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UNCERTAINTY IN SOUND POWER DETERMINATION AND IMPLICATIONS FOR POWER PLANT ACOUSTICS

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ABSTRACT
This paper makes use of the results of a sound power test program, initiated by the US National Institute of Standards and Technology, using aerodynamic reference sound sources. The uncertainties produced have implications for noise prediction and estimation, specifically, the uncertainty in sound power of the source will have an effect on the estimated sound pressures and the corresponding far field sound level contours. As a result, the spectral content of the source has a frequency dependent uncertainty at the receiver. Thus is established a lower bound on the uncertainty in impact assessment at a given position and on the uncertainty in locating and depicting sound level contours. Examples are given for far field receptors relative to a typical power plant noise source.

1 - INTRODUCTION

Uncertainty in noise measurement and prediction is often overlooked when making decisions about the ramifications of noise. The source uncertainties, measurement uncertainties, and predictive modeling assumptions are rarely included in environmental acoustics assessments. Graphical depictions of discrete far field environmental noise contours predict the locations for a given far field sound pressure level, whereas the inherent uncertainty of such predictions requires careful qualification. International standards [1,2] commonly contain "uncertainty" statements purporting to estimate the cumulative effects of a range of causes of uncertainty. Ray [3] provided valuable insight to the uncertainty due to measurement of environmental noise strictly as a result of instrumentation errors. Putnam [4] demonstrated the critical need for addressing uncertainty in the graphical depiction of sound levels over large areas. This paper discusses the effects of these various sources of uncertainty on far field noise predictions and in particular demonstrates the significance of the most basic element of uncertainty, the laboratory measurement of sound power level.

2 - DISCUSSION

In 1998, the US National Institute of Standards and Technology issued a report discussing the proficiency of NVLAP accredited laboratories for the determination of sound power [5]. The testing program involved seven laboratories performing the conventional ISO and ANSI tests (ISO 374x and ANSI S12.3x series) for determination of sound power. The test articles were aerodynamic reference sound sources.
Table 1 shows the results for four small simple sources measured in all the participating laboratories. The standard deviation (SD) indicates the variability among the laboratories under controlled conditions. These SDs represent the Best Attainable Precision (BAP) to be expected, under the most favorable of circumstances in or out of the laboratory. Real systems, under the best of conditions, cannot be expected to exhibit better precision than presented here and may exhibit larger SDs.

Source	Frequency, hertz 63	80	100	125	160	200	250	315	400	500	630	800
Ave. Lw #1	54.6	51.8	52.6	58.4	55.2	57.1	59.7	62.9	67.5	69.9	75.1	74.6
Standard Deviation	0.4	0.3	1.5	1.5	0.4	0.5	0.4	0.3	0.3	0.4	0.4	0.6
Ave. Lw #2	74.8	77.5	78.2	79.1	79.7	80.2	80.1	79.9	79.6	80.0	80.6	81.4
Standard Deviation	0.2	0.2	2.0	0.7	0.5	0.5	0.4	0.5	0.5	0.6	0.4	0.5
Ave. Lw #3	70.5	73.9	75.7	79.4	77.0	76.4	76.7	77.3	77.8	79.1	80.8	82.4
Standard Deviation	0.1	0.7	1.5	0.7	0.8	0.5	0.5	0.5	0.3	0.6	0.6	0.5
Ave. Lw #4	71.1	74.1	75.8	78.7	77.3	77.0	76.6	77.0	77.8	79.3	81.4	83.1
Standard Deviation	0.1	0.5	2.0	1.0	0.5	0.8	0.5	0.6	0.7	0.4	0.6	0.9

Source	Frequency, hertz 1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Ave. Lw #1	79.6	78.9	75.9	74.7	75.1	73.6	73.5	72.9	72.5	71.1	66.0
Standard Deviation	0.8	0.5	0.3	0.5	0.5	0.4	0.5	0.4	0.5	0.5	2.0
Ave. Lw #2	83.4	83.9	84.1	83.3	82.4	81.7	81.1	81.2	80.5	78.5	74.7
Standard Deviation	0.8	0.4	0.3	0.6	0.5	0.5	0.5	0.4	0.5	0.6	2.1
Ave. Lw #3	82.9	83.1	82.9	82.7	81.4	79.9	78.8	77.9	78.0	78.0	75.9
Standard Deviation	0.4	0.4	0.4	0.5	0.7	0.6	0.4	0.4	0.5	0.2	1.1
Ave. Lw #4	83.6	83.8	83.8	88.3	82.6	80.5	79.5	78.4	78.4	78.0	75.6
Standard Deviation	0.4	0.4	0.6	0.9	0.7	0.6	0.5	0.5	0.5	0.7	2.4

Table 1: Average sound power levels of four reference sound sources for all laboratories.

The SD values in Table 1 are combined in Table 2 by calculating the root-mean-square (RMS) value of the four Table 1 values in each 1/3rd-octave band.

	Frequency, hertz											
	63	80	100	125	160	200	250	315	400	500	630	800
Ave. For All Sources	.23	.47	1.77	1.03	.57	.59	.45	.49	.48	.51	.51	.65
95% Conf.	.46	.94	3.54	2.06	1.14	1.18	.92	.98	.96	1.02	1.02	1.3

	Frequency, hertz										
	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Ave. For All Sources	.63	.43	.42	.70	.61	.53	.48	.43	.50	.53	1.96
95% Conf.	1.26	.86	.84	1.4	1.22	1.06	.96	.86	1.0	1.06	3.92

Table 2: RMS standard deviation of all tests where 95% confidence interval is twice the average for all tests.

The SDs shown in Table 2, are further combined into full octave band SDs as shown in Table 3. The RMS method is used to combine the constituent 1/3 octave band SDs into full octave band values. The 63 Hz octave band value has been arbitrarily assigned a value equal to the 125 Hz octave band rounded value. This was done because the 63 Hz band was composed of only two 1/3-octave bands from the laboratory data, and because prior experience suggests a diminishing precision at progressively lower frequencies, the calculated 63 Hz value of 0.73 dB was considered spurious. The octave band SD values derived for Table 3 should be regarded as representing the BAP in the determination of sound power levels by whatever means, using appropriate standard test methods. For simplicity, the rounded values will be assumed to represent BAP.

	Frequency, hertz							
	63	125	250	500	1000	2000	4000	8000
Full Octave 95% Conf.	0.74	2.45	1.03	1.00	1.15	1.17	0.960	2.42
ROUNDED 95% CONFIDENCE	2.4**	2.4	1.0	1.0	1.2	1.2	1.0	2.4

Table 3: The 95% confidence interval, the best attainable precision, in terms of full octave bands, derived from the full set of combined NVLAP data (** rounded 95% confidence arbitrarily set equal to 125 Hz value; see discussion text for rationale).

It is common to refer to the "95% confidence interval" as lying within two standard deviations of the mean for normal distributions. For any given set of sound power level data, it is expected that, with 95% confidence, the values of Table 2 or 3 represent the BAP of the reported value for a normal distribution. This is true for a laboratory test of a simple, well-controlled, almost omni-directional sound source. For any real source, such as machinery and components common to power plant installations, the variability for the same test will be greater than the BAP and the variability due to individual models and operating conditions will increase the uncertainty further. Perhaps more significantly, the reported sound power levels for many types of equipment are not based upon well-controlled laboratory tests, but upon experimental extrapolations or interpolations of data from less precise laboratory tests, and even from in-situ tests using engineering grade or survey grade methodology.

In Draft ISO standard 3747 [6], which deals with determining sound power in-situ, the upper values of SD are given as ranges, from 1.5 to 4.0 dB. These values are supported by the work of Probst [7]. Furthermore, these quoted SDs are for A-weighted measures only. Experience suggests that certain octave band results will have higher SDs. The corresponding 95% uncertainty of such tests would be on the order of plus or minus 3 to 8 dB(A). Another source of uncertainty in sound level predictions is the effect of directivity of the source emissions: 5 dB or more is not uncommon. This may not be accounted for in the reporting of overall source sound power. In the field, the orientation and directivity of the source is not always considered when applying the source sound power. This results in yet further additive error in the predicted far field sound level. Hence, real sources of sound power emissions will differ, often considerably, from laboratory based published sound power levels.

Based upon the tested and reported sound power level, the predicted sound pressure level at far field positions will reflect at least the 95% uncertainty given in Tables 2 and 3, [8]. If the sound power of a particular operating source is unknown, its sound power can be estimated by measuring sound pressure level at a known distance in an approximately free field. The sound power may then be calculated and then, in turn, used to calculate the predicted far field level in another setting or at another distance. This calculation requires further assumptions about the source type and the method of extrapolating to the hypothetical far field positions. The uncertainty of the initial measurement is then compounded by the uncertainty of the effective distance from the acoustical center and assumptions about the details of the wave divergence. When making decisions on environmental noise impacts, these uncertainties in sound power estimates yields uncertainties in calculated contours. This in turn affects the determination of the locations of potentially impacted areas.

3 - ILLUSTRATIVE EXAMPLES

In outdoor noise analysis, whenever there is uncertainty about the true sound power level of a sound source, there will be corresponding uncertainty regarding the calculated A-weighted sound level at a receiver. This yields a corresponding uncertainty in the spatial positioning of predicted sound level contours, called "isopleths", commonly depicted as discrete contours on a two-dimensional plan view of the affected area. Table 4 is a hypothetical power plant sound power level spectrum, used to predict the A-weighted sound level at far field positions ranging from 100 m to 3200 m from the acoustical center of the hypothetical power plant. For this analysis, the actual noise generating components, the relative positions and height, the effect of ground absorption and conservative downwind propagation are neglected. To simplify the analysis, the sound power spectrum was converted to a far field position using only hemispherical diffusion and atmospheric absorption per ISO 9613 [9].

	Frequency, hertz								
	63	125	250	500	1000	2000	4000	8000	dBA
Reference Lw Spectrum	12.3	7.9	-2.4	-9.5	-9.6	-9.6	-9.3	-4.6	0

Table 4: Illustrative example sound power spectrum shape, representative of a large stationary power plant.

Information on the uncertainty in the 31.5 Hz band was not available from the NVLAP study [5]. Tables 3 and 4, and this analysis, do not include the 31.5 Hz octave band. Noise regulations are sometimes given in terms of either 31.5 Hz octave band or C-weighted criteria. For power plant noise emissions the uncertainties associated with either of these parameters will be directly related to the uncertainty assigned to the 31.5 Hz band, and will not vary much as a function of distance.
Example #1: Figure 1 is the A-weighted sound level uncertainty band, the 95% confidence band of Table 3, applied to the spectrum of Table 4. This is the BAP, the minimum uncertainty at a given distance from the source. No determination of sound power levels can achieve any better precision than Figure 1 depicts. The increasing values with increasing distance from the source is due to the effect of atmospheric absorption on the hypothetical power plant spectrum. As the distance from the source increases there is a larger dependence upon the lower frequencies' contribution to the A-weighted level.

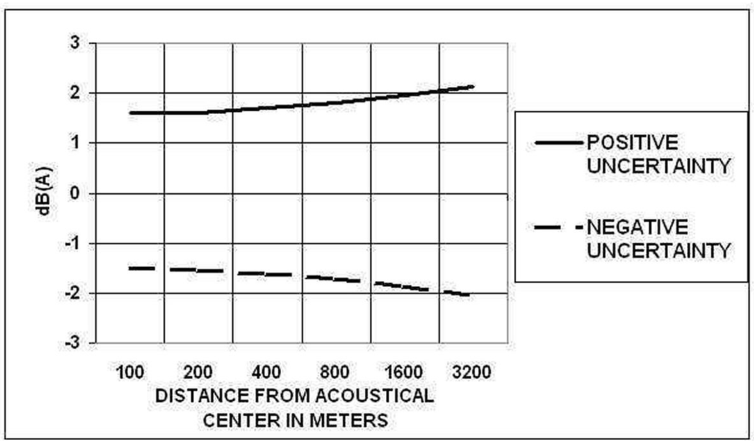

Figure 1: The 95% uncertainty bands for the best attainable precision (BAP) for sound power level extrapolated to far field distances from the acoustical center of a typical large stationary power plant.

Example #2: The method of depicting far field sound level isopleths using customarily discrete, thin, lines on an area map, has significant consequences. Figure 2 shows the radial trend of the "zero error" far field A-weighted sound level calculation, assuming no variability due to uncertainty. Also shown are the plus and minus BAP uncertainty limits. The plus and minus BAP uncertainty curves quantify the distance error which can occur if a graphical A-weighted sound level isopleth was drawn at the zero error distance.
Figure 3 is a plot of these potential distance errors, as a function of distance from the source. The true isopleth may lie anywhere in this region depicted by Figure 3. At 3200 m nominal radius for a zero uncertainty calculation, conventional practice would draw a contour line on the map at that radius. With usual map scales, the width of the line so drawn might be 20 m or more. But consideration of the 95% uncertainty inherent in all estimates of sound power levels indicates that the true isopleth may lie anywhere from 2531 m (3200 m − 669 m) to 4084 m (3200 m + 884 m). At closer distances the errors, on a percentage-of-nominal-radius basis, are comparable. At 200 m, the error is plus 40 m, minus 32 m. In fact, for the distances considered here, the overall error-of-distance estimate, measured as a percentage of the nominal distance, ranges from 36% at 100 m, to 48% at 3,200 m.

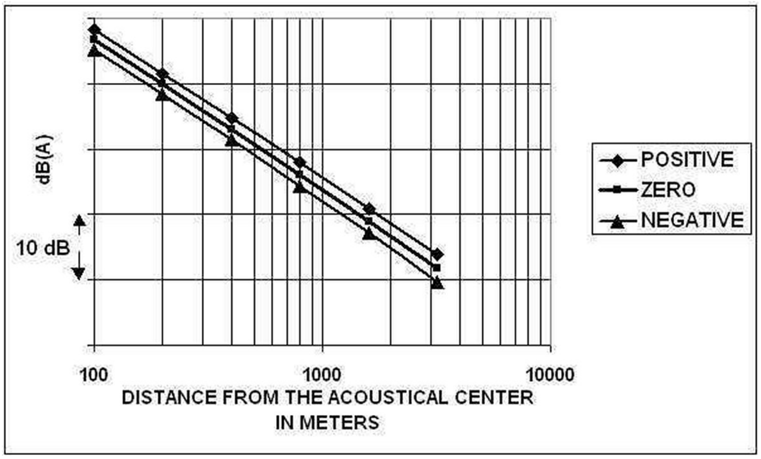

Figure 2: The 95% uncertainty, BAP, both positive and negative variations, for a typical large stationary power plant sound power spectrum, relative to the distance from the effective acoustical center of the power plant.

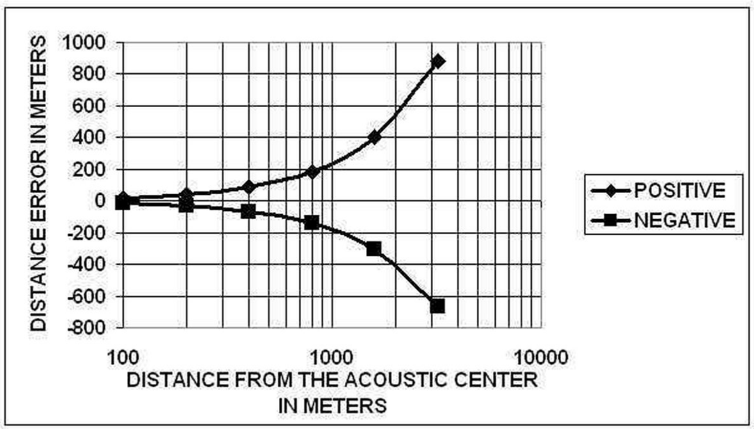

Figure 3: The 95% uncertainty, BAP, on the error of location of an A-weighted sound level isopleth in the far field, relative to the acoustical center of a large stationary power plant.

Figure 3 represents a significant error for the graphical depiction of sound level isopleths. Furthermore, this analysis represents the very best accuracy possible using perfect propagation models and perfect instruments. The BAP uncertainty was derived from the laboratory based optimally controlled tests on small individual sources. Real world sources and situations yield even larger levels of uncertainty due to any additional instrumentation uncertainty and measurement uncertainty.

4 - CONCLUSIONS

The uncertainty of estimating source sound power levels, and ultimately, sensitive receiver sound levels, will be larger than the BAP 95% uncertainty bands presented here. In addition, the uncertainty associated with calculating estimated sensitive receiver sound levels varies with the nature of the source spectrum and the distances involved, but in any case will be larger than the BAP 95% uncertainty bands presented here. Lastly, the uncertainty associated with attempting to present sound level isopleths, on area maps, is very significant. The common practice of depicting such contours using discrete lines is discouraged. Alternative formats for sound level isopleths, with appropriate discussions of the uncertainties involved, should be considered.

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