



On the performance of wavelength meters: Part 2—frequency-comb based characterization for more accurate absolute wavelength determinations

Kristian König¹ · Phillip Imgram¹ · Jörg Krämer¹ · Bernhard Maaß¹ · Konstantin Mohr^{1,2} · Tim Ratajczyk¹ · Felix Sommer¹ · Wilfried Nörtershäuser¹

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Abstract

Wavelength meters are widely used for frequency determinations and stabilization purposes since they cover a large wavelength range, provide a high read-out rate and have specified accuracies of up to 10^{-8} . More accurate optical frequency measurements can be achieved with frequency combs but only at the price of considerably higher costs and complexity. In the context of precise and accurate frequency determinations for high-resolution laser spectroscopy, the performance of five different wavelength meters was quantified with respect to a frequency comb. The relative precision as well as the absolute accuracy has been investigated in detail, allowing us to give a sophisticated uncertainty margin for the individual instruments. We encountered a prominent substructure on the deviation between both device types with an amplitude of a few MHz that is repeating on the GHz scale. This finally limits the precision of laser scans which are monitored and controlled with wavelength meters. While quantifying its uncertainty margins, we found a high temporal stability in the characteristics of the wavelength meters which enables the preparation of wavelength-dependent adjustment curves for wide- and short-ranged scans. With this method, the absolute accuracy of wavelength meters can be raised up to the MHz level independently from the wavelength of the reference laser used for calibrating the device. Since this technique can be universally applied, it can lead to benefits in all fields of wavelength meter applications.

1 Introduction

Accurate determinations of laser frequencies and frequency differences or the corresponding stabilization at a fixed frequency are crucial for many laser spectroscopy experiments and can rely on several approaches: natural transition lines in atoms, ions or molecules offer the opportunity to lock lasers at well-known but fixed frequencies [1–4]. Small frequency

changes can be achieved with electro-optical or acousto-optical modulation [5]. Alternatively, the frequency of a second laser can be stabilized relative to such a frequency reference with the frequency-offset-lock technique [6, 7]. However, this covers about 100 GHz to both sides of the reference line which is negligible compared to the frequency span of more than 400 THz across the visible spectrum. Modern wavelength meters especially designed for laser wavelength identification offer the possibility to measure wavelengths and thus frequencies with relative accuracy of up to $\Delta\lambda/\lambda = 10^{-8}$ covering nearly the complete spectral range from the near UV deep into the infrared. Based on solid Fizeau interferometers which offer a high reliability [8, 9], a direct laser stabilization with drifts of only a few MHz/day and much higher performance at smaller time scales becomes possible [10–12]. Higher frequency stability and/or higher precision in the absolute frequency determination on a similar large wavelength range can only be achieved with frequency combs, which are capable of measuring with sub-Hz accuracy [13]. However, these are significantly more

We use the term “absolute” frequency to refer to a measurement where we are interested in the actual value of the laser frequency in contrast to measurements of relative stability to a fixed value. It is measured with a GPS-referenced frequency comb relative to the SI second.

✉ Kristian König
kkoenig@ikp.tu-darmstadt.de

¹ Institut für Kernphysik, Department of Physics, Technische Universität Darmstadt, 64289 Darmstadt, Germany

² GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

expensive, more complex to handle and not well suited to control fast laser scans.

Even though they are used in numerous applications, to our knowledge only the long-term stability of wavelength meters has been investigated in detail so far [11, 12]. Together with [14] we want to shed light on the reliability during frequency scans which is of special interest in many experiments where only small frequency ranges, e.g., due to isotope shifts [15–17] or different Rydberg states [10, 18] are investigated. It is expected that the relative precision of wavelength meters is much higher than the absolute accuracy, which is specified by the manufacturer. Nevertheless, the absolute accuracy has been tested as well in comparison to a frequency comb and enabled us to generate individual calibration curves for more accurate wavelength measurements.

First indications for abnormal and unsteady deviations have been observed in previous studies at the COLLinear Apparatus for Laser spectroscopy and Applied physics (COALA) at TU Darmstadt where frequency measurements with wavelength meter and comb were performed synchronously:

- In resonance ionization spectroscopy experiments of $^{10,11}\text{B}$ [15] the laser frequency was scanned across several GHz. The step size was controlled with a wavelength meter due to its higher response rate and the capability to perform sufficiently large frequency steps.

Nevertheless, in regular distances of 100 MHz the frequency was also measured with a comb. Unexpectedly, changes in the frequency discrepancy between comb and wavelength meter in the MHz regime were observed during this measurement.

- Similar deviations have been observed during measurements at the collinear apparatus albeit without consequences for the experiments since they were conducted at a fixed frequency [19, 20]. In these cases, the lasers were stabilized by wavelength meters but continuously measured with a comb. In periods spanning from 30 min to some hours, the laser frequency was changed showing again wavelength-dependent deviations between both measuring devices.

These observations together with the need for reliable frequency measurements with wavelength meters in projects at GSI Darmstadt and MPIK Heidelberg [21] motivated this intense study of the wavelength meters.

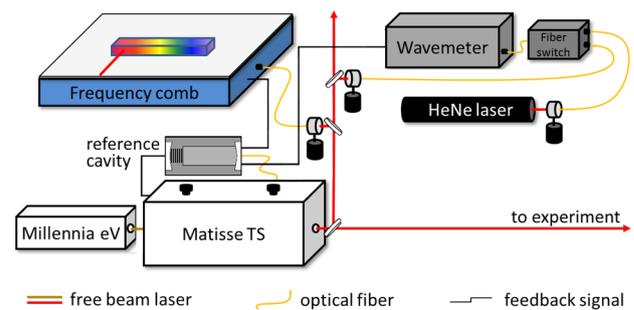


Fig. 1 Laser system used for the investigations. Pumped by a Millennia eV Nd:YAG laser, light between 700 and 1000 nm can be generated with a Matisse Ti:Sa laser. A small fraction of the fundamental light is fed into the wavelength meters and the frequency comb. The laser frequency determined with these devices can be used for the long-term stabilization of the Matisse's reference cavity

2 Experimental setup

We analyze and quantify the corresponding uncertainty margin in this study with five different wavelength meters from HighFinesse (WSU2, WSU10, WSU30, WS7 and WS7-IR)¹ of Fizeau-interferometer type. These have been compared to a frequency comb (FC 1500-250-WG) from Menlo Systems. As shown in Fig. 1, the commercial Ti:Sapphire laser (Ti:Sa) Matisse 2 TS from Sirah Lasertechnik that is pumped by a Spectra Physics Millennia 20 eV laser, was frequency-stabilized to its reference cavity. The cavity was locked to the frequency comb and all devices measured its frequency synchronously with an interrogation time of several seconds.

Each of the investigated wavelength meters consists of five Fizeau interferometers with different free spectral ranges (FSR) and two CCD line arrays to collect the resulting fringe patterns. The different resolution scales enable to trace down the wavelength of the irradiating laser by comparing it to reference patterns. The achievable resolution directly depends on the FSR of the finest interferometer which are 2 GHz (WSU) and 4 GHz (WS7) in our case, leading to 0.2–1 MHz (depending on the model) and 2 MHz, respectively. By using non-moving optics only and correcting for temperature and pressure changes, a high temporal stability is achieved. The investigated devices were calibrated with an iodine-stabilized Helium-Neon (HeNe) laser (Lasertex LJCS-3-11) to correct for remaining drifts. Depending on the device, the calibration laser is fed through the same port as the laser of interest by using a switch box or by using an additional rear port (only WSU10). In the latter case, the beam paths differ slightly making this approach more vulnerable to changes of external conditions. The devices are very sensitive and

¹ The WSU series has in the meantime been replaced by its successor, the WS8 series.

Table 1 Characteristics of the investigated wavelength meters

	WSU2	WSU10	WSU30	WS7(-IR)
Specified accuracy	2/10/30 MHz ^a	10/30 MHz ^b	30 MHz	60 MHz
Month/year of manufacture	11/2016	08/2012	05/2016	09/2012 (11/2007)
Frequency deviation across FSR	± 1.5 MHz	± 2 MHz	± 3 MHz	± 3.5 MHz
Drift after 1 h of operation	0.3 MHz/h	0.4 MHz/h	0.25 MHz/h	2 MHz/h
Drift after 2 days of operation	< 0.15 MHz/h	0.25 MHz/h	< 0.1 MHz/h	1.2 MHz/h
Drift autocalibrated	< 0.05 MHz/h	< 0.05 MHz/h	< 0.05 MHz/h	0.2 MHz/h

The manufacturers specifications for the absolute accuracy listed in the first row are fulfilled in all cases. On top of a global trend, a local variation of the wavelength meter's deviation to the real frequency was observed which was repeating with a period corresponding to the free spectral range (FSR) of the interferometer with highest resolution. The amplitude of this relative deviation can be regarded as the lowest uncertainty limit for the precision in case of laser scans. The WS7 behaved similar to the WS7-IR which are also examined in more detail in [14]. The temporal stability of the investigated wavelength meters in a temperature-stabilized room is given for a settling time of 1 h, of 2 days and with automatic calibration. The latter induced frequency jumps of up to one MHz even with stabilized reference lasers when calibrating the WSU10 via the rear port. Here, the drift of the mean value that is averaged over several calibration intervals is given. See text and Fig. 6 for more details

^a ± 2 nm/ ± 200 nm/elsewhere around calibration wavelength

^b ± 200 nm/elsewhere around calibration wavelength (according to 3σ criterion)

require only small laser powers of a few 10 μ W for operation at short exposure times of a few ms. All lasers are fed into the wavelength meter via single mode fibers. More specifications on the investigated wavelength meters can be found in Table 1 or in general on the website of the manufacturer (<http://www.highfinesse.com>).

The frequency comb is based on a femtosecond-fiber laser which is operated at 1550 nm in the Menlo Systems figure 9 ® mode locking technology. The mode spacing of 250 MHz is locked to a global-positioning-system disciplined quartz oscillator. The comb light is amplified and frequency doubled to access the visible and near-infrared spectrum. Feeding the light into a nonlinear photonic crystal fiber and optimizing particularly the initial polarization, frequency-comb light between 700 and 1000 nm can be generated. Sending this light as a free beam on a grating, a small wavelength range can be selected, coupled into an optical fiber and transported to a Menlo Systems beat detection unit (BDU). The laser of interest is coupled into the BDU via a single-mode fiber as well, where a fast photo diode is used to measure the beat frequency that can be monitored on a spectrum analyzer. By slightly adapting the comb's mode spacing, the beat frequency is shifted to 60 MHz and measured by a counter with corresponding frequency filter (Menlo Systems, FXM 4 channels) for data analysis. The integration time for each data point is 1 s. The absolute laser frequency measurement has an uncertainty of at most 50 kHz mainly introduced by the laser linewidth. The number of observed beat nodes is sent digitally to the Matisse control software to correct for long-term drifts of its reference cavity which has proven to be a very reliable laser stabilization. Slow but automatic frequency scans can be performed by slightly changing the mode-spacing of the comb since the laser is regulated to

reach its beat set point [22]. Adapting the laser frequency in ≈ 120 MHz steps corresponds to a change to the next beat which is located at the counter's filter acceptance frequency of 60 MHz. For investigating the spectral range between 750 and 950 nm, the laser frequency as well as the grating of the comb were adapted for each measurement.

3 Results

Five different characteristics of the wavelength meters were investigated in this study: to quantify the scanning behavior, coarse scans spanning several GHz were performed at several points in the accessible optical spectrum. The observed substructure was investigated in detail by increasing the resolution during a second set of measurements (fine scan). Besides these relative measurements, the absolute frequency offset to the frequency comb was analyzed and encountered to be strongly wavelength dependent. Additionally, the long-term stability of the wavelength meters with and without automatic calibration to a reference laser was analyzed. With these results a well-founded uncertainty estimation becomes possible.² We also demonstrated that a wavelength-dependent adjustment curve for the absolute frequency determination can be extracted from such measurements leading to a significant gain in the accuracy for experiments applying this wavelength meter.

² The values presented here are, however, only valid for the investigated devices. They can be different in case of other manufacturers, other production dates or even for devices from the same series.

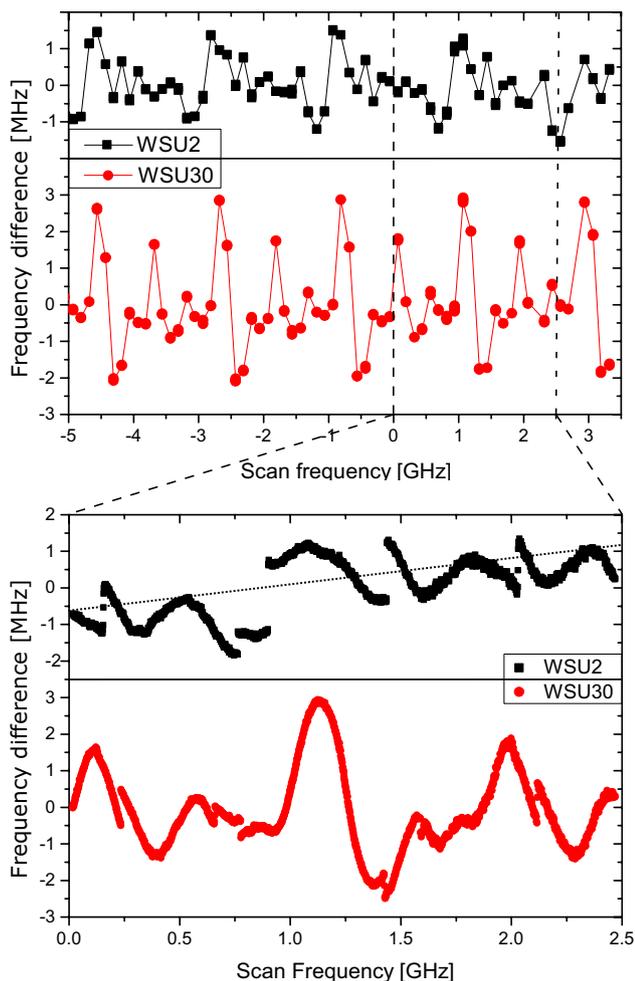


Fig. 2 Relative deviations of the frequencies measured with a WSU2 and a WSU30 wavelength meter from the real laser frequency determined with a frequency comb at 880 nm. Top: The laser frequency was scanned across 8.5 GHz in 120-MHz steps. The structure starts repeating with a period corresponding to the FSR of the most precise interferometer of the wavelength meter which is 2 GHz in case of a WSU. The mean offset which is discussed in Sect. 3.3 was set to 0 and the scale of the y-axis is identical for both traces. Bottom: A 2.5-GHz interval was repeated with higher resolution (1.3-MHz step size). For all investigated wavelength meters the function is not continuous and shows relative deviations of several MHz even for small laser scans of some 100 MHz. Since this measurement took several hours and the wavelength meters were calibrated with a HeNe only before the measurement, the slight drift of the mean deviation of the WSU2 (dotted line) can be ascribed to slow drifts of the device

3.1 Coarse scan

To investigate the scanning behavior of the wavelength meters in wide-range scans of several GHz, the Ti:Sa laser was scanned in steps of 120 MHz. At each set point, the laser was stabilized to the comb and frequency measurements with comb and wavelength meters were performed synchronously.

This procedure was conducted at several positions in the measurable spectral range between 750 and 950 nm. In all cases, a periodic structure in the difference between the frequency measured with the two device types was observed. A typical example for a measurement with the WSU2 and the WSU30 at about 880 nm is shown at the top in Fig. 2. For better comparison, the offset of the mean frequency was set to 0 and the scale is identical for both traces. At other wavelengths, the structure changes slightly in form but the periodical behavior stays constant: the structure is repeating with a period of 2 GHz in case of the WSUs and of 4 GHz in case of the WS7s. This periodicity corresponds to the free spectral range (FSR) of the highest-resolution interferometer of the corresponding wavelength meter and indicates that it is caused by nonlinear effects in the interferograms when scanning across the FSR.

During every period, the deviation from the real frequency changes quite rapidly: a laser scan by a few 100 MHz can easily lead to nonlinearities in the frequency axis of the order of several MHz. This contradicts the hope for a high relative precision of the wavelength meters in short-ranged scans and is of utmost importance if, e.g., hyperfine structure parameters or isotope shifts are to be extracted from the spectrum as is discussed in a second paper on this topic [14]. In Table 1 the amplitudes of the fluctuations are listed for the investigated wavelength meters in the third row. It corresponds to the lowest uncertainty limit that can be assumed in relative measurements as long as the nonlinearities are not precisely known and taken into account.

3.2 Fine scan

To analyze these unexpectedly large and periodically repeating deviations, a fraction of the coarse scan was repeated with higher resolution. The wavelength meters and the comb were read out in 1.3-MHz steps across a 2.5-GHz interval covering a complete period observed above. The corresponding results for the same devices are shown in the lower graph of Fig. 2. Surprisingly, the response is not smooth but shows several jumps which can be of the order of some MHz. This intensifies the problems for laser scans since they lose continuity. At other wavelengths similar patterns are observed.

All wavelength meters were calibrated with a HeNe laser before the scan measurements. Since the fine scan measurement took several hours, an additional drift of the WSU2 can be observed which is indicated by the dotted line in Fig. 2. Please note that calibrations of the wavelength meters with other reference lasers did not change this structure even if the reference was close to the measurement frequency.

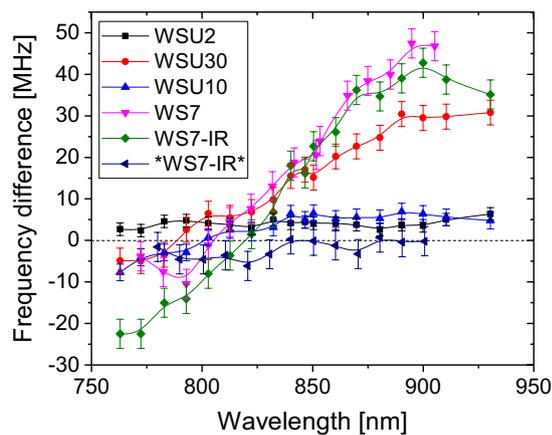


Fig. 3 Difference of the frequencies measured with various wavelength meters with respect to the comb. All wavelength meters were calibrated with an iodine-stabilized HeNe laser (exception *WS7-IR*, see text). The WSU2 and the WSU10 show the best performance while WSU30 and both WS7 show a wavelength dependent deviation to the comb. After updating the WS7-IR at the manufacturer with the latest calibration schemes, its performance could be significantly improved as shown by the *WS7-IR* curve. The spline curves connecting the data points are only introduced to guide the eye. All curves are only valid for the investigated devices and cannot be readily applied to other wavelength meters

3.3 Absolute frequency determination

Besides the relative precision of the wavelength meters, their absolute accuracy was investigated. As shown in Fig. 3, measurements were performed in the range from 750 to 950 nm in 10-nm steps. Before each measurement, all wavelength meters were calibrated at 632 nm with a HeNe laser of well-known frequency. The error bars depicted in Fig. 3 correspond to the variations across the GHz scale that were discussed above since these induce a local variation on top of the global trend.

While the frequency difference of the WSU2 and the WSU10 compared to the comb stays remarkably constant across the complete investigated range, the WSU30 and both WS7s show a large wavelength dependence. The offset to the real frequency changes by about 65 MHz for both WS7s, 35 MHz in case of the WSU30, 15 MHz for the WSU10 and 5 MHz for the WSU2 in the examined spectral range which nicely agrees with the manufacturers specifications listed in Table 1. The manufacturer informed us that the accuracy has been improved in the generations after 2016 by using an advanced opto-mechanical configuration and a new software algorithm that considers more reference measurements and includes an improved model to adapt for changes of environmental parameters. To verify this, the WS7-IR was updated after the first measurements and we tested its performance again depicted as *WS7-IR* in Fig. 3. The agreement with the frequency comb is significantly improved, reducing the

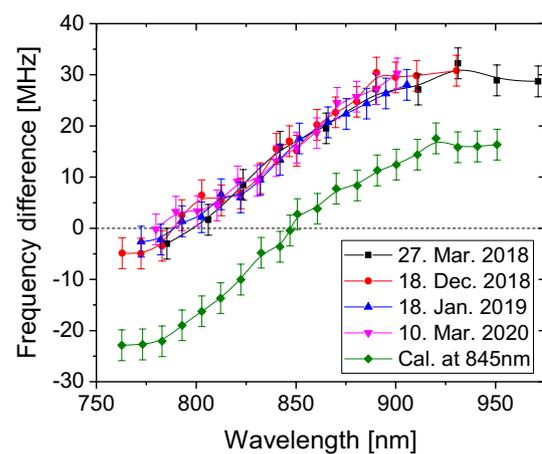


Fig. 4 Long-term observation of the frequency difference of the WSU30 to the comb and its dependence on the calibration point. If calibrated with the same HeNe laser (exception 10. March 2020, see text), no hints for changes were observed over several months of observation. A calibration with another reference laser at 845 nm induced a shift that removes the difference at this wavelength but kept the wavelength-dependent trend otherwise constant. The spline curves connecting the data points are only introduced to guide the eye

deviations below 10 MHz. Please note that the manufacturer clearly stated that this good agreement will not be achieved with the (new) WS7 in general and higher deviations should be considered. In case of this specific WS7-IR, the internal configuration of the interferometers is similar to those of the new WS8 and hence, many benefits of their recent developments take effect. This also shows that these curves are only valid for the examined wavelength meters. Nevertheless similar deviations will be observed for comparable devices across wavelength range.

The strong wavelength dependence of the WSU30 and both WS7 illustrates that the offset to the real frequency is not constant even for small wavelength differences of a few nm. However, this trend has been measured to be temporally stable as depicted exemplarily for the WSU30 in Fig. 4. Under constant external conditions, no indications for a change of the wavelength dependence could be found even after 2 years of observation time. Measurements with the other wavelength meters confirmed this long-term stability. In the same diagram, a measurement with another calibration source than the HeNe is shown. Here, the frequency-comb stabilized Ti:Sa operated at 845 nm was used as reference laser. This does not change the wavelength-dependent trend of the wavelength meter but shifts the curve vertically until the new calibration point at 845 nm coincides with the frequency measurement of the comb. Please note that the calibration for the *WS7-IR* in Fig. 3 and for the WSU30 measurement at 10. March 2020 in Fig. 4 were performed with a SIOS HeNe laser SL 02-1, which is stabilized by the two-longitudinal mode polarization locking technique and

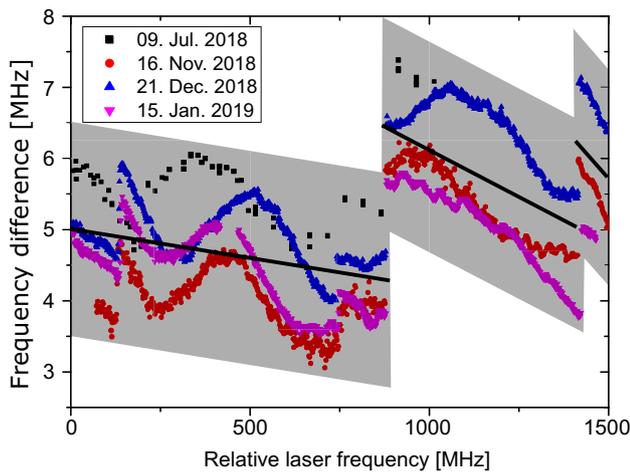


Fig. 5 Frequency-comb based characterization of the WSU2 at about 880 nm. During several months and transport of wavelength meter and calibration laser, no major changes in its deviation to the comb could be observed allowing us to define a frequency-dependent adjustment curve (black line). Taking the frequency jumps into account which have been discussed in Sect. 3.2, the uncertainty of the absolute frequency determination can be reduced into a ± 1.5 -MHz interval as indicated by the shaded area

was referenced to the iodine-stabilized HeNe 1 year before the measurement.

3.4 Wavelength-dependent adjustment curves

The long-term stability of the wavelength-dependency observed in Fig. 4 opens the opportunity to decrease the uncertainty in the absolute wavelength determination by characterizing the wavelength meter with a frequency comb. With such a measurement, a wavelength-dependent adjustment curve can be generated for the individual wavelength meter and an absolute frequency determination in the ± 5 -MHz range becomes possible. Otherwise, an increase in accuracy can only be accomplished using a laser providing a reference close to the wavelength of interest.

An even higher accuracy can be achieved for a frequency region of interest by a distinctive characterization of the wavelength meter with a comb exactly for this frequency. This was demonstrated for a high-precision experiment on trapped Ar^{13+} ions [21] in Heidelberg, Germany. Before and after the experiment, the WSU2 was compared to the comb at TU Darmstadt. External conditions and in particular the HeNe laser for calibration were kept constant which allowed us a frequency determination within a ± 1.5 -MHz uncertainty interval as depicted in Fig. 5. Measurements taken with the WSU30 in parallel, showed a similar stability. This illustrates that the observed substructure is also stable for a time period of at least several months and including transports which can be ascribed to the compact setup of the Fizeau

interferometers that includes no moving parts. This allows a calibration including the pattern leading to an accuracy of ± 1.5 MHz.

3.5 Temporal stability and automatic calibration

As demonstrated in [11], we also observed an improved stability when installing the wavelength meters inside of insulation boxes to reduce their sensitivity to temperature fluctuations. In our case the external temperature in the laboratory was already stabilized to 21.8 ± 0.3 °C but the temperature changes introduced by the air-conditioning system still caused corresponding fluctuations on a timescale of several minutes. In first order, the consequences of temperature and pressure changes are considered in the calculation of the wavelength but residual effects of thermal expansion and the change of the refraction index of all elements in the wavelength meter cannot be completely corrected. To buffer the external condition changes, the wavelength meters were placed in insulation boxes for all measurements described in this work.

The temporal stability of the wavelength meters was investigated as follows: the Ti:Sa laser was locked to the frequency comb, excluding drifts of the laser frequency. The strongest running-in effects of the wavelength meters were avoided by starting the measurement after 1 h settling time in which the laser beam was already fed into the operating wavelength meter. In this still not completely thermalized state, drifts of a few 100 kHz/h were observed for the WSUs and of about 2 MHz/h for the WS7s. Continuing this measurement, the drifts became less by time. After 2 days of continuously measuring the same laser, the WSU30 and the WSU2 exhibited drifts of less than 150 kHz/h. Contrary, the WSU10 and the WS7s still drifted significantly (see Table 1).

With the exception of the first hour of operation, these drifts can be reduced below 50 kHz/h (200 kHz/h for the WS7s) by a regular calibration ($t_{\text{cal}} < 10$ min) with a stable reference laser. The drawback of this method is that every calibration can induce a frequency jump which can be in the MHz regime. While this naturally depends on the stability of the reference laser, also large differences between individual wavelength meters have been observed: as shown in Fig. 6, the measured wavelength of the comb-locked Ti:Sa laser changed after every calibration when using the WSU10 which is calibrated through its rear port with an iodine-stabilized HeNe laser. Using the same iodine-stabilized HeNe to calibrate the WSU30 simultaneously by splitting the signal in a 90/10 optical fiber coupler, no frequency changes of the Ti:Sa frequency are observed. The higher laser power compensated additional losses in the switch box and both wavelength meters were operated at similar exposure times of a few 10 ms. The manufacturer states that this is due to

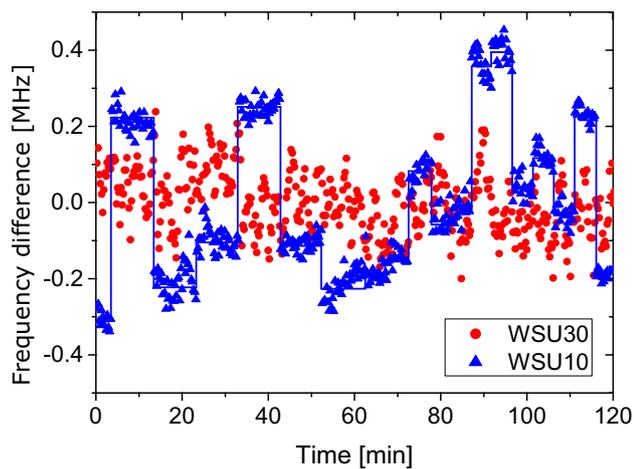


Fig. 6 Stability of the wavelength measurement using automatic calibration of the wavelength meters with an iodine-stabilized HeNe laser. The laser frequency that is measured is locked to a frequency comb. Hence, all frequency drifts can be ascribed to the wavelength meter. Using the automatic calibration function with an interval of 10 min in the first hour and of 5 min afterwards, no long-term drifts are observed. However, sudden frequency shifts that are correlated to the automatic calibration occurred in case of the WSU10 which is calibrated through its rear port. Contrary, the measurement of the WSU30, which is calibrated through a switch box with the same HeNe simultaneously by using a 90/10 optical fiber coupler, is not affected, by the calibration process

the complex and sensitive calibration algorithm. Even a very stable source can lead to such shifts when using the rear port for calibration purposes since both beam paths differ slightly in this configuration which makes this approach more vulnerable against external condition changes. Therefore, this option is not sold anymore for high-precision wavelength meters and switch boxes should be used instead. These frequency jumps even occurred when using the same laser for the measurement and the calibration by feeding it into both ports. This allows an easy test of this behavior if a stable laser system is at hand.

4 Conclusion

In temperature-stabilized environments, wavelength meters can be utilized for long-term monitoring of a fixed-frequency laser with sub-MHz relative accuracy if a stable calibration source is available. Besides fixed-frequency measurements, the studies presented here analyzed the performance in case of laser scans across several GHz. These revealed local deviations of a few MHz from the actual frequency even for laser scans of only a few 100 MHz. Since the response of the wavelength meters is unsteady on this scale, this has to be considered carefully.

The absolute accuracy of the wavelength meters meets the specifications of the manufacturer but cannot be expected to be significantly better. However, as has been demonstrated for the refurbished WS7-IR, a higher accuracy is reached for devices produced after end of 2016. The measurements presented here revealed a global trend of the wavelength meters' deviation from the real frequency which stayed constant over the examination period of 2 years. This allows to decrease the uncertainty for absolute frequency determinations even for older devices into a ± 5 -MHz interval by characterizing the wavelength meter with a frequency standard like a frequency comb in the corresponding range. Since this accuracy is sufficient for many experiments, this could become a cost-efficient and very flexible approach because a frequency comb would not be required permanently. As demonstrated in this work, the uncertainty in the absolute frequency determination can even be reduced into a ± 1.5 -MHz interval if the substructure of the frequency range of interest is resolved in the characterization measurements. Hence, this frequency-comb-based adjustment of wavelength meters can become a useful technique combining the advantages of both devices: the wavelength meters gain a high absolute accuracy but still offer the high flexibility and stay moderate in price. With the appropriate equipment, the effort for such a characterization is about 1 day.

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