Measurement Uncertainty Analysis Frequently Asked Questions

Integrated Sciences Group answers frequently asked questions relating to the calculation and analysis of measurement uncertainty. The answers are intended to provide clarification and dispel common misconceptions. If you have any questions or comments regarding any of our uncertainty analysis FAQ topics or would like us to answer additional questions, please contact us at tech@isgmax.com.

Question	**Answer**
What is measurement uncertainty?	All measurements are accompanied by error. Measurement uncertainty is a quantification of our lack of knowledge of the sign and magnitude of measurement error. The uncertainty in the value of a measurement error is the standard deviation of the measurement error distribution.
Why should I estimate measurement uncertainty?	Uncertainty estimates play an important role in making decisions, managing risk, developing tolerances, selecting measurement methods, developing capability statements, achieving laboratory accreditation, hypothesis testing, establishing calibration intervals and communicating technical variables.
How do I calculate measurement uncertainty?	The basic steps for measurement uncertainty calculation are outlined below. 1. Define the Measurement Process. The first step in any uncertainty analysis procedure is to identify the physical quantity whose value is estimated via measurement. For multivariate measurements, this also requires the development of an equation that defines the mathematical relationship between the quantity of interest and the measured quantities. 2. Identify the error sources. Measurement process errors are the basic elements of uncertainty analysis. Once these fundamental error sources have been identified, we can begin to develop uncertainty estimates. 3. Select the appropriate error distributions. Another important aspect of uncertainty analysis is the fact that measurement errors can be characterized by probability distributions. The distribution for a given measurement process error is a mathematical description that relates the frequency of occurrence of values with the values

	themselves. 4. Estimate process uncertainties. Uncertainty is defined as the standard deviation of the error distribution. There are two approaches to estimating the standard deviation of an error distribution. Type A estimates involve data sampling and analysis. Type B estimates use engineering knowledge or recollected experience of measurement processes. 5. Combine process uncertainties. In combining uncertainties, we must account for any correlations between measurement process errors or any cross-correlations between measurement components. For multivariate measurements, it is also important that the uncertainties are weighted or multiplied by the appropriate sensitivity coefficients. 6. Compute the effective degrees of freedom for the combined uncertainty. The degrees of freedom signify the amount of information or knowledge what went into an uncertainty estimate. The Welch-Satterthwaite formula (equation G.2b of the GUM) is commonly used to compute effective degrees of freedom.
Shouldn't uncertainty estimates be conservative?	No. Uncertainty estimates should be based on the best available information and on appropriate estimation methods. Conservative (i.e., intentionally inaccurate) uncertainty estimates can lead to erroneous decisions.
What is an uncertainty budget?	An uncertainty budget provides a concise, tabulated summary of key information about the sources of measurement error and the associated uncertainties that contribute to the combined uncertainty in the measurement result. The uncertainty budget should include a brief description of each error source, along with the appropriate error distribution, error containment limits and associated containment probability or confidence level. In our software and documentation, subject parameter is the quantity (or attribute) whose value we seek to determine through measurement.

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What information do I need to compute a Type A uncertainty estimate?	A sample of data containing repeat measurements of the quantity of interest. It is important that each repeat measurement is independent, representative and taken randomly. Type A uncertainty estimates typically use sampled values. However, the data may be comprised of sampled mean values or sampled cells.
What information do I need to compute a Type B uncertainty estimate?	A Type B uncertainty estimate is computed from what we know about the probability distribution for a given error source. This includes information about the error containment limits and containment probability.
Are error limits always stated as ± numbers?	No. Error limits may be asymmetrical or even single-sided.
Is it valid to assume that all errors follow the uniform (rectangular) distribution?	No. The uniform distribution applies only to a very small fraction of measurement errors. Chief among these are errors due to digital readout resolution and phases of detected electromagnetic signals. In general, you must consider which distribution is applicable for each error source. It is never a recommended practice to use a one-distribution-fits-all-errors approach.
Do all errors follow the normal distribution?	The normal distribution applies to a wide variety of cases. However, there are several notable exceptions. Among these are bias distributions for parameters with asymmetric specifications and distributions of randomly phased electromagnetic signals.
Is it acceptable to compute uncertainties using short-cuts and simplified methods, so long as everyone uses them?	No. An uncertainty estimate is not an entity into itself. The better the uncertainty estimate, the more valid the measurement-based decision or action will be. Uncertainty estimates obtained from overly simplified or "dumbed down" calculation methods often give results that can lead to erroneous decisions, regardless of agreement between users.
Can a simple algorithm be used to estimate uncertainties for all sources of error?	The uncertainty estimation algorithm must apply to the specific error source. As discussed above, the errors encountered in a given measurement process may not all be

	characterized by the same probability distribution. In some cases, iterative methods may be required to analyze the appropriate error distribution(s).
Are spreadsheet applications sufficient for estimating uncertainty?	In many cases, no. Developing and using a simplified spreadsheet or template can provide an unrealistic assessment of measurement uncertainty. Conversely, developing rigorous analysis spreadsheets requires considerable programming effort and technical expertise in the mathematical and statistical methods for estimating and combining measurement process uncertainties. This includes the evaluation of various error distributions and error correlations, and the calculation of sensitivity coefficients and degrees of freedom. When developing an uncertainty analysis within a spreadsheet application, it is difficult to ensure the integrity of equations and macros after the spreadsheet has been widely distributed. Spreadsheets developed with MS Excel are particularly vulnerable to macro viruses.
What information should I include when reporting an uncertainty estimate?	An uncertainty estimate must be reported in a way that can be readily understood and interpreted by others. At a minimum, the measured value, the combined standard uncertainty, its estimate type (A, B or A/B) and degrees of freedom should be reported, along with a reference to the associated uncertainty analysis procedural document. In some instances, confidence limits with an associated confidence level or an expanded uncertainty with associated coverage factor may also be reported.
How many digits should I use when reporting measured values and uncertainty estimates?	The number of decimal digits used in reporting measured values and uncertainty estimates should be informative, but not misleading. It is a recommended practice to base the decimal digits on the following factors: • The resolution of the measuring device. • The measurement units used. • The uncertainty units used. • The information that needs to be conveyed.

	For example, consider a dc voltage measurement made with a device with a range setting of 0 V to 10 V and a digital resolution of 1 mV. If a single measured value is obtained, then the measured value would be reported to three decimal digits (e.g., 5.001 V). An extra decimal digit may be justified when reporting an average value obtained from repeat measurements (e.g., 5.0014 V). In either case, the number of decimal digits used to report the corresponding uncertainty should adequately convey the estimated value (e.g., 0.0006 V, 0.6 mV or 600 µV). In instances where the estimated uncertainty is very small compared to the measured value, it may be beneficial to employ scientific notation (e.g., 6×10^{-4} V).
What should I include in my uncertainty analysis procedural document?	When reporting the results of an uncertainty analysis, Section 7 of the GUM recommends that the following information be included: • The estimated value of the quantity of interest (measurand) and the combined uncertainty and degrees of freedom. • The functional relationship between the quantity of interest and the measured components, along with the sensitivity coefficients. • The value of each measurement component and its combined uncertainty and degrees of freedom. • A list of the measurement process uncertainties and associated degrees of freedom for each component, along with a description of how they were estimated. • A list of applicable correlation coefficients, including any cross-correlations between component uncertainties. It is also a good practice to include a brief description of the measurement process, including the procedures and instrumentation used, as well as additional data, tables and plots that help clarify the analysis results. The analysis report should also provide sufficient calculation detail to allow others to reconstruct (recompute) the uncertainty

	estimates.
What is the difference between standard uncertainty and expanded uncertainty?	Standard uncertainty is synonymous with measurement uncertainty. Expanded uncertainty is a symmetric ± limit obtained by multiplying an uncertainty estimate by a specified coverage factor. **Note**: The term expanded uncertainty and uncertainty are often used interchangeably. This, of course, should be avoided because it can lead to incorrect inferences and miscommunications.
What is the difference between confidence limits and expanded uncertainty?	In reporting measurement results, the combined uncertainty and its degrees of freedom can be used to establish a numerical interval that contains the true value with some confidence or probability. Confidence limits are computed assuming that the uncertainty estimate is for a combined error that follows either the normal (infinite degrees of freedom) or Student's t distribution (finite degrees of freedom). Expanded uncertainties provide an approximate confidence limit, in which a coverage factor of k = 2 is used in place of the t-statistic. Expanded uncertainties are computed assuming a combined uncertainty estimate with infinite degrees of freedom for a combined error that is normally distributed.
What is the difference between the GUM and Monte Carlo uncertainty analysis methods?	Both methods require the identification and evaluation of error distributions for the measurement process being analyzed. Consequently, appropriate error distributions must be applied to achieve realistic results from either analysis method. The main difference between the GUM and Monte Carlo methods is the way that the uncertainty in the combined error is computed. The Monte Carlo method employs repeated computation of random or pseudo-random numbers to simulate and combine deviates for each error distribution. The combined uncertainty is the computed standard deviation of the combined error distribution. The GUM method employs mathematical and statistical

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	functions to compute and combine the variances of each error distribution. The combined uncertainty is computed by taking the square-root of the combined variance. Taylor Series approximation is employed for analyzing multivariate measurements. The GUM and Monte Carlo methods can accommodate correlated errors. However, applying the Monte Carlo method to cases were the correlation coefficient is not equal to +1 is a challenging endeavor.
What is uncertainty growth?	The increase in uncertainty over time. See calibration interval analysis FAQs for more details.
How do I control uncertainty growth?	Through periodic calibration of your measuring equipment. See calibration interval analysis FAQs for more details.