Calibration of the amplification coefficient in interference microscopy by means of a wavelength standard

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ABSTRACT

We propose an *in situ* method for establishing the amplification coefficient (height scale) for an interference microscope as an alternative to the traditional step height standard technique for routine calibration. The method begins by determining the properties of the microscope illuminator equipped with a narrow-band spectral filter, using a spectrometer to provide traceability to the 546.074nm [198]Hg line. A data acquisition with the interference microscope links this wavelength standard to a calibration of the properties of the optical path length scanning mechanism of the interferometer. A capacitance sensor in the scanner maintains this calibration for subsequent measurements. A targeted k=1 uncertainty of 0.1% is favorable when compared to calibration using physical artifacts, and the calibration procedure is easier to perform and less sensitive to operator error.

Keywords: coherence scanning interferometry, interference microscopy, calibration, standardization

1. INTRODUCTION

Fundamental to the interpretation of surface height measurements is the amplification coefficient, defined as the slope of the linear fit to the output of a measuring instrument over a range of heights [1, 2]. In a laser Fizeau interferometer, for example, the measured phase θ is scaled to surface heights h as follows:

$$h = \theta\,\lambda/4\pi \, . \qquad\qquad (1)$$

Proper scaling in this case requires knowledge of the emission wavelength λ. For a red helium-neon laser based system, even without stabilization, the relative uncertainty in wavelength is 0.0003%. This level of accuracy is fully sufficient for even the most demanding applications in surface topography measurement [3].

In interference microscopy, the common practice is to calibrate the amplification coefficient by means of a material measure in the form of a physical artifact, most often a step height standard (SHS) such as chrome-coated etched glass, instead of relying on a laser emission wavelength [4, 5]. The specified expanded uncertainty of certification of a commercial SHS is typically on the order of 0.6%, to which we add the uncertainty associated with the nonlinearity in the height response, differences in software, and operator variability. This level of uncertainty is a disappointment when compared to the high accuracy of laser interferometers.

The reluctance to calibrate an interference microscope using a known wavelength is related in part to the history of these instruments. Optical 3D microscopes are often non-contact alternatives to mechanical stylus profilers, and the custom of calibrating stylus systems with physical artifact such as an SHS is well established [6]. There is also a widespread but mistaken belief that *traceability* requires a certification linked to a national metrology institute (NMI), as in "NIST traceable;" whereas what is actually required is an unbroken chain of measurements to a realization of the meter, with known uncertainty for each link in the chain [7].

Added to this historical precedence in using SHS artifacts are reasonable technical considerations, such as the broadband spectrum of microscope light sources, which are usually not lasers, and the complexities of the optical geometry of the instrument, especially at high numerical aperture (NA) [8]. Further, the measurement principle is often quite different from that of laser interferometers: In coherence scanning interferometry (CSI), currently the most widely used method of interference microscopy, a scan of the optical path difference (OPD) generates the data for surface height measurement [2, 9]. The scan rate defines the amplification coefficient, as opposed to a direct scaling to the wavelength of light [10].

The present work reconsiders the question of calibration of CSI microscopes and proposes a technique based on a known emission wavelength to realize the meter independent of an NMI. The proposed method uses the interferometer itself to link the instrument height response to a wavelength standard. The technique has the potential to be both more convenient and more accurate than a calibration based on physical SHS artifacts.

2. CALIBRATION WITH A STEP HEIGHT STANDARD

We begin with a review of the traditional approach to setting up a CSI microscope using physical artifacts. What we commonly call *calibration* of the amplification coefficient for this type of instrument is the determination of the scan rate by measurement of an SHS transfer artifact. Figure 1 illustrates the traceability train: The upper row of boxes are the subsystems or system parameters that carry the scaling information, while the lower row of boxes in Figure 1 are the links in the chain. Starting from the left in the figure, an NMI certifies a master artifact using a stylus profiler instrumented with laser displacement gages [11]. The realization of the meter follows from knowledge of the laser wavelength. A vendor then distributes secondary SHS artifacts certified as traceable to the NMI master. A specialized step height measurement or series of measurements on multiple SHS samples establishes the scan rate of the CSI system, to an uncertainty that depends on the skill of operator and the uncertainty in the SHS certification. Once the scan rate is known, a defensible assumption is that the scan will repeat at a consistent rate of speed, usually by equipping the scanning mechanism with a feedback mechanism that is both stable over time and with changes in mechanical loading.
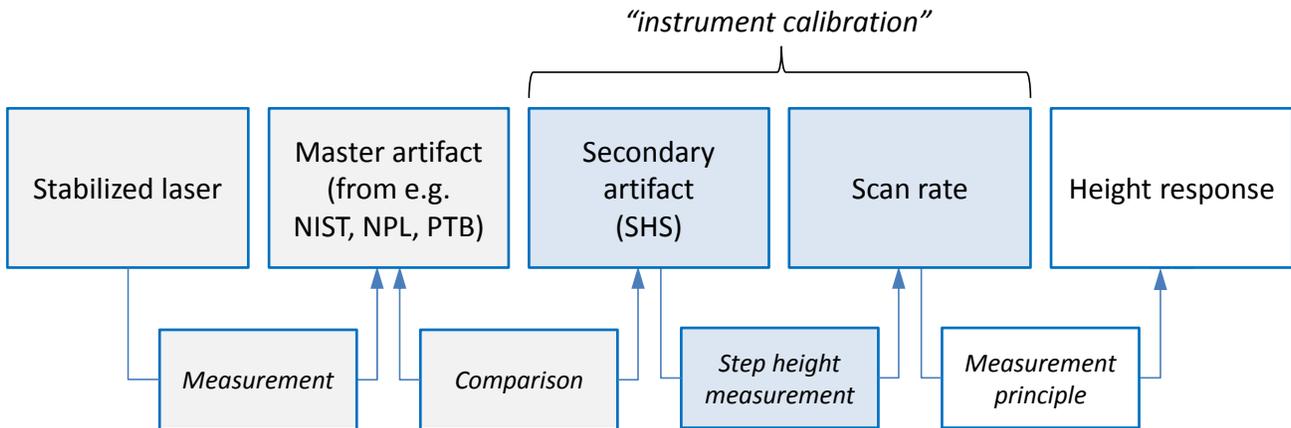

Figure 1: Traceability chain for calibration of the height response amplification coefficient of a CSI microscope using an SHS as a secondary or transfer artifact.

The use of an SHS artifact has a number of advantages. The method allows for the calibration of many different types of instruments, from confocal microscopes to mechanical stylus profilers, with a common calibration procedure. This simplifies comparisons and standardization. The method also instills confidence, since the physical SHS, which you can hold in your hand, is clearly stable on the scale of the stated uncertainty almost indefinitely. The SHS calibration method is also closely linked to the end purpose of the instrument, which after all, is to measure surface heights. These are several of the reasons why good-practice guides today recommend a physical SHS for establishing the amplification coefficient in interference microscopes [12].

There are, however, significant disadvantages. Correct use of the SHS requires some skill. The typical achieved uncertainty is significantly worse than for other types of interferometers, especially after including differences in the way that the measurement software may interpret the 3D map of the SHS surface, imperfections in the planarity or flatness of the SHS surfaces, and variability associated with part setup and alignment. Perhaps most importantly, the widespread use of just one SHS value, often just a few microns in height, conflates the amplification coefficient and the linearity of the height response. This last problem can be overcome by the use of multiple step heights or by repeated measurements of a single step height over a range of offset positions, but at the cost of time and complexity [13]. The end result is that in practice, the SHS calibration is infrequent or inconsistent with the expectations of the procedure.

3. PRIOR WORK IN CALIBRATION USING INTERFEROMETRY

Researchers and instrument manufacturers have at times proposed equipping the instrument with an entirely separate, laser-based displacement measuring interferometer to continuously monitor the OPD scan motion and improve upon the traditional SHS approach [14]. The concept dates back at least to Ikonen et al. [15], and has appeared in several configurations [16, 17]. Limitations of this approach include the Abbe offset between the laser interferometer and the measurement path, cosine error, and the need for additional hardware.

An attractive possibility is to use the signal from the interference microscope itself—after all, it is an interferometer and it would make sense to calibrate using nearly the same configuration as for the final measurement. Zhang *et al.* [18] and Kiyono et al. [19] propose a tilted-fringe method to calibrate for linearity, but fall back to a separate DMI in the sample stage to determine the amplification coefficient. Laubscher et al. describe a calibration method involving a diffraction grating to select a specific wavelength, but the method involves a substantial and impractical hardware change for routine measurements [20]. Kim et al. propose Fourier analysis of spectrally-broadband CSI signals; but the concept involves a pre-calibration using a SHS artifact as the ultimate link to a traceable standard [21].
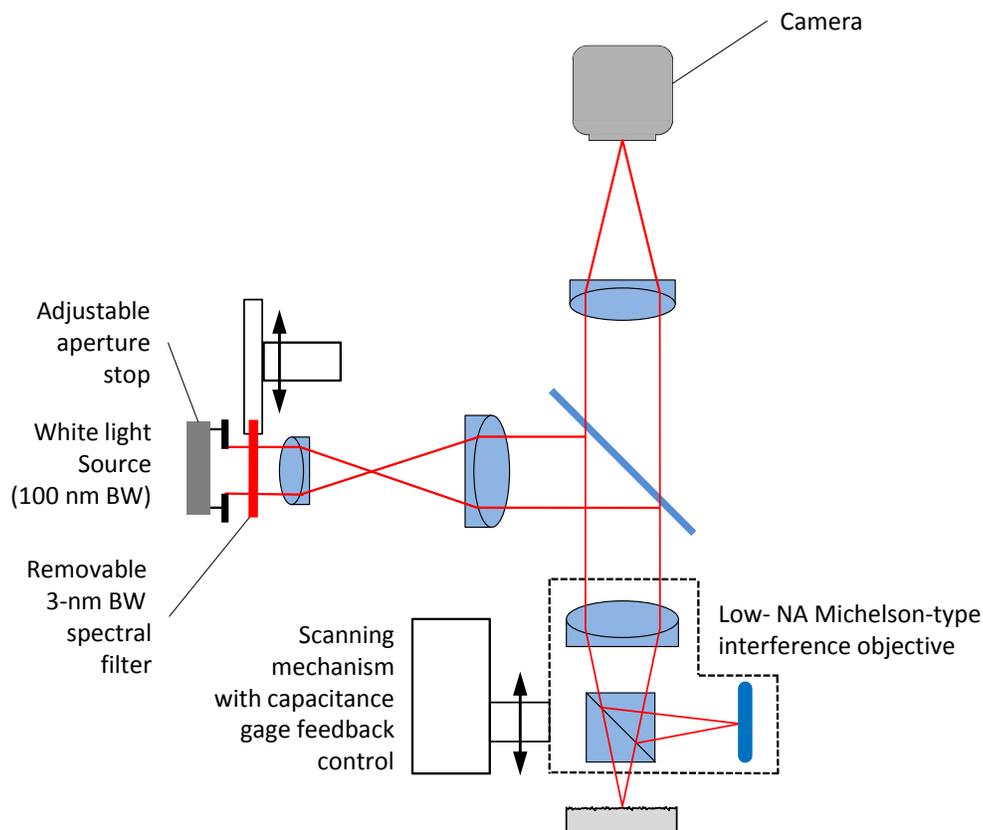
4. PROPOSED SYSTEM AND METHOD

Figure 2: System layout for the proposed in situ calibration for the amplification coefficient of a CSI microscope based on a low-magnification objective, an aperture stop to define the objective NA, and a calibrated, traceable central wavelength of a narrow-bandwidth illumination spectrum. A capacitance gage embedded into the PZT type objective scanner assures stability between calibrations.

Figure 2 illustrates a generic CSI microscope, here equipped with the necessary components to perform our proposed *in situ* calibration using a wavelength standard. These components include an aperture stop to restrict the spatial extent of the illumination and a removable narrow bandwidth (BW) interference filter to define the center wavelength of the optical spectrum scaled to the ambient index of refraction of air. Not shown in the figure are a calibrated spectrometer and integrating sphere, used to establish the effective illumination wavelength traceable to a primary length standard.
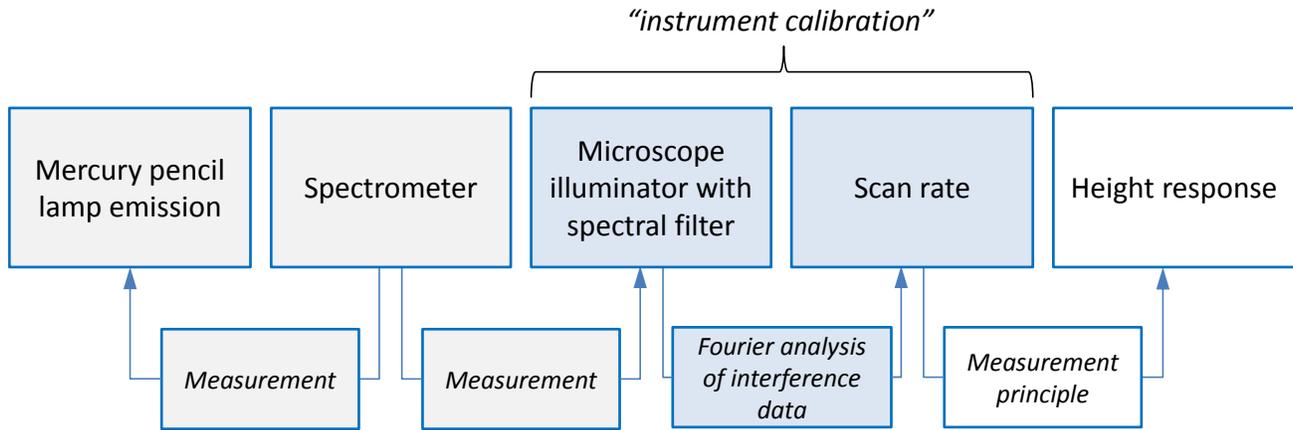
Figure 3: Traceability chain for calibration of the height response amplification coefficient of a CSI microscope using a wavelength standard.

Figure 3 shows the proposed traceability path. Starting on the left in Figure 3, a mercury argon pencil lamp realizes the meter by means of its spectral properties [22, 23]. Measuring the lamp emission links the spectrometer to this primary reference, and then transfers this calibration to the microscope illumination with the narrow bandwidth (BW) filter in place. This is the foundation of the autonomous wavelength standard which is stable to the sub-nanometer level over long periods of time [24]. The spectral analysis includes the illuminator optical elements and the interference objective.

Instrument calibration involves a data acquisition by means of an extended OPD scan with the interference filter in place, which produces a signal trace of N camera frames. An aperture stop defines the NA of the illumination, which allows for a precise determination of geometric effects, including the obliquity factor Ω. A digital Fourier transform determines the peak frequency f as an interpolated bin number in units of cycles/trace (Figure 4). From first principles, we know that the interference fringe frequency in units of radians or 2π cycles per unit distance should be

$$K = \frac{4\pi}{\Omega\lambda} \tag{2}$$

where the product $\Omega\lambda$ is the *equivalent wavelength* in air. The predicted numerical Fourier frequency is

$$f = KN\Delta_z/2\pi \tag{3}$$

where Δ_z is the average scan increment, for the data acquisition trace, and therefore the product $N\Delta_z$ is the total scan length, in units of distance/trace. Then

$$\Delta_z = \frac{\Omega \lambda f}{2N} \qquad (4)$$

is the average distance traveled by the scanner per camera frame, which is the value that we seek. The system is now calibrated, with all subsequent measurements based on our precise knowledge of the scan motion per camera frame. From the user perspective the instrument calibration is quite simple and entirely automated [25].
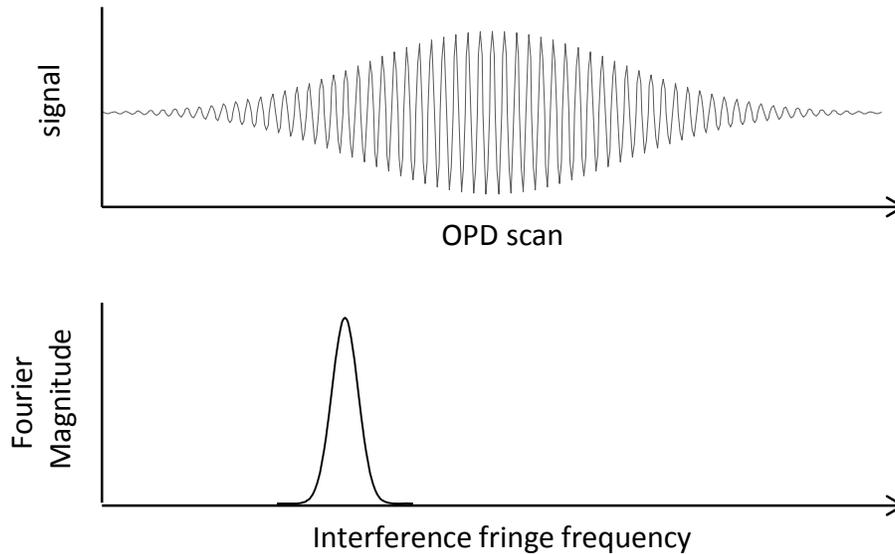

Figure 4: Conceptual illustration of the interference signal and its Fourier Transform that allows for calibration of the microscope scan mechanism using a wavelength standard. In the actual method, the data acquisition scan covers a 145 micron range and the interference fringes are much denser than shown here.

5. SOURCES OF UNCERTAINTY

5.1 Realization of the meter

High purity gas or vapor lamps are the primary standards recommended for testing wavelength accuracy of spectrometers. For our system, we use the 546.074 nm [198]Hg line from an Ocean Optics HG-1 calibration source, valid in air. This line is close to the 549 nm nominal center wavelength of the removable 3-nm bandwidth interference filter employed in the calibration. The uncertainty in this wavelength is below 0.001% and is therefore a negligible error source.

5.2 Effective wavelength of the microscope illumination

The spectrometer determines the system wavelength by evaluating the spectrum of the light reaching the measurement area of the microscope after passing through the interference objective that is later used in the calibration procedure. Empirical testing shows that the determination of the center wavelength of the system, including the step of calibrating the spectrometer and measuring the microscope illumination as seen by the test part, is highly stable and reproducible with changes of illumination intensity and over time (Figure 5). We therefore view the dominant sources of uncertainty, estimated at 0.025% (k=1), to be optical or detector influences on the perceived wavelength, together with any mechanical, thermal or temporal variations in any of the components that are part of the illumination chain in the system.
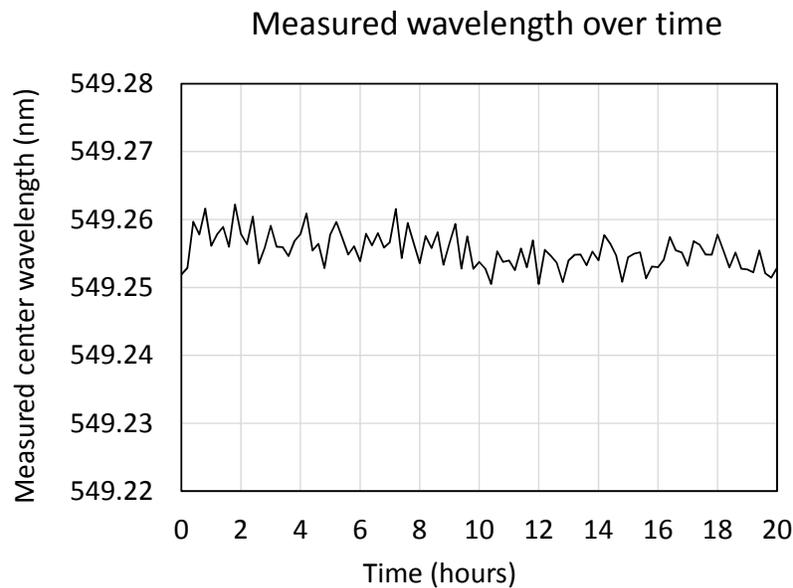
Measured wavelength over time

Figure 5: Stability of the spectrometer measurement of the center wavelength of the illumination spectrum as viewed through the interference objective in Figure 2 using an integrating sphere. The standard deviation is 0.003 nm.

Table 1: Parameters and corresponding obliquity factors for low-magnification interference objectives.

Magnification	Focal length (mm)	Pupil (mm)	NA	Ω
2X	100.0	11.0	0.055	1.00076
	100.0	4.7	0.023	1.00014
	100.0	2.9	0.014	1.00005
2.5X	80.0	12.0	0.075	1.00141
	80.0	4.7	0.029	1.00021
	80.0	2.9	0.018	1.00008
5X	40.0	10.4	0.130	1.00426
	40.0	4.7	0.059	1.00086
	40.0	2.9	0.036	1.00032

The next major consideration is the geometry of measurement. In an interference microscope with incoherent illumination, as noted previously, we must attend to the obliquity factor associated with a filled pupil and high NA. The problem has been studied extensively given the importance for calibration for PSI microscopy [26, 27]. The best approach is a complete simulation of the signal generation process [28]; however, we have found that these results are closely matched by the Sheppard formula

$$\Omega = \frac{3}{2}\left(\frac{1 - \cos^2(\alpha)}{1 - \cos^3(\alpha)} \right)$$

(5)

where

$$\alpha = \sin^{-1}\left(A_N\right) \tag{6}$$

and A_N is the numerical aperture of the illumination, including the illumination aperture stop [29]. Table 1 provides example combinations of objectives and apertures, with their associated obliquity factors, assuming that the pupil is entirely and uniformly filled by the image of the light source. By constraining the calibration configuration to 5X magnification or lower and including an aperture stop to reduce the NA, we can readily obtain an uncertainty in the effective wavelength related to the obliquity effect of 0.01%.

5.3 Data acquisition and Fourier analysis

Averaging of at least five data scans reduces statistical error contributions such as air turbulence, nonlinearity, vibration and other effects. Similarly, averaging over many image pixels greatly enhances the signal to noise level.

Additional considerations are focus, aberration, vignetting and retrace contributions, which even at low magnifications might influence the shape of the coherence envelope and the DC bias term in the measured signal. There may be imperfections and approximations in the way that the center wavelength is calculated using Fourier methods. For example, if the coherence envelope is not fully captured by the data acquisition, there may well be ringing and frequency leakage that displace the measured center wavelength. We estimate these uncertainty contributions to be less than 0.025%.

5.4 Stability of the scanner

The measurement principle for CSI depends on the fidelity and consistency of the scanning mechanism, as well as any effects that can appear as scanning errors, such as vibration and air turbulence. We can gain some insight into the stability of the scanner by repeatedly calibrating the system over time. The data in Figure 6 show calculations of the scan rate in terms of the displacement per camera frame. Each data point is the average of 5 data acquisitions, so as to reduce air turbulence and other transitory effects. The graph shows that individual CSI measurements are highly consistent over time. The experiment also shows high stability of the wavelength standard, as expected from Figure 5. A statistical analysis leads to a k=1 uncertainty contribution of less than 0.02% over time periods of at least several days.
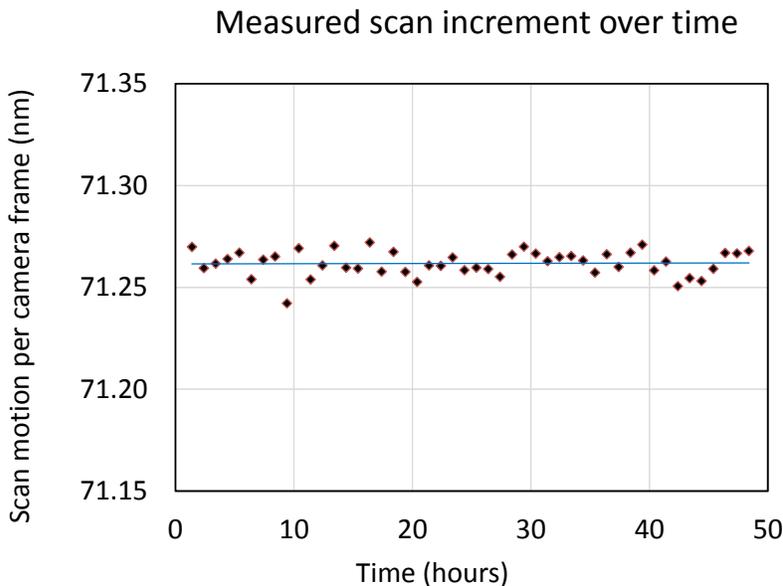

Figure 6: Stability of the scan increment as measured with the wavelength standard over a 48-hour period in a normal laboratory environment. The standard deviation is 0.009%. Data taken with a 2.75X objective with a SiC flat object.

6. VERIFICATION

6.1 Scanner adjustment

In a first evaluation of the technique, we performed a calibration using the wavelength standard technique on 12 separate interference microscopes, each with its own illumination, data acquisition, electronic imaging and optical hardware, at different times over a period of several weeks. We compared our calibrations to the nominal scan rates as determined at the point of manufacture of the PZT objective scanning mechanism. The result is the scan calibration—a number that our instrument software uses to adjust the height response. Perfect agreement between our calibration and the nominal scan rate as determined by the manufacturer would yield a scan calibration equal to one.

The results are shown in Figure 7. Our wavelength-based calibration fits comfortably within the limits of the ±0.5% maximum permissible error (MPE) defined in the manufacturer's control specification. The manufacturer uses an entirely different calibration technique from ours, based on a HeNe laser displacement gage, many weeks or months in advance of integration into our microscopes. This experiment validates the stability of the scanner over time and differing operating conditions, while increasing confidence in the wavelength standard as a means to calibrate CSI microscopes *in situ*.
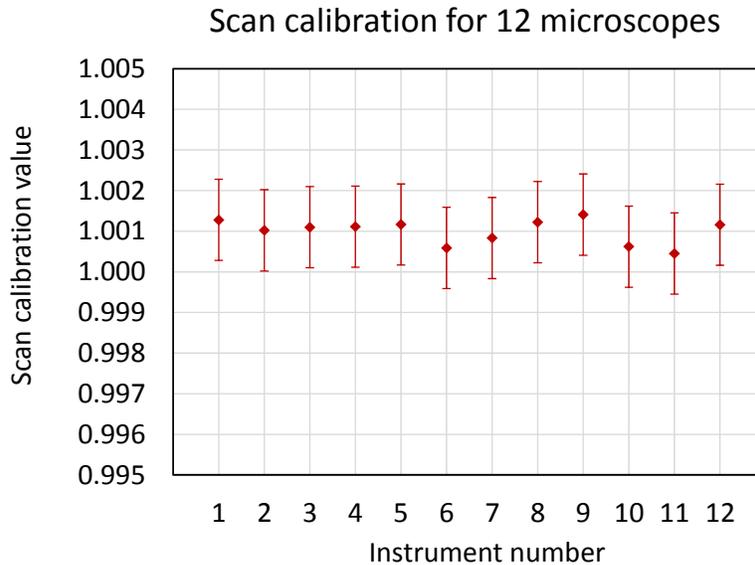

Figure 7: Measured scan calibration for 12 interference microscopes independently evaluated using the wavelength standard method, normalized to the calibration provided by the supplier of the scanning mechanism. The uncertainty in the supplier calibration is 0.5% MPE. The error bars correspond to the targeted 0.1% combined uncertainty in the wavelength standard calibration.

6.2 Measurements of step height standards

Although we would argue that the wavelength standard can be relied upon entirely for calibration, verification using an SHS is useful for determining if the instrument is functioning correctly. Here we clearly distinguish between calibration (section 2.39 of Ref.[30]), which establishes the amplification coefficient, and verification (section 2.44 of Ref. [30]), which in this context is merely confirming that the instrument measures the correct height within the expected margins of error. If the measured value for a step height falls outside of the uncertainty boundaries of the certification after calibration using the wavelength standard, for example, this would be an indication that the wavelength standard has become compromised, or that the instrument requires servicing for some other reason.

Using the same 12 instruments as in the previous section, we measured two SHS artifacts certified traceable to the meter through NIST with values of 1.795 µm ±0.011 (Figure 8) and 23.976 µm ±0.145 (Figure 9). The results in are consistent from instrument to instrument within the targeted 0.1% uncertainty of the wavelength calibration method, and are also within the 0.6% k=2 uncertainty limits of the certifications for these step heights.

Measurements of a step height
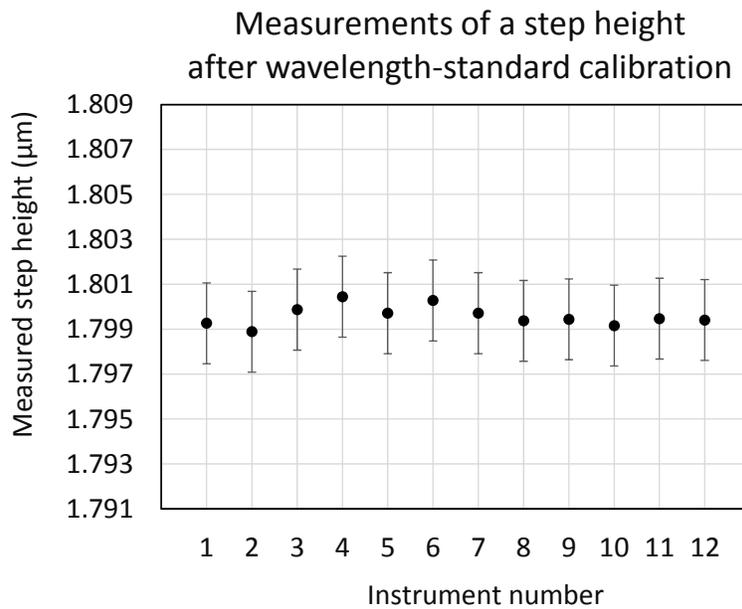## after wavelength-standard calibration

Figure 8: Measurements of a nominal 1.8µm step height on 12 interference microscopes, each of which was independently calibrated as in Figure 7 using the wavelength standard prior to the SHS verification.

Measurements of a step height
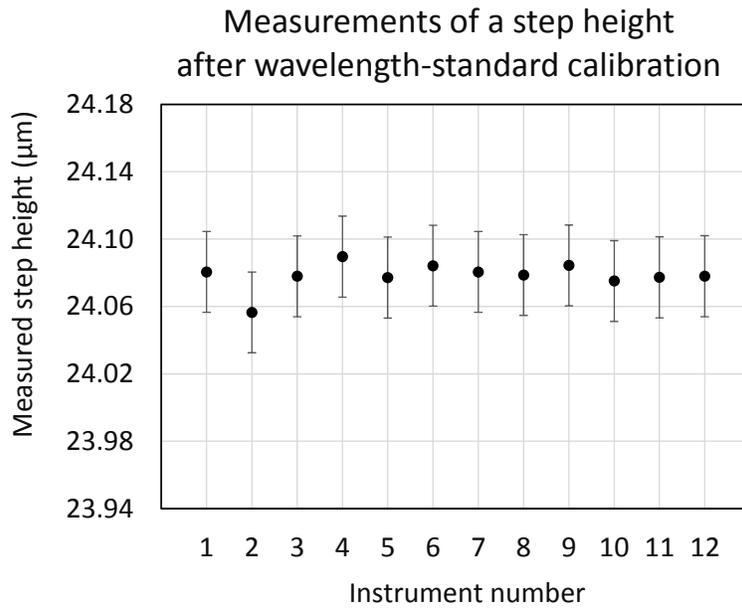## after wavelength-standard calibration

Figure 9: Measurements of a nominal 24µm step height on 12 interference microscopes, each of which was independently calibrated using the wavelength standard prior to the SHS verification.

7. DISCUSSION AND CONCLUSION

The data for the measurement of the amplification coefficient in Figure 7 shows good consistency with the independent laser displacement gage calibration of the scanning mechanism prior to assembly into the microscope. The measurements of two SHS artifacts, as shown in Figure 8 and Figure 9, verify the calibration with the uncertainty of the SHS certifications, while illustrating consistency in the calibration from one system to another to within the targeted 0.1% uncertainty.

As is the accepted practice with CSI microscopes when using SHS artifacts, the wavelength standard method need only be applied at infrequent intervals with a single low-magnification objective. Subsequent measurements may be with any objective, with the assumption that the amplification coefficient depends uniquely on the velocity of the objective scanning mechanism. For CSI systems that include optional phase shifting interferometry (PSI) modes that rely on wavelength as the basic height metric, the scan rate calibration may be transferred to the PSI measurement for any objective by first performing a CSI measurement and a Fourier analysis to determine the equivalent wavelength for that objective [31].

Advantages of the wavelength scanning method include the separation of errors related to scanner linearity, which can be a complication for SHS methods, particularly if only one SHS value is employed in the calibration. Further advantages include ease of use, since no part alignment within the field of view is necessary. Surface form, which can sometimes be an issue with mechanical standards, is not important to the wavelength standard. Finally, there is at least the potential for more consistent results with higher accuracy and confidence. This last point merits further work to rigorously confirm superior uncertainty values when compared to the well-established methods that rely on mechanical transfer artifacts.

ACKNOWLEDGMENTS

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