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Measure for Measure – Does Accuracy Matter to You?

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Accuracy in Measurement Results

Many decisions are based on accurate measurement results. Should medicine be prescribed for high cholesterol or high glucose? Should a measuring instrument or standard be adjusted to meet tolerances? Is there really global warming or climate change? Answers to these questions are all based on measurement results and as a patient, scientist, citizen, or policy maker, we make assumptions about the accuracy of measurement results we receive in reports and calibration certificates. We assume they are good, that is *right*, or more correctly *accurate*. Note that accuracy is often defined as *hitting the center of the target or a true value*. A colleague of the authors was noted to regularly say "the only true value is on a sign above a hardware store." However, measurement users often trust the accuracy of measurement results they receive, usually without question. Users of measurement results believe that the results are of good quality and are *good* and *right*.

However, a measurement result alone is incomplete without some assessment and measure of reported uncertainty associated with the result. People can estimate the temperature outside on a warm spring day within a few degrees based on their experience and scientists can estimate the temperature in a laboratory within a degree based on their experience working in environmentally controlled spaces. However, using a thermometer, we first hope that it is accurate and giving us the correct or right temperature, but then we must consider the resolution of the standard. Is the readability of the thermometer 1 °C, 0.1 °C, or 0.01 °C. Our confidence in the results, if they are right, will be dependent upon the readability or resolution of the standard or measuring instrument. Our confidence should not be based on the fact that a calculator or spreadsheet will give us a calculated value to 15 decimal places when the resolution or uncertainty is only to 1 or 2 decimal places!

Repeatability of the instrument or standard is also a variable of concern. How often do people naturally repeat measurements to get a sense of whether multiple values agree? Even simple measurements such as stepping on a scale to get an idea of one's weight (where we always hope the second or third reading will be lower), inserting a kitchen thermometer into the turkey to see if it has reach the desired temperature, or checking our mileage over time to calculate fuel efficiency for our vehicles, are all common in daily life.

In a calibration laboratory, the assignment of uncertainty to the measurement result is a rigorous, documented, and validated process that is assessed nearly as often as the measurement results themselves. Measurement scientists often use internationally accepted procedures to obtain standardized measurement results, and use the Guide to the *Expression of Uncertainty in Measurement*[1] as a guiding document on evaluating and reporting measurement results and their associated uncertainties.

The readability or resolution and repeatability of the measurement results give us a sense of confidence, or lack of confidence, and is a measure of the uncertainty associated with the measurement results. It is a wise practice to ask for the measurement uncertainty and use it as an assessment of the quality of a measurement result and its precision. Uncertainty values provide a measure of confidence in the measurement result; it provides a quantification of the boundaries or limits within which the measurement result should agree with a true quantity value.

Accuracy in Terminology and Communications

Once accurate measurement results and associated uncertainties are available, they need to be communicated. Communications may be in a newspaper, on television, in a scientific paper, or on a calibration certificate. Thus, accuracy in our words and measurement results is also critical. As in the case of measurement uncertainties, measurement scientists also have guiding documents to help standardize communications. In this case, the *International Vocabulary of Metrology* (VIM)[2] is used as the guiding document on terms used with measurement and calibration results. Uses of terms like accuracy, traceability, uncertainty, and reference standards all have very specific meaning to measurement professionals and should be used by all scientists.

For example, the VIM defines accuracy, as related to a measurement result, as:

2.13 (3.5)

measurement accuracy
accuracy of measurement
accuracy
closeness of agreement between a measured quantity value and a true quantity value of a measurand

NOTE 1 *The concept "measurement accuracy" is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.*

NOTE 2 T*he term "measurement accuracy" should not be used for measurement trueness and the term "measurement precision" should not be used for "measurement accuracy," which, however, is related to both these concepts.*

[1] Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008 GUM 1995 with minor corrections, available free at: http://www.bipm.org/en/publications/guides/gum.html, 2015-01-12.

[2] International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM 3rd edition) JCGM 200:2012 (JCGM 200:2008 with minor corrections), available for free: http://www.bipm.org/en/publications/guides/vim.html, 2015-01-12.

NOTE 3 *"Measurement accuracy" is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.*

According to the VIM, measurand is "the quantity intended to be measured." But, it becomes obvious that when comparing measurement results from one laboratory or between countries, scientists must be able to talk about the same thing. Thus, the use of standardized definitions is essential. As the reader can see, even the definition of accuracy requires explanatory notes! Use of standardized terminology can help avoid a *Tower of Babel Effect*[3] when communicating measurement results!

Accuracy in Presenting Units, Symbols, and Measurement Results

Finally, measurement results must be communicated with proper quantities, units, and symbols. In fact, many countries adopt the International System of Units (SI) as the reference basis for measurement results. Again, there is a standardized document for referencing and presenting measurement units, symbols, and results.[4] The U.S. Metric Program of the National Institute of Standards and Technology (NIST), Office of Weights and Measures (OWM), helps implement the national policy to establish the SI (International System of Units, commonly known as the metric system) as the preferred system of weights and measures for U.S. trade and commerce. It provides leadership and assistance on SI use and conversion to federal agencies, state and local governments, businesses, trade association, standards development organizations, educators, and the general public. Together NIST Special Publication (SP) 330, *The International System of Units (SI)*, and NIST SP 811,[5] *Guide for the Use of the International System of Units (SI)*, provide the legal interpretation of and guidelines for the use of the SI in the United States, as described in the Interpretation of the International System of Units (SI) for the United States. These publications provide standardized guidance on how measurement units and results should be presented in writing.

Black Dots

One of the authors is often quoted as saying "if we [measurement scientists] don't get communication of measurement results right, who will?" Regular review of measurement results and measurement uncertainties on calibration certificates and in laboratory documents yield numerous errors that can negatively impact the interpretation of the results by a user. Examples are often observed where measurement uncertainties are not included, are incomplete, or are inaccurate, incorrect terminology is used, typographical errors are left uncorrected, results are presented without appropriate significant digits, unit conversions are made inaccurately, and incorrect units and symbols are presented or correct units are inconsistently used. The authors refer to these errors in communications as *black dots*. That is, a black dot on a clear page is what is noticed and is obvious by the reader or customer. These types of

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[3] In the Bible, a city (now thought to be Babylon) in Shinar where God confounded a presumptuous attempt to build a tower into heaven by *confusing the language of its builders into many mutually incomprehensible languages*. (http://www.thefreedictionary.com/Babel+effect, 2015-01-12.)

[4] SI Brochure: The International System of Units (SI) [8th edition, 2006; updated in 2014], available for free: http://www.bipm.org/en/publications/si-brochure/, 2015-01-12.

[5] The International System of Units (SI), NIST SP 330, Edition: 2008. Guide for the Use of International System of Units (SI), NIST SP 811, Edition: 2008. Available for free: http://www.nist.gov/pml/wmd/metric/metric-pubs.cfm, 2015-01-12.

blemishes will be what are remembered, despite the presence of other accurate information that's presented. Errors in reporting results can lead to confusion or bad decisions by the user, often with critical impacts. Black dots destroy credibility of the provider of the measurement results.

Examples of common black dots, as ripped from the headlines or as readily observed in daily life, include[6]:

- Failure to include leading zeroes when presenting measurement results so that a child is given a 5 mL dosage instead of a 0.5 mL dosage leading to death;

- Failure to effectively communicate requirements and convert measurement units when using two measurement systems lead to the loss of the NASA Mars Climate Orbiter;

- The 2003 Disneyland Tokyo Space Mountain roller coaster accident highlights a scenario where axle and bearing design specifications were converted to metric units and implemented in an amusement ride. After the design change took place, time passed and routine maintenance called for the replaced bearings. However, instead of being replaced with the updated design (metric) bearings, they were replaced with the incorrect size based on the original (non-metric) design. Use of the wrong size bearing created a gap between the axle and bearing. Over time, extra vibration and stress cause the axle to fail and the roller coaster to derail. Luckily, no passengers were injured during the ride![7]

- Recently, a measurement calculation mistake was discovered in a laminate wood flooring study conducted by the U.S. Centers for Disease Control and Prevention (CDC). The federal agency issued a correction notice to a report about the quantity of formaldehyde in the product revealing that, as result of not converting from feet to meters, an incorrect value for ceiling height caused CDC scientists to significantly underestimate the health risks in the original study report.[8,9]

- The NIST Office of Weights and Measures (OWM) conducted a labeling assessment of over 1100 packages, including products food, home and personal care products, hobby and arts and crafts products, automotive, hardware, office products, and pet supplies and observed that some inappropriate unit symbols were in use within the net quantity of contents statements.[10] OWM

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[6] U.S. Metric Association, Unit Mixups (2016-02-26) http://www.us-metric.org/unit-mixups/

[7] U.C. Davis, ChemWiki, Case Studies: Metric/English Conversion Errors (2016-02-26) http://chemwiki.ucdavis.edu/Core/Analytical_Chemistry/Quantifying_Nature/Case_Studies%3A_Metric%2F%2FEnglish_Conversion_Errors#Disneyland_Tokyo:_A_Bumpy_Blunder

[8] CDC Fixes Major Error in Flooring Risk Report: Not Converting to Metric, Retraction Watch (2016-02-24) http://retractionwatch.com/2016/02/22/cdc-fixes-major-error-in-flooring-risk-report-not-converting-to-metric/

[9] CDC Revises Health Risk Assessment of Flooring After Math Error, Vocativ (2016-02-24) http://www.vocativ.com/news/289002/cdc-laminate-cancer/

[10] NIST OWM Marketplace Assessment - Metric Labeling on Packages in Retail Stores (December 2009) http://www.nist.gov/pml/wmd/metric/upload/Marketplace-Assessment-Metric-Labeling-Retail-Stores-Dec2009.pdf

offers packaging and labeling training opportunities to help packers and retailers become more familiar with state and federal labeling requirements.

Document control is also important within both laboratory and a wide variety of operational environments. Version control and archiving records are essential tools to ensure changes made over time are effectively communicated to all personnel impacted by a change. Failure to maintain adequate control of laboratory documents, for example calibration certificate templates, can be the root cause for black dots that are released to customers.

One goal of ensuring quality when communicating accurate measurement results should always be to avoid black dots! Quality communications of measurement results require a rigorous review of all communications for use of accurate terminology, completeness, and use of appropriate measurement units and symbols in addition to editorial reviews for typographical and grammatical errors. The use of the publications noted in this article will guide the user to standardized resources for improving the quality, accuracy, and communication of measurement results.

Avoid the Black Dot: Know Where to Get the Answers

Knowing where to find the answers to common technical questions can be invaluable. Many questions arise when writing laboratory documents, clarifying measurement results, and implementing measurement system best practices. The proper use of measurement units and symbols in laboratory documents, such as calibration reports, control charts, uncertainty tables, and standard operating procedures (SOP) is critical to effectively communicating technical information both internally between laboratory personnel and externally with customers.

Congress has assigned the responsibility to interpret or modify the SI (International System of Units) for use in the United States to the Secretary of Commerce. This responsibility has been delegated by the Secretary to NIST. To accomplish this mission, NIST provides a number of SI resources and information to support science, technology, trade, and commerce.

NIST Special Publication (SP) 811, *Guide for the Use of the International System of Units (SI)*, provides[11] detailed rules for SI writing style, including a useful Editorial Checklist at the beginning of the document.

Figure 1. NIST SP 330 and SP 811 – Key technical SI resources.

Together NIST Special Publication (SP) 330, International System of Units (SI), and SP 811 provide the legal interpretation of and guidelines for the use of the SI in the United States. NIST also serves as the U.S.

[11] NIST SP 811, Guide for the Use of the International System of Units (SI), (2016-02-24), http://www.nist.gov/pml/pubs/sp811/indexfull.cfm

technical representative to the International Bureau of Weights and Measures (BIPM) that defines the SI. These publications are used to guide the measurement unit style in technical and documentary standards.

SP 811 is written for technical professional audiences, including engineers, scientists, and academics. Appendix B provides rounding guidance as well as Unit Conversion Factors for a broad set of measurement units. NIST has produced several other similar technical guides for a diverse group of audiences, including LC 1137, *Metric Style Guide for the News Media*, which provides condensed SI content to highlight commonly used measurement information.[12] A convenient hub of SI style guidance is available on the NIST Metric Program's "Writing with Metric Units" website.[13]

Use a Leading Zero. It's appropriate to use what's known as a leading zero before the decimal marker to ensure the quantity is appropriately interpreted and avoid the consequences of a misplaced decimal point. For numbers less than one, a zero is written before the decimal marker. [14] Without a leading zero, a value like .25 might be visually misinterpreted as 25, an error of 100 times greater magnitude. For example, if the quantity represented a pharmaceutical medication dose, it's highly likely that harm or a worse health effect would result from the error.

Avoid Unit Conversions Errors. A fundamental benefit of SI use is a reduction of errors due to measurement conversions between U.S. customary units and the SI. Eliminating conversions altogether can negate the need to document which conversion factors are being used and their source. Conversion calculations require rigorous software validation, which is an expensive and time consuming process. At best, the price of conversion calculation errors can be expensive. At worst, consequences can be a matter of life and death.

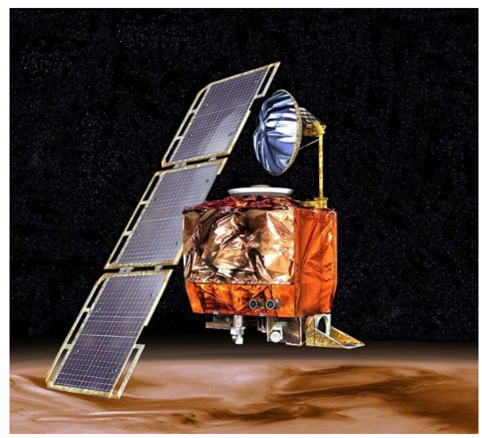

Figure 2. NASA Mars Obiter.

The crash of the $125 million NASA Mars Climate Orbital spacecraft in 1999 was a wake-up call for potential errors related to working with multiple measurement systems. The mishap occurred when the spacecraft entered the Mars atmosphere on a trajectory that was too low.[15] NASA later determined that the root cause of the erroneous trajectory and velocity calculations were due to the contractor failing to use SI units of force (Newton, N), as specified by NASA, within the coding of a ground software file used in trajectory models. One corrective action recommended by NASA was a

[12] NIST LC 1137, Metric Style Guide for the News Media (2016-02-26)

[13] NIST Metric Program, Writing with Metric Units (2016-02-24) http://www.nist.gov/pml/wmd/metric/writing-metric.cfm

[14] NIST SP 811, Guide for the Use of the International System of Units (SI), Section 10.5.2 (2016-02-24), http://www.nist.gov/pml/pubs/sp811/indexfull.cfm

[15] CNN, Metric Mishap Caused Loss of NASA Orbiter (2016-02-26) http://www.cnn.com/TECH/space/9909/30/mars.metric.02/

software audit to evaluate specification compliance on all data transferred between NASA and the contractor.[16]

Several helpful conversion factor resources have been made available on the NIST Metric Program's "Unit Conversion" website.[17] Caution is recommended to those developing unit conversion software or using an online calculator for technical purposes. It's important to conduct a rigorous validation and verification analysis before implementing unit conversion software.

Spelling and Pronunciation. Spelling and pronunciation of measurement units can also be challenging topics in practice. One of the advantages of the SI over the many other historic and customary measurement unit systems is that although unit names and prefixes may be spelled differently in different languages, the SI provides a coherent set of internationally accepted unit symbols that can be used to communicate across all languages. For example, the names of the units themselves vary in spelling and pronunciation according to national practices.[18]

	Unit Symbol		
Language	**m**	**s**	**kg**
English (U.S)	meter	second	kilogram
Spanish	metro	segundo	kilogramo
Italian	metro	secondo	chilogrammo

In NIST SP 811, the spelling of English words is made in accordance with the U.S. *Government Printing Office Style Manual*, which follows Webster's Third New International Dictionary rather than the *Oxford Dictionary*. The spellings "meter," "liter," and "deka" are used rather than "metre," "litre," and "deca" as in the original BIPM English text of the SI Brochure.

The *BIPM SI Brochure* is the definitive international reference on the SI and is published by the International Bureau of Weights and Measures (BIPM).[19] The text is published in French language (official version), followed by the English language text. Neither the French or English text provide pronunciation guidance. The SI Brochure content is widely translated into many other languages, which may also explain why pronunciation isn't specifically addressed. Interestingly, the *International Vocabulary of Metrology* (VIM) doesn't address pronunciation.[20]

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[16] National Aeronautics and Space Administration (NASA), Mars Climate Orbiter Mishap Investigation Board Phase I Report, November 10, 1999.

[17] NIST Metric Program, Unit Conversion (2016-02-24) http://www.nist.gov/pml/wmd/metric/unit-conversion.cfm

[18] Metric Methods, SI Crosses All Language Barriers (2016-02-26) http://metricmethods.com/Multilingual_SI_unit_names.gif

[19] Bureau International des Poids et Mesures/ International Bureau of Weights and Measures, SI Brochure (2016-02-26), http://www.bipm.org/en/publications/si-brochure/

[20] VIM3: International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (2016-02-26) http://www.bipm.org/en/publications/guides/vim.html

Capitalization of Units, Symbols, and Prefixes. The names of all units start with a lower case letter except at the beginning of the sentence or title, for example: pascal, becquerel, newton, tesla. In the example for degree Celsius (symbol °C), the unit "degree" is lower case but the modifier "Celsius" is capitalized because it is the name of a person. A space is left between the numerical value and unit symbol and values are not hyphenated (20 °C and 10 kg are correct; 20°C, 20° C, 10-kg or 10kg are not correct). If the unit name is spelled out during use, then normal grammar rules are applied.

Unit symbols are written in lower case letters (e.g., m for meter, s for second, kg for kilogram). However, symbols for units derived from the name of a person are capitalized (W for watt, V for volt, Pa for pascal, K for kelvin, etc.). The recommended symbol for the liter in the United States is also capitalized as L to avoid misinterpreting l (lowercase L) with the numeral 1. The period punctuation mark should not be used following a unit symbol (or abbreviation). For example, gram is represented "g" not "g." (g period). Symbols of prefixes that mean a million or more are capitalized and those less than a million are lower case. For example, M for mega (millions), m for milli (thousandths).

U.S. Customary Units. Since the development of the SI, many of the style requirements have been applied to non-SI measurement systems, including U.S. Customary units (e.g., inch, feet, yard, mile, ounce, pound, fluid ounce, gill, gallon). Although NIST does not publish a style resource for U.S. Customary units, NIST Handbook (HB) 44, *Specifications, Tolerance, and Other Technical Requirements for Weighing and Measuring Devices*, Appendix C. General Tables of Units of Measurement is a good resource for U.S. Customary units used in trade and commerce, their relationships, and unit conversion factors.

Because of the importance of the SI (metric system) as an international standard, its use in product design, manufacturing, marketing, and labeling is essential for U.S. industry's success in the global marketplace. The NIST Metric Program encourages the use of the SI in all facets of education, including honing of worker skills. The successful voluntary transition of the United States to the SI is a critical factor in the competitive economic success of industry. Questions regarding metric system (SI) use, style, or related publications can be directed to TheSI@nist.gov.

Accuracy in the use of terminology, measurement results, and measurement units is critical for avoiding the embarrassment of having others find black dots in your scientific communications. Numerous resources are available to help you avoid being responsible for inaccuracies reported on calibration certificate and the next problematic news headline regarding the inaccurate use of measurement units.