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ABSOLUTE DISTANCE MEASUREMENTS BY LASER INTERFEROMETRY

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ABSTRACT - A double-channel Michelson type interferometer is presented which allows absolute distance measurement up to 3 m with an uncertainty of 0,1 µm. It uses the principle of synthetic wavelength and can be used under vacuum or in any gaseous medium, with the help of a new type of source, called an air-wavelength standard. The CNES (Centre National d'Etudes Spatiales) is interested in an absolute measurement both in space (vacuum) and on the ground, in air, to characterize optical instruments.

1 - INTRODUCTION

Laser interferometry allows one to realize dimensional measurement with a low uncertainty (the 10^{-8} level can be reached when the measurements are made under vacuum). In air, however an additional uncertainty arises from the unknowledge of the refractive index of the medium n.
To determine n, one needs to measure the temperature, the pressure, the carbon dioxide concentration and the relative humidity with the help of calibrated sensors and the Edlen formula. Nevertheless the relative uncertainty is still about 1 part in 10^{7} which limits the accuracy of dimensional measurement.
In this paper, we describe an interferometer which enables one to measure distances between 0.4 and 3 m, in air and in vacuum, with a relative uncertainty close to 1 part in 10^{8}.

2 PRINCIPLE [Junc 97] [Ikes 92] [Dänd 88][Gill 83]

Fig 1 shows the principle of the apparatus. It is based on a double channel Michelson-type interferometer illuminated by the beam of a frequency tuneable laser diode around 1.55 µm of frequency ν_1. The beam splitter-compensator assembly is composed of 3 identical Fresnel parallelepipeds optically adhered together and forming an optical block. One of the parallelepipeds has a semireflecting coating on the internal face. Only one of the arms of the interferometer has a totally reflecting glass-air or vacuum interface, the glass part of the other arm behaves as a compensating plate. The first arm of the interferometer is ended with a corner-cube reflector mounted on a piezoelectric transducer. The second one is ended with an identical reflector situated a distance **D** further from the optical block.

Any incident beam whose polarizsation is oriented at 45° to the plane of incidence (equivalent to the plane of Fig. 1), can be split into two orthogonal polarizations, p and s, respectively parallel and perpendicular to the plane of incidence. We can consider that these two orthogonally polarized output beams interfere independently inside the interferometer. After a simple total reflection for each direction of propagation, these beams acquire a phase difference $\Delta\Phi$ derived from the Fresnel formulae

$$\tan\left(\frac{\Phi_p}{2}\right) = \frac{n_g\sqrt{n_g^2\sin^2 i - 1}}{\cos i}$$
$$\tan\left(\frac{\Phi_s}{2}\right) = \frac{\sqrt{n_g^2\sin^2 i - 1}}{n_g\cos i} \qquad (2.1)$$

from which we deduce

$$\tan\left(\frac{\Phi_p - \Phi_s}{2}\right) = \tan\left(\frac{\Delta\Phi}{4}\right) = \frac{\cos i\sqrt{\sin^2 i - 1/n_g^2}}{\sin^2 i} \qquad (2.2)$$

where i is the beam angle of incidence on the total reflecting surface and ng is the refractive index of the medium. An angle of incidence i=55° is necessary to obtain a 90° phase shift at λ=633nm with an optical block made from Schott BK7 glass (n_g=1.515)

At the output of the optical block, a polarizing beam splitting cube separates the p and s components of the polarization. The two output intensities are

$$I_p = \frac{I}{2}(1+\cos\varphi)$$
$$I_s = \frac{I}{2}(1+\sin\varphi) \qquad (2.3)$$

where I_0 is proportional to the intensity. The quantity $\varphi = 2\pi\frac{\nu_1}{c}2nD = (k+\varepsilon)2\pi$ is the output phase of the interferometer, c is the speed of light in vacuum, n and ν_1 are defined above. D is the distance to be measured, k is the integer part of the interference order and ε is the fractional part. From the output beam of the interferometer and using two perpendicular polarizers set in front of detectors, we obtain the two signals in phase quadrature given in (2.3)

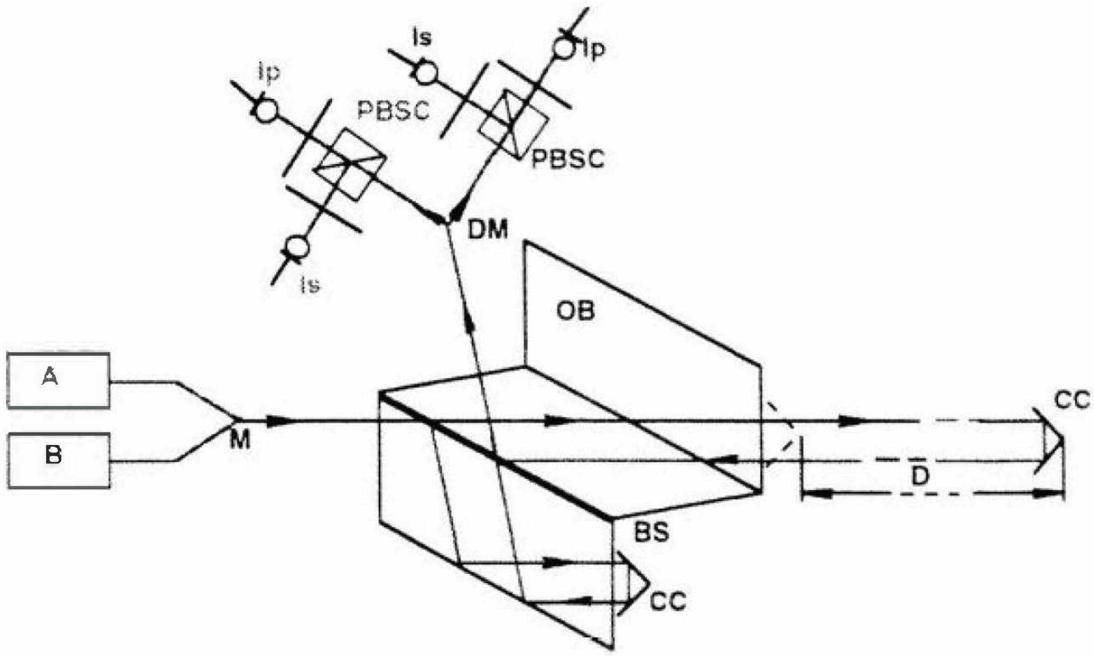

Fig 1 Interferometric set-up OB optical block , CC corner cube , P polarizer , D_s and D_c cosine and sine detectors , M and DM multiplexer and demultiplexer , D distance to measure , ν_a and ν_a' source A frequencies , ν_b source B frequency

After an appropriate electronic treatment (subtraction of DC levels and intensity normalisation), these two signals are reduced to

$$\begin{aligned} I_p &= \cos\varphi \\ I_s &= \sin\varphi \end{aligned} \qquad (2.4)$$

For control purpose, these two quadrature signals can be visualised by sending them to the inputs of an oscilloscope set to the XY configuration The position of the spot gives directly a value of φ (Fig 2) Practical values of φ are obtained by adequate computer treatment of these signals

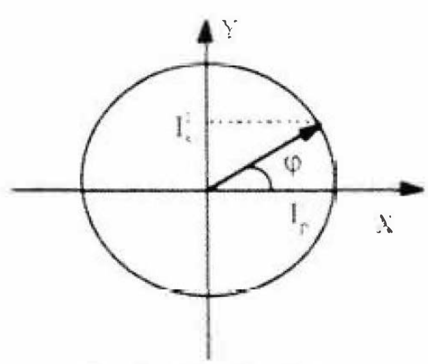

Fig 2 Lissajou figure

- After computing, I_p and I_s are send to an A/D converter and to a sine and cosine inputs of a reversible counter This counter determines the integer number of half fringes during the scan of the laser frequency

To determine the fractional part, we have to
- measure φ over 255 steps uniformly distributed over $2\times 2\pi$ rad (the digital scan is ensured by a computer controlled piezoelectric transducer upon which the reference corner cube is mounted)
- normalise the sine and cosine experimental data by a procedure which determines the extreme values (suppression of error gain adjustment G_X and G_Y)
- determine the means-squares-circle [Raze 97] of the data recorded over 2π rad (centre of the circle $O(O_X,O_Y)$ and the radius R_0)
Such that we have finally

$$X = \frac{I_c^i}{G_X} - O_X$$
$$Y = \frac{I_s^i}{G_Y} - O_Y \qquad (2.5)$$

The value of φ is given by $\varphi=\tan^{-1}(Y/X)$ From which we extract $\varepsilon=\varphi/2\pi$ (where $0<\varepsilon<1$) with an uncertainty $d\varepsilon$ of order 10^{-3}

3 - MEASUREMENT UNDER VACUUM

3 - 1 - Description

The frequency ν_L of the tuneable laser diode is scanned from ν_a to ν_a', reference frequencies corresponding to two optical transitions near 1,5µm of the acetylene molecule The absolute distance **D** can be determined for each frequency

$$D = (k_i + \varepsilon_i)\frac{c}{2\nu_i} \qquad (3.1)$$

where k_i is the integer part of the interference order and ε_i is the fractional part
D is also given by

$$D = (\Delta k + \Delta\varepsilon)\frac{c}{2\Delta\nu} \qquad (3.2)$$

where $\Delta k=k_a-k_a'$, $\Delta\varepsilon=\varepsilon_a-\varepsilon_a'$ and $\Delta\nu=\nu_a-\nu_a'$ The ratio $c/\Delta\nu$ is often called the synthetic wavelength
In our case $\nu_a-\nu_a'$ is of order 292 Ghz
In this step, Δk is known unambiguously and fractional parts at the beginning and end of the scan are determined by the method explained above From equation (3.2) we calculate a first value of **D** with an uncertainty around 1.5µm derived from the uncertainty of the frequency difference $\Delta\nu$ (97 kHz in our case) and from the uncertainty of $\Delta\varepsilon$ ($1.4\ 10^{-3}$) With this uncertainty it is not possible however to obtain a better accuracy in the measurement of **D** by using equation (3.1) directly since the determination of k remains ambiguous
This ambiguity can be solved by using a third frequency standard ν_b such that $\nu_b-\nu_a$ (900 GHz in our case) is three times larger than $\nu_a-\nu_a'$ This allows one to reduce the uncertainty of **D** to 0,5µm
For this latter case, since it is not possible to scan continuously the laser frequency from ν_a to ν_b, the value k_b-k_a cannot be measured directly It is however calculated without ambiguity from the values determined using the first step of the measurement

Equation (3.1) constitutes the last step of the measurement since now the uncertainty of **D** obtained by step 2 permits a determination of k_a. The final uncertainty in **D** is obtained using equation (3.1) and becomes 2.5nm (10^{-9} relative uncertainty for **D**=3m).

3 - 2 - Experimental results

For the moment, we realised the first step of the measure, which consists in

- determining ε_a
- counting the number of fringes during the scan of the laser diode frequency from ν_a to ν_a'
- determining ε_a'

Because the measure of ε_a and ε_a' is not simultaneous, we have to take into account any vibration or thermal expansion of our interferometer during the measuring time of around 30s. So that we use a second laser source which is a He-Ne laser at λ_r=633nm. It works as a classical interferometer.
At last, the absolute distance **D** is given by

$$D = (\Delta k + \Delta\varepsilon - d_r)\frac{c}{2\Delta\nu}$$
$$d_r = \frac{\nu_a}{\nu_r}(\varepsilon_r - \varepsilon_r) \qquad (3.3)$$

The quantity d_r is the correction determined from the calculation of ε_r and ε_r' at the beginning and the end of the scan.
Distance measurements are made under vacuum (10^{-5}mbar and 0.1mbar) at about 0.41 and 3m. The reference hollow corner cube in then moved from about 77µm by mean of the piezoelectric transducer. The panel below summarizes the results obtained by 100 measurements each time. The mean value, the experimental standard deviation (esd), the repeatability, the reproducibility and the global uncertainty are calculated.

	10^{-5}mbar		0.1mbar	
	3m	0.41m	3m	0.41m
D (m)	2.956901	0.411941	2.956900	0.411936
esd (µm)	1.5	2.1	1.1	0.43
repeatability (µm)	1.2	1	1	0.43
reproducibility (µm)	2.8	1.7	2.5	0.43
uncertainty (µm)	**1.4**	**1.1**	**1.1**	**0.43**
Corner cube displacement (µm)	around			
D (m)	-	-	2.956821	0.411857
esd (µm)	-	-	0.9	0.8
repeatability (µm)	-	-	1	0.4
reproducibility (µm)	-	-	1	0.72
uncertainty (µm)	-	-	**1**	**0.5**

The uncertainty obtained here is of the same order than theoretical uncertainty calculated into 3 - 1
The uncertainty is greater at 10^{-5}mbar than 0.1mbar because we worked with the vacuum pump on,
we suppose that it is the cause of interference vibrations
The displacement of the corner cube measured by the interferometer is 79µm

We also examined the effect of the external temperature T (the variation is about 2°C) on the absolute distance **D** and we observe a linear relation between **D** and T. The factor is 12.5µm/°C at 3m (Fig 3)

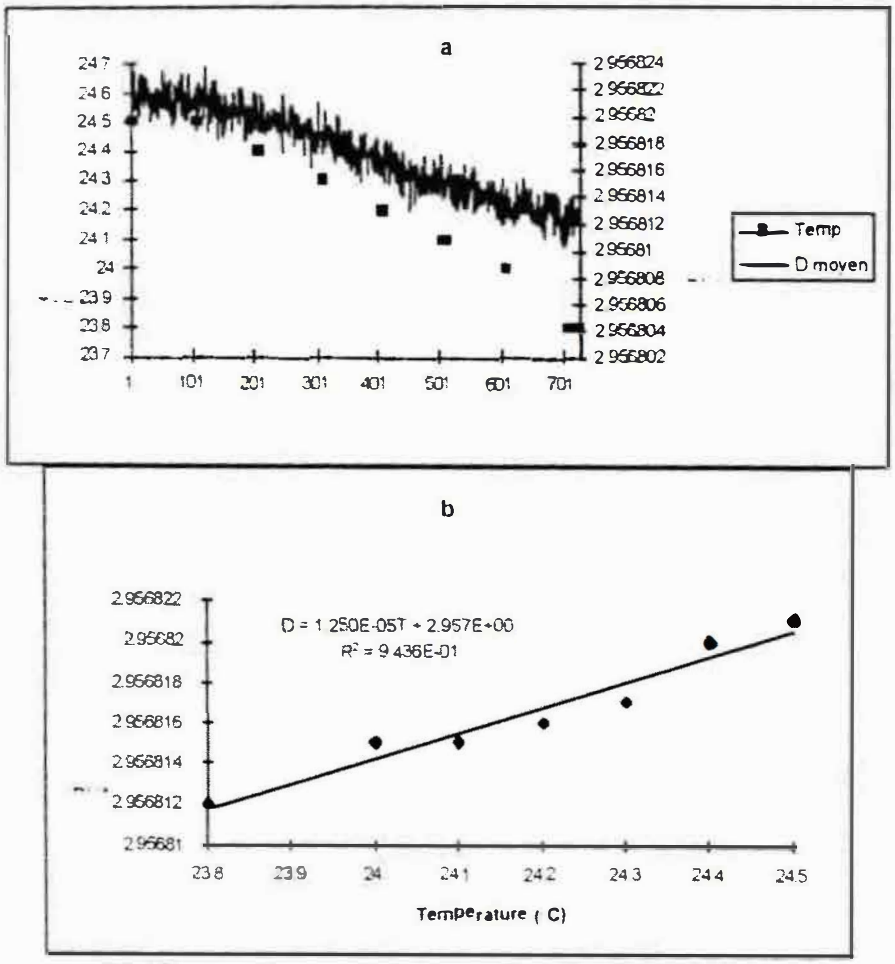

Fig 3 a)Temperature and absolute distance vs time
b) Absolute distance vs temperature

We submitted the laser source at temperatures of 10, 20 and 30°C and we made absolute distance measurements at 3m as described above. The panel below shows the results

	10°C	20°C	30°C
D (m)	2.956904	2.956906	2.956905
uncertainty (µm)	2.6	1	1.5

We also examined the correlation between the absolute distance measured as described above and the displacement determined by the visible source working as a classical interferometer (Fig 4)

We can see that the two curves have the same behaviour . the visible measurement is 1.44µm and the infrared one is 1.61µm

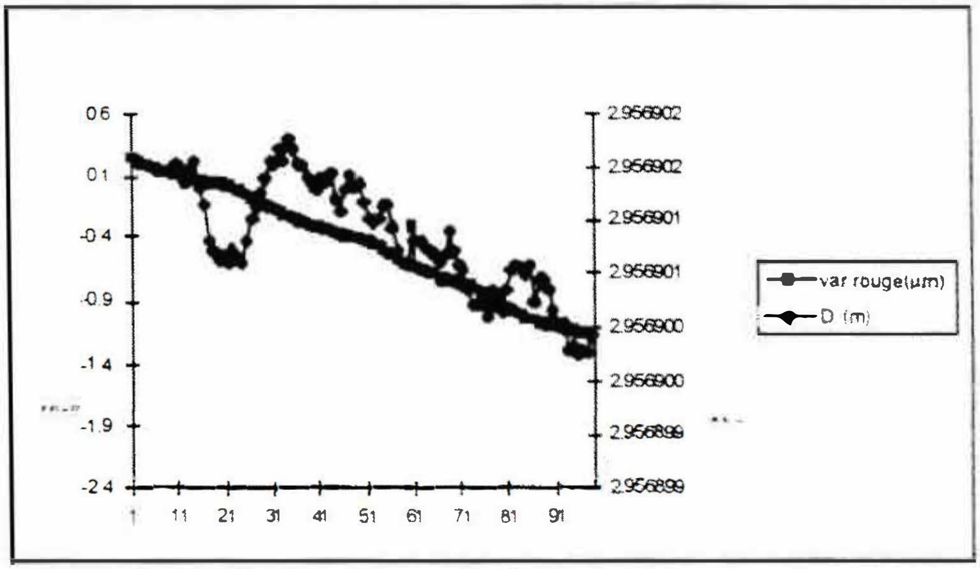

Fig. 4 Absolute distance and visible measurement vs time

We prove that we can measure an absolute distance with an uncertainty of 2 µm We show that a second source is necessary to make a correct measurement of **D** We show too that our system can detect any variation of **D** around a face value, 0.41 or 3 m

If the method is applied to distance measurement in air the relative uncertainty will be increased to 10^{-7} because of the unknowledge of the refractive index n

4 - MEASUREMENT IN AIR OR ANY GASEOUS MEDIUM

In order to make distance measurement in air (or another gaseous medium), a new type of source is used with the interferometer described above The source in question is an air wavelength standard developed at the BNM-INM (Bureau National de Metrologie-Institut National de Metrologie) Its relative uncertainty $\frac{d\lambda}{\lambda}$ is about 1 part in 10^8 and it is insensitive to the refractive index of the medium, generally air Fig. 5 shows the principle of this wavelength standard

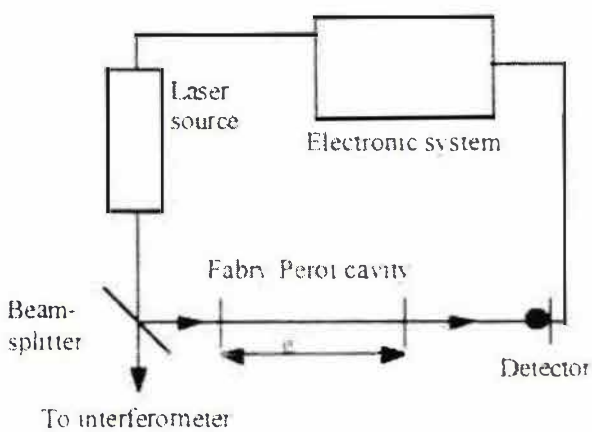

Fig 5 Air wavelength standard

The source is based on a plane-plane Fabry Perot cavity with a zerodur spacer to which the silica mirrors are optically adhered The gold coated mirrors have a reflectivity of 97% at 633nm and even higher in the infrared (1550nm)

The design of this system allows one to determine unambiguously the interference order k of the transmission peak to which the frequency ν_l of a laser diode is locked after locking, the frequency of the laser source tracks in real time the refractive index fluctuations such that $n\nu_l$ =constant The wavelength of the source given by $\frac{2e}{k}$ remains unaltered This wavelength is determined by measuring e under vacuum, with the help of an optical standard and the method of exact fractions

Using this system, the three preceding reference frequencies ν_3, ν_3', and ν_b are replaced by the reference wavelength given by a laser diode locked on different transmission peaks of known interference orders The distance **D** is determined as described above

The measurement uncertainty is limited by the wavelength standard (about 10^{-8}) and is free of refractive index corrections

5 - CONCLUSION AND PERSPECTIVES

In this paper we have outlined the principles of distance measurements using a device based on a fringe counting sigmameter and the concept of synthetic wavelengths A prototype interferometer has been developed at CSO Mesure in order to prove the feasibility of the first step of the measurement We prove that we can measure an absolute distance up to 3m with an uncertainty of 2µm in using one synthetic wavelength and the continuous scan between two frequencies It will allow us to link two discrete frequencies (synthetic wavelength about 310µm) thus reach an uncertainty of 0.1µm Finally we will use the basic wavelength (1.5µm) to measure the absolute distance with an absolute uncertainty about 3nm

The next step consists in associating our interferometer and the air-wavelength standard and to show that we can make distance measurement in air without any problem

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