Development of an horizontal interferometric dilatometer for gauge blocks

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ABSTRACT:

Based on a heterodyne interferometric measurement, an original system to measure the linear thermal expansion coefficient (LTEC) of parallel gauge blocks (GB) has been developed. The automatic instrument measures the displacement of the parallel reference faces of the GB, which is mounted in horizontal way. The dilatometer has to measure the change of temperature and displacement of the GB simultaneously. The measurement displacement is carried out by a laser interferometer using the reference surface of a GB as part of the flat mirror optical interferometer. Termistor sensors in the body of the block measure the temperature. The GB changes its temperature by thermal conduction from electrical heaters. The optical system consists of two plane mirror high stability interferometers and an optical fiber to receive the measurement signal from interferometers. Two laser beams reflect the surface of the GB face in order to provide an optical resolution of $\lambda/4$. The total resolution of the commercial interferometric system is $\lambda/128$.
For the measurement of GB of steel and tungsten carbide, a reproducibility of 0,03 x 10^{-6} K^{-1} has been achieved. The estimated uncertainty in the measurement of LTEC is less than 3 x 10^{-7} K^{-1} for GB of 100 mm.
The results for short GBs, the uncertainty analysis and uncertainty budget, the measurement time optimization and the capability to easure objects of different shape of GB are discussed.

Keywords: expansion coefficient, dilatometer, heterodyne measurement.

1. INTRODUCTION

As is know, the measurement uncertainty using parallel gauge blocks (GB) have their main source in the use of this GB in a temperature different of 20 °C. The corresponding correction due the thermal deformation is proportional to the length of the GB and the lineal thermal expansion coefficient (LTEC).

For the above reason the high accuracy measurement of LTEC in GB a very important component in the budget uncertainty for industrial measurements and calibration laboratories; moreover the influence of the uncertainty in LTEC of large GB increase with the length of the block.

The present dilatometers developed for high accuracy measurement of LTEC in GB and other shape materials, are based on interferometric measurements. Used to heat transfer by radiation inside of vacuum chambers [1,2,3]. The range of measurement is between 0 °C to 30 °C to determine LTEC and higher temperatures for no linear thermal expansivity. The uncertainty of these systems is less than 5 x 10^{-8} K^{-1}, and the time to complete one measurement process could be more than 10 hours.

2. DEFINITION OF THE LINEAR THERMAL EXPANSION COEFFFICIENT

The coefficient of thermal expansivity is defined for a temperature T as follows:

$$\alpha_T = \frac{1}{L_o}\frac{dl}{dT}\Big|_T$$

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where; dl is the change of length due thermal expansion,
dT the change of temperature and Lo is the nominal length.

α_T is usually expressed as $\alpha_T = a + bT + cT^2 + ...$ and, for a short range of temperature it must be reduce to the linear term, where LTEC is defined.

3. INSTRUMENT DESCRIPTION

Entire measurement elements of the dilatometer are inside of a cabin of aluminum walls, thermically isolated with polyethylene expanded. The base of optical components is an iron plate thermal insolated from an optical table. The measurement region is bigger enough to mount objets of different shape of GB in order to measure their LTEC.

The dilaometer's assembly is shown in figure 1. One personal computer receives data from the high resolution ADC and control temperature measurement, barometer readings, electronic temperature control, two interferometric axis card and thermometric bridge.

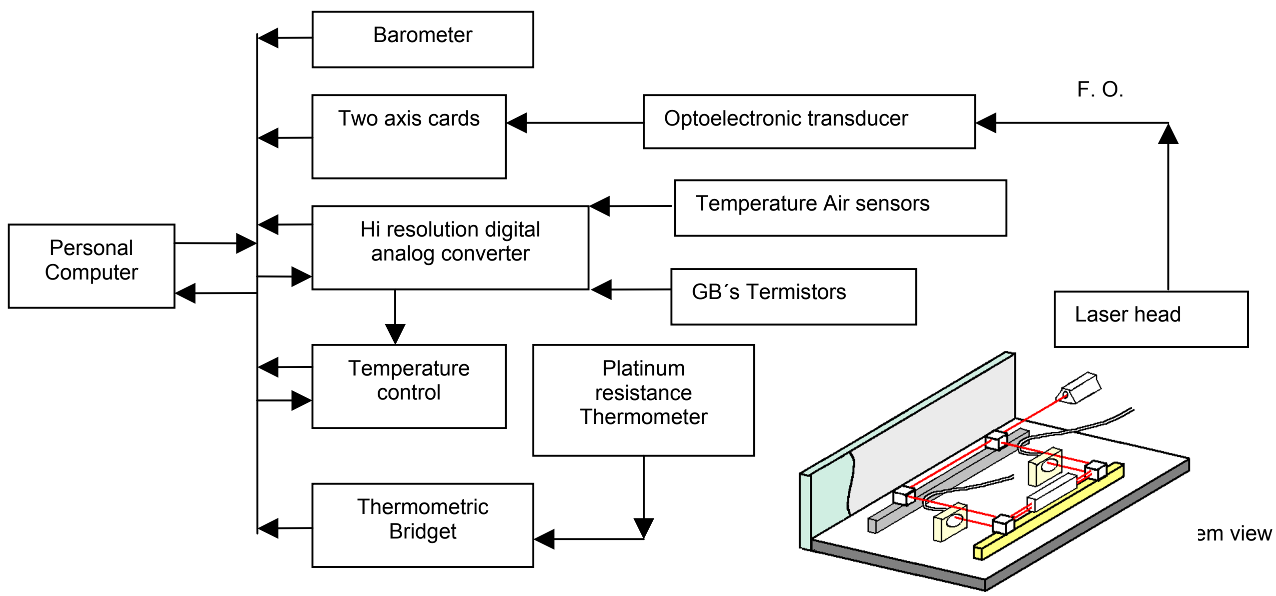
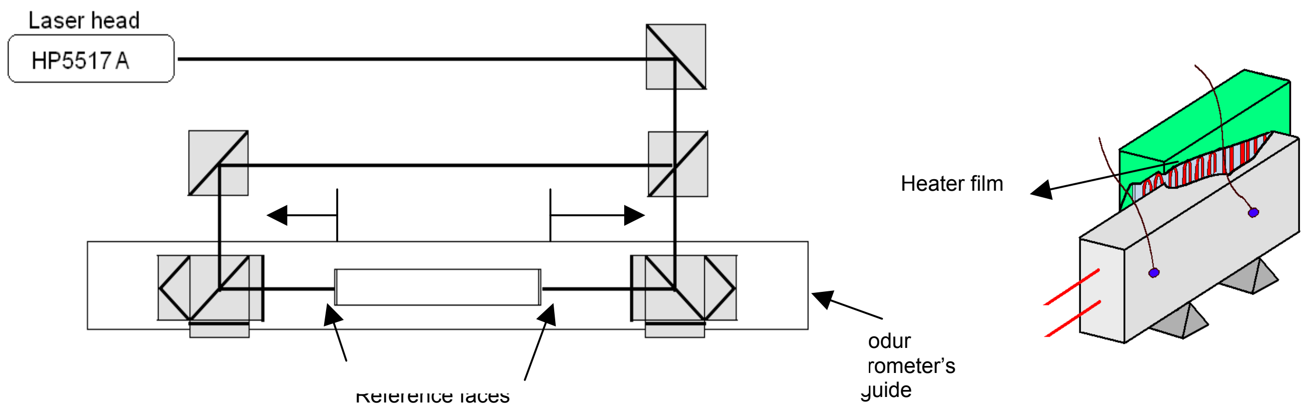


Figure 1. Blocks Diagram of dilatometer.

The principal component of the mechanical support system, is a Zerodur bar which is used as a guide for optical elements of the interferometers and provide a base to support the GB. Also the Zerodur bar is used as a reference interferometer's separator due to its low thermal expansion coefficient.
The mechanical support is designed for the free expansion of the GB in direction of both faces, so its important not to fix GB supports to the base.
One thermal isolated cover keeps the GB block thermal isolated reducing the heat transfer to the air cabin. Inside of the cover there are symmetric heater films and measuring thermistor sensors as shown in figure 2b.



a) b)

Figure 2. a) Diagram Over View. b) Gauge block detail

The temperature control module keeps low heat transfer at rates less than 0.6 W on continuos power while the measurement take place in order to keep low air temperature changes inside the cabin. The temperature of mechanical parts include Zerodur bar increase at most 0.05 °C during a measure cycle, this condition produce a low drift in length which must be included in the uncertainty budget.

Two commercial interferometric axis cards measure the length and send it to PC. The control of GB temperature, interferometric measurement, temperature measurement and the total instrument control are realized by a PC, using preloaded measurement sequences in order to achieve automatic measurements of LTEC.

3. THE OPTICAL SYSTEM.

Displacement measurement is made by two high thermal stability and high resolution flat mirror interferometers and commercial axis cards, because the optical resolution is $\lambda/4$ and the card resolution is $\lambda/32$ the total resolution of the card interpolator is $\lambda/128$ (5 nm). The optical measurement is sensible to any movement of the reference faces of the GB. Two laser beams are reflected by each of the reference face's of the GB. Only the movement of the central position between beams is measure due the construction of the optical array. The measurement length increase if the GB is heated following the optical axis otherwise a cosine error is present in the measurement and must be corrected. However, usually the length displaced of few micrometers produce a negligible cosine error.

Figure 3 shows the optical elements of the interferometers, each one consist of a polarized beam splitter, cube corner, two plane mirror (one is the reference face of the GB), and two $\lambda/4$ waveplates. The laser head send to beam splitter two linear polarized wavelengths (frequencies ν_1 and ν_2); the polarized beam splitter separate the wavelengths and send one to reference plane mirror while the other is send to GB reference surface. The waveplates produce a total rotation of the linear polarized beams therefore only one wavelength travels to the face of the GB while the other travels only inside the optics. Thermal stability of the array is produced by the same travel length of both wavelengths inside de optics and because the double path of the measure wavelength this optical arrangement has $\lambda/4$ optical resolution.

The Instrument makes corrections by dead path and air wavelength according to the modified Edlen formulae [4]. The parameters measured for the refractive index calculation are air temperature and ambient pressure. The humidity is only controlled around 50% in laboratory; those data are acquired for the computer which adjusts the wavelength to air conditions.

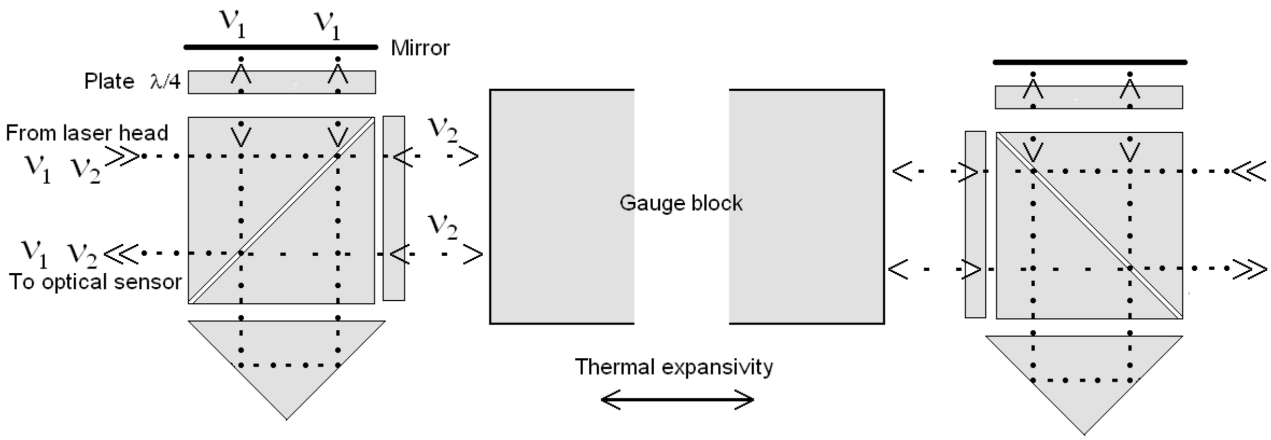


Figure 3. Optical arrangement

The gauge surface displacement measurement is affected by the change of refractive index of air inside the isolated cabin, and the correction is proportional to the length of optical dead path.

The change of temperature in the optical system (interferometers and supports) must also be corrected in order to reduce the length measurement repeatability. Finally, there is a correction factor proportional to the temperature of GB produced by the change of the air volume temperature next to the exposed measurement surface (both faces of the GB). This phenomena require a correction like the death path correction but only temperature dependent.

5. THE GAUGE TEMPERATURE MEASUREMENT

A high-resolution data acquisition card (ADC), measure temperature into the dilatometer cabin and temperature of gauge blocks (GB) using thermistors as temperature sensors. There are 8 temperature measurements inside de cabin: 1 interferometer temperature from each one of the optical arrays; 4 measurement temperatures on the body of the GB and 2 air temperatures inside de cabin. Additional there is one sensor outside de cabin to measure the lab air temperature.
The digital set point to the temperature control module is send by the computer program through the ADC card. The temperature control module change the temperature of the gauge by means of electrical foil heaters. The control is based on a pulse width modulator (PWM) controlled by the electronic comparison between set point and reference thermistor.

The dilatometer calibrates their thermistors with thermometric bridge and standard PRT using an aluminum block mounted in the place of GB. The software produces the necessary temperature stable points and read data from the thermometric bridge and ADC card in order to get resistance readings from thermistors.

The temperature measured by the four thermistors on the lateral faces of the GB is calculated by average of resistance measurements, using 24 bits analog digital converter (ADC). Due absolute temperature measurement is no required the contributions to the uncertainty comes from the no lineal behavior, the hysteresis of the sensor for the thermal cycles and the calibration uncertainty using a PRT standard.

The evaluation for the thermistor's hysteresis and no linear behavior in the range of measurement was done with several calculations of the calibration parameters for the measurement sensors.

In the calibration and hysteresis experiments, three stable temperature points are taken at 20 C, 24 C and 26 C, the cycles are automatically controlled by the PC. The data are adjusted using Steinhart and Hart equation in order to compare the results in Celsius degrees. The experiment was done using the standard PRT inside of the aluminum block used for thermistors calibration. The PRT and the standard thermometric bridge have an no linearity less than 1 mK in the range of 20 C to 30 C. An example of the results of these experiments are as follow:

Average Thermistors Temperature (C)	Temperature of standard PRT	Difference (C)
20.956	20.957	0.000
24.011	24.012	-0.002
26.207	26.215	-0.008
20.957	20.955	0.003
24.014	24.017	-0.003
26.208	26.212	-0.004
20.956	20.953	0.003
24.015	24.020	-0.005
26.207	26.216	-0.009

Table 1 - Example of temperature cycles for hysteresis and no linearity evaluation

From the results of the table 1, thermistors linear behavior of less than 9 mK is observed, while cycle hysteresis. Is no more than 5 mK, defined as the difference between 20 C – 26 C –20 C temperature points.

6. THE MEASUREMENT PROCESS

To operate the dilatometer, the user mades a program sequence which the dilatometer PC program can executes later. In the case of LTEC measurements the sequence only include cycles of change of set point of control temperature and finding thermal stability, the number of cycles is defined by user. While the stability is reach the program writes to file the status of all sensors readings in order to verify any environment disturbance in the lab.

The computer takes readings of temperature while thermal control is trying to stabilize the GB temperature. The measurement algorithm consider thermal stabilized the GB when the temperature and displacement measured points are inside of a band less than 10 mK and 20 nm wide respectively; the length of the band is preset by user (usually 30 minutes). After this time the program compensate data of interferometers and thermistors temperature before calculate LTEC. In next step, the program sends a new reference temperature to thermal control in order to find the next temperature point. Usually 10 o more temperature points are programmed for a night measurement of 15 hours.

8. UNCERTAINTY ANALISIS

As the operation of the instrument is based on two independent measurements of length, and measurement of temperature, the uncertainty budget derived from the measurement model according with [5] must include all the know sources of uncertainty, some of them are statistically obtained and other experimentally determined.
The expression used to represent the LTEC a is as follow:

$$\alpha = \frac{l}{\Delta t L_{GB}} \tag{1}$$

With l = Total displaced length of both arms
Δt = Change of temperature of gauge block
L_{GB} = Length of gauge block

$$l = \frac{m\lambda_0}{n_f} + l_{CM}\left(\frac{1}{n_i} - \frac{1}{n_f}\right) + \varepsilon_{faces} + \varepsilon_{t\_\text{interf}} \tag{2}$$

The interferometric length measurement of each arm is as follow:
Were m = fracctions number of resolution 1/128 of λ.

λo= Measurement wavelength in vacuum.
l_{CM} = Length of dead path (distance betwen the face of gauge block and the face of the inteferometer)
n_i , n_f = Refractive index of air, at reset time and at measure time respectively.
λ_{faces}= Correction for change of refractive index in the volume next to the faces of gauge block when a change of temperature is applied.
λ_{interf}= Temperature changes of optical elements (interferometers).

For the temperature measurement the Steinhart and Hart equation 3 is used to get linear the resistance readings only in the range of measurement (20 C to 30 C), achieving in this way the maximal repeatability.

$$\frac{1}{t} = a + bLnR + c(LnR)^3 \tag{3}$$

The difference of temperature between the first stable point to the second one is $\Delta t = t_2 - t_1$. (4)

Following the law of propagation of uncertainty from [5] we calculate the uncertainty for α calculation expression 5, the length measurement expression 6, and the temperature measurement expression 7.

$$\mu_\alpha^2 = \left(\frac{l\mu_L}{\Delta t L_{GB}{}^2}\right)^2 + \left(\frac{l\mu_{\Delta t}}{\Delta t^2 L_{GB}}\right)^2 + \left(\frac{\mu_l}{\Delta t L_{GB}}\right)^2 + \mu^2_{\text{Reproducibility}} \tag{5}$$

$$\mu_l^2 = \left[\frac{\lambda_0}{n_f}\mu_m\right]^2 + \left[\frac{m}{n_f}\mu_{\lambda 0}\right]^2 + \left[\left(\frac{m\lambda_0}{n^2{}_f}\right)^2 + \left(\frac{lcm}{n^2{}_f}\right)^2\right]\mu_{nf}^2 + \left[\frac{lcm}{n^2{}_i}\mu_{ni}\right]^2 + \left[\left(\frac{1}{n_i} - \frac{1}{n_f}\right)\mu_{lcm}\right]^2 + \mu_{caras}^2 + \mu_{t\_\text{interf}}^2 \tag{6}$$

$$\mu_t^2 = \mu_{nolin\_hist}^2 + \mu_{cal}^2 \tag{7}$$

were
μ_α= Uncertainty of LTEC calculation
μ_l= Uncertainty of length measurement
μ_t= Uncertainty of temperature measurement
μ_{nolin_hist}= Uncertainty of no linear behavior and hysteresis of thermistors
μ_{cal}= Uncertainty of thermistor's calibration.

UNCERTAINTY BUDGET

The next is a numeric evaluation of the above expressions under the conditions of table 2.

Parameter (units)	Values	Uncertainty	Parameter (units)	Values	Uncertainty
a Gauge Block	1.15E-05		e caras (m)	5.00E-08	2.24E-09
Temperature interval (C)	6.00		e t_interf (m)	5.00E-08	2.24E-09
			length measurement hist (m)		2.89E-09
displaced length (m)	3.45E-06		Air temperature (C)	25	0.05
Gauge Block length (m)	1.00E-01	5.00E-08	Air presure (Pa)	81000	20
m face fraction, resolution (no dimensions)	6.98E+02	2.26E-03	Humidity of air (%)	50	10
l vacuum (m)	6.33E-07	2.00E-15	Temperature hist_lineal (C)		8.61E-03
initial refractive index	1.00217	1.33E-07	Temperature calibration (C)		6.26E-03
final refractive index	1.00214	1.33E-07	Temperature measurement (C)		8.00E-03
Length dead path (m)	7.50E-02	1.34E-04	Reproducibility (K^{-1})		4.00E-08

Conditions for uncertainty budget - Table 2.

Source (Simbol)	Standard	Degree	Sens. Coeff.			
	m	of freedom	c	C * m	$(c\ m)^2$	%
Gauge Block length (L)	5.00E-08	99.00	0.0000575	2.88E-12	8.27E-24	0.00%
Measurement of Length	3.11E-08	81.77	1.67E+00	5.18E-08	2.68E-15	54.36%
fase fracction, resolution(m)	0.002255	30.00	6.32E-07	1.42E-09		
l vacuum (lo)	2.00E-15	1000.00	6.96E+02	1.39E-12		
final refractive index (n_f)	1.33E-07	30.00	0.074681987	9.93E-09		
initial refractive index (n_i)	1.33E-07	30.00	0.074675263	9.93E-09		
Length dead path (lcm)	1.34E-04	10.00	3.62762E-05	4.87E-09		
e caras (e_{cara})	2.24E-09	10.00	1	2.24E-09		
e interf ($e_{t\ interf}$)	2.24E-09	10.00	1	2.24E-09		
length measurement hist (l_{hist})	2.89E-09	30.00	1	2.89E-09		
Interval Temperature (Dt)	0.03	20.38	9.58E-07	2.55E-08	6.51E-16	13.21%
Temperature hist_lineal (t_{hist})	8.61E-03	5.00	1	8.61E-03		
Temperature calibration (t_{cal})	6.26E-03	5.00	1	6.26E-03		
Temperature measurement (t_{meas})	8.00E-03	30.00	1	8.00E-03		
Reproducibility (Rep)	4.00E-08	50.00	1	4.00E-08	1.60E-15	32.43%
				Standard Uncertainty	7.02E-08	K^{-1}
				Effective degree of freedom	152.12	
				Uncertainty k=2	1.42E-07	K^{-1}

Table 3 – Uncertainty budget evaluation.

The reported uncertainty has been calculated to a coverage factor of k=2, and correspond to a confidence level of approximately 95 %.

RESULTS

According to the realized measurements and the proposal corrections, the measurement has achieve a maximal thermal drift in gauge temperature of 15 mK in temperature and 20 nm in displacement during a period of 13 hours. And is possible to get 10 LTEC measurement results from one cycle of approximately 15 hours.

The measurement results on GB of 100 mm of tungsten carbide, steel and ceramic materials produce a reproducibility less than 0,04 x 10^{-6} K^{-1} and according with the uncertainty budget for 100 mm. its possible to achieve an uncertainty less than 0,3 x 10^{-6} K^{-1} for 100 mm length GB.

Typical measurement cycle of 100 mm ceramic GB is shown on table 4.

Time	Temperature Change (C)	Average Temp. (C)	s of Temperature (C)	Average Displacement (um)	s of Displacement	LTEC
14:28:39	0	20.981	0.002	0	0	0
15:36:45	-5.338	26.319	0.002	5.072	0.007	9.501
17:01:50	5.331	20.988	0.005	-5.076	0.007	9.522
17:47:55	-5.325	26.313	0.005	5.087	0.006	9.554
19:30:01	5.316	20.996	0.004	-5.077	0.007	9.550
20:29:07	-5.328	26.324	0.008	5.105	0.007	9.581
22:23:12	5.336	20.989	0.004	-5.120	0.006	9.596
23:52:17	-5.326	26.314	0.004	5.083	0.006	9.543

01:17:22	5.324	20.991	0.004	-5.085	0.007	9.552
02:01:28	-5.326	26.316	0.006	5.081	0.007	9.541
03:51:33	5.313	21.004	0.005	-5.080	0.007	9.561
04:42:37	-5.329	26.333	0.006	5.091	0.007	9.553
06:31:43	5.343	20.990	0.002	-5.114	0.006	9.571
07:52:47	-5.352	26.341	0.006	5.120	0.006	9.567
09:33:52	5.353	20.988	0.004	-5.119	0.006	9.562

Table 4 – Results of typical measurement cycle of LTEC

Mean LTEC 10.55 x 10^{-6} K^{-1}
Standard deviation of mean 0,02 x 10^{-6} K^{-1}

CONCLUSIONS

The uncertainty of α calculation in the instrument developed comes mainly from the length measurement. As the uncertainty budget estimates, the length in dead path and all other corrections affected by changes in refractive index of air, are the most important contributions to the total uncertainty. Improvement in the accuracy of humidity and pressure sensor is necessary in order to achieve better uncertainty in length measurement. Moreover increasing interferometer resolution do not improve the length measurement because of the main restriction to the uncertainty comes from the corrections for air measurement.
The interferometers temperature correction and the faces effect correction affect the reproducibility which could be improve introducing a thermal control for the walls of the cabin in order to remove the power introduced by the thermal control of the GB.
The performance of the instrument measure by the reproducibility of the results, was satisfactory for use it in calibration of industrial standards, GB and other standard artifacts, taking advantage of the short time needed to complete the measurement cycles.

The measurements have probe to be insensible to the material of the supports, the expansion of aluminum supports tested is orthogonal to measurement axis and its possible to mount artifacts of different shape of GB supported outside the zerodur base of interferometers. The requirement to achieve the uncertainty quote is to have parallel flat faces with an angular deviation less than 1 degree in order to reduce the cosine error to a negligible value.

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