SI-Traceable High-Accuracy EDM based on Multi-Wavelength Interferometry

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Abstract. An electro-optical distance measurement with an uncertainty below 1 ppm over distances of several hundreds of metres requires two challenges to be overcome: for once, the optical distance measurement must be performed with a respective measurement precision, and in addition, the index of refraction needs to be determined at the same level of uncertainty. These requirements are non-trivial, in particular in the uncontrolled environment typical for surveying.

At the Physikalisch-Technische Bundesanstalt (PTB), the German national metrology institute, multi-wavelength interferometry (MWLI) is investigated to find solutions to both problems. It is based on the combined analysis of the interferometric phase information of several well defined single mode lasers. The realization of this electro-optical technique benefits from modern optical sources and developments in beam manipulation. Two approaches to MWLI based EDM developed in the frame of the European Joint Research Project EMRP SIB60 Surveying will be presented:

Optical frequency combs are ideal sources for MWLI as they provide thousands of individual laser lines in parallel. However, unconventional measurement schemes are required to benefit from this property. We developed a novel method to access the available phase information and to enable a one-shot distance measurement with a macroscopic range, but potentially nanoscopic uncertainty and performed first proof-of-principle experiments of this potential approach.

Using robust high performance solid state lasers as sources, we developed in parallel the so-called TeleYAG system, a distance meter intended as a primary standard for the calibration of geodetic baselines. Nonlinear frequency-doubling and heterodyne MWLI enable a robust realization of dispersion-based refractivity-compensation. The optical set-up of the interferometer head was optimized for robustness, and the performance of the whole system was investigated in the field during measurement campaigns at three major baselines in Europe.

Keywords. EDM, multi-wavelength interferometry, index of refraction, EMRP JRP SIB60 Surveying

1 Introduction

One of the overall goals of the European joint research project SIB60 "metrology for long distance surveying" is the development of novel electro-optical distance measurement (EDM) methods targeting measurement uncertainties in the order of 0.1 ppm for measurements up to one kilometre in air (Pollinger et al. (2015)). The SI definition of the metre links the definition of the unit "metre" to the propagation velocity of light in vacuum c_0:

> The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. (Giacomo (1984)).

Due to the universality of the fundamental constant c_0 this definition is of indisputable conceptual beauty and robustness, and spiritual father of upcoming new definitions of other fundamental units within the SI system (Stenger and Ullrich (2014)).

There are different ways to implement this definition into the measurand (Quinn (2001), Schnatz (2012)). The direct implementation is to measure the propagation time for the distance in question. State-of-the-art EDMs often use pulse or amplitude modulation techniques to realise such a time-of-flight based measurement (e.g. Köhler (2012)). Time-of-flight based methods are ultimately limited by the time resolution capability

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of the detection and analysis electronics in practice to 1 ppm.

The relation $c = \lambda\,\nu$ connects the propagation velocity c, frequency ν, and wavelength λ of electromagnetic waves. Thus, if the frequency is known with high accuracy, the wavelength of an electromagnetic wave represents a natural scale which is directly traceable to the SI definition of the metre. This can be exploited by the interferometric measurement principle allows measurements with sub-nanometre accuracy in well controlled environments, in particular in vacuum. Already in the 19th century, Michelson and Benoît (1895) described the potential of this measurement method. The problem for the application in surveying, however, is twofold: for once, the range of non-ambiguity of this scale is limited to half the optical wavelength, and thus, in practice in the order of a few hundred nanometres. The extension of the range of non-ambiguity to macroscopic dimensions leads to the principle of multi-wavelength interferometry (MWLI, e.g. Meiners-Hagen et al. (2009)) which is introduced in the second chapter of this contribution. A second challenge is the fact that surveying measurements are usually not performed in vacuum, but in air. This alters the propagation velocity c of electromagnetic waves and, since the frequency remains constant, the wavelength λ and thus, the used scale. The index of refraction n relates the propagation velocity in the medium to the vacuum speed of light by

$$c = \frac{c_0}{n} \tag{1}$$

The index of refraction is dependent on the environmental parameters pressure p, temperature T, relative humidity h, and carbon dioxide contents p_{CO2}. The classical way to account for the index of refraction is to measure these quantities and to use semi-empirical formulas by, e.g., Ciddor et al (1996, 1999), or Bönsch and Potulski (1998) to deduce the index of refraction. The accuracy of such a measurement, however, is of course limited. Under uncontrolled environmental conditions in free space, e.g., even most dense environmental sensor networks are limited in their uncertainty. In sunshine, standard deviations of 1 K are a typical value (cf. Pollinger et al. (2012a)), limiting the knowledge of the index of refraction, and thus, also the achievable uncertainty of the length measurement to 1 ppm at best. For a measurement of typical geodetic distances of a few hundred meters with uncertainties reliably below 1 ppm, other approaches to refractivity-compensation must be used. It has been shown that inline spectroscopy can be used to derive effective values for temperature and humidity for the optical path (e.g. Hieta et al. (2012) and Pollinger et al. (2012b)). In this contribution, we apply dispersion-based optical two-colour compensation for our potential novel primary standard TeleYAG. The measurement principle is introduced in section 2.2.

Optical frequency combs are generally seen as highly potential sources in length metrology with direct traceability to the SI definition of the metre (Udem et al. (2002), Kim (2009)). They offer a broad and extremely well-defined spectrum. The frequency of the comb lines are completely determined by two frequencies only, the offset frequency f_{CEO} and the repetition frequency f_{rep}, which are typically in the radio frequency band and can be easily traced to primary high accuracy frequency standards. In a very straightforward application, for example, their high frequency stability can be used as precise and robust modulation sources for time-of-flight based measurements (Minoshima and Matsumoto (2000) and Doloca et al. (2010)). Again, also for this type of optical source, an interferometric measurement principle would have the potential of higher accuracy. First demonstrations have been highly successful (see, e.g., van den Berg et al. (2015) and references therein). In this project, a promising implementation of such a direct interferometric measurement has also been explored and the current status will also be discussed in this contribution.

After a brief introduction into the fundamentals of the methods discussed above, the paper will review the activities of the Physikalisch-Technische Bundesanstalt (PTB), the German national metrology institute, towards novel optical standards for long distance measurement. Experimental details can also be found in the specialised articles published already. In case of the TeleYAG system, the publications by Meiners-Hagen et al. (2014) and (2015), and Bosnjakovic et al. (2015) discuss the method and the experimental realisation in detail. A more thorough discussion on comb based distance metrology can be found in Yang et al. (2014) and (2015), and in Mildner et al. (2016, under review).

2 Method

2.1 Absolute distance interferometry

The measurement goal of absolute distance interferometry is the extension of the range of non-ambiguity from the optical wavelength scale of a few hundred nanometres to macroscopically accessible dimensions. In MWLI, this is achieved by the joint analysis of a simultaneous interferometric measurement with multiple wavelengths λ_i ($i = 2, 3, ...$). The phase difference $\Delta\phi_{ij}$ of two wavelengths $\lambda_{i,j}$ (with $\lambda_j > \lambda_i$) for a given optical path difference l is given by (Meiners-

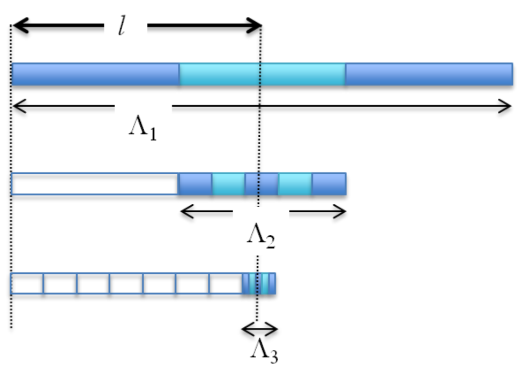

Fig. 1 Interpolation principle of ideal MWLI. More uncertain length results derived by longer synthetic wavelengths Λ_i are used to unwrap the more precise length information derived by shorter synthetic wavelength with a more limited range of non-ambiguity to determine the absolute length l with lowest possible uncertainty.

Hagen et al. (2015))

$$\Delta\phi_{ij} = \phi_i - \phi_j = \frac{4\pi n_{ij}^{g}}{\Lambda_{ij}} l \tag{2}$$

with the synthetic wavelength Λ_{ij} given by

$$\Lambda_{ij} = \frac{\lambda_i \lambda_j}{\lambda_j - \lambda_i} \tag{3}$$

and the group refractive index

$$n_{ij}^{g} = n_i - \frac{n_j - n_i}{\lambda_j - \lambda_i} \lambda_i . \tag{4}$$

Thus, by combination of the phase information of two interferometric measurements the range of non-ambiguity can be extended to half the synthetic wavelength which can be understood as envelope of the beat note between both measurement wavelengths. Unfortunately, the uncertainty of the observation scales with the ratio Λ_{ij}/λ_i. To obtain both, a long range of non-ambiguity and a minimum measurement uncertainty, typically multiple scales of different synthetic wavelengths are generated. The range is then determined iteratively: the length results determined by longer wavelengths are only used to unwrap the range of nonambiguity of shorter wavelengths. Using this interpolation, the absolute distance can be determined with potentially high accuracy (see also figure 1).

2.2 Optical refractivity-compensation

Already in the late 1960s Earnshaw and Owens (1967) developed a method to combine the measurement of two optical path length $l_1{=}n_1 l$ and $l_2{=}n_2 l$ with the knowledge on the functional dependence of the dispersion of the index of refraction n to derive the mechanical path distance l according to

$$l = l_1 - A(l_2 - l_1) , \tag{5}$$

with the parameter A depending only on the vacuum wavelengths. Strictly, this result is only valid for dry air. Nevertheless, the famous “Terrameter”, a commercial refractivity-compensating EDM available in the early 1980s was based on this principle (Hugget (1981)). In 2008 Meiners-Hagen and Abou-Zeid could show that for moist air, a similar formalism can be applied. Unfortunately, also this procedure comes with a cost in terms of uncertainty. Any uncertainty on the optical lengths is scaled up by the parameter A for the mechanical lengths. The TeleYAG system discussed in section 4 is based on the analysis of synthetic wavelengths. Thus, the dispersion of the group refractive index is relevant for the refractivity-compensated analysis. For the 1064 nm/532 nm wavelength combination used, the equivalent to the A factor amounts to 21 (Meiners-Hagen et al. (2015)).

3 MWLI based on optical frequency combs

In frequency space, the spectrum of an optical frequency comb can be understood as composed of

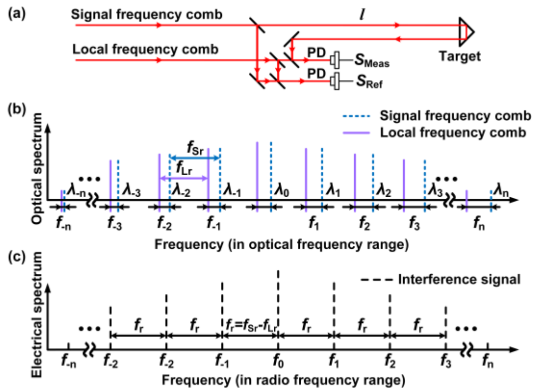

Fig. 2 Heterodyne signal processing scheme for a comb-based MWLI after Lay et al. (2003). (a) Optical setup of the heterodyne interferometer head. (b) Optical spectrum of the two combs. (c) Resulting radio frequency comb in the radio frequency band. (Figure modified from Yang et al. (2015))

thousands of well-defined continuous wave (cw) lasers. One prime challenge of MWLI, the configuration of an optical source providing multiple well-defined and mutually stabilized probe beams of different wavelengths is therefore fulfilled. The challenge, however, is an efficient extraction of the wealth of phase information. In 2003, Lay et al. proposed the so-called MSTAR scheme to use heterodyne detection for this purpose. It is sketched in figure 2. Two combs of different mode spacing f_{Sr} and f_{Lr} act as optical probes, one as signal comb S and the other one as local oscillator comb L (Figure 2(a)). The signal comb is divided on the interferometer head into reference and measurement beam. The phase shift of the individual comb modes due to the different path lengths of the two S beams, one (the measurement beam) traversing the unknown distance l, the other one (the reference beam) being measured directly on the head is the targeted measurand. The local oscillator comb L is also split and interferes with reference and measurement beams separately. Due to the different mode spacing and offset frequency of S and L combs, the frequency distance f_i between neighbouring comb modes $\lambda_{i,\mathrm{S}}$ and $\lambda_{i,\mathrm{L}}$ depends on the mode index i (figure 2(b)). In consequence, after interference, the beat note frequencies f_i form a comb in the radio frequency band whose modes can be directly traced back to the corresponding optical frequencies. The phase differences between reference and measurement beam of the optical comb modes are preserved in the down conversion. By digital lock-in detection, the phase information can be

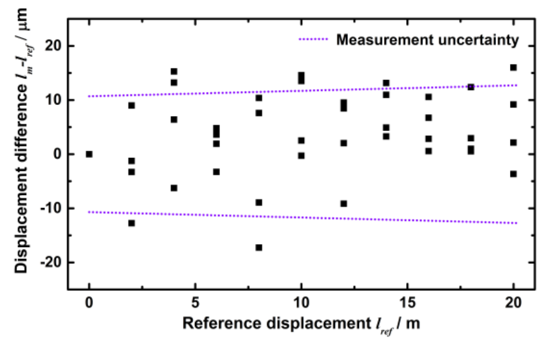

Fig. 3 Deviation of the length determined by the CEFCG-based dual comb heterodyne interferometer from the reference length determined by a counting reference interferometer (cf. Yang et al. (2015)).

derived for each electronic comb mode separately. The now accessible rich phase information can then be used to construct synthetic wavelengths series of different ranges of ambiguity. The challenge for an implementation of this measurement scheme, however, is the realisation of the coherent comb pair of different mode spacing. Within the SIB60 project, two approaches were followed.

In a first bottom-up approach, a comb doublet was generated by two coupled cavity-enhanced electro-optic frequency comb generators (CEFCGs) seeded by a single narrow bandwidth diode laser (Yang et al. (2014) and (2015)). This scheme allows a relative free choice of frequency parameters. While the comb mode spacing can be set relatively large (9.2 GHz in our case), the detuning of the two combs can be chosen to be as small as possible leading to carrier frequencies in the order of a few kHz only. Moreover the investment in optical components is limited. Frequency combs spanning over a spectral range of 300 GHz were generated in practice. Up to 16 comb lines were analysed in parallel, enabling a true instant multi-wavelength measurement. A measurement up to 20 m was successfully demonstrated, and a measurement uncertainty achieved of (see figure 3)

$$U(l) = \sqrt{(10.4\,\mu\mathrm{m})^2 + \left(1.1\times10^{-7}\times l\right)^2} \quad . \qquad (6)$$

The dominating length-independent uncertainty term was mainly attributed to the comb stability and bandwidth. Particularly promising was the scaling behaviour of the system. Neglecting refractivity effects, the uncertainty scales only in the order of 0.1 ppm with the measurement length.

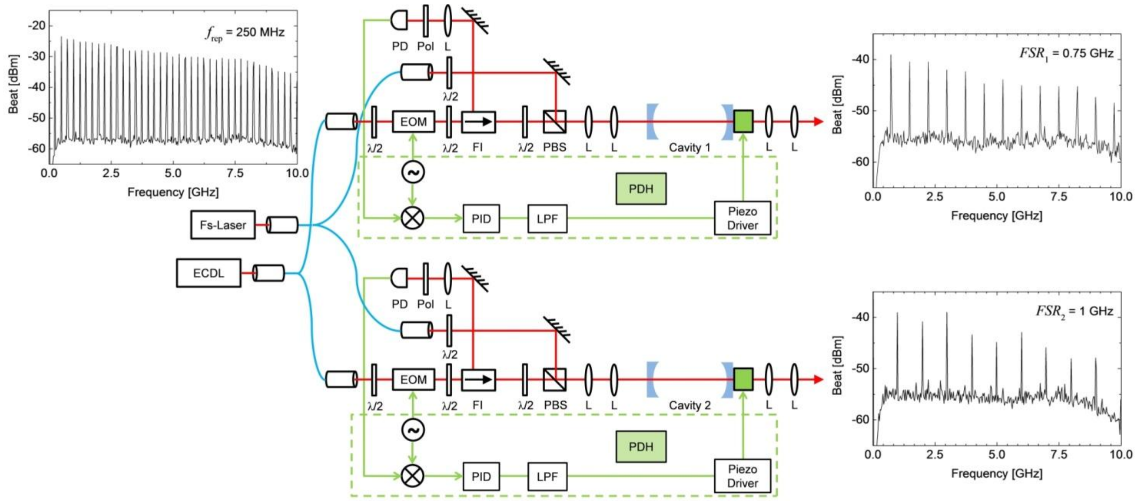

Fig. 4 Left: original spectrum of the seeding fibre comb with a repetition rate f_{rep} of 250 MHz. Centre: scheme of the dual comb generatore (Fs-laser: seed laser, ECDL: external cavity diode laser, EOM: electro-optic modulator, FI: faraday isolator, L: lens, PBS: polarizing beam splitter, PD: photo diode, POL: polarizer, PDH: Pound-Drever-Hall stabilization, LPF: low-pass filter, PID: controller). Right: resulting filtered mode spectra with repetition rates according to the free spectral ranges (FSRs) of the filtering cavities of 0.75 GHz (top) and 1.00 GHz (bottom).

Although the CEFCG scheme is definitely promising for application as an absolute distance measurement scheme due to its performance and limited costs, a further substantial reduction of uncertainty requires more stable combs of significantly broader bandwidths. Commercial fibre-based optical frequency combs easily achieve bandwidths of several THz with frequency stabilities solely determined by the stability of the frequency reference (i.e. typically 10^{-11} or better). The investment for such a comb system, however, is non-negligible. We currently investigate a dual comb generator scheme based on repetition rate multiplication (see Mildner et al. (2016), under review). Using Pound-Drever-Hall (PDH) stabilized cavities, the dense optical spectrum of a single commercial fibre comb is thinned out, generating two combs of different spacing in the GHz regime (cf. figure 4). A disadvantage is the fact that the degree of freedom for the choice of frequencies is much smaller than in the CEFCG case. As a consequence, one has to deal with relatively high frequencies in the signal branch. The detection electronics has meanwhile been successfully developed and tested, and first results on length measurements are expected soon.

4 The TeleYAG system

The core of the TeleYAG system are two Nd:YAG laser systems (Innolight Prometheus 20) emitting both the fundamental 1064 nm and the frequency-doubled 532 nm. The frequency difference of the fundamental beams is stabilized by a home-designed phase-locked loop (PLL) to $\Delta\nu = 20.01$ GHz, fixing the two synthetic wavelengths between the emitted light beams at 1064 nm to approximately $\Lambda_{1064} \approx 15$ mm and at 532 nm to $\Lambda_{532} \approx 7.5$ mm. The beat frequency $\Delta\nu$ is stabilized against a 20 GHz reference frequency derived from a 10 MHz rubidium frequency standard. This secures direct traceability to the SI definition of the metre. This basic scheme was introduced in 2010 by Azoigui et al. as an efficient and stable two colour synthetic wavelength source. However, using these synthetic wavelengths only, the range of non-ambiguity would be limited to 7.5 mm, requiring a pre-value with an uncertainty of better than 3.75 mm. In principle, for a geodetic reference baseline a pre-value of this quality is feasible. Nevertheless, to extent the range finding capabilities of the TeleYAG system, additional longer synthetic wavelengths of up to 150 m are generated by acoustooptic beam manipulation. For

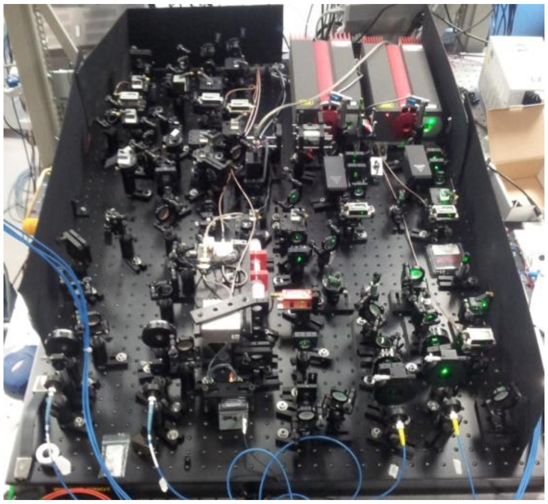

Fig. 5. Set up of the TeleYAG light source. (Figure from Bosnjakovic et al. (2015)).

signal detection, a heterodyne detection scheme was implemented. For the generation of the longer synthetic wavelengths and the necessary optical signal and local oscillator beams, seven acoustooptic modulators (AOMs) must be used. In practice, this implementation leads to considerable space request of the optical source (cf. figure 5). Mounting of this optical source on a geodetic pillar is in this current stage impossible. For field measurement campaigns, the optical source had to be stored into a transporter. Therefore, the measurement head was separated from the optical source and carefully designed to achieve maximum stability (see figure 6, cf. also Bosnjakovic et al. (2015)). Green and infrared measurement beams are superposed on the measurement head. The perfection of this superposition is critical for a meaningful joint analysis of the refractivity compensated length. All six interferometer signals are optically down-converted to different carrier signals in the MHz regime which are detected by two photo receivers for each wavelength. The photo receiver voltages are digitized by a commercial 100 MHz 16 analogue-to-digital (AD) conversion card with field programmable gate arrays (SIS3302 Struck Innovative Systeme). Details on the FPGA-based phase phase meter can be found in Köchert et al. (2012).

Using this prototype system, verification and design optimisation measurements were performed in 2014 on the 50 m indoor interference comparator at PTB Braunschweig, Germany, and in 2015 in outdoor campaigns on the 600 m geodetic baselines of PTB

Fig. 6. Field-capable TeleYAG measurement head mounted on the geodetic fundamental baseline in Nummela, Finland.

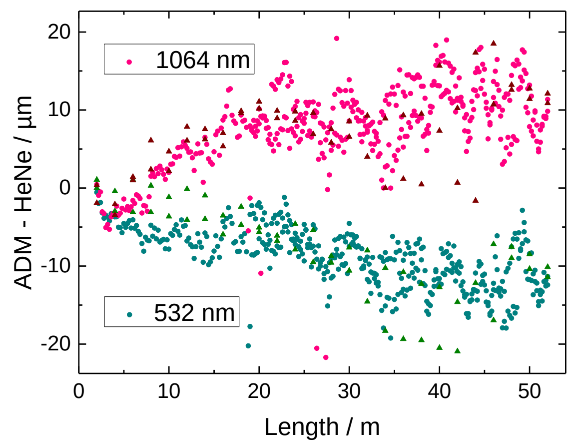

Fig. 7. Deviation of the lengths determined with the shortest synthetic wavelengths in the green and infrared from the reference length determined by a counting HeNe interferometer. The index of refraction for the analysis of this data was derived from the dense environmental sensor monitoring network installed at the PTB 50 m interference comparator. (Figure from Bosnjakovic et al. (2015))

Braunschweig, Germany, on the 1 km reference baseline of the Universität der Bundeswehr in Neubiberg, Germany, and on the 864 nm reference baseline of the Finish Geospatial Research Institute (FGI) in Nummela, Finland. On the indoor 50 m comparator, the deviation of the measured lengths of the shortest two synthetic wavelengths in the infrared and green remained below 20 µm for a conservative refractivity compensation scheme based on the twenty temperature and the two pressure sensors distributed along the 50 m bench (see figure 7). However, this measurement campaign also revealed a weakness of the initial design. The functional dependence of the observed deviation is almost linear and can be attributed to imperfect collimation. With the available degrees of freedom of the collimator optics used, a better achromatic collimation was not achievable. When correcting this effect in the raw data, the resulting refractivity-compensated length deviates by less than 200 µm over the 50 m (see figure 8). For the latter result, only the (collimation-corrected) optical length values and the value of the relative humidity were used, i.e. in particular no other external environmental sensor information.

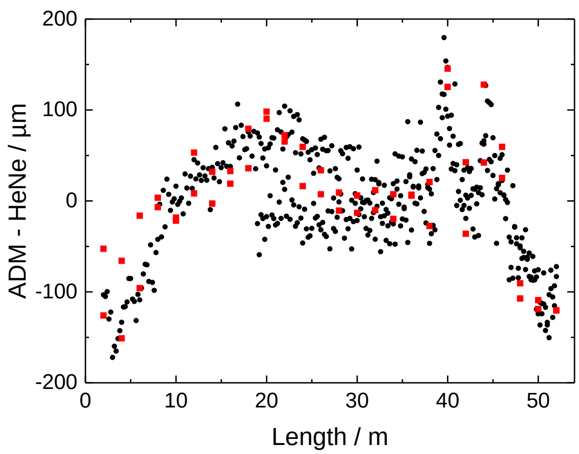

Fig. 8. Deviation of the refractivity-compensated length results for two measurements from the reference length determined by a counting HeNe interferometer. The raw optical lengths were corrected for the collimation error. For the derivation of the refractivity compensated ADM length, only the collimation-corrected length values and the relative humidity were used. (Figure from Bosnjakovic et al. (2015)).

After modification of the collimation optics, outdoor measurement campaigns were performed. Field conditions revealed further weaknesses of the design, such as missing degrees of freedom for the alignment optics of the green measurement beam. While this could be fixed, outdoor campaigns in Neubiberg and Braunschweig made clear that despite the large effort for mechanical stability, the offset of the head remained unstable on tenth of millimetre level. Thus, the notion of an EDM capable of a "true" absolute measurement had to be abandoned. For baseline calibrations, however, differential measurements (i.e. retro-reflector on pillar 1 and pillar 2 to determine the pillar distance) are acceptable, too. Using such a strategy, convincing preliminary results for the refractivity-compensated distance measurement could be obtained on the baseline of Nummela, with deviations on sub-millimetre level for the full distance of 864 m. Details will be reported once the joint overall analysis has been performed and the performance is independently confirmed

5 Conclusions

MWLI is a powerful tool to realise a refractivity-compensated absolute distance measurement with high accuracy. The fundamental experimental studies on frequency comb based heterodyne MWLI show promising results, but there is of course still a lot of development necessary before this technology might find a broader application.

In case of the TeleYAG, the ambition to develop a novel primary standard for baseline measurements with uncertainties on 0.1 ppm level was high indeed. With no doubt, the current extension and complexity of the system prevents a broader use and the identified remnant instabilities require a strict measurement protocol to follow. However, the latest outdoor measurement campaigns indicate that the boundary conditions of the system are now pretty well understood. Moreover, if these boundary conditions are accepted and respected by the measurement protocol, the system has shown a convincing performance. Primary calibration on 0.1 ppm level of baselines is definitely possible. Nevertheless, PTB will continue the optimisation of the measurement principle. A simplification and compactification of the source has high priority to enable broader applications.

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