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GUIDED WAVE RADAR LEVEL SENSORS: CALIBRATION AND ENVIRONMENTAL IMPACTS

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This study presents a detailed uncertainty analysis for guided wave radar level sensors, focusing on the calibration schemes and environmental influence factors. Guided wave radar level sensors are used in numerous industrial applications, especially for harsh environmental conditions. While some of the sensors are designed for technological operations control and do not require extreme precision levels, there are applications where a high level of precision is crucial. The analysis highlights the impact of environmental factors, such as temperature, pressure, and air humidity, on measurement accuracy and calibration effectiveness. Key uncertainty contributions─including those from reference instruments, random noise (signal-to-noise ratio impact), nonlinearity, and dielectric constant variability─are assessed under reference and extended environmental conditions. Results demonstrate that under controlled environments, measurement uncertainties remain within acceptable thresholds. However, when significant environmental variability is introduced, contributions from dielectric constant changes and time estimation noise amplify uncertainty bands, especially for long-range measurements. Practical calibration recommendations are provided to maintain measurement accuracy in controlled and harsh operational conditions. Additionally, the study compares scenarios using high-accuracy calibration setups with cost-effective alternatives for non-critical applications. These comparisons guide sensor manufacturers and metrological regulators in optimizing calibration practices while balancing cost and performance. The findings underscore the importance of compensating for dielectric constant variability in dynamic environments. Future work should explore uncertainty reduction techniques, including real-time correction. The provided insights are instrumental for improving polymetric sensor systems and ensuring reliable level measurements in diverse applications, fostering advancements in industrial automation and process control.

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

Проведено детальний аналіз невизначеності для хвилеводні радарні рівнеміри, зосереджуючись на схемах калібрування та впливі факторів навколишнього середовища. Хвилеводні радарні рівнеміри широко застосовуються в промисловості, особливо в умовах жорстких експлуатаційних середовищ. Частина таких сенсорів призначена для технологічного контролю і не потребують високого рівня точності, тоді як інші застосування вимагають надвисокого рівня точності. У дослідженні розглянуто вплив факторів навколишнього середовища, таких як температура, тиск і вологість повітря, на точність вимірювань та ефективність калібрування. Проаналізовано компоненти невизначеності включно з похибками еталонних інструментів, випадковими некомпенсованими флуктуаціями результатів вимірювань, нелінійністю функції перетворення та варіативністю діелектричної проникності. Аналіз виконано для еталонних умов і розширеного діапазону умов навколишнього середовища. Результати показують, що невизначеність вимірювань залишається в межах допустимих норм для малих контрольованих відстаней та референсних умов експлуатації. Однак, за умов значної мінливості навколишнього середовища, зміни діелектричної проникності та шуму в оцінці часу значно збільшують загальну невизначеність, особливо для вимірювань на великих відстанях. Наведено практичні рекомендації щодо підтримання точності вимірювань для різних умов експлуатації. У статті наведено порівняння сценаріїв використання високоточних калібрувальних стендів із альтернативами відносно низької вартості, придатними для некритичних застосувань та забезпечення рівня невизначеності типової для технологічного контролю. Такі порівняння є корисними як для виробників сенсорів, так і для метрологічних служб підприємств або регуляторних установ для оптимізації підходів до калібрування, балансуючи між вартістю та продуктивністю. Результати дослідження підкреслюють важливість компенсації варіативності діелектричної проникності для застосувань зі значними змінами умов експлуатації. Перспективною тематикою подальших досліджень є розробка методів зменшення невизначеності, включно з дослідженням невизначеності за умов введення корекцій. Наведені моделі та висновки є цінними для вдосконалення поліметричних систем, забезпечуючи надійність вимірювань рівня в різноманітних застосуваннях і сприяючи розвитку промислової автоматизації та управління технологічними процесами.

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

Introduction

Accurate measurement of liquids and solids levels 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 safety-related applications. Uncertainty represents confidence in a measurement result, often defined by statistical analysis, while MPE refers to the maximum allowable deviation from the true (actual) 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 various 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 accurate 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 the tuning of sensors during production. It verifies 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 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 reducing 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):

$$L = \frac{c}{2\sqrt{\varepsilon}}t. \tag{1}$$

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 – the 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 that estimates 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 based on reference knowledge about distances or time-of-flight. In contrast, others require the 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 the 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]. National reference standards are employed for the most precise calibrations, 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, equipment manufacturers employ their own calibration setups due to the costliness and timings of the complete calibration cycle with national standards. 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 temperature and humidity to be

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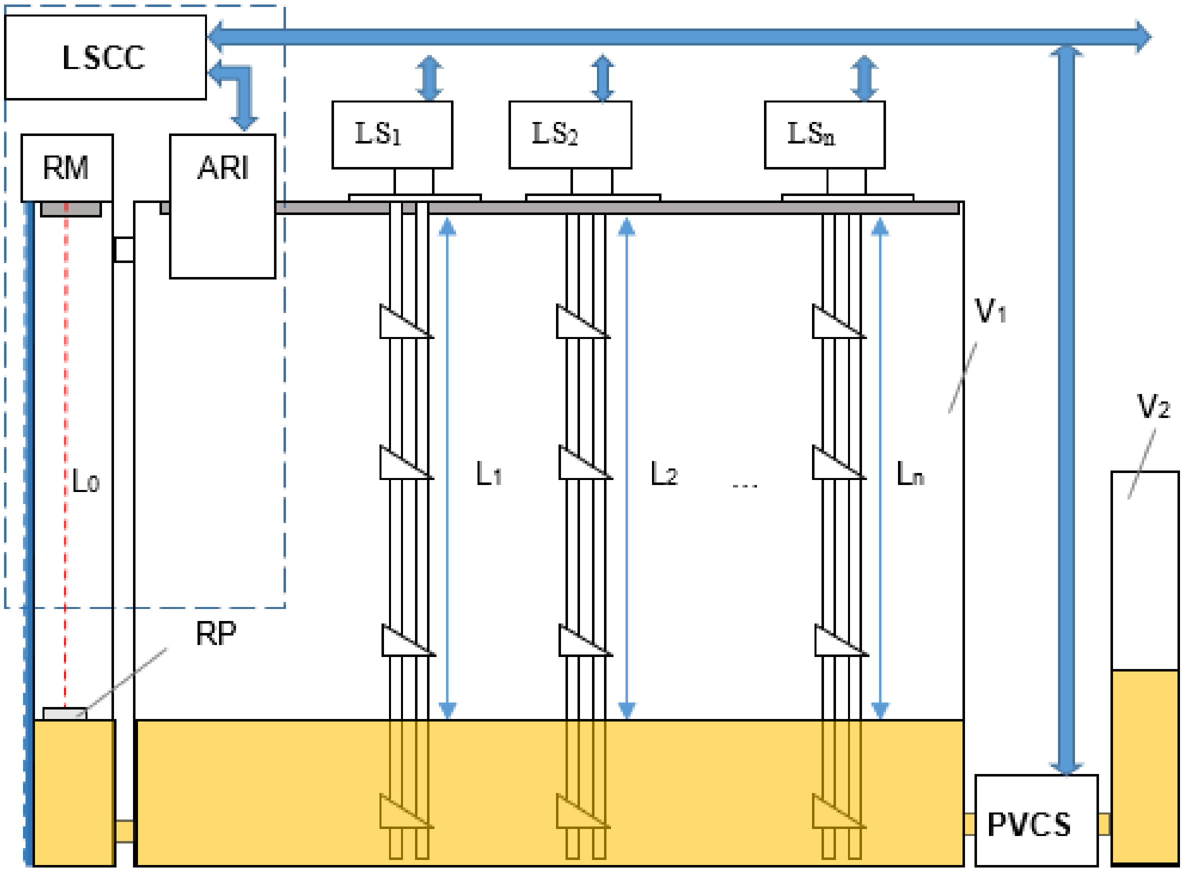

Figure 1 – Structural Diagram of a Calibration Stand for Evaluation and Tuning of Level Sensors

measured at multiple points along the sensing axis of level sensors and the temperature of liquids.

- 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, several 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.

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]:

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

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

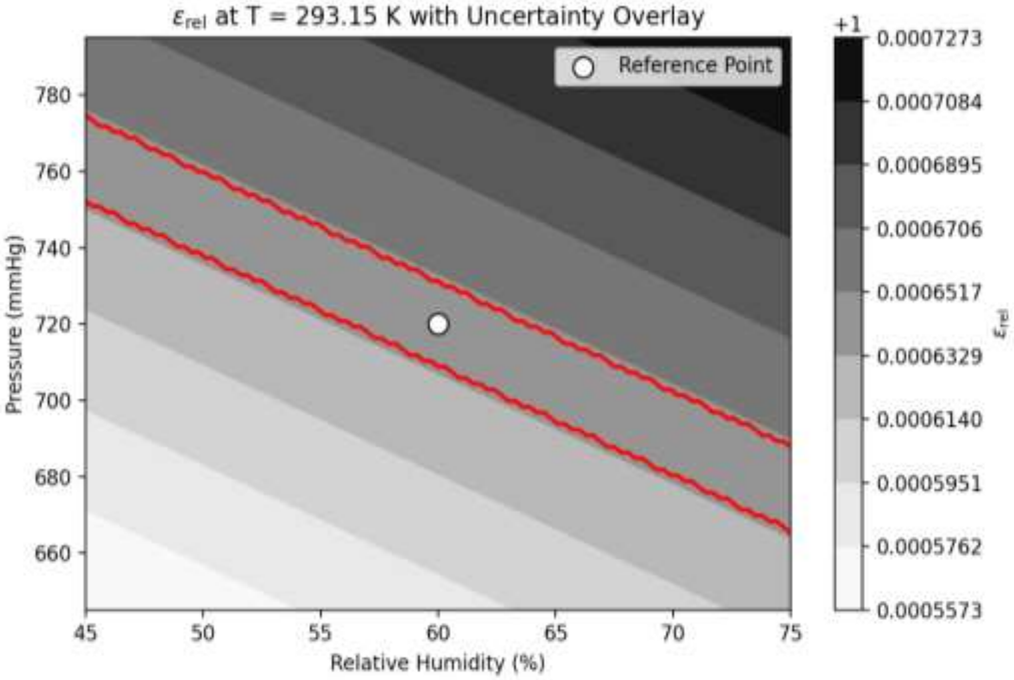

Figure 2 – Dielectric constant of air depending on humidity value and pressure for a fixed temperature value

pressure of saturated water vapors 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 $\Delta\varepsilon$. Two main approaches to define $\Delta\varepsilon$ depend 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, the dielectric constant is recalculated for air using Equation (2). The uncertainty in $\Delta\varepsilon$ can then 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 $\Delta\varepsilon$ 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 the air as a media of wave propagation.

Figure 2 also shows a point with the dielectric constant value 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 consistently analyze 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.

This uncertainty component generally 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 the 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:

$$\Delta t_r(L) = A \cdot \exp(B \cdot L), \tag{4}$$

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):

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

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 varies with the distance L and is modelled using noise analysis on the 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:

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

Using Equations (2), (5), and (6) along with the 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.

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 the 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 the 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 more considerable variations in dielectric permittivity. Figure 3c also shows the application of a low-accuracy reference instrument (ΔL_{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 3a shows that the uncertainty contributions from time measurement and dielectric constant variation at short distances 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 the required levels of accuracy. In contrast, complex high-accuracy reference equipment must be used for long-range distances and precision applications.

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 each factor's relative impact and significance, guiding improvements in sensor calibration.

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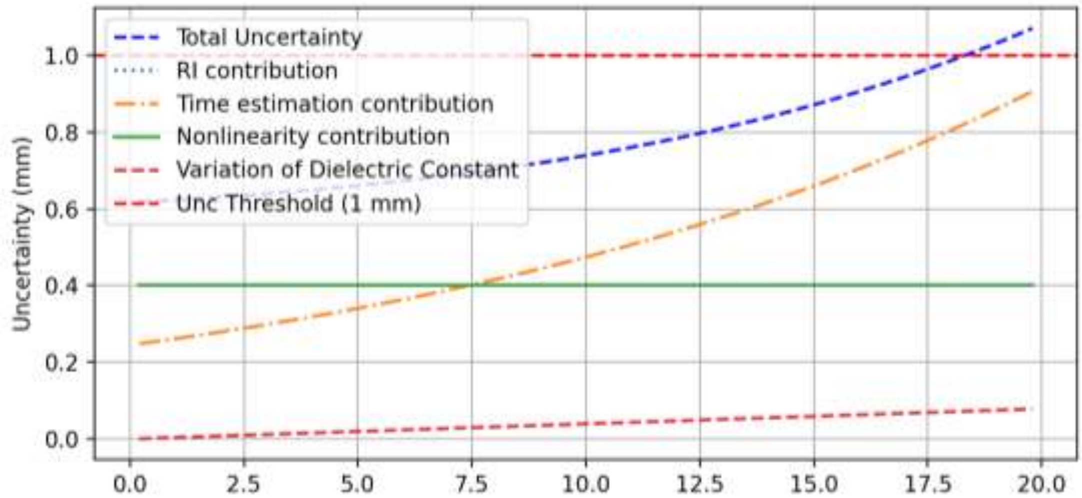
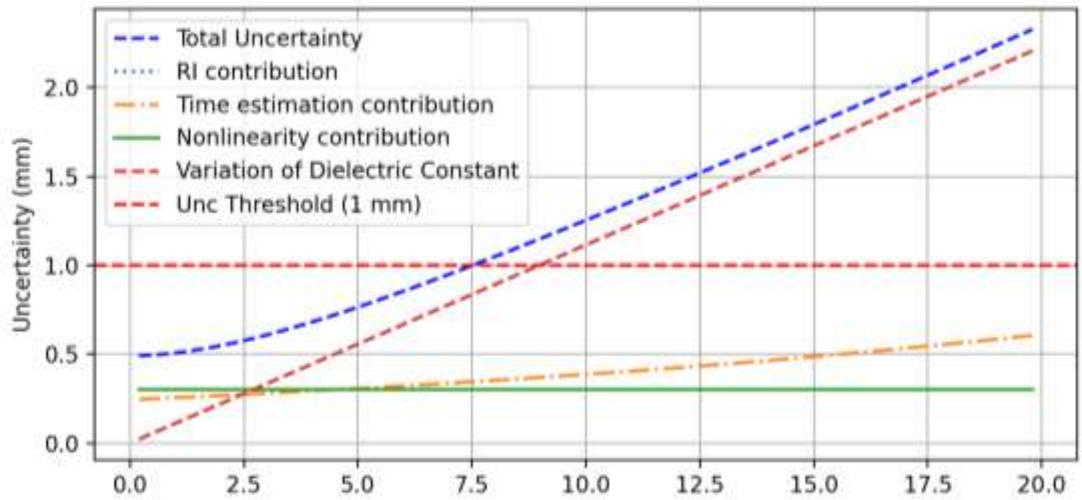


a)



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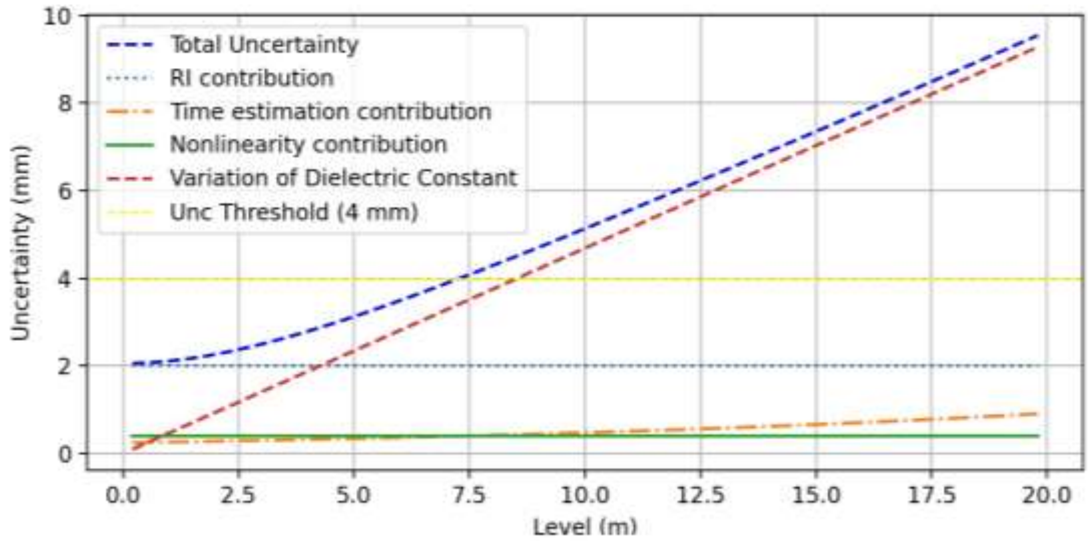

c)

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

Comparisons across varying conditions demonstrate the critical role of controlling humidity, pressure and temperature to provide necessary corrections. 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 highlights the significance of future efforts in assessing uncertainty, both with and without dynamic correction for environmental variations, especially in applications functioning under highly variable conditions. The analysis supports further enhancement of polymetric sensors utilizing GWR, enabling advanced signal processing for maximum information extraction..

References

1. Zivenko, A.V., Nakonechniy, A.G., & Motorkin, D.Y. Level measurement principles & sensors. *Materialy IX mezinarodni vedecko-prackticka conference "Veda a technologie: krok do budoucnosti - 2013"*. 2013.Dil. 28, Technicke vedy, Prague, 85–90.

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

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

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

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

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

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

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

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

10. Huang P.H., Ripple D.C., Moldover M.R., Scace G.E. 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)*. 2006. Rio de Janeiro, Brazil.

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

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

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

14. Emerson Rosemount. *Technical Note: Using Guided Wave Radar for Level in High Pressure Steam Applications.* 2019. Available: https://www.emerson.com/documents/automation/technical-note-using-

guided-wave-radar-for-level-in-high-pressure-steam-applications-rosemount-en-76264.pdf.

15. Chegrinec, V.N. Correction of the transformation function of a level measurement by means of the polymetric information system. *Vimiryuvalna ta Obchislyuvalna Tekhnika v Tekhnologichnikh Protsesakh*. 2013. Vol. 2. P. 33–38. [in Ukrainian]

16. International Organization of Legal Metrology (OIML). *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) 2008.

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

18. Zivenko O., Nakonechnyi A., Motorkin D., Gudyma E. 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, Mykolaiv: National University of Shipbuilding. 2013. P. 424–427. [in Ukrainian]

19. Nakonechnyi A.G., & Zivenko A.V. 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. Mykolaiv: National University of Shipbuilding. 2015. P. 337–340. [in Ukrainian]

20. Buck Research Instruments. *Buck Research CR-1A User's Manual, Appendix 1.* 1996.

ХВИЛЕВОДНІ РІВНЕМІРИ: КАЛІБРУВАННЯ ТА ВПЛИВ УМОВ НАВКОЛИШНЬОГО СЕРЕДОВИЩА

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