

TOWARDS NEW ABSOLUTE LONG DISTANCE MEASUREMENT SYSTEMS IN AIR

Speaker : Jean-Pierre WALLERAND, LNE-INM/CNAM, 61 rue du Landy, 93210 La plaine saint Denis, France, tel:+33 1 40 27 20 54, Fax :+33 1 50 80 89 00, email:jpw@cnam.fr.

Authors: Ahmed Abou-Zeid⁹, Thomas Badr⁶, Petr Balling³, Jorma Jokela⁴, Rupert Kugler¹, Michael Matus¹, Mikko Merimaa⁷, Markku Poutanen⁴, Emilio Prieto², Steven van den Berg⁸, Jean-Pierre Wallerand⁶, Massimo Zucco⁵

¹ Bundesamt für Eich- und Vermessungswesen (BEV), Austria

² Centro Español de Metrologia (CEM), Spain

³ Czech Metrology Institute (CMI), Czech Republic

⁴ Finnish Geodetic Institute (FGI), Finland

⁵ Istituto Nazionale di Ricerca Metrologica (INRiM), Italy

⁶ Laboratoire National de Métrologie et d'Essais-Institut National de Métrologie (LNE-INM/CNAM), France

⁷ Centre for Metrology and Accreditation (MIKES), Finland

⁸ NMi Van Swinden Laboratorium B.V. (NMi VSL), Netherlands

⁹ Physikalisch-Technische-Bundesanstalt (PTB), Germany

Abstract:

For the first time, the different national laboratories of metrology constituting EURAMET decided to create an European Metrology Research Program (EMRP). Length is one of the quantities represented in this program. In this framework, a project called “Absolute long distance measurements in air” has been elected. This project is bringing together during 3 years, 9 laboratories from 8 different european countries, sharing skills and facilities : France (LNE), Germany (PTB), Italy (INRiM), Finland (MIKES and FGI), Czech Republic (CMI), Netherlands (NMi VSL), Austria (BEV) and Spain (CEM). As suggested by its title, the project has the ambition to improve the current state of the art in the long range distance measurements (> 10 m up to 1 km outdoor), reaching a relative accuracy of 10^{-7} , that is at present time a challenge.

The greatest challenge is precise knowledge of effective refractive index over such a long range. Indoor or outdoor systems (‘weather stations’) only measure local parameters such as air temperature, pressure and humidity from which air refractive index is deduced. No technique currently exists to measure the mean air refractive index in rather long range (several 100 m) and *a fortiori* outdoor. We will develop a spectroscopic technique to measure effective temperature and humidity all along the measurement path and paralelly we will develop a technique of partial air index compensation, that needs also a humidity measurement. These two techniques will be validated indoor over 30 m with an absolute refractometer under well controlled atmosphere. The capability of these instruments to work outdoor will then be tested in a 1 km baseline equipped with several classical weather stations along the path.

Classical optical interferometry is not appropriate for long range absolute distance measurements because of the great sensitivity to atmospheric and mechanical perturbations and of the interferometric fringe order determination. We will develop a technique using a synthetic wavelength of the order of some millimeters, generated by two different lasers, frequency separated by some 10 GHz. This has the advantage of low sensitivity to perturbations and of a less restrictive fringe order determination issue. Two different systems will be developed in two different laboratories. Associated to air index determination

techniques and to air index compensation developed in the project, this should allow us to reach the accuracy targeted.

We will also use techniques based on frequency comb as a tool for distance measurements. Two different techniques will be implemented. The first one will use the fact that the phase relation between the pulses emitted by the ultrafast laser is conserved. As a result interference between different pulses is possible. Another way of applying the fs frequency comb for long distance measurement, is to use the comb as an advanced frequency modulator.

Finally, we will organize outdoor comparisons. Systems based on synthetic wavelength developed independently in two different laboratories will be used to measure two well known 1 km long baselines located in two different places.

Introduction

Long range absolute distance measurements in air with a relative accuracy of 10^{-7} are at present time a challenge. Currently, long-range measurements are performed with electronic distance measurement (EDM) instruments. Best of these instruments is undoubtedly Kern Mekometer ME5000 with measurement range of 20 to 8000 m, a relative accuracy better than 10^{-6} and a relative resolution of 10^{-7} (0,1 mm over 1 km). Many of these instruments are still in use, but new instruments have not been available since 1990's. They are based on the principle of measuring the phase shift of a modulation frequency along the measurement path. Such instruments may be calibrated using a calibrated baseline. The traceability to the meter is ensured by 1 m quartz gauge blocks, which the Väisälä comparator virtually multiply the length up to around 1 km. At the moment the Finnish Geodetic Institute is the only metrological institute in the world maintaining and developing this. The relative accuracy of such measurements is 10^{-7} , under good atmospheric conditions. The realisation of such calibrations is very time-consuming and requires very stable atmospheric parameters. What we propose is the conception of a new generation of instruments making easier these calibrations and basically with a higher resolution. Moreover, the validation of these new techniques for such calibrations would be greatly benefit for the confidence in the traceability chain in long distance measurements.

These techniques are now often supplanted by GPS technology, which takes its traceability from frequency metrology. However, there are many effects which limit the accuracy and traceability of GPS system. Unmodelled errors often require independent site calibration. In many cases, such a calibration is very time-consuming or even impossible to perform. Due to these, distances measured with GPS are not traceable to the definition of metre. On global scale one can achieve 10^{-9} relative accuracy but there is no direct check on the absolute scale. Over shorter distances (> 10 m up to several km) GPS scale traceability will be the major problem and accuracy is about 10^{-6} or worse.

New precise instruments should be urgently developed for geodetic metrology and more generally for long range workshop environment distance measurement. Precisely calibrated geodetic baselines will be used for verification and further development of global mapping systems like e.g. Galileo, which, at the moment, derive traceability via frequency metrology.

1. Air refractive index determination

Challenge in the field of long distance measurement is precise knowledge of effective refractive index over the large range. Traditionally the refractive index of air has been directly measured using refractometers or calculated using the empirical Edlén equations.

Since the update of the Edlén equations, refractive index in controlled environments is almost universally calculated from the environmental parameters for a given wavelength: temperature, pressure, CO₂ concentration in air, and partial pressure of water vapour [1], [2]. For open air measurements the Ciddor formula [3] is taken as standard by International Association of Geodesy. The accuracy of these formulas is admitted to be $3 \cdot 10^{-8}$ by the international community, validated by international comparisons. In long range measurements, environment can not be stabilized and especially temperature or humidity changes can be fast. Local measurements made by several sensors along the measurement path can reflect only partially the actual changes in the mean value of measurands along the path. We propose to apply spectroscopic methods to measure humidity and temperature that would be measured along the path where the distance measurement is achieved. To obtain an accuracy of 10^{-7} for the refractive index, assuming no other contribution, the accuracy required for the temperature measurement is 0.1 °C (2σ) and 4% for the relative humidity. Instruments measuring these effective temperature and air humidity over several 100 m are not available today.

1.1 Absolute refractometer

Local refractive index can be measured primarily by refractometers. Accuracies of the traditional refractometers are typically some 10^{-8} [4], but lowest uncertainty can be obtained only with stationary devices. Thus, more accurate methods are needed for reference methods, and more compact and transportable devices are desirable for practical measurements.

Traditional local gas refractometers are based on an optical resonator. The index of the gas is deduced by measuring the frequency shift of a laser locked to a peak of the resonator, when the resonator, initially under vacuum, is filled with the gas. The accuracy of such an instrument is essentially limited by the knowledge of the mechanical characteristics of the Zerodur resonator. The issue is that the mechanical length of the resonator varies due to the pressure change. This implies that a correction has to be applied to the final result, requiring a mechanical modelization of the cavity and knowledge of the mechanical properties of the material. Typically, the uncertainty of the value of the Young modulus (given by manufacturer) leads to a final uncertainty for the air index of some 10^{-8} . To overcome this limitation, we will use a new improvement recently implemented in NIST [5]. The idea is to use a first mechanical calibration step using a given pressure of helium. The refractive index of helium may be determined via ab initio calculation of its polarizability with an accuracy of some 10^{-11} , if the pressure and temperature of helium are known with sufficient accuracy [6]. So, the contribution of distortion of the cavity may be discriminated from the contribution of the air refractive index variation, for any given pressure.

1.2 Spectroscopic methods

Spectroscopic approach to measure humidity and temperature has an inherent potential to significantly improve the accuracy of long-distance dimensional measurements, especially in outdoor environment. Spectroscopic measurement of the parameters of the ambient air is fast and allows synchronization with the actual length measurement. Furthermore, the same beam path can be used in both spectroscopy and length measurement, thus yielding perfect spatial and temporal overlap with the determination of the refractive index or humidity and the length measurement.

Humidity sensor :

Water has relatively strong absorption bands around 1.38 μm and 1.88 μm [7], and a line with suitable intensity could be selected for each desired distance range to optimize for sensitivity. Laser sources are commercially available for both wavelength ranges [8].

Temperature sensor :

In theory, temperature measurement could be performed through careful measurement of the Doppler-broadened line shape, but this is inherently difficult due to linewidth insensitivity to temperature already at around room temperature and broadening caused by other atmospheric gases. Comparison of absorption strengths of two lines with different lower state energies would yield easier and more accurate measurement [9], as the line strengths depend only on temperature. For temperature measurement using the spectroscopic line strength comparison method at near room temperature, potential candidate molecules are oxygen and water, possibly allowing combination of the humidity and temperature measurement. Oxygen is relatively weak absorber, but suitable line pairs can be selected to optimize sensitivity, see Figure 1. Also much of the previous work has been done with oxygen in combustion. The measurement is essentially similar to the concentration measurement using diode laser spectroscopy, with which we have already been involved, and laser sources are commercially available at the 760 nm range.

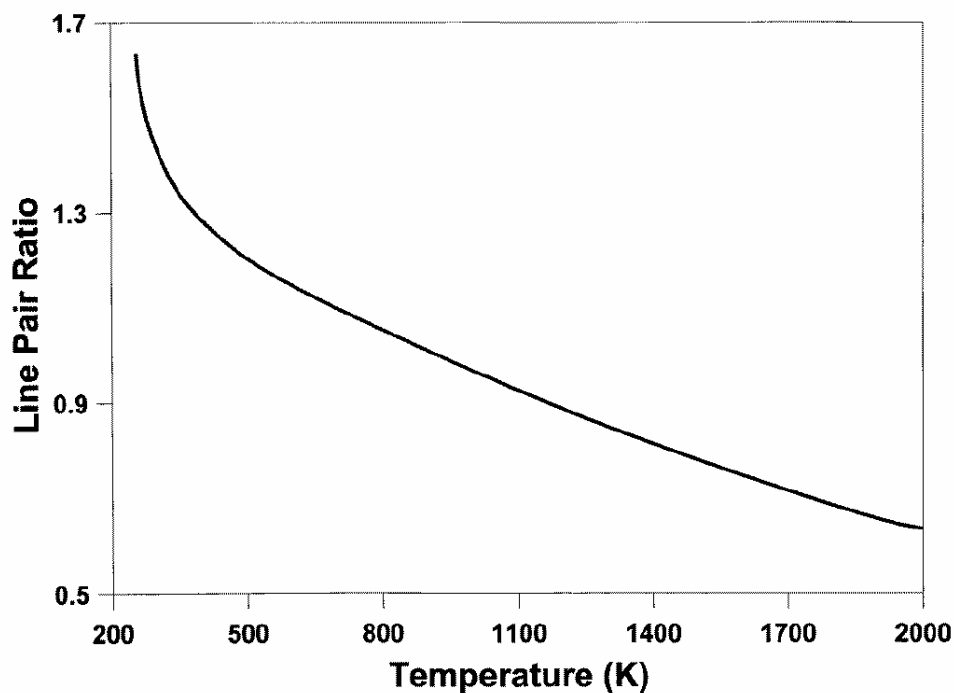


Figure 1. Dependence of the line pair ratio on temperature for oxygen molecular lines $R_{13}Q_{14}$ and $R_{15}R_{15}+R_{43}Q_{44}$ at around 760 nm. Notice enhanced sensitivity at room temperature. Figure from Ref. [9].

The proposed task will go beyond existing methods through applying purely spectroscopic methods to measure ambient conditions using very nearly the exactly same beam path that is used in the long-range distance measurement. Spectroscopic method allows synchronization between environment monitoring and length measurement at an unprecedented scale. Even though the uncertainty of the temperature measurement will be modest compared to traditional locally measuring thermometers, even 1 $^{\circ}\text{C}$ accuracy for the average temperature in the beam path would be significant improvement to the existing methods in the outdoor environment. The major technical risks in the project are related to the attainable

spectroscopic accuracy: if absorption can not be measured at sufficient uncertainty the uncertainty of the result will be too high to yield meaningful measurement. However, uncertainty below 1 °C seems realizable, considering the uncertainties in relative spectroscopic measurements and the sensitivity shown in Fig 2. The expected output result will be a spectroscopic instrument that can be integrated as a part of an long-range distance measurement and which will provide, through measurement of humidity and temperature, the refractive index of air at an uncertainty that will reduce the overall uncertainty of the measured dimension.

1.3 Partial compensation of air index

A well known alternative approach to the air index measurement is to measure a length with two different wavelengths. Both measured lengths $L1$ and $L2$ differ due to the air index dispersion if they are calculated with the vacuum wavelengths. The mechanical length L is then given by $L = L1 - A (L2 - L1)$. In dry air the factor A depends only on both wavelengths and not on the environmental parameters. In moist air however the influence of the partial pressure of water vapour remains in the equation for the length. We performed two wavelength interferometry where the relative humidity and the air pressure were measured. The effective temperature in the measurement path and therefore the mechanical length can be calculated from both length results using these values. A better approach for long range applications would be to measure the effective humidity in the measurement path by absorption spectroscopy. Here also the pressure is measured conventionally and the effective temperature is calculated from both length results.

1.4 Validation of techniques

The instruments developed concerning humidity and temperature measurements will be compared in the same atmosphere in a special room temperature controlled to 0.1°C and humidity controlled to 2%, located in Finland (MIKES). The instrument developed in PTB will be verified outdoor with their own baseline.

Air refractive index: the refractometer developed in task 2.1 will be implemented in MIKES in an air controlled room, where a moving rail of 30 m is available. This will enable us to map the air refractive index over a given path. Along this path, the air refractive index will be measured by Edlèn formulas. This will permit to compare the direct measurement of the air refractive index with Edlèn formulas applied in a controlled atmosphere using our new effective atmospheric sensors.

Outdoor comparisons: The temperature and humidity sensors developed in the WP will measure atmospheric conditions along the Nummela baseline. These mean values will be compared to the value derived from local measurements given by classical sensors distributed along the path.

2. Absolute distance measurements by synthetic wavelength interferometry.

In order to achieve low uncertainties in long range distance measurement, it is usual to use optical beam techniques. Classical optical interferometry is not appropriate for long range absolute distance measurements. The principle of classical interferometry is to express a distance as a number X of optical wavelengths. This technique is excellent for measuring incremental displacements with a nanometric resolution,. Though, it is not immediately

suitable for ADM if the distance to be measured is larger than the optical wavelength: the fractional part of X can be measured but there is an ambiguity about the integer part of X . Moreover, for long distance measurement in an uncontrolled environment, air index fluctuations and mechanical vibrations can make the technique useless. In response, researchers have developed multi-wavelength interferometric measurement, based on a 'synthetic wavelength' (spatial beat frequency in an interferogram obtained from an interferometer injected by two different wavelengths). In this technique, the unknown distance is expressed in terms of the synthetic wavelength, that can be much larger than the optical wavelength (from μm to meters). Thus, the integer part ambiguity and the sensitivity to air index fluctuations and vibrations are greatly reduced. By using different synthetic wavelengths, the ambiguity can be removed and absolute distance measurement can be performed.

The sine/cosine technique, commonly used to extract the phase information (corresponding to the fractional part of X) from homodyne interferometers, can not be applied easily to heterodyne interferometers injected by two close frequencies. Fortunately, a technique known as 'superheterodyne', based on polarisation-dependant frequency shifts of the optical waves, allows one to extract the phase information from a synthetic wavelength interferometer [10]. As interferometric distance measurements are based on wavelengths (optical or synthetic), the result of a measurement will be affected by the index of refraction of the medium, and a correction is necessary. In this workpackage, two instruments will be developed, each corresponding to a different task, to a different laboratory, and each having a different approach of the air index correction. Each instrument will be validated by a classical interferometric displacement system in a controlled atmosphere.

The generation of synthetic wavelengths requires two optical waves at different frequencies. As the synthetic phase stability depends critically of the optical phase noises, it is necessary to maintain a stable phase relation between the two waves [11]. This relation can be obtained by using a single laser and an acousto-optic modulator, or by using two phase-locked laser sources. The first solution is more compact and less expensive, but the modulator's bandwidth (some gigahertz) limits the frequency separation between the two waves, thus the synthetic wavelength value λ_s to some centimeters (λ_s is the ratio between the speed of light and the frequency separation). The second solution, more expensive, allows to quickly set different values to λ_s .

In this task, two lasers will be used. The ambient air parameters (pressure, temperature, humidity, carbon dioxide) will be measured by conventional means in order to calculate the air index of refraction (with enhanced Edlèn formulae) and correct the length measurement. The validation of the ADM at INRiM is obtained using the 100 m interferometer in controlled environment. The moving carriage is controlled in position or in velocity by a reference interferometer allowing a complete characterization of the ADM performances.

3. Absolute distance measurement by femtosecond technology

Within this workpackage we will apply a femtosecond frequency comb laser as a tool for distance measurements. Two different techniques will be implemented. The first is using the phase locking property between frequency of pulses emitted by the ultrafast laser. This allows for interference between different pulses. Secondly, a femtosecond laser is applied as an advanced frequency modulator. The absolute distance measurement with fs comb in vacuum is straightforward, but when measuring in air the determination of group refractive index of air is a key issue. This will be treated with a new method recently developed. The

femtosecond technology applied for advanced distance measurement is very new and we propose to do pioneer work. We plan to reach a relative accuracy below 10^{-6} , and to state the limitation of this technology for distance measurement in air.

3.1. Interferometric distance measurement with femtosecond laser pulses

Since the first demonstration of the stabilized, self-referenced optical frequency comb at the beginning of this century, numerous applications in the field of optical frequency measurement have been developed [12]. One of them being the measurement of the frequency of iodine-stabilized helium neon lasers and other primary length standards, that are maintained by most national metrology institutes. The frequency comb thus enables direct traceability from the practical realization of the meter to the definition of the second.

For these measurements the repetition rate f_{rep} and the carrier-envelope offset frequency f_0 of the comb laser are phase locked to a reference value provided by a time standard.

As a result the individual pulses show mutual phase stabilization as well, as illustrated in Fig. 2. This means that the subsequent pulses that are emitted from the laser are phase coherent, allowing for interferometry between different pulses [13]. This property will be exploited here for absolute distance measurement.

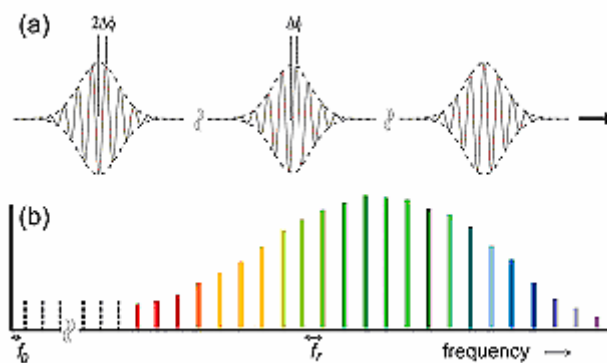


Fig 2. a) Illustration of the carrier-envelope phase shift in the time domain. A pulse to pulse phase shift $\Delta\phi$ is observed. b) the corresponding optical frequency spectrum, with f_0 the offset frequency due to the carrier-envelope phase shift, and f_r the pulse repetition rate. Once both f_0 and f_{rep} are phase-locked to a frequency reference, the comb is stabilized and phase coherence between the pulses is realized.

A typical measurement scheme is shown in Fig. 3. The setup consists of a long measurement arm and an adjustable reference arm. The reference arm is adjusted such that the pulses traveling through either reference, or measurement arm, coincide on the detector (i.e. the path length difference is adjusted close to the multiple of the interpulse distance l_{pp}). At this position a cross-correlation function is measured and its center is determined by curve fitting. Once the position of the cross correlation function is known the path length distance between both arms (or displacement from a reference value) can be determined. The synthetic wavelength is in the order of 1 m. Due to this large non-ambiguity range, the required initial value of the distance to be measured can be easily obtained by conventional techniques, like time-of-flight measurement. Another way to obtain an initial value is to adjust the parameters of the mode-locked laser (e.g. f_{rep}). The displacement of the reference arm is measured independently. Recently, a proof of principle of the proposed method has been delivered by measuring the cross correlation between two subsequent pulses, corresponding to a measured distance of about 15 cm [14]. The main task is to extend the measurement range to distances

up to 100 m and to identify the limits of this technique.

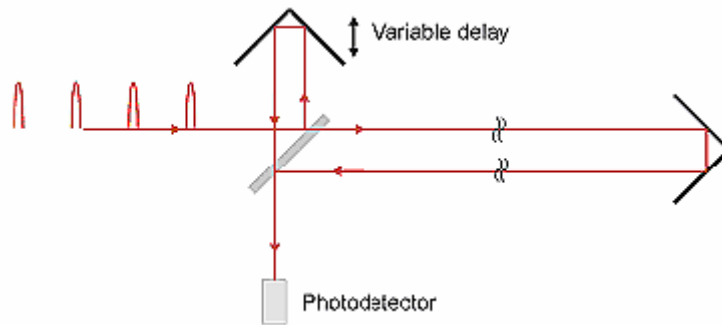


Fig. 3 Schematic of the proposed setup. A pulse train from a phase stabilized laser propagates through an interferometer. Interference occurs when the path length difference is a multiple of the interpulse distance. This may be accomplished by adjusting the short reference arm.

3.2. Femtosecond frequency comb as a modulator

Another approach to use femtosecond laser for long distance measurements is to apply it as the source of an electro optical distance meter (EDM). In a typical EDM setup a modulation frequency (generally RF) is applied to a single frequency laser, to get a modulated source. The modulated beam is split into two with a beamsplitter. When the beams travel different paths a phase difference between the RF waves develops. The phase difference is detected by measuring the modulation frequencies with a photodiode. The phase is a measure of the path length difference. The non-ambiguity range is given by half the wavelength of the modulation wave. Here we will apply a femtosecond laser as the modulated source [15]. The advantage of using fs comb as source of radiation is that it contains many phase locked modulation frequencies ranging from ~100-1000 MHz to tens of THz, much higher compared to the current instruments using a maximum frequency modulation of 1GHz. The light of the pulsed laser split in two beams. One reference beam is directed on a photo detector near the beam splitter. The other beam is directed on the target reflector and the back reflected light impinges on a second photo detector. For a given beat frequency f_b the phase difference of both electrical signals is proportional to the length with a periode of $c/2nf_b$, with c the speed of light in vacuum and n the refractive index of air. We aim at a bandwidth up to 3 GHz, which corresponds to a periodicity of the phase of 5 cm. The detected signals will be mixed down with fixed frequencies. Phase detection will be performed by applying an adapted phase detection unit from a heterodyne interferometer. To remove the ambiguity from the measurement a few (2-3) different beat frequencies will be chosen. Length measurements with an accuracy $<10^{-6}$ are targeted.

3.3. Measurement and correction of refractive index and dispersion in air

As already addressed in section 1, the knowledge of the refractive index of air is often a limiting factor in distance measurement. Within the workpackage on femtosecond frequency combs, we therefore incorporate a task that is dedicated to measuring the refractive index in a 'real' environment with a femtosecond laser. Such a measurement has already been performed by Zhang and colleagues in dry air [16]. The dispersion will be measured using the continuous spectral band of the femtosecond laser, eventually combined with the frequency doubled pulse. Moreover a method based on the measurement of spectral modulation will be considered. We will investigate the possibility to derive the absolute refractive index from the dispersion measurement. The influence of the dispersion to the shape of interferograms will

be modelled and compared to experimental results obtained from the distance measurements with the femtosecond frequency comb.

4. Baseline measurements

A workpackage of our project is devoted to the validation of the instruments that will be developed. The validation itself will take place when all instruments will have been realized and validated indoor, in laboratory conditions. We will use two different baselines, the first in FGI (Finland) and the second in BEV (Austria). FGI is the unique laboratory in the world to be able to directly link a baseline length to the meter *via* a Vaissala interferometer. This is the only method used today. The use of two baselines will enable us to estimate the reproducibility of the instruments developed in the JRP, by measuring two baselines in different conditions.

The standard baseline provided by BEV is composed of 7 pillars which materialise lengths between 30 m and 1080 m. It was build around 1986 and different measurements campaigns during the years did not indicate a movement of the pillars during ~20 years. The baseline is equipped with standard mountings and fixtures for providing a good positioning repeatability of attached instruments. The last calibration was performed in 2007 with the Mekometer 5000 from the Technical University of Munich to a level of around 10^{-6} . FGI plans to calibrate this baseline with about $5 \cdot 10^{-7}$ uncertainty. For further validation works the BEV baseline allows more diverse applications than the shorter Nummela Standard Baseline. Nevertheless, the Väisälä method will not be used at the BEV baseline, since it is extremely laborious, weather dependent and needs special baseline design and observation pillars.

The BEV baseline will be calibrated by transferring the scale from the Nummela Standard Baseline. Kern Mekometer ME5000 EDM instrument will be used as transfer standard. This instrument will be properly calibrated in Nummela before and after the transfer. The results of the latest (2007) interference measurements will be used as true distances. The calibration is also possible to perform as a repeated or two-way measurement, e.g. in 2008 and 2009, with Finnish and Austrian instruments. For the entire baseline length uncertainty level of $5 \cdot 10^{-7}$ ($k=2$) is expected.

These two calibrated baselines will serve to finally validate the absolute distance measurement instruments (ADM), developed in the JRP. This comparison will concern the two synthetic wavelength systems developed in PTB and LNE-INM, that will be transportable. Air index measurement will be integrated in the PTB system, while the MIKES spectroscopic sytem will be added to the LNE-INM ADM. The expected value is the true distance of the baseline. This would be a validation of our new instruments at the scale at which the true distance is known. For FGI baseline the relative uncertainty is 10^{-7} , and for BEV it will be $5 \cdot 10^{-7}$ after calibration by FGI. The validation can not be done with an uncertainty lower than the best possible today. Nevertheless, with a carefull estimation of the accuracy of our ADMs, by an argued uncertainty budget it would be possible to obtain an accuracy better than the current best state-of-the-art.

Conclusion

The consortia formed by 9 different institutes in 8 different european countries is bringing critical mass and a balance of skills, sharing different facilities. This should lead to significant improvements in long range measurement systems. Improvements are expected in the different workpackages that are constituting this joint research project. Air refractive index measurement systems over long distance (1 km) outdoor, including temperature and relative

humidity, will be developed in order to get average values over the measurement path. An interferometric measurement system based on synthetic wavelength will be developed. The objective is clearly to develop a system, directly traceable to the metre, enabling outdoor measurements over 1 km with a relative accuracy of 10^{-7} . Special facilities, especially baselines calibrated at the highest level, will serve to validate the measurement system. Novel techniques based on femto second technology will be implemented, including coherent pulse interferometry and high frequency modulation phase shifting. For this new technology, the objective is more to do pioneer work and to clearly state the practical limitation of this technology for distance measurements in air.

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