

A Multiwavelength Interferometer for Geodetic Lengths

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Abstract:

Within the EURAMET joint research project 'Absolute Long-distance Measurement in Air' an absolute measuring heterodyne interferometer was developed for a measuring range of 1 km with a targeted accuracy of 0.1 mm. Since one dominating uncertainty source for interferometric length measurement is the refractive index of air, especially under outdoor conditions, a two wavelength compensation method is integrated in the set-up. Measurements were performed on a 50 m comparator equipped with a HeNe laser interferometer.

Introduction

Length measurements in the range of the order of 1 km are usually performed by electronic distance meters (EDM) or total stations. Both are measuring the time of flight of laser light by a high frequency modulation of the intensity or polarisation. The largest uncertainty contribution for such outdoor measurements is the measurement of the refractive index of air, especially the temperature. The refractive index is normally calculated from an upgraded version of the Edlén equation [1]. A temperature uncertainty of 1 K, which is difficult to obtain for outdoor conditions, leads to an uncertainty in the refractive index and therefore the length of 1 mm/km. There is, however, increasing demand for lower uncertainties for high accuracy applications like calibrating geodetic baselines and GPS systems.

Interferometers have much higher resolutions in the nanometre range compared to EDMs and total stations but also suffer from the uncertainty of the refractive index. However, since more than 40 years it is known that the influence of the refractive index can be cancelled out by measuring a length with two different wavelengths simultaneously and considering their dispersion. In dry air this so called two colour method works without any knowledge of air temperature, pressure, and CO₂ content, see for example [2]. For moist air, the partial pressure of water vapour has to be known as the only air parameter [3]. In order to apply this principle for long range outdoor measurements, we developed an absolutely measuring interferometer. It deploys both wavelengths of a frequency doubled Nd:YAG laser making a compensation of the refractive index of air possible. In this paper, we discuss the set-up of the multiwavelength interferometer and present its performance under controlled conditions indoors up to a distance of 50 m.

Experimental set-up

Conventional interferometers perform only relative measurements and require counting of interference fringes during the continuous movement of the reflector. For long distance measurements up to 1 km length this technique is practically not applicable. A multiwavelength technique which deploys more than one wavelength in the interferometer allows an absolute measurement within half of the longest synthetic wavelength [4].

The basic idea of our interferometer is to use acousto-optic modulators (AOM) as frequency shifters to generate different synthetic wavelengths from a single laser source. Therefore the laser frequency does not have to be stabilized, e.g. to an atomic or molecular absorption line. The intrinsic frequency stability of the Nd:YAG (Innolight Prometheus 20) laser source used in the experiments of a few parts in 10^{-6} is sufficient. With this laser both, the Nd:YAG emission at ~ 1064 nm wavelength (1 W power), and the frequency doubled light at ~ 532 nm (20 mW power) are available at separate output ports. These two wavelengths are used also for the determination of the refractive index of air.

The 532 nm light is frequency shifted by an AOM operating at 1.7 GHz (Brimrose BRI-TEF-1700-200-532). Together with the unshifted light a synthetic wavelength of ≈ 176 mm is available. The 1064 nm light is frequency shifted by an AOM operating at 82 MHz which gives a synthetic wavelength of $c/82 \text{ MHz} \approx 3656$ mm. Since the set-up is a heterodyne interferometer, additional AOMs at frequencies of 80 MHz, 82 MHz and 83 MHz are used to get heterodyne frequencies of 2 MHz and 3 MHz. Figure 1 shows a schematic view of the optical set-up. By using the -1^{st} diffraction order of the 83 MHz AOM for the infrared light only 3 AOMs are necessary here. All other AOMs are used in the $+1^{\text{st}}$ order. Each two beams which are fed into a polarization maintaining single mode fibre are combined by a polarizing beam splitter (PBS). In front of each fiber a polarizer and a half waveplate are used to match the polarization maintaining axis of the fiber. The polarizers lead to a loss of 50% of the optical power.

The interferometer head is separated from the laser head and AOMs of Figure 1 and is shown in Figure 2. The corresponding beams of the 1064 nm and the 532 nm light are aligned on the same path. 50% of the intensity is directly brought to interference on the right side to get reference signals. The reference signals allow a compensation of the phase changes on the path from the breadboard with the laser source and AOMs through the optical fibres. Both the measurement and reference beam are directed through a polarizing beam splitter to get symmetric glass paths. A Fresnel rhomb acts as a broadband quarter waveplate. The returning beams interfere on the left side of Figure 2. Each of the four photo

receivers (FEMTO models HCA-S-200M-SI and HCA-S-200M-IN) detects a 2 MHz and a 3 MHz heterodyne signal.

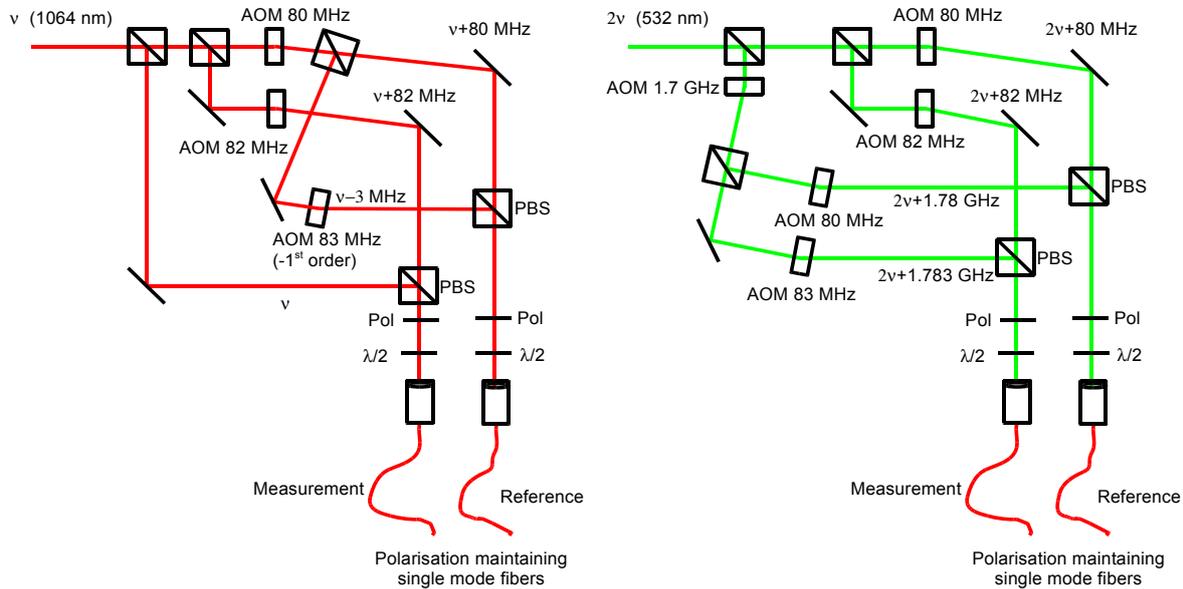


Fig. 1: Schematic view of the optical set-up for the generation of the heterodyne frequencies and the synthetic wavelengths for the 1064 nm wavelength (left) and the 532 nm wavelength (right).

The four heterodyne interferometer signals from the photo detectors are amplified by 10 MHz voltage amplifiers (FEMTO model HVA-10M-60-B) and digitized by a 100 MSample/s 16-bit A/D converter (SIS GmbH model SIS 3302). Each detector signal consists of a 2 MHz and a 3 MHz signal simultaneously. The A/D converter has one FPGA per two channels. An FPGA program converts the raw samples from one reference and measurement signal into two pairs of sine and cosine values of the phase difference $\Phi_{\text{meas}} - \Phi_{\text{ref}}$ for the 2 MHz and 3 MHz signal respectively. The digital lock-in detection works by multiplying a block of 1650 A/D samples ($16.5 \mu\text{s}$) with pre-calculated table entries of sine and cosine values (2 MHz and 3 MHz) which have a Gaussian amplitude shape. The sums of these products result in low pass filtered sine and cosine values of the phase. A detailed publication of this technique is in preparation, but a short introduction is given in [5].

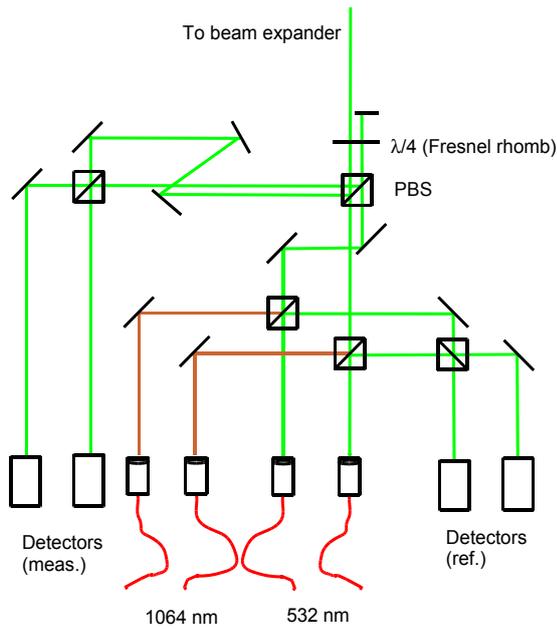


Fig. 2: Schematic view of the interferometer head. The beam expander for the measurement beam is not shown.

Measurement results

The performance of the interferometer was investigated at the 50 m comparator of the PTB. A counting HeNe laser interferometer was used as reference. 21 Pt-100 temperature sensors along the bench, two hygrometers and two pressure gauges were used to measure the air parameters and calculate the refractive index of air for the HeNe interferometer.

Figure 3 (left) shows the standard deviation of the length as measured with the 176 mm synthetic wavelength. The standard deviation decreases from 0.4 mm for the shortest possible measurement time of 16.5 μ s to approximately 10 μ m for a suitable averaging time of 1 s. The slope decreases for longer times indicating the beginning of drift effects.

It should be noted that for synthetic wavelength measurements the uncertainty scales with the ratio of synthetic to optical wavelength. Here, it is a factor of 176 mm/532 nm \approx 330.000. Therefore, a standard deviation of 10 μ m for the synthetic wavelength corresponds to a standard deviation of 30 pm for the difference of the lengths as measured with 532 nm wavelength. In the right part of Figure 3 the comparison to the HeNe laser interferometer is depicted for an averaging time of 0.3 s. The scatter increases with length so that for the targeted 1 km range longer averaging times are necessary.

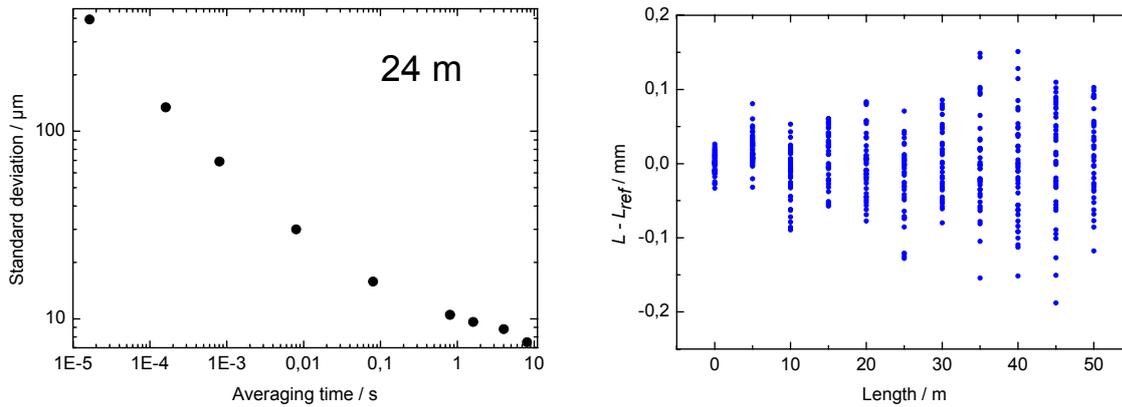


Fig. 3: Left: dependence of the standard deviation of the averaging time for a length of 24 m.

Right: difference between measured length and the HeNe interferometer reference length (L_{ref}). The averaging time was 0.3 s.

For this measurement the refractive index of air was derived from the dispersion between 532 nm and 1064 nm. By measuring the length with two different wavelengths a compensation of the refractive index is possible. Details about this compensation method in moist air are given in [3]. With this method only the partial pressure of water vapour is necessary to calculate the length which was taken from the hygrometers. The temperature and pressure have not to be measured. However, both lengths must be known with a typical interferometric accuracy. The present multiwavelength interferometer allows the absolute distance measurement only with the two synthetic wavelengths whose accuracies is not sufficient. Therefore the phases from one 1064 nm and one 532 nm wavelength were used.

As noted in [3], it is also possible to calculate the effective air temperature in the beam path from the measured lengths if the partial pressure of water vapour and the air pressure are known. Figure 4 shows the so calculated temperature along the 50 m bench compared to the Pt-100 temperature sensors. The difference is about ± 0.1 K over the 50 m, therefore the interferometer is also capable of measuring the temperature in the beam path synchronously to the length. The elevated temperatures at shorter path lengths are due to the heating of the electronics of the set-up which is located at the zero position.

Conclusion and outlook

The multiwavelength heterodyne interferometer is capable of measuring the absolute distance within the unambiguous range of ≈ 90 cm with a built-in compensation of the refractive index of air. Only the partial pressure of water vapour has to be measured separately. From

the length data it is also possible to calculate the effective temperature in the beam path if the air pressure is known. The interferometer will be used within the EURAMET joint research project 'Absolute Long-distance Measurement in Air' to measure the distances between the pillars of geodetic baselines up to 1 km length.

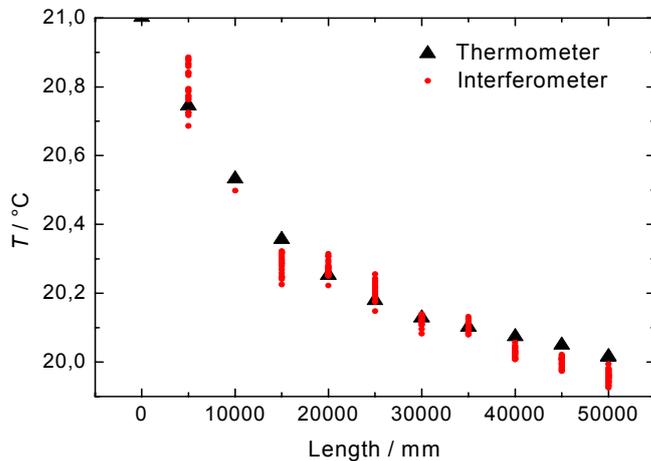


Fig. 4: Air temperature calculated from the lengths (red) and measured temperatures by Pt-100 sensors (black).

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References

- [1] B. Edlén, "The refractive index of air", *Metrologia* **2**, 71-80 (1966)
- [2] K. B. Earnshaw and J. C. Owens, "Dual wavelength optical distance measuring instrument, which corrects for air density", *IEEE J. Quantum Electron.* **3**, 544-550 (1967)
- [3] K. Meiners-Hagen and A. Abou-Zeid, "Refractive index determination in length measurement by two-colour interferometry", *Meas. Sci. Technol.* **19** (2008)
- [4] G. L. Bourdet and A. G. Orszag, "Absolute distance measurements by CO₂ laser multiwavelength interferometry," *Appl. Opt.* **18**, 225-227 (1979)
- [5] Ch. Weichert, J. Flügge, R. Köning, H. Bosse, and R. Tutsch, 2009, "Aspects of design and the characterization of a high resolution heterodyne displacement interferometer", *Fringe 2009*
- [6] G. Bönsch, E. Potulski, "Measurement of the refractive index of air and comparison with modified Edlen's formula", *Metrologia* **35**, 133-139 (1998)