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An acoustic thermometer for air refractive index estimation in long distance interferometric measurements

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Abstract
We present a method to measure the temperature along the path of an optical interferometer based on the propagation of acoustic waves. It exploits the high sensitivity of the speed of sound to air temperature. In particular, it takes advantage of a technique where the generation of the acoustic waves is synchronous with the amplitude modulation of a laser source. A photodetector converts the laser light to an electronic signal used as reference, while the incoming acoustic waves are focused on a microphone and generate the measuring signal. In this condition, the phase difference between the two signals substantially depends on the temperature of the air volume interposed between the sources and the receivers. The comparison with the traditional temperature sensors highlighted the limit of the latter in case of fast temperature variations and the advantage of a measurement integrated along the optical path instead of a sampling measurement. The capability of the acoustic method to compensate the interferometric distance measurements due to air temperature variations has been demonstrated to the level of 0.1°C corresponding to 10^{-7} on the refractive index of air. We applied the method indoor for distances up to 27 m, outdoor at 78 m and finally tested the acoustic thermometer over a distance of 182 m.

Keywords
Speed of sound, long distance measurements, air refractive index, interferometric measurements, acoustic thermometry, thermometry

1. **Introduction**

Acoustic gas thermometry is a well established primary method used to measure the thermodynamic temperature in a low density monoatomic gas (helium or argon) in a cavity reaching relative uncertainties in the order of $3 \cdot 10^{-6}$ or less[1]. The air refractive index is a parameter of crucial importance for length interferometric measurements. In general, in the field of dimensional measurements, interferometric techniques use the wavelength of light as a ruler, since the wavelength of a coherent light, such as a laser, can be measured with extremely high precision. Hence, ideally it is possible to measure the dimension of an object or the distance covered by a moving target "simply" by counting the number of wavelengths encompassed between the start and the end of the object or of the movement. Actually, the real world is not in vacuum, but in air and the wavelength of an electromagnetic radiation in air is equal to the wavelength in vacuum divided by the air refractive index, n_{air}. Therefore, it is extremely important to know the accurate value of n_{air}. This strictly depends on environmental parameters, such as temperature, ambient pressure, relative humidity and carbon dioxide content, by means of a rather complicated model, because many different gases in different concentrations compose air. However, there are some mathematical models, such as the Edlen's formula [2-4] or other alternative formulae proposed by Ciddor or by Bonsch and Potulski [5, 6], which allows calculation of the air refractive index value from the measured environmental parameters. According to these models, an uncertainty on temperature of 0.1 °C brings to a relative uncertainty on refractive index of 10^{-7} (in terms of distance, it means an uncertainty of one micrometer over 10 m). As far as the other environmental parameters are concerned, a relative uncertainty on refractive index of 10^{-7} could be brought by an uncertainty on ambient pressure of 40 Pa or by an uncertainty of 12% (at 20 °C) on relative humidity. However, these two parameters are less critical than temperature since ambient pressure and partial pressure of water generally vary slowly with time and are rather uniform in space, while air temperature can undergo also fast temperature variations both with time and with space. Therefore, it is extremely challenging to measure accurately air temperature over long distances in order to provide the air refractive index for long distance interferometric measurements with an accuracy target of 10^{-7}.

To this aim, a new technique to measure the real time acoustic temperature averaged near the interferometer path has been developed. The technique is based on the propagation of sound in air and exploits the high sensitivity of the speed of sound u_A to air temperature. If the air temperature increases by 1 °C, u_A increases by about 0.6 m/s, i.e. a relative increase of about $1.8 \cdot 10^{-3}$, therefore the effect of temperature on u_A is about 1800 larger than the effect on the speed of light in air.

For an ideal monoatomic gas the speed of sound depends only on temperature and not on pressure according to the Newton – Laplace formula. For a real multispecies mixture, like air, u_A depends also on pressure and on the concentration of the different constituents.

The final attainable temperature accuracy of air depends on the accuracy of the model that relates u_A to the temperature of air and to the other physical quantities. Different models have been developed, to name but a few: Cramer calculates the empirical formula presented in [7] and reported in the ISO standard [8] valid for temperature from 0 °C to 30 °C , pressure from 75 kPa to 102 kPa, up to 0.06 H_2O mole fraction and CO_2 concentration up to 1% with a claimed relative uncertainty of $3 \cdot 10^{-4}$. Zuckerwar in [9] reports the predicted speed of sound u_A in air taking into account also the dispersion of different frequencies in the range 0 Hz – 100 kHz giving a relative uncertainty of about 10^{-3}.

Different acoustic thermometers for dimensional metrology applications have been realized. Korpelainen and co-authors at MIKES used an acoustic thermometer for the correction of the index of refraction in a laboratory for dimensional metrology using pulses of 50 kHz emitted by acoustic piezo transducers. The claimed uncertainty is 25 mK in a distance range limited to 12 m and temperature in the 19.5 °C – 21.0 °C interval [10]. Underwood and co-authors at NPL realized a device based on the integration of an acoustic thermometer and a tuneable diode laser absorption spectrometer able to carry out fast measurements of relative humidity and temperature with an uncertainty of less than 0.1°C [11].

The paper presents the work we have carried out to measure the acoustic temperature outdoor reaching a resolution of 0.1 °C over a distance up to 182 m and uncertainty mainly limited by the accuracy of the Cramer model. A further application of the method is envisaged for the measurement of vertical temperature gradients which is one of the accuracy limiting factors of surveying and large volume dimensional measurements based on optical methods (interferometers, laser trackers, laser tracers etc.) [12]. By coupling two or more transmitter receiver acoustic pairs, indeed, it is easy to evaluate temperature gradients orthogonal to the measurement axis without the use of physical thermometers.

The set-up and the measuring method are described in section 2, while in section 3 some considerations on the capability of the method to deduce the distance are discussed. The comparison with the local temperature measurements and the effectiveness of the acoustic method to correct fast temperature changes effect on interferometric measurements up to 27 m is discussed in section 4. In section 5 is described an experiment to compensate an absolute interferometer for outdoor measurements at 78 m. Finally, in section 6, is demonstrated the possibility of measuring the temperature over a distance of 182 m.

2. The acoustic method

We have realized two different prototypes of acoustic thermometer at INRIM, one for long distance outdoor experiment and described in section 6 and one for indoor experiments. This second prototype is drawn in Figure 1 and is composed of two parts: on the left hand side there is the "transmitter" unit, made by a piezoelectric loudspeaker and a laser source next to it; on the right hand side, the "receiver" unit made by a photodetector and a condenser microphone.
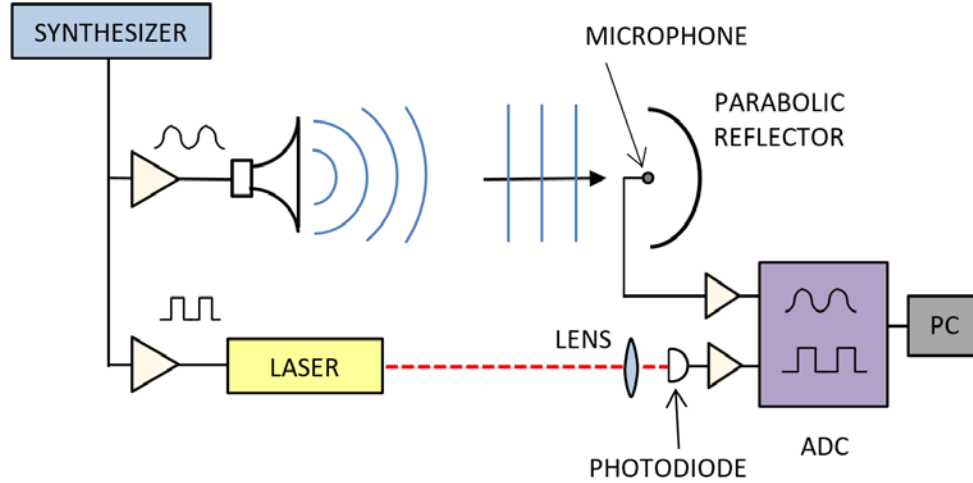
Fig. 1. Schematic of the measurement principle. Left: the "transmitter" unit, made by a loudspeaker and a laser source next to it. Right: the "receiver" unit made by a photodetector and a condenser microphone.

In the transmitter unit, a synthesizer generates two synchronous signals at a frequency f selectable in the range $(10 - 40)$ kHz: the sinusoidal signal is sent through a power amplifier to the loudspeaker while a synchronous square wave is used to switch on and off the laser source (a 650 nm, 1 mW diode laser). Therefore, the generation of the acoustic waves is synchronous to the amplitude modulation of the laser light. In front of them, at a variable distance L, the amplitude modulated light is received by the photodetector and converted to an electronic signal, used as reference; next to the photodetector, the incoming acoustic waves are focused by a parabolic reflector on the microphone and an electronic circuit extracts a sinusoidal signal at frequency f. The reflector, having a diameter of 30 cm and a focal length of 10 cm, allows increasing the acoustic energy collected by the microphone as well as giving the microphone a good directionality in the ultrasound range. The directionality is needed to discriminate between the acoustic waves coming directly from the loudspeaker (and so synchronous with the laser) and those waves coming from reflections on the laboratory walls (when used in the laboratory described in section 3) or other obstacles. The two received signals are finally sent to a data acquisition device (NI6259, maximum sampling rate of 500 kSamples/s) and a program implemented in LabView measures the phase difference between the two signals with an In-phase Quadrature (IQ) demodulation similar to the one used in [13]. The phase measurement is calculated for each acoustic period, so the readout is very fast. Practical measurements can be based on the average of a number of samples to reduce the noise at the expenses of response time.

The measurand of the apparatus is the fractional phase ϕ, the phase difference between the audio and laser signals at the receivers. From ϕ it is possible to calculate N as the total phase or number of audio wavelengths λ_A in the audio distance L_A, decomposed in $\bar{N}$ the integer part and ϕ is the measured fractional phase expressed in cycles. Since the dependence of light on temperature variation is about three orders of magnitude smaller with respect to audio, we can consider the laser signals as a stable reference and the formula is:

$$N = \bar{N} + \phi = \frac{L_A}{\lambda_A} = \frac{f\,L_A}{u_A} \tag{1}$$

Where f is the signal frequency and L_A is the audio distance between the audio source and the microphone and has to be measured in the way presented in section 3. In our apparatus u_A is presently calculated from the environmental parameter using the Cramer model whose relative uncertainty of $3\cdot10^{-4}$ limits the final attainable accuracy in temperature to about 0.17 °C. Nevertheless we have planned as a future work to measure u_A in a controlled environment to decrease its uncertainty, as in [10], to reach lower levels of uncertainty in T.

The relative sensitivity of u_A on temperature variation δT is expressed as

$$\frac{\delta uA}{uA} = \alpha_T \,\delta T \tag{2}$$

where α_T is about $1.8 \; 10^{-3} \, °C^{-1}$,

Considering from (1) the sensitivity of the measured total phase δN on the variation of the speed of sound

$$\delta N = -\frac{f L_A}{u_A} \frac{\delta u_A}{u_A} \tag{3}$$

Joining equation (2) and (3), in the approximation that f and L_A do no change during the measurement, we have the formula to obtain the change in temperature from the change of measured phase.

$$\delta T \approx -\frac{uA}{f \, L_A \, \alpha_T} \delta N \tag{4}$$

where both u_A and α_T depend on the environmental parameters. Also a change of pressure or relative humidity would change u_A and would be seen as change in temperature in formula (4). In the following table the variation of P and RH that corresponds to a change of 0.1 °C in formula (4) for different air temperature is reported

At T (°C)	δP (kPa)	δRH (%)
10	-20	9
20	-10	5
30	-5.7	3

Table 1: the variation on pressure P and relative humidity RH that gives the same change in the speed of sound as a variation of 0.1 °C in air temperature.

The absolute measurement of air temperature is obtained by measuring the speed of sound u_A from equation (1).

$$u_A = \frac{f \, L_A}{N} \tag{5}$$

From the measured u_A and environmental parameters (P, RH and $c(CO_2)$) we obtain the temperature with the help of the Cramer formula or an equivalent empirical formula.

In order to evaluate the limit of our technique we consider in equation (6) the different sources of uncertainty in the measurement of u_A

$$\frac{du_A}{u_A} = \sqrt{\left(\frac{dL_A}{L_A}\right)^2 + \left(\frac{dN}{N}\right)^2 + \left(\frac{df}{f}\right)^2} \tag{6}$$

As an example, considering a target uncertainty in air temperature of 0.1 °C the corresponding relative variation in u_A is $\frac{du_A}{u_A} \sim 2 \; 10^{-4}$. For a setup with the conditions: L_A = 100m, f = 1kHz, we have that $N \sim 300$, considering the different contributions in eq (6), the acoustic distance L_A has to be measured better than 2 cm, the total phase N has to be measured better than 0.06 cycle and the frequency f has to be measured better than 0.2 Hz. The uncertainty constraint on phase measurement can be loosened by using higher audio frequency, if we use f = 10 kHz, then $N \sim$ 3000 and the phase has to be measured better than 0.6 cycles. Unfortunately the sound attenuation increases by increasing the audio frequency, to give an indication of the distance in meters where the amplitude gets half is reported in table 2, extracted from reference [8].

T(°C)	RH(%)	Central frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
10	70	50170	14680	6020	3170	1630	620	180	50
20	70	66900	17710	5330	2150	1200	670	260	80
30	70	86010	23160	6270	1920	810	470	260	100
15	20	22300	9260	4930	2230	730	210	70	30
15	50	43000	12040	4930	2740	1430	560	170	50
15	80	60210	17710	5470	2510	1470	730	250	70

Table 2: distances in meters where the sound gets attenuated by half for different frequency and at different temperature and relative humidity. As from reference [8]

3. Distance estimation (acoustic fringes counting)

We presently describe a simple method to measure the audio distance L_A, the distance between the audio source and the receiver, through the determination of the integer number of acoustic waves (total phase N in section 2) needed to apply the formula (1). If we keep L_A fixed and change the frequency f, the phase will change with a slope depending on L_A. So, in principle it is sufficient to sweep the frequency in a certain interval Δf measure the associated ΔN and knowing u_A obtain L_A as

$$L_A = \frac{\Delta N \, u_A}{\Delta f} \qquad (7)$$

This method is similar to what is used in synthetic wavelength interferometry to find the absolute distance [13]. The magnitude of the frequency interval Δf in order to find L_A unambiguously is a matter of resolution in the phase measurement in a similar way to what discussed at the end of section 2. The final accuracy would be limited by the knowledge of u_A anyway.

Until now, we have considered phase changes occurring along the scan solely due to the relationship (1). Actually phase changes are also due to the dynamical behavior of the transducers used, i.e. the loudspeaker and the microphone (electronics if well designed can be neglected). Indeed resonant frequencies encountered along the scan could cause important phase changes which cannot be known a priori. To evaluate this effect in our system, we have taken the five curves phase vs frequency and fitted with a straight line, the residual phase changes are presented in Figure 3. From the fact that the curves are identical for different distances we could infer that the effect of reflection of the audio signal from the walls or other surfaces in the laboratory is smaller than the dispersion of the curves and there are no critical resonances in the frequency interval. The resulting shape of the residuals is due to combined spurious effect of the loudspeaker-microphone pair and can be taken into account in the model. The dispersion of the curves of about 0.1 cycle gives the final resolution of the audio temperature from equation (4), as an example with L_A = 100 m, f = 2kHz a resolution of 0.1 cycle corresponds to a resolution of dT = 0.1 °C.
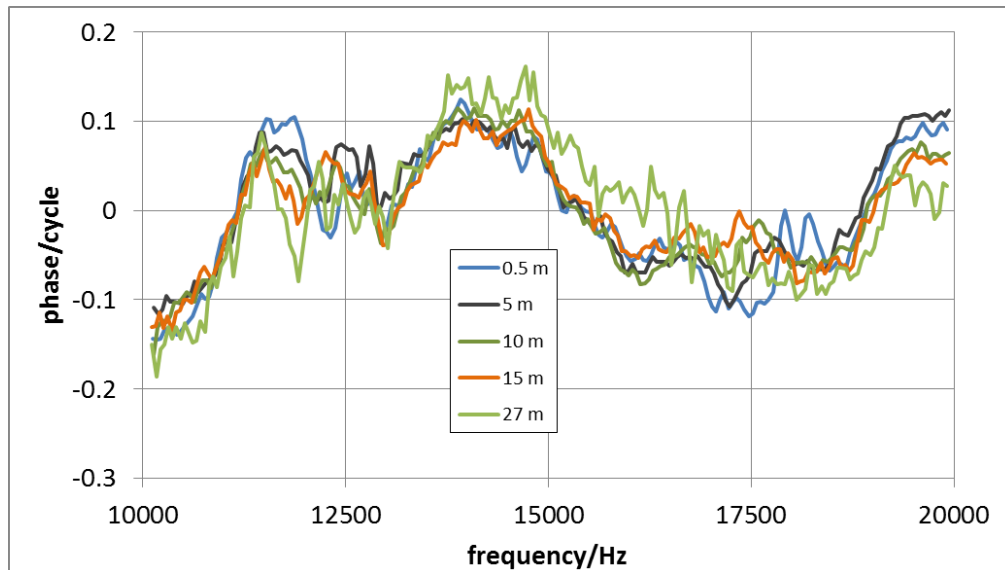
Fig. 3. Residual phase changes due to the loudspeaker-microphone pair measured for five different distances along the 10-20 kHz frequency sweep.

The audio distance L_A is the characteristic of a particular loud speaker–microphone pair, it is better to measure it in a controlled environment like in a laboratory in such a way that there are no other sources of instabilities or systematic effects. Once L_A is measured for the particular set-up, it is sufficient to transpose the audio distance to a dimensional distance by adding one reference to the loud-speaker structure and one to the microphone structure. When the apparatus is moved to a different condition, and is mounted with correct alignment of the two parts, it is sufficient to measure the dimensional distance between the two references using an electronic distance measurement instrument (EDM) and obtain the audio distance with the uncertainty required which could be of the order of few cm, as discussed in section 2.

4. Experimental tests in the INRIM long distance facility

At INRIM a facility for the measurement of long distances was developed and is currently operating to calibrate EDM and interferometers. It is based on an incremental heterodyne interferometer, with a moving arm made by a carriage hosting a retro-reflector and sliding on a rail 28 m long. The facility can be used to calibrate absolute interferometers and telemeters at a level of uncertainty of few parts in 10^{-7}, or it can be used to calibrate commercial laser distance measuring instruments, such as EDMs. A detailed description of the facility can be found in [14]. In Figure 4 a picture of the acoustic thermometer set-up used to compensate interferometric measurements is shown. Note that the loudspeaker is mounted on the carriage as close as possible to the interferometer mirror, in order to measure the temperature of approximately the same volume of air along the interferometer path.
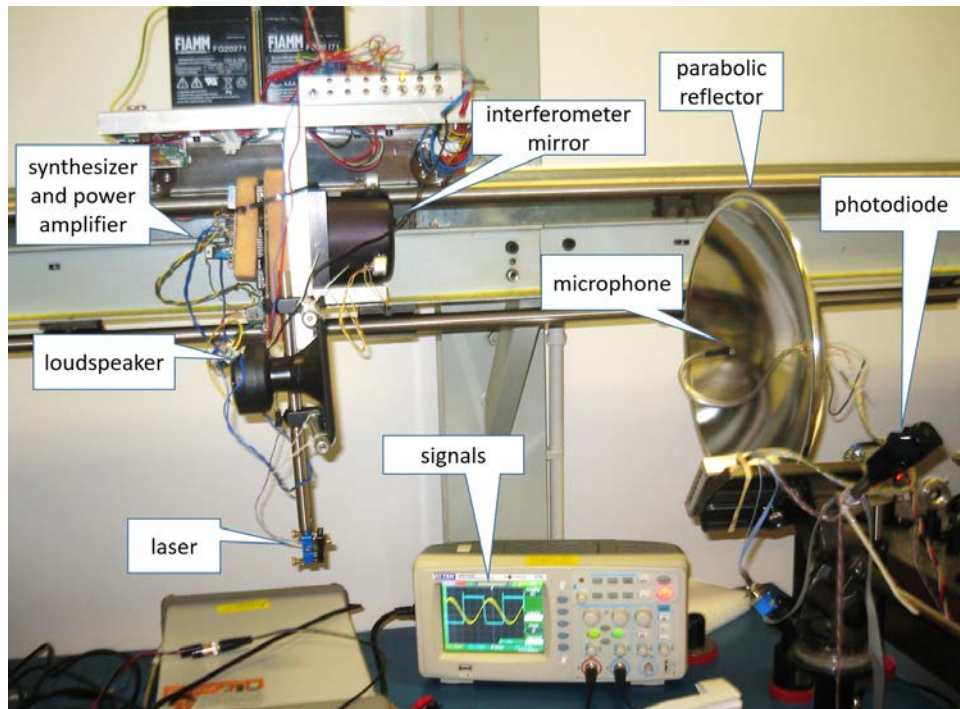
Fig. 4. Photograph of the experimental set-up, mounted in the long range interferometer facility (described in section 4) when the carriage is at the beginning of the rail, close to the parabolic reflector: on the left, the carriage with the optical retroreflector, the loudspeaker and the laser source is visible; on the right the parabolic mirror to focus the acoustic waves on the microphone is visible; the photodetector is not visible since it is hidden behind the mirror. On the oscilloscope the signals coming from the photodetector (blue) and the microphone (yellow) are visible.

The air temperature of the laboratory is roughly controlled at 20°C by the air-conditioning plant and it is measured by 14 thermistors placed along the interferometric path at intervals of 2 m, to evaluate the air refractive index (see Figure 5). The thermistors have been individually calibrated in the framework described in [14] with an uncertainty of 0.05°C in the interval 18 °C -22 °C. Ambient pressure and relative humidity are also measured, but in this case, the measurement is performed only in one point, assuming these parameters almost constant along the laboratory. With this set-up, the estimation of the refractive index of air n has proven to be to the required 10^{-7} level. We have used this facility for the first test of the acoustic thermometer described in this section.
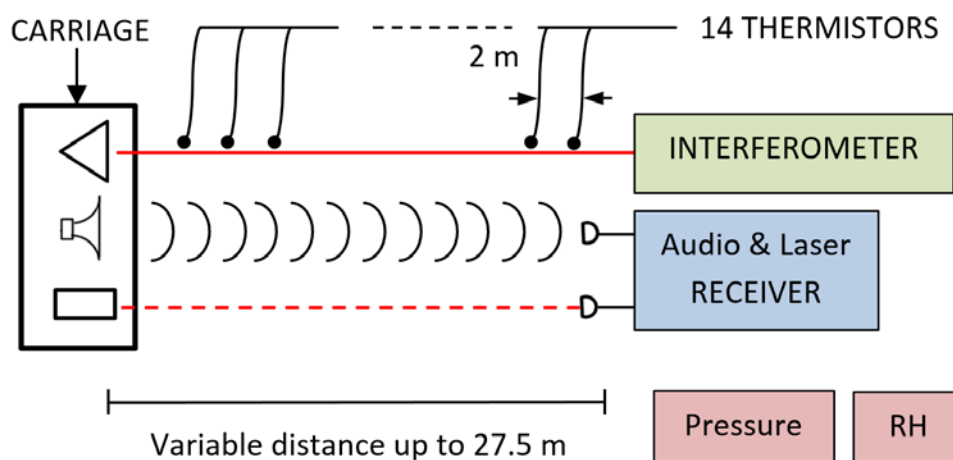

Fig. 5. Set up for the comparison of the acoustic thermometer and classical temperature measurement.

4.1 Comparison with thermistors

In order to compare the acoustic method with the local temperature measurements performed by means of the thermistors, a cyclic air temperature modulation was induced acting on the set-point of the temperature conditioning plant of the laboratory. The comparison between the two air temperature measurement techniques averaged over the 27.5 m range is reported in Figure 6. The temperature of the laboratory is changed periodically acting on the conditioning plant, which is switched on and off every 5 minutes. The agreement between the acoustic method at f = 20 kHz and the averaged thermistor measurement is well within 0.1 °C, confirming the estimated level of uncertainty for the acoustic method. The data from the acoustic thermometer are averaged over a period of 1 s, while the data from the thermistors are sampled every 7 s, which is the time required by the scanning multimeter to measure the 14 thermometers.
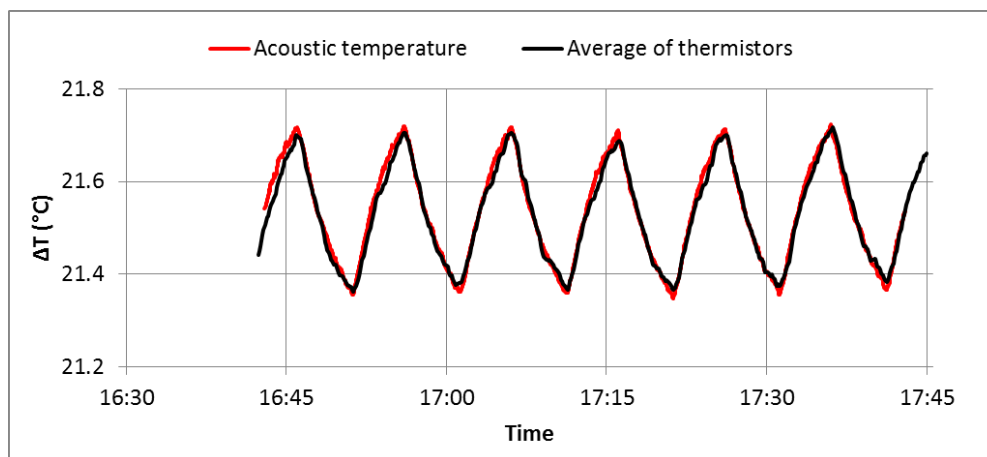

Fig. 6. Fast air temperature variations (10 minute period) measured by means of the acoustic method at f = 20 kHz and by the thermistors.

4.2 Application to the interferometric measurements in laboratory conditions

In order to evaluate the capability of the acoustic method to compensate the air temperature variations on the interferometric distance measurement, the signal from the interferometer was registered synchronously with the speed of sound measurement, with the carriage at rest at a distance of 27 m. The air temperature was modulated according to a cycle of approximately 10 minutes acting on the temperature conditioning plant of the laboratory (as in Figure 6).

In Figure 7 are shown the changes in the interferometric measurement (blue curve) induced by the air temperature variations: when the temperature grows, the optical length measured by the interferometer apparently decreases because of the decreasing of the refractive index, as explained in the introduction. When we correct in the green curve the distance measured by the interferometer for the air temperature variations measured by the acoustic system (red curve) the refractive index effect is cancelled. The residual changes in the corrected interferometric measurements (about 5-6 μm peak-to-peak) are the real physical length changes of the rail supporting the interferometer induced by the thermal effect on the whole structure. This result indeed is compliant with the variations of the rail length estimated on the basis of the temperature directly measured on the rail.
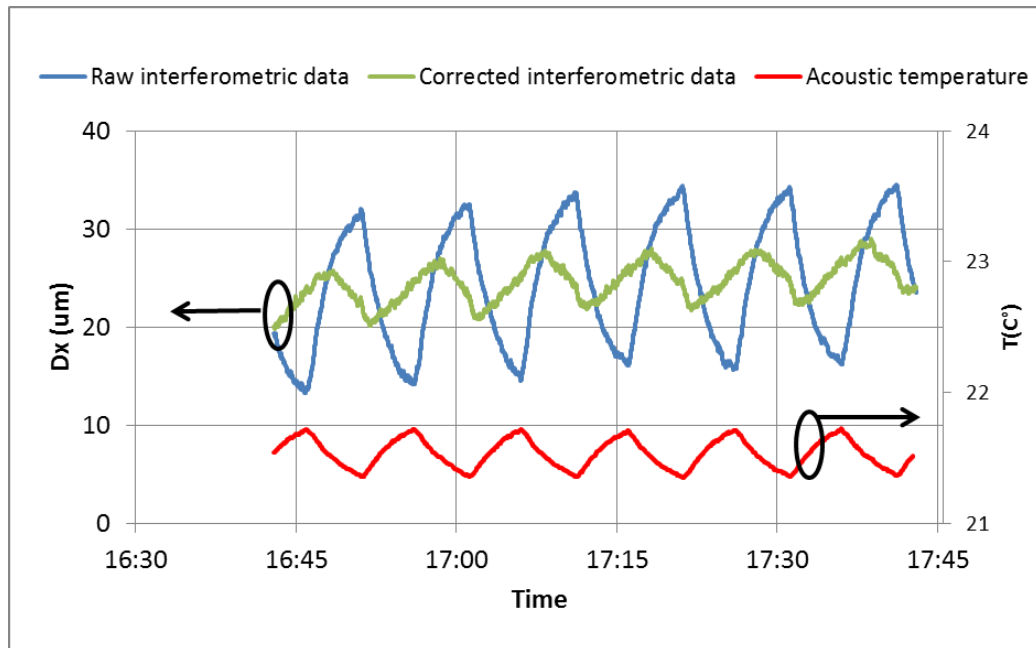
Fig. 7. Effect of air temperature variations on the interferometric distance measurement.

5. Open air interferometric measurements

We tested the device in an open-air environment. A picture of the experimental set-up is presented in Figure 8. The acoustic thermometer is the same as described so far, while the interferometer is a synthetic wavelength absolute interferometer developed for space applications and described in [13]. The interferometer and the acoustic thermometer share the same path between two windows of two buildings at INRIM being at a distance of 78 m. The average temperature between the two buildings has been measured with two thermometers placed close to the two windows and a third between the buildings. Several hours of measurement have been recorded continuously with the five instruments. A sample of the results is reported in Figure 9. The record has been taken in winter soon after the sunset. The measurements of the thermometers (right scale in degrees Celsius) are reported together with the interferometer measurement (left scale in micrometers). Assuming that the distance between two buildings is roughly constant, we can attribute the apparent distance change to the change in refractive index of air and we see a very good agreement between the measurements. We could now subtract the effect of the temperature to the distance measurement and retrieve the real distance change between the two buildings: Figure 10.
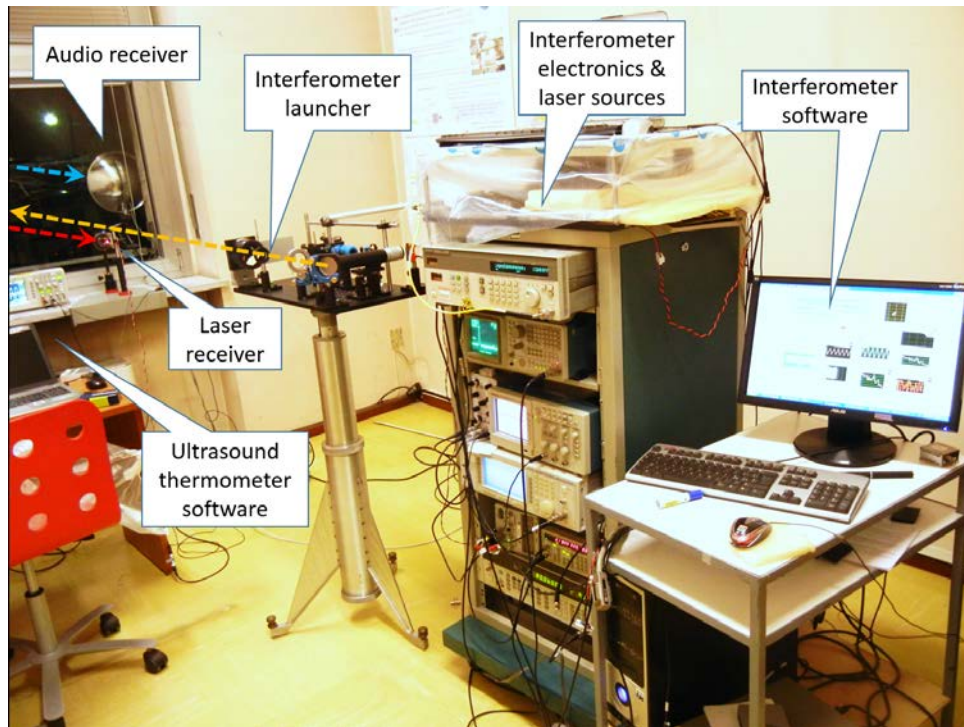
Fig. 8 Picture of the experimental set-up used to compensate the absolute synthetic wavelength interferometric measurement. The interferometer laser beam (λ = 1542 nm modulated at 20 GHz) is sent through the window towards another building where, 78 m apart, are the ultrasonic emitter, the synchronization laser and the corner cube retroreflector.
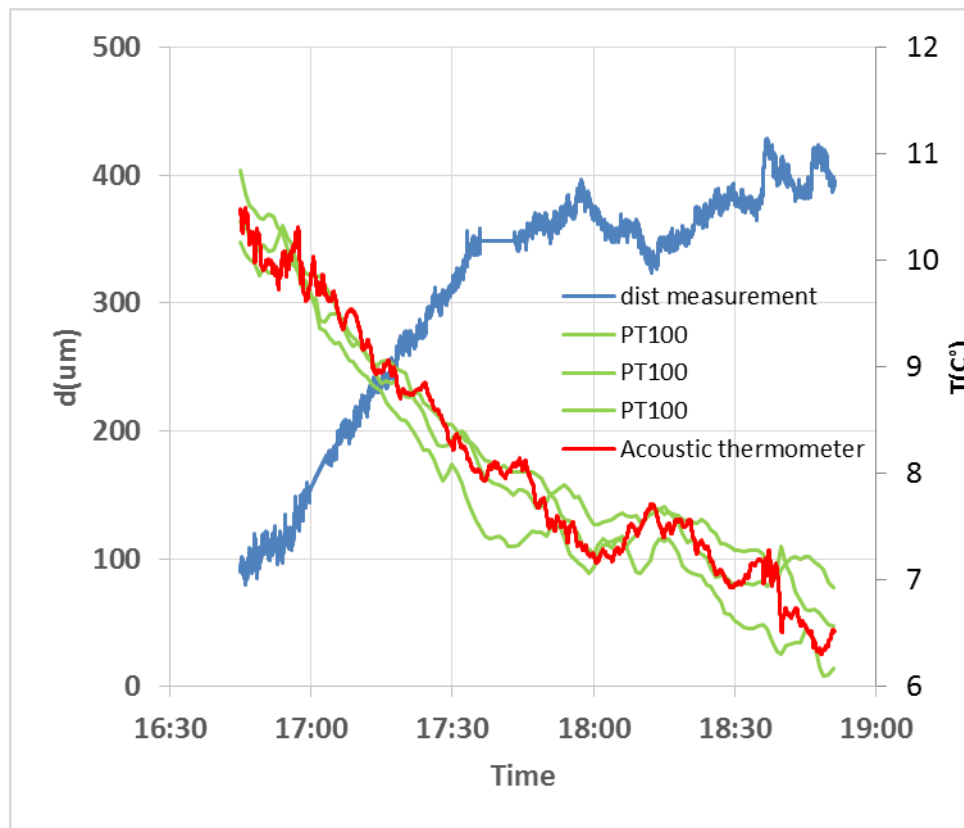

Fig. 9. The temperature of air (right scale in °C) is measured with the acoustic thermometer (red) and with three classic thermometers (green) together with the distance variation (in blue)

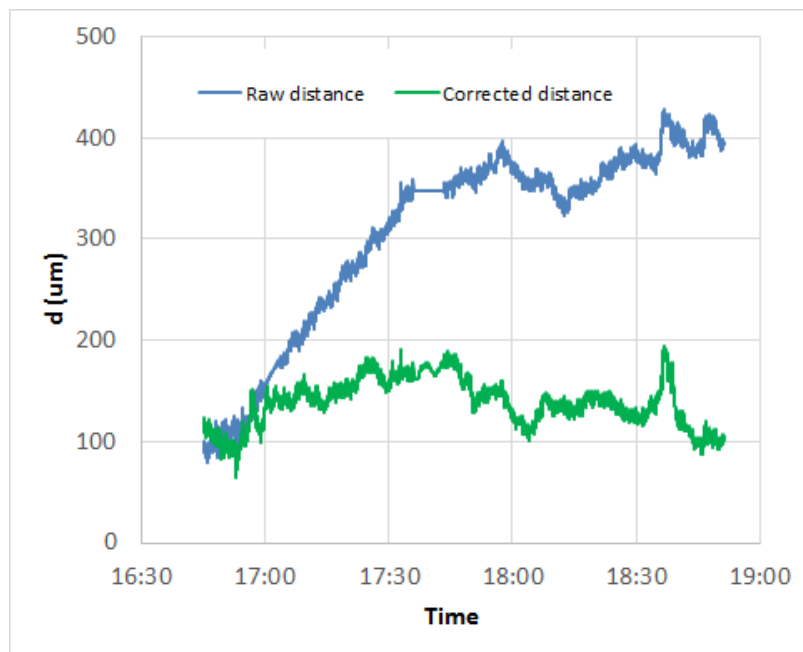between the two buildings measured with the absolute interferometer (left scale in micrometers).

Fig. 10. The distance variation between the two buildings measured with the synthetic wavelength interferometer before (blue) and after (red) the temperature correction using the acoustic thermometer. The vertical scale is in micrometers.

## 6. Long distance thermal measurements

The method can be applied to virtually any distance provided that an acoustic signal can be transmitted and received over that distance. The experiment described here has the aim to demonstrate the possibility of measuring the average temperature of air over long distances.

As discussed in section 2, in order to increase the phase resolution we have to increase the audio frequency with the drawback that sound gets more attenuated over the long distance, decreasing the signal to noise ratio. A compromise between the resolution and the signal to noise ratio must be found by adjusting the audio frequency for different distance ranges.

For the application in open air at a distance up to 182 m we have built a second apparatus, reported in Figure 11, where the acoustic wave is generated by a synthesizer and amplified with a power audio amplifier (NAD 912) coupled with a home made loudspeaker cabinet. The frequency range was from 46 to 150 Hz. The loudspeaker has very poor directionality at low frequencies, thus the quite loud sound audible close to the cabinet was hardly audible at the receiver side. The receiver is made by an array of nine condenser microphones placed in line and electrically connected in parallel. The microphones are distributed along a 2 m bar and the generated currents are summed and converted into voltage by a single circuit. This arrangement maximizes the sensitivity along the direction normal to the bar while reducing the sensitivity to environment noise coming from other directions. As explained in section 3 also for this second apparatus the audio distance L_A was measured in controlled conditions and characterized by measuring the dimensional distance between two reference points. In Figure 12 are reported the result of a typical acquisition run taken in summer from the sunset to the morning, a time interval with very low wind speed. The frequency was set to 47 Hz. In these experimental conditions, the signal to noise ratio is sufficient to achieve a resolution on the phase measurement better than 1/100 of an acoustic fringe. The red curve represents the audio temperature, the green curve the average of eight thermometers distributed along the path, in blue the temperature measured by a meteorological station close to the microphone side. The wind speed was monitored by the meteorological station and during the whole measurement was within 0.5 m/s.

The difference of few degrees Celsius between the three measurements can be attributed to the undersampling of the classical thermometers also considering strong temperature variations along the path due to the hot asphalt of the road, the grass and to the component of the wind

along the measurement axis. Since the measurement is unidirectional, the projecting of the wind along the audio transmission axis causes systematic errors in the estimation of u_A. This effect could be measured and corrected using an anemometers or doubling the system. A wind speed of about 0.5 m/s along the transmission axis corresponds to an error in the estimation of T of 0.5 °C. In a more accurate model, also the effect of transverse wind, which is not cancelled by doubling the system, must be taken into consideration.
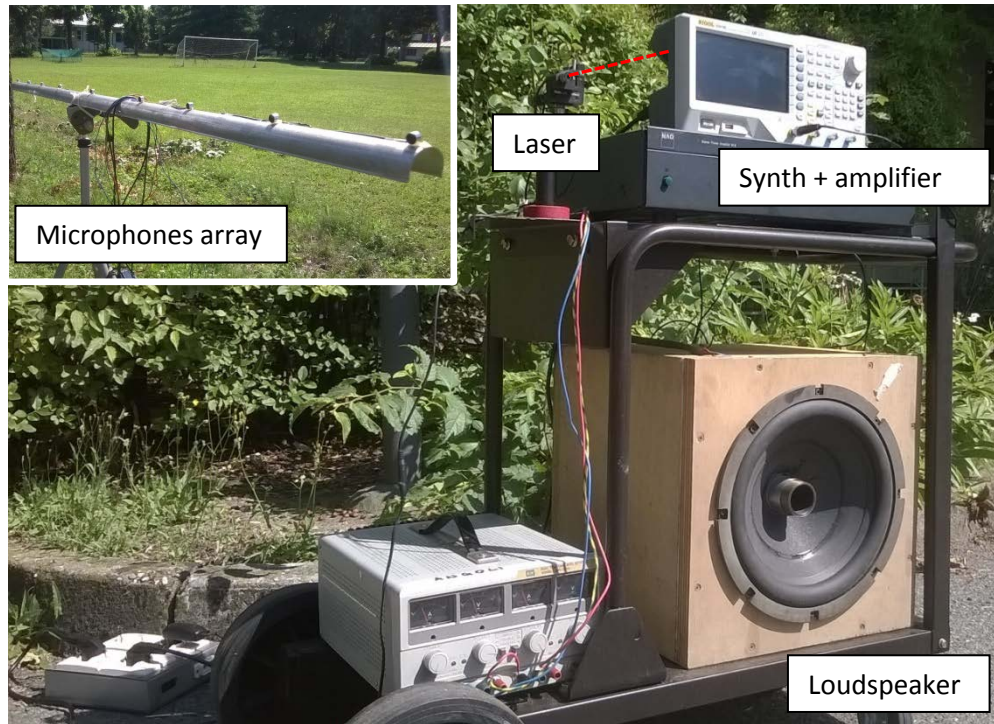
Fig. 11 Picture of the apparatus for the measurement of the audio temperature over long distance measurements.
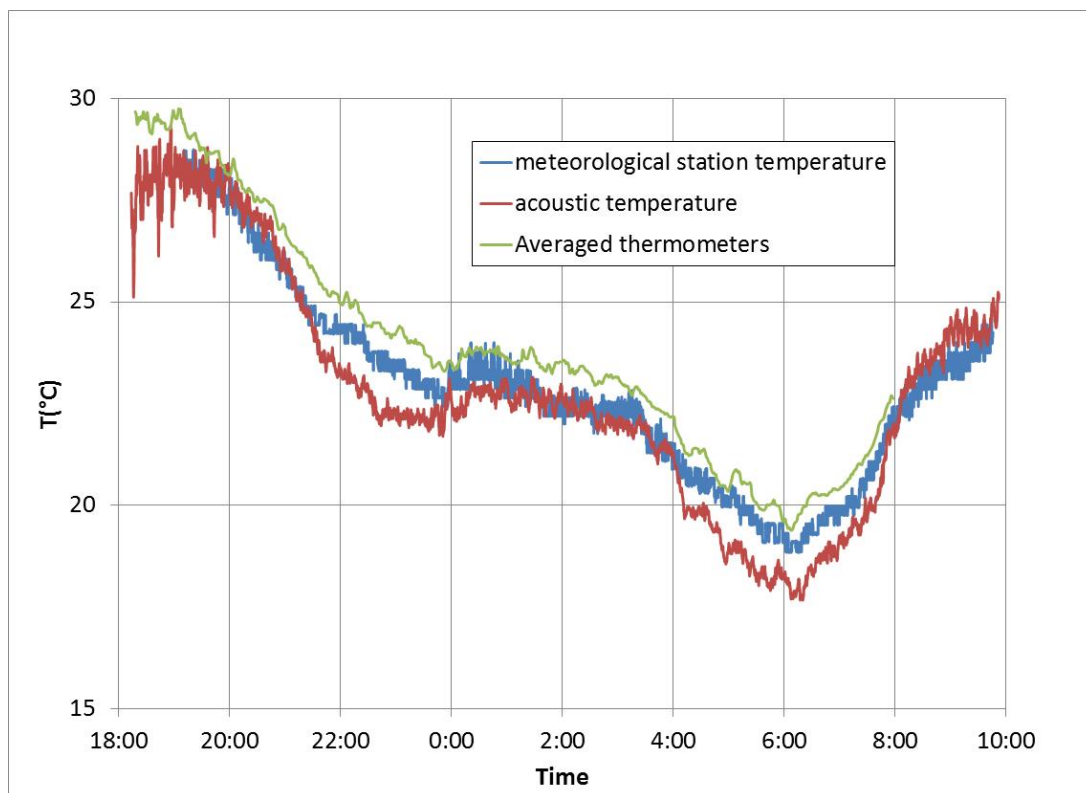
Fig. 12. In red the temperature measured with the acoustic thermometer operating at 47 Hz on a distance of 182 m. In green the average of the 8 thermometers distributed along the path. In blue the temperature measured by a meteorological station close to the microphone side.

7.   Conclusions and outlook

An acoustic method for air temperature estimation for long distance interferometric measurements in air has been developed. The comparison with the traditional temperature sensors highlighted the advantages of a measurement technique which is able to follow even fast temperature variations and which is integrated along the optical path instead of a sampling measurement requiring a high number of sensors. The resolution (mainly limited by the turbulence of air) is about 0.1°C leading to a potential relative accuracy of the interferometric measurement of 10^{-7} limited in our realization by the knowledge of the speed of sound in air. The capability of the acoustic method to compensate the interferometric distance measurements due to air temperature variations has been demonstrated on a 27 m distance indoor and a 78 m distance outdoor. Furthermore, using a second apparatus the acoustic thermometer has been tested on a distance of 182 m and the measurement was compared with distributed thermometers; the agreement between the two is better than 2°C limited by the discrete sampling of the classical temperature measurement and by the effect of the wind. The acoustic method can be applied to even longer distance measurement providing the following conditions are considered:

1) The space between the measurement points must be free from large reflecting surfaces in order to avoid the possibility of interference of acoustic waves;
2) The larger distances must be covered by longer audio wavelengths (low frequencies) to reduce attenuation and phase jump risks;
3) The use of a directional microphone is suggested (parabolic reflector for high frequencies and microphone arrays for long waves).
4) A further important limitation is air turbulence, caused by convective motion and by wind, which can cause phase jumps thus limiting or impeding the measurement. On the basis of our experience, however, the weather conditions limiting the acoustic temperature

measurement also have similar or worst effect on interferometric measurement, which indeed require quite still air to be done. Moreover, the projection of wind speed along the measurement axis causes important systematic effects, which can be measured and corrected by using anemometers and/or by adopting a bidirectional set-up.

Finally, using the same apparatus, by applying the sweeping frequency method, we have measured the acoustic distance with the accuracy required for this application allowing a self-consistent use of the apparatus.

At present, the accuracy of the method is limited by the a priori knowledge of the speed of sound u_A. Since the sensitivity of the method is significantly better than said limit, we believe that the method can be effectively used to measure u_A in a controlled environment reducing the uncertainty of u_A in specific environment conditions.

8.   Acknowledgments

Reference list

1. Moldover M.R. et al, "Acoustic gas thermometry", *Metrologia*, **51**, R1-R19, 2014.
2. Edlen B., "The refractive index of air", *Metrologia* **2,** 71-80, 1966
3. Birch K.P. and Downs M.J., "An updated Edlen equation for the refractive index of air" *Metrologia,* **30,** 155-162, 1993
4. Birch K. P. and Downs M.J., "Correction to the updated Edlén equation for the refractive index of air", *Metrologia,* **31,** 315-316,1994
5. Ciddor P.E.," Refractive index of air: new equations for the visible and near infrared" *Appl. Opt.* **35** (9) 1566-1573, 1996
6. Bonsch G. and Potulski E., "Measurement of the refractive index of air and comparison with modified Edlen's formula", *Metrologia,* **35,** 133-139, 1998
7. Cramer O., "The variation of the specific heat ratio and the speed of sound in air with temperature, pressure, humidity, and CO_2 concentration" , *J. Acoust. Soc. Am.*, **93**(5), 2510-2515, 1993
8. ISO/IEC 9613-2 "Attenuation of sound during propagation outdoors",   International Organization for Standardization, Geneva, Switzerland.
9. Zuckerwar A.J., Handbook of the speed of sound in real gases, Academic Press, 2002.
10. Korpelainen V. and Lassila A., "An acoustic method for determination of the effective temperature and refractive index of air in accurate length interferometry", *Opt. Eng.* , **43**(10), 2400-2409, 2004
11. Underwood, R., et al. "An improved non-contact thermometer and hygrometer with rapid response." Metrologia **54** , 2017.
12. Pollinger, F. et al. "Metrology for Long Distance Surveying: A Joint Attempt to Improve Traceability of Long Distance Measurements." IAG 150 Years. Springer, Cham, 651-656, 2015.
13. Pisani M., Zucco M., Mottini S. "Absolute distance interferometric measurement for on board satellite metrology", In Metrology for Aerospace (MetroAeroSpace), 2016 IEEE 2016 Jun 22 (pp. 511-515).
14. Astrua, M., M. Pisani, and M. Zucco. "Traceable 28 m-long metrological bench for accurate and fast calibration of distance measurement devices." *Measurement Science and Technology,* **26**.8 : 084008, 2015