Estimation of uncertainty on carrier frequency precision in optics and optoelectronic systems

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ABSTRACT

We remind the general method for the estimation of the measurement uncertainty related to opto-electronic and photonic systems. It follows the modern method, as it is recommended in the Guide to the Expression of Uncertainty in Measurement. We review the elementary uncertainty terms separated into two distinct types, « A » related to statistic distribution and « B » for other elementary uncertainty terms such as those linked to international standards, calibration certificates or manufacturer data, as well as elementary terms related to the variations in environmental parameters such as temperature, acceleration, or hygrometry, or those linked to quantities studied such as the wavelength of lasers or to the misalignment of the beam in space. We illustrate this method with two examples, an optoelectronic oscillator and a Brillouin Light Scattering measurement system.

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

1. INTRODUCTION

The general idea of this proceedings paper is to show how the modern method for estimating uncertainties in power and frequency measurements can be successfully applied from the radiofrequency domain to the optical domain.

To begin, we recall the main recommendations and standards that apply to this type of work, reminding the general method for the estimation of the measurement uncertainty related to opto-electronic and photonic systems. We follow the modern method, as it is recommended in the Guide to the Expression of Uncertainty in Measurement [1 – 3] of *Bureau des Poids et Mesures* (BIPM). It mainly consists in separating the possible cause of errors into two categories of elementary uncertainty terms. They are listed in two distinct types. The first category is called « A », related to statistic distribution. Th second one is called « B », and regroup other elementary uncertainty terms such as those linked to international standards, calibration certificates or manufacturer data, as well as elementary terms related to the variations in environmental parameters such as temperature, acceleration, or hygrometry, or those linked to quantities studied such as the wavelength of lasers or to the misalignment of the beam in space. We illustrate this method with two examples, an optoelectronic oscillator [4] and a Brillouin Light Scattering measurement system [5].

2. RECOMMENDATIONS AND STANDARDS

Measurement uncertainty corresponds to the estimate characterizing the range of values within which the true value of a measured quantity lies. This theme is still a hot topic as we can see in reference [6] and [7].

Measurement uncertainty generally includes several components. Some can be estimated based on the statistical distribution of the results of a series of measurements and can be characterized by an experimental standard deviation. The estimation of other components can only be based on experience or other information.

We can for instance refer to a typical list of elementary uncertainty terms in three sub categories as follow:

- Standard (calibration certificate, drift, interpolation between known values)
- Measurement means (linearity, resolution, stability…)
- Various contribution (Mismatch, Temperature, Instability, Repeatably of connectors, harmonics, etc.)

We assume that the category of elementary terms of Type A (statistics) can be typically estimated as $A=(\text{Sum of } A_i^2)^{1/2}$.

For elementary terms of Type B (evaluated by other means), they can be appreciated with two sub-categories respectively called BR (related to standards) and BL (other), which are an arithmetic sum of BL_i.

To illustrate this kind of list, we can take an example, in the domain of the calibration of power meters. In this case, the contribution of the Reference standards can be:

- Calibration
- Drift
- Interpolation

Main means of measurements are bolometers bridges, i. e. voltmeters: the power is substituted in the standard, then the power is substituted in the unknown device (balance resistance, bridge calibration factor, bridge zero, voltmeter calibration and drift), it is possible top estimate the ratio of the powers detected on the side arm, and the associated value which depends on an indirect measurement.

Elementary terms come as follow:

- Mismatches: Couplers/Tees (Directivity), Generator (Internal Reflection Factor), Mounts (Reflection Factor)
- Instabilities
- Temperature Effects
- Connector Repeatability

The basic principle of calibration is the direct comparison of the unknown power meter to a known bolometric device. It is detailed in a report [8]. In this report, we see that the main contribution is due to the standards and not to the bench itself, although the possible mismatches are not negligible.

The total uncertainty expressed at 1 σ, is found thanks to this equation: $u_c = (A^2+BR^2+BL^2)^{1/2}$

3. OPTOELECTRONIC OSCILLATORS

In this section, we will refer to recent work concerning the estimation of the uncertainty on the phase noise of the signal delivered by an optoelectronic oscillator (OEO) with optical delay lines [9] or based on a Whispering Gallery Mode optical resonator [4, 10]. We follow the modern method [11] as previously done [12-14]. The OEO diagram is given in Figure 1.

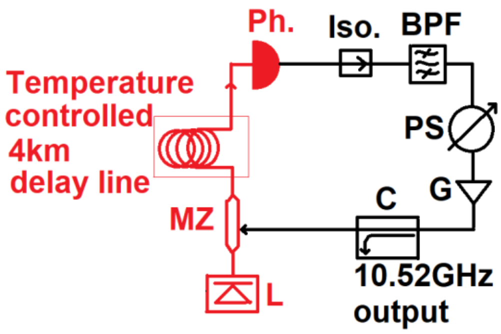
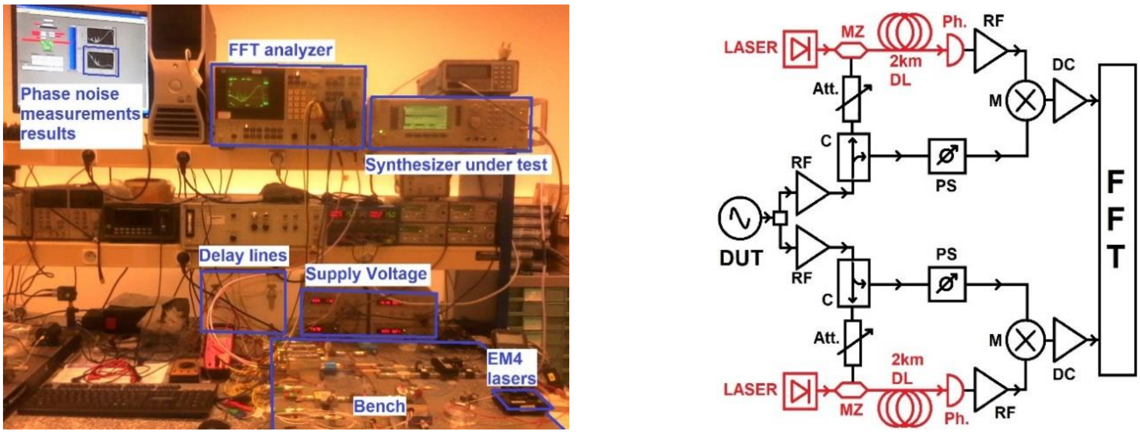


Fig. 1. OEO: Optical and electrical elements are drawn in red and black colors, respectively. L—laser; MZ—Mach Zehnder modulator; Ph—photodetector; Iso—isolator; BPF—band pass filter; PS—phase shifter; G—microwave low noise amplifier; C—coupler.

Concretely, the spectral density of phase noise is considered as a function of the offset to the microwave carrier of the output signal of the OEO. The OEO is here based on a WGM optical resonator [9]. We can also measure an OEO with an optical delay line (DL). Phase noise is better than -145 dBc/Hz at a $3x10^4$Hz Fourier frequency for a 10.5 GHz OEO [4]. The main goal is to demonstrate the feasibility of a compact oscillator. It means a volume less than 1 litter. Performances are expected to be compatible with aeronautics. Feasibility is demonstrated on table with those performances:

– Global uncertainty ±1.44 dB at 2σ [4].
– OEO at 10.52 GHz based on a 4 km delay line, using the bench previously presented.
– Spectral density of phase noise -145 dBc/Hz at 3x104 Hz from the carrier.

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 1.



(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 1. Phase noise of an OEO with an output power of 5 dBm at 10.52 GHz, measured by our Instrument and by the 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)
2×10^3	−100	−100
4×10^3	−109	−112
6×10^3	−115	−118
10^4	−119	−130
2×10^4	−125	−140
3×10^4	−125	−145
4×10^4	−123	−141

Noise Floor is determined with 500 Averages with an Anritsu Synthesizer at the Input of Our Bench £(f) in dBc/Hz versus Offset to the 10 GHz Carrier Fourier Frequency (Hz) decreases from -90 at 10 Hz to -170 at 10 kHZ and few 10^5 Hz [4]. We followed a modern approach to express uncertainty in measurement as we write in the introduction. We are getting to the significant part about uncertainties.

Uncertainty at a 1 σ interval of confidence is calculated as follows:

$$u_c = \sqrt{(A^2 + BR^2 + BL^2)} \qquad \text{(ii)}$$

According to Equation (i), it can then be considered that the whole statistical contribution is better than 0.69 dB. We deduce from (ii) that the uncertainty at 1 sigma, noted as u_c, is better than $\sqrt{(0.692 + 0.202)}$ dB. Its leads to a global uncertainty of ±0.72 dB at one σ.

We choose to keep U = ±1.44 dB at 2 σ for a common use of the phase noise optoelectronic instrument. This final uncertainty is defined at 2 σ, according to the empirical rule 68.27% at 1 σ is not enough, but 95.45% at 2 σ is more efficient for a normal distribution in statistics.

4. BRILLOUIN LIGHT SCATTERING

Uncertainty budget of a Brillouin scattering bench is investigated. The principle is to reveal acoustic frequencies in the microwave frequency domain [16-17]. 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.

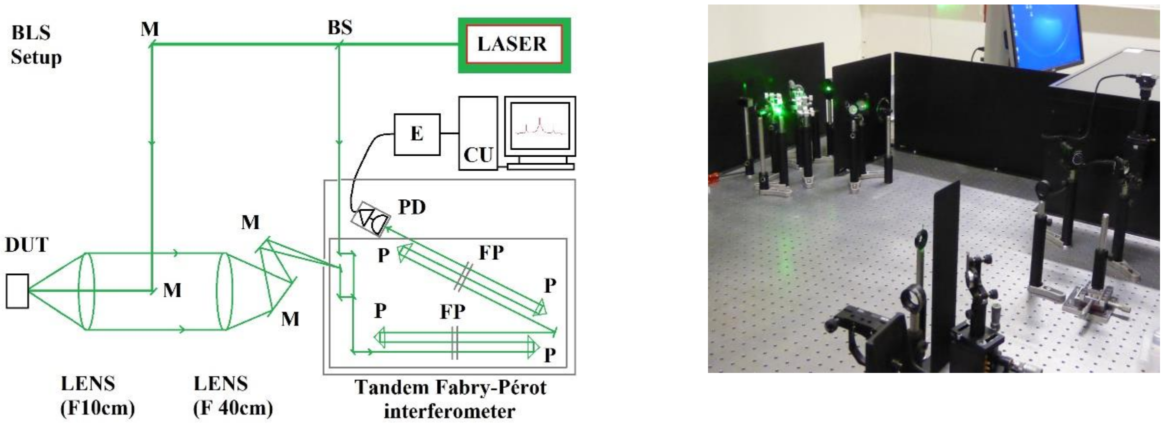


Fig. 3. (a): Typical setup for BLS. BLS: Brillouin Light Scattering. DUT: device under test. M: mirror. FP: Fabry-Pérot. P: prism. PD: photodetector. E: electronics. CU: computer unit. (b): Commercial Tandem Fabry-Pérot interferometer is inside the box on the right side of this picture.

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 ν_B for PMMA as an example of an isotropic material. The measured Brillouin frequency shift is ν_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 [5], 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 BIPM recommendations, we show that it is possible to systematically prepare an uncertainty budget. In this paper it is illustrated by determining them for an OEO and for a BLS bench.

We clearly see that, for estimation of measurement uncertainties, it is necessary to have:

- Expertise in instrumentation / metrology
- Rigorous, transversal and multidisciplinary vision, risk-taking in a too few-exploited field on different subjects.
- Legitimacy to analyze confidence in the results of measurements of different types.

AUTHOR CONTRIBUTIONS

All aspects of research in this article, including concept, measurements, and redaction, P.S.; presentation of the corresponding poster to the conference, A. A.

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