The Measurement Uncertainty Evaluation Technique for the Advanced Calibration of

C.Wanchai, P.Chanin, H.Pisit, and N.Sarinya

Abstract— **Currently, laser distance meters are mostly used in the area of construction, and in other measuring applications such as interior design, construction services and so on. A length calibration laboratory technically needs to find out the calibration result and measurement uncertainty, in order to improve the length standard traceability. This research emphasizes a method for minimizing measurement uncertainty by using the smart measuring probe technique. The measurement uncertainty of the three units under calibration was 0.69 mm, 0.70 mm and 0.90 mm, respectively, with a reference distance of 20 000 mm at a confidence level of 95 %.**

Index Terms—**laser distance meter, smart measuring probe, calibration, measurement uncertainty.**

I. INTRODUCTION

LASER distance meters (LDMs), also known as electronic distance meters (EDMs) or DISTOs, use the time of flight principle [1], with a laser (solid state) beam to determine the distance to an object, and were developed in 1993. They have many length and dimension measuring applications in construction, interior decoration, and so on.

Generally, an LDM is simply calibrated using the comparison method, such as comparing it using interferometry, a high precision EDM, or a standard tape set up on a long-range calibration bench. Usually, these comparison methods would be provided by the national metrology institute and follow the EURAMET supplementary comparison (L-S20) [2] at a range of up to 50 m. A standard tape calibration system for 50 m in the length and dimensions calibration laboratory of the Department of Science Service (DSS) was therefore developed in 2009 [3], in order to provide a traceability chain for long-range electronic distance devices. An LDM calibration method using the interferometry technique has been used by the DSS since 2017, and is typically based on ISO 16331-1/2012 (part 1) (performance of handheld laser distance meters) [4]. Practically, the measurement uncertainty of LDM calibration is at least 1.0 mm, and is caused by technical problems of measurement error. There are also some effects of setting up the calibration.

However, the LDM calibration technique solution in [5] uses an advanced design of a smart measuring probe (SMP) technique with the interferometry system. This technique needs more clarity through the evaluation of measurement uncertainty. Therefore, this research presents a method for obtaining a perfect evaluation of the measurement uncertainty at the 95% confidence level. The results of the measurement uncertainty decrease significantly between the manual method and the newly developed technique. Future research will investigate the short- and long-term stability of the SMP.

II. PRINCIPLE

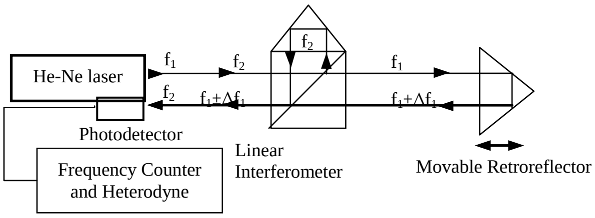

Fig. 1. The interferometry method

The LDM calibration technique [5] based on the interferometry method is shown in Fig. 1. The light source is an He-Ne laser with a long-range option of up to 80 m, wavelength (λ) 633 nm and power output less than 1 mw. The light interference principle applied is Michelson's interferometer principle, and a heterodyne interferometer is used with the two frequencies f_1, f_2 and Δf ($f_1 \pm \Delta f_1$). The resulting intensity pattern is determined by the phase difference (ϕ) between the two waves, as set out in Eq. (1) [6].

$$\Delta f = \frac{\Delta\phi}{2\pi}\lambda \tag{1}$$

Manuscript received August 6, 2021; revised August 25, 2021.

C.Wanchai, he is a Head of Calibration Section and Head of Length Standard Calibration Laboratory, Department of Science Service, Ratchathewi, Bangkok 10400, Thailand, Phone: 662-2017317, Fax: 662-2017323, (email: wanchai@dss.go.th).

P.Chanin, he is a Scientist of Length Standard Calibration Laboratory, Department of Science Service, Ratchathewi, Bangkok 10400, Thailand. (email: chanin@dss.go.th).

H.Pisit, he is a Scientist of Length Standard Calibration Laboratory, Department of Science Service, Ratchathewi Bangkok 10400, Thailand. (email: pisit@dss.go.th).

N.Sarinya, she is a Scientist of Length Standard Calibration Laboratory, Department of Science Service, Ratchathewi Bangkok 10400, Thailand. (email: sarinya@dss.go.th).

The LDM calibration method makes a direct comparison with the interferometry measuring system, to re-align the light beam direction of the LDM to project on the SMP screen and target the positioning with the program controller [7]. The SMP is automatically controlled for the positioning of each calibration point (CP) via Bluetooth, which is the wireless communication between the microcontroller set as the SMP's server on the carriage and a PC. The data transfer (linear measurement or distance) of the laser measurement system uses a wireless WIFI system, as shown in Fig. 2 and Fig. 3.

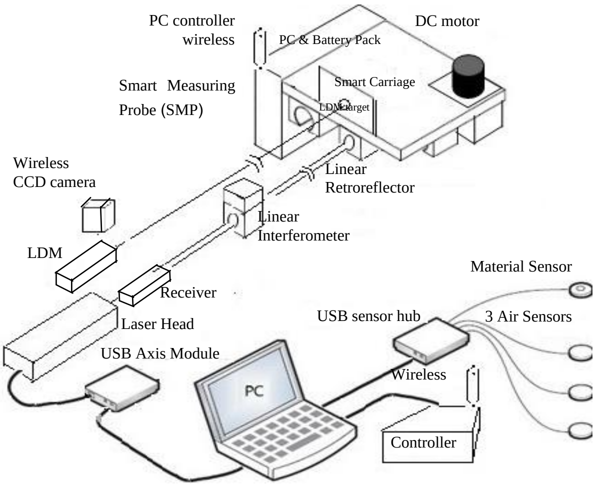

Fig. 2. Diagram of the interferometry technique with a smart measuring probe (SMP) for the LDM calibration system

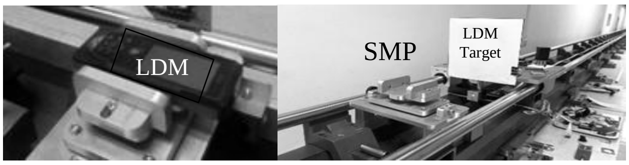

Fig. 3. The LDM is the unit under calibration (left), and the SMP is shown on the right

This research uses a comparison method between manual and automatic with the SMP calibration technique based on the standard document (ISO 16331-1). The laboratory set up has the maximum range, as the reference distance of 20 000 mm (20 m). Each calibration point takes one measurement with the reference distance measurement system, in order to make sure that the configuration alignment of the LDM to the target is correct.

III. MEASUREMENT UNCERTAINTY

The measurement uncertainty evaluation is based on the guideline for the expression of uncertainty in measurement [8] and M3003 [9]. The combination of uncertainty sources is shown as a flowchart in Fig. 4.

This can be writed in the mathematical model of LDM measurement uncertainty evaluation. From Eq. (2), the measurement uncertainty of the measured LDM is the sum of the sources of the uncertainties, as set out below.

$$U_{(yi)} = \sum_{i=1}^{n} u_{yi} \tag{2}$$

Each source of the measurement uncertainty budget is declared: $u_{dev}^2,\ u_s^2,\ u_{ds}^2,\ u_t^2,\ u_{rl}^2,\ u_{dp}^2, u_{as}^2, u_{al}^2, u_{cs}^2, u_{cl}^2$ $u_{zr}^2,\ and\ u_{rf}^2$. Therefore the root sum square of the combined uncertainty (u_c) is as in Eq. (3):

$$\begin{aligned} u_c^2 = {} & u_{dev}^2 + u_s^2 + u_{ds}^2 + u_t^2 + u_{rl}^2 + u_{dp}^2 + u_{as}^2 + u_{al}^2 + u_{cs}^2 \\ & + u_{cl}^2 + u_{zr}^2 + u_{rf}^2 \end{aligned} \tag{3}$$

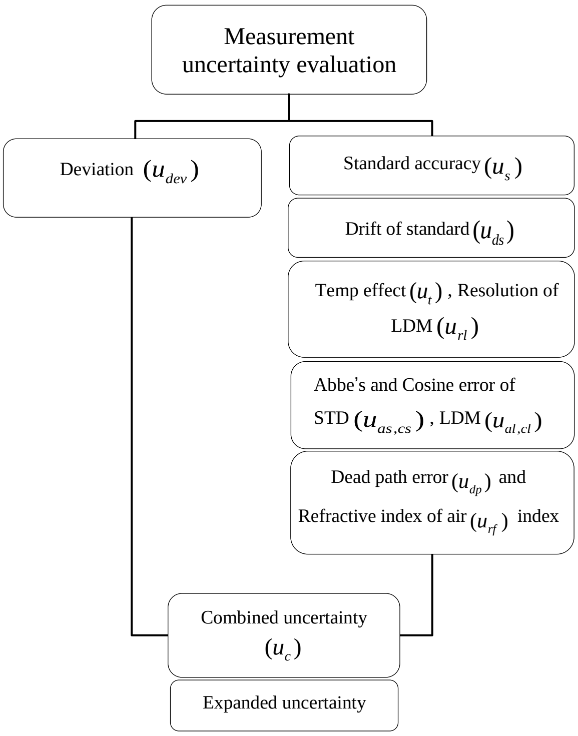

Fig. 4. Flowchart of measurement uncertainty evaluation

In the case of the dead path error and the resolution of the standard, the budget items are included in the specification of the standard. The cosine error of the standard and the refractive air index are ignored because they are negligible. Nothing changes the budget and they are limited by the setup of the equipment. Hence, Eq. (3) can be rewritten as Eq. (4).

$$u_c^2 = u_{dev}^2 + u_s^2 + u_{ri}^2 + u_{ab}^2 + u_{as}^2 + u_t^2 + u_{ds}^2 + u_{cs}^2 + u_{cl}^2 \tag{4}$$

The artefacts used for this measurement evaluation are the three units to be calibrated, 411D [10], D8 and A5 [11], which are defined, respectively, as 411D-SMP, D8-SMP and A5-SMP with the smart measuring probe technique.

A. Deviation (u_{dev})

Deviation is obtained by taking a reading from the laser interferometer, set as type A uncertainty, from 10 measurements (each measurement having 10 repeats). The standard deviations of 411D-SMP, D8-SMP, and A5-SMP are considered at the same measuring point. Therefore the uncertainty contributions are estimated as 0 mm, 0.21/√10 = 0.066 mm, and 0 mm respectively.

B. *Standard accuracy* (u_s)

The standard accuracy is obtained from the linear measurement accuracy of the laser measurement system, and is considered to have (0.1×10^{-6})L when (L: unit in mm), with a rectangular distribution. Therefore, at the length 20 000 mm, the uncertainty contribution is 0.002/√3 = 0.00115 mm.

C. *Drift of standard* (u_{ds})

The drift of standard is obtained from the accuracy of the linear measurement, which is (0.1×10-6)L or 0.002 mm at 20 000 mm, with a rectangular distribution, and therefore the uncertainty contribution is calculated as 0.002/√3 = 0.00115 mm.

D. *Temperature effect* (u_t)

The temperature effect or temperature variation takes a reading from the standard and the LDM, and the estimated uncertainty of temperature variation ± 1 ℃, multiplied by the sensitivity coefficient (Ci) as shown in each Table of 0.23 mm/℃, and is 1×0.23/√3 = 0.133 mm.

E. *Abbe's error of standard* (u_{as}) *and measuring bench* (u_{ab})

The Abbe's error or sine error, obtained from the misalignment of the standard with the optical on the carriage, is ± 2 mm and for the measuring bench is the total length, and from the rectangular distributions the contributions are 0.542/√3 = 0.313 mm and 0.00582/√3 = 0.00336 mm respectively.

F. *Cosine error of standard* (u_{cs}) *and LDM* (u_{cl})

The uncertainties for cosine error (*l′*) [12] at the reference distance (*l*: 20 000 mm) and a maximum deviation of 50 mm are set between the standard and the LDM as shown in Fig. 5. The rectangular distributions are calculated as 0.000625 mm, 0.000625/√3 = 0.000361 mm, and 0.0625/√3 = 0.0361 respectively.

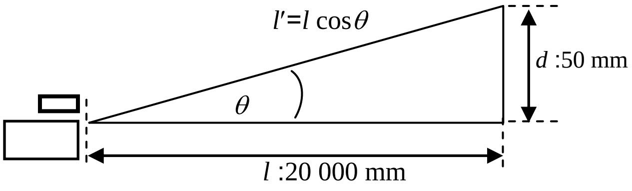

Fig. 5. Cosine error of standard and LDM

G. *Resolution of LDM* (u_{rl})

The uncertainty of the LDM resolution is 1.0 mm (411D-SMP, D8-SMP, and A5-SMP), and is considered to have a rectangular distribution of 0.5/√3 = 0.288 mm.

H. *Expanded uncertainty* (u_{ex})

The uncertainty budgets of LDM calibration were combined to be a standard uncertainty, at a confidence level of 68%. The expanded uncertainty of each of 411D-SMP,

TABLE I
THE MEASUREMENT UNCERTAINTY BUDGET OF 411D-SMP

Symbol	Source of Uncertainty	Value	Distribution	Divisor	Ci	Standard Uncertainty
u_s	Standard accuracy	2.00E-03	Rectangular	√3	1	1.15E-03
u_{rl}	Resolution of LDM	1.00E-01	Rectangular	√3	1	2.89E-02
u_{ab}	Abbe error of measuring bench	5.82E-03	Rectangular	√3	1	3.36E-03
u_{as}	Abbe error of standard	5.42E-01	Rectangular	√3	1	3.13E-01
u_t	Temperature effect(℃)	1	Rectangular	√3	0.2300	1.33E-01
u_d	Drift of standard	2.00E-03	Rectangular	√3	1	1.15E-03
u_{cs}	Cosine error of standard	6.25E-04	Rectangular	√3	1	3.61E-04
u_{cl}	Cosine error LDM	6.25E-02	Rectangular	√3	1	3.61E-02
u_a	Repeatability	0.00E+00	Normal	1	1	0.00E+00
	Combined standard uncertainty: u_c					0.343080
	Expanded uncertainty (k=2)					0.68616
	Reported uncertainty					**0.69**

TABLE II
THE MEASUREMENT UNCERTAINTY BUDGET OF D8-SMP

Symbol	Source of Uncertainty	Value	Distribution	Divisor	Ci	Standard Uncertainty
u_s	Standard accuracy	2.00E-03	Rectangular	√3	1	1.15E-03
u_{rl}	Resolution of LDM	1.00E-01	Rectangular	√3	1	2.89E-02
u_{ab}	Abbe error of measuring bench	5.82E-03	Rectangular	√3	1	3.36E-03
u_{as}	Abbe error of standard	5.42E-01	Rectangular	√3	1	3.13E-01
u_t	Temperature effect(℃)	1	Rectangular	√3	0.2300	1.33E-01
u_d	Drift of standard	2.00E-03	Rectangular	√3	1	1.15E-03
u_{cs}	Cosine error of standard	6.25E-04	Rectangular	√3	1	3.61E-04
u_{cl}	Cosine error LDM	6.25E-02	Rectangular	√3	1	3.61E-02
u_a	Repeatability	6.60E-02	Normal	1	1	6.60E-02
	Combined standard uncertainty: u_c					0.34940
	Expanded uncertainty (k=2)					0.69874
	Reported uncertainty					**0.70**

TABLE III
THE MEASUREMENT UNCERTAINTY BUDGET OF A5-SMP

Symbol	Source of Uncertainty	Value	Distribution	Divisor	Ci	Standard Uncertainty
u_s	Standard accuracy	2.00E-03	Rectangular	√3	1	1.15E-03
u_{rl}	Resolution of LDM	1.00E+00	Rectangular	√3	1	2.89E-01
u_{ab}	Abbe error of measuring bench	5.82E-03	Rectangular	√3	1	3.36E-03
u_{as}	Abbe error of standard	5.42E-01	Rectangular	√3	1	3.13E-01
u_t	Temperature effect(°C)	1	Rectangular	√3	0.2300	1.33E-01
u_d	Drift of standard	2.00E-03	Rectangular	√3	1	1.15E-03
u_{cs}	Cosine error of standard	6.25E-04	Rectangular	√3	1	3.61E-04
u_{cl}	Cosine error LDM	6.25E-02	Rectangular	√3	1	3.61E+02
u_a	Repeatability	0.00E+00	Normal	1	1	0.00E-0
	Combined standard uncertainty: u_c					0.44740
	Expanded uncertainty (k=2)					0.89488
	Reported uncertainty					**0.90**

D8-SMP, and A5-SMP is calculated to be 0.68616 mm, 0.69874 mm, and 0.89488 mm. The reported uncertainty is round up (2 significant figures) to be approximately 0.69 mm, 0.70 mm, and 0.90 mm at a confidence level of 95%, as shown in Table I, Table II, and Table III respectively.

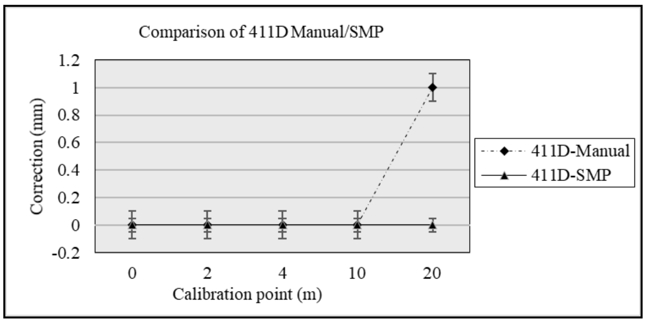

Fig. 6. Comparison for the 411D manual and SMP techniques with measurement uncertainties

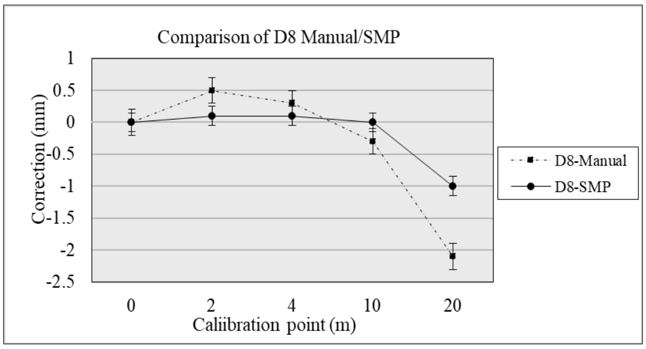

Fig. 7. Comparison for the D8 manual and SMP techniques with measurement uncertainties

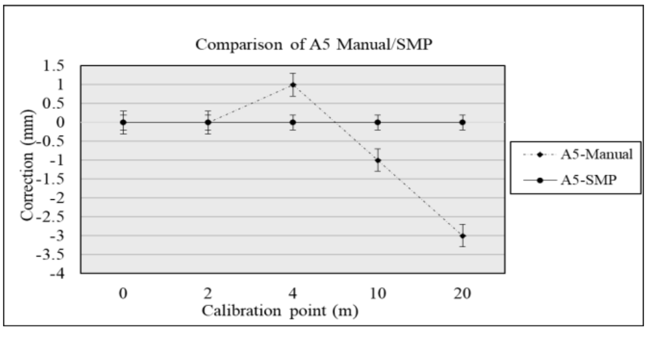

Fig. 8. Comparison for the A5 manual and SMP techniques with measurement uncertainties

IV. CONCLUSION

The comparison measurement uncertainty of SMP and Manual as shown in Fig. 6 (411D), Fig. 7 (D8), and Fig. 8 (A5) are 0.69 mm, 0.90 mm, and 0.70 mm at reference distance 20000 mm that were reduced 50.7%, 10.7%, and 60% respectively at the confidence level 95%. The results were decreased significantly with the high performance SMP controlled repeatability within maximum permissible error ±1.0 mm. This calibration technique is therefore suitable for the calibration of LDM that can be further used for the calibration of other application device by using SMP.

ACKNOWLEDGMENT

The authors would like to thank the technical staffs, Department of Science Service (DSS) Bangkok, Thailand for their helpful and kindly supports on their high precision equipment in the length standard calibration laboratory and Assoc. Prof. Vittaya Tipsuwanaporn, King Mongkut's Institute Technology Ladkrabang (KMITL) Bangkok, Thailand, for technical knowledge discussion.

REFERENCES

[1] The principle of time of flight, https://en.wikipedia.org/wiki/ Time_of_flight.

[2] EURAMET Supplementary Comparison, EURAMET.L-S20 (#1169), Comparison of laser distance measuring instruments, Final Report, https://www.bipm.org/utils/common/pdf/final_reports/L/S20/ EURAMET.L-S20.pdf

[3] W.Chinchusak, and V.Tipsuwanporn "Investigation of yaw errors in measuring tape calibration system" Journal Measurement, Volume 125/September 2018, p.142-150.

[4] ISO 16331-1(2012) Optics and optical instrument Laboratory procedures for testing surveying and construction instruments, Part 1: "Performance of handheld laser distance meters" First edition, 2012-05-01.

[5] C.Wanchai, P.Chanin, H.Pisit, and N.Sarinya, An advanced technique of laser distance meter calibration, published first edition of DSS's Bulletin, August 2021, ISSN 2286-7708.

[6] Instruction manual, Laser Measurement System 5529A Agilent Technologies, Inc., 2010, - User's Guide. Hewlett-

Packard Company, 5301 Stevens Creek Boulevard, Santa Clara, California 95052-8059. May 10, 2010.
[7] Program XAMPP version3.2.2, work instruction for Laser Meter Certification Project – LMCP, First Edition, 2020-10-13.
[8] GUM, The guideline to the expression of uncertainty in measurement (JCGM 100, 2008).
[9] M3003, The Expression of Uncertainty and Confidence in Measurement based on GUM, JCGM 100, 2008. EDITION 3, NOVEMBER.
[10] User manual, Laser distance meter, Fluke 411D, July 2008.
[11] User manual of Leica DISTO D8, V 1.0 /2013 and DISTO A5/ 2005.
[12] Cosine error, Fundamentals of Dimensional Metrology, TED Busch, Wilkie brothers foundation, Delmar Pub (1 August 1974), ISBN-13: 978-0827301931.