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XL-80 and XC-80 error budget and uncertainty calculations

Introduction

This document summarises the system linear measurement uncertainty calculations for a Renishaw XL-80 laser interferometer when used with a Renishaw XC-80 environmental compensator. These calculations are used to derive the published specification of 0.50 ppm.

General information on the methodology used

The derivation of error budgets is a standard part of Renishaw's new product development process which is covered by the group's ISO 9001:2015 compliant quality management system. ISO 9001:2015 is the internationally recognised standard for quality management systems and is verified at Renishaw by BSI management systems (UKAS accredited).

Error budgets are calculated following the guidance as outlined in EA-4/02 'Expression of the Uncertainty of Measurement in Calibration' and NIST technical note 1297. The contributory elements to the budget are derived from a combination of the validation of component specifications, experimental evidence of performance and derivation from theoretical calculations. The combination of these individual terms results in the system level specification. All specifications are published with 95% (k=2) confidence level.

The error budgets are reviewed and signed off by qualified personnel. The sections below show the overall budget for the interferometer system followed by the detailed error budgets for the refractive index (environmental compensation) and laser frequency.

Uncertainty in the XL-80 linear interferometer measuring system

The following table shows the calculated uncertainty for a XL-80 system operating at 0°C, 1150 mbar and 50% relative humidity. This condition represents the worst case situation.

Source of uncertainty	Uncertainty value	Probability distribution	Uncertainty ± ppm
Refractive index (XC-80 compensator)	±0.49 ppm	Normal (k=2)	0.25
Laser frequency	±0.49 ppm	Normal (k=2)	0.03
Combined uncertainty (k=1)			**0.25**
Expanded uncertainty (k=2)			**0.50**
Published specification (k=2)			**0.50**

Uncertainty in the XC-80 environmental compensator

The following table shows the uncertainty in refractive index measured by an XC-80 environmental compensator operating at 0 °C, 1150 mbar and 50% relative humidity. This condition represents the worst case situation.

Source of uncertainty	Uncertainty value	Probability distribution	Uncertainty ± ppm
Air pressure sensor	± 1 mbar	Normal (k=2)	0.144
Air temperature	± 0.2 °C	Normal (k=2)	0.122
Relative humidity	± 6% RH	Normal (k=2)	0.007
Edlen equation	± 0.06 ppm	Normal (k=2)	0.030
Measurement environment inhomogeneity	± 0.30 ppm	Normal (k=2)	0.150
Combined uncertainty (k=1)			**0.243**
Expanded uncertainty (k=2)			**0.486**
Published specification (k=2)			**0.49**

Uncertainty in the frequency of the XL-80 laser

Source of uncertainty	Uncertainty value	Probability distribution	Uncertainty ± MHz
Mid frequency acceptance criterion	± 10.00 MHz	Rectangular	5.77
Frequency measurement	± 5.86 MHz	Normal (k=2)	2.93
Counter error	± 0.02 MHz	Normal (k=1)	0.02
Switch on repeatability	± 1.26 MHz	Normal (k=2)	0.63
Environmental frequency drift	± 3.00 MHz	Normal (k=1)	3.00
Drift (3 years)	± 12.70 MHz	Normal (k=2)	6.35
Multiple pre-heats	± 5.90 MHz	Normal (k=2)	2.95
Stability	± 4.65 MHz	Normal (k=2)	2.30
Combined uncertainty (k=1)			**10.27**
Expanded uncertainty (k=2)			**20.55**
Published specification (k=2)			**23.68 (0.05 ppm)**

- The nominal vacuum wavelength of the XL-80 laser is 632.9905770 nm (473,612,829.2 MHz) or 632.990000 nm (473,613,260.9 MHz). See the label on the underside of the XL-80 laser for its relevant wavelength.

General notes for all tables

- The first column lists the sources of the uncertainty errors considered.
- The second column gives the uncertainty value for the source of uncertainty in the appropriate units.
- The third column gives the probability distribution function for the source of the errors and the coverage factor used. This coverage factor is used to convert uncertainty values to k=1. An additional multiplier is applied to account for the size of the sample data.
- The fourth column lists the uncertainties for the appropriate source of uncertainty.
- Individual values are combined using a 'root sum square' calculation to produce the total combined uncertainty.
- These uncertainty calculations assume the measurement environment inhomogenetity is less than 0.3 °C per minute.
- Specified measurement uncertainties do not make allowance for errors in the alignment and set up of measuring optics or in the implementation of the measuring procedure, both of which can affect the accuracy of a practical measurement. Details of these factors are detailed in the system manuals.

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Part no.: H-9908-0481-02-A