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ABSOLUTE CALIBRATION OF QUARTZ BARS OF VÄISÄLÄ INTERFEROMETER BY WHITE LIGHT GAUGE BLOCK INTERFEROMETER

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Abstract - Measurement of a baseline with Väisälä interferometer is a traditional high accuracy length measurement in geodesy. An accurate length up to 1 km is achievable by interferometrically multiplying the length of a 1 m quartz bar. Therefore, the absolute length of the bar should be known with small uncertainty. A measurement setup and procedure for calibration of length of a quartz bar by combined white and laser light gauge block interferometer has been developed. The calibration procedure, results and uncertainty evaluation are presented. A standard uncertainty of 35 nm has been achieved.

Keywords: quartz bar, Väisälä interferometer, geodetic baseline

1. INTRODUCTION

1.1. Väisälä baselines

White light interference observations for geodetic length measurements were first proposed by Väisälä in 1923 [1]. Established Väisälä baselines were first used in calibration of invar wires; later they served in calibration of high-precision EDM instruments. Encouraged by the good results of the first interference measurements at the Nummela Standard Baseline in 1947 – 864 m with an accuracy better than 10^{-7} [2] – the International Association of Geodesy recommended in 1951 that Väisälä baselines be measured in different countries. In 1954, it resolved that each country participating in the general adjustment of the European triangulation net should establish such a baseline.

In recent decades geodetic reference systems and frames have shifted towards unified global and continental solutions, which are replacing national terrestric networks. The orientation, form and scale of the new three-dimensional networks originate in space and satellite geodetic techniques. The traditional geodetic length measurements are nowadays relevant mostly in local measurements. Since their scientific applications usually require high accuracy, and the importance of good quality is increasingly emphasised in more practical work, the demand of calibration services has not been appreciably reduced. To make calibrations in an actual working environment, most Väisälä baselines are established and used in field conditions.

1.2. Absolute calibration of quartz bars

Since the origin of the traceability for Väisälä interferometer measurements is the calibrated length of the quartz bar, a low uncertainty of absolute calibration is essential. Over several decades, a number of laboratories have performed calibrations for the Finnish Geodetic Institute (FGI). The last six measurements of absolute length of the quartz bars were performed excellently by the Physikalisch-Technische Bundesanstalt (PTB) in 1964 - 1995.

To guarantee the traceability and continuity of measurements with Väisälä interferometers, the Centre for Metrology and Accreditation (MIKES) has established an absolute calibration service for quartz bars. This paper outlines the setup and procedure for absolute calibration of quartz bars at MIKES and discusses the analysis of corrections and uncertainty.

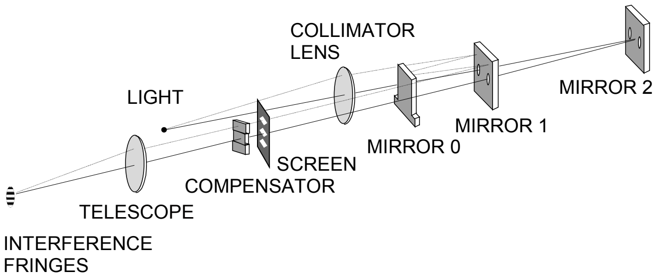

Fig.1. Principle of the Väisälä interference comparator. For the shortest multiplication the 1 m long quartz bar is placed between mirrors 0 and 1. The distance 0-2 is an exact multiple of the distance 0-1, usually 5 or 6 m. When the maximum of interference fringes is visible, angles in compensator glasses are registered, and positions of mirrors are measured with 0,001 mm resolution.

2. VÄISÄLÄ INTERFERENCE COMPARATOR

In the Väisälä interference comparator, white light from a point-like source is rendered parallel by a collimator lens and divided into two beams (see Fig. 1). One part of the light travels between the front mirror and the middle mirror, the other part between the front mirror and the back mirror. First the distance between front mirror and middle mirror is set to approximately 1 m by accurately adjusting a 1 m quartz bar between these mirrors. This is done with an optical and mechanical contact between mirror 0 and the quartz bar end, and observing Newtonian rings between mirror 1 and the quartz bar at the other end. [3]

The distance between the front and back mirrors is an integer multiple n of the distance between the front and middle mirrors. The light beam travels n times between the first two mirrors, and once to and from the back mirror. The mirrors are adjusted such that the two beams, travelling different paths but equal distances meet at the focal plane of the observing telescope. The distances are adjusted equal by observing the maxim of white light interference of the combined beam. Since it is difficult to adjust mirrors under field conditions within 1 µm, which is the coherence length for viewing the interference, a pair of compensator glasses is used. With these plane achromatic glasses in front of the telescope, the path of either of the beams can be changed by about 0-500 µm.

The relative standard uncertainty obtained with this method, after several multiplication and projections to reference points, is 7×10^{-8} for a length of 864 m.

2.1. Properties of quartz bars

Väisälä selected quartz as the material for the bars due to its low thermal expansion coefficient. In order to allow accurate positioning of mirror plates, using observation of Newtonian rings, the ends of the quartz bars have spherical curvatures of 1 m and 5 m. However, this kind of construction proved very sensitive to changes of contact points between the quartz bars and plane mirrors. Due to small deviations during manufacture, the shortest distance between the spherical surfaces was not necessarily the same as between the centre points of the ends. For that reason, the ends of the quartz bars with a shorter radius of curvature were later marked with circles. Concentric alignment of a circle and Newtonian rings fixes the position of the bar and the plane mirror at the end. The same alignment method was used both for baseline measurements and for absolute calibration of the quartz bar. One problem with quartz material is the stability of length with time. Other problems related to quartz bars are relatively large pressure coefficient and modulus of elasticity.

The quartz bars have a hollow core but monolithic ends. That is why the Bessel points are located differently than the points of a bar with a uniform cross-section. The separation of the points is approximately 603 mm.

3. CALIBRATION PROCEDURE

The device constructed at MIKES for quartz bar calibrations has some advantages over previous installations. The main principle for operation is the same as that described by Engelhard in 1959 [4]. In the current setup, the use of a gauge block interferometer with combined white and laser light eliminates the need for prior knowledge of the length of the bars. The use of the circle mark at end of the quartz bar for positioning is essential for reproducibility of results.

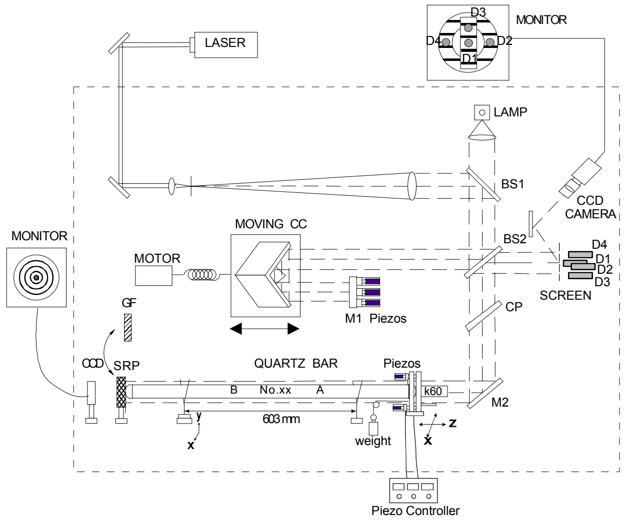

Fig. 2. Schematics of the calibration setup.

3.1. Calibration setup

Fig. 2 shows the configuration of the setup for calibration of the quartz bars. To enable measurement of the quartz bar length by gauge block interferometer, the bar is placed between a normal steel reference platen SRP (Ø 50 mm, thickness 12 mm) and a good quality steel gauge block k60. The quartz bar is supported at points that keep its ends parallel. The support closer to the reference plate has XY-adjustments for control for the bar direction. The Teflon supports allow small movements due to thermal expansion. The reference platen is fixed to a mirror holder at the far end. At the other end, the gauge block is fixed to a piezo adjustable mirror holder on a low friction free-moving crossed roller bearing a translator stage. During the measurements, the gauge block is pressed against the end of the quartz bar.

The collimated laser light and white-light beams meet at the first plate beam splitter BS1. The beam splitter of the Michelson type interferometer is BS2. The reference arm is formed by a cube corner retroreflector (CC) and a piezo-controlled plane mirror M1. With M1, it is possible to adjust the interference pattern seen at the screen appropriately for measurement. There are four small holes in the screen through which photo detectors D1, D2, D3 and D4 record interference signals. The detectors are arranged so that D1 (sees light reflected from the gauge block surface) is in the middle of detectors D2 and D4 (which see light reflected from the reference platen). Detector D3 is used with D4 to give direction-sensitive input signals for interference counters.

The optical path length in the reference arm can be changed by moving the carriage on which the CC is mounted. The compensation plate CP and the quartz bar are located in the main arm of the interferometer where the beam is directed by a mirror M2. The gauge block interferometer is described in more detail elsewhere [5].

3.2. Alignment of quartz bar and gauge block

The quartz bar is first aligned in the right position using a glass flat GF. The reference arm of the interferometer terminates in a separate corner cube. The GF is then adjusted normal to the laser beam by observing the centre of the interference fringes. The end of the quartz bar and the glass plate is set in close contact and the Newtonian interference rings are observed through the glass plate with a CCD camera. The direction of the quartz bar is then adjusted by centrally aligning the Newtonian rings and engraved circle at the end of the quartz bar. This fixes the mutual angular position of the bar and platen. Next the GF is replaced by the SRF, which is in turn adjusted to normal incidence. Then the gauge block k60 is drawn to form a mechanical contact with the other end of the quartz bar, using a traction force formed by the gravity of a small weight of 50 g. The angular position of the gauge block is adjusted by piezos so that the interference fringe pattern has the same orientation and fringe separation than that on the reference platen.

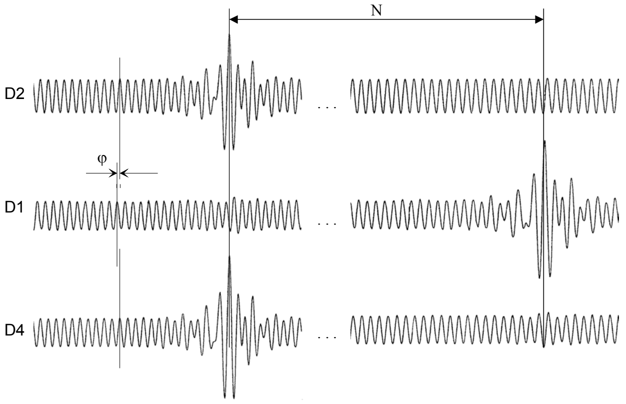

Fig. 3. Determination of length of the quartz bar-gauge block combination.

3.3. Measurement procedure

The measurement program drives the CC of the reference arm and simultaneously follows the interference signals recorded by D1, D2, D3 and D4. With aid of the separate counter, the program counts the number of interference fringes between positions when white light interference is seen from the gauge block surface and from the reference plate. This gives the approximate length between surfaces. A more accurate number of fringes is obtained when the phase difference φ of sinusoidal interference signals between D1 and D2&D4 is determined and combined with an approximate result (see Fig. 3). The vacuum wavelength λ_0 is determined earlier by beat measurement against an iodine stabilised reference laser. The refractive index of air n is calculated by the updated Edlén's formula [6, 7] from measured air temperature t, pressure p, humidity h and CO_2 content x. Three Pt100 sensors are used to measure the material temperature of the quartz bar and the gauge block.

3.4. Applied corrections

Several corrections are needed before an accurate result for length of the quartz bar l_{qb} is achieved (see (1)). First, the length of the gauge block l_{gb} has to be subtracted from the total length. In order to eliminate the effects of slight curvature of the interference fringe pattern and non-flatness of the reference platen, the length of the gauge block is measured when it is wrung to the same platen and in the same position as during quartz bar calibration.

Because good contact is guaranteed by applying mechanical force, a correction to eliminate deformation of the quartz bar, of its faces and of the surfaces of the platen and the gauge block is needed. The correction is determined experimentally by measuring the length of the bar - gauge block combination with different contact forces and then extrapolating to zero force. In these tests, nothing else was changed than the weight forming the traction force. Fig. 4 shows the results of force-dependency measurements for quartz bar #50. Linear fit to the data gave a coefficient of χ_{qb}=–0,15 µm/N. In separate measurements it was determined that the friction force of the translator stage was approximately 0,37 N. Correction due to contact force f is then –18 nm.

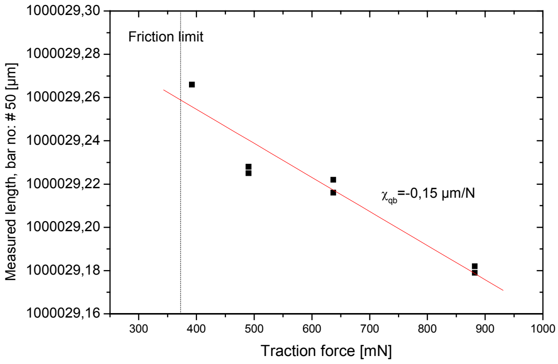

Fig. 4. Length of a quartz bar as function of traction force. Line is linear fit to the data.

The structure and material properties of the quartz bars also make them sensitive to atmospheric pressure. The pressure coefficients of Finnish quartz bars have been measured earlier and are listed elsewhere [8]. The typical pressure coefficient β is 0,74 nm/hPa. The results are corrected to a standard pressure of 1013,25 hPa. Thermal expansion of the gauge block and of the quartz bar is taken into account separately. The thermal expansion coefficient α_{gb} of the gauge block is $11{,}2\times10^{-6}$ K^{-1}. The corresponding coefficient α_{qb} for the quartz bars is $0{,}42\times10^{-6}$ K^{-1}.

The length of a quartz bar in single measurement is then:

$$l_{qb} = \frac{(N+\frac{\varphi}{2\pi})\,\lambda_0}{2\,n(t,p,h,x)} - l_{gb} + \alpha_{qb}L_{qb}(20-t_{qb}) + \alpha_{gb}L_{gb}(20-t_{gb}) + \beta(p-101325\,\mathrm{Pa}) + \chi_{qb}f, \quad (1)$$

where L_{qb} is nominal length and t_{qb} temperature of the quartz bar and L_{gb}, t_{gb} of the gauge block, respectively. Thermal expansion corrections are done already during the measurements; other corrections are applied afterwards.

4. RESULTS

In order to validate the measurement service several test calibrations were made. The absolute lengths of quartz bars Nos. VIII, 49, 50 and 51 were measured. The alignments of quartz bars were repeated several times and lengths were measured for up and down positions of bars. The quartz bar No. VIII has a different structure, therefore a different coefficient was used. The results are shown in Table I. Also listed are the results of the last calibration at PTB in 1995 for quartz bars 49 and 50. The results agree well with the results of the PTB even taking into account the annual lengthening of roughly 5 nm. The differences in length between up and down positions were from 2 to 40 nm.

TABLE I. Results of absolute calibrations of quartz bars.

Quartz bar No.	Length / µm MIKES 2000	PTB 1995
VIII	1000151,371	
49	1000032,346	1000032,350
50	1000029,248	
51	1000018,362	1000018,380
stand. uncertainty	0,035	0,030

5. EVALUATION OF UNCERTAINTY

Table II shows the uncertainty budget for calibration of 1 metre quartz bars. Analyses of most of the components are described in detail elsewhere [5]. If the value of the uncertainty has changed this is because of increased experience and history with the device. Also, the effective degree of freedom was evaluated according the 1993 ISO guidelines [9].

Experimental standard deviation of the mean calculated from the data gives a value for type A uncertainty. The typical value (n=6) was 12 nm. The uncertainty of Edlén's formula has improved significantly during the last decade [7]. The uncertainty of the thermal expansion coefficient of the quartz bars is estimated to be half the value at the most. The temperature of the quartz bar deviated from the normal temperature by a maximum of 0,1°C (rectangular distribution). The uncertainty contribution is then 12 nm.

TABLE II. Uncertainty budget for absolute calibration of quartz bar. (u stand. uncertainty, v degrees of freedom)

Component	Uncertainty	Prob. distr.	Sensitivity coefficient	u [nm]	v
TYPE A					
Repeatability n=6	12 nm	norm.	1	12	5
TYPE B, length dependent, L=1 m					
λ_0, relative u	4 $\times 10^{-9}$	norm.	1 m	4	8
t_{qb}	10 mK	norm.	0,4 µm/K	4	8
t	10 mK	norm.	0,93 µm/K	9	12
p	5 Pa	norm.	2,7 nm/Pa	14	12
h, dew point	0,2 K	norm.	30 nm/K	6	8
x	50 ppm	norm.	0,15 nm/ppm	7	12
$n()$, relative u	10 $\times 10^{-9}$	norm.	1 m	10	8
α_{qb}	0,2 $\times 10^{-6}$/K	rect.	0,1 Km	12	8
Independent of length					
l_{gb}, t_{gb}, etc.	15 nm	norm.	1	15	8
$\chi_{qb} f$	8 nm	norm.	1	8	2
$\beta \, \Delta p$	5 nm	norm.	1	5	4
$N+\varphi/2\pi$	2 nm	norm.	1	2	8
Non-ideal optics	6 nm	norm.	1	6	2
Total				35	59
Expanded uncertainty (k=2)				71	

The uncertainty of length of the gauge block is calculated as in ref. [5]. However, those systematic error components that affect both measurements equally are considered to cancel each other out and not to affect the result. That is why the uncertainty for the length of the gauge block is smaller than usual.

The uncertainty of the force correction is based on the experiments and is almost half of the applied correction. The uncertainty of the pressure correction is strongly dependent on average atmospheric pressure during calibrations. The value in the table is calculated by estimating that the standard uncertainty of the pressure coefficient is one third of the value, and that the average pressure differs by 20 hPa from the normal pressure.

The standard uncertainty in calibration of the length of a 1 m quartz bar is 35 nm. Comparison of the measurement results of several quartz bars with the results measured earlier by PTB support the uncertainty estimation.

6. CONCLUSION

A device and procedure for absolute calibration of quartz bars by combined white and laser light gauge block interferometer was presented. The results, detailed analysis of corrections and uncertainty estimate were discussed. The use of white light to give approximate length makes the calibration of quartz bars an easier task.

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