УДК 681.5.073

DOI 10.31471/1993-9981-2023-2(51)-5-15

Guided Wave Radar Level Sensors: Calibration and Environmental Impacts

O. Zivenko, A. Greshnov, Yu. Zhukov

Precision Instrumentation Department, Educational and Scientific Institute of Automation and Electrical Engineering, Admiral Makarov National University of Shipbuilding
208, Central Ave. 3, Mykolaiv, 3650, Ukraine; e-mail: oleksii.zivenko@nuos.edu.ua

This article presents an uncertainty analysis for guided wave radar level sensors, focusing on calibration scheme and uncertainty components under diverse environmental conditions. The study explores the interplay between various uncertainty contributions—reference instruments, time noise, nonlinearity, and dielectric constant variability. Key calculation results demonstrate the importance of accounting for environmental factors, such as temperature, pressure, and humidity, to maintain measurement accuracy. Practical recommendations for sensor manufacturers and metrological regulators are provided to enhance calibration approaches and ensure measurement quality in both controlled and harsh environments.

Keywords: measurement uncertainty, calibration, guided wave radar level sensor, dielectric permittivity.

ХВИЛЕВІДНІ РІВНЕМІРИ: КАЛІБРУВАННЯ ТА ВПЛИВ УМОВ НАВКОЛИШНЬОГО СЕРЕДОВИЩА

Зівенко О., Грєшнов А., Жуков Ю.

Кафедра морського приладобудування, Навчально-науковий інститут Автоматики та Електротехніки, Національний Університет Кораблебудування імені адмірала Макарова
208, Проспект Центральний 3, Миколаїв, 3650, Україна; e-mail: oleksii.zivenko@nuos.edu.ua

Проведено аналіз невизначеності для хвилевідних рівнемірів (guided wave radar), розглядаючи схему калібрування та компоненти невизначеності в різних умовах навколишнього середовища. Досліджено різні внески до загальної невизначеності, як від еталонів що використані для калібрування, випадковими похибками, нелінійністю передаточної функції та варіативністю діелектричної проникності і залежності від умов навколишнього середовища. Результати розрахунків демонструють важливість врахування факторів навколишнього середовища, зокрема температури, тиску і вологості повітря, для контролю та забезпечення якості вимірювань. Наведені практичні рекомендації як для виробників сенсорів так і для працівників метроолгічних служб щодо вдосконалення підходів до калібрування та забезпечення якості вимірювань як у контрольованих, так і в «жорстких» умовах експлуатації.

Ключові слова: невизначеність вимірювань, калібрування, радарний датчик рівня направленої дії, діелектрична проникність.

Introduction

Accurate level measurement of liquids and solids is essential for standard industrial processes [1]: controlling storage tanks, ensuring precise filling in production lines, preventing overflows or dry running, and complying with stringent safety and environmental regulations. The reliability and precision of level sensors directly impact operational efficiency and product/process quality in industries such as oil and gas, food and beverage, chemical and energy, and manufacturing.

The quality of level sensing can be characterized by accuracy, repeatability, resolution, response time, and the influence of different environmental factors on the measurements. Measurement uncertainty or maximum permissible error (MPE) are critical concepts considered for several applications, such as warehouse monitoring, technological overfill protection, or any safety-related applications. Uncertainty represents the degree of confidence in a measurement result, often defined by statistical analysis, while MPE refers to the largest allowable deviation from the true value during operation. Understanding and minimizing uncertainties makes processes reliable and allows using results of such measurements for specific purposes, e.g., custody transfer applications. This article focuses on guided wave radar (GWR) sensors, which leverage electromagnetic energy for precise level measurement. GWR sensors can operate effectively in a variety of liquids and under extreme environmental conditions. While radar-based sensors are notable for their non-contact operation, which minimizes contamination risks, GWR sensors stand out for applications demanding high precision, such as monitoring liquids with low permittivity or in pressurized vessels. Another advantage of GWR sensors is their ability to work as a polymetric system, enabling simultaneous measurement of multiple parameters, such as level, temperature, and pressure, using a single device. However, achieving and sustaining such accuracy necessitates a meticulous calibration process and corresponding techniques. This process ensures traceability, enhances accuracy and provides consistent performance.

A calibration procedure aligns a sensor's output to a known standard or reference. This involves adjusting measurements for level sensors to reflect true product levels under controlled conditions.

Calibration can establish/correct the measurement scale during manufacturing and test the accuracy and performance throughout the sensor's lifecycle. By using appropriate reference standards, calibration enables tuning of sensors during production and provides a means to verify the sensor's performance under standard or specific required conditions if a predefined calibration table is available.

This article addresses the calibration of GWR sensors, examining the impact of dielectric permittivity variations under reference and non-reference environmental conditions. It then makes recommendations to reduce measurement uncertainty, which is valuable for manufacturers, end-users, and regulators.

The main objective of this study is to analyze the influence of the environmental factors under reference and non-reference environmental conditions and to

1. evaluate the uncertainty in level estimation across extended environmental conditions for particular level sensor and calibration procedures;
2. propose recommendations for sensor manufacturers, end-users and independent evaluators on how to reduce measurement uncertainty.

Literature review and analysis. It's essential to consider a measurement model and corresponding calibration scheme to highlight possible sources of uncertainties. A typical GWR level sensor uses a widely known time domain reflectometry principle [3-9]; the simplified measurement model is described by Eq. (1):

$$L = \frac{c}{2\sqrt{\varepsilon}} t, \quad (1)$$

where L – distance from generator/receiver of electromagnetic pulses; c – speed of light in vacuum; ε – dielectric constant of the vapor phase of a product through which the electromagnetic pulse propagates; t – time delay between moments of sounding and receiving the reflected pulse; the coefficient of ½ stands for the fact that the electromagnetic pulse propagates along double the length of the probe (forward and backward).

In this case, the main feature used to estimate distance L is the time delay t (if the vapor's dielectric constant is considered a constant).

However, sources [10-13] show significant variability in the dielectric constant of air (or correlated parameters under changing environmental conditions). Limited focus has been given to how these variations propagate into measurement uncertainty as this influence is traditionally considered as t. This leads to a need for appropriate corrections both for calibration and measurement stages to reduce the overall uncertainty. For example, some known correction techniques consider changes in the dielectric constant of the media, especially when working with vessels under high pressures [14-16]. It's worth noting that some of these techniques use dynamic or online correction, which is based on some reference knowledge about distances or time-of-flight, while others require direct use of provided correction coefficients and uncertainty measures. Independent of the technique applied, understanding the reference uncertainty after initial calibration is crucial for calculating total uncertainty for a specific application.

Methodology. The calibration process for level sensors is typically performed under reference conditions, as defined for accurate sensors in [17]. For the most precise calibrations, national reference standards are employed, such as the Ukrainian National Standard of the Unit of Length for the Liquid Level (DETU 03-02-15) [18]. This standard reproduces the unit of length based on the global constant—the speed of light in a vacuum—and achieves an extended uncertainty of U_{NS}=±0.3 mm over a range of 0 to 20 meters. Using interferometers enables highly accurate distance measurements, with the transfer of the unit of length to high-precision level meters conducted via direct comparison.

However, due to the costliness of the full calibration cycle with national standards, equipment manufacturers often employ their own calibration setups. These setups are optimized for their specific technological processes and are generally less accurate than national standards but more practical and cost-effective for routine operations. For instance, the calibration setup at AMICO Group is an example of such an approach. Fig. 1 illustrates the calibration setup used in this study, along with its simplified design and working scheme.

Figure 1 illustrates the components of the calibration setup for level sensors:

- Level Sensors Calibration Complex (LSCC): control system managing the calibration process.
- Reference Measurement (RM) Instruments: Equipment responsible for the reference level estimation: laser rangefinder + magnetic encoders-based system to measure the position of the reference plate or reflector;
- Reference Plate (RP): reference plate or reflector.
- Additional Reference Instruments (ARI): temperature, pressure, and humidity sensors distributed in the measurement zone. They allow measuring temperature and humidity at multiple points along the sensing axis of level sensors and the temperature of liquids additionally.
- Pumps and Valves Control Subsystem (PVCS): This subsystem regulates the flow and level of the liquid in the calibration setup;
- Level Sensors under test (LS_1..LS_n): The sensors are being calibrated.
- Vessels with controllable liquid (V1, V2): These reservoirs store liquid and set a specific liquid level during calibration.

The reference measurement instrument (RM) relies on a precision reflector for accurate operation. During a single calibration cycle, multiple level sensors can be calibrated simultaneously. The procedure involves repeated measurements, capturing the readings from the level sensors under test and those from the reference instrument RM. At the same time, all the environmental parameters are monitored to satisfy the requirements of the particular procedure.

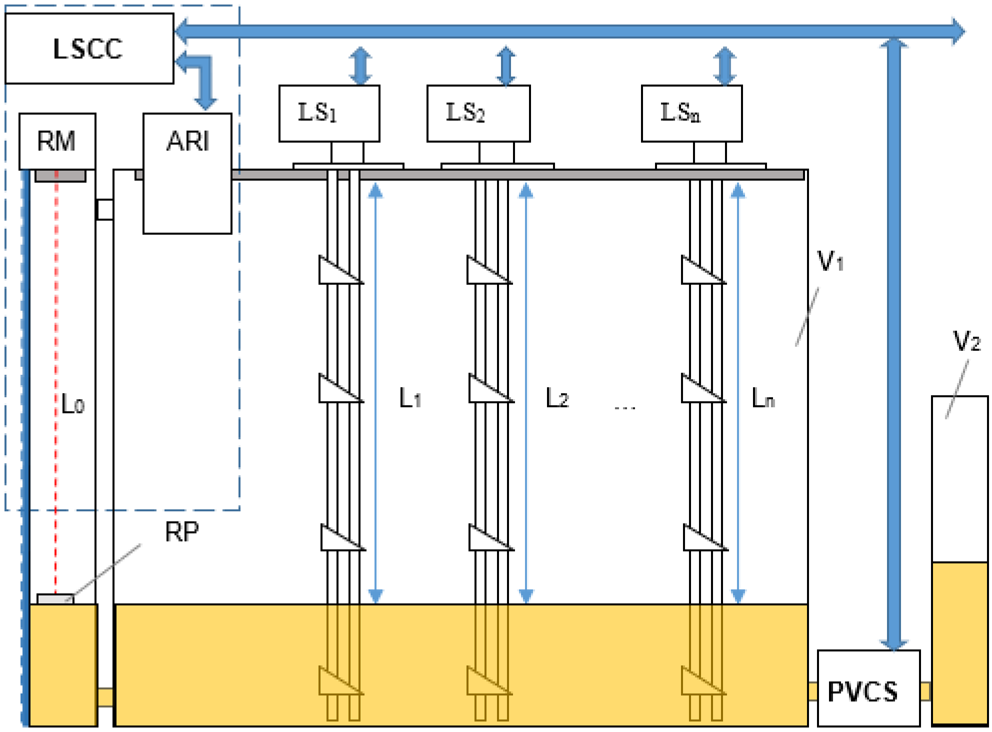

Figure 1 – Structural Diagram of a Calibration Stand for Evaluation and Tuning of Level Sensors

Uncertainties of the reference instruments. The distance (level) measurement reference instrument has an extended uncertainty of $\Delta L_{RM} = 0.4$ mm. Temperature sensors in the calibration complex have extended uncertainty $\Delta T = 0.5$ °C, $\Delta P = 1$ kPa for pressure and $\Delta RH = 2.5$ % for relative humidity.

Environmental Influence. The study considers the following reference conditions:

- Temperature (T) in [15, 25] °C.
- Relative Humidity (RH) in [40, 80]%.
- Pressure (P) in [86, 106] kPa.

Values for dielectric permittivity can be interpolated using experimental tabular data [12] or applying known equation [13]:

$$\varepsilon = \varepsilon_0 + \frac{\varepsilon_0 \cdot 211}{T}\left(P + \frac{48 \cdot P_S}{T} \cdot RH\right) \cdot 10^{-6}, \qquad (2)$$

where ε_0 is the permittivity of vacuum, T is the absolute temperature (K), RH is the relative humidity (%), P (mm Hg) is the pressure of the air, and PS (mm Hg) is the pressure of saturated water vapor at the temperature T.

Uncertainty Propagation. The effect of the changes in ε_{air} on the distance estimation ΔL_ε can be roughly assessed by substituting (2) into the relation for the level estimation (1).

$$\Delta L_\varepsilon = \left|\frac{\partial L}{\partial \varepsilon}\right| \cdot \Delta\varepsilon = \left|-\frac{ct}{4\varepsilon^{3/2}}\right| \cdot \Delta\varepsilon, \qquad (3)$$

where ΔL_ε is the contribution of the uncertainty in distance estimation due to uncertainty in the dielectric permittivity value $\Delta\varepsilon$. There are two main approaches to define $\Delta\varepsilon$ depending on the measurement mode used. The first mode is the most widely used, and it assumes no corrections if the measurements are performed within specified ranges of pressure, humidity, and temperature, without applying any corrections for environmental conditions. In this case, the maximum uncertainty in permittivity is defined by the maximum difference in dielectric permittivity values within the given ranges. This approach assumes a worst-case scenario where no compensations for environmental influences are applied, potentially leading to higher uncertainty in distance estimation.

The second approach assumes that the sensor is applying corrections depending on the data about the dielectric constant and uncertainty or based on the environmental conditions and model provided. In this case, for air, the dielectric constant is recalculated using Equation (2). The uncertainty in Δε then can be propagated through the uncertainties of the reference measurements. In this case, corrections are applied to account for the influencing factors, reducing the overall uncertainty in distance estimation and calibration. However, the resulting Δε depends on the accuracy and reliability of the reference instruments used.

It is essential to assess the impact of these factors on the uncertainty in level estimation, considering the trade-off between simplicity, where measurements are taken without additional corrections, and improved accuracy, achieved by applying corrections. Based on the specified reference conditions within the given ranges, the variation analysis reveals the following results for the dielectric constant of air. The minimum value, 1.000543±0.000007, occurs under 45.00% relative humidity, a temperature of 15.0°C, and a pressure of 645 mmHg. The maximum value, 1.000766±0.000010, corresponds to conditions of 75.0% relative humidity, a temperature of 25.0°C, and a pressure of 795 mmHg. The Arden Buck equations were applied to calculate the saturation vapor pressure P_s to temperature for moist air [21].

The stated uncertainty interval is derived from uncertainty propagation using Equation (2), based on the uncertainties of the reference sensors for temperature, pressure, and humidity. It's worth noting Figure 2 shows an example of the dielectric constant dependence for some fixed temperature values while varying the pressure and humidity of air as a media of wave propagation.

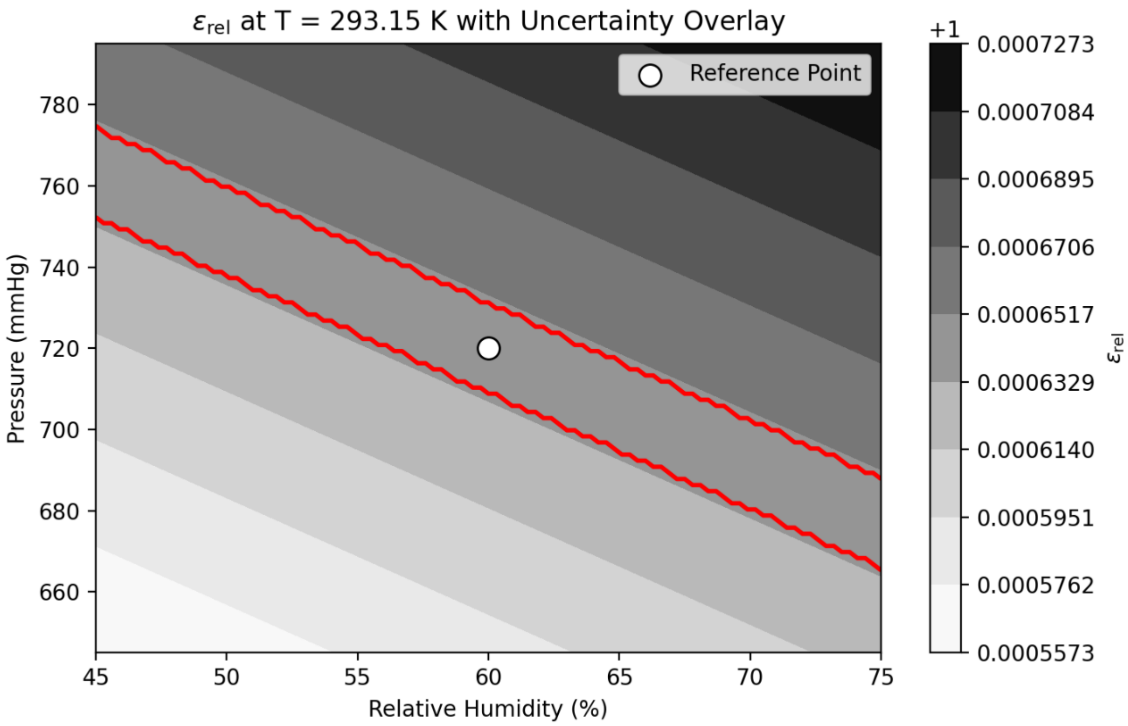

Figure 2 – Dielectric constant of air depending on humidity value and pressure for a fixed temperature value

Figure 2 also shows a point with the value of the dielectric constant corresponding to given reference conditions and a region where the dielectric constant lies within the calculated uncertainty region.

It's necessary to consider additional sources of uncertainty to make a consistent analysis of the contribution to the measurement process. Related to simplified Equation (1) the uncertainty comes from uncertainty in time estimation Δt_R and uncertainty in distance measurement, which comes from the reference measurement instrument ΔL_{RM}. Several factors, including the sounding pulse shape and the signal-to-noise ratio, influence uncertainty in time estimation. These characteristics vary for each specific sensor and play a critical role in determining the accuracy of time measurement.

In general, this uncertainty component depends on the distance between the sensor and the measured surface (or reflector). As the electromagnetic wave propagates, the shape of the reflected pulse changes with distance, introducing additional variability in the time measurement (the amplitude of the reflected signal decreases with the increase in distance decreasing signal-to-noise ratio). To model this dependency, the uncertainty in time estimation Δt_R can be expressed as a function of the distance L. A practical approach is to approximate this relationship using an exponential curve:

$$\Delta t_R(L) = A \cdot \exp(B \cdot L), \qquad (4)$$

where L is the distance between the generator and interface air-liquid (or reflector), parameters A and B are determined during the calibration process based on the sensor's characteristics and its operating conditions.

The calibration function is usually stored in a tabular form, and level calculation is done according to Equation (5):

$$L = L_{c,i} + \frac{L_{c,i+1} - L_{c,i}}{t_{c,i+1} - t_{c,i}} \cdot (t - t_{c,i}), \qquad (5)$$

where $t_{c,i} \le t \le t_{c,i+1}$ – measured delay between sounding and reflected pulses; $L_{c,i}, L_{c,i+1}$ – corresponding data about distances saved in the calibration table.

The following contributing factors were considered to analyze measurement uncertainty:

Nonlinearity between Calibration Points: Hardware tolerances in the guidewave system introduce a nonlinearity of up to ±0.3 mm, representing the maximum permissible deviation between two calibration points. This is a fixed contribution for each segment of the calibration table.

Random Error in Time Estimation Δt_R. The random error in time measurement, which varies with the distance L, is modeled using noise analysis and experimental data. The uncertainty in time estimation is calculated using Equation (4) and is distance-dependent, accounting for the degradation of the signal-to-noise ratio with increasing distance.

Uncertainty of the Reference Instrument: The accuracy of the reference device used during the calibration procedure directly impacts the calibration uncertainty. This contribution is considered fixed.

Uncertainty Due to Changes in Dielectric Constant: Variations in environmental conditions affect the propagation time of the electromagnetic pulse, introducing additional uncertainty, and this can be simulated using Equation (6), which propagates uncertainty in the dielectric constant into uncertainty in time estimation due to difference in dielectric constant:

$$\Delta t_\varepsilon(L) = \left|\frac{L}{c\sqrt{\varepsilon}}\right| \cdot \Delta\varepsilon \qquad (6)$$

Using Equations (2), (5), and (6) along with uncertainty propagation model, the contributions from each factor were analyzed. The results of these calculations are presented and discussed in the next section of this article, providing insights into the impact of each uncertainty component on the overall measurement reliability and quality.

Figure 3 provides a comprehensive view of these findings, highlighting the interplay of uncertainty contributions from reference instruments, time noise, nonlinearity, and dielectric constant variability under various environmental scenarios. Figure 3a highlights results for Reference Conditions without considering additional variability of the dielectric constant.

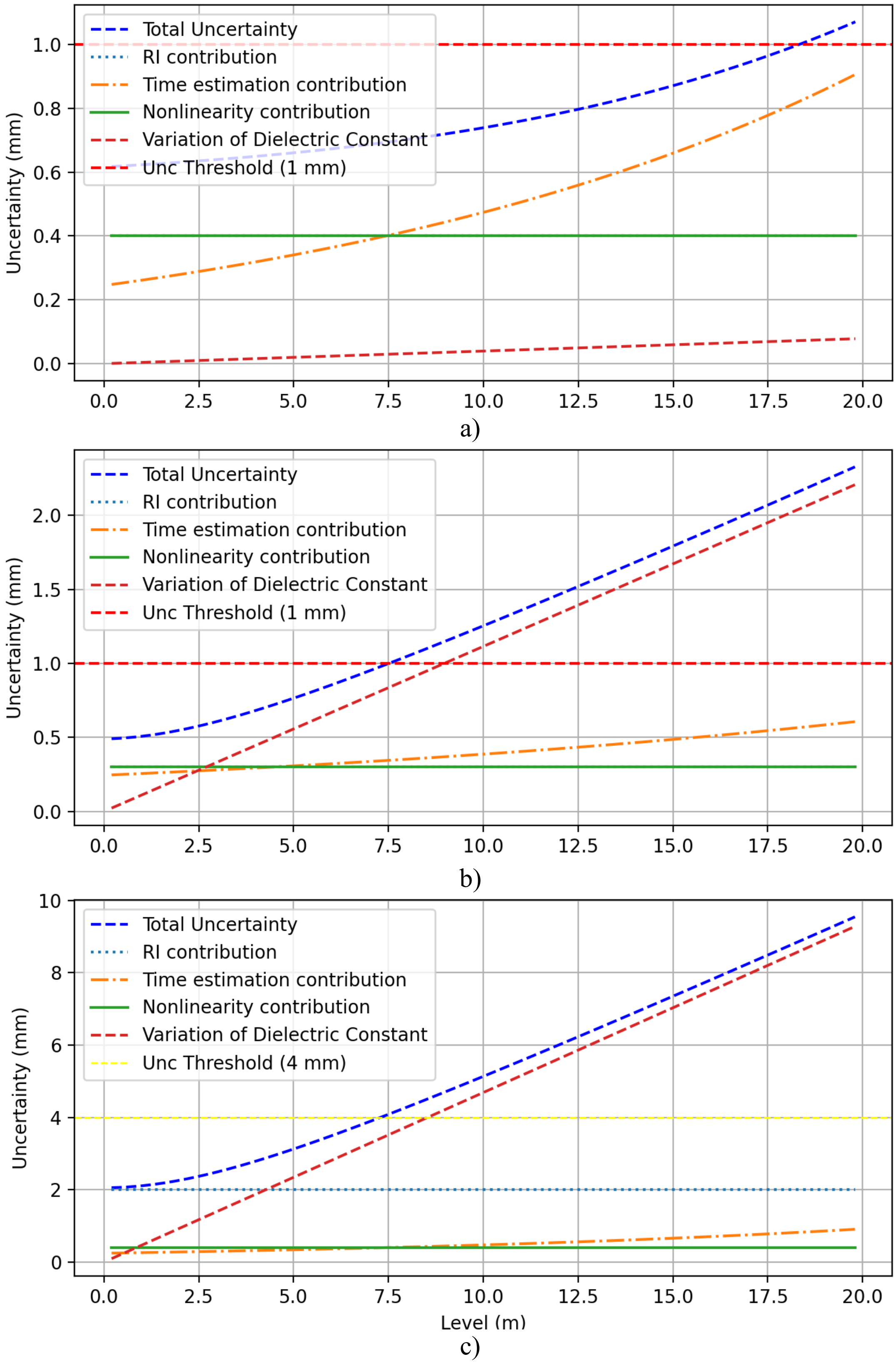

Figure 3 – Uncertainty Estimation Results for GWR Level Sensor: Analysis of Contributions and Key Components Across Various Environmental Scenarios

The uncertainty band is calculated under reference environmental conditions RH = 60±2.5%, T = 20±0.5°C, P = 96±1kPa. These conditions assume minimal variation in the dielectric constant of air. The measurement uncertainty for this case remains within the 1 mm band for distances up to 16.5 meters for the given setup and sensor characteristics. The uncertainty contributions from individual sources remain balanced, with no dominant contributor. This scenario is representative of controlled environments where variations in temperature, pressure, and humidity are minimal.

Figure 3b explores the impact of maximum allowed variability in environmental conditions within the specified reference range (T ∈ [15, 25] °C; RH ∈ [40, 80]%, P ∈ [86, 106] kPa).Variations in the dielectric constant for this case significantly expand the uncertainty band, especially at greater distances from the level interface. The effect of distance amplifies this uncertainty as the time delay becomes more sensitive to changes in dielectric constant at longer distances. This result shows the importance of accounting for environmental variability during calibration and measurement phases. Figure 3c demonstrates results for extended practical conditions. For those $T \in [-20, 55]$ °C; $RH \in [20, 90]$%, $P \in [50, 120]$ kPa. The uncertainty band increases substantially which reflects the influence of larger variations in dielectric permittivity. Figure 3c also shows the application of a low-accuracy reference instrument ($\Delta L_{RM} = 2$ mm), which results in higher uncertainty while simplifying the calibration procedure and reducing timings and costs, making it suitable for many practical applications where precision requirements are less stringent.

Figure 3 shows that at short distances, the uncertainty contributions from time measurement and dielectric constant variation are relatively small, while the nonlinearity between calibration points becomes more noticeable. The multiplicative effect of dielectric constant variation dominates the total uncertainty at longer distances. Corrective actions, such as dynamic compensation, are critical for those cases, and their efficiency should be researched additionally.

In a controlled environment, uncertainty levels are well within the acceptable threshold. However, incorporating dielectric constant corrections becomes essential for broader environmental variability and distances (Figures 3b, 3c) to maintain accuracy, particularly for long-range measurements. For relatively small ranges (up to 5 m), even mid-accurate calibration systems can be used to enable required levels of accuracy. In contrast, for long-range distances and precision applications, complex high-accuracy reference equipment must be used.

Conclusions. The presented results highlight the calibration scheme's effectiveness under controlled conditions and recommend appropriate reference instruments. Detailed uncertainty estimations were performed, providing numerical results for various combinations of uncertainty sources. These results help to understand the relative impact and significance of each factor, guiding improvements in sensor calibration. Comparisons across varying conditions demonstrate the critical role of controlling humidity, pressure and temperature to provide corrections when needed. For small-range sensors, calibration setups can be relatively simple and cost-effective. However, increasing the measurement range leads to a nonlinear rise in complexity and associated costs. The study underscores the importance of future work in evaluating uncertainty with and without dynamic correction for environmental variations, particularly in applications operating under highly variable conditions..

References

1. Zivenko, A.V., Nakonechniy, A.G., & Motorkin, D.Y. (2013). Level measurement principles & sensors. *Materialy IX mezinarodni*

vedecko-prackticka conference "Veda a technologie: krok do budoucnosti - 2013", Dil. 28, Technicke vedy, Prague, 85–90.

2. Zhukov, Yu.D., & Zivenko, O.V. (2020). Intelligent polymetric systems industrial applications. In *Proceedings of the 2nd International Workshop on Information-Communication Technologies & Embedded Systems (ICTES 2020)*, Mykolaiv, Ukraine, 122–137. Available: https://www.ceur-ws.org/Vol-2762/paper8.pdf.

3. Fellner-Feldegg, H. (1969). Measurement of dielectrics in the time domain. *The Journal of Physical Chemistry*, 73(3), 616–623. https://doi.org/10.1021/j100723a023.

4. Topp, G.C., Davis, J.L., & Annan, A.P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, 16(3), 574–582.

5. Robinson, D.A., & Friedman, S.P. (2003). A method for measuring the solid particle permittivity or electrical conductivity of rocks, sediments, and granular materials. *Journal of Geophysical Research: Solid Earth*, 108(B2), 2076. https://doi.org/10.1029/2001JB000691.

6. Glebovich, G.V., Andrianov, A.V., & Vvedensky, I.P. (1984). *Investigation of Objects Using Picosecond Pulses.* Moscow: Radio i Svyaz.

7. Nemarich, C.P. (2001). Time domain reflectometry liquid level sensors. *IEEE Instrumentation & Measurement Magazine*, 4(4), 40–44.

8. Hollywood, P.M. (1997). TDR level measurement. *Measurement & Control*, 31(6), 94–98.

9. Cataldo, A., Tarricone, L., Attivissimo, F., & Trotta, A. (2008). Simultaneous measurement of dielectric properties and levels of liquids using a TDR method. *Measurement*, 41(3), 307–319. https://doi.org/10.1016/j.measurement.2006.11.006.

10. Younglove, B.A. (1972). Dielectric constant of compressed gaseous and liquid oxygen. *Journal of Research of the National Bureau of Standards - A. Physics and Chemistry*, 76A(1), January-February, 1–10.

11. Huang, P.H., Ripple, D.C., Moldover, M.R., & Scace, G.E. (2006). A reference standard for measuring humidity of air using a re-entrant radio frequency resonator. In *Proceedings of the 5th International Symposium on Humidity and Moisture (ISHM 2006)*, Rio de Janeiro, Brazil.

12. Chattopadhyay, R. (1997). An empirical formula for computing the dielectric constant of humid air. *ResearchGate*. Available: https://www.researchgate.net/publication/262040448.

13. Santo Zarnik, M., & Belavic, D. (2012). An experimental and numerical study of the humidity effect on the stability of a capacitive ceramic pressure sensor. *Radioengineering*, 21(1), 201–206.

14. Zhukov, Y.D., Zivenko, A.V., Gudyma, I.A., & Raieva, H.N. (2019). Correction technique for guided wave radar LPG level measurement sensors. *Shipbuilding and Marine Infrastructure*, 2(12), 27–34. https://doi.org/10.15589/smi2019.2(12).3.

15. Emerson Rosemount. (2019). *Technical Note: Using Guided Wave Radar for Level in High Pressure Steam Applications.* Available: https://www.emerson.com/documents/automation/technical-note-using-guided-wave-radar-for-level-in-high-pressure-steam-applications-rosemount-en-76264.pdf.

16. Chegrinec, V.N. (2013). Correction of the transformation function of a level measurement by means of the polymetric information system. *Vimiryuvalna ta Obchislyuvalna Tekhnika v Tekhnologichnikh Protsesakh*, 2, 33–38.

17. International Organization of Legal Metrology (OIML). (2008). *OIML R 85-1 & 2: Automatic level gauges for measuring the level of liquid in stationary storage tanks.* Paris, France: Bureau International de Métrologie Légale (BIML).

18. State Primary Standard of the Unit of Length for the Liquid Level. Available: http://www.metrology.kharkov.ua/index.php?id=347&L=2. Accessed: [29.11.2024].

19. Zivenko, O., Nakonechnyi, A., Motorkin, D., & Gudyma, E. (2013). Automated calibration of level channels in polymetric systems considering the temperature of the electronic unit. *Innovations in Shipbuilding and Ocean Engineering*, Proceedings of the IV International Scientific and Technical Conference, 424–427. Mykolaiv: National University of Shipbuilding.
20, Nakonechnyi, A.G., & Zivenko, A.V. (2015). Automation of calibration of level measurement channels in polymetric systems. *Innovations in Shipbuilding and Ocean Engineering*, Proceedings of the VI International Scientific and Technical Conference Dedicated to the 95th Anniversary of Admiral Makarov National University of Shipbuilding, 337–340. Mykolaiv: National University of Shipbuilding.
21. Buck Research Instruments (1996). *Buck Research CR-1A User's Manual, Appendix 1.*

Список використаних джерел

1. Зівенко, О.В., Наконечний, А.Г., та Моторкін, Д.Ю. (2013). Принципи та датчики вимірювання рівня. *Матеріали IX міжнародної науково-практичної конференції "Veda a technologie: krok do budoucnosti - 2013"*, Dil. 28, Technicke vedy, Прага, 85–90. [англійською].
2, Жуков, Ю.Д., та Зівенко, О.В. (2020). Промислові застосування інтелектуальних поліметричних систем. У *Збірнику матеріалів 2-го Міжнародного семінару з інформаційно-комунікаційних технологій та вбудованих систем (ICTES 2020)*, Миколаїв, Україна, 122–137. Доступно: https://www.ceur-ws.org/Vol-2762/paper8.pdf. [англійською].
3. Фелльнер-Фельдегг, Г. (1969). Вимірювання діелектриків у області часу. *Журнал фізичної хімії*, 73(3), 616–623. https://doi.org/10.1021/j100723a023. [англійською].
4. Топп, Г.С., Девіс, Дж.Л., та Аннан, А.П. (1980). Електромагнітне визначення вологості ґрунту: вимірювання в коаксіальних лініях передачі. *Водні ресурси*, 16(3), 574–582. [англійською].
5. Робінсон, Д.А., та Фрідман, С.П. (2003). Метод вимірювання твердочасткової проникності або електропровідності скель, осадів та гранульованих матеріалів. *Журнал геофізичних досліджень: тверда Земля*, 108(B2), 2076. https://doi.org/10.1029/2001JB000691. [англійською].
6. Глєбович, Г.В., Андріанов, А.В., та Введенський, І.П. (1984). *Дослідження об'єктів за допомогою пікосекундних імпульсів*. Москва: Радіо і Зв'язок. [російською].
7. Немаріч, К.П. (2001). TDR для вимірбвання рівня. *IEEE Instrumentation & Measurement Magazine*, 4(4), 40–44. [англійською].
8. Голлівуд, П.М. (1997). Вимірювання рівня TDR. *Вимірювання та контроль*, 31(6), 94–98. [англійською].
9. Кальдальдо, А., Тарріконе, Л., Аттівіссімо, Ф., та Тротта, А. (2008). Одночасне вимірювання діелектричних властивостей і рівнів рідин методом TDR. *Вимірювання*, 41(3), 307–319. https://doi.org/10.1016/j.measurement.2006.11.006. [англійською].
10. Янглав, Б.А. (1972). Діелектрична проникність стислих газоподібного і рідкого кисню. *Журнал досліджень Національного інституту стандартів і технологій (NIST)*, 76A(1), Січень-Лютий, 1–10. [англійською].
11. Хуанг, П.Х., Ріппл, Д.С., Молдовер, М.Р., та Скейс, Г.Е. (2006). Еталон для вимірювання вологості повітря за допомогою радіочастотного резонатора. У *Матеріалах 5-го Міжнародного симпозіуму з вологості та вологи (ISHM 2006)*, Ріо-де-Жанейро, Бразилія. [англійською].
12. Чаттопадхай, Р. (1997). Емпірична формула для обчислення діелектричної проникності вологого повітря. *ResearchGate*. Доступно:

https://www.researchgate.net/publication/262040448. [англійською].

13. Санто Зарнік, М., та Белавіч, Д. (2012). Експериментальне та числове дослідження впливу вологості на стабільність ємнісного керамічного датчика тиску. *Радіоінженерія*, 21(1), 201–206. [англійською].

14. Методика корекції показань хвилеводних рівнемірів для зрідженого вуглеводневого газу / Жуков Ю.Д., Зівенко А.В., Гудима І.А., Раєва А.М. // *Суднобудування і морська інфраструктура*, №2(12), 2019, с. 27–34. https://doi.org/10.15589/smi2019.2(12).3.

15. Emerson Rosemount. (2019). Технічна записка: Використання хвилеводних радарів для рівня в умовах високого тиску пари. Доступно: https://www.emerson.com/documents/automation/technical-note-using-guided-wave-radar-for-level-in-high-pressure-steam-applications-rosemount-en-76264.pdf. [англійською].

16. Чегрінець, В.Н. (2013). Корекція функції перетворення при вимірюванні рівня за допомогою поліметричної інформаційної системи. *Вимірювальна та обчислювальна техніка в технологічних процесах*, 2, 33–38. [російською].

17. Міжнародна організація законодавчої метрології (OIML). (2008). *OIML R 85-1 & 2: Автоматичні рівнеміри для вимірювання рівня рідини у стаціонарних резервуарах.* Париж, Франція: Бюро міжнародної метрології (BIML). [англійською].

18. Державний первинний еталон одиниці довжини для рідинного рівня. Доступно: http://www.metrology.kharkov.ua/index.php?id=347&L=2. Дата доступу: [29.11.2024].

19. Зівенко, О., Наконечний, А., Моторкін, Д., та Гудима, І. (2013). Автоматизація калібрування каналів рівня у поліметричних системах з урахуванням температури електронного блоку. *Інновації в суднобудуванні та морській інженерії*, Матеріали IV Міжнародної науково-технічної конференції, 424–427. Миколаїв: Національний університет кораблебудування. [російською]

20. Наконечний, А.Г., та Зівенко, А.В. (2015). Автоматизація калібрування каналів вимірювання рівня у поліметричних системах. *Інновації в суднобудуванні та морській інженерії*, Матеріали VI Міжнародної науково-технічної конференції, присвяченої 95-річчю НУК ім. адмірала Макарова, 337–340. Миколаїв: Національний університет кораблебудування. [російською]

21. Buck Research Instruments. (1996). *Buck Research CR-1A User's Manual, Appendix 1.* [англійською].