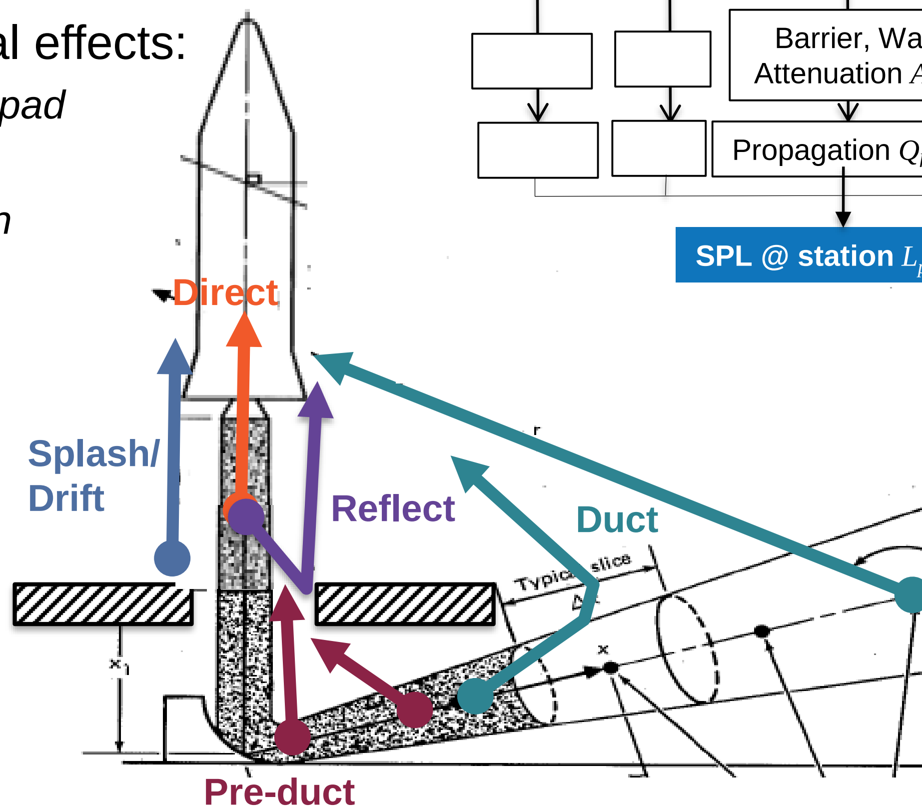
SP-8072 Model

- NASA SP-8072 provides a basic methodology to develop Liftoff Acoustic Loads by subdividing plume into increments of apparent acoustic sources
- Example SP-8072 model used here to illustrate uncertainty margin implementation
- Model includes additional effects:
  - *Reflections from Launchpad*
  - *Water attenuation*
  - *Deck / bridge attenuation*
  - *Splash / drift effect*





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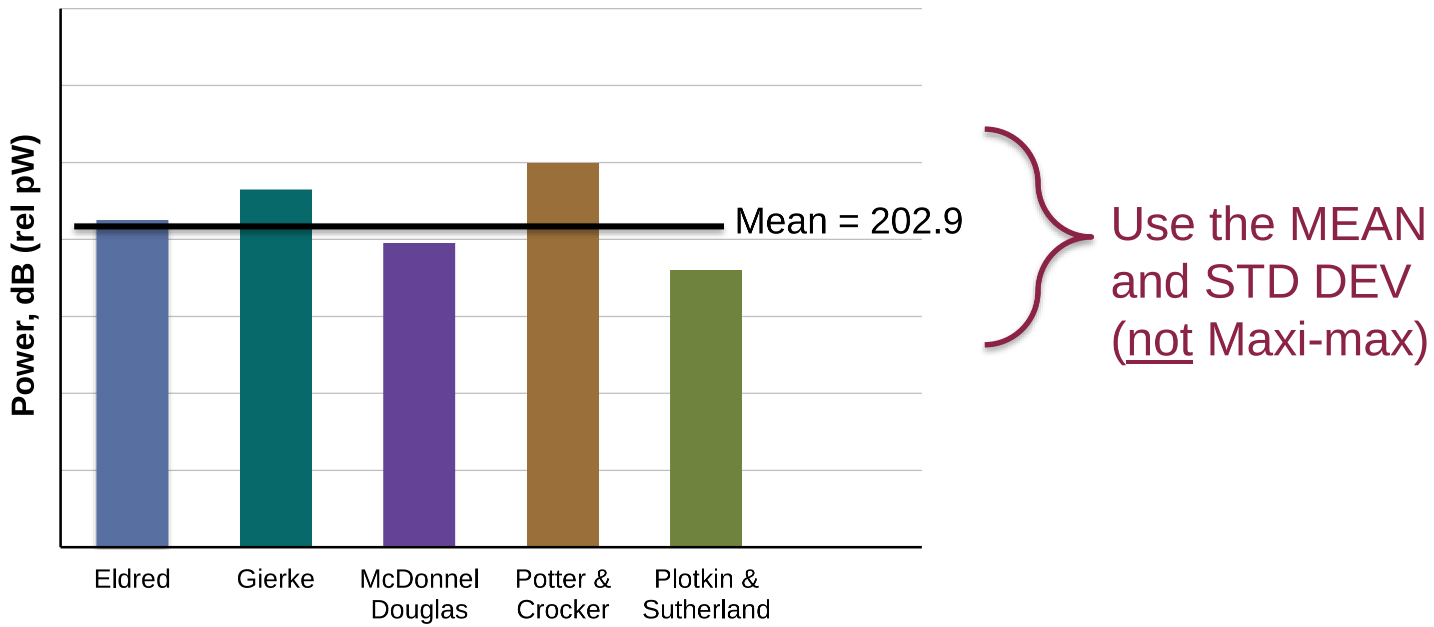
Engine Parameters & Overall Sound Power

- Overall sound power calculated using five methods
  - *Eldred, Gierke, McDonnel Douglas, and Potter & Crocker (small-medium engines only)*
  - *Sutherland & Plotkin method implemented, but requires data which many not be available*
- Data can be augmented or replaced with hot fire test data once available
- Different estimates can be used for uncertainty analysis
  - *Mean sound power is used*
  - *Standard deviation used in uncertainty analysis*



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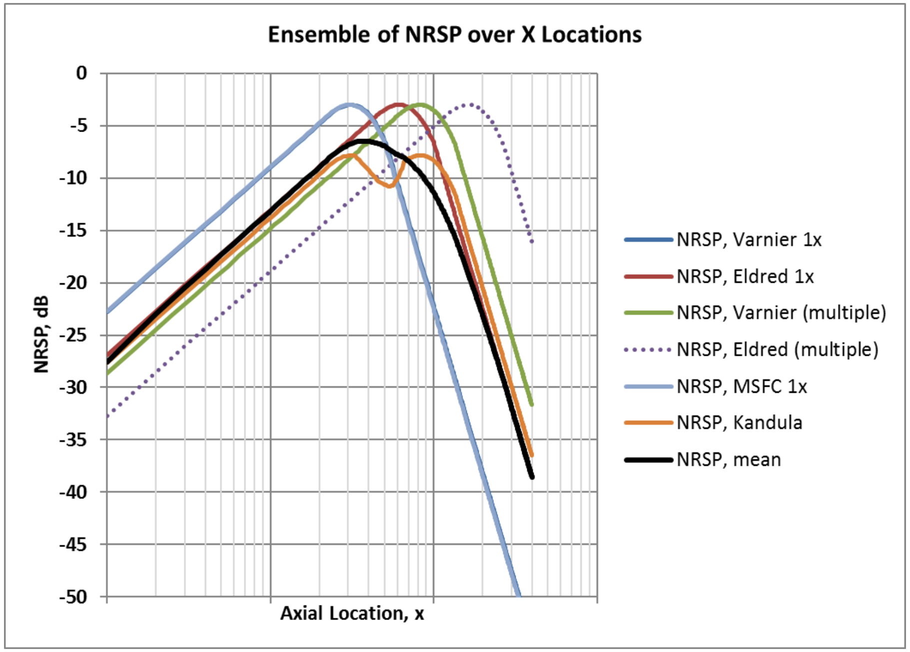
Source-Power Distribution and Propagation

- Power is distributed along plume length according to NRSP model
- Several different models / assumptions available for cluster of multiple engines
  - *Correlation to test data may lead to weighting one model more than another*
  - *These models could be augmented or replaced with hot fire test data*



Use the MEAN and STD DEV (<u>not</u> Maxi-max)

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Directivity Index

- Several different sets of directivity index have been published
  - *Eldred, Sutherland / Plotkin, and MSFC Thiokol RSRM*
  - *Data can be augmented or replaced with hot fire test data*
  - *Different DI methods can be used in uncertainty analysis*

MSFC / Thiokol RSRM data from:
"Modifications to the NASA SP-8072 Distributed Source Method II for Ares I Lift-off Environment Predictions",
Kenny, Haynes, 2009
NASA Document 20090023640

Original Eldred Directivity Index from SP-8072

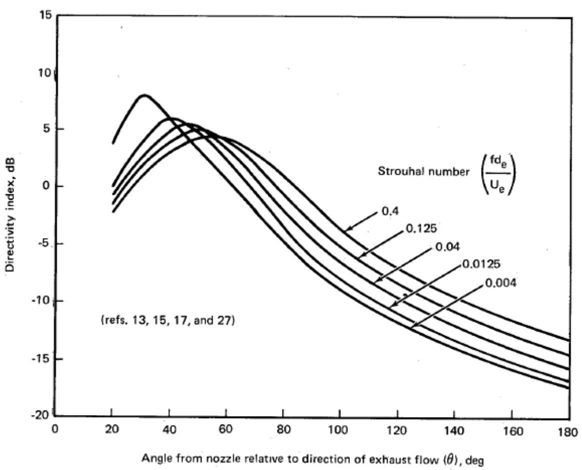
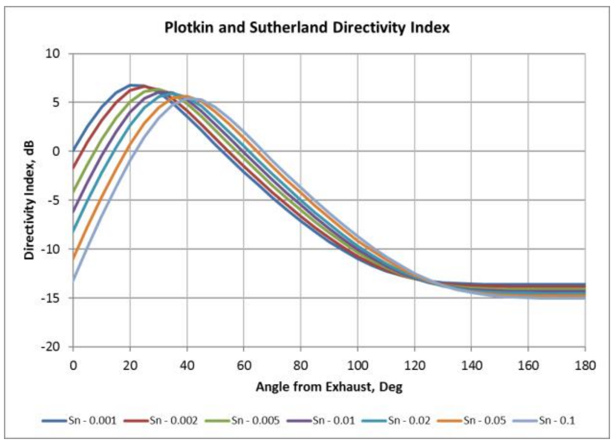


Figure 10. – Directivity of far-field noise for standard chemical rockets for several values of Strouhal number.

Plotkin and Sutherland Directivity Index



Use MEAN and STD DEV over these differing estimates (<u>not</u> Maxi-max)

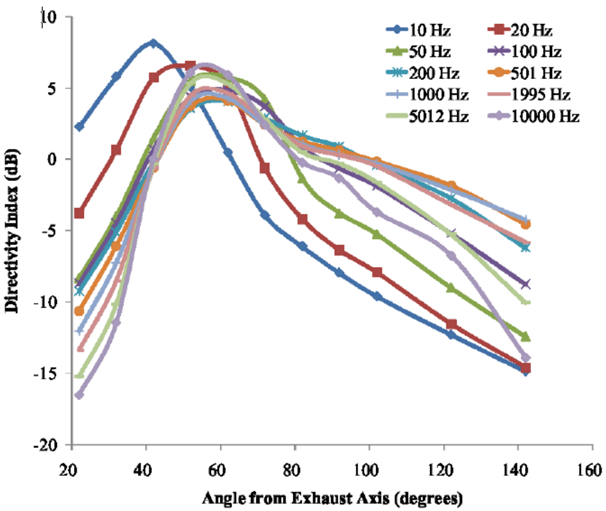


Figure 11. RSRM Directivity Index.

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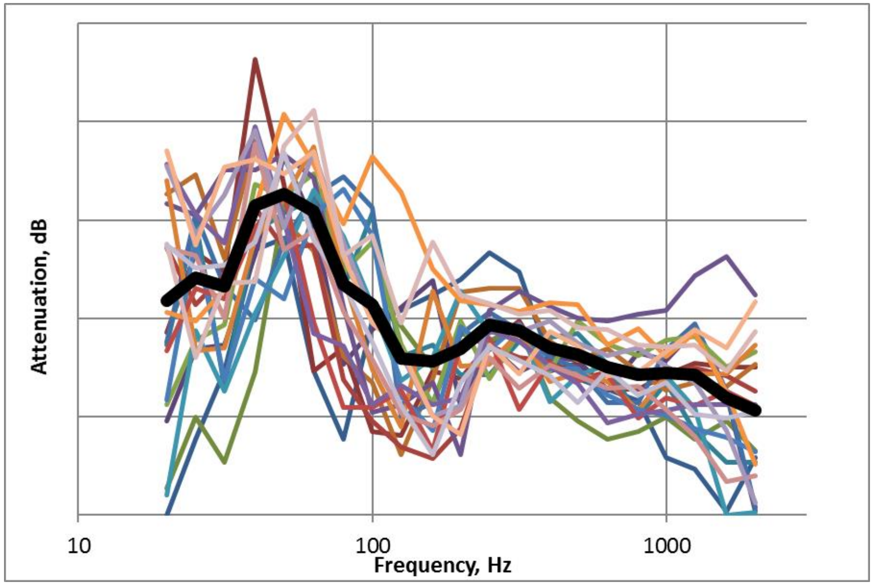
Water Attenuation

- Water attenuation scales with ratio of water mass / propellant mass (Ww/Wp)
- For apparent sources below deck and attenuated by water, a frequency dependent attenuation is applied
  - *These values are empirical "fit to SPL data" estimates only*
- Above deck "Rainbird" water attenuation estimates are based on SMAT and ASMAT test data published by MSFC
  - *These two data sets provide an excellent ensemble for calculating a mean and standard deviation for use in uncertainty analysis*



Use the MEAN and STD DEV (<u>not</u> Maxi-max)

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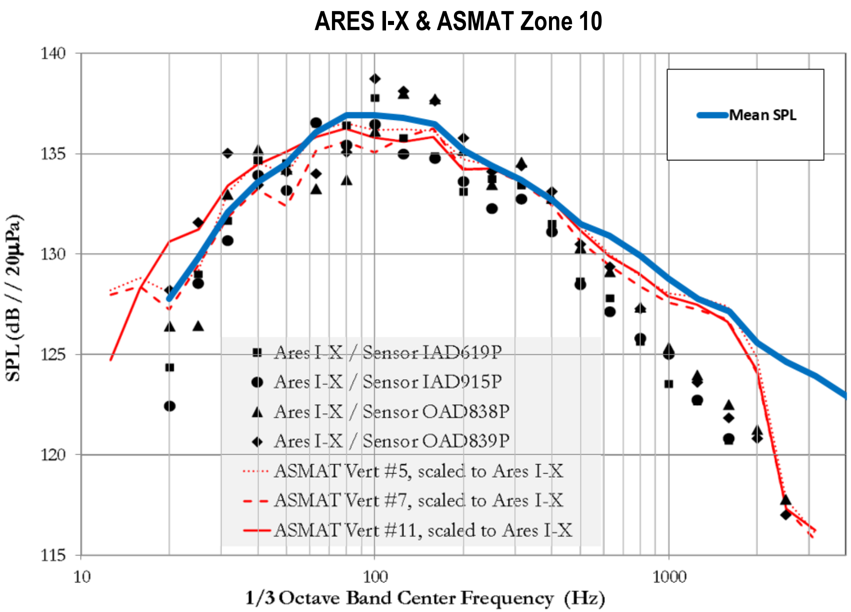
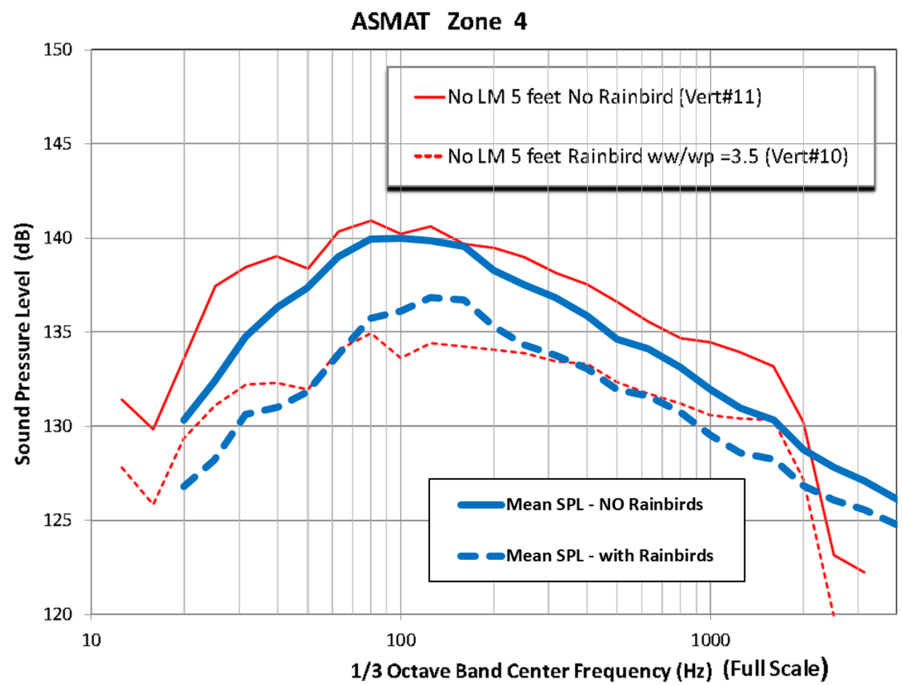
Calculated SPL on Vehicle – Mean Result

- Calculate overall SPL level
- Sample results are **MEAN overlays only**



Data from:
"Verification of Ares I Liftoff Acoustic Environments via the Ares I Scale Model Acoustic Test", Counter, Houston, 2012
NASA Document 20130000589



Data from:
"Ares I Scale Model Acoustic Test Above Deck Water Sound Suppression Results", Counter, Houston, 2011
NASA Document 20120001741

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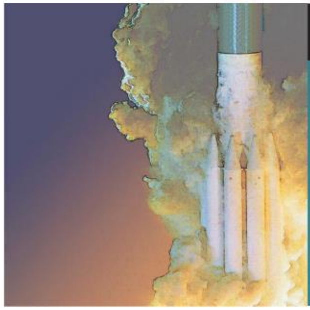

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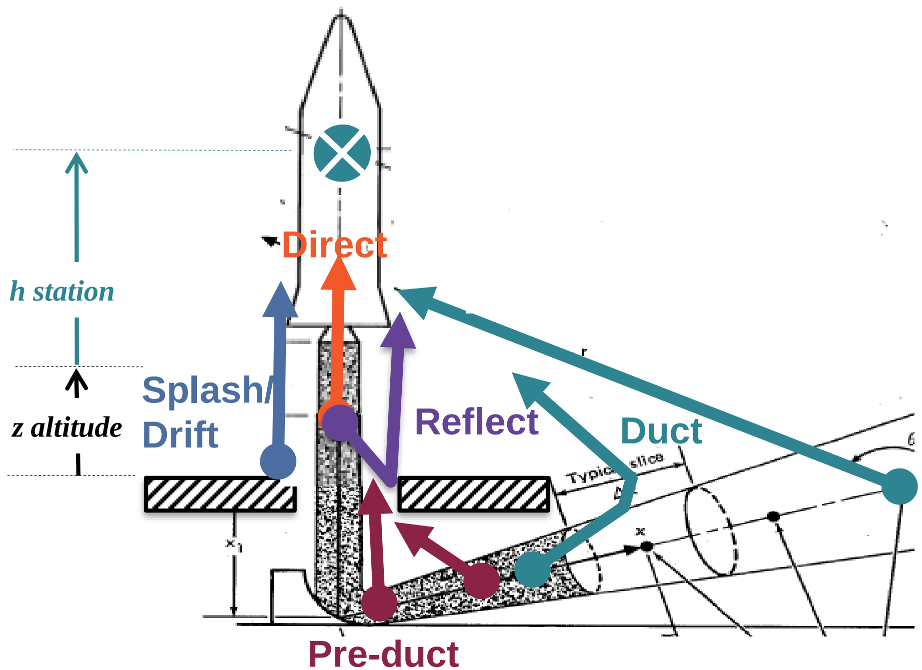
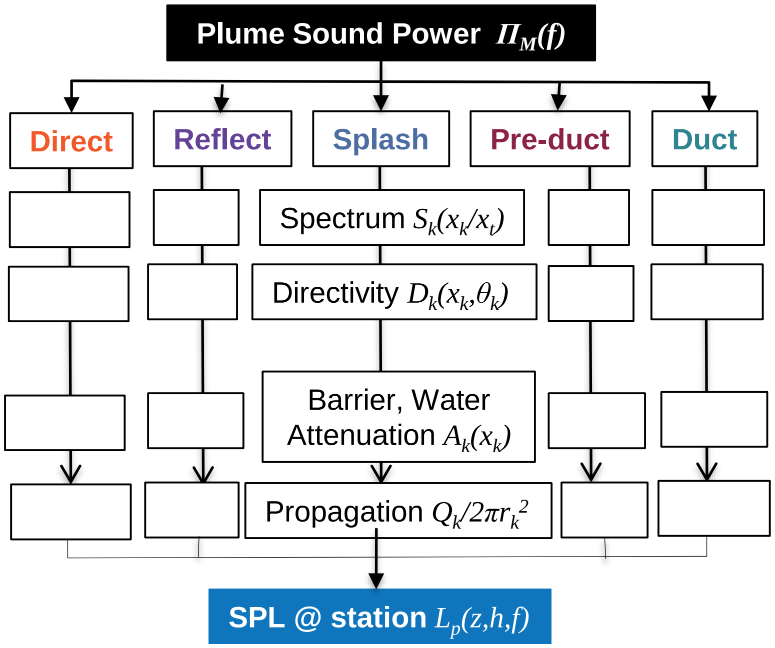
Uncertainty model

End-to-end math model of SP-8072





$$L_P(z,h,f) = 10Log\left\{\overline{p}^2_{Direct} + \overline{p}^2_{Reflect} + \overline{p}^2_{Splash} + \overline{p}^2_{PreDuct} + \overline{p}^2_{Duct}\right\}$$

$$= 10Log\left\{\left(\frac{A_i\overline{D}_i\overline{S}_i\overline{\Pi}_M}{4\pi\overline{r}_i^2}\right)_{Direct} + \left(\frac{A_j\overline{D}_j\overline{S}_j\overline{\Pi}_M}{2\pi\overline{r}_j^2}\right)_{Reflect} + \left(\frac{A_s\overline{S}_s\overline{\Pi}_M}{2\pi\overline{r}_s^2}\right)_{Splash} + \left(\frac{A_k\overline{D}_k\overline{S}_k\overline{\Pi}_M}{2\pi\overline{r}_k^2}\right)_{PreDuct} + \left(\frac{A_l\overline{D}_l\overline{S}_l\overline{\Pi}_M}{2\pi\overline{r}_l^2}\right)_{Duct}\right\}$$

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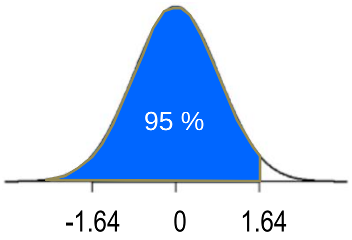
Uncertainty model

MPE from Normal Tolerance Limit



$$P95\left[L_p\right] = \left\langle L_p \right\rangle + 1.64\,\sigma_{L_p}$$

$$P05\left[L_p\right] = \left\langle L_p \right\rangle - 1.64\,\sigma_{L_p}$$

$$L_P = 10Log\left\{\overline{p}^2_{Direct} + \overline{p}^2_{Reflect} + \overline{p}^2_{PreDuct} + \overline{p}^2_{Splash} + \overline{p}^2_{Duct}\right\} \quad dB$$

Statistics of Log of Sum of Random Variables

$$\left\langle L_{\Sigma p^2} \right\rangle \neq 10Log\left\{\left\langle \Sigma p^2 \right\rangle\right\}$$

$$= 10Log\left\{\left\langle \Sigma p^2 \right\rangle\right\} - 5Log\left\{1 + r^2\left[\Sigma p^2\right]\right\}$$

$$\sigma^2\left[L_{\Sigma p^2}\right] = 43.4Log\left\{1 + r^2\left[\Sigma p^2\right]\right\}$$

where Relative Variance is defined

$$r^2\left[\Sigma p^2\right] = \sigma^2_{\Sigma p^2} \Big/ \left\langle \Sigma p^2 \right\rangle$$

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Uncertainty model

Relative Variance from Component Variances

Variance of total Lp from variance of each plume Segment SPL contribution

$$\langle \Sigma p^2 \rangle = \langle p^2_{Direct} \rangle + \langle p^2_{Reflect} \rangle + \langle p^2_{PreDuct} \rangle + \langle p^2_{Splash} \rangle + \langle p^2_{Duct} \rangle$$

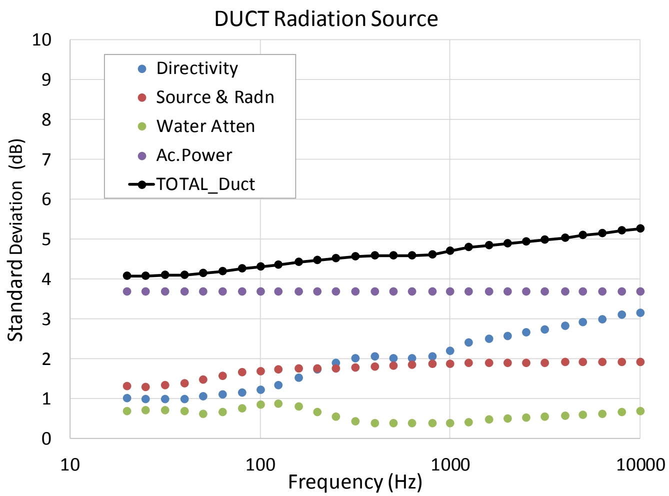
$$\sigma^2\left[\Sigma p^2\right] = \sigma^2\left[p^2_{Direct}\right] + \sigma^2\left[p^2_{Reflect}\right] + \sigma^2\left[p^2_{Splash}\right] + \sigma^2\left[p^2_{PreDuct}\right] + \sigma^2\left[p^2_{Duct}\right]$$

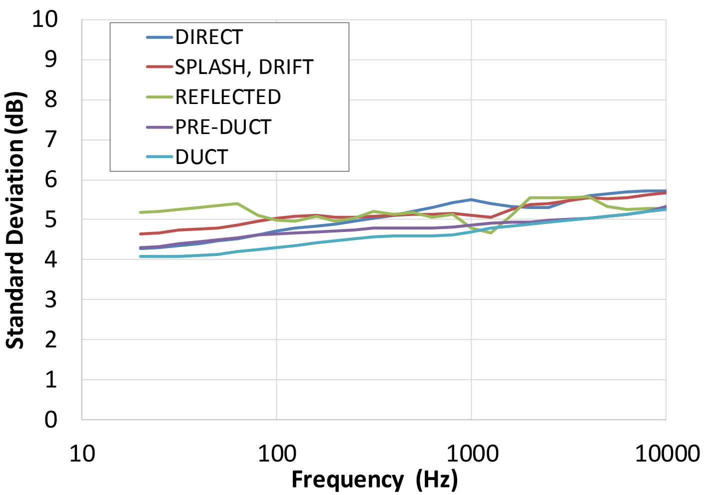
Segment SPL variance from Component Sound Power & Radiation variances

$$\langle p^2_\xi \rangle = \langle \Pi_m \rangle \langle A^{water}_\xi \rangle \langle S_\xi \rangle \langle D_\xi \rangle / \langle 4\pi R^2_\xi \rangle$$

$$r^2\left[p^2_\xi\right] \approx r^2\left[\Pi_m\right] + r^2\left[A^{water}_\xi\right] + r^2\left[S_\xi\right] + r^2\left[D_\xi\right] + r^2\left[R^2_\xi\right]$$

$$\frac{\sigma^2_{p^2_\xi}}{p^2_\xi} \approx \frac{\sigma^2_\Pi}{\langle \Pi_m \rangle} + \frac{\sigma^2_{A_\xi}}{\langle A_\xi \rangle} + \frac{\sigma^2_{S_\xi}}{\langle S_\xi \rangle} + \frac{\sigma^2_{D_\xi}}{\langle D_\xi \rangle} + \frac{\sigma^2_{R^2_\xi}}{\langle R^2_\xi \rangle}$$





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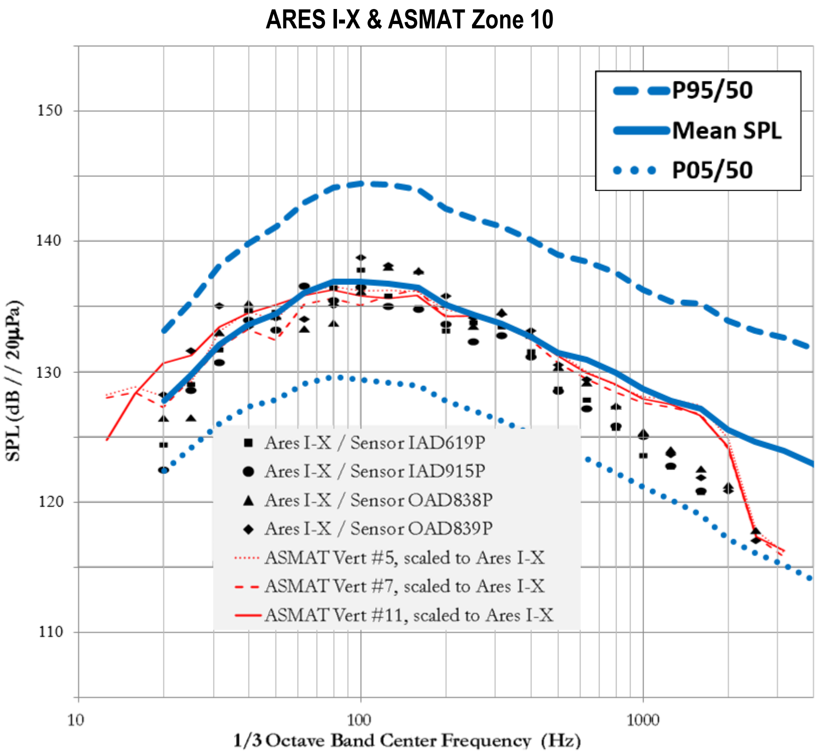
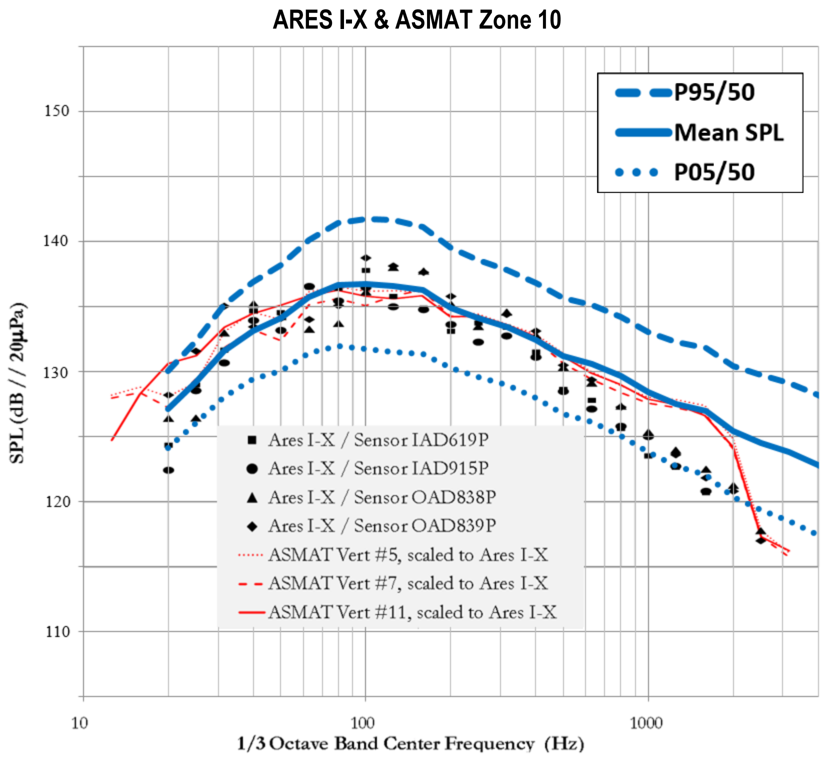
Comparison with ASMAT, SMAT

Testing reduces uncertainty margins

MPE before Hotfire testing



Improvement after Hotfire testing



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SUMMARY

- Inputs to SP-8072 are frequently uncertain which can lead to large uncertainty margins
- **Quantitative uncertainty analysis:**
  - *Robust statistical basis for MPE (eg. P95/50)*
  - *Identifies dominant sources of uncertainty*
  - *Justifies testing to burn down margins*
- **Hotfire testing** to measure overall sound power and directivity can reduce two uncertainties in the model
  - *Test may also be devised to extract source distribution*

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Questions ?