

## Absolute distance interferometer in LaserTracer geometry

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### Abstract

An absolute distance interferometer based on a hybrid measurement technique was developed with the goal to achieve optimum performance in a LaserTracer. The challenges lie in the compact dimensions as very limited space is available and in the special design of the LaserTracer with a steel sphere as an interferometer reflector. To enable accurate absolute distance measurements three diode lasers are used, two permanently stabilized to D1 and D2 absorption lines of potassium at wavelengths of 770.1 nm and 766.7 nm. These are used for a two-colour measurement with the resulting synthetic wavelength of 174  $\mu\text{m}$ . The third laser is modulated and used for variable synthetic wavelength interferometry. Its measurement is used to unwrap the more accurate two-colour measurement. First results of this set-up in the laser tracer geometry up to 2.3 m length are presented, providing insight into the performance of this measurement principle in 3 D.

### 1. Introduction

Three dimensional measurements in large volumes up to the order of ten meters dimension with a relative uncertainty of  $10^{-6}$  get more and more important in coordinate metrology. These accuracies are required by a variety of practical applications such as the positioning of components in automotive engineering, or in aerospace industries. Optical measurements of such distances are usually performed by tracking laser interferometers as laser trackers [1] or laser tracers [2, 3]. Due to the special design based on a fix reference point, realized by a steel sphere around which the interferometer head is turned during tracking, laser tracers achieve interferometric accuracies for relative length changes. When using at least four laser tracers the absolute position of a common reflector can be determined during its motion from the measured relative length changes of the tracers [4]. However, to keep the correct length information, the beam must not be interrupted during a measurement. To remedy this problem, last generation's laser trackers have additionally a time of flight based absolute distance measuring system with an accuracy of approximately 10  $\mu\text{m}$ . This allows the initial length to be recovered after beam interruption within this accuracy limit.

Accurate absolute distance measurements have been in the focus of research in interferometry for approximately 30 years [5, 6]. Interferometric systems achieve a smaller resolution than systems measuring the time of flight but they require a continuous displacement of the reflector. There are various approaches to absolute distance interferometry. One approach is the application of two or more wavelength interferometry. The length is measured by different wavelengths. The interferometer phase difference corresponds to the phase of a synthetic wavelength which is longer than the optical ones. An unambiguous determination of the absolute distance is now possible within half of the synthetic wavelength which can, in principle, be arbitrarily increased. However, the measurement uncertainty increases according to the ratio of the synthetic to the optical wavelength which limits the useful measuring range.

Alternatively, the emission frequency of a laser can be tuned continuously. During the tuning the interferometer phase change is measured. Since the measured phases belong to slightly different wavelengths the principle is basically the same as the synthetic wavelength approach mentioned above. The unambiguous measuring range is only limited by the coherence length of the laser and the speed of the detection electronics. However, this "variable synthetic wavelength" approach is very sensitive to any movement of the reflector during a tuning period, e.g. to vibrations. Therefore, such movements have to be monitored and corrected by use of a second frequency-stabilized laser.

In this paper, a combination of variable synthetic and two-wavelength interferometry is deployed in a proof-of-principle experiment in laser tracer geometry. The study serves as a first step to investigate the potential of this technique for application in high-accuracy coordinate metrology.

## 2. Theoretical background

An absolute distance measuring unit for coordinate metrology must provide both, an absolute length measurement, but also a high-accuracy measurement, and not at least, a certain flexibility in order to offer an advance as compared to state of the art laser tracers. The combination of all aspects is non-trivial. In the past decades several approaches to high-accuracy absolute distance measurements have been investigated: classical multi-wavelength interferometry [5], frequency-sweeping absolute distance interferometry [7], or femtosecond-laser based white light interferometry [8]. None of these methods, however, completely fulfil all three of the criteria at once. Multi-wavelength interferometry suffers from a very limited unambiguity range, while even the most sophisticated schemes for frequency-sweeping interferometry do not achieve relative uncertainties better than  $10^{-6}$  on measured distances up to 30 m [9]. The applicability of white-light interferometry, on the other hand, is strongly impeded by the necessity of variable reference paths, i.e. moving mechanics.

Combinations of the former two approaches, so-called hybrid measurement approaches, have turned out to be extremely fertile [10, 11, 12]. Recently, the Physikalisch-Technische Bundesanstalt (PTB) demonstrated a diode-laser based homodyne interferometer to achieve relative uncertainties in the order of  $5 \times 10^{-7}$  with unambiguity range of up to 20 m. This level of accuracy can be obtained with reasonable effort. Therefore, this measurement principle was applied to improve the measuring capability of LaserTracers. In the following, the concept of the hybrid interferometry is discussed. A thorough treatment can be found, e.g. in reference [13].

Assuming a classical interferometer with a continuous wave light frequency  $\nu$  and a path difference  $l$ , the interference phase  $\phi$  is determined by

$$\Phi(l, \nu) = \frac{4\pi n}{c} \nu l \quad (1)$$

with  $n$  representing the index of refraction, and  $c$  the speed of light in vacuum. If for a fixed path difference  $l_x$  the frequency is tuned by a change of  $\Delta\nu$ , the phase changes by

$$\Delta\Phi(l_x, \Delta\nu) = \frac{4\pi n}{c} l_x \Delta\nu \quad (2)$$

If such a phase measurement is performed simultaneously for a well known path difference  $l_{ref}$  and an unknown path distance  $l_x$  with two adjacent interferometers, the length  $l_x$  can be determined by a linear regression of the data pairs  $(\Delta\phi_{ref}(\Delta\nu), \Delta\phi_x(\Delta\nu))$  by the linear relation

$$\Delta\Phi_x(\Delta\nu) = \frac{l_x}{l_{ref}} \frac{n_x}{n_{ref}} \Delta\Phi_{ref}(\Delta\nu) \quad (3)$$

where  $n_x$  and  $n_{ref}$  are the refractive indices in the measurement and reference path. In practice, however, uncertainties due to vibrations and thermal drift effects are scaled up by the ratio of  $\nu/\Delta\nu$ ,

leading to unacceptably large uncertainties. Therefore, the optical components must be monitored by a complementary experiment, e.g. an interferometer with a fixed wavelength  $\lambda_2$ . The phase change  $\Delta\phi(\Delta\nu)$  observed by the frequency change can then be corrected for vibration induced changes  $\delta\phi$  according to

$$\Delta\Phi_{corr}(\Delta\nu) = \Delta\Phi(\Delta\nu) - \frac{\lambda_2 n_1}{\lambda_1 n_2} \delta\Phi(\lambda_2) \quad (4)$$

with  $\bar{\lambda}_1$  representing the central wavelength of the frequency shift and  $n_1$  and  $n_2$  the respective indices of refraction.

But even if vibration and drift effects are compensated, the uncertainty of length deduced by the frequency sweeping measurement remains in the order of several micrometers. The uncertainty is quickly rising to several tens of microns with observed distances [13]. Therefore, this measurement is used in the hybrid measurement scheme only to unwrap the phase of a classical two-wavelength distance measurement. For this purpose, the phases  $\phi_1$  and  $\phi_2$  of two well-defined wavelengths  $\lambda_1$  and  $\lambda_2$  for the distance  $l_x$  are determined. The difference of these phases is

$$\Phi_1 - \Phi_2 = \frac{4\pi}{\Lambda} l_x$$

with 
$$\Lambda = \frac{\lambda_1 / n_1 \lambda_2 / n_2}{\lambda_2 / n_2 - \lambda_1 / n_1}. \quad (4)$$

The phase difference is formally equivalent to a phase of a so called synthetic wavelength  $\Lambda$  which is longer than the optical wavelengths  $\lambda_{1,2}$ . The measurement uncertainty of such a synthetic wavelength measurement is increased by a factor  $\Lambda/\lambda$  compared to the uncertainty of measurement with the optical wavelengths  $\lambda_1$  or  $\lambda_2$ . This limits the useable range for a synthetic wavelength. The lasers used in proof-of-principle experiment are stabilized onto Doppler reduced D1 and D2 absorption lines of potassium with wavelengths of approximately 766.7 nm and 770.1 nm which leads to a synthetic wavelength of 176  $\mu\text{m}$ . The required accuracy level of the coarse measurement using the variable wavelength approach must be below  $\pm\Lambda/4 \approx 44 \mu\text{m}$  in order to get the correct fringe order of the synthetic wavelength phase.

### 3. Experimental set-up

The former set-up described in [13] used two laser sources. One laser was permanently stabilised onto a potassium K-D1 absorption line at a wavelength of approximately 770.1 nm. The second laser was used alternatively with a laser frequency modulation for the variable synthetic wavelength method with a stabilisation on a K-D2 absorption line at approximately 766.7 nm for the fixed synthetic wavelength measurement. Switching between both modes, however, takes some time and delays the measurement. Therefore, the improved set-up described in this paper uses three diode lasers; two of them are external cavity lasers in the Littrow configuration which are permanently stabilised on a D1 and D2 absorption line of potassium. The third laser is a Littman type external cavity diode laser which is frequency modulated for the variable synthetic wavelength method. The wavelength of this laser is not critical and is around 780 nm. The interferometer phase of one of the stabilised lasers is also used for vibration compensation as described in section 2.

The interferometer is designed as a heterodyne type, where for each laser two acousto-optic modulators (AOM) operated with different frequencies are used to generate laser frequency shifts for

the measurement and reference beam. The optical set-up is straightforward as depicted in figure 1. The AOM frequencies are chosen so that the heterodyne frequencies, i.e. the frequency differences, are 1.5 MHz, 2.5 MHz, and 3.25 MHz. Small fractions of the light of both Littrow type lasers are coupled out by a half wave plate and a polarising beam splitter (PBS) for the stabilisation onto Doppler reduced potassium D1 and D2 absorption lines (figure 1, right part). The absorption lines are detected by a polarisation-optical differential technique [14].

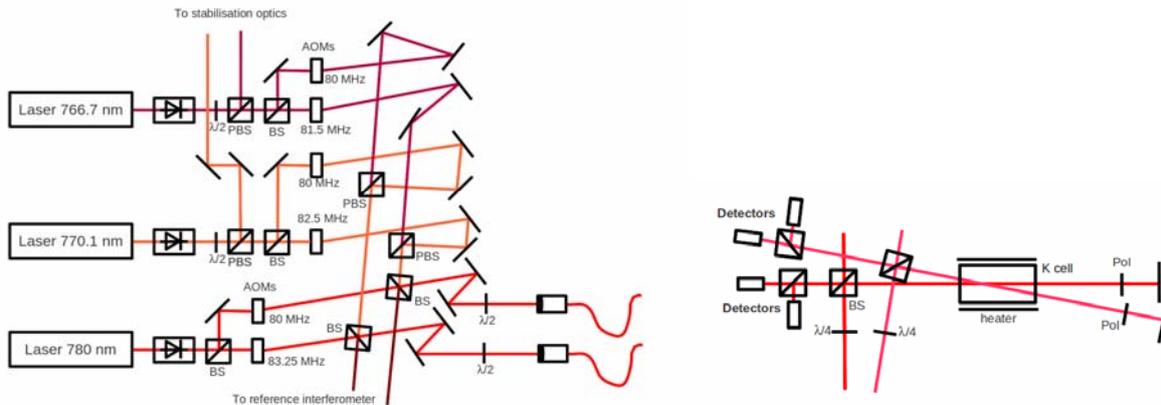


Figure 1: Optical set-up without interferometer head. Right part shows the stabilisation optics

For the variable synthetic wavelength method according to equation 3 a mechanically stable reference interferometer with fixed length is necessary. This reference interferometer (figure 2, left) is mounted together with the optics shown in figure 1 on the same breadboard. The light for the measurement interferometer head is coupled into polarisation maintaining single mode fibres. The three different reference and measurement beams are combined within a single fibre each. Since the two laser beams from the stabilised lasers are combined with a PBS only two beams match the polarisation maintaining axes of the fibres while the third one is polarised perpendicular to them. The optical power of the two Littrow type lasers behind the optical isolators is less than 1.5 mW. Due to the several optical components only approximately 50  $\mu\text{W}$  is present at the fibre outputs for each laser. The Littman type laser provides 6 mW power which is reduced by a grey filter so that the total optical power at each fibre output is  $\sim 170 \mu\text{W}$ .

The measurement interferometer head is constructed in the geometry of a tracking LaserTracer and is shown in the right part of figure 2. The beam for the measurement path (left fibre) is reflected by a PBS and then focused on the centre of a steel sphere with 12 mm diameter. The highly accurate sphere serves as stable reference (stationary point in space) when the interferometer head automatically follows a target corner cube and thus moves around the fixed sphere when tracking. The light reflected from the sphere then passes both PBS due to the lower quarter wave plate (Fresnel rhomb in this case) and is expanded to a diameter of 25 mm. After reflection from the target corner cube the light leaves the upper PBS and is brought to interference with the second beam. Due to the two PBS in the path all wavelength components of the beam must have the same polarisation. As mentioned above, the polarisation of the light on one laser is perpendicular to the others so that a half waveplate and a polariser are used at each fibre output. This drops off half of the optical power. A typical power level at the input of the lower PBS is about 40  $\mu\text{W}$  while at the output of the upper PBS only 7  $\mu\text{W}$  remains. Due to the non-polarising BS in front of the detector only  $\sim 3 \mu\text{W}$  are involved in the interference signal, almost evenly distributed on the three wavelengths. Nevertheless, the signal to noise ratio of the three interferometer signals reaches 30 dB.

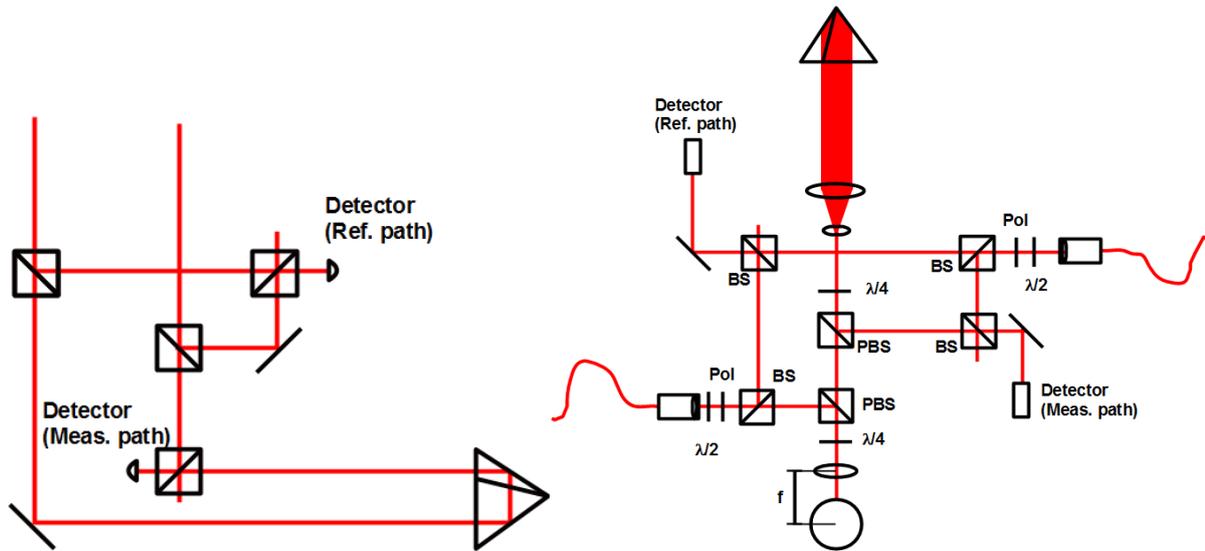


Figure 2: Reference interferometer head (left) and measurement interferometer head in LaserTracer geometry (right)

The demodulation and processing of the interferometer signals is done in software. At each of the four photo detectors (measurement path and reference path for measurement and reference interferometer) three heterodyne interferometer signals are present at frequencies of 1.5 MHz, 2.5 MHz, and 3.25 MHz. The detector signals are amplified to a voltage of  $\sim 3\text{V}$  peak to peak and coupled into a 16 bit A/D converter with a sample rate of 100 MSamples/s (SIS GmbH model SIS 3302). Onboard FPGAs convert the raw sample data from reference and measurement path into two pairs of sine and cosine values of the phase difference between them for all three heterodyne frequencies. This lock-in detection works by multiplying a block of 400 A/D samples ( $4\ \mu\text{s}$ ) with pre-calculated table entries of sine and cosine values of virtual references (1.5 MHz, 2.5 MHz, 3.25 MHz simultaneously). The amplitudes of the table entries have a Gaussian shape. The sums of these products are the low pass filtered sine and cosine values of the interferometer phases. Details about this procedure can be found in [15]. The resulting data are transferred via USB to a PC and are processed further to the length values.

#### 4. Experimental results

##### Synthetic wavelength measurements

The result of a length measurement with both stabilised lasers at a short distance of 0.35 m is shown in the left part of figure 3. The displayed length is only the fractional part, i.e. the integer multiples of  $\lambda/2$  corresponding to the fringe order are not considered. The black curves are calculated from the raw phase values with an averaging time of  $4\ \mu\text{s}$  while the red curves are moving averages over 1 ms. The noise on the signal of the 766.7 nm laser is higher due to lower optical power for this laser. The correlation of the standard deviation to the averaging time  $\sqrt{s}$  depicted in the right part of figure 4. It turns out that the standard deviation does not follow a  $1/\sqrt{N}$  law and decreases much slower with averaging time. The main reason is that the set-up was placed at the 50 m length comparator of the PTB without an air damped optical table. Vibrations of a couple of nanometres limit the standard deviation to some 2 nm.

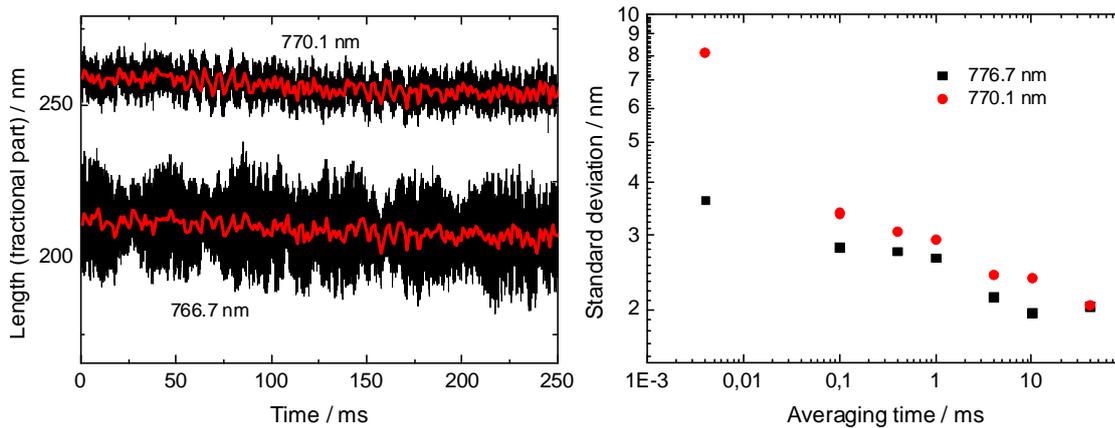


Figure 3: Fractional part of the length at 0.35 m as measured with both stabilised lasers (left). The red line is a 1 ms average over the raw 4  $\mu$ s samples. Corresponding standard deviations for the lengths are shown in the right figure.

Figure 4 shows the resulting length from the synthetic wavelength using the same data as in figure 3. In the red curve with the 1 ms average a 50 Hz ripple is visible. The dependence of the standard deviation on the averaging time displayed in the right part of figure 4 reflects this. For a suitable averaging time of 10 ms the standard deviation reaches a level of 0.1  $\mu$ m. The synthetic wavelength method is therefore working with sufficient resolution although the origin of the 50 Hz ripple must be clarified.

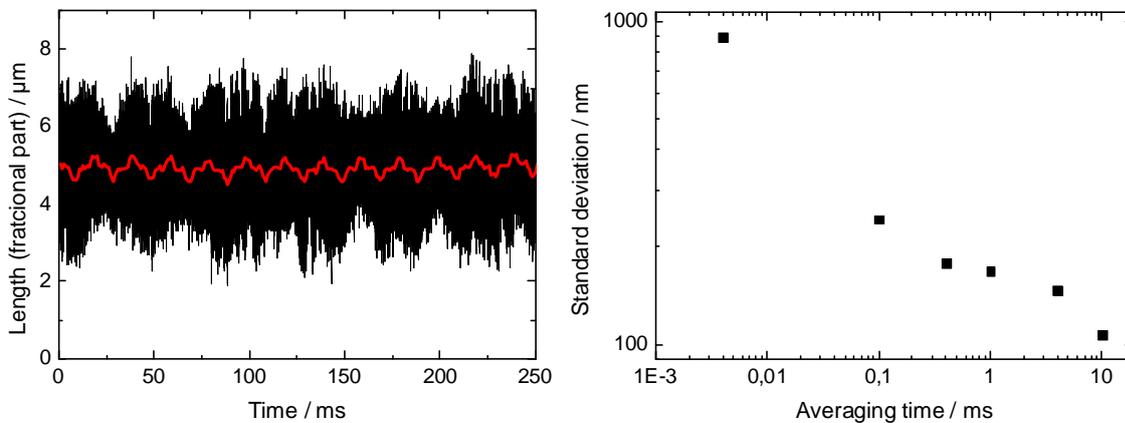


Figure 4: Fractional part of the length at 0.35 m as measured with the synthetic wavelength (left). The red line is a 1 ms average over the raw 4  $\mu$ s samples. The corresponding standard deviation for the length is shown right.

#### Variable wavelength measurements

The Littman type laser is modulated by its piezo with a 7.5 Hz sine signal. This leads to a laser frequency modulation of approximately 60 GHz while the resulting modulation form is a distorted sine. For an absolute distance measurement according to equations 3 and 4 at least a rising and a falling edge of the modulation must be measured due to a slight difference of the slope between  $\Delta\phi_{\text{ref}}(\Delta\nu)$  and  $\Delta\phi_x(\Delta\nu)$ . The raw phase values are corrected for vibrations and drifts according to equation 4. Here a problem occurs due to the short averaging time of only 4  $\mu$ s because the scatter turns out to be too large (see figure 3). The vibration correction has barely an effect if the raw phase

data from a stabilized laser is used. Therefore, the phases from the stabilized laser are first smoothed by 25 point moving average (100  $\mu$ s) which is fast enough to compensate typical vibrations in a laboratory.

For the length calculation the rising and falling edges of the modulation are searched in the sampled data. The length is then calculated by applying a linear fit on each edge between both corrected phase changes  $\Delta\phi_{\text{ref}}(\Delta\nu)$  and  $\Delta\phi_x(\Delta\nu)$ , using the average slope in equation 3. The minimum time for one absolute distance measurement is  $1/7.5 \text{ Hz} = 0.133 \text{ s}$ . Typical sampling times are 256 ms and 512 ms. The at first unknown length of the reference interferometer is calibrated by a comparison with a counting HeNe laser interferometer.

Figure 5 depicts the vibration corrected phase of the measurement arm after subtracting the linear fit. Besides the visible nonlinearities the scatter of the resulting data is of the order 0.5 rad and much larger than the scatter of the phases of the stabilized lasers. As an example, the standard deviation of 3.6 nm for the 770.1 nm laser in figure 3 corresponds according to equation 1 to a standard deviation of the phase of 0.06 rad. The signal-to-noise-ratio for this laser is the best one of the three lasers due to its higher optical power. The reason for the high scatter is still unresolved and may be caused by the dynamic behavior of the heterodyne signal processing. It should be noted that the phase scatter of this laser without modulation is smaller than that of the other lasers. This point is still under investigation. The homodyne interferometer used in the set-up in [13] did not show any differences in the scatter between the modulated and the stabilized mode of the laser.

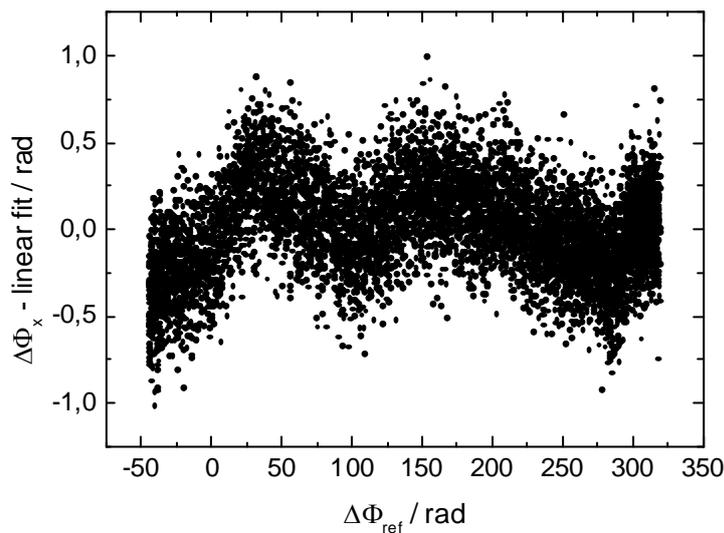


Figure 5: Phase of the measurement interferometer for one edge of the modulation after subtracting the linear fit plotted against the phase of the reference interferometer.

The large scatter in the phase accordingly leads to a large scatter in the measured length. Figure 6 shows an example of a length measurement at 2.344 m distance. An averaging time of more than one second is necessary to get an *uncertainty* safely below the allowed limit of half of the synthetic wavelength ( $\pm\Lambda/4 = 44 \mu\text{m}$ ) to determine the correct fringe order of the synthetic wavelength.

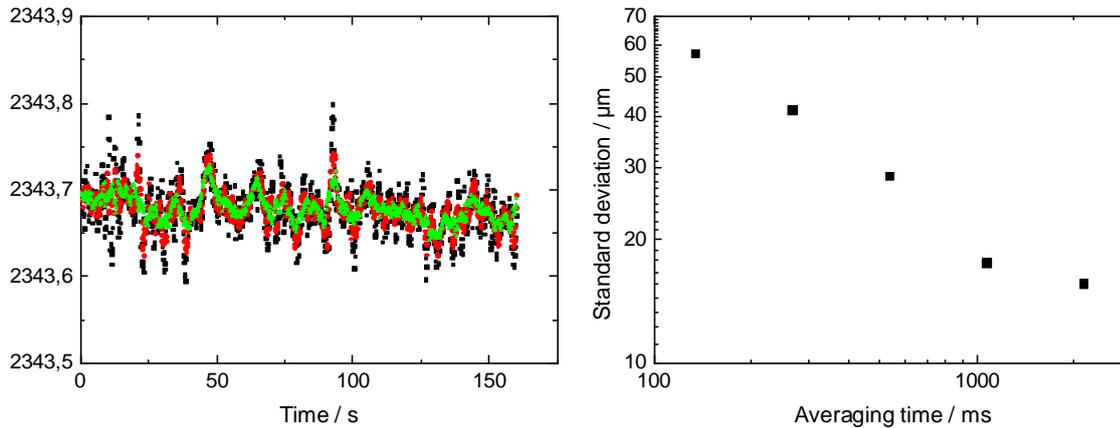


Figure 6: Stability of the measured length for the variable synthetic wavelength procedure for 0.5 s, 1 s, and 2 s averaging time (left) and the standard deviations (right).

## 5. Conclusion

An absolute measuring interferometer in LaserTracer geometry has been realised in this study. As approach, a hybrid combination of two-wavelength and variable synthetic wavelength interferometry was followed, promising a single-shot absolute distance measurement with interferometric accuracy without the necessity of moving parts. The design was successfully optimised to apply the complex multi-beam scheme in the limited geometry of the tracking head of a laser tracer.

The results presented in this paper, however, demonstrate that the compactification of the hybrid technique is a major challenge. The stability of the preliminary set-up deployed in this study is definitely insufficient. In particular, the remaining probing power of the two-wavelength laser sources must be increased. The laser tracer-typical geometry with a steel sphere as an interferometer reflector has a tremendous effect on the available optical power. Only 17 % of the incident light remains after travelling through the optics and after reflection at the sphere and a corner cube. Nevertheless, a signal to noise ratio of 30 dB could be reached with the heterodyne lock-in detection technique. The study reveals, however, that the deployed FPGA-based lock-in detection may have problems with the modulated signal for the variable synthetic wavelength method. In this case, the averaging time has to be at least 1 s to get the right fringe order for the synthetic wavelength. The reason is not completely clear at the moment and still under investigation. In the case of the interpolating two-wavelength experiment, averaging time scales of 0.1 ms were sufficient to obtain results with reasonable accuracies.

Together, this study demonstrates that the hybrid multi-wavelength interferometer can indeed be a tool to realise absolute distance interferometry within the laser tracer geometry. But it also revealed unexpected problems in particular in the digital data analysis which must be solved before the technology can be successfully deployed to daily and continuous use.

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