Uncertainty Assessment of Optical Distance Measurements at Micrometer Level Accuracy for Long-Range Applications

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Abstract-We have developed a transportable distance meter based on a 1550-nm laser diode, that is, intensity modulated at 5 GHz. This fiber-based prototype is realized using telecommunication components that are reliable, largely available, and affordable. We have identified and quantified the different sources of error when measuring with this technique a distance between two positions of the same reflector. Minimizing these errors and evaluating their uncertainties lead to a global uncertainty of 4 μ m (k = 1) up to 1 km. This value does not include the additional errors caused by the evaluation of the atmospheric parameters. This uncertainty has then been verified over 100 m by comparison with an optical interferometer. The prototype was also tested outdoors over 5.4 km and has shown a resolution of 25 μ m for an integration time of 10 ms. Distance measurements for long distances with this prototype are still limited by the air refractive index effect. Nevertheless, we have demonstrated that the uncertainty on optical distances reached with this simple technique is compatible with the future development of a twowavelength system with air index compensation.

Index Terms—Absolute distance measurement, air refractive index, intensity modulation, long-distance telemetry, phase-based distance measurement.

I. INTRODUCTION

CCURATE absolute distance measurements over several kilometers are of great interest for several applications such as the construction and surveying of huge structures, for instance, dams, colliders [1], tunnels [2], or geological faults [3]. Nowadays, the most accurate commercial optical absolute distance meters (ADMs) used for these applications claim a standard uncertainty of 0.6 mm + 1 ppm up to 1 km (see manufacturers specifications). Nevertheless, in the 1990s, better performances have been reached with the Mekometer

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ME5000 from the former Kern Company [2]. This instrument, no longer manufactured, but still used by several geodetic institutes, can achieve an accuracy (coverage factor, k = 1) of 75 μ m + 0.5 ppm, i.e., 575 μ m at 1 km, with a recording of meteorological conditions at each end of the line, and under favorable atmospheric conditions [2]. However, for distances of several kilometers, millimetric accuracy cannot be reached with classical electronic distance meters (EDMs) due to the determination of the air refractive index: an accuracy of 1 mm over 5 km implies a knowledge of the average temperature along the optical path at 0.2 °C, and of the average pressure at 75 Pa, which is, in practice, impossible to achieve with classical sensors, especially for air temperature.

To overcome this physical limitation, a two-wavelength approach has been early proposed [5] and implemented [6], [7]. A commercial version was even manufactured in a few copies in the 1990s [8]. Its physical principle is based on the knowledge of the model of the air index dispersion: measuring simultaneously optical distances with two different wavelengths allows to deduce the geometrical distance, without the need to measure air temperature and atmospheric pressure. If we call *D* as the true distance, L_1 and L_2 as the optical distances (defined as the product of the geometrical lengths by the air indexes *n*) at the wavelengths λ_1 and λ_2 , respectively, *D* is given by

$$D = L_1 - \frac{n_1}{n_2 - n_1} \times (L_2 - L_1)$$

= $L_1 - A(\lambda_1, \lambda_2) \times (L_2 - L_1)$ (1)

where A is a factor independent of atmospheric parameters under the assumption of dry air, a limit case giving a good approach of the principle. A only depends on a couple of wavelengths used. Formula (1) shows the price to pay to apply this method efficiently: the A factor amplifies the uncertainty of the difference $L_2 - L_1$. Therefore, to obtain a given uncertainty u_D on the true distance, the optical path difference L_2-L_1 must be determined with an uncertainty A times lower than the targeted uncertainty.

This A factor is equal to 47 for the couple of wavelengths 780/1550 nm when the group index is relevant [7]. Thus, to obtain a submillimetric uncertainty on the true distance for this couple of wavelengths, the uncertainty on the optical path difference $L_1 - L_2$ must be better than 20 μ m.

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This performance is far from being achieved with classical EDM instruments, even when only dealing with the optical distances (i.e., without air index determination), especially for distances of several kilometers. The challenge lies in finding a technical solution enabling a good compromise between accuracy of optical distance measurements at each wavelength, robustness of the system, cost efficiency, and ability to measure over several kilometers, outdoors, in field conditions.

Many techniques have already been implemented for highaccuracy optical distance measurements, including two-color principle. Femtosecond lasers have been widely used in recent years, either as high-frequency modulators [9], [10] or as multiwavelength generators for interferometry [11]–[14], time-of-flight measurements [15], or combination of optical interferometry and time-of-flight methods [16]. These techniques can basically resolve one optical wavelength for overcoming fringe ambiguity and so open the way to absolute distance measurements with nanometer accuracy. Nevertheless, they remain expensive and difficult to implement in an instrument made for field measurements. Recently, the demonstration of interferometry with simultaneous measurements at two wavelengths, 532 and 1064 nm, was realized outdoors, showing submillimeter accuracy over 800 m [17].

In this paper, we present the telemetric system based on the measurement of the RF phase of an intensity-modulated laser diode after propagation in air. The use of fiber-optic components of the telecommunication industry makes possible the production of a compact, easy-to-use, and affordable instrument. This work is a first step toward the achievement of an air refractive index-compensated system for applications in the field. Figs. 1 and 2 provide an overview of the developed ADM, and of its compact design. We have quantified the different sources of errors of this telemeter when measuring an optical distance, i.e., the product of the air refractive index by the mechanical distance. The resulting uncertainty budget refers to the instrument itself and does not take into account the atmospheric parameters and the mechanical offset of the telemeter.

II. PRINCIPLE AND IMPLEMENTATION OF THE ADM PROTOTYPE

The ADM is based on the measurement of the phase shift ϕ of a modulation frequency along a measurement path. As shown in the following equation, this phase shift is proportional to the distance L traveled by light:

$$L = \frac{1}{2} \times \left(\frac{\phi}{2\pi} + k\right) \times \frac{c}{n \times f_{\rm RF}} \tag{2}$$

where *c* is the speed of light in vacuum, *n* is the group refractive index of air, f_{RF} is the modulation frequency, and *k* is an integer number, called order, and corresponding to the number of times that the phase of the amplitude modulation has rotated by 2π during the propagation.

The operation principle of the telemeter is basically the same as the one described in our previous publication [18].

As depicted in Fig. 3, a 1550-nm optical carrier is emitted by a distributed feedback (DFB) laser diode and intensity



Fig. 1. Photograph of the ADM mounted on a tripod.



Fig. 2. Cross section view of the optical head and of a hollow corner cube with a clear aperture of 127 mm.

modulated by an RF carrier around 5 GHz, thanks to a built-in electro-absorption modulator (EAM). This fiber-guided optical signal is then emitted in free space and collimated by an offaxis parabolic mirror for a long-distance propagation: the spot size of 48 mm (at 1% power level) is reflected back toward the telemeter by a hollow corner cube. The returned signal is finally directed toward a high-speed photodiode, and the phase of the photodetected RF signal is measured after a frequency down-conversion at 10.75 MHz. A variable optical attenuator (VOA) sets the optical power received by the photodetector around 50 μ W to limit the amplitude to the phase coupling effect, as discussed in Section III-B2. Then, RF amplification stages adjust the RF power around 0 dBm for optimum operation of the phasemeter. The phase measurement is achieved digitally by a field-programmable gate array (FPGA) that integrates each individual phase measurement over 10 ms.

To compensate for phase variations in the fiberoptic and electronic components, a fiber-optic reference distance of around 20 cm is measured every second and then subtracted from the free-space measurement. The switch from this reference path to the measurement one is performed



Fig. 3. Functional setup of the ADM.

by a fiber-optic optical switch. It has to be noted that the measurement path also includes 20 cm of optical fiber between the output of this switch and the free-space propagation. Thus, this compensation technique makes the system only sensitive to the difference between the fiber-optic reference path and the same length of fiber path comprised between the optical switch and the fiber end of the measurement path. The efficiency of this drift compensation was tested by heating the whole optical head (including laser diode, frequency synthesizers, and optical fibers) over 7 °C while measuring a fixed distance of 2-m indoors: a linear drift of the evolution of the mechanical offset with the temperature. A complete study should be conducted subsequently to go toward absolute distance measurements.

The distance measurements in Sections III–V are always performed using this compensation technique, the switch between both measurement paths being realized every half second.

The procedure for a distance measurement involves three steps, in addition to the measurement of the reference path. First, the order is determined. For this purpose, five different modulation frequencies are used sequentially: 4778, 4778.01, 4778.5, 4839, and 4978 MHz. Thus, five phase-shift measurements are obtained, and for each of them, an infinite number of distances according to the value of the order k can be calculated. In order to limit the number of solutions, we limit the maximum distance to an arbitrary value of 8 km. The order is the value k for which a common distance exists between each frequency. With this procedure, distance is known within 30 mm, i.e., a half a synthetic wavelength: $c/(n \times f_{\rm RF})$. The time needed for this first step is approximately 10 s, but it can be greatly reduced by a specific design of the FPGA.

In the second step of the distance measurement procedure, a fine measurement of the distance is performed. This consists of measuring the average phase shift over a large number of observations for a modulation frequency of 4895 MHz.

Finally, when the order and the fine distance have been obtained, the optical distance is corrected from the air refractive index using the Bönsch and Potulski formula [4].

The principle of the developed ADM is finally based on a well-known technique: the phase-based amplitude-modulated light telemetry. This approach is, for instance, the one applied in the Mekometer ME5000. However, the use of ten times higher RF carrier than the Mekometer system leads to a better distance resolution according to (2) and a lower sensitivity

to the crosstalk effect when converted into distance error. Furthermore, adopting up-to-date technologies, such as fiber-optic components not requiring optical alignment and digital electronics providing an efficient signal processing, we can exceed the performances of the Mekometer ME5000 and of the current commercial ADMs, at least for differential measurements (measurement of a distance between two positions of a corner cube).

III. SOURCES OF ERROR AND UNCERTAINTY BUDGET OF DIFFERENTIAL OPTICAL DISTANCE MEASUREMENTS

According to (2), the optical distance measurement is deduced from a phase-shift measurement and the knowledge of the frequency of modulation. In addition, to deduce a geometrical distance from the optical distance, the air refractive index through which the optical beam is propagated should be properly determined. The standard uncertainty on the measured distance u_L can, therefore, be separated into two components: $u_{instrument}$, the component coming from the measurement of the optical distance itself and u_n , the component coming from the measurement of air refractive index—which depends on the air temperature, the atmospheric pressure, the partial pressure of water vapor, and the CO₂ content—and from its fluctuations. $u_{instrument}$ can itself be divided in a phase measurement accuracy component u_{Φ} and in an RF accuracy component u_{fRF}

$$\left(\frac{u_L}{L}\right)^2 = \underbrace{\left(\frac{u_\phi}{\phi + 2k\pi}\right)^2 + \left(\frac{u_{f_{\rm RF}}}{f_{\rm RF}}\right)^2}_{\text{instrument component}} + \underbrace{\left(\frac{u_n}{n}\right)^2}_{\text{air index component}}.$$
 (3)

In order to state if the uncertainty budget is compatible with a future production of a dispersion-based air indexcompensated system, only the uncertainty components of the instrument are relevant since only the optical distances are required in (1).

A. Frequency of the Modulation: u_{fRF}

An error in the value of the modulation frequency leads to a scale error in the distance measurement. In practice, the modulation frequency is generated by a synthesizer locked on a miniature Rubidium (Rb) clock (model SA.22c from Microsemi, Application Profile 3), that is, specified to have a monthly relative aging rate of $\pm 3 \times 10^{-10}$. The frequency of this clock can be compared in our laboratory to a global positioning system (GPS)-disciplined Rb clock with a relative standard uncertainty of 3×10^{-12} . By measuring yearly the frequency delivered by the frequency synthesizers, a relative uncertainty of the frequency of modulation better than 4×10^{-9} is ensured

$$\frac{u_{f_{\rm RF}}}{f_{\rm RF}} = 4 \times 10^{-9}.$$
 (4)

B. Phase Measurement: u_{Φ}

The phase measurement can be affected by two different sources of systematic measurement error, the crosstalk effects 4

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and amplitude to phase coupling. In addition, a random noise limits the resolution of the telemeter for a given integration time. The systematic measurement errors have been minimized during the design phase of the instrument so that they do not lead to a correction. Nevertheless, measurement uncertainty on these errors has been quantified. In the end, the uncertainty on the phase measurement can be expressed as follows:

$$\frac{u_{\phi}}{\phi + 2k\pi} \times L = \sqrt{u_{\text{crosstalk}}^2 + u_{\text{AM/PM}}^2 + u_{\text{random}}^2}.$$
 (5)

1) Crosstalk Effect (ucrosstalk): An RF leakage of the modulation frequency from the emission stages to the reception ones leads to the addition of a spurious signal to the ideal measurement signal. This leakage, due to poor optical or electromagnetic isolations in some components, and excessive RF radiations from other ones, induces a cyclic error, sinusoidal with the distance that depends on the relative phase and relative amplitude between the crosstalk and the ideal signal. The period of this cyclic error is equal to half a synthetic wavelength, i.e., 30 mm in practice. The signal-to-crosstalk ratio (SCR), expressed in decibels, is quantified by measuring the amplitudes of the signals at an intermediate frequency, i.e., 10.75 MHz, at the phasemeter input when an optical beam is received, then when it is interrupted. The amplitude (half peak-to-peak) of this cyclic error can be well approximated by

$$A_{\text{crosstalk}}[\mu \text{m}] = \frac{1}{4\pi} \times \frac{c[m/s]}{f_{\text{RF}}[\text{MHz}]} \times 10^{-\text{SCR[dB]/20}}.$$
 (6)

As this error is a sine function, its probability density function is an arcsine distribution and its variance is half the square of the amplitude of the periodic error [19]. The uncertainty component due to crosstalk is so

$$u_{\text{crosstalk}}[\mu\text{m}] = \frac{A_{\text{crosstalk}}}{\sqrt{2}} = \frac{1}{\sqrt{2}} \times \frac{1}{4\pi} \times \frac{c}{f_{\text{RF}}} \times 10^{-\text{SCR/20}}.$$
(7)

In the developed system, the crosstalk level is typically -75 dBm and the signal level is 0 dBm, i.e., an SCR of 75 dB, which corresponds to an uncertainty component of 0.6 μ m (k = 1).

The experimental verification of (7) was realized using an interferometric bench as a reference of displacements. The difference between the interferometric distances and the ones given by the ADM was recorded over a distance of one synthetic wavelength, i.e., 61 mm. As depicted in Fig. 4, a dedicated setup was realized to vary the SCR: a fiber-optic splitter was added at the output port of the ADM to direct a part of the modulated light toward another retroreflector. This modulated signal, with a fixed RF phase, was added to the measurement signal in order to simulate a crosstalk. Its amplitude can be changed by slightly misaligning the reflector of the crosstalk path. Finally, for a given configuration, the SCR is stable at ± 0.5 dB. As shown in Fig. 5, the high goodness of fit between the experimental curves and the simulated ones shows that (6) fully reflects the effect of crosstalk on the measurement accuracy.



Fig. 4. Experimental setup for the simulation of the crosstalk effect.



Fig. 5. Nonlinearity of the instrument due to the crosstalk effect for different SCRs.

2) Amplitude to Phase Coupling $(u_{AM/PM})$: This effect corresponds to a conversion of an intensity variation of the modulated optical signal into a phase variation of the electrical signal generated by the photodetector. This effect has already been studied in [20] and [21] with several types of photodetectors: it has been demonstrated that the use of a positive-intrinsic-negative (p-i-n) photodetector with low optical input power limits the amplitude to phase coupling. Additional power-dependent phase shift can also be generated by the RF components following the photodetector. In that case, the solution consists in using an RF chain working at an intermediate frequency as depicted in Fig. 3. In practice, a variation of the RF signal at the phasemeter input due to optical power variation induces a variation of the measured distance as depicted in Fig. 6. A linear variation of the measured distance is observed when the RF power varies from -10 to +5 dBm with a slope of $-0.15 \ \mu m/dB$. When a distance measurement is made with a peak-to-peak power variation of x dB and assuming a rectangular probability function, the uncertainty associated with the amplitude to phase coupling can be written as

$$u_{\text{AM/PM}}[\mu \text{m}] = \frac{1}{2\sqrt{3}} \times 0.15[\mu \text{m/dB}] \times x[\text{dB}].$$
 (8)

For long-distance measurements, x is of the order of 10 dB. In that case, $u_{AM/PM}$ is of the order of 0.4 μ m (k = 1).

3) Random Noise (u_{random}): The standard deviation of a short-distance measurement, in a quiet environment without amplitude variation (no amplitude to phase coupling) and without distance variation (no visible crosstalk effect), is 0.8 μ m for a sample of 6000 points during 60 s. Using (2) to convert distance variations into phase variations for a modulation frequency around 5 GHz, this value corresponds to phase noise



Fig. 6. Variation of the measured distance as a function of the detected RF power at intermediate frequency.



Fig. 7. Relative distance as a function of time. n = 1 means that no air refractive index correction was applied.

of $2\pi/37500$ for 10 ms of integration time. For comparison to an optical interferometer at 633 nm, this would correspond to a distance noise of 8 pm. Fig. 7 shows this relative distance measurement obtained in laboratory conditions for a distance of 244 mm. This internal random noise is then quantified by

$$u_{\rm random} = 0.8 \ \mu {\rm m}. \tag{9}$$

C. Air Refractive Index: u_n

The uncertainty on the air refractive index can be classified into two components, $u_{naverage}$ and $u_{nturbulences}$.

The first component, $u_{naverage}$, is linked to the correction made by the operator. In general, the latter calculates the average air refractive index along the optical path using physical models such as Edlén or Bönsch and Potulski which have an accuracy of 3×10^{-8} . Hence, the uncertainty on the air refractive index will mainly depend on our capacity to measure properly different atmospheric parameters: the air temperature, the pressure, the partial pressure of water vapor, and the CO₂ content. As indicators, an error of 1 °C on the measured temperature has an impact of 1 mm/km, and an error of 100 Pa on the pressure has an impact of 270 μ m/km.

The second component, $u_{nturbulences}$, is linked to the dynamic variations in air density. As observed in our



Fig. 8. Data points obtained over 864 m at FGI baseline (Nummela, Finland).

measurements, the latter bring a turbulence-induced noise at the instrument level that depends on the measured distance and on the atmospheric conditions.

Outdoors, in quiet atmospheric conditions, we observe a short-term random noise due to the fluctuations of the atmospheric parameters of only 3.3 μ m over 864 m, for an integration time of 10 ms for each data point (Fig. 8).

Tests have also been conducted over longer distances, over 4.1 km, in harsh conditions: it was a warm and sunny day with temperatures around 35 °C and important beam scintillations. Under these conditions, as there is no active pointing servo system to keep the optical head on the corner cube, it is necessary to regularly slightly realign the optical head in the vertical direction to optimize the received signal. The results have shown standard deviations up to 40 μ m over 20 s of measurement. This is the maximum observed standard variations for such distances.

The extra random noise due to atmospheric turbulences is, therefore, quantified by values from 3 μ m/km in quiet environment to 10 μ m/km in harsh conditions

$$3 \times 10^{-9} < \frac{u_n \text{ turbulences}}{n} < 10 \times 10^{-9}.$$
 (10)

D. Uncertainty Budget

A global uncertainty budget for the measurement of a mechanical displacement (distance between two positions of the same reflector) can be formally written, taking into account different sources of uncertainty listed earlier, as u_L , shown at the bottom of this page.

The component coming from the measurement of the optical distance itself, $u_{\text{instrument}}$, is obtained by omitting air index components in this expression. It is below 4 μ m (k = 1) for distances less than 1 km. For a distance of 1 km, peak-to-peak amplitude variations of the signal of 10 dB and an SCR

$$u_{L} = \sqrt{\frac{u_{f_{\rm RF}}^{2}}{f_{\rm RF}^{2}}L^{2} + u_{\rm crosstalk}^{2} + u_{\rm AM/PM}^{2} + u_{\rm random}^{2} + \frac{u_{n \text{average}}^{2}}{n^{2}}L^{2} + \frac{u_{n \text{turbulences}}^{2}}{n^{2}}L^{2}}$$
(11)

TABLE I UNCERTAINTY BUDGET FOR DIFFERENTIAL OPTICAL DISTANCE MEASUREMENTS WITH THE TELEMETER PROTOTYPE

Standard uncertainty component	Source of uncertainty	Standard uncertainty	Sensitivity coefficient	Contribution
$u_{f_{RF}}$	accuracy of the modulation frequency	$4 \cdot 10^{-9} f_{RF} \mathrm{Hz}$	L / f_{RF} m.s	$4 \cdot 10^{-9} L \ \mu m^{\dagger}$
u _{crosstalk}	value of the signal to crosstalk ratio	$10^{-75/20}$ / $\sqrt{2}$	c / $(4\pi f_{RF})$ m	0.6 µm * †
u _{AM/PM}	variations of the signal amplitude	$10/2\sqrt{3}$ dB	-0.15 µm/dB	0.4 µm **
u _{random}	random noise on the phase measurement	0.17 mrad	4.7 μm/mrad	0.8 µm
* for SCR of 75 dB ** for peak-to-peak amplitude variations of 10 dB				
for f_{RF} = 5 GHz				
Combined standard uncertainty		$u_{k=1}(L) = \sqrt{(1.1 \mu\text{m})^2 + (4 \cdot 10^{-9} L)^2}$		



Fig. 9. Setup realized for the comparison between a linear interferometer and the developed ADM.

of 75 dB, the uncertainty of the instrument is

$$u_{\text{instrument}} = \sqrt{\frac{u_{f_{\text{RF}}}^2}{f_{\text{RF}}^2}} L^2 + u_{\text{crosstalk}}^2 + u_{\text{AM/PM}}^2 + u_{\text{random}}^2$$

= $\sqrt{(4 \times 10^{-9} \times 10^9)^2 + 0.6^2 + 0.4^2 + 0.8^2} \mu \text{m}$
= $4.1 \mu \text{m}.$ (12)

The uncertainty budget of the instrument, excluding air index determination and mechanical offset of the instrument, is summarized in Table I.

IV. VALIDATION OF THE UNCERTAINTY ESTIMATION AND RANGE OF OPERATION

The validation of the uncertainty budget should be conducted by comparison to a reference system with an uncertainty better than or equivalent to the claimed uncertainty of the developed instrument. This was done up to 100 m using a linear bench whose displacement is measured by a 633-nm interferometer. In that case, environmental parameters are well controlled and have a negligible effect on the comparison.

A. Comparison to a 100-m Interferometric Displacement

The telemeter was compared to a 50-m-long interferometric bench, indoors, in a controlled environment. As depicted in Fig. 9, the interferometric beam was propagated over 50 m, whereas the telemeter beam was propagated over 100 m, thanks to a double round trip. The interferometric distance has therefore been multiplied by a factor of two for the comparison.



Fig. 10. Error as a function of the interferometric displacement.



Fig. 11. Measurement of $100-\mu$ m steps displacement of the corner cube after a propagation over 5.4 km in air.

The difference between twice the interferometric distance at 633 nm and the ADM distance at 1550 nm was lower than 2 μ m the first day (vs. 8 μ m the second day) with a standard deviation of only 1.0 μ m (vs. 2.2 μ m the second day). As both instruments do not operate at the same wavelength, a small error can occur if atmospheric parameters are not properly estimated. Nevertheless, this error is negligible at the micrometer scale: if the temperature measurement is made with an error of 1 °C, this implies only 100-nm error in the comparison.

During the comparison, the SCR was always higher than 75 dB. Formula (7) shows that, in that case, the uncertainty component associated with crosstalk is lower than 1.5 μ m, which is compatible with the comparison depicted in Fig. 10.

B. Resolution and Range of Operation Outdoors

The telemeter has been tested over 5.4 km, above an urban area, between the roofs of two buildings located in Paris



Fig. 12. Distribution of the recorded distances for three corner cube positions.

(LNE building) and nearby Paris (Meudon observatory). Two weather stations were installed at each end of the line: temperatures were 8.2 °C and 10 °C, pressures 1003.6 and 992.9 hPa (the Meudon observatory is located about 80 m above the LNE building), and relative humidities 57% and 68% in Paris and Meudon, respectively. The sky was overcast with a ~14 km/h wind. The short-term (15 s) sample standard deviations were between 10 and 40 μ m for 10 ms of integration time for each individual measurement point.

The 5.4-km distant corner cube was moved by steps of 100 μ m, thanks to a micrometric translation stage, from 0 to -1 mm, then from -1 to 0 mm. Between each step, additional measurements of the 0-mm position were realized to estimate the distance drift that occurred during the 10-min measurement due to the evolution of the atmospheric parameters. As depicted in Fig. 11, at the top, a polynomial drift has been considered (red curve). A distance variation of 200 μ m for 10 min, as the one depicted in Fig. 11 (in the plot above), corresponds to a variation of the average temperature along the 5.4-km path of only 0.04 °C, for which drift of the instrument is negligible. At the bottom, we easily distinguish the distance variations despite the atmospheric disturbances.

For each position of the corner cube, a distribution of the measured distances can be plotted. In Fig. 12, the histograms of the measurement values obtained at the three last positions of Fig. 11 are depicted. We obtain normal distributions with standard deviations between 21 and 28 μ m. These values correspond to the instrument resolution (1 σ) at 5.4 km.

V. CONCLUSION

We have developed a robust, compact, and easily transportable distance meter.

Indoors, in a controlled environment, its uncertainty for a displacement measurement is around 2 μ m (k = 1) up to 100 m. Outdoors, in quiet environmental conditions, the measurement resolution is 3 μ m (1 σ) over 850 m. In field conditions and urban environment, the resolution of the prototype is around 25 μ m for 5.4 km of measured distance (10.8 km of propagation). The accuracy of the mechanical distance measured by the prototype is still limited by air index determination along the propagation path of the optical beam. However, the uncertainty obtained for optical path measurement with the prototype is compatible with a future improvement of the setup by the addition of a second wavelength in order to partially

compensate the air index effect. This second wavelength could be obtained by frequency doubling of the 1550-nm light. Even if the implementation of all fiber-optic system, for both wavelengths, is more complex, this has already been demonstrated in [22]. In that case millimeter uncertainty on a distance measurement could be reached over 5 km without air temperature and pressure measurement.

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