LONG DISTANCE INTERFEROMETRIC MEASUREMENTS WITH REFRACTIVE INDEX CORRECTION BASED ON SPEED OF SOUND

Milena ASTRUA[1], Marco PISANI[1] and Massimo ZUCCO[1]

1 Istituto Nazionale di Ricerca Metrologica, Str. Delle Cacce, 73, 10135, Torino, Italy, m.pisani@inrim.it

Abstract:

At INRIM a novel absolute long distance interferometer has been developed for application in space missions. The interferometer has been successfully tested for long distance measurements in air. Main limitation of such measurements is the knowledge of refractive index of air which in turn is mainly affected by air temperature. A method to measure average air temperature based on the measure of the speed of sound has been developed and combined with the absolute interferometer achieving measurement uncertainties less than 1 ppm in open air up to a 78 m distances.

Keywords: Long distance interferometry, refractive index of air, temperature measurement, synthetic wavelength

1. INTRODUCTION

Long distance measurements on Earth have many applications ranging from geodetic surveying, constructions, large industrial plants, particle accelerators and so on. At present the accuracy of such measurements relies on triangulation methods (theodolites) and on laser ranging methods (EDMs). Both methods do not allow measurements better than 1 ppm in accuracy because of technologic limits.

New industrial needs (e.g. aerospace industry) and research needs [1,2] require more accurate measurements. The goal of the research in this direction is the development of practical measurement methods allowing 10^{-7} relative uncertainties on a distance scale ranging from tens to hundreds of meters.

The best distance measurement methods developed so far are based on laser interferometers and amongst these the best candidate for absolute measurements is the so called synthetic wavelength interferometer [3]. The technique consists in modulating (in amplitude or phase) a laser beam and measuring the phase difference between the outgoing beam and the beam returning from a reflecting target. The phase measurement in combination with the knowledge of the modulation frequency allows accurate measurement of the absolute distance of the target.

The main limit of interferometer based measurements is the knowledge of the refractive index of air which affects the optical path and hence accuracy of the length measurement. Generally, for short distances, the air refractive index is calculated from the measured environmental parameters by means of a mathematical equation, such as the Edlen's [4] or the Ciddor's formula [5]. For long distances measurements, instead, this approach is limited essentially by the temperature measurements, because it's difficult to measure the temperature variations of a big air volume with traditional temperature sensors at an accuracy level of 0.1 °C.

In the present paper we present the use of a synthetic wavelength interferometer in combination with an acoustic thermometer to perform accurate absolute distance measurements in air with a relatively simple and compact set-up.

2. EXPERIMENTAL SET-UP

2.1 The Synthetic Wavelength Interferometer

The interferometer was originally developed for a compact sensor to be used onboard satellites to measure the relative position of different parts of the satellite or for formation-flight missions. The synthetic wavelength interferometer is schematically presented in figure 1. Two external cavity diode lasers with high spectral purity emitting around 1542 nm are superposed in polarization maintaining fibers generating a synthetic frequency $\nu_2 - \nu_1$ that range from 0 to about 40 GHz by tuning the laser cavity temperature. The narrow linewidth allows long coherence length for long range distance measurement. The information on the distance is contained in the phase at the variable synthetic frequency that is too high to be conditioned and acquired by Radio-Frequency electronic. For this reason we have implemented the super-heterodyne detection scheme to down convert the phase information to the fixed frequency of 120 kHz [6]. This is realized by driving the two Acoustic Optic modulators (AOM) with two different frequencies, f_1 = 79940 kHz and f_2 = 80060 kHz. The radiations are mixed at the detectors giving the signal at the super heterodyne frequency $f_{SH} = f_2 - f_1$ = 120 kHz. When the retro-reflector is moved by a distance ΔL the phase $\Delta\Phi$ of f_{SH} changes by the quantity

$$\Delta L = \frac{\Delta\Phi}{2\pi}\frac{\Lambda}{2} \qquad (1)$$

Where Λ is the synthetic wavelength $\Lambda = \frac{c}{\nu_2 - \nu_1}$.

It is clear from equation (1) that the resolution and accuracy of ΔL is related to $\Delta\Phi$ and Λ. With our set-up we can obtain Λ as small as 7.5 mm.

$\Delta\Phi$ is measured with a fast acquisition board with 800 ksample/s acquisition and 16-bit resolution. The phase is then obtained from the digitized signals with an I/Q demodulation software. When the lasers are free running the variation of the synthetic frequency is too big in the measuring interval to reach a good level of accuracy in ΔL. We have therefore phase locked the synthetic frequency to a synthesizer, referenced to the SI second, by acting on the laser cavity temperature for the large and slow variations and on the laser PZT for the fast and small variations.

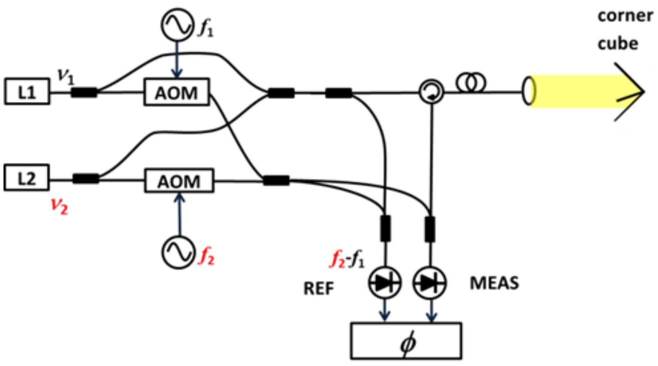

Fig. 1: Simplified schematic of the synthetic wave interferometer. A synthetic wave is generated by mixing two extended cavity lasers in the PM fibers. A superhetherodyne detection system is used to measure the phase of the synthetic wave at the fixed frequency of 120 kHz.

The synthetic wavelength interferometer has been validated for accuracy by comparison with the reference interferometer in the metrological long distance facility [7]. For resolution and repeatability tests have been carried out both in laboratory and in open air at different distances ranging from 0.5 to 137 m. The following results have been achieved: accuracy of about 14 µm in determination of the absolute distance, repeatability of about 80 µm at target distance up to 60 m. As for the resolution we can refer to the noise spectra of figure 2. For high frequencies the resolution is limited by the electronic noise to few nm/√Hz, for lower frequencies the limit is given by acoustic noise and eventually by thermal drifts mainly affecting the uncompensated fiber path of the interferometer.

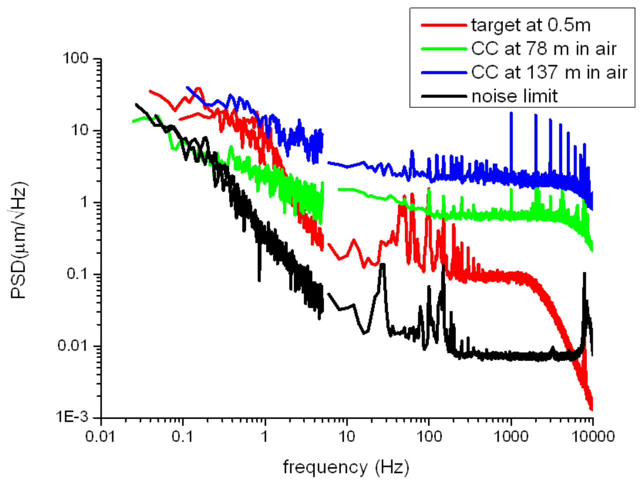

Fig. 2: Noise spectral density (in micrometer/√Hz) of the distance metrology. Black curve is obtained by short circuiting the fiber interferometer, other curves are obtained in air at different distances. Long distance measurements are limited by the air turbulence. Short distance measurements (red curve) is representative of the interferometer resolution.

2.2 The Acoustic Thermometer

In the acoustic system developed at INRIM and sketched in fig. 3, a sinusoidal wave with frequency *f* in the ultrasound range is sent to a loudspeaker while a digital signal synchronous with the first one is used to modulate a laser source (switched on-off) close and parallel to the loudspeaker.

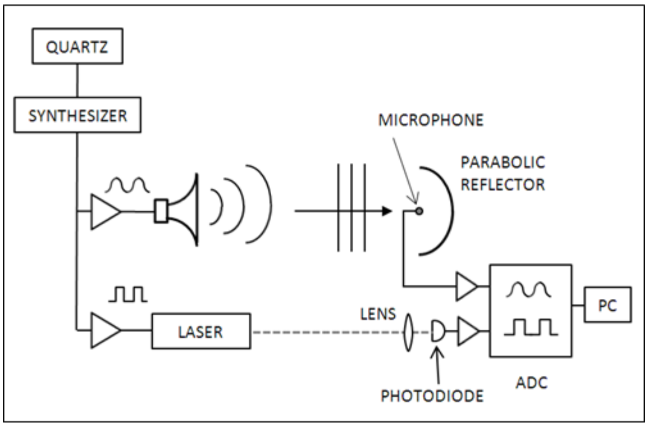

Fig. 3: Simplified schematic of the acoustic set-up for the measurement of the speed of sound at large distances

In front of them, at a distance variable up to 28 m, the amplitude modulated laser light is received by a photo-detector and converted to an electronic signal, considered as reference. Next to the photo-detector, the incoming acoustic waves are focused on a microphone placed in the focus of a parabolic reflector and an electronic circuit extracts a sinusoidal signal at frequency *f*. The phase difference Φ between the two signals depends on the distance between the transmitter and the receiver *d*, on the acoustic frequency *f* and on the speed of sound in air v_0, according to the simple equation: $\Phi = 2\pi \cdot d \cdot f / v_0$. In turn, the speed of sound in air strictly depends on the air temperature and on the other environmental parameters, through a rather complicated formula reported in references [8, 9].

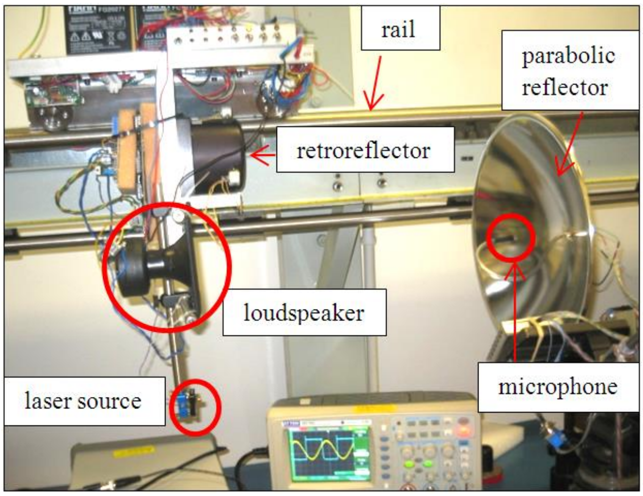

Fig. 4 Picture of the acoustic thermometer set-up. In the oscilloscope, the acoustic signal from the microphone (yellow trace) is displayed with the signal from the photo-diode (blue trace).

Furthermore by varying the acoustic frequency is possible to calculate the absolute distance. In fact, the knowledge of the temperature by the speed of sound depends on the a priori knowledge of the real distance d between loudspeaker and microphone at least at the level of the acoustic wavelength. In other words the number N of wavelengths must be known. A method to find N is to continuously change the acoustic frequency from f_1 to f_2 and to count the number of entire phase revolutions ($\Delta\Phi/2\pi$): $N = f_0 \cdot \Delta\Phi/2\pi/(f_2 - f_1)$ where f_0 is the operative frequency. In the experimental set-up the frequency is changed from 10 to 20 kHz and f_0 is between 18 and 20 kHz.

3. EXPERIMENTAL RESULTS

The acoustic method and the synthetic wavelength interferometer have been validated in the temperature controlled underground metrological gallery at INRIM. Furthermore, the combination of the two instrument has been tested in open air.

Fig 5. The metrological gallery where the acoustic method and the synthetic wavelength interferometer have been validated up to 28 m distance.

In Fig 6 the a typical recording obtained during the validation of the acoustic thermometer is shown. The temperature of the metrological gallery at INRIM was changed periodically by acting on the conditioning plant. The temperature of the air along a 28 m long path has been measured by 14 calibrated thermistors. The same volume of air was used for the speed of sound measurement. The temperature calculated by the speed of sound is plotted together with the temperature measured with the thermometers. The agreement of the two is better than 0.1 °C.

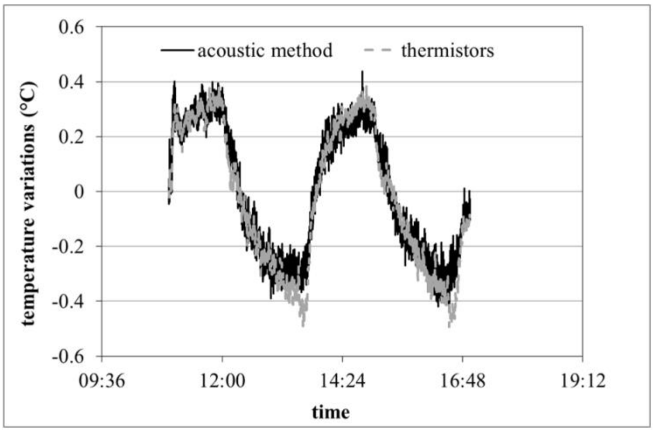

Fig 6: Measurement of the temperature changes in the 28 m air path with thermistors and the acoustic method. The agreement is better than 0.1 °C.

Furthermore, we have tested the combination of synthetic wavelength interferometer and the acoustic method by placing both experimental set-ups to measure the distance between two buildings of INRIM. The distance was about 78 m. In between, two calibrated thermometers measured the temperature of the air. In figure 7 the temperature measured by the thermometers and by the acoustic method is plotted together with the distance variation measured by the interferometer during the cooling period after the sunset (about 2 hours). Assuming that the physical distance between the two ends of the interferometer was constant within few micrometers, the apparent length measurement change can be attributed to the air temperature change so, the interferometer length is expressed in temperature change according to the formula ΔT [°C] = ΔL [µm] / 78.

Fig. 7: Distance measurement at 78 m is recorded together with temperature of air measured with thermometers and through speed of sound. The apparent displacement can be corrected to better than 10 µm in open air.

The agreement between the three curves demonstrated that the acoustic method works well also for large distances in open air and that is able to compensate interferometric measurements for temperature changes to a level better than 0.5 °C. This allows to obtain 0.5 ppm measurement accuracy in open air on long distances without the need of distributed thermometer measurements.

4. CONCLUSIONS

An accurate method to measure distances in air has been developed and tested at INRIM. The method is based on a synthetic wavelength interferometer based on a beat note generated by a pair of tunable infrared lasers. The temperature of the air in the optical path of the interferometer is estimated through a measurement of the speed of sound. The average temperature is estimated better than 0.1 °C. This measurement coupled with pressure and humidity measurements allows to estimate the refractive index of air to a level of 10^{-7} leading to an accuracy of the length measurement better than 10^{-6}. The device has been tested at various distances up to 78 m in open air.

REFERENCES

1. http://projects.npl.co.uk/luminar/
2. http://www.ptb.de/emrp/sib60-project.html
3. R. Dandliker, R. Thalmann, and D. Prongué, “Two-wavelength laser interferometry using superheterodyne detection,” Opt. Lett., vol. 13, no. 5, pp. 339–341, May 1988
4. Edlen B, Metrologia 2, pp 71-80 (1966)
5. Ciddor PE, Appl. Opt. 35 (9), pp 1566-1573 (1996)
6. S Azouigui, T. Badr, J.P. Wallerand, M. Himbert, J. Salgado, and P. Juncar, “Transportable distance measurement system based on superheterodyne interferometry using two phase-locked frequency-doubled Nd: YAG lasers,” Rev. Sci. Instrum., vol. 81, no. 5, pp. 053112, 2010.
7. M.Pisani et al., Proc of 15th International Metrology Congress, Paris (France) October 2011
8. Cramer O, J. Acoust. Soc. Am. **93** (5), pp 2510-2515 (1993)
9. CEI EN 61094-2:2010-09