Strengthening optical and photonic metrology through robust uncertainty evaluation and international intercomparisons

Patrice Salzenstein [1], Thomas Y. Wu [2], David Bassir [3,4], Dinghua Yang [5]
[1] Centre National de la Recherche Scientifique (CNRS), Université Marie et Louis Pasteur (UMLP), FEMTO-ST Institute, 15B avenue des Montboucons, F25030 Besançon Cedex, France
[2] National Metrology Centre (NMC), Agency for Science, Technology and Research (A*STAR), 8 CleanTech Loop, #01-20, Singapore 637145, Republic of Singapore
[3] Smart Structural Health Monitoring and Control Laboratory, DGUT-CNAM, Dongguan University of Technology, D1, Daxue Rd., Songshan Lake, Dongguan, Guangdong Province, People's Republic of China
[4] ENS-Paris Saclay University, Centre Borelli, UMR CNRS 9010, Gif-sur-Yvette, France
[5] Science and Technology Research Institute (STRI), China Three Gorges Corporation, Beijing, 101149, People's Republic of China

e-mail: *patrice.salzenstein@cnrs.fr , thomas_wu@a-star.edu.sg , david.bassir@ens-paris-saclay.fr , yangdinghua1@outlook.com*

ABSTRACT

Advances in optical and photonic technologies continue to redefine the limits of precision in dimensional metrology, enabling ultra-sensitive measurements in spectroscopy, frequency metrology, and nanoscale characterization. As measurement systems become increasingly complex, the reliability of their results critically depends on rigorous uncertainty estimation and on the global consistency ensured through international intercomparisons. This contribution highlights how expert-driven uncertainty analysis and structured comparison campaigns together reinforce the foundations of modern metrology. Recent work on Brillouin spectroscopy using scanning tandem Fabry-Pérot interferometers has demonstrated the importance of detailed uncertainty evaluation when extracting small frequency shifts, accounting for instrumental finesse, scan linearity, and noise contributions. Likewise, the uncertainty assessment of phase-noise performance in high-frequency optoelectronic oscillators illustrates the interplay between optical, electronic, and environmental parameters in advanced hybrid systems. At a broader scale, international comparisons remain essential for validating measurement capabilities and ensuring global coherence, as emphasized in a recent overview of their critical role in the metrological infrastructure. This paper argues that the integration of rigorous uncertainty budgeting with coordinated international comparisons is indispensable for sustaining confidence in next-generation optical and photonic dimensional metrology.

Keywords: metrology, optoelectronic, intercomparisons, uncertainty analysis, OEO, Brillouin, Wind turbine.

1. INTRODUCTION

The rapid advancement of optical and photonic technologies has transformed the landscape of dimensional metrology, enabling unprecedented measurement precision across domains ranging from micro- and nanofabrication to frequency-based sensing. As measurement capabilities continue to push the limits of resolution and stability, the assurance of metrological integrity, through rigorous uncertainty estimation and systematic international intercomparison, becomes critically important. This work highlights the essential interplay between uncertainty quantification, experimental knowledge, and global comparison frameworks in the development of reliable, high-performance photonic metrology systems. Uncertainty evaluation remains a cornerstone of dimensional metrology, particularly when dealing with frequency-based optical measurement techniques. In high-resolution spectroscopic systems such as scanning tandem Fabry-Pérot interferometers, uncertainty sources arise not only from instrumental parameters but also from nonlinearities, environmental effects, and data-processing procedures. We demonstrated a comprehensive methodology for estimating the uncertainty of Brillouin frequency shift measurements, identifying how instrumental finesse, scanning stability, and signal-to-noise ratio collectively shape the achievable measurement confidence [1]. Our work establishes a metrological framework that is generalizable to other photonic systems where frequency-shift detection forms the basis for dimensional or material characterization. Similarly, high-frequency optoelectronic oscillators (OEOs) are emerging as essential tools for generating ultra-stable microwave signals used in advanced metrology and sensing applications.

The uncertainty analysis of phase-noise performance, as we investigated [2], illustrates the intricate coupling between optical, electronic, and environmental parameters in complex hybrid systems. Our study on a 10.52 GHz OEO underscores that a deep understanding of noise mechanisms—along with rigorous uncertainty budgeting - is required to exploit the full potential of photonic-microwave links in precision measurements. This work exemplifies how practical experience and detailed physical modelling jointly contribute to robust metrological assessment. Beyond individual system-level uncertainty analyses, the coherence of global metrology relies heavily on international comparisons that validate measurement capabilities across national laboratories. A recent overview [3] emphasizes the pivotal role of comparison campaigns in ensuring worldwide consistency, enabling the mutual recognition of measurement standards. Their analysis highlights that intercomparisons are not merely administrative exercises but foundational scientific processes that reveal hidden systematic effects, promote methodological convergence, and support the evolution of uncertainty frameworks. For optical and photonic dimensional metrology—where instrument diversity and measurement complexity are rapidly expanding—these comparisons serve as the backbone for international confidence in measurement results.

This paper synthesizes these perspectives to argue that the future of advanced dimensional metrology will rely increasingly on integrating expert-driven uncertainty evaluation with structured international intercomparison schemes. The accumulated expertise of practitioners demonstrates that deep physical understanding, extensive experimental experience, and global collaboration form an inseparable triad for achieving trustworthy measurements. As optical and photonic technologies continue to evolve, reinforcing this triad will be essential for ensuring that metrology keeps pace with scientific and industrial innovation. Optical and photonic technologies have become indispensable in modern dimensional metrology, enabling the exploration of physical phenomena and measurement regimes well beyond the limits reachable with conventional mechanical or electrical techniques. As the precision and resolution of optical instruments continue to improve, new challenges emerge in establishing measurement traceability, ensuring global consistency, and characterizing sources of uncertainty that arise from increasingly complex measurement systems. Highly sensitive optical interferometers, high-frequency optoelectronic oscillators, Brillouin-based spectroscopic systems, and hybrid photonic–microwave sensors all rely on sophisticated physical principles whose interactions are not trivial to model, quantify, or validate. Against this backdrop, our work addresses two pillars of metrological robustness: (1) rigorous uncertainty estimation grounded in physical understanding and experimental expertise, and (2) international intercomparison as a global mechanism for validating and harmonizing measurement capabilities. These two dimensions, uncertainty evaluation and intercomparison, are increasingly central in metrology, especially as measurement technologies evolve faster than the establishment of standards traditionally can. The present extended abstract synthesizes insights drawn from three recent publications [1-3]. Together, these works converge toward a common message: high-accuracy photonic and optical metrology cannot rely solely on instrumental performance; it must be supported by deep, experience-based knowledge of measurement processes and by systematic international comparison activities that ensure coherence across laboratories worldwide.

We also enlarge the scope of the paper by discussing another one related to wind turbine in the last part. This document develops this message in detail, highlighting the increasing importance of expert-driven uncertainty analysis, the need for robust cross-laboratory validation, and the broader metrological and scientific implications for advanced dimensional metrology.

2. ADVANCED OPTICAL AND PHOTONIC DIMENSIONAL METROLOGY: CONTEXT AND CHALLENGES

The first metrological international comparison of time and frequency standards (clocks) were coordinated by *Bureau International des Poids et Mesures* (BIPM) and reported in the 7th General Conference on Weights and Measures (CGPM) in 1927 [4]. Measurement uncertainties are estimated following the Guide to the Expression of Uncertainty in Measurement (GUM) [5]. The GUM is under ongoing revision to accommodate modern measurement methods, complex models, and digital metrology [6, 7]. There is still a debate regarding the determination of measurement uncertainty. Reference [8] argues that, contrary to the GUM, the concepts of measurement error and measurement uncertainty are fundamentally the same, challenging the distinctions made in GUM without compelling evidence. Reference [9] has examined the conceptual foundations of measurement uncertainty defined in the GUM, distinguishing between the 'realist' view, which considers measurement as an estimation of an unknowable true value, and the 'instrumentalist' view, which treats measurement as assigning values to a measurand, thereby clarifying the longstanding ambiguities in metrology. The field of dimensional metrology is undergoing a profound transformation due to the rapid evolution of photonic instrumentation and techniques. Optical frequency combs, ultra-stable lasers, Brillouin-based systems, whispering-gallery resonators, Fabry–Pérot interferometers, high-purity microwave generation, and new classes of hybrid optoelectronic oscillators now form the backbone of high-precision measurement infrastructures. These advances allow resolutions on the order of femtometers, sub-attometers, or fractional frequency stabilities better than 10^{-16}, opening unprecedented scientific and industrial opportunities. Yet these exceptional capabilities bring with them an equally exceptional sensitivity to external perturbations, coupling phenomena, and complex error sources, presenting metrologists with a series of significant challenges. One key difficulty lies in quantifying uncertainties in systems that exhibit non-linear, multi-parameter, and multi-domain behavior, as hybrid metrology systems often integrate optical, electronic, thermal, mechanical, and computational domains, making uncertainty analysis far from trivial. Another challenge is maintaining stability and traceability across extended time scales and broad measurement ranges, since factors such as temperature drifts, mechanical instabilities, and laser fluctuations can dominate long-term performance. Ensuring comparability between different instruments and laboratories also remains critical, given the wide variation in techniques across institutions while global traceability must be preserved. Moreover, establishing robust metrological frameworks for emerging photonic technologies proves difficult because many new optical systems evolve more rapidly than standardization bodies can develop reference procedures. Precision modelling of physical processes represents yet another hurdle, as shrinking uncertainty budgets elevate the significance of subtle effects that were once negligible. Our work addresses these central challenges by integrating rigorous theoretical analysis, systematic experimental methodologies, and active participation in international comparison initiatives to advance reliable and precise measurement science.

3. UNCERTAINTY ESTIMATION IN BRILLOUIN FREQUENCY SHIFT MEASUREMENTS

In reference [1], we presented a thorough uncertainty analysis applied to Brillouin frequency shift (BFS) measurements performed using a scanning tandem Fabry-Pérot interferometer, illustrated in Fig. 1. Brillouin spectroscopy has become a key technique for characterizing materials, stress distributions, and acoustic–optical interactions based on the frequency shift induced by photon–phonon scattering, and such measurements are widely used in sensing, dimensional metrology, and material diagnostics. However, achieving sub-MHz or even sub-kHz accuracy in BFS determination is challenging because the measured frequency shift depends on the complex interplay between instrumental resolution, interferometer finesse, scanning linearity, environmental conditions, and spectral fitting models. The contribution presented in this work is significant for several reasons. First, we developed a comprehensive uncertainty budget that goes beyond the statisticaldispersion of repeated measurements by identifying and quantifying multiple systematic contributions, including interferometer plate parallelism and cavity uniformity, residual non-linearity in the scanning mechanism, laser frequency stability, environmental variations such as temperature and vibration, signal-to-noise ratio and background noise, and the influence of data-processing algorithms. Second, the analysis highlights the importance of expert-guided assessment of system behavior, emphasizing that realistic uncertainty estimation requires deep experimental experience, particularly when aligning and calibrating Fabry–Pérot interferometers, since metrologists must understand how small misalignments, spectral distortions, or fitting assumptions can influence BFS results. Third, the proposed uncertainty methodology extends beyond the specific case of Brillouin spectroscopy and can be applied more broadly to resonance-based or frequency-shift-based optical measurement techniques used in dimensional metrology. Finally, by providing a structured and transparent methodology for uncertainty budgeting, the work strengthens the traceability of BFS measurements and supports reliable inter-laboratory comparisons. Overall, this study illustrates how the combination of physical insight and rigorous metrological analysis can establish reliable measurement frameworks for advanced optical systems.

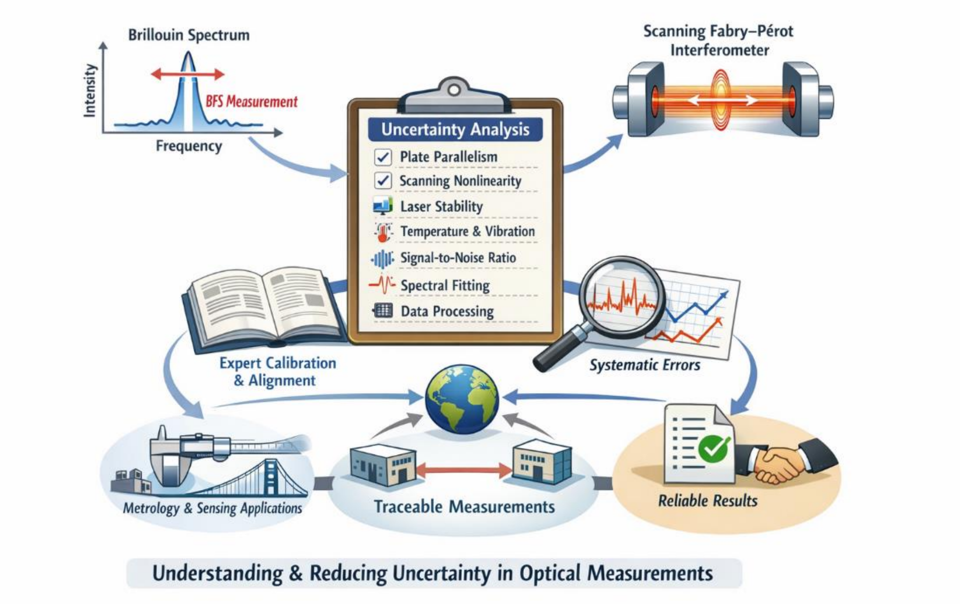

Fig. 1: Application of uncertainty analysis to Brillouin Light Scattering.

4. UNCERTAINTY EVALUATION IN OPTOELECTRONIC OSCILLATORS

Optoelectronic oscillators (OEOs) are key devices in modern metrology, optical communications, and advanced sensor systems because they generate ultra-low phase-noise microwave signals through the combination of optical delay lines, electro-optic modulators, and feedback loops. The ability to derive high-purity microwave signals from optical systems is particularly important in dimensional metrology, where such signals are used in applications such as interferometric distance measurement, frequency references, and time-resolved sensing. In this context illustrated on Fig. 2, the study presented in Reference [2], which evaluates the phase-noise uncertainty of a 10.52 GHz OEO, is especially noteworthy because earlier work rarely addressed the metrological analysis of OEO performance with the same level of depth and rigor. The authors concentrate on several critical aspects of the system’s behavior and measurement methodology. First, they identify the dominant noise mechanisms affecting the oscillator, noting that noise can arise from multiple sources including the laser, modulator non-linearity, fiber dispersion, electronic amplifiers, temperature drift, and the feed back loop itself, and that understanding the interactions between these elements requires expertise in both optical and microwave engineering. Second, they develop a comprehensive uncertainty budget for phase-noise measurements, recognizing that a phase-noise spectrum contains multiple frequency offsets, each associated with different physical noise processes such as flicker noise, thermal noise, or cavity-related effects, and that estimating the uncertainty of these contributions requires a hybrid methodology that combines measurement statistics, electronic characterization, and system identification. Third, the study places strong emphasis on long-term stability, demonstrating that environmental control, thermal stabilization, and mechanical isolation are essential factors, as long-duration measurements reveal how environmental variations propagate through the system and ultimately contribute to measurement uncertainty. Finally, the work contributes to the broader effort toward standardization in photonic microwave generation by proposing an uncertainty model that supports the development of best metrological practices in a field where technical standards and norms are still evolving, thereby reinforcing the idea that expert-driven uncertainty estimation is not merely a statistical exercise but rather a detailed physical investigation into the behavior of a complex photonic-electronic system. Note that results obtained in reference [2] are partially based on other works [10-12].

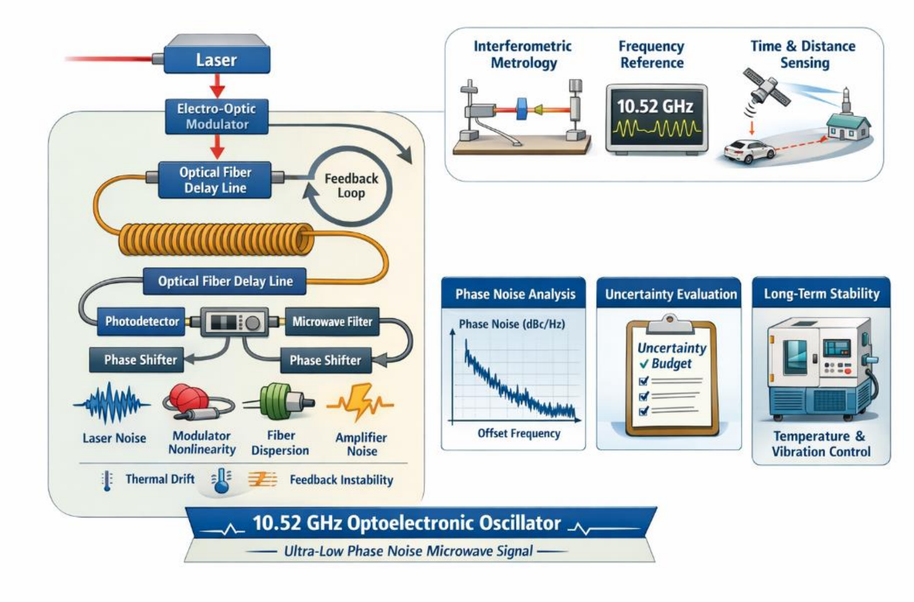

Fig. 2: Application of uncertainty analysis to an Optoelectronic Oscillator (OEO).

5. THE ROLE OF INTERNATIONAL COMPARISONS

Uncertainty evaluation alone does not ensure the global coherence of measurement systems; therefore, international comparisons (ICs) play a fundamental role in validating laboratory capabilities, establishing mutual recognition between institutions, and revealing hidden systematic effects that may not appear in individual laboratory analyses. The 2025 overview presented in reference [3] places ICs at the very center of modern metrology and emphasizes their structural importance within the global measurement infrastructure. According to the cited paper, interlaboratory comparisons constitute the foundation of the global metrology system because they ensure reliable equivalence of measurements across laboratories worldwide. Through these comparisons, discrepancies between laboratories can be revealed, overlooked sources of uncertainty can be identified, measurement procedures can be harmonized, and calibration and measurement capabilities (CMCs) can be validated in a transparent and internationally recognized framework. The paper also highlights that optical and photonic metrology present challenges that differ significantly from those encountered in electrical or mechanical measurements. Optical systems are generally more sensitive to environmental conditions in laboratories, the instrumentation used can vary considerably between institutions, and the technologies involved evolve at a much faster pace. As a result, ICs in photonic metrology must address several specific difficulties, including ensuring the comparability of laser sources or frequency references, standardizing interferometric setups across laboratories, establishing robust connections between optical frequencies and the International System of Units (SI), and aligning the spectral, temporal, and spatial characteristics of measurements performed in different environments. Beyond their technical dimension, the authors emphasize that ICs also function as mechanisms for knowledge transfer within the metrology community. They provide valuable opportunities for training researchers and engineers, encouraging the exchange of ideas between laboratories, and disseminating best practices that improve measurement reliability worldwide. Historically, intercomparison campaigns have also acted as powerful drivers of metrological innovation. By revealing systematic biases and subtle discrepancies, they have often led to the development of new standards, improved methodologies, and sometimes even new scientific insights. As photonic technologies continue to advance, ICs are expected to maintain this role by uncovering subtle physical or instrumental effects that require deeper investigation. Finally, the paper stresses the necessity of developing forward-looking intercomparison strategies adapted to the emerging landscape of photonics. Future systems—such as integrated optical sensors, photonic chips, quantum optical instruments, and large-scale optical frequency networks—will require new forms of intercomparison capable of addressing distributed architectures, extremely high frequencies, and increasingly complex measurement infrastructures.

6. SYNERGY BETWEEN UNCERTAINTY ESTIMATION AND INTERCOMPARISONS

The three papers converge toward a shared metrological philosophy in which uncertainty budgeting and intercomparison are viewed as mutually reinforcing and inseparable processes that are essential for achieving trustworthy measurements in advanced optical and photonic systems. Within this perspective, several complementary mechanisms explain how the two practices support one another. First, expert-driven uncertainty estimation plays a crucial role in identifying what parameters and measurement conditions must be compared, because well-constructed uncertainty budgets make the most critical contributors visible and therefore guide the design and focus of intercomparison exercises. Second, intercomparison itself acts as a diagnostic tool for the uncertainty budget, since unexpected discrepancies between laboratories often reveal that a measurement team has either omitted a relevant uncertainty contribution or underestimated a physical effect influencing the measurement. Third, the repetition of intercomparison campaigns over time further strengthens the evaluation of uncertainty, as long-term international comparisons progressively refine uncertainty budgets across different laboratories and across successive generations of instrumentation. Finally, the combined effect of these processes is the establishment of global confidence in advanced photonic measurements: only by merging rigorous uncertainty evaluation with systematic international intercomparison can the scientific community build and maintain trust in emerging technologies and methodologies in optical metrology.

7. IMPLICATIONS FOR THE FUTURE OF DIMENSIONAL METROLOGY

The synthesis of the referenced works points toward several broader implications for the future of metrology and photonic technologies. First, the increasing complexity of modern photonic systems—such as integrated photonics platforms and quantum sensors—demands significantly deeper and more sophisticated approaches to uncertainty analysis, as traditional models may no longer adequately capture the intricate interactions and noise sources present in these advanced systems. At the same time, international intercomparisons, which are fundamental to ensuring global measurement consistency, must evolve to address the challenges introduced by emerging technologies including distributed optical networks, quantum frequency links, and satellite-based measurement infrastructures, all of which operate across geographically dispersed and technologically heterogeneous environments. Furthermore, the growing convergence of optical, microwave, and quantum technologies is giving rise to a form of hybrid metrology that requires practitioners to develop cross-domain expertise, since future metrologists will increasingly need to understand and operate within multiple physical domains simultaneously. In this context, the interplay between theory, experiment, and expert interpretation becomes ever more central: beyond purely numerical simulations, a deep physical understanding of measurement processes remains essential for correctly interpreting complex phenomena and identifying subtle systematic effects. Altogether, these trends suggest that photonics will continue to push the boundaries of dimensional metrology, and optical technologies are likely to become the dominant framework for ensuring SI traceability in fundamental quantities such as length, frequency, and time. Note that previous work is in uncertainty estimation [13, 14] or signal propagation in the frequency domain [15].

8. EXAMPLE OF AN ANALYSIS OF CONTRIBUTION TO METROLOGY IN WIND TURBINE ANALYSIS

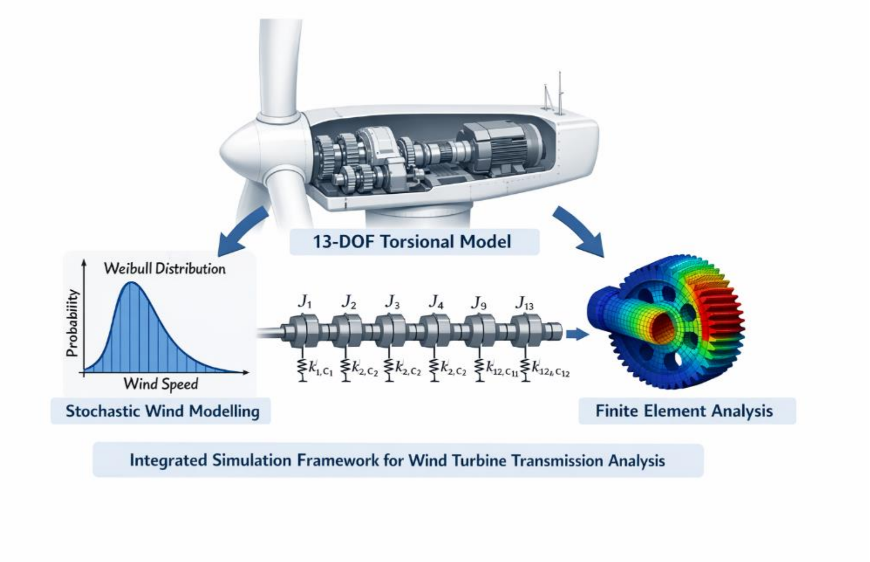

Fig. 3: Application of uncertainty analysis to wind turbine analysis.

Work published in reference [16], and illustrated on Fig. 3, develops a comprehensive simulation framework for wind turbine transmission chains by combining stochastic wind modelling, dynamic system equations, and finite-element validation. The use of a Weibull distribution to represent natural wind variability introduces a probabilistic description of environmental inputs, which supports uncertainty evaluation in drivetrain loads and dynamic responses. By linking stochastic wind inputs, a 13-degree-of-freedom torsional model, and finite-element stress analysis, the methodology allows cross-verification of results from different modelling approaches, strengthening the robustness of the predictions. Such a structured modelling and validation workflow could facilitate international intercomparisons, since the approach relies on standardized physical parameters (wind statistics, drivetrain components, and numerical solvers) that can be reproduced by other research groups. Overall, the framework provides a basis for comparing simulation results across laboratories and improving reliability assessments of wind turbine drivetrain dynamics under uncertain wind conditions.

9. CONCLUSION

The rapid evolution of optical and photonic technologies is profoundly reshaping the field of dimensional metrology, enabling measurements with unprecedented levels of sensitivity, resolution, and stability. However, as measurement systems become increasingly complex and multidisciplinary, ensuring the reliability and global consistency of their results requires a strengthened metrological framework built upon rigorous uncertainty evaluation and coordinated international comparison activities. This paper has highlighted how detailed uncertainty analysis, grounded in physical understanding and experimental expertise, constitutes a fundamental component of trustworthy measurement science. The studies discussed here demonstrate this principle across several advanced systems. The uncertainty assessment of Brillouin frequency shift measurements using a scanning tandem Fabry-Pérot interferometer illustrates how instrumental parameters, environmental conditions, and data-processing procedures collectively influence measurement accuracy. Likewise, the evaluation of phase-noise uncertainty in high-frequency optoelectronic oscillators shows that reliable characterization of hybrid photonic–microwave systems demands careful modelling of multiple interacting noise sources and long-term system stability. These examples emphasize that uncertainty estimation is not merely a statistical exercise but rather a comprehensive investigation of the physical mechanisms underlying measurement processes. Beyond individual experimental systems, international intercomparisons play a crucial role in maintaining the coherence of the global metrology infrastructure. By enabling laboratories to validate their capabilities, identify hidden systematic effects, and harmonize measurement methodologies, such comparisons provide the collective verification necessary for worldwide confidence in measurement results. In rapidly advancing domains such as photonic metrology, where instrumentation evolves quickly and experimental configurations vary widely between laboratories, these collaborative efforts are indispensable. The example related to wind turbine drivetrain modelling further illustrates how uncertainty-aware methodologies and structured modelling frameworks can support reproducibility and facilitate cross-laboratory validation, extending metrological principles beyond traditional laboratory measurements into complex engineering systems. Taken together, the works synthesized in this contribution demonstrate that the future of advanced dimensional metrology will depend on a strong synergy between expert-driven uncertainty evaluation and systematic international intercomparisons. As optical, microwave, and quantum technologies continue to converge, metrology will increasingly rely on interdisciplinary knowledge, rigorous modelling, and global collaboration. Strengthening these interconnected pillars will be essential for ensuring that measurement science continues to provide the reliable foundation required for scientific discovery, industrial innovation, and technological progress.

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