Wavemeter calibration by frequency comb

Patrick F Egan

National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, United States of America

E-mail: egan@nist.gov

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Abstract

Upgrades to the vacuum wavelength calibration service at the National Institute of Standards and Technology are reported. The instrumentation centerpiece is an optical frequency comb stabilized to a GPS-disciplined oscillator, thereby providing direct traceability to the SI second. Historically, the service has covered lasers at the popular interferometry wavelengths red and green. Recently, capability has been added for calibrating wavemeters at multiple telecom wavelengths in the range $(1520 < \lambda < 1570)$ nm. For most commercially available wavemeters, the test uncertainty ratio is about 10^4.

Supplementary material for this article is available online

Keywords: frequency comb, wavemeter calibration, vacuum wavelength

1. Introduction

Since 2010, vacuum wavelength (laser frequency) calibration at the National Institute of Standards and Technology (NIST) has been directly traceable to the SI second via an optical frequency comb stabilized to GPS [1]. The bulk of the demand continues to be frequency stabilized helium-neon lasers operating at 633 nm—the workhorse of dimensional metrology—but the service can also cover other wavelengths. Recent examples include: (i) the Kibble balance [2] and crosscheck on an iodine stabilized laser at 532 nm, (ii) multicolor gage block and sphere diameter metrology [3] at 543 nm, and (iii) accelerometry [4] using a scanning wavelength around 1550 nm. While these wavelengths are somewhat unusual, there is nothing unusual about the end application: precision interferometry relies on known wavelengths.

More recently, an unusual request has been accommodated: the calibration of wavemeters at multiple wavelengths in the telecom C-band. Wavemeters are not lasers: they are instruments that estimate the vacuum wavelength of an input laser. Among various operating principles, a precise implementation is based on a scanning Fabry–Perot interferometer with an internal stabilized laser of known wavelength. A Fabry–Perot interferometer produces an interference peak when an integer number of half-wavelengths fit between the mirrors.

If one of the mirrors is scanned (displaced), a series of peaks is produced. The spacing between adjacent peaks is one half-wavelength. So, the internal stabilized laser calibrates the relationship between the mirror displacement and wavelength. Therefore, the wavelength of a laser under test may be determined by comparing its separation in peaks relative to that of the internal stabilized laser. A wavemeter almost seems self-calibrating, but there are algorithms (e.g. peak detection, and perhaps scan linearization or chromatic correction) between the known wavelength of the internal laser and the output wavelength indication. How might one be certain a wavemeter is accurate?

A look into the answer 'by calibration' reveals [5] two things. First, calibration lags instrument performance. Approximate uncertainty at national metrology institutes [5] is 0.5 pm, which is $3 \times 10^{-7} \cdot \lambda$ at 1550 nm. However, the typical precision of a wavemeter is $10^{-8} \cdot \lambda$, and several manufacturers of wavemeters advertise accuracy at that level (and lower). The second thing of interest is that calibrations [5] sometimes employ a 'master wavemeter.' A 'master wavemeter' might mean a wavemeter which has had its indication calibrated by comparison to the known vacuum wavelength of an absorbing molecule listed in the *mise en pratique* of the meter [6]. However, for end user quality systems, one may imagine an auditor taking issue with at least two things:

(i) convoluted traceability (wavemeter calibrated by a wavemeter), and (ii) if the 'master wavemeter' is only compared to one known wavelength (e.g. acetylene near 1533 nm [7]), what does it mean if the end user operates the wavemeter at a different wavelength? (To confound the issue further: Best knowledge of the acetylene absorption features near 1533 nm were obtained with a wavemeter which had been calibrated at a single wavelength 1560 nm stabilized to a rubidium absorption feature [7].)

In truth, neither of the two 'interesting things' above—calibration capability or circular traceability—are of tragic concern. Firstly, a user who seeks $10^{-6} \cdot \lambda$ on a nominal wavelength is rarely encountered. (Alternately stated: most people using $10^{-6} \cdot \lambda$ will be doing interferometry, with traceability via the traditional route of frequency calibrating a stabilized laser.) Moreover, an argument may be made that a wavemeter employing an internal red helium–neon or an acetylene stabilized laser might be considered 'intrinsically accurate' because it satisfies 'Method C' for traceability to the SI meter [6]. In the case of helium–neon, the consensus [8] uncertainty would be a few $10^{-6} \cdot \lambda$; and for acetylene, commercial stabilized lasers are demonstrating $10^{-7} \cdot \lambda$. Nevertheless, this hand-waving argument about a 'wavemeter not requiring calibration' may not satisfy the fastidious auditor who wonders how the instrument indication relates to the internal wavelength standard and the SI.

There is a more rigorous way of doing things, with direct traceability to the SI second, and delivering $10^{-12} \cdot \lambda$ calibration uncertainty for almost any wavelength. The rigorous way calibrates the wavemeter with a laser locked to an optical frequency comb, which is the main subject of this article. The optical frequency comb serves as a transfer oscillator, linking the optical frequencies calibrating the wavemeter to an rf frequency standard [9].

2. Configuration and methods

Optical frequency combs [10] became commercially available in the mid-2000s. The system reported here is a commercial system. Indeed, almost everything reported below is commercially available, and the only minor challenge has been system integration. Nevertheless, some minor upgrades since the initial report of 2010 [1] will be described first. Then, details about how the wavemeter calibration has been implemented will follow.

2.1. Minor upgrades

A schematic of the setup is shown in figure 1. The main upgrade to the 2010 system is that most things have been fiberized. There is a good technical reason behind this upgrade, besides the neater appearance on the bench. At visible wavelengths, it is a challenge to obtain a beat signal with sufficient signal-to-noise ratio between a laser under test and an individual comb tooth. Fiberizing both lasers is one method [11] of improving the signal-to-noise ratio because it ensures optimal mode matching. Elsewhere in the present

system, the setup of figure 1 now permanently employs a synthesizer to control the repetition frequency of the comb. Detection of the offset frequency in the f–$2f$ interferometer is now completely in fiber—a great simplification over past freespace implementations.

The main additions to the bench are two auxiliary lasers, which will lock to a tooth of the frequency comb, in either the visible or infrared. The auxiliary lasers are labeled 'HeNe' and 'ecdl' in figure 1. Locking an auxiliary laser to the frequency comb requires three things:

(i) tuning the frequency of the auxiliary laser with a response rate of 1 kHz or faster
(ii) an error signal relative to the fixed frequency of a comb tooth
(iii) closed-loop feedback to the tuning actuator of the auxiliary laser

It is only item (i) that changes depending on the auxiliary laser type. In figure 1, frequency tuning of the helium–neon laser is accomplished by a single pass through an acousto-optic modulator. The external cavity diode laser does not require extra appendages, and its frequency was tuned by the diode current. For item (ii), the frequency error signal is produced by a digital phase detector [12], labeled 'dxd' in figure 1. This frequency error signal is proportional to the frequency difference between (a) the beat frequency between the auxiliary laser and the nearest comb tooth and (b) the reference frequency produced by the GPS-disciplined oscillator. The frequency error signal is driven to zero by feedback to the auxiliary laser tuning actuator, via a proportional-integral-derivative controller, labeled 'PID' in figure 1. Consequently, the auxiliary lasers will offset lock to a tooth of the frequency comb, with a frequency separation referenced to the GPS-disciplined oscillator.

Calibrating infrared wavemeters [13] has motivated this added functionality with auxiliary lasers, as described next. The present implementation covers all wavelengths in the range 1520 nm–1570 nm with one external cavity diode laser. In principle, the approach can be extended to cover visible wavemeters, but with the added complexity that each visible wavelength may require a dedicated laser.

2.2. Wavemeter calibration

A laser locked to an arbitrary tooth N of the comb becomes a stable and accurately known optical frequency

$$\nu_{\text{cll}} = N f_{\text{rep}} \pm f_{\text{off}} \pm f_{\text{beat}}, \qquad (1)$$

with $f_{\text{rep}} = 250$ MHz and $f_{\text{off}} = 20$ MHz the repetition and offset frequencies of the comb, respectively, and $f_{\text{beat}} = 20$ MHz the beat frequency between the auxiliary laser and the nearest comb tooth. The frequency values mean $N \approx 780\,000$ near 1542 nm. When a frequency comb is stabilized to a GPS-disciplined oscillator, all three radio frequencies on the right-hand side of equation (1) are directly traceable to the SI second. The GPS signal is produced by cesium frequency
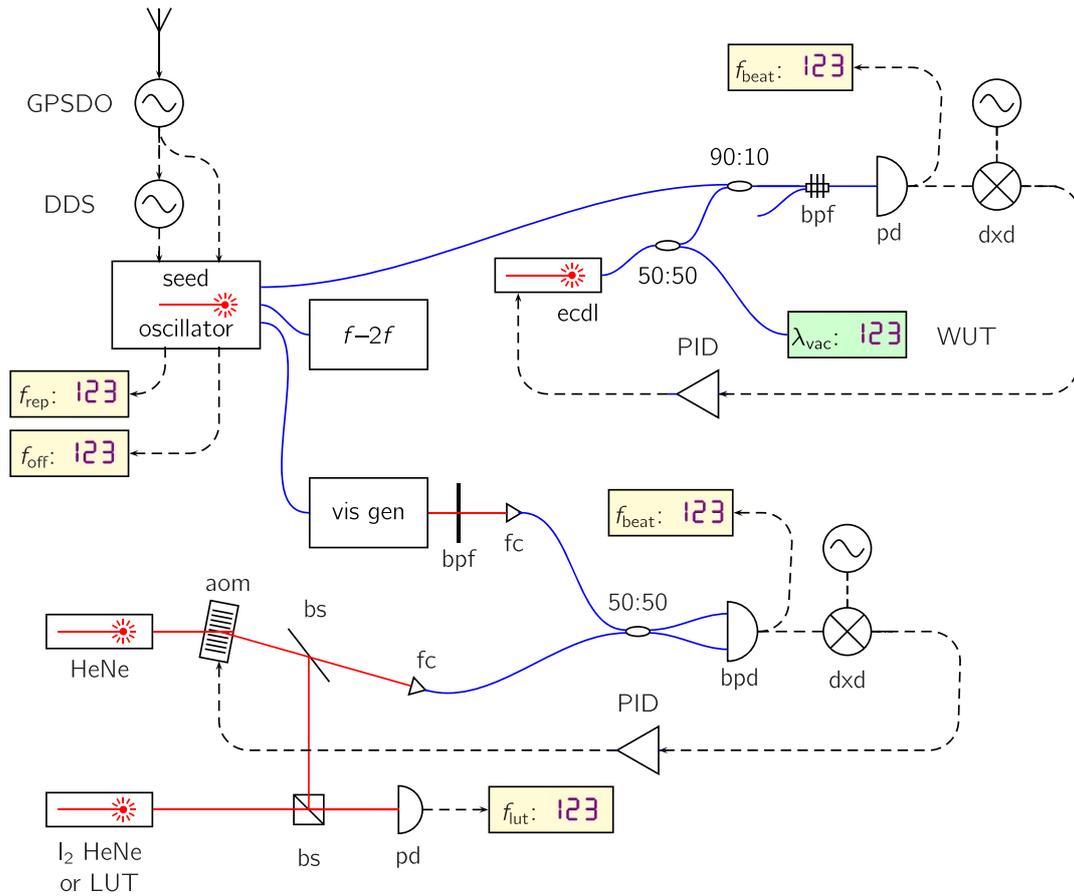
Figure 1. Setup schematic. Blue lines: polarization-maintaining fiber. Red lines: freespace beams. Dashed black lines: electrical signals. Components include: GPS-disciplined oscillator (GPSDO), direct digital synthesizer (DDS), helium–neon laser (HeNe), external cavity diode laser (ecdl), acousto-optic modulator (aom), beam-sampler or splitter (bs), photodetector (pd) and balanced photodetector (bpd), digital phase detector (dxd), proportional-integral-derivative controller (PID), optical bandpass filter (bpf), fiber coupler (fc). WUT: wavemeter under test. LUT: laser under test.

standards onboard the orbiting satellites; the SI second is defined by the transition frequency of cesium. The GPS signal is continuously monitored and archived [14] by comparison to cesium frequency standards on Earth. All three radio frequencies are measured with frequency counters referenced to the GPS-disciplined oscillator. Consequently, the frequency of the comb locked laser ν_{cll} is accurately known and directly traceable to the SI second. The purpose of the comb locked laser is to provide a reference wavelength $\lambda_{cll} = c/\nu_{cll}$ with which to test the wavemeter, with c being the speed of light in vacuum. To be clear, in this approach the wavemeter calibration is traceable to the SI second through the comb locked laser.

[The signs in equation (1) are easily determined using the ν_{wut} displayed on the wavemeter under test. The laser is locked to a comb tooth, and f_{off} or f_{beat} are individually shifted some megahertz from their lockpoints. The N may be determined by the method of excess fractions [15]. The f_{rep} is set to several values across a range of several megahertz, and a system of equations is built for possible answers for N. The method

of excess fractions deduces only one value of N that will produce a constant valued equation (1) for all set values of f_{rep}. The method of excess fractions substitutes the requirement that ν_{wut} should be *accurate* within 10^{-7} with the requirement that ν_{wut} need only be *stable* within 10^{-7} over about 1 h. This stability requirement is easily satisfied by modern wavemeters.]

The calibration consists of feeding the comb locked laser to the wavemeter and recording the difference between the indication of the wavemeter under test λ_{wut} and the reference wavelength λ_{cll}. The calibration reports 'error in the indication' $\delta\lambda = \lambda_{wut} - \lambda_{cll}$. An example of a wavemeter calibration is shown in figure 2. The reproducibility tests over time at 1550 nm in figure 2(a) exhibit fractional error in indication of $(0.6 \pm 1.5) \times 10^{-8}$. The reproducibility measurements sample the short term stability of the wavemeter, with power ups and shut downs interspersed in the testing. If a customer intends to use the wavemeter over some range of wavelengths, they would also be interested in how the wavemeter indication error depends on the wavelength ('spectral error'). A test of the
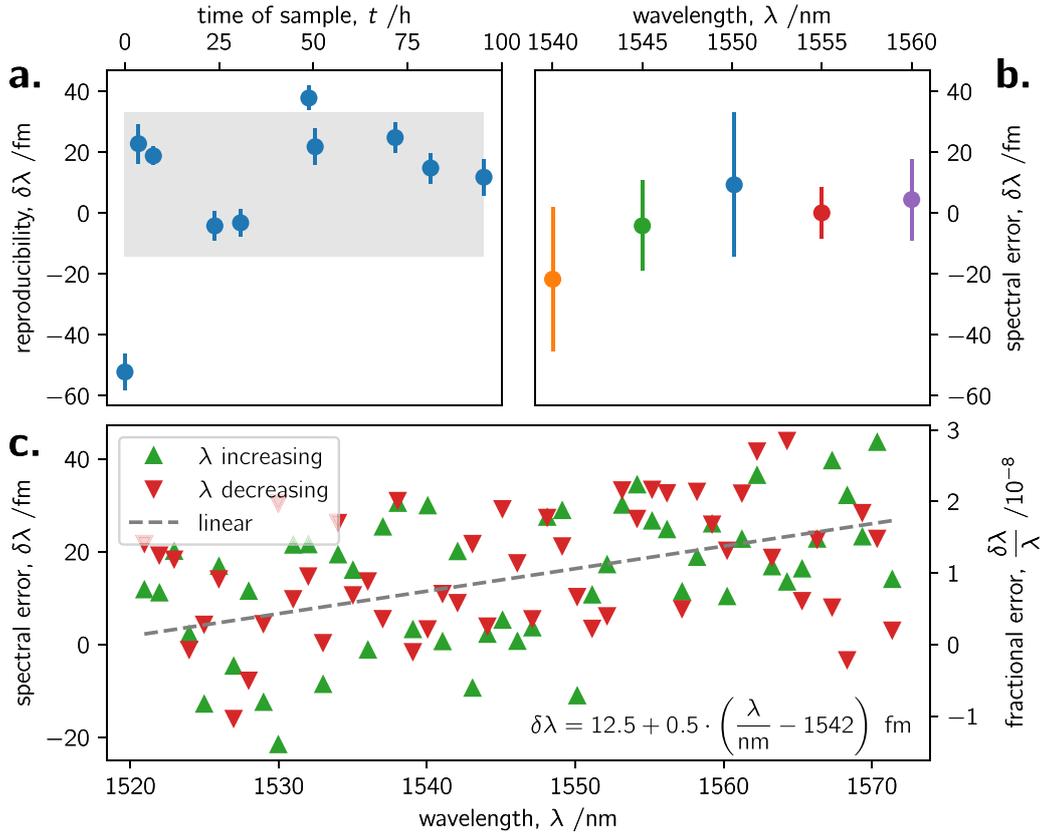
Figure 2. Example of a wavemeter calibration with the comb locked laser. (a) Reproducibility tests at $\lambda = 1550$ nm over time. Error bars span standard deviation on ten samples at each measurement point. Shaded area spans standard deviation for the entire sample set. (b) Wavemeter error as a function of wavelength. Errorbars span standard deviation for the entire three day sample set at each wavelength. (c) Refined estimate of spectral error by a continuous test over 3 h.

spectral error is shown in figure 2(b), and exhibits root mean square fractional deviation from a linear fit of 1.0×10^{-8}. For this wavemeter, the manufacturer datasheet specifies relative 'accuracy' of 10×10^{-8} at $k = 1$ coverage factor. Clearly, figure 2 shows the manufacturer has a firm grasp on uncertainty of λ_{wut}. Next, follows a discussion about the uncertainty of λ_{cll}.

But before uncertainty, an aside: A calibration report will include tests of reproducibility and indication error as a function of wavelength at three selected wavelengths, as shown in figures 2(a) and (b). These two tests will cover likely errors in the wavemeter as intended for use around some nominal wavelength. However, the calibration system can also provide a refined estimate of the indication error as a function of the wavelength. A test is shown in figure 2(c), which was carried out over 3 h of continuous operation, sampling $\delta\lambda$ for increasing and decreasing wavelengths, in 1 nm increments of λ_{cll}. (To perform this test, figure 1 needed a slight change: the fiber Bragg grating bandpass filter was replaced with a diffraction grating and the comb–diode laser beat signal was photodetected in freespace. The beam diffracted from the grating required manual adjustment onto the photodetector at each wavelength increment.) The test identifies a linear error as a function of wavelength, in fractional terms $3.1(8) \times 10^{-10}$ nm^{-1}. Without knowing the internal workings of the wavemeter, any explanation of this error would

be conjecture. Nevertheless, the finding of figure 2(c) does support the speculation that line center determinations in pre-comb era spectroscopy might have small biases caused by wavemeter error [16]. [Elaborating further: Hrabina *et al* [16] speculated that observed frequency biases of 26 kHz nm^{-1} in the line centers of hydrogen cyanide might have originated in wavemeter error. For comparison, the wavemeter calibrated in figure 2(c) has a spectral error of 62 kHz nm^{-1}.]

2.3. Validation and uncertainty

An extended discussion of uncertainty for comb based laser frequency calibration is contained in [1]. Below is a brief discussion about uncertainty in the vacuum wavelength of a comb locked laser, with a focus on how it contributes to wavemeter calibration. The notation $u(x)$ is used to denote the standard uncertainty of the quantity x. Unless otherwise stated, all stated uncertainties are one standard uncertainty, corresponding to approximately a 68% confidence level.

Validating the accuracy of a comb locked laser faces the same challenges as validating the operation of a frequency comb [1]. The exacting will argue that the reference frequency to which the comb is stabilized should be compared to that of a cesium clock. However, animating this argument is a belief in red herring error: that the frequency of a disciplined oscillator might secretly depart from the steering algorithm of GPS
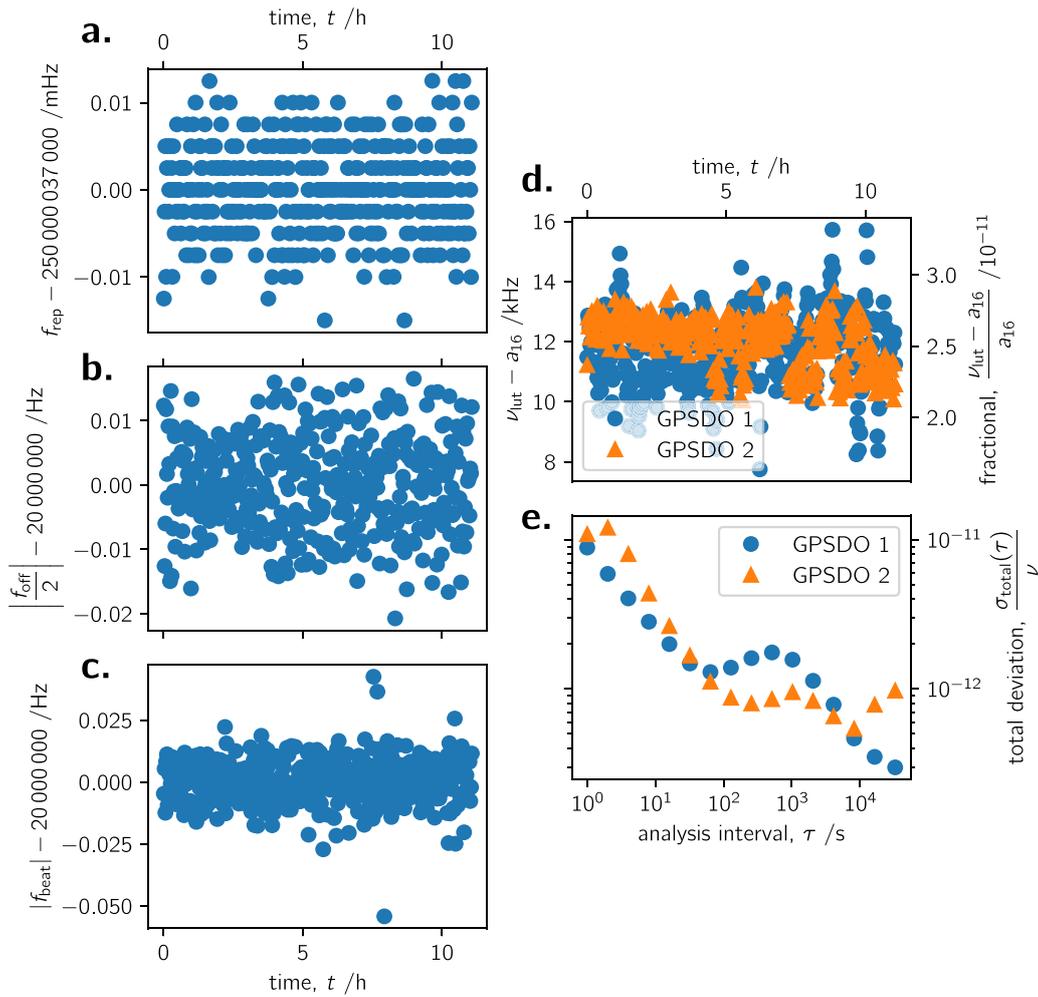
Figure 3. Frequency metrology associated with validation of the comb locked laser near $\nu_{\text{cll}} \approx 474$ THz. (a) Repetition and (b) offset frequencies of the frequency comb. (c) Beat frequency between comb locked HeNe laser and nearest comb tooth. (d) Absolute frequency of the iodine stabilized HeNe laser ν_{lut} determined by comparison to the comb locked laser expressed as difference from the reference value of the iodine absorption a_{16} [17]. (e) Total deviation on the beat frequency between the comb locked laser and the iodine stabilized HeNe laser.

(which is derived from cesium clocks). Rather than enter the epistemological debate, the alternative here is simply to validate performance by comparing a comb locked laser to a known optical frequency reference, such as an iodine stabilized laser. To be clear, the wavemeter calibration discussed above employed a comb locked diode laser near 1550 nm, but the validation described next was carried out with a comb locked HeNe laser at 633 nm. It is the property of phase coherence in a frequency comb based on a mode locked laser that ensures the comb structure and equation (1) applies for all wavelengths [10]. (For visible wavelengths, N is larger and f_{off} is doubled by the second harmonic generation process.)

The comb locked laser was compared to the frequency of an iodine stabilized laser, using the layout schematic of figure 1. The relative uncertainty of a 'relaxed' iodine stabilized laser is some parts in 10^{11} [17–19]; the 'relaxed' condition means no effort has been made to compensate for the factors affecting the iodine absorption frequency (cold finger and cell wall temperatures, intracavity power, dither amplitude). The results of the test are shown in figure 3. On the left-hand side of the figure are all radio frequencies contributing to equation (1):

comb repetition f_{rep} and offset f_{off} frequencies and the beat frequency f_{beat} between the comb locked laser and tooth $N = 1\,894\,450$ of the comb (note that N is easily determined when compared to an iodine stabilized laser). The diagnostics on the left-hand side of figure 3 are 'in loop'—that is, the counters that record the radio frequencies are referenced to the same GPS-disciplined oscillator to which the comb is stabilized. It is therefore misleading to read much into the hertz level performance (10^{-15} fractional).

Independent ('out of loop') accuracy validation of the comb locked laser is figure 3(d), which shows the difference between two absolute optical frequencies. One frequency $\nu_{\text{lut}} = N f_{\text{rep}} \pm f_{\text{off}} \pm f_{\text{beat}} \pm f_{\text{lut}}$ is the absolute frequency of the iodine stabilized laser, as determined by comparison to the comb locked laser, with the corresponding beat frequency f_{lut}. The other frequency $a_{16} = 473\,612\,353\,604$ kHz is the reference value [17] for the absorption line to which the iodine stabilized laser was locked. The disagreement is 2.5×10^{-11}, and is within uncertainty for the 'relaxed' condition iodine stabilized laser. However, the scope of this validation is not limited to a 2.5×10^{-11} statement for relative wavelength accuracy of the comb

Table 1. Relative standard uncertainty for a wavemeter calibration. The entries 'reproducibility' and 'spectral error' are instrument specific.

Component	$u_r(\lambda_\text{wut})$ $/10^{-8}$
Reference wavelength λ_cll	10^{-4}
Reproducibility	1.5
Spectral error	0.8
Combined ($k = 1$)	1.7

locked laser. Rather, without further validation, one may confidently expect [1] that the comb locked laser is as accurate as the GPS-disciplined oscillator reference frequency to which the comb is stabilized. The ultimate level of accuracy is best evaluated by the total deviation plot in figure 3(e): for analysis intervals $\tau > 1000$ s the GPS steering algorithm clearly drives the average frequency error below 10^{-12}. The redundant result of the test performed with a GPS-disciplined oscillator from a different manufacturer is also shown in figures 3(d) and (e). Both oscillators are rubidium standards and consecutively use the same antenna, but the steering algorithms are evidently different, visible in the total deviation of figure 3(e). Assuming that the iodine stabilized laser was a constant reference frequency in the two tests and taking the 10 h average of all data in figure 3(d), the fractional agreement for the two inferred estimates of ν_cll is within 7×10^{-13}.

So, from the validation test above, $u_r(\lambda_\text{cll}) = 10^{-12}$ for averaging times of 1 h. With a test uncertainty ratio of 10^4, one may confidently attribute typical 10^{-8} relative errors in $\delta\lambda = \lambda_\text{wut} - \lambda_\text{cll}$ to the (short term) performance of the wavemeter. The wavemeter uncertainty may be characterized by two statistical components: reproducibility and spectral error. The entries listed in table 1 are representative of one particular wavemeter. The reproducibility uncertainty was evaluated by monitoring the indication error at a single wavelength over a period of four days, during which the wavemeter was powered off and on several times; see figure 2(a). The entry in table 1 is the standard deviation of the indication error across this testing period, and gives a fair estimate of the wavemeter reproducibility. The spectral error uncertainty was evaluated from the data of figure 2(c), which shows indication error as a function of wavelength. The data were fit with a linear function, and the entry in table 1 is the standard deviation of the residuals from the fit. This two-part evaluation is somewhat conservative, because the influence of (very short term) wavemeter stability is sampled twice. However, the two-part evaluation is fair. For example, one 'lucky' wavelength tested on figure 2(b) shows fractional reproducibility of only 0.7×10^{-8}, which is equivalent to the 10 fm digit resolution of the wavemeter, and a too optimistic reflection of wavemeter performance. In contrast, separate (fine frequency) tests reveal that indication error can change by as much as 60 fm for λ_cll that differ by only 20 pm. (The fine frequency finding is similar to König *et al* [20], and likewise periodic.)

In summary, calibration uncertainty is completely determined by the performance of the wavemeter. The two-entry evaluation of table 1 is a fair estimate of the standard uncertainty for short timescales within a specific wavelength range.

3. Conclusion

In response to customer demand for wavemeter calibration, new capabilities have been added to the vacuum wavelength calibration service at NIST. The centerpiece of the instrumentation is an optical frequency comb stabilized to a GPS-disciplined oscillator. A laser locked to a tooth of the comb serves as a reference wavelength, which feeds the wavemeter and determines the indication error of the instrument. The system performance has been validated by comparison to an iodine stabilized laser. The estimated relative standard uncertainty in a reference wavelength is $10^{-12} \cdot \lambda$. An example calibration for a wavemeter has been described, and the instrument exhibited relative imprecision at some parts in 10^8.

At present, NIST calibrates telecom wavemeters at wavelengths ($1520 < \lambda < 1570$) nm; visible wavemeters are limited to a single wavelength of 633 nm, but other wavelengths might be calibrated upon request. This new capability compliments the existing services in vacuum wavelength calibration [21], already covering metrology lasers at 532 nm, 543 nm, 633 nm, 1523 nm, 1542 nm, and 1560 nm.

Finally, the motivation for this work comes from customer interaction, and a perceived mistrust of how wavemeters are regarded in a quality system. It is germane to conclude with some general guidance about wavemeters:

- It is unlikely that a functioning wavemeter with an internal stabilized laser from a reputable manufacturer could ever have errors as large as $10^{-6} \cdot \lambda$.
- Readily available stabilized lasers at 633 nm and 1533 nm allow wavemeter errors to be minimized at these wavelengths. It is unlikely that a wavemeter from a reputable manufacturer could have errors larger than $10^{-7} \cdot \lambda$ at (633 ± 50) nm or (1533 ± 50) nm.
- For operation more than 50 nm away from 633 nm or 1533 nm, error in the wavemeter indication as a function of wavelength is likely to exceed $10^{-7} \cdot \lambda$.
- A calibrated wavemeter may hold $10^{-8} \cdot \lambda$ accuracy at its calibrated wavelength for short time periods. Applications requiring long term $10^{-8} \cdot \lambda$ performance might be better served by pursuing comb based frequency metrology.

ORCID iD

Patrick F Egan ⬤ https://orcid.org/0000-0003-2403-3950

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[21] NIST Store Laser frequency/vacuum wavelength SKU: 14510C (available at: https://shop.nist.gov/ccrz__ProductDetails?sku = 14510C&cclcl = en_US) *Note added in proof*: Capability has been added for comb-referenced wavemeter calibration at 1310 nm and 1625 nm using two distributed feedback lasers.