# Uncertainty analysis in optoelectronic and photonic metrology: phase noise, frequency stability, and Brillouin scattering measurements

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## ABSTRACT

In recent years we significantly advanced the field of uncertainty analysis in optics and optoelectronics, focusing on precision measurement and signal stability. Our research addresses the evaluation and minimization of uncertainties in laser frequency stabilization, phase noise, and time/frequency metrology, which are critical for high-performance optical systems. We have used and developed innovative methodologies combining statistical analysis, Allan variance techniques, and Phase noise point of view to accurately quantify measurement uncertainties. This work enables better characterization of oscillators, optical resonators, and photonic devices, enhancing the reliability of systems used in telecommunications, sensing, and fundamental physics. By integrating rigorous uncertainty models with experimental validation, this work contributed to improving the traceability and confidence of measurements in both industrial and scientific contexts. This contribution supports the development of more stable and accurate optical frequency metrology approach.

**Keywords:** Optoelectronic oscillator, Brillouin Light Scattering, microwave signal, uncertainty, uncertainty analysis, error, noise.

## 1. INTRODUCTION

Substantial contributions to the uncertainty analysis of signals in optics and optoelectronics, focus on metrological evaluation of phase noise, frequency stability, and Brillouin scattering measurements. Our work provides rigorous frameworks for quantifying measurement uncertainties in advanced optoelectronic systems, which are essential for applications ranging from high-precision oscillators to fibre optic sensing. We follow the modern method, as it is recommended in the Guide to the Expression of Uncertainty in Measurement [1] of Bureau des Poids et Mesures (BIPM). We developed a detailed uncertainty estimation for phase noise measurements in optoelectronic metrology systems, addressing both type A (statistical) and type B (systematic) uncertainty sources in complex experimental setups [2,3] on an optoelectronic oscillator [4]. Later, we extended this work to evaluate uncertainties in optoelectronic oscillators operating at 10.52 GHz, combining experimental data with comprehensive error modelling to establish confidence levels on phase noise performance [5,6]. With Wu, we presented an uncertainty estimation methodology for Brillouin frequency shift measurements using a scanning tandem Fabry-Pérot interferometer [7]. Across these works, we integrate methods such as Allan variance and sensitivity analysis to enhance traceability and reproducibility in optoelectronic measurements. Such contributions aim to help strengthening international metrology to improve the reliability of photonic and microwave systems critical to telecommunications, sensing, and fundamental physics research.

## 2. RECOMMENDATIONS AND STANDARDS

Measurement uncertainty refers to the quantified doubt about the result of a measurement. In other words, it represents the estimate that characterizes the range of possible values within which the true value of a measured quantity is believed to lie. No measurement can be perfectly exact because every measuring process is influenced by small errors and limitations of instruments, methods, and environmental conditions. For this reason, the concept of uncertainty is central in metrology, the science of measurement. This theme continues to be a hot topic in scientific and engineering communities, as shown by ongoing research and discussions in references [8] and [9]. Uncertainty in measurement is not a single number but usually a combination of several

contributing factors as in reference [10] for instance. These components can originate from different sources: some are random and can be evaluated using statistics, while others are systematic or rely on expert judgment and prior knowledge. Typically, part of the uncertainty can be estimated through repeated measurements, which provide information about variability. Other parts, however, cannot be captured through repetition and must be assessed using external data such as calibration reports, manufacturer specifications, or past experience.
It is detailed in a report [11]. In this report, from Table 1, we see that the main contribution is due to the standards and not to the bench itself, although the possible mismatches are not negligible.

**Table 1.** Numerical example: Direct comparison of the unknown wattmeter relatively to a known bolometer [10].

| Parameter | Contribution (expressed in %) | Importance |
|---|---|---|
| Calibration certificate | 2 | Major |
| Drift | 0.1 | Minor |
| Interpolation | 0.2 | Minor |
| Power on standard | 0.5 | Minor |
| Power on unknown arm | 0.5 | Minor |
| Ration of power on lateral arm | 0.1 | Minor |
| Mismatch (depending on internal reflection factor) | 0.5%+6 $\Gamma$ | Not negligible |
| Repeatability of connectors | 0.3 | Minor |
| Instabilities of generators | 0.05 | Minor |

In practical applications, measurement uncertainty is not a single source of error but rather the combination of many elementary contributions that are usually classified into three broad subcategories: standard contributions, measurement means, and various contributions. Standard contributions are directly related to reference standards and calibration data, and they include, for example, the calibration certificate, which documents the accuracy of a measuring instrument as determined by a recognized calibration laboratory; drift, which is the slow variation in an instrument's performance over time and can lead to systematic deviations if not corrected; and interpolation between known values, which arises when measurement results are estimated between calibration points instead of being directly measured, thereby introducing an additional layer of uncertainty. Measurement means, on the other hand, concern the intrinsic characteristics and limitations of the measuring device or method itself. Important factors in this category are linearity, which refers to how accurately the instrument maintains proportionality across its measurement range; resolution, which represents the smallest detectable change in the measured quantity; and stability, which reflects the instrument's ability to maintain consistent performance without unexpected fluctuations during repeated or prolonged use. Finally, there are various contributions, which encompass a wider set of practical influences that can distort results. These include mismatch, caused by imperfect coupling of electrical or optical signals that can lead to reflections and losses; temperature effects, which describe how environmental variations affect sensors, connectors, or other components of the measurement chain; connector repeatability, where repeated disconnection and reconnection of connectors introduces small but measurable inconsistencies; and harmonics and noise, which correspond to undesired additional signals in the system that interfere with the accuracy of the true measurement. Together, these three categories provide a comprehensive framework for identifying and analyzing the multiple factors that contribute to the overall uncertainty of a measurement.

The elementary contributions to measurement uncertainty are generally classified into two main categories, known as Type A and Type B evaluations. Type A evaluation refers to the statistical treatment of uncertainty components and is based on repeated observations of the same quantity under the same measurement conditions. By performing a large number of repeated measurements, it is possible to assess how much the results vary from one another. This variability is quantified using statistical tools, most commonly the experimental standard deviation, which measures the spread of the data around its mean value. When multiple independent Type A contributions exist, their combined effect on uncertainty is determined using the root-sum-of-squares method, expressed mathematically as $U_A = \sqrt{\sum A_i^2}$. This approach provides a rigorous, numerical way of describing the random fluctuations that naturally occur in repeated experiments. In contrast, Type B evaluation deals with uncertainty components that cannot be assessed by repetition but must instead be estimated through other means, such as calibration certificates, technical specifications, previous measurement data, or expert judgment. Type B contributions are further divided into two subcategories: BR and BL. The BR (related to standards) components are directly linked to uncertainties provided by reference standards or calibration data, while the BL (other contributions) components account for all other sources of uncertainty, such as environmental influences, limitations of the measuring method, or theoretical assumptions. Unlike Type A uncertainties, Type B contributions are often combined using arithmetic summation, reflecting the fact that they are not based on statistical variability but rather on informed estimates of possible deviations. Together, the Type A and Type B frameworks provide a structured and comprehensive way to evaluate all possible sources of measurement uncertainty, ensuring that both random and systematic effects are properly accounted for.

In the field of high-frequency and microwave engineering, the calibration of power meters provides a clear example of how measurement uncertainty is analyzed and managed. The reference standard most commonly used in this context is a bolometric device, which operates by measuring power through the heating effect of absorbed energy. This reference itself introduces several sources of uncertainty: the calibration of the bolometer, which represents the documented accuracy provided by a calibration laboratory; drift, which accounts for gradual changes in its performance over time due to aging or environmental influences; and interpolation, which arises when calibration data are only available at certain discrete frequencies, forcing engineers to estimate intermediate values between these points. Beyond the reference standard, the calibration process also relies heavily on measurement means such as bolometer bridges and voltmeters. The method works by first applying a known standard power to the bolometric reference device and then substituting the same power into the unknown power meter under test. Throughout this procedure, multiple factors contribute to uncertainty: the balance resistance and bridge calibration factor determine the accuracy of the power ratio being measured, while bridge zero offsets and voltmeter calibration and drift introduce additional errors in the electrical readings. Importantly, the determination of the unknown power is not made through a single direct measurement; instead, it is an indirect measurement derived from several intermediate steps, each of which carries its own uncertainty that must be identified, quantified, and combined to produce a reliable calibration result.

Some further examples of uncertainty contributions in this application include for the calibration of power meters, several additional elementary terms contributing significantly to the overall measurement uncertainty, and each of them requiring careful consideration to ensure reliable results. One major factor is mismatches, which occur due to imperfect impedance matching in the microwave path and lead to unwanted reflections that alter the measured signal. These mismatches can originate from different components, such as couplers or tees, where directivity errors prevent the complete separation of incident and reflected waves; from signal generators, which may have a non-ideal internal reflection factor; or from mounts and adapters, which introduce their own reflection factors depending on their quality and design. Beyond mismatches, instabilities also represent a source of uncertainty, as fluctuations in the generator's output power or changes in the sensitivity of the detector can vary over time, even under supposedly stable operating conditions. Temperature effects further complicate the process, since variations in ambient or device temperature can affect the electrical and mechanical characteristics of both the reference standard and the power meter under test, leading to drift or non-linear responses. Finally, connector repeatability is another subtle but important contribution, because every time a coaxial connector is disconnected and reconnected, small differences in physical alignment and contact resistance can alter the measured values, introducing additional variability. Together, these factors highlight the complexity of real-world calibration processes, where even seemingly minor influences can accumulate into measurable and significant uncertainty.

The fundamental principle behind calibration remains the direct comparison of an unknown device against a known standard. In the case of power meters, the unknown device is compared to a bolometric reference, which has a traceable calibration to national or international standards. By systematically analyzing all possible sources of error and uncertainty, and combining them according to established rules, one can provide a reliable statement about the range in which the true measurement value lies. This process ensures that measurements are both accurate and traceable, enabling confidence in scientific, industrial, and commercial applications. The total uncertainty expressed at 1σ, is found thanks to this equation: $u_c = (A^2+BR^2+BL^2)^{1/2}$.

## 3. EXAMPLE OF AN OPTOELECTRONIC SYSTEM

In reference [5] we report on a compact optoelectronic oscillator (OEO) prototype delivering a 10.52 GHz microwave signal at +5 dBm, with particular focus on its phase-noise characteristics and rigorous uncertainty assessment following the GUM (Guide to the Expression of Uncertainty in Measurement) recommended by the International Bureau of Weights and Measures (BIPM) and the JCGM, following modern method for estimating uncertainties [12]. The experimental setup employs an optical delay‑line [13] OEO architecture that is fully desk-sized with potential integration in ~1-L volume, and phase noise measurements are performed using a photonic delay line as a frequency discriminator combined with cross-correlation to suppress instrument background noise. The system achieves a low instrument noise floor (down to −170 dBc/Hz at 10 kHz offset from the carrier) and a measured phase noise for the DUT that is high-quality across the offset spectrum. We carefully decompose the uncertainty into Type A (statistical contributions like repeatability, standard deviations over repeated measurements) and Type B (systematic effects such as calibration, environmental stability, component specifications), evaluating each component's influence. We compute the combined standard uncertainty and report a ±1.44 dB total expanded uncertainty, which is of approximately ±2 dB at the 2σ (95 %) confidence level for the phase-noise measurements. This level of uncertainty aligns very favorably with state-of-the-art OEO measurement systems. The work thus demonstrates not only a compact, effective OEO emitting at X-band frequencies, but also a solid application of modern uncertainty estimation based on the GUM recommendation, showing metrological validity: each uncertainty source is listed, quantified, combined, and reported transparently—ensuring the reported phase-noise figures are traceable and meaningful. Overall, the article showcases both engineering (miniaturized OEO with good power and spectral purity) and metrology rigor (uncertainty accounting to GUM standards), making it an excellent example of applying GUM-based uncertainty evaluation in microwave photonics measurement systems. The OEO setup is given in Fig. 1. Before the measurement, we calibrated the system with a commercial frequency synthesizer. The setup of this measurement is given on Figure 2. The bench developed at the laboratory is compared to a commercial one, and its performances are given in Table 2.

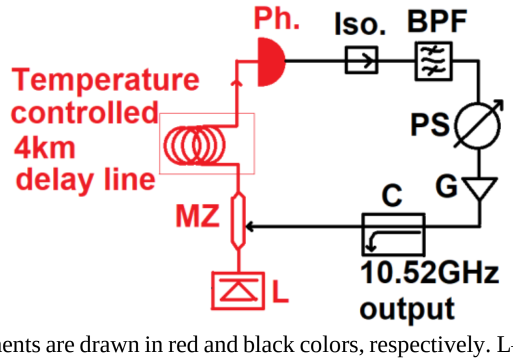



**Fig. 1.** OEO: Optical and electrical elements are drawn in red and black colors, respectively. L—laser; MZ—Mach Zehnder modulator; Ph—photodetector; Iso—isolator; BPF—band pass filter; PS—phase shifter; G—microwave low noise amplifier; C—coupler.


(a) (b)

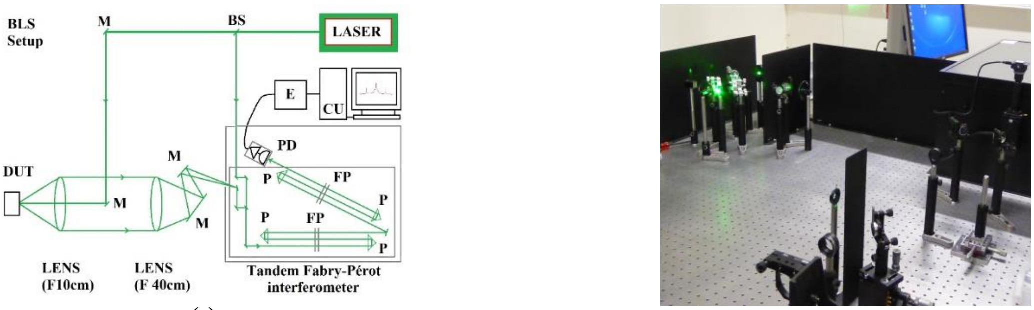
**Fig. 2.** (a) Photo of the phase noise measurement bench developed at the laboratory while measuring the phase noise of a synthesizer under test. (b) Schematic view of phase noise measurement bench system using a double optical delay line. Optical elements and electrical elements are respectively drawn in red and black colors. DUT—device under test; MZ—Mach–Zehnder modulator; DL—delay line; Ph—photodetector; M—mixer; DC—DC amplifier; RF—microwave amplifier; Att.—attenuator; C—directive coupler; PS—phase shifter; FFT—fast Fourier transform analyser.

**Table 2**. Phase noise of a 5 dBm 10.52 GHz OEO, measured by our Instrument and a commercial Rohde and Schwarz (R&S) bench.

| Offset to the 10.52 GHz Carrier Fourier Frequency (Hz) | Measure with R&S Bench Phase Noise (dBc/Hz) | Measure with Our Bench Phase Noise (dBc/Hz) |
|---|---|---|
| $2 \times 10^3$ | −100 | −100 |
| $4 \times 10^3$ | −109 | −112 |
| $6 \times 10^3$ | −115 | −118 |
| $10^4$ | −119 | −130 |
| $2 \times 10^4$ | −125 | −140 |
| $3 \times 10^4$ | −125 | −145 |
| $4 \times 10^4$ | −123 | −141 |

## 4. EXAMPLE OF BRILLOUIN FREQUENCY SHIFT MEASUREMENTS

Uncertainty budget of a Brillouin scattering bench is investigated. The principle is to reveal acoustic frequencies in the microwave frequency domain [14-16]. The challenge is to characterize metamaterials in the future. We proceed by analyzing the refracted light emitted by a material. The Fabry–Pérot Tandem interferometer produces peaks shifted from the laser frequency to characteristic frequencies depending on the material. We use a 532 nm CW class 4 laser: its power is more than 500 mW. The setup and a picture is given in Figure 3.




(a) (b)

**Fig. 3.** (a): Typical setup for BLS. BLS: Brillouin Light Scattering. DUT: device under test. M: mirror. FP: Fabry-Pérot. P: prism. PD: photodetector. E: electronics. CU: computer unit. (b): Commercial Tandem Fabry-Pérot interferometer is inside the box on the right side of this picture.

It is necessary to calibrate accurately the instrument. It is sensitive to mechanical vibrations, temperature and hygrometry. Alignment process requires an alignment of the two cavities. Each of the two cavities consists in a pair of parallel mirrors. Tandem interferometer produces two series of absorption peaks with respect to a flat noisy intensity level. We then obtain a curve providing the number of absorbed photons versus frequency. We have measured the Brillouin frequency $\nu_B$ for PMMA as an example of an isotropic material. The measured Brillouin frequency shift is $\nu_B$ = 15.70 GHz (longitudinal acoustic mode), with a Brillouin linewidth of 324 MHz. Estimating the uncertainty requires the knowledge of the contribution of the different fixed parameters, such as the optical index, the wavelength, the diffusion angle, the density of the material, and the longitudinal and shear modulus, but especially fluctuation of the source, mechanical stability of the setup, and environmental parameters in the room. The Brillouin spectroscopy is a non-intrusive measurement method for bulk materials and thin films. A scanning 6-pass TFPI has been described for BLS measurement. Following the GUM, and with reference [6], we have made detailed analysis and estimation of the uncertainties in the Brillouin frequency shift measurement, which is related to the speed of propagation of phononic waves in bulk materials.

## 4. CONCLUSION

Following the BIPM recommendations, this work demonstrates that it is possible to systematically prepare an uncertainty budget, which is illustrated here through its determination for both an optoelectronic oscillator (OEO) and a BLS bench, and the study clearly shows that, in order to properly estimate measurement uncertainties, it is essential to combine strong expertise in instrumentation and metrology with a rigorous, transversal, and multidisciplinary vision that accepts the need for risk-taking in a field that is still too little exploited across different subjects, while also ensuring the legitimacy to analyse and validate the level of confidence in the results of diverse types of measurements.

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