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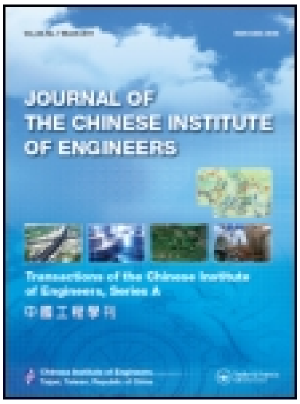

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Establishing an invar leveling calibration system

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Short Paper

ESTABLISHING AN INVAR LEVELING CALIBRATION SYSTEM

Chun-Sung Chen*, Chien-Ting Wu, Ming-Wei Chang and Wei-Chen Chang

ABSTRACT

Precise height systems are widely utilized in civil engineering projects such as high-speed railroads, and highways and bridge construction. However, highly precise height data is obtained using precise leveling. An extremely precise invar leveling rod is necessary for obtaining precise results.

In this study, an automatic calibration system for invar leveling has been established by the National Measurement Laboratory (NML). The content belongs to the long scales calibration system of D17 of the NML. This system utilizes a steady frequency laser interferometer, a CCD microscopic monitor, and a precise moving mechanism. With this system, an invar rod and a mark invar leveling rod are applied to estimate uncertainty with a 95% confidence level. Uncertainty results are 22 μm and 21 μm for the invar leveling rods and mark invar leveling rods, respectively.

Key Words: invar leveling rods, calibration system.

I. INTRODUCTION

Vertical control is generally carried out by a precise leveling survey. In leveling surveying, a striped invar leveling rod with an electronic level, or an invar leveling rod with an optical level, is employed for height surveying. Ni and Fan (2002) investigated areas of soil liquefaction and consequent damage using precise leveling survey. To obtain precise results, a level must be calibrated regularly. For normal use, a calibration value ≤ 50 μm is the invar ministry standard. In 3-D Surveying, GPS technology is also a convenient way to obtain the coordinates, though the precision in the horizontal direction is better than the precision in the vertical direction (Chen and Yeh, 2002). Hsu and Hsiao (2002) suggested a procedure to pre-compute the positional sensitivity of a GPS station in deformation monitoring. In Taiwan, the construction of a calibration system for GPS receivers has already been finished (Yeh *et al.*, 2006). Unfortunately, there is no leveling calibration system at the National Measurement Laboratory in Taiwan.

In this study, a rule calibration system of National Measurement Laboratory (NML) is improved for estimating sources of error and expanded uncertainty. The calibration ability at the 95% confidence level is shown in Table 1. For 3-m length, the uncertainty is 21.4 μm, which is worse than that in other countries.

To establish a calibration system for invar leveling rods, a laser interferometer, a charge-coupled device (CCD) microscopic monitor, and a precise moving mechanism are utilized. Between May and July 2003, a strip invar leveling rod produced by Kern and a mark invar leveling rod made by Zeiss were used to test calibration system stability. Additionally, ISO (ISO, 1995) was used to measure system uncertainty and to estimate whether the uncertainty of the strip and mark invar leveling rods are qualified for the norm.

II. INTRODUCTION AND RETRACE TO THE CALIBRATION SYSTEM

The calibration system is designed to measure

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Table 1 The calibration ability of invar leveling rod on the world.

	Taiwan	Korea	America	Canada	Switzerland
	CMS	KRISS	NIST	NRCC	SFOM
Measure range	3 m	3 m	3 m	3 m	4 m
Uncertainty (μm)	Q[4,7L]	Q[10,3L]	20~50	>10	Q[11,1.4L]

The unit of L is m

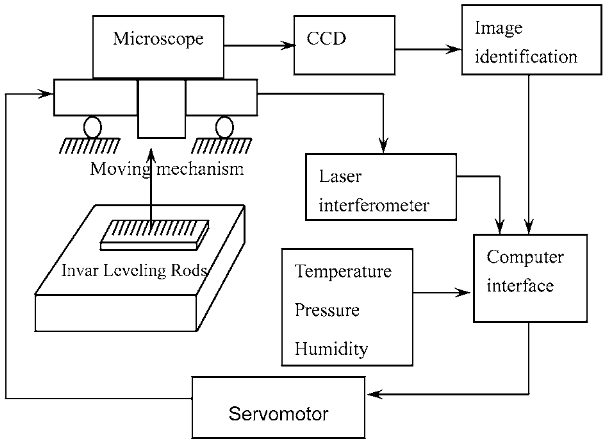

Fig. 1 Calibration system configuration

data directly. In this system, a stabilized-frequency laser interferometer, a CCD microscopic, monitor, and a precise moving mechanism are utilized to constitute the structure. Fig. 1 presents the system configuration (Developmental Center of the Industrial Technology Research Institute, 2003).

The measurement theory for the invar leveling calibration system requires setting a critical value to acquire and calculate the strip edge on the marked invar leveling rods. This study uses a moving mechanism to move the edge of the invar leveling rods to the CCD image center. This process is repeated until the edges of the invar leveling rods are moved to the CCD image center, then recording the reading value of the laser interferometer and the circumstance parameters. Using these reading values, the optical wave length and the thermal expansion coefficients can be modified. Fig. 2 presents this process.

In the field of the measurement of quantities, the measurement retrace can be connected with a special reference system using a continuous comparison chain with uncertainty. In the long rule calibration system, the standard-stabilized-frequency laser interferometer can be retraced to the stabilized-frequency laser calibration system. The laser wavelength and frequency calibrations are utilized to realize the definition of a meter; that is, a meter is 1/299792458th of the movement of light in one second in vacuum, the retracing Figure is shown as Fig. 3.

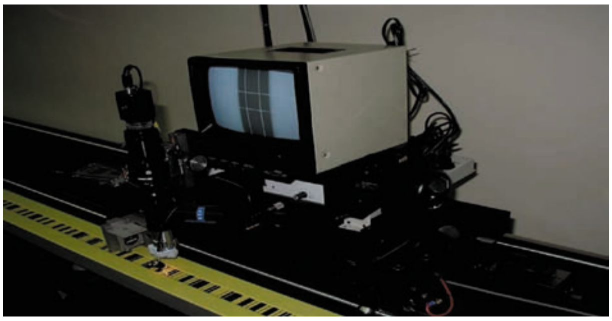

Fig. 2 The actual calibration system

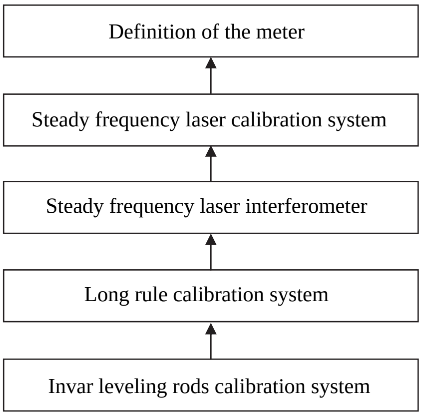

Fig. 3 The retracing figure

III. MEASUREMENT METHOD AND RESULTS

1. Preparation Before Calibration

Several tasks must be completed before measuring.

(1) Invar the source of electricity in the laser stable-pressure instrument.
(2) Activate the thermometer.
(3) Activate the electricity source for the moving system.
(4) Check that the multimeter and the IEEE488 port connected line of the switch is OK. Activate the sensor.
(5) Place the unit to be tested on the granite platform, tune the unit until the level-vial is at the vacancy

Table 2 Filenames of input and output

The unit to be calibrated	Automatic measuring program	Filename of input	Filename of output
Strip invar leveling rod	Miron.exe	Rinput.dat	Routput.dat
Mark invar leveling rod	Mlevel.exe	Linput.dat	Loutput.dat

of the center joint of the platform. Move the moving system to the center of the unit–which needs to be calibrated–activate the furfle, CCD, and source of fluorescence screen, then the cushion is placed below the standard unit.

(6) When the unit under test is a strip invar leveling rod, the microscope object lens is 5, and that for the mark invar leveling rods is 3. A cushion is necessary for both cases.

(7) The alignment adjustment of the unit is based on the lower line of the strip line of the unit. The lower line is tuned to the two parallel lines on the monitor.

(8) Move the moving system to the initial position. For calibrating strip invar leveling rods, move the moving system to 16 cm in front of the strip manually. Under this condition, a strip appears every 200 nm. For calibrating the mark invar leveling rods, move the moving system to the trapezoidal sculpture of zero; be careful as the reflector lens must not bump the spiral cap of the unit.

(9) Activate the air-conditioning system in the lab.

(10) Maintain a stable lab temperature for 8 hours.

2. Calibration Steps

(1) Turn on the power for the moving system; activate the reset key for the remote control; turn on the red bulb in the control box.

(2) The calibrated file of the strip invar leveling rods is at C:\tape\Miron.exe, whereas the calibrated file of the mark invar leveling rods is at C:\tape\Mlevel.exe. First, establish the input file, and then execute the automatic measuring program; the output file is the uncalibrated results file, see Table 2.

(3) To measure the next data, the power for the remote control must be turned off. Move the moving system to the original point manually. Turn on the power again for the remote control; press the reset key, and execute the next measurement. Turn off the power to the remote control before moving the moving platform manually.

3. Data Analysis

After the calibration procedure, the raw data file will be obtained automatically. For example, the raw data file for the strip invar leveling rod is Routput dot. With the stripe reading the laser interferometer, the temperature of the lab, relative humidity, and atmospheric pressure, Excel software can be used to correct the thermal expansive coefficient and refraction.

IV. DISCUSSION FOR THE UNCERTAINTY

The uncertainty of the invar leveling rods is estimated using “the measuring uncertainty guide book” (ISO, 1995).

1. Establish the Mathematical Model

The equation for L is as follows: (ISO, 1995)

$$L = \left(\frac{\lambda_0}{128 n_{tpf}}\right) N \left[1 - \frac{\theta^2}{2}\right] + d(\sin\beta)\ , \tag{1}$$

where L is the moving distance of the moving platform, λ_0 is the vacuum laser wavelength, d is the distance between the laser axis and measuring axis, β is the degree of error of the straight-line, θ is the angle between the laser axis and measuring axis, n_{tpf} is the refraction index of the air under t, p and f condition.

Based on the temperature of the invar leveling rods, thermal expansion coefficient, air refraction index and error of the sculptural line, Eq. (1) can be modified as Eq. (2). (ISO, 1995)

$$\begin{aligned} L_s &= [1 + \alpha_s(20 - t_s)] \\ &\quad \cdot \left[\left(\frac{\lambda_0}{128 n_{tpf}}\right) N \left(1 - \frac{\theta^2}{2}\right) + d(\sin\beta)\right] + E \\ &= F(\lambda_0, n_{tpf}, \alpha_s, t_s, \beta, \theta, d, N, E)\ , \end{aligned} \tag{2}$$

where α_s is the thermal expansion coefficient, t_s is the temperature of the invar leveling rod, N is the number of laser interferometers, $\frac{\lambda_0}{n_{tpf}}$ is the laser wavelength, and E is the positioning error of the sculptural line.

The laser wavelength changed due to the air refraction index; measuring the air refraction index of the light route and modifying the laser wavelength

Table 3 The error analysis of invar leveling rod calibration

Sources of error(xi)	Estimate error	Type	Distribution	Coefficient	Standard uncertainty $u(x_i)$	$\frac{\partial F}{\partial x_i}$	$\left\lvert\frac{\partial F}{\partial y_i}u(y_i)\right\rvert$	v_i
Laser wave-length (λ_0)		B	rectangle	$1/\sqrt{3}$	1.15 nm	1	1.15 nm	50
Refraction of air (n_{tpf})	3×10^{-8}	B	rectangle	$1/\sqrt{3}$	1.732×10^{-8}	–0.9997 L	0.0173×10^{-6} L	50
Temperature (t)	0.5°C	B	rectangle	$1/\sqrt{3}$	0.289°C	9.53×10^{-7} L°C^{-1}	0.275×10^{-6} L	50
Pressure (p)	263 Pascal	B	rectangle	$1/\sqrt{3}$	151.87 Pascal	-2.68×10^{-9} L Pa^{-1}	0.407×10^{-6} L	50
Humidity (f)	10%	B	rectangle	$1/\sqrt{3}$	5.77%	8.5×10^{-9} L%$^{-1}$	0.049×10^{-6} L	50
Thermal expansion coefficient (α_s)	1.5×10^{-6} °C^{-1}	B	rectangle	$1/\sqrt{3}$	0.87×10^{-6} °C^{-1}	–0.3 L°C	0.261×10^{-6} L	12.5
Measurement of temperature (ts)	0.5°C	B	rectangle	$1/\sqrt{3}$	0.29°C	-11.5×10^{-6} L°C^{-1}	333×10^{-6} L	50
Straight line degree error (β)	7.5"	B	rectangle	$1/\sqrt{3}$	4.33"(≒2.1×10^{-5})	40 mm	0.84 μm	12.5
Alignment (θ)	20"	B	rectangle	$1/\sqrt{3}$	11.55"(≒5.6×10^{-5})	-5.6×10^{-5} L	0	50
Manual focusing error (d)	2 mm	B	rectangle	$1/\sqrt{3}$	1.15 mm	6.35×10^{-7}	0.73 mm (≒0)	12.5
Stripe edging position (E)	5.2 μm	B	rectangle	$1/2\sqrt{3}$	151 μm	1	1.51 μm	12.5
Numbers of the laser Interferometer (N)	3	B	rectangle	$1/\sqrt{3}$	2	4.93 nm	9.9 nm	50

is necessary. The influential factors for the air refraction index are temperature, relative humidity, atmospheric pressure and vapor. These factors are measured using the Edlen formula (Edlen, 1966). The Birch modified formula and Wexler vapor modified formula for the modified laser wavelength can be calculated with Eq. (3) (Birch and Downs, 1993). Table 3 shows results.

$$\lambda_{tpf} = \frac{\lambda_0}{n_{tpf}} = \frac{\lambda_0}{1 + A_\lambda \times B_\lambda - C_\lambda}\,, \tag{3}$$

where

$$A_\lambda = \frac{P[8343.05 + 2406294(130 - \sigma^2)^{-1} + 15999(38.9 - \sigma^2)^{-1}10^{-8}}{96095.43}\,,$$

$$B_\lambda = \frac{[1 + p(0.601 - 0.00972t_{90})10^{-8}]}{1 + 0.003661t^{90}}\,,$$

$$C_\lambda = f(3.7345 - 0.0401\sigma^2)10^{-10},$$

$$f = RH \times e_{sw}(T)/100,$$

$$e_{sw}(T) = \exp[\sum_{i=0}^{6} A_i \times T^{i-2} + A_7 \times 1_n(T)]\,,$$

$$A_0 = -2.9912729 \times 10^{3}$$

$$A_1 = -6.0170128 \times 10^{3}$$

$$A_2 = 1.887643854 \times 10^{1}$$

$$A_3 = -2.8354721 \times 10^{-2}$$

$$A_4 = 1.7838301 \times 10^{-5}$$

$$A_5 = -8.41504171 \times 10^{-10}$$

$$A_6 = 4.4412543 \times 10^{-13}$$

$$A_7 = 2.858487.$$

P is air pressure (Pascal), t^{90} is the air temperature (°C), σ is $\frac{1}{\lambda_0}$ (μm^{-1}), f is vapor pressure (Pascal), RH is relative humidity, $e_{sw}(T)$ is saturated vapor pressure (Pascal), and T is the absolute temperature (°K)

2. Discussion of the Inference Factors

Table 3 lists the influential factors, such as laser wavelength, air refraction index, and temperature, for calibrating invar leveling rod errors.

3. Expanded Uncertainty

Typically, uncertainty is measured using expanded uncertainty. The definition for expanded uncertainty is

$$U = K \times u_c \text{ (ISO, 1995)} \tag{4}$$

where K is the convergence factor, u_c is the uncertainty, and U is expanded uncertainty.

The effective degree of freedom can be obtained by inserting the degree of freedom for all different uncertainties into the Welch-Satteithowaite formula. Using the 95% confidence level in usual international use, the K value can be obtained from the t-distribution table; therefore, expanded uncertainty can be determined. According to the Welch-Satterthwaite formula (ISO, 1995), the effective degree of freedom is obtained with the following formula:

$$V_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{n} \frac{u_i^4(y)}{V_i(y)}} . \tag{5}$$

Using the 95% confidence level, the degree of freedom is selected conservatively or 56, the expanded coefficient K is 2.01 from the t-distribution table, and the expanded uncertainty U for strip invar leveling rod is

$$U = K \times u_c = 2.01 \times [(1.73)^2 + (3.38L)^2]^{1/2}$$
$$= [(4)^2 + (7L)^2] \ (\mu\text{m}). \tag{6}$$

For the expanded uncertainty of the mark invar leveling rod is

$$U = \lfloor (8)^2 + (7L)^2 \rfloor^{1/2} \ (\mu\text{m}). \tag{7}$$

Suppose the value of the L in Eqs. (6) and (7) is 3 m, the expanded uncertainties are 21 um, and 22 um for the strip and mark invar leveling rods, respectively.

V. QUALITY CONTROL FOR SYSTEM MEASURING

To protect the stability and accuracy of the system, the SP676-II of the National Institute of Standards and Technology (NIST) is selected for inspecting and auditing the measuring of the invar leveling rods.

1. Quality Control Design

For quality control of the calibration system, the parameters and measuring system must be between an upper limit and lower limit using a t-test. The inspection procedure measures the checking unit before measuring the unit under testing. The checking units of this system are a 3-m long strip invar leveling rod made by Zeiss, and a 3-m long mark invar leveling rod made by DDR. The checking parameters selected are 1 m, 2 m and 2.7 m. These checking parameters are utilized to calculate the mean, standard deviation, and upper and lower limits of the calibration system.

2. Setting Up the Procedure Parameter

The checking parameters for the strip and mark invar leveling rods are 1 m, 2 m, and 2.7 m. Using these checking parameters, the mean AC, standard deviation SC and upper control limit UCL and lower control limit LCL can be calculated.

3. Procedure Control

After setting up the procedure parameters, inspection of the calibration system is executed before calibration proceeds. The unit tested is measured and a checking parameter C_i is adopted. The t-test (NIST) is used to determine whether the calibration system is between control limits.

$$t = \frac{|C_i - AC|}{SC} \tag{8}$$

Suppose $t \leq 3$ from Eq. (8), the calibration system is between control limits, whereas $t > 3$, the calibration system is not good. In this case, the calibration system, circumstance, laser interferometer, and thermometer are investigated again.

4. Control Map

Table 4 lists 30 sets of checking parameters for 1 m, 2 m, and 2.7 m of the strip invar leveling rods. Using these data, completed relative figures, which are called control maps, can be drawn.

VI. CONCLUSIONS

Calibration of the invar leveling rods can be classified into strip and mark invar leveling rods. The uncertainties for strip and mark invar leveling rods can be calculated separately using $[(4)^2 + (7L)^2]^{1/2}$ (μm) and $[(8)^2 + (7L)^2]^{1/2}$ (μm). When the calibrating length is 3 m, the confidence interval is 95%, and the uncertainties are 21 μm and 22 μm. These values are superior to the value for the first-order leveling standard of 50 μm. However, these values are inferior to some in other countries; for example, the Korea Kriss is 13 μm. The US NIST is 20–50 μm, the Canada NRCC is 10 μm and the Swiss SFOM is 16 μm. The possible influence factors can be described as follows.

1. The physical lens of the microscope does not have a focus function in the calibration system; therefore, errors will be produced for uncorrected focus.
2. The calibration system needs many different

Table 4 The Checking parameters of the strip invar leveling rods

	relative position						
Times	1 m	2 m	2.7 m	Times	1 m	2 m	2.7 m
1	999.9742	1999.948	2699.973	16	999.9741	1999.949	2699.973
2	999.9765	1999.952	2699.976	17	999.9723	1999.948	2699.97
3	999.9732	1999.95	2699.973	18	999.9709	1999.948	2699.971
4	999.9717	1999.949	2699.971	19	999.974	1999.95	2699.974
5	999.978	1999.953	2699.979	20	999.9722	1999.95	2699.968
6	999.9735	1999.948	2699.97	21	999.9722	1999.95	2699.968
7	999.9731	1999.947	2699.971	22	999.978	1999.956	2699.976
8	999.9715	1999.947	2699.97	23	999.9731	1999.95	2699.972
9	999.9755	1999.954	2699.976	24	999.973	1999.951	2699.973
10	999.977	1999.955	2699.977	25	999.9773	1999.955	2699.977
11	999.9723	1999.95	2699.972	26	999.9724	1999.95	2699.971
12	999.9725	1999.947	2699.971	27	999.9724	1999.95	2699.971
13	999.972	1999.949	2699.971	28	999.9735	1999.95	2699.973
14	999.9766	1999.953	2699.975	29	999.9747	1999.952	2699.974
15	999.9754	1999.952	2699.976	30	999.9743	1999.951	2699.973

calibrations; the optical axis alignment of the laser interferometer is influenced. Therefore, errors may be produced during the calibration procedures.

3. The distances between the optical axis and measuring axis of the laser interferometer must differ for different objects, such as a rule or invar leveling rod.

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