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ABSTRACT

An important characterization for surface topography instruments is a traceable calibration of the height scale. We calibrate our coherence scanning interference microscopes using a natural spectral emission line in place of a sequence of material measures such as step-height specimens. The uncertainty budget for our approach includes estimates for several error sources associated with long term drift. Here we summarize results collected over 3 years' experience from our laboratories to provide statistical support for confirming and refining these uncertainty contributions. We find that the source wavelength stability is < 0.005% RMS and the stability of the height scaling factor (the amplification coefficient) is < 0.02% RMS over 900 days. Both values are better than our original estimates. We also show < 0.13% RMS reproducibility of the complete traceable process using acceptance test data for over 100 manufactured instruments. Finally, we report results of 3 years of experience in certifying step-height specimens using the traceable wavelength method.

Keywords: Metrology, measurement uncertainty, calibration, standardization, specification, interferometry

1. INTRODUCTION

A critical component for interpretation of surface height measurements is the calibration of the height scale of the surface topography instrument[1, 2]. The height scale is referred to in the ISO 25178 standards documents as the amplification coefficient for the "*z*" axis of the instrument, and the instrument height response is comprised of both the amplification coefficient and the nonlinearity, as illustrated in Figure 1[3]. Calibration of the amplification coefficient is most often followed by adjusting the instrument so that the reported topography data are scaled according to standardized units.

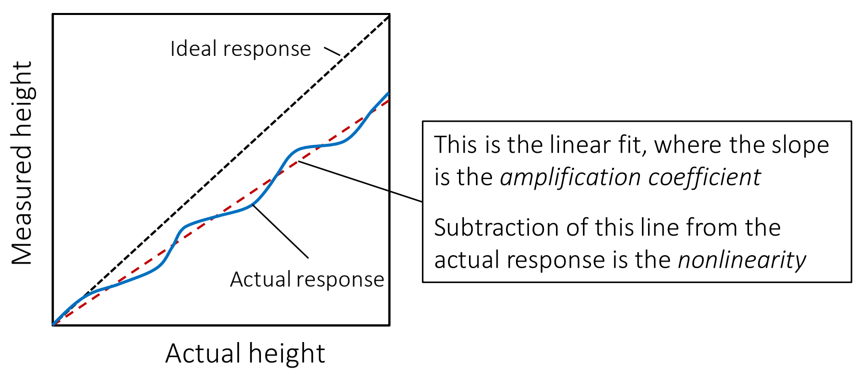

Figure 1: Height response of an instrument designed for determining surface heights.

Important features that instill confidence in a height scale calibration include *traceability* to the SI unit of length (the meter), reproducibility over time, and low uncertainty. An appropriate metrological terminus for a traceable calibration of the amplification coefficient can be a competent laboratory using a certified step-height specimen[4], or alternatively, a reference to a natural constant[1, 5]. In our labs, we calibrate our coherence scanning interferometry (CSI) microscope systems by first comparing a spectral emission line to the spectrally-filtered illumination wavelength of the instrument, and then by performing an interferometric measurement to determine an overall scaling factor for surface height measurements[6, 7].

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The uncertainty budget for our approach at the time of the original development included contributions based on best estimates for several error sources associated with long term drift. Here we summarize results collected over 3 years' experience with the method to evaluate the uncertainty budget based on long-term measurements of wavelength and piezoelectric-actuated scanner stability. We also include data from verification testing for over 100 manufactured instruments, as well as results collected from our step-height certification services. These results demonstrate the reliability, convenience and low uncertainty of the wavelength method when compared to traditional calibration techniques.

2. REVIEW OF THE WAVELENGTH METHOD AND ITS TRACEABILITY CHAIN

Figure 2 is a simplified diagram of a CSI microscope and the associated hardware for calibration of the amplification coefficient[6]. In CSI, surface topography height values are linked to the meter by the velocity of the scanning mechanism, which in our instruments is controlled by an integrated capacitance gauge feedback sensor[8]. The calibration task therefore is to determine the mean scanning velocity using a traceable technique.

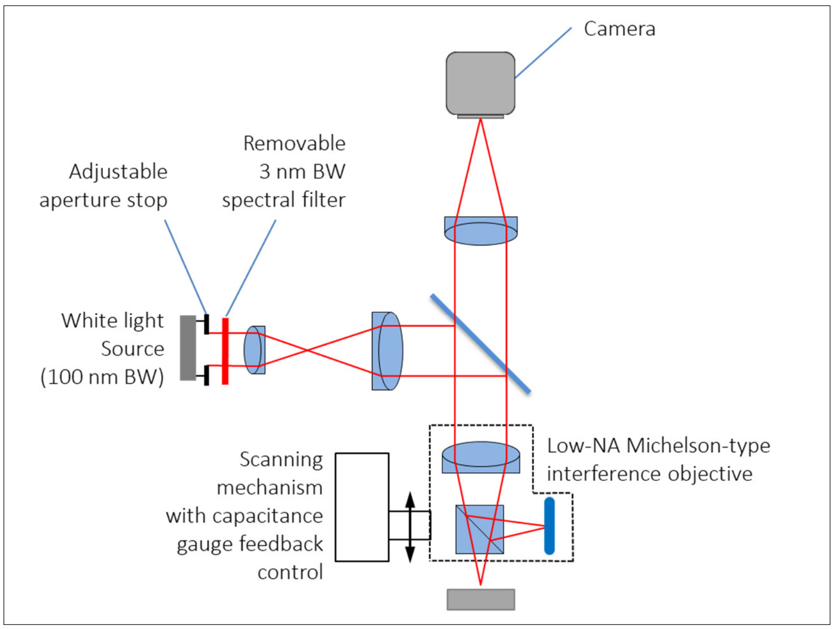

Figure 2: System layout of a Zygo coherence scanning interference microscope configured with a narrowband spectral filter and a low numerical aperture to calibrate the scanning mechanism as a transfer standard for traceable calibration of the amplification coefficient.

The wavelength calibration method uses a spectral emission line (the 546.074 nm ^{198}Hg line) of a mercury argon (HgAr) pencil lamp to independently realize the meter[9, 10]. The emission line provides a point of reference for a spectrometer, which then measures the central wavelength of a 3 nm bandwidth (BW) filtered illumination for the microscope. Using the same filtered illumination, the CSI microscope then collects interference data from a flat specimen during a continuous axial motion of an interference objective. The scan rate follows from a Fourier analysis of the interference fringe spacing, and a scale factor is then assigned to all future measurements based on this calibration. Figure 3 summarizes the complete traceability chain for the method[6].

The wavelength method offers several advantages when compared to traditional methods of calibration using a sequence of step-height specimens. Once the microscope illuminator has been calibrated, the wavelength-based process of resetting the correction factor for the scan rate involves only rescanning a smooth, flat surface. This is especially useful for high-performance instruments that require frequent calibration and adjustment of the scanner, as is needed for example for systems that rely on overlapping images to measure complex aspheres[11]. The wavelength method also relieves users of maintaining multiple sizes of certified step-height specimens, which can be difficult to find with certified values having with an uncertainties comparable to that of the wavelength method.

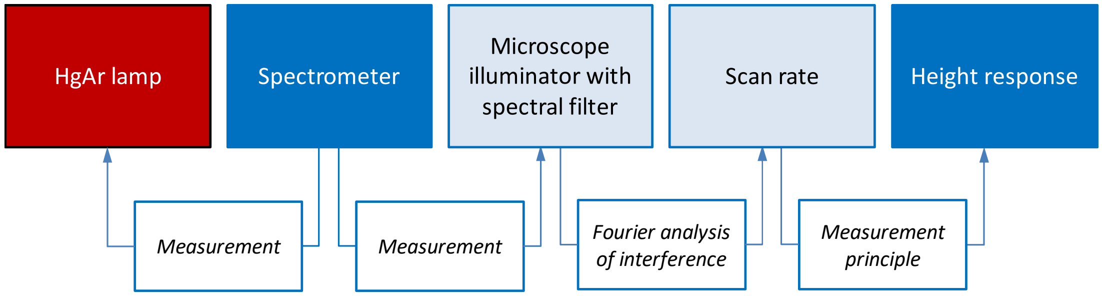

Figure 3: Traceability chain for calibration of the height response amplification coefficient of a CSI microscope using the wavelength method.

3. UNCERTAINTY CONTRIBUTIONS

Table 1 summarized the estimated k=1 uncertainties of the primary contributors, based on a more detailed analysis of multiple influence factors. The combined results in a total k=1 uncertainty estimate of < 0.05%. The major contributions to the total uncertainty include uncertainty of the wavelength produced by the 3 nm BW filter and illumination chain, the geometry of the measurement, errors in the scanning mechanism, and noise during data acquisition or data processing. With the benefit of 3-years of use of the wavelength method, we can now evaluate the long-term drift contributions experimentally (i.e. transition those terms from Type B to Type A evaluations)[12].

Table 1: Summary table of estimated k=1 contributions to the uncertainty of the wavelength method of height scale calibration, for which the expanded k=2 uncertainty is 0.1%. Contributions such as wavelength and scan error incorporate long-term effects that were originally estimated, but now can be verified experimentally.

Total:	0.046%
Contribution	**Uncertainty**
Illumination center wavelength	0.026%
Optical geometry	0.024%
Scan error	0.024%
Measurement and data processing	0.015%

Given that the wavelength of the filtered light source is the keystone of the method, it is important to know if the wavelength is stable over time. The 3 nm BW filter is integrated into our Nexview™ NX2 product and can be re-introduced at any time for calibration of the scanner velocity. In our certification lab, we have 3 years of intermittent results for the measured center wavelength with respect to the HgAr emission line. Figure 4 shows that the wavelength remains more repeatable and stable than originally predicted by the uncertainty budget of Table 1. The allowed k=1 uncertainty of the wavelength due to contributions such as measurement details and items in the optical path was 0.025%, and the RMS stability of measurements is much better at < 0.005%. If the final k=2 uncertainty goal is 0.1%, it is not necessary to use a HeNe laser or any other primary wavelength standard as an embedded source in the instrument; it is sufficient to calibrate the filtered light source.

Another important uncertainty contribution is the stability of the scanner calibration over time. In effect, we rely on the long-term consistency in the capacitance gauge sensor integrated into the scanning mechanism as a transfer standard for the calibration, and encourage our users to rely on the factory or field-service calibration for months at a time. Again using data from our Nexview™ interference microscope, we evaluated the long-term drift in the measurement of a 14.5 µm type groove-type step-height specimen previously certified to 2.5 nm at the National Physical Laboratory in the UK. Figure 5 shows the measurement stability over time, without making any adjustments to the instrument. The RMS stability of the capacitance gauge sensor for the scan rate is < 0.02%, while the specified uncertainty for this measurement is 0.3%. This indicates that the embedded capacitance gauge sensor in the piezo scanner is a reliable transfer standard for traceable calibration of the amplification coefficient, even over a time span of years. These results also demonstrate that for step heights of this size, the linearity of the scan is not an important contributor to measurement uncertainty for this instrument.

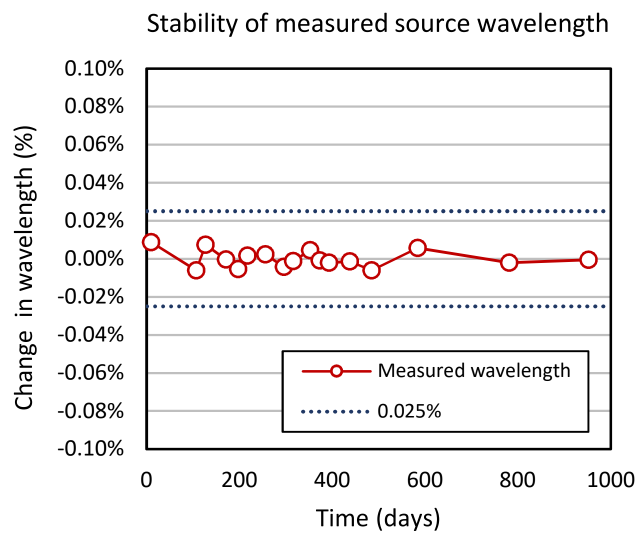

Figure 4: Measured mean wavelength of the spectrally-filtered microscope source illumination. The average value is 550.618 nm and the RMS stability is 0.005% over 960 days.

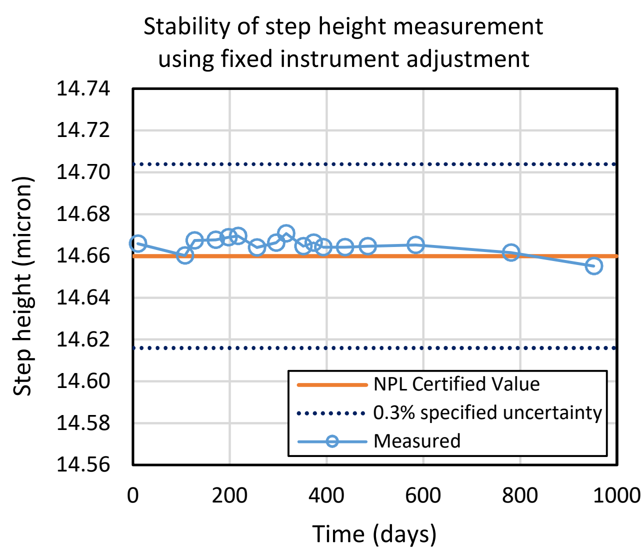

Figure 5: Measured height value for a certified step-height specimen, using a fixed adjustment value for the instrument over 960 days. The RMS stability is 0.04% without recalibration.

4. REPRODUCIBILITY OF CALIBRATION ACROSS INSTRUMENTS

We calibrate our interference microscopes during the manufacturing process using the wavelength method. The full traceable calibration is performed for each CSI microscope, and the calibration is verified during acceptance testing by measuring a step-height specimen calibrated by our certification lab. Figure 6 and Figure 7 illustrate the reproducibility of the complete traceable process in manufacturing over 130 instruments is 0.12% for 1.8 µm step-height specimens and 0.06% for 24 µm step-height specimens, respectively. We expect that the higher variability we see for the smaller step-height size is caused by factors that do not scale with step height such as topography error, residual flatness, or air turbulence. This supports the case for using step sizes larger than 10 µm for verification testing when verifying the calibration for scanners for CSI microscopes.

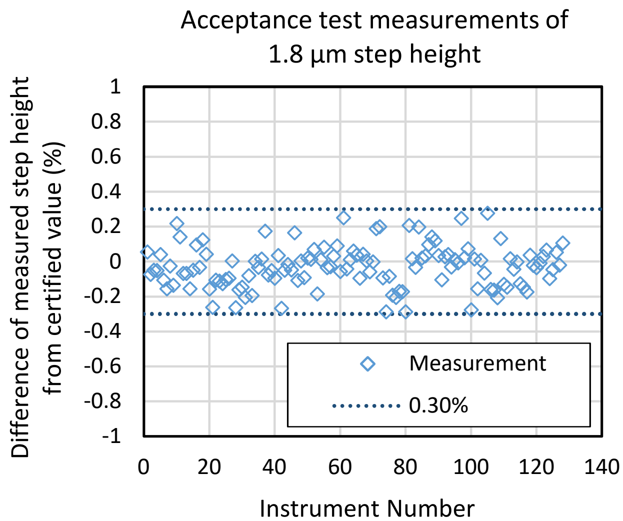

Figure 6: Measurements of 1.8 µm step-height specimens on 130 interference microscopes, each one of which was independently calibrated using the wavelength method prior to acceptance testing in manufacturing. The relative standard deviation is 0.12% RMS.

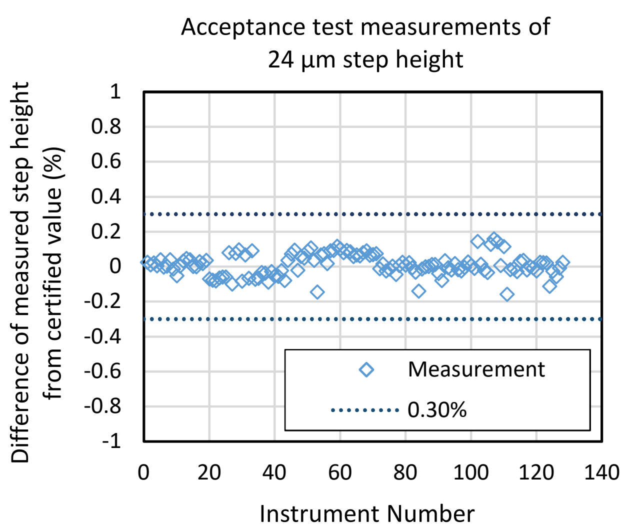

Figure 7: Measurements of 24 µm step-height specimens on 130 interference microscopes, each one of which was independently calibrated using the wavelength method prior to acceptance testing in manufacturing. The relative standard deviation is 0.06% RMS.

5. RESULTS FROM STEP-HEIGHT SPECIMEN CERTIFICATIONS

The wavelength method is used in our certification lab as part of an ISO-17025-compliant certification service for step-height specimens. This includes the step-height specimens used in our manufacturing facilities to verify initial calibration of newly built microscopes, as well as those used by our field service team to verify maintained calibration of microscopes at customer sites. The nominal step height sizes used for these purposes are 1.8 µm and 24 µm.

Our certification lab annually re-certifies the step-height specimens which are then used in the field to verify calibration of our CSI microscopes. Table 2 shows the three-year recertification history on five of each type of step-height specimen. The data shows that, with a calibrated microscope, a 1.8 µm step-height specimen can be measured reproducibly to 0.002 µm, and a 24 µm step-height specimen can be measured reproducibly to 0.013 µm.

Table 2: Summary of annual recertification values for two types of step-height specimens, showing the reproducibility of the complete calibration process over 3 years.

1.8 µm steps						**24 µm steps**					
Sample	Date	Measured (µm)	avg (µm)	stdv (µm)	stdv (%)	Sample	Date	Measured (µm)	avg (µm)	stdv (µm)	stdv (%)
	8/23/2016	1.8025					8/23/2016	24.0229			
1	8/16/2017	1.8018	1.8035	**0.0024**	**0.131%**	6	8/16/2017	24.0163	24.0270	**0.0133**	**0.055%**
	8/8/2018	1.8062					8/8/2018	24.0419			
	8/23/2016	1.7991					8/23/2016	24.0404			
2	8/16/2017	1.7991	1.8003	**0.0021**	**0.115%**	7	8/16/2017	24.0384	24.0474	**0.0138**	**0.058%**
	8/8/2018	1.8027					8/8/2018	24.0633			
	10/20/2016	1.8145					10/20/2016	24.0957			
3	10/6/2017	1.8177	1.8159	**0.0016**	**0.090%**	8	10/6/2017	24.0964	24.0876	**0.0146**	**0.061%**
	10/30/2018	1.8155					10/16/2018	24.0708			
	10/21/2016	1.7876					10/21/2016	23.7331			
4	10/6/2017	1.7916	1.7899	**0.0021**	**0.115%**	9	10/6/2017	23.7388	23.7307	**0.0096**	**0.040%**
	9/25/2018	1.7905					9/25/2018	23.7201			
	10/21/2016	1.7970					10/21/2016	24.1584			
5	10/6/2017	1.7993	1.7991	**0.0020**	**0.109%**	10	10/6/2017	24.1797	24.1641	**0.0136**	**0.056%**
	9/25/2018	1.8009					9/25/2018	24.1543			
	Average Reproducibility			**0.0020**	**0.112%**		**Average Reproducibility**			**0.0130**	**0.054%**

6. SUMMARY

In previous publications, we have proposed a traceable calibration of the height scale for surface topography instruments using a natural spectral emission line. The method has several benefits, including convenience, separation of linearity from the amplification coefficient, traceability directly to the meter without relying on external laboratory certifications, and improved uncertainty values when compared to calibrating using common commercial step-height specimens.

The present work establishes the reliability and reproducibility of the calibration method over long time periods. Data from our manufacturing and certification activities experimentally confirm and refine values for contributions to our uncertainty budget. We find that the source wavelength stability is < 0.005% RMS and the stability of the height scaling factor (the amplification coefficient) is < 0.02% RMS over 900 days, which both show improvement over their original estimates. We also examine test data from over 100 manufactured instruments, showing < 0.13% RMS reproducibility of the complete traceable process. Finally, we report 3 years of reproducibility from certifying individual step-height specimens.

An area that merits further study is the sensitivity of the wavelength method to environmental effects such as temperature and humidity. The results to-date reflect performance in laboratory environments with modest temperature controls and vibrations characteristic of a quality control lab, as opposed to the shop floor near manufacturing equipment. A logical next step is to investigate how a more production-oriented environment might influence *in situ* calibration and its long-term stability.

7. ACKNOWLEDGEMENTS

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