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ACCURACY DEGRADATION OF MEASUREMENT CHANNELS IN GAS TRANSPORT SYSTEMS AND EARLY DETECTION OF METROLOGICAL FAULTS

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Abstract. The paper systematically analyses the in-service degradation of the accuracy characteristics of measurement channels (pressure, temperature, and flow rate) in gas trunk pipelines and the causal link between this process, metrological failures, and the safety of the gas transport system. A structural error model, a Wiener process with drift describing instrument drift, and an apparatus for estimating metrological reliability are presented. Failure precursors (growth in signal variance and Allan variance, speed-of-sound residual, divergence trends of redundant channels, and inter-parameter residuals) and the statistical tools for their detection (CUSUM, EWMA), together with their limitations, are assessed. Following the GUM methodology, an uncertainty budget for an orifice metering run is developed, and the economic and safety dimensions of uncertainty are demonstrated. The need to move from calendar-based to condition-based management of calibration intervals and towards multivariate, regime-aware, data-driven diagnostics is substantiated.

Keywords: metrological assurance, measurement channel, drift, degradation, uncertainty, metrological reliability, Allan variance, CUSUM, EWMA, accident detection, gas transport.

Annotatsiya. Maqolada magistral gaz quvurlaridagi o'lchash kanallari (bosim, harorat va sarf) aniqlik xususiyatlarining ekspluatatsiya jarayonida pasayishi hamda ushbu jarayon, metrologik nosozliklar va gaz transport tizimi xavfsizligi o'rtasidagi sababiy bog'liqlik tizimli ravishda tahlil qilinadi. Xatolikning strukturaviy modeli, asboblarning dreyfini tavsiflovchi dreyfli Viner jarayoni hamda metrologik ishonchlilikni baholash apparati taqdim etilgan. Nosozliklarning dastlabki belgilari (signal dispersiyasi va Allan dispersiyasining ortishi, tovush tezligi qoldig'i, takroriy kanallar tafovutining tendensiyasi va parametrlararo qoldiqlar) hamda ularni aniqlash uchun statistik vositalar (CUSUM, EWMA) ularning cheklovlari bilan birgalikda baholangan. GUM metodologiyasiga muvofiq, diafragmal o'lchash liniyasi uchun noaniqlik byudjeti ishlab chiqilgan hamda noaniqlikning iqtisodiy va xavfsizlik jihatlarini ko'rsatib berilgan. Kalibrlash intervallarini kalendar asosida boshqarishdan texnik holatga asoslangan boshqaruvga o'tish hamda ko'p o'zgaruvchili, ish rejimini hisobga oluvchi va ma'lumotlarga asoslangan diagnostikaga o'tish zarurati asoslangan.

Kalit so'zlar: metrologik ta'minot, o'lchash kanali, dreyf, degradatsiya, noaniqlik, metrologik ishonchlilik, Allan dispersiyasi, CUSUM, EWMA, avariyani aniqlash, gaz transporti.

Аннотация. В статье системно анализируется эксплуатационное снижение характеристик точности измерительных каналов (давления, температуры и расхода) на магистральных газопроводах, а также причинно-следственная связь между данным процессом, метрологическими отказами и безопасностью газотранспортной системы. Представлены структурная модель погрешности, процесс Винера с дрейфом, описывающий дрейф средств измерений, а также аппарат оценки метрологической надёжности. Оцениваются предвестники отказов (рост дисперсии сигнала и дисперсии Аллана, остаток скорости звука, тенденция расхождения резервированных каналов и межпараметрические остатки), а также статистические инструменты их выявления (CUSUM, EWMA) с учётом их ограничений. В соответствии с методологией GUM сформирован бюджет неопределённости для измерительной линии с диафрагменным расходомером и показаны экономические аспекты и аспекты безопасности, связанные с неопределённостью. Обоснована необходимость перехода от календарного управления межкалибровочными интервалами к управлению на основе технического состояния, а также к многомерной, учитывающей режим работы диагностике, основанной на данных.

Ключевые слова: метрологическое обеспечение, измерительный канал, дрейф, деградация, неопределённость, метрологическая надёжность, дисперсия Аллана, CUSUM, EWMA, обнаружение аварий, транспортировка газа.

INTRODUCTION

The continuous and safe transportation of natural gas through main gas pipelines (MGPs) directly depends on the quality of measurement results, particularly their accuracy, reliability, and traceability. The total length of the main gas pipeline network of the Republic of Uzbekistan exceeds 13,000 km, with a significant portion of the network having been constructed during the 1960s–1980s. Along with the physical aging of the pipelines, the long-term operation of their measurement and control instruments—including pressure transmitters, temperature sensors, and flow meters—gradually leads to a decline in the accuracy of measurement channels, a process referred to as accuracy degradation. This process constitutes the central subject of the present study.

Measurement results in gas transportation systems serve two important functions. The first is commercial accounting, which involves determining the volume and mass of the transported gas. The second is technological and environmental safety, which involves the early detection of faults and emergency conditions, including gas leaks, through inconsistencies in measured parameters [1]. These two functions are intrinsically linked through a common physical factor—the metrological condition of the measurement channel. Since pressure, temperature, and flow rate in an MGP represent interrelated parameters of a single thermohydraulic process, an undetected bias in one measurement channel can propagate into quantities calculated from the other channels and, consequently, affect diagnostic conclusions.

A distinctive and potentially hazardous characteristic of a metrological failure is its hidden nature. Unlike a functional failure, in which a device stops operating and the failure is immediately apparent, a metrological failure allows the device to continue functioning apparently normally while its measurement indications have already exceeded the permissible error limits. If such a failure remains undetected until the next scheduled calibration, performed according to a calendar-based interval, it may, during this period, result in commercial imbalances, generate a background of false alarms in an emergency detection system, or, conversely, produce a systematic bias that masks an actual gas leak.

The theoretical premise of this study can be formulated as follows: the sensitivity limit of an emergency (leakage) detection system is fundamentally constrained by the metrological quality of the measurements. In a balance-based approach, the minimum leakage rate that can be reliably detected is determined by the combined uncertainty of the inlet and outlet flow measurement channels [1]. Therefore, improving the quality of metrological support is not only a matter of improving accounting accuracy but also a means of ensuring the design-level sensitivity of emergency detection systems.

A review of the literature indicates that most existing studies focus either on purely metrological issues, such as sensor drift and calibration intervals, or on purely diagnostic problems, such as leakage detection algorithms and statistical analyses of emergency events [1, 2]. A comprehensive approach that incorporates the metrological condition of measurements—including uncertainty, drift, and accuracy degradation—as an integral component of an emergency detection model remains insufficiently developed. Therefore, the objective of this study is to systematize the problem of measurement-channel accuracy degradation and the early detection of metrological failures from an integrated metrological-diagnostic perspective, analyze its theoretical models, precursor indicators, and practical limitations, and substantiate approaches for transitioning toward condition-based management.

LITERATURE REVIEW

The metrological reliability of measurement channels is an important component of the safe and efficient operation of gas transport systems. Existing studies in this field generally address two closely related areas: the degradation of measurement accuracy during long-term operation and the development of methods for detecting abnormal or emergency conditions in gas pipelines. Research on measurement-system degradation has shown that the accuracy characteristics of pressure transmitters, temperature sensors, flow meters, and related instrumentation may change gradually due to aging, environmental exposure, mechanical loads, thermal cycling, contamination, and changes in sensor characteristics over time. Such changes are commonly manifested as drift, increased noise, bias, and deterioration of measurement stability.

A significant body of metrological research considers calibration intervals and the probability that a measuring instrument remains within specified permissible error limits during operation. International guidance documents, including OIML D 10 and ILAC-G24, emphasize that calibration intervals should be determined by considering the stability, historical performance, operating conditions, and reliability characteristics of measuring instruments rather than relying exclusively on fixed calendar periods [3]. This approach creates a methodological basis for moving toward condition-based calibration management, in which the actual state of the measurement channel becomes the primary criterion for determining the need for recalibration.

Stochastic models are increasingly applied to describe the time-dependent evolution of measurement

errors. In particular, the Wiener process with drift provides a convenient representation of degradation because it simultaneously reflects a systematic trend and random fluctuations. Such models make it possible to estimate the probability of a measurement error reaching a permissible boundary and to determine the first-passage-time distribution. Consequently, they provide a theoretical framework for evaluating metrological reliability and forecasting the remaining period during which the measurement channel can be expected to satisfy accuracy requirements.

Another important direction in the literature is associated with the transition from the classical error-based approach to the measurement-uncertainty framework. According to the Guide to the Expression of Uncertainty in Measurement (GUM), the reliability of an indirect measurement result should be evaluated through the combined effects of the uncertainty components of all input quantities [4]. This is particularly important in gas-flow measurement, where pressure, temperature, differential pressure, gas composition, and other parameters jointly influence the calculated flow rate. Degradation in any individual measurement channel can therefore increase the combined uncertainty of the final measurement result.

Studies devoted to gas-pipeline diagnostics mainly focus on leakage detection, mass-balance methods, statistical process monitoring, model-based residuals, and data-driven diagnostic algorithms [1, 2]. Methods such as CUSUM and EWMA are widely used to identify gradual changes in process variables, while redundant-channel comparison, signal variance, Allan variance, and physical consistency checks can provide useful indicators of developing measurement faults. However, diagnostic performance is strongly dependent on the quality of the input measurements. Increased measurement uncertainty, undetected bias, or long-term drift may lead either to false alarms or to reduced sensitivity to actual leakage events.

The literature therefore indicates an important methodological gap. Metrological degradation and emergency diagnostics are often considered separately, even though they are physically and statistically interconnected. A comprehensive approach should integrate measurement-channel drift, uncertainty growth, metrological reliability, precursor indicators, and diagnostic sensitivity within a single analytical framework. Such integration is particularly relevant for main gas pipelines, where early recognition of gradual metrological degradation can improve both the reliability of commercial measurement and the effectiveness of safety-related diagnostic systems.

RESEARCH METHODOLOGY

It is appropriate to represent the current error of a measurement channel as a structural model decomposed, as a function of time, into three physically distinct components:

$$\Delta(t) = \Delta c + \xi(t) + d(t), \quad (1)$$

where Δc is the systematic component identified during calibration and remaining after correction; $\xi(t)$ is the random (noise) component with a mean close to zero; and $d(t)$ is the slowly varying drift–degradation component. A **metrological failure** is defined as a condition in which the absolute value of $d(t)$ exceeds the permissible limit. This three-component model is of important methodological significance: the random component can be reduced by averaging, the systematic component is corrected during calibration, whereas the drift–degradation component remains the primary “hidden” source of failure because it gradually increases over time.

Both deterministic (linear and exponentially saturating) and stochastic models are used to characterize drift. In practice, a particularly versatile model is the **drifted Wiener process**:

$$d(t) = \nu \cdot t + \sigma \cdot W(t), \quad (2)$$

where ν is the mean drift rate, σ is the diffusion coefficient, and $W(t)$ is a standard Wiener process. This model simultaneously accounts for both the directional (trend) and random (fluctuation) nature of drift and makes it possible to determine the distribution of the first-passage time of the error to the permissible boundary and, consequently, to evaluate the **metrological reliability** of the measurement channel:

$$P(t) = \Pr\{|\Delta(\tau)| \leq \Delta_{dop}, \tau \leq t\}, \quad (3)$$

where $P(t)$ is the probability that the measurement channel error remains within the permissible limit over the interval $[0, t]$. This mathematical framework forms the basis for the scientific justification of calibration intervals, including the “reliability target” approach recommended in OIML D 10 and ILAC-G24 [3]. Its principal advantage is that it enables a transition from calendar-based calibration intervals to **condition-based determination**, for which the parameters ν and σ must be continuously estimated from operational data.

In assessing the quality of indirect measurement results calculated from multiple measurement channels, the transition from the “error” paradigm to the “uncertainty” paradigm represents a key trend in modern metrology. For a measurand $y = f(x_1, \dots, x_n)$, the combined standard uncertainty is determined according to the GUM methodology (JCGM 100; GOST 34100.3) [4]:

$$u_c^2(y) = \sum (\partial f / \partial x_i)^2 u^2(x_i), \quad U = k \cdot u_c, \quad k = 2 \quad (4)$$

where $\partial f / \partial x_i$ are the sensitivity coefficients, and U is the expanded uncertainty with a coverage factor of $k =$

2, corresponding approximately to a 95% confidence level. The research method is based on integrating Eqs. (1)–(4) into a unified framework: through the drift–degradation component $d(t)$, the uncertainty components $u(x_i)$ increase over time, leading to an increase in the combined uncertainty u_c and, consequently, to a reduction in the sensitivity of emergency detection systems.

ANALYSIS AND RESULTS

Degradation Mechanisms of Measurement Channels

The physical mechanisms of degradation depend on the type of device. Understanding these mechanisms is essential both for correctly selecting precursor indicators and for estimating the parameters of model (2).

In pressure transmitters, degradation manifests itself as zero and span shifts caused by the elastic aftereffect and fatigue of the sensing membrane, changes in the properties of the filling fluid, temperature cycling, and overpressure events. In platinum resistance temperature sensors, degradation is associated with mechanical stress in the sensing element, a decrease in insulation resistance, and drift of the secondary transducer channel [5]. Since these two channels—pressure and temperature—are directly involved in determining gas density through calculation methodologies based on p , T , and Z [6–8], and consequently in calculating the converted gas flow rate, even relatively small drifts in these channels can have an amplified effect throughout the metrological chain of flow measurement.

The degradation mechanisms in flow meters are considerably more diverse. In turbine flow meters, bearing wear increases friction torque and causes a shift in the calibration coefficient, typically in the direction of underestimating the flow rate [9]. In differential-pressure orifice meters, wear and rounding of the edge increase the actual flow coefficient and, consequently, cause a systematic underestimation of the flow rate calculated using the standard coefficient, in some cases by up to 0.5–1% [10, 11]. In ultrasonic flow meters, degradation may result from aging of the piezoelectric transducers, accumulation of deposits on the surfaces—which alters the acoustic path length and transit-time characteristics—and drift of the electronic timing circuitry [12]. Thus, degradation can produce a systematic bias toward underestimation of the flow rate in a wide range of practical cases, making this pattern particularly hazardous for commercial accounting and balance-based leak detection [13].

Under laboratory conditions, standardized metrological characteristics may deteriorate during actual operation due to a number of factors, including installation effects, seasonal temperature cycles, vibration and pulsations near compressor stations, and the condition of impulse lines. An objective indicator of this process is the statistics of “**as-found**” errors recorded in calibration protocols. Across an equipment population, the variance of such errors generally increases with device age and the severity of operating conditions; for some individual devices, out-of-tolerance conditions may be recorded toward the end of the calibration interval. Unfortunately, these statistics often remain unused in paper-based documentation, even though they represent a direct source of information for estimating the parameters of model (2) by equipment population and device type and, consequently, for differentiating calibration intervals [3].

Particular attention should also be given to **dynamic (transient) error**. Due to the thermal inertia of a thermometric thermowell ($\tau \approx 10\text{--}60\text{ s}$), the temperature channel lags behind the actual temperature during rapidly changing operating conditions. Thus, even a channel that is fully compliant in terms of static performance may produce a temporally mismatched indication during transient processes, introducing an error into gas-density and converted-flow calculations. Therefore, degradation analysis should account not only for static accuracy but also for the **dynamic characteristics of the measurement channel**.

Precursor Indicators of Metrological Failures and Their Detection

An important practical characteristic of metrological failures is that they usually do not occur suddenly; rather, they are preceded by observable changes in the statistical properties of measurement signals. Such precursor indicators include an increase in signal variance and in the contribution of high-frequency components; the development of a trend in the difference between the readings of parallel (redundant) channels; and a systematic increase in inconsistencies between technologically related parameters. Early detection of these indicators makes it possible to identify drift before it reaches the permissible limit, thereby enabling a transition toward **condition-based management**.

The **Allan variance** is an effective tool for quantitatively characterizing noise components and distinguishing the onset of drift against the background of ordinary variance:

$$\sigma^2 A(\tau) = \frac{1}{2} \langle (\bar{y}_i + I(\tau) - \bar{y}_i(\tau))^2 \rangle \quad (5)$$

where $\bar{y}_i(\tau)$ is the mean value of the signal over consecutive intervals of duration τ . The dependence of $\sigma A(\tau)$ on τ , particularly its slope on a logarithmic scale, makes it possible to identify the type of noise, such as white noise, flicker noise, or random walk. The emergence of a random-walk component is an indication that drift–degradation has begun.

In ultrasonic flow meters, a key diagnostic precursor is the monitoring of the **speed of sound**. For each acoustic path, the measured speed of sound is compared with the value calculated from chromatographic data in accordance with AGA Report No. 10 / ISO 20765 [7, 14]:

$$\delta c = (c_{meas} - c_{calc}) / c_{calc} \cdot 100\%, \quad |\delta c| \leq 0.2-0.3\% \quad (6)$$

Exceeding this limit may indicate changes in geometry due to deposits, electronic drift, or inaccuracies in gas-composition data. In addition, inter-path velocity ratios (for flow-profile monitoring), amplification levels (AGC), signal-to-noise ratio, and turbulence indicators are monitored. For turbine flow meters, a classical diagnostic test is the measurement of the rotor free-running stop time, which serves as an indicator of bearing condition [9]. The advanced self-diagnostic capabilities of ultrasonic methods constitute one of their major metrological advantages over differential-pressure orifice-based methods [12].

Traditional statistical tools for detecting drift in flow and other measurement signals include **Shewhart control charts** and their modifications, which are more sensitive to small shifts: **cumulative sum (CUSUM)** and **exponentially weighted moving average (EWMA)** charts:

$$C_i^+ = \max\{0, x_i - (\mu_0 + K) + C_{i-1}^+\} \quad (7)$$

$$Z_i = \lambda_e \cdot x_i + (1 - \lambda_e) \cdot Z_{i-1}, \quad 0 < \lambda_e \leq 1 \quad (8)$$

where μ_0 is the nominal value of the monitored quantity; K is the sensitivity parameter; and λ_e is the smoothing coefficient. Although CUSUM and EWMA charts are considerably more sensitive to small shifts than Shewhart charts, they have important general limitations: they are essentially univariate, assume process stationarity, and cannot reliably distinguish technological regime changes—such as compressor-station operating maneuvers and fluctuations in consumption—from measurement drift. As a result, either the control limits must be widened, reducing sensitivity, or the number of false alarms increases. This limitation necessitates a transition toward **multivariate, regime-context-aware, data-driven diagnostics**.

Furthermore, an emergency event itself produces not a single indicator but a **multivariate signature** in the space of measured parameters [1, 2]. Such a signature may include a rapid local pressure decrease and its propagation as a negative pressure wave, opposite-direction changes in the dynamics of inlet and outlet flow rates, a temperature anomaly caused by the Joule–Thomson effect, and changes in the noise structure, including variance and spectral density. Under conditions where threshold-based logic applied to individual indicators is unreliable, this multivariate signature space provides a natural application domain for modern methods of anomaly detection and classification.

Uncertainty Budget and Its Practical “Cost”

To quantitatively assess the impact of degradation on commercial accounting and safety, an uncertainty budget is constructed [4]. For the differential-pressure orifice measurement method, in accordance with ISO 5167 [10, 11], the following structure can be obtained in terms of relative uncertainties:

$$(u_{qm}/q_m)^2 = (u_c/C)^2 + (u_\varepsilon/\varepsilon)^2 + [2\beta^4/(1-\beta^4)]^2 (u_D/D)^2 + [2/(1-\beta^4)]^2 (u_d/d)^2 + 1/4 (u_{\Delta p}/\Delta p)^2 + 1/4 (u_\rho/\rho)^2 \quad (9)$$

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Uncertainty Component	Relative Uncertainty, %	Sensitivity Coefficient	Contribution, %
Flow coefficient (C)	0,50	1	0,500
Expansibility coefficient ε	0,05	1	0,050
Differential pressure Δp	0,15	0,5	0,075
Density ρ (p, T, Z)	0,15	0,5	0,075
Orifice-bore diameter (d)	0,05	2,30	0,115
Pipe diameter (D)	0,10	0,30	0,030
Combined standard uncertainty (u_c)	—	—	0,53
Expanded uncertainty (U) ((k=2))	—	—	≈ 1,05

Two important conclusions can be drawn from the table. First, the uncertainty budget is dominated by the uncertainty of the flow coefficient: regardless of how much the other measurement channels are improved, it is difficult to achieve an uncertainty below approximately 1% ($k = 2$) with the orifice-plate method without individual flow calibration. Second, although the apparent contributions of the pressure, temperature, and compressibility-factor channels are relatively small, they increase over time due to drift. If the uncertainty budget is not continuously monitored as a “living” document, the actual uncertainty may significantly exceed its nominal value.

For comparison, a similar uncertainty budget for a calibrated ultrasonic metering system operating at

high pressure—with a calibration uncertainty of 0.2%, installation effects of 0.2%, pressure–temperature–compressibility (p , T , Z) conversion uncertainty of 0.25%, and a 0.1% allowance for interval drift—yields an expanded uncertainty of approximately 0.8% ($k = 2$).

The practical “cost” of uncertainty manifests itself in two dimensions. The **economic dimension** is as follows: for a pipeline route with an annual throughput of 10 billion m³, a systematic error of only 0.5% is equivalent to an accounting imbalance of 50 million m³ per year. The **safety dimension** is that the combined uncertainty of flow measurement channels directly determines the minimum leakage rate that can be detected using the balance method [1]:

$$q_{cu3,min} \approx k \cdot \sqrt{u^2(Q_{kup}) + u^2(Q_{out}) + u^2(dM_3/dt)} \quad (10)$$

where $u(Q_{in})$ and $u(Q_{out})$ are the standard uncertainties of the inlet and outlet flow rates, respectively; dM_3/dt is the rate of change of the gas inventory within the pipeline section; and k is a coefficient determined by the acceptable false-alarm probability.

Equation (10) quantitatively supports the central premise of this study: if the combined uncertainty of the flow measurement channels is, for example, 1%, leaks smaller than approximately 1% of the nominal flow rate remain, in principle, **undetectable by the balance method**. Thus, improving metrological characteristics and maintaining their stability are not merely accounting-accuracy requirements; they are essential for ensuring the **design sensitivity of emergency detection systems**.

CONCLUSION AND SUGGESTIONS

The analysis presented above substantiates the need to advance metrological support to a qualitatively new level—**digital and data-driven metrological support**. The following elements can be identified as the main components of this transition.

The first is **self-validation of measurement channels**, in which each measurement value is generated together with an estimate of its reliability or measurement uncertainty. The second is the **condition-based management of calibration intervals**, based on models (1)–(3) and operational data. This approach involves moving away from the calendar-based principle and relying instead on actual estimates of the drift parameters ν and σ . The third is a platform that integrates technological and diagnostic data on a common time axis and maintains a **digital twin** of the pipeline and measurement system [15, 16].

The fourth and decisive element is the transition to **multivariate, regime-context-aware diagnostics**. The inability of conventional univariate control charts, such as CUSUM and EWMA, to distinguish regime changes from measurement drift (Section 3) necessitates the use of multivariate methods that jointly analyze inter-parameter residuals, trends between redundant channels, and the statistical properties of measurement signals. Such methods include **recurrent and convolutional neural networks, autoencoders**—which detect anomalies through reconstruction error—and **ensemble methods**. Their physical basis is defined by the functional relationships among the parameters expressed in Eqs. (1)–(10): each parameter contains information about the remaining parameters and the condition of the pipeline; therefore, their joint dynamics provide a substantially richer diagnostic signature than any individual signal considered separately.

At the same time, the application of **artificial intelligence methods in legal metrology** [17] introduces specific requirements, including algorithm verifiability and software identification in accordance with the principles of OIML D 31 [18], explainability of decisions, traceability of training data, and cybersecurity. These requirements call for approaches that are **metrologically justified, explainable, and verifiable**, rather than relying exclusively on “black-box” models. An integrated approach that treats the metrological condition of measurements as an integral component of the emergency detection model—considering metrological support and intelligent diagnostics as two aspects of a single scientific and technical problem—therefore represents a major source of scientific novelty in this field.

From the perspective of practical implementation in Uzbekistan, several priority problem areas can be identified: the lack of a sufficiently developed national reference-standard infrastructure for calibrating flow meters used with high-pressure natural gas [19, 20]; the determination of calibration intervals according to calendar-based rules, irrespective of the actual condition of the devices; limited measurement and information coverage of linear pipeline sections; and telemetry polling intervals and time-synchronization capabilities that do not meet the requirements of modern emergency detection methods. In addition, the documentation workflow for metrological activities—including calibration results and **as-found/as-left protocols**—has not yet been fully digitized. Taken together, these conditions make continuous, data-driven monitoring of the metrological condition a particularly relevant practical direction of the present study.

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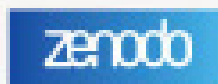
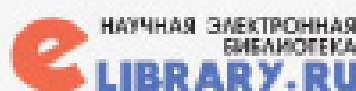
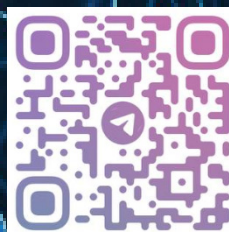
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