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Elements of Uncertainty in the Prediction and Measurement of Airborne Sound

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ABSTRACT

Acoustical and noise control engineering practitioners of all types regularly test and report on sound emissions and imissions with little or no regard to the uncertainties involved, or even how any such identified uncertainties are to be treated or combined collectively or even quantified. This paper is a synopsis of selected elements of acoustical uncertainty, intended to be a sobering reminder to all practitioners of our inability to precisely define source sound power, to accurately model either single or complex sources, or to precisely model the far field propagation of sound emissions. Further, several seldom considered aspects of uncertainty are addressed, such as a) the careless omission of the Confidence Interval being employed whenever uncertainty is addressed at all, b) the inevitable upward creep in sound level resulting from multiple source uncertainties and c) the often overwhelming influences of atmospheric and vegetation inhomogeneities. The proper methods for combining these several elements of uncertainty are reviewed, in terms of laboratory or field measurements or in the modeling of complex sources.

1 INTRODUCTION

Whether an acoustical professional is concerned with regulatory requirements for sound levels in communities[1,2], or the characterization of a particular sound source or assembly of sound sources[3,4], or evaluating compliance with sound emission guarantees [5,6], all such determinations invariably involve acoustical uncertainties. That is: uncertainties, plural. There are virtually no acoustical measurements or predictions that do not involve multiple elements of uncertainty. The reason for this is that, at some level, every step in every acoustical analytical process and every acoustical instrument employed is never perfectly accurate. For this reason, the words “accurate’ or “accuracy” are nowhere employed any further in this paper, nor should they ever be used in the context of any discussions of acoustical uncertainty. Instead, since all uncertainty involves a lack of precision, the words “precision” and “uncertainty” are to be used, and they are considered synonymous here.

Acoustical uncertainty encompasses all elements of imprecision, inaccuracy, test tolerances, instrument tolerances, modeling simplifications and variables both known and unknown. Uncertainty may be regarded as the degree to which a measured level differs from the true level, even though the true level is never known. In terms of computer modeling of predicted sound levels propagating to the far field, the uncertainty is the degree to which an analytically predicted level differs from the level which would be predicted if all input parameters were perfectly known and perfectly modeled.

The following discussion will highlight several sources of such uncertainties and will provide a reminder as to how the totality of those uncertain elements are analytically combined. No paper, and perhaps not even a textbook, can possibly treat all potential sources of acoustical uncertainty. The five distinct elements discussed in the following paragraphs are abbreviated from the universe of potential topics. Further, the specific subjects addressed are themselves only a part of each element. However, these partial considerations of select portions of potential uncertainty elements yields a sufficiently shocking magnitude of estimated uncertainty. The point is: uncertainties likely to be encountered in real life situations are always significant and therefore are never to be ignored.

2 INSTRUMENTATION UNCERTAINTY

There is certainly no mystery among acoustical professionals about the uncertainty inherent in the instrumentation [7,8]. Yet, in the experience of the authors, it seems to be very seldom, if ever, noted in any reports or papers or literature not directly related to the design of the equipment itself or the governing instrumentation standards. This may perhaps be excused as being of little relevance to the subject of most such analyses, reports or papers. Yet, we are concerned and feel a distinct need to call attention to the matter. Instrumentation uncertainty is doubly significant in the context of this paper because the elements of uncertainty are presented here in order, mimicking the analytical process from the determination of sound power level via sound pressure level measurements to the end point of measurements of sound pressure level in the field. Thus, the same instruments, with all their associated uncertainties, are used at both ends of this process, thereby doubling their impact on real world situations.

Figure 1 presents the prescribed standardized limits for the commonly used, and it is hoped the exclusively used, “standard” classes of sound pressure measuring instruments.

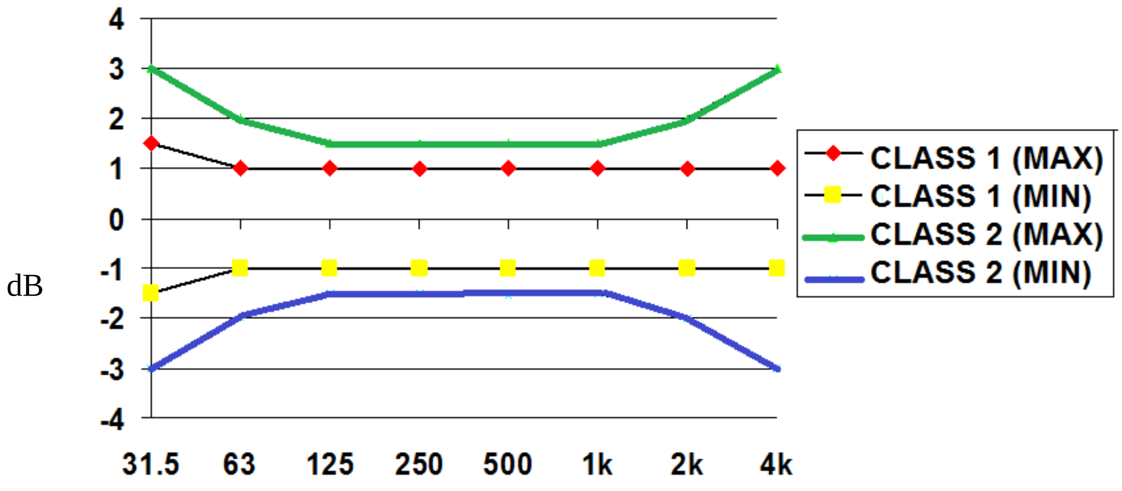


Figure 1: *The maximum and minimum permissible envelope of octave band sound level for Class 1 and Class 2 sound level meters.*

Clearly, experience suggests laboratory calibration testing typically yields a precision for most such instruments that falls well within the limits shown. Nevertheless, the conventional prescription describing, erroneously, the ‘accuracy’ of Class 1 sound level meters of ±1 dB is the best that can be said. Of course, there should never be instances where acoustical professionals employ anything other than certified and properly calibrated Class 1 or Class 2 instruments.

Figure 2 presents an example of an actual laboratory calibration test of a typical microphone used on a Class 1 sound level meter. Note that this is the microphone response only, and only at the single prescribed incidence angle. The response will usually be worse at other angles

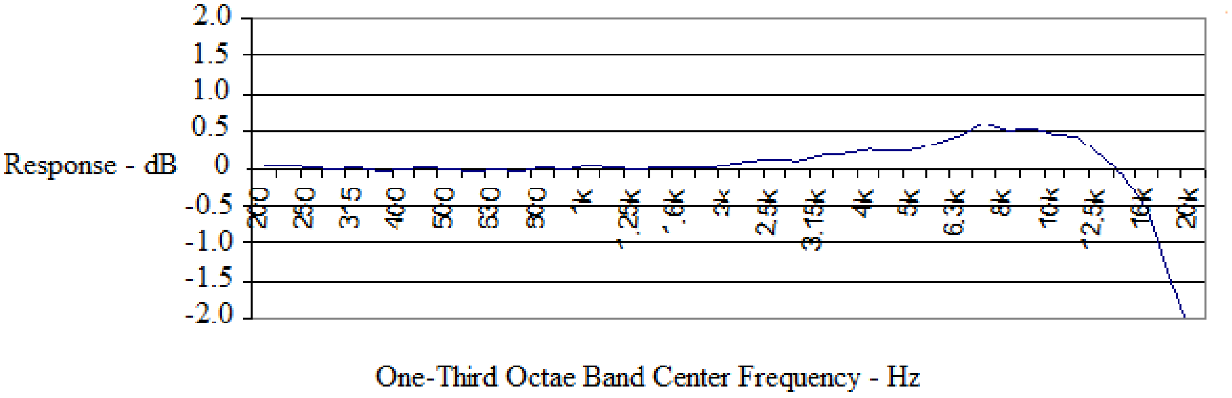
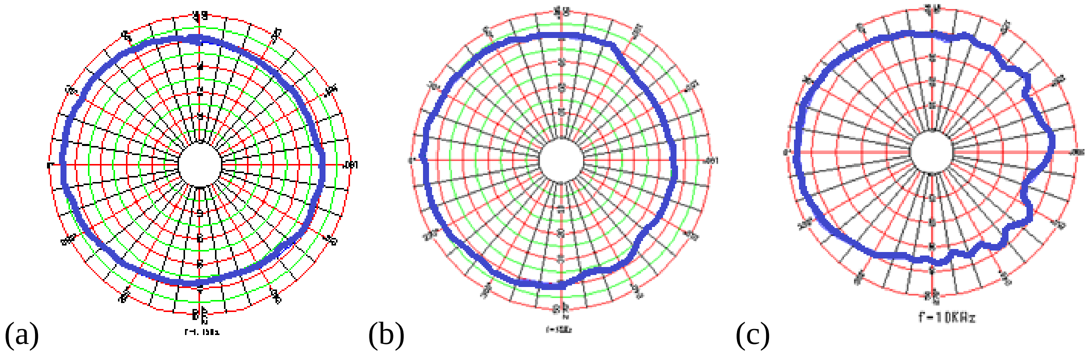


Figure 2*: Typical normal incidence microphone response calibration curve; laboratory certification testing.*

In Figure 3 are examples of actual laboratory calibration tests of a typical microphone used on a Class 1 sound level meter. The three directivity charts shown are for higher frequencies at 2.5kHz, 5 kHz and 10 kHz, where the directivity effect is relatively more pronounced.



(a) (b) (c)

Figure 3: *Laboratory test results showing directivity variations for a typical microphone to be used on a Class 1 sound level meter for the frequencies (a) 2.5 kHz (b) 5 kHz, and (c) 10 kHz. The arbitrary scale used in each of the above polar plots is 'zero dB' at the innermost circle, then 5 dB increments such that the outermost circle is 50 dB.*

In terms of measuring instruments then, there are permissible instrumentation uncertainties in the sound level meter itself of up to 1 dB in the mid frequencies, greater at the higher and lower octave bands, plus even larger uncertainties resulting from high frequency response of the microphones as well as pronounced high frequency directivity effects. As has been stated, sound level instrumentation is employed at what is referred to as both ends of the process envisioned here. Thus, when first calculating sound power from sound pressure level measurements and then measuring resultant sound levels in the field, the process brings into play all these uncertainties twice, so that a blanket assumption of ±1dB uncertainty for instrumentation is not at all excessive and may even be regarded as conservative in many cases. Further, a different sound level meter, each with its own uncertainties, might be used at each end of the measuring chain.

3 SOUND POWER UNCERTAINTY

Whenever an acoustical analysis makes use of a presumed source sound power level, users must recognize and appreciate that such sound power levels have been calculated based upon some form of sound pressure level tests. Naturally, the most reliable such tests will be those conducted in a controlled and accredited laboratory setting consisting of an anechoic or reverberant test space, employing standardized methodologies. Much less precise determinations of source sound power are made from field measurement of sound pressure level.

In order to determine the very best precision that can be expected in determining sound power levels of any source, a program was devised [9] to test several sound power sources in a statistically significant number of laboratory qualified reverberant rooms, using the same standardized test methodology. In this case, seven laboratories were used. Four sample sound sources were used in the ensemble of tests. Table 1 shows the result of this series of test in terms of the 95% confidence interval, in those octave bands for which a statistically significant result was obtained.

***Table 1**: The 95% Confidence Interval, in decibels, of four different sound sources tested in seven different qualified laboratories.*

Sound power level uncertainty, in decibels						
Precision: 95% Confidence Interval	Octave Band Center Frequency, Hz					
	125	250	500	1K	2K	4K
	2.4	1.0	1.0	1.2	1.2	1.0

Importantly, the results shown in Table 1 should be regarded as the very best uncertainty, at the 95% confidence interval, that can be expected from any sound power source calculation, regardless of how carefully controlled are the test conditions, the measurement methodology or test environment, and regardless of what are the requirements or level of precision of the test instrumentation. It should be assumed that every source sound power level used in any application, for whatever use in whatever model, will be less precise, that is more uncertain, than the octave band values shown in Table 1. Sound Power Levels can only ever be inferred and only imprecisely.

4 PROPAGATION UNCERTAINTY

Certainly, all acoustical professionals will appreciate that there are myriads of influences falling under the category of propagation uncertainty. Whether the discussion concerns the assumptions called for in computer modeling or the practical pitfalls encountered in performing field measurements, uncertainty abounds. For the purposes of this discussion we focus on only two such influences, firmly confident that these two results will sufficiently forewarn the acoustical professional of the magnitude of the potential errors.

The two topics of immediate interest are, first, the impact that the sound power uncertainty of Section 3 above will have on estimates of far field sound level and, second, attention is given to a little known disconnect in all predictive far field community noise modelling.

4.1 The Impact of Section 3, Table 1 Sound Power Uncertainty

Consider how the sound power level uncertainties tabulated in Table 1 of Section 3 translate to far field estimated sound levels for typical sound emission sources. In order to assess this impact for consideration in this review two assumptions were required.

First, the uncertainties of Table 1 were extended by a gross assumption to the 31.5 Hz, 63 Hz and 10KHz octave bands. Specifically, the value shown for 125 Hz was replicated for 31.5 Hz and 63 Hz., and the value for 4KHz was given to 8KHz. This is conservative in the sense that the trends at each end of the spectrum given in Table 1 seem to suggest that even larger uncertainties might have been valid.

Second, the full spectrum of uncertainties assumed were applied to a reasonably typical total plant far field sound pressure level spectrum. Begin with this assumed neutral spectrum and its associated A-weighted sound level as a function of distance from the acoustical source. We then estimate the resulting far field A-weighted sound level if each octave band's uncertainty in Table 1 (as extended) is first added, then subtracted, from the neutral spectrum. The result of this exercise yields curves shown in Figure 4.

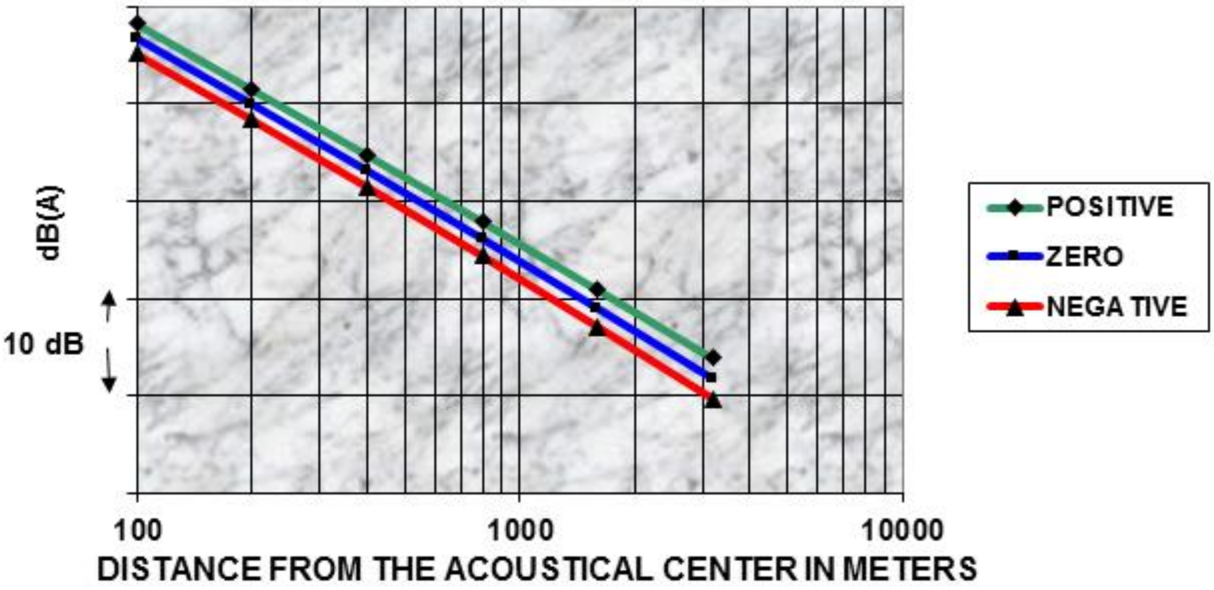


Figure 4: *A hypothetical far field A-weighted sound level propagation trend of a typical plant sound emissions spectrum, without excess attenuations considered, together with (a) the positive addition of the octave band uncertainties of Table 1, and (b) the negative, that is, the subtraction, of the octave band uncertainties of Table 1.*

The difference between the positive and the negative trends of Figure 4 represents the 95% confidence interval which might be expected in modeling far field plant sound level propagation, simplified by considering only the spherical inverse-square law attenuation. The magnitude of the difference, the 95% confidence interval, is approximately ±2dB at every position along this hypothetical trend, and it is not necessary to be more specific in order to demonstrate the point to be made here.

Normally, this ±2dB spread at any given distance might be noted and appreciated by an acoustical professional and at first blush would probably not appear alarming. However, at this point it is important to remind the reader that this level of uncertainty has been calculated using the values of Table 1 and for that reason is representative of the very best attainable laboratory precision in the estimation of source sound power levels. Therefore, every actual situation encountered in the real world will necessarily involve source sound power level uncertainties in such a model that are larger than is depicted by the negative-to-positive spread in Figure 4. Still, that is not the point here.

The point of this exercise[5] is not to look at the vertical differences in Figure 4 at any distance. Instead, consider the horizontal spread of the negative to positive curves of Figure 4and the difference in estimated distance indicated by the 95% confidence interval for a given A-weighted sound level. That effect is plotted in Figure 5.

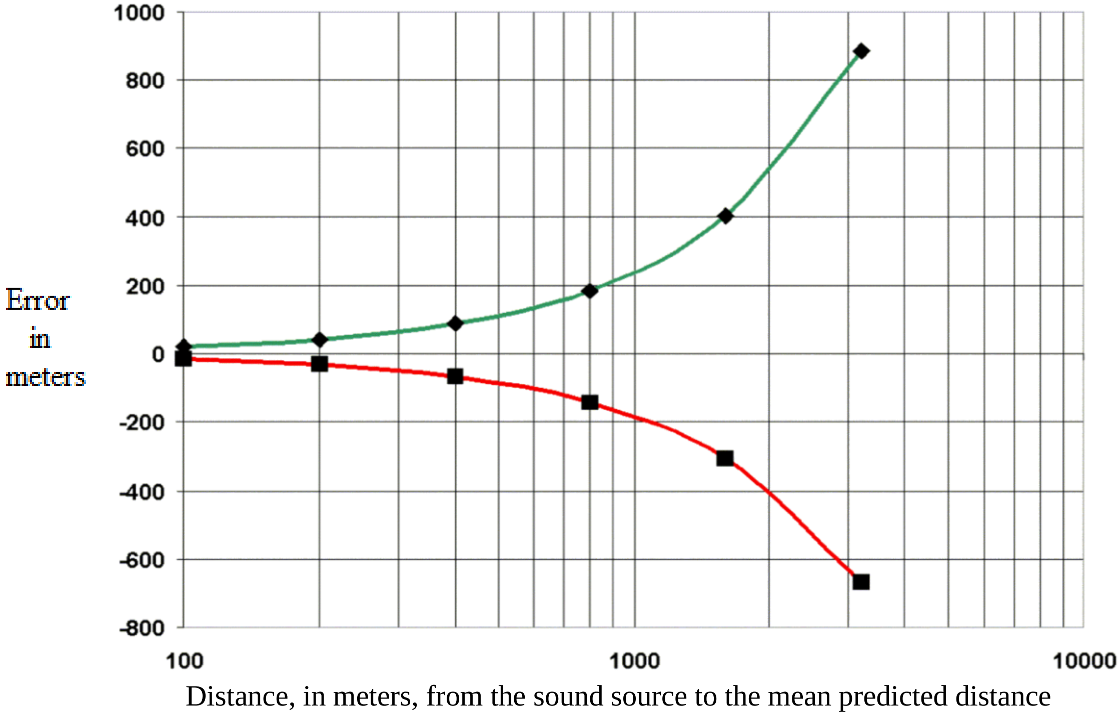


Figure 5*: The difference, at a given A-weighted sound level, in distance between the neutral, or zero, curve of Figure 4 and the positive or negative curve's distance at the same A-weighted sound level. The vertical axis is the distance from the zero curve of Figure 4 at which the comparison is made.*

For example, Figure 5 tells us that if one were to evaluate this hypothetical example, selecting the predicted A-weighted sound level at, say, 1 kilometer from the acoustical source center, the 95% confidence interval, in terms of distance, tells us that the actual A-weighted sound level might lie anywhere between 800 meters and 1250 meters from the acoustical source center. Once again, we are obliged to remind the reader that this level of uncertainty has been calculated using the values of Table 1 and for that reason is representative of the very best attainable precision in the estimation of source sound power levels, ever, anywhere! Therefore, every actual situation encountered in the real world will necessarily involve source sound power level uncertainties and associated distance estimation uncertainties that are larger than are depicted by the negative-to-positive spread in Figure 5. This should be sobering to all acoustical analysts constructing computer models and presenting calculated far field A-weighted sound level contours in any form.

4.2 Modeling L50 versus Measuring Leq

The authors feel obliged to address this item because to our knowledge it has never been either evaluated or discussed, except by Putnam and Hetzel [2] and again by Putnam and Haywood [5], but can be a significant source of uncertainty in far field acoustical compliance surveys. Consider that predictive computer modeling of far field sound levels requires special analytical techniques to estimate a statistical histogram of sound level imissions at some distant receiver. Otherwise the default predicted sound level, in whatever form, will be the L50 sound level. Then, when acoustical professionals are called upon to measure the actual far field sound levels of the operating systems, for either validation/verification or regulatory compliance, the measure of choice is almost universally the Leq sound level. Measuring Leq is always called for because real world situations always involve time-varying sound levels yielding a histogram. Only in rare occasions are compliance surveys constrained to report on the L50 sound levels as a compliance measure.

The modeling of L50 and the measuring of Leq presents a mathematical difference in sound level as a function of the standard deviation of the sampled histogram of sound levels, independent of the distance from the source or of the absolute sound levels.

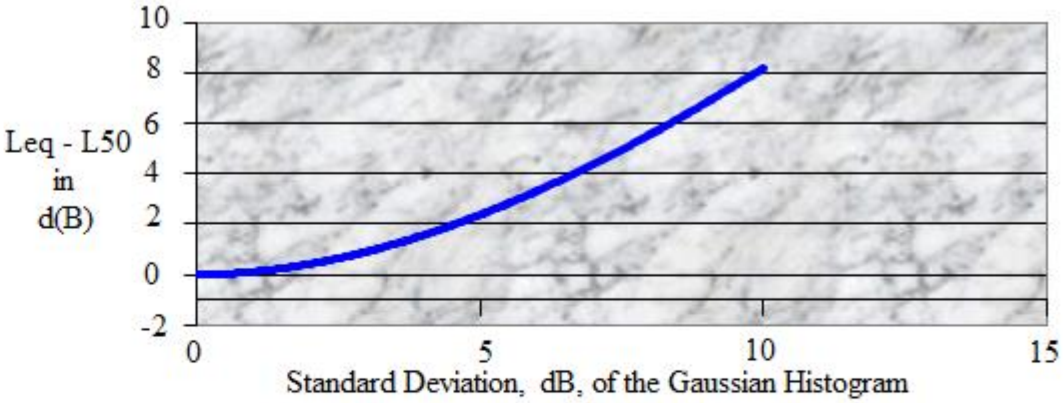


***Figure 6**: The difference between Leq and L50 for any histogram exhibiting a normal distribution of sound levels*

Figure 6 shows the difference in decibels between Leq and L_{50} as a function of the standard deviation of a normal, Gaussian, sound level histogram. This difference will always manifest in every sound level survey with normal distribution while for real-world non-normal distributions, the effect will at least be similar. This difference will manifest as a type of uncertainty in evaluating far field sound levels because even if everything else in the analysis and prediction of the far field sound levels is perfect – although it will never be perfect – there will be this additional uncertainty represented by the difference between what is predicted and what is measured, unless proper account is taken.

5 MODELING UNCERTAINTIES

The preceding discussion in Section 4 confined itself specifically to the effects on predicted far field sound levels due to the uncertainty inherent in source characterization. In this section we review a test case that exposes the variability in user assumptions in modeling far field sound level[10]. This could be considered a type of uncertainty in that any given model could, and probably will, yield a different result from another analyst's attempt to model the same situation. Perhaps this is a part of an adversarial situation in which common ground is hoped-for, but a discrepancy is revealed where neither party can fairly be considered more correct. In that case, the reality of an unknown uncertainty, and perhaps a whole class of unknown uncertainties, must be acknowledged.

The referenced ASTM round robin-proficiency test of 1999, previously reported, exposed such a surprising range of results the authors feel obliged to remind readers once again of the significance of these results and do not hesitate to classify the results generally as uncertainty.

In order to test the hypothesis that computer models using similar though slightly differing algorithms yield substantially similar results a simple test case was submitted to six volunteer analysts. Modeling real world situations requires the consideration of several variables, but the standardized methodologies should not, it was believed, yield anything more than minor discrepancies.

The test case consisted of a point source and a receiver both 1.5m above grade, 300m apart. An infinitely long barrier, 3 meters in height, was to be modeled at 10 meters from the source. Ambient conditions were prescribed as 65 F, 50% relative humidity with flat unobstructed moderately absorptive ground. No special wind or thermal gradients were to be assumed other than the nominal light downwind condition common to most models.

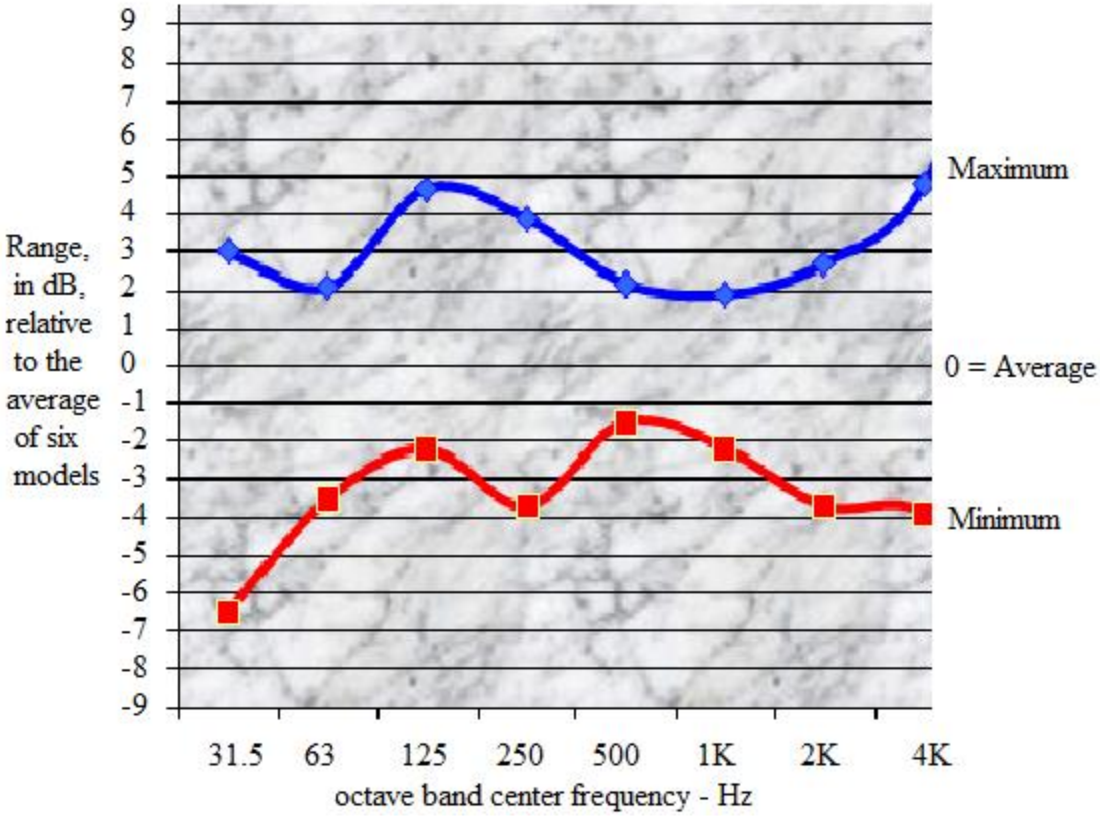


***Figure 7**: Envelope of results from the classic referenced ASTM round robin modeling exercise, showing the maximum and minimum of the six computer models for each octave band relative to the average of the six in that band*.

The results of the round robin modeling exercise are presented in Figure 7 and are hardly substantially similar. These differences should be regarding as a type of uncertainty in the same sense as any other source of error in sound level predictions. These results suggest that computer model uncertainties, but perhaps not the algorithms themselves, are as large, or larger, than any of the other elements considered here. That should be a sobering thought.

6 COMBINING UNCERTAINTIES

Having presented herein several potential sources of uncertainty in measuring and modeling, the question now becomes what to do with them all in order to assign some quantitative measure to the ensemble of whatever uncertainties can be identified.

6.1 Combining Uncertainties per ASME PTC 19.1

As indicated previously, the guiding principles for combining uncertainties are contained in ASME Performance Test Code 19.1 [11], which in turn is intended to conform to The ISO Guide to Uncertainty in Measurement [12].

The most thorough description of the ASME PTC 19.1 guidance applicable to acoustical testing is contained in ASME PTC 36 [13]. The constituents of uncertainty, as applied to acoustical measurements, are denoted Type A and Type B. The Type A components are all those elements of uncertainty evaluated using statistical methods on a series of repeated measurement, such as the 95% confidence interval of a measurement sample. The Type B components are all those other elements that lead to an imprecision in the determination of the apparent sound level. In order to evaluate the overall uncertainty of a given measurement, the known or estimated uncertainties are combined using the classic square-root-sum-of-squares method, as shown in Equation 1.

$$U_C = (U_A^2 + U_{B1}^2 + U_{B2}^2 + U_{B3}^2 + \ldots)^{1/2} \tag{1}$$

Where: U_C = combined uncertainty
U_A = Type A uncertainties
U_{Bn} = Type B uncertainties

To demonstrate by way of example, Table 2 presents some estimated uncertainties such as acoustical analyses might encounter, using approximate values for possible minimum, or best, uncertainty compared to possible maximum, or worst uncertainty, along with the resultant combined uncertainties for each case.

***Table 2**: Example estimated range of uncertainties and calculated combined uncertainty*

Element	Definition	Estimated uncertainty	Worst estimated uncertainty
U_A	Standard error of estimate	0.5 dB	1.5 dB
U_{B1}	Calibration error	0.2 dB	0.3 dB
U_{B2}	Instrumentation Train	0.2 dB	0.4 dB
U_{B3}	Microphone mounting uncertainty	0.3 dB	0.9 dB
U_{B4}	Uncertainty of distance from acoustic center	0.1 dB	0.2 dB
U_{B5}	Uncertainty of air impedance	0.1 dB	0.3 dB
U_{B6}	Uncertainty of source PWL	0.4 dB	0.9 dB
U_{B7}	Background noise influence	0.1 dB	0.8 dB
U_C	**Combined uncertainty**	**0.8 dB**	**2.2 dB**

It is important to note that, characteristic of any such square root sum of the squares (SRSS) combinatorial, the combined value will always be larger than the largest of the constituent values. Further, the combined uncertainty will always continue grow larger whenever the analyst continues to identify additional relevant elements of uncertainty.

6.2 The Exception to SRSS – Multiple Modeled Sources

The preceding discussion regarding the various components of measurement uncertainties in terms of ASME PTC 19.1, utilizing guidance of ISO Guide 98, instructs us to combine uncertainties via SRSS. This will be valid for all cases but one. Probst and Donner [14] have provided a rationale for the important exception to the SRSS rule. Their work was directed toward the uncertainty to be expected from a specific computer model's prediction of far field sound levels, and is not to be confused with the treatment in Section 5 above of the variations among identical models run using independent programs by unrelated analysts.

For the case of a complex sound source being modeled as a distinct set of separate sources, whenever the uncertainty of the estimated sound power levels for the various component sources can be assigned, a logarithmically weighted ensemble uncertainty may be calculated, and will take the form of a weighted root-mean-square (rms) expression as shown in Equation 2.

$$\sigma = \frac{\sqrt{\sum\left(\sigma_n \cdot 10^{0.1 \cdot L_n}\right)^2}}{\sum 10^{0.1 \cdot L_n}} \tag{2}$$

Where σ = One standard deviation of the ensemble
σ*n* = Standard deviation of the nth source
Ln = Sound Power Level of the nth source

The requirement for this expression to apply is merely that the sources themselves are incoherent and that the sound at the receiver from each of the sources be statistically uncorrelated. Note that the ensemble standard deviation is always less than the average of the standard deviations in this case and that in the event the uncertainty of every source is the same then Equation 2 reduces to Equation 3.

$$\sigma = \frac{\sigma'}{\sqrt{n}} \tag{3}$$

Thus, for a larger and larger number of contiguous incoherent modeled sound sources the standard deviation of the ensemble's uncertainty become progressively lower and lower. Conceptually, we regard this tendency as being due to the various individual uncertainties offsetting one another.

7 CONCLUDING COMMENTS

From among the vast number of potential sources of uncertainty in acoustical analyses, only a few selected sources of uncertainty have been treated here, yet even with this abbreviated list of influences being considered, significant levels of uncertainty have been identified.

Certified round robin testing of closely controlled calibrated sound sources has shown that sound power level itself may never be quantified within one or two decibels. And often, sound power of equipment is based on ideal testing methods, not as they are installed in the field.

Consideration of the measuring instruments given both standardized Class 1 or Class 2 precision and the effects of microphone directionality, not to mention wind screen attenuations, uncertainties are clearly in excess of 1 dB for most cases.

The realization that source sound power levels are never precisely known means that estimates of the far field distance at which a given sound level might occur will result in huge distance uncertainties; at distances of 1 km from a typical industrial source the errors are at least +25%, -20%. This magnitude of distance uncertainty is found even before consideration is given to the added uncertainty resulting from the common disconnect between predicted L50 and measured Leq sound levels.

Modeling uncertainties cannot unequivocally be identified but evidence of the surprising range of results using standardized models by different analysts should give all acoustical professionals pause.

The only saving grace identified in this review is the expectation that a large ensemble of modeled sound sources is expected to exhibit mutually offsetting uncertainties in most cases.

The totality of these reviewed uncertainties, especially since only a small portion of the potential field of uncertainties have been considered here, should be a warning to all acoustical professionals and analysts that your results are almost certainly more uncertain than anything discussed here. So, approach the work with care and humility.

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