Overview of Uncertainty Analyses for Gauge Block Calibration

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Gauge blocks continue to be essential reference artifacts in manufacturing because of their simple geometry, but also because they can provide very high accuracy for a reasonable cost. The calibration technique of optical interferometry can directly link gauge block central length to the distance light travels in vacuum in 1/299792458 of a second, the definition of the International System of Units (SI) of length, the metre [1]. Gauge blocks calibrated by interferometry are then used in turn as reference standards to calibrate gauge blocks by mechanical comparison techniques, subsequently propagating the definition of the metre along the chain of calibrations, each with a specified measurement uncertainty. Even though these two calibrations involve the same artifact, dominant components in the evaluations of measurement uncertainty for these two techniques are fundamentally different. This is due to the fact that the method of calibration for interferometry involves measuring light waves in air and absolute gauge block temperature, whereas mechanical comparison involves tactile probing and the important temperature measurement is actually the temperature difference between reference standard and client gauge blocks. Detailed measurement uncertainty evaluations in accordance with the ISO Guide to the Expression of Uncertainty in Measurement (GUM) [2] for calibration of gauge blocks by techniques of interferometry and mechanical comparison can be found in the literature (see below). Some of the dominant components of these uncertainty budgets are highlighted for discussion.

Uncertainty Evaluations for Gauge Block Calibration – Some Good Examples: Gauge block calibration is one of the mainstay's of many calibration and measurement labs; moreover the geometrical simplicity of gauge blocks makes them an ideal subject for instructive documentation on uncertainty evaluation. Therefore there are several interpretations of gauge block measurement uncertainty evaluations in the literature. A general uncertainty evaluation should be applied thoughtfully to an individual measurement set-up, carefully making sure the components of the budget correctly represent the particularities of the individual measurement.

Hariharan [3] gives a brief but accurate description of what an interferometer is and how the method of exact fractions for gauge block length measurement by optical interferometry works. Several versions of uncertainty budgets for gauge block calibration by interferometry are published in the literature [4, 5, 6, 7], each corresponding to slightly different optical set-ups and routine practices (see below for mention of contributions for refractive index of air).

For gauge block calibration by dual probe mechanical comparison, an uncertainty budget for reference and client gauge blocks made of the same material can be found in the GUM [8], the summary table from which can also be found in the NIST reference on uncertainty evaluation [9]. Decker and Pekelsky [10] provides detailed worked example along this same formalism, including detailed consideration of the higher-order uncertainty contributions. In this model the higher-order components manifest almost all the thermal contributions. The different versions of uncertainty budgets differ in the way that the model equation is manipulated before the GUM guidelines are applied. In the example of ISO/TS 14253-2:1999(E) *Guide to the estimation of uncertainty in GPS measurement in calibration of measuring equipment and in product verification* [11] which outlines the Procedure for Uncertainty of Measurement Management (PUMA) the equations describing thermal contributions are completely general, all contributions are treated in first order (drift testing is helpful for this as described below) and equations describing the correlation contributions are provided. Yet another model describing an averaging or substitution-method model equation is adopted in [12]. Another detailed example employing a very similar model equation can be found (for free) in the European co-operation for Accreditation publication, which also gives some useful insight on measurement uncertainty evaluation [13].

A word about the PUMA method: it applies GUM guidelines in a series of iterations where a very conservative analysis is the starting point. Based on whether or not the resulting total expanded uncertainty is satisfactory for the application, each component in the uncertainty budget is then re-visited to see if more information or measurements would yield an uncertainty that is desired. The premise is that it is acceptable if the uncertainty is greatly overestimated, so long as it's value meets requirements. This method of analysis is convenient in applications where uncertainty evaluations are required primarily for quality documentation obligations. However, in applying this procedure one should already have a feeling as to the dominant uncertainty contributions to the measurement. As a note of caution – sometimes experimental evidence uncovers components that unexpectedly turn out to be large.

Preparing a measurement uncertainty evaluation has the potential for being a thorough learning tool. For example, the relative importance of measurement influences become immediately apparent. A straightforward application of GUM shows immediately where improvements to the calibration set-up would have the most value. For example, in our experience, uncertainties associated with the measurement of air pressure made surprisingly large contributions through evaluation of the refractive index of air by empirical equations. It was large enough to be a significant contributor to the overall gauge block uncertainty budget, but was easily remedied by purchasing and calibrating a new, more accurate, pressure sensor. Refractive index of air is one of the largest corrections to any length measurement made by interferometric methods, and therefore the uncertainty contributions are also very important since they can dominate the uncertainty budget. Ideas on how the measurement of air temperature, air pressure and relative humidity influences the application of empirical equations or refractometer methods can be found in the discussion of this topic in the literature [14, 15, 16, 17] (and references therein). A couple of articles of particular relevance for shop-floor or Cal-lab applications are [18, 19].

Uncertainties associated with end effects vs. length-dependent influences can make the same uncertainty evaluation look completely different simply depending on the nominal length of the gauge block. End effects dominate the uncertainty of short gauge blocks (interferometry: fringe fraction measurement, wringing, phase change on reflection, optical wavefront errors, gauge block geometry; mechanical comparison: reference gauge calibration, measured length difference, correction for elastic deformation between reference and client gauge), whereas the length dependent influences dominate the uncertainty of long gauge blocks (interferometry: obliquity, temperature, refractive index of air; mechanical comparison: temperature). For example, refractometer techniques offer a lower uncertainty alternative for long gauge block lengths (125 mm to 1 m nominal length), whereas for gauge blocks shorter than about 100 mm the end effect components dominate the total uncertainty budget and installing a refractometer in the set-up would not offer very much advantage. Similarly, gauges with almost-zero value of thermal expansion coefficient will change the relative size of components in the uncertainty budget, which means that they can be a useful diagnostic tool.

Measurement uncertainty evaluation for mechanical comparison where reference and client gauge blocks are dissimilar materials can be dominated by the first order temperature contributions which now become very large. Moreover, the uncertainty contribution for elastic deformation correction [20, 21, 22] can also make a significant contribution. A detailed treatment of measurement uncertainty for dissimilar materials can be found in [23, 24]. Further detailed considerations regarding uncertainty evaluation for corrections of elastic deformation or thermal environment have been proposed for the next updated version of the standard ASME B89.1.2 *Calibration of Gage Blocks by Contact Comparison Methods.*

Phase Stepping or Phase Shifting Applications: Phase step techniques are becoming increasingly popular in many length- and/or form-analysing instruments. The output of these interferometer instruments is a phase map of the optical wavefront, or the interferometer image field of view. The measurand for length applications is usually a phase difference between different areas of the image, which is often converted to a fractional order of an interference fringe for further analysis by the method of exact fractions. These instruments offer the advantageous potential for very precise measurement of interference fringes, however the disadvantage is that the systematic component of measurement uncertainty associated with the phase readings can be dependent on the actual phase value measured. In most commercial instrumentation the errors that contribute to these systematic components such as phase shifter errors, or camera nonlinearities, have been characterized and minimized by the instrument manufacturer. However for confidence in claims of better than 0.01 fringe measurement uncertainty these errors should be characterized experimentally. These considerations have been discussed in [25], along with correlation between phase measurements from two parts of the same image that used for refractivity and length evaluation, respectively. It turns out that these correlations can be small if the systematic components are also small, but that they are length dependent, reflecting the length-dependent influence of the refractive index of air (larger error in the phase measurement has larger impact on evaluated refractivity). Also of concern for precision instrumentation applying phase stepping analysis is the accurate and repeatable location of the reference point on a gauge in an image, and the assignment of an associated uncertainty to the length measurement. For high-precision applications such errors can be significantly large and the uncertainties associated with these measurements are best evaluated experimentally [26].

Measuring a length difference relative to a reference can have smaller uncertainty than measuring a similar absolute length. In measuring the length difference between two similar gauge blocks when the thermal influences are well controlled, the difference measurement adds only a small component to the uncertainty of the reference standard (for the same gauge block materials). Thermal influences are discussed in detail in the ISO/TR 16015:2003(E) *Systematic errors and contributions to measurement uncertainty of length measurement due to thermal influences* standard [27]. This document describes techniques for carrying out and analyzing results from empirical drift testing to result in realistic length-equivalent corrections and estimations of measurement uncertainty. The drift test technique integrates all influences and therefore the mathematical modeling and analysis need not be so sophisticated in order to completely capture all measurement influences. Given the unique high-precision and digital image processing characteristics offered by phase step interferometry techniques, differential measurement of gauge blocks by optical interferometry is being considered as a method to further reduce uncertainty in gauge block calibration.

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