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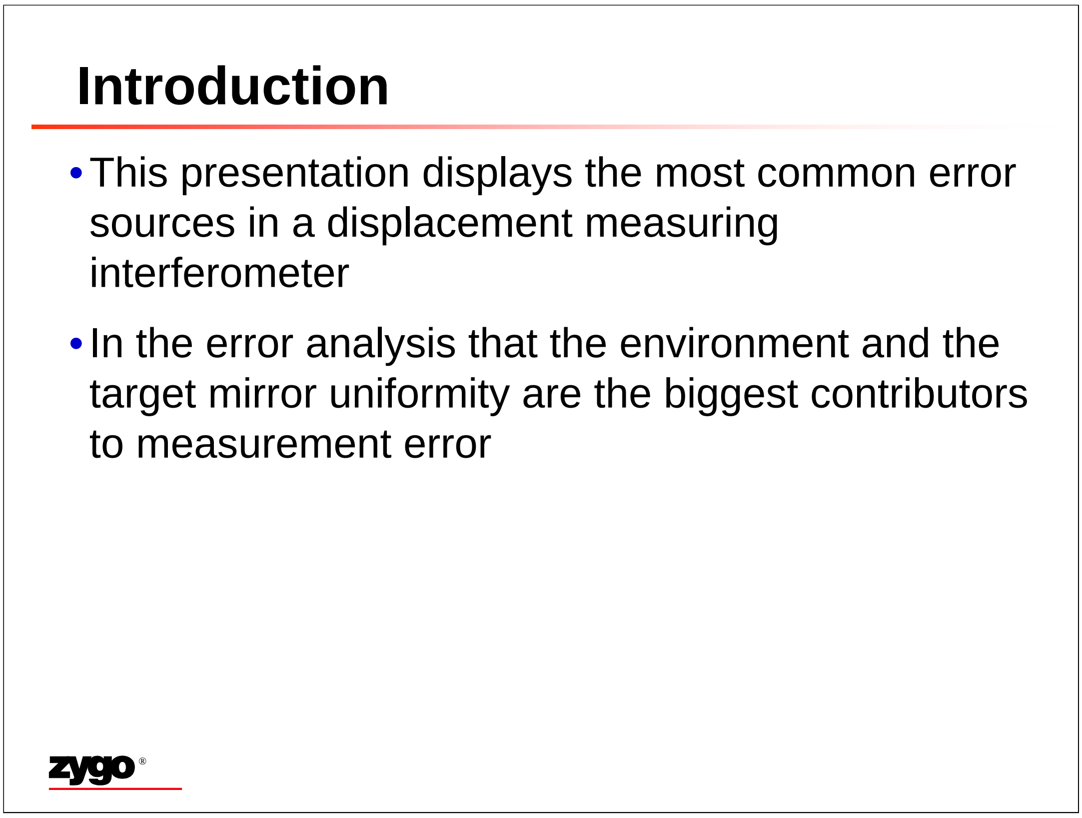
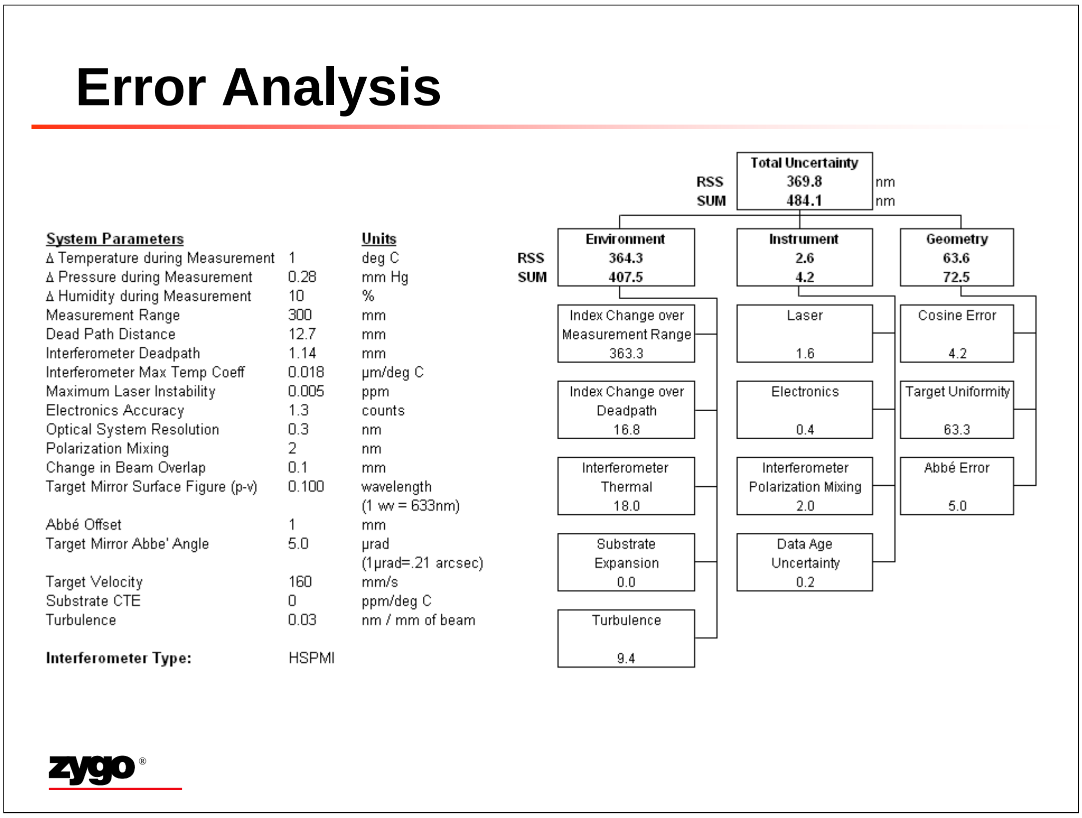
Error Sources



Introduction

- This presentation displays the most common error sources in a displacement measuring interferometer
- In the error analysis that the environment and the target mirror uniformity are the biggest contributors to measurement error

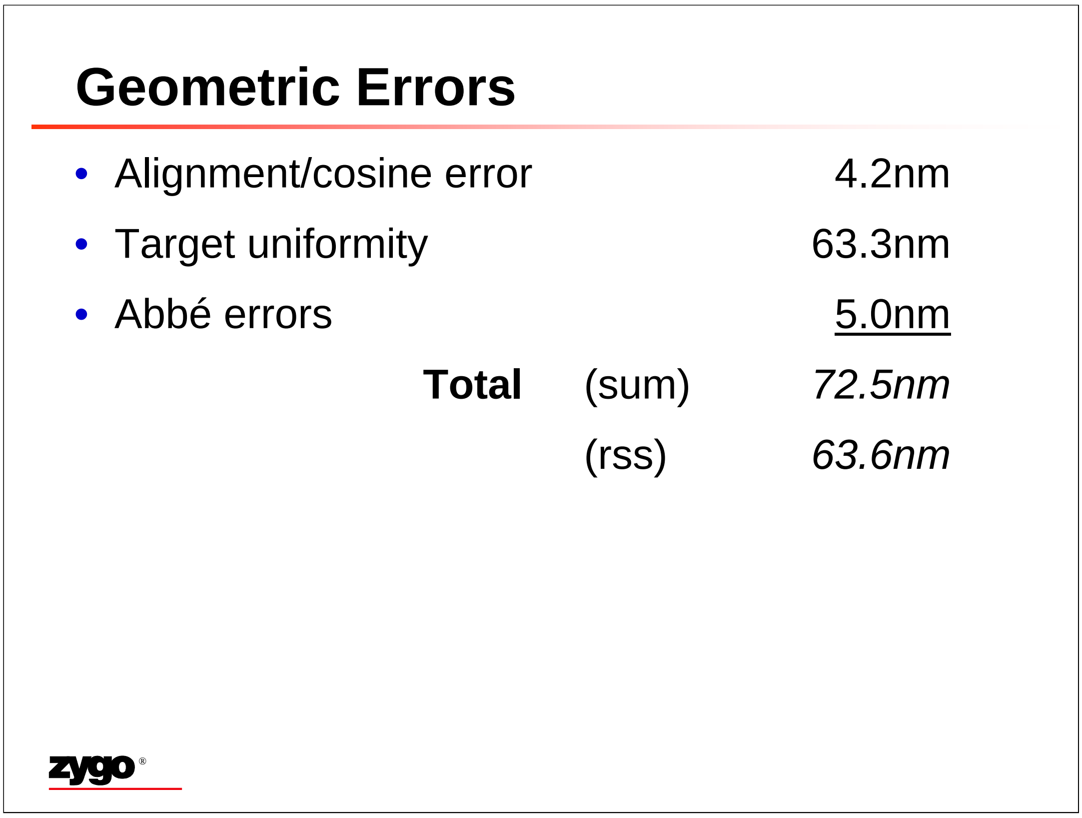


Error Analysis

System Parameters		Units
Δ Temperature during Measurement	1	deg C
Δ Pressure during Measurement	0.28	mm Hg
Δ Humidity during Measurement	10	%
Measurement Range	300	mm
Dead Path Distance	12.7	mm
Interferometer Deadpath	1.14	mm
Interferometer Max Temp Coeff	0.018	µm/deg C
Maximum Laser Instability	0.005	ppm
Electronics Accuracy	1.3	counts
Optical System Resolution	0.3	nm
Polarization Mixing	2	nm
Change in Beam Overlap	0.1	mm
Target Mirror Surface Figure (p-v)	0.100	wavelength (1 wv = 633nm)
Abbé Offset	1	mm
Target Mirror Abbe' Angle	5.0	µrad (1µrad=.21 arcsec)
Target Velocity	160	mm/s
Substrate CTE	0	ppm/deg C
Turbulence	0.03	nm / mm of beam
Interferometer Type:	HSPMI	

This sample error analysis assumes the following system specifications. The resolution of the DMI system is 0.31nm but the total system accuracy can exceed 300nm due to other error contributors. The most significant error contributors are the responsibility of the user (U) with the two largest being the environment and the quality of the target optic. The error sources that are the responsibility of the DMI manufacturer (M) include the laser frequency stability, interferometer polarization mixing and electronics linearity.

U	Temperature variation	1.0°C
U	Pressure variation	0.25 mm Hg
U	Humidity variation	10%
U	Range of motion	60 mm
U	Deadpath distance	12.7 mm
M	Interferometer deadpath	10.96 mm
M	Thermal coefficient	0.01 µm/°C
M	Laser stability	0.01 ppm
M	Electronics accuracy	1.3 counts (1.61 nm)
M	Polarization mixing	2 nm
U	Target mirror angle	5 µrad
U	Abbé offset	1 mm
U	Target mirror flatness	λ/10 P-V (63.3 nm)



Geometric Errors

• Alignment/cosine error		4.2nm
• Target uniformity		63.3nm
• Abbé errors		5.0nm
Total	(sum)	*72.5nm*
	(rss)	*63.6nm*

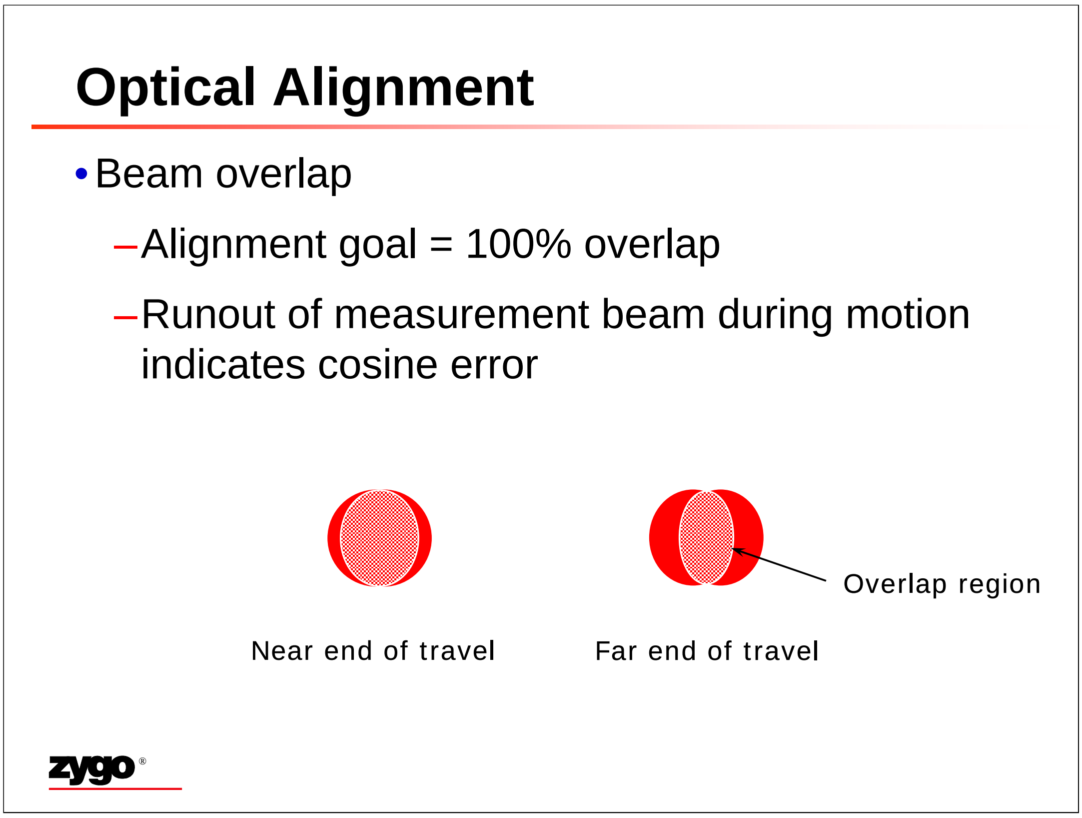
Geometric errors can be minimized by following a stringent set-up and system alignment procedure and using an optically flat target mirror or compensating for a distorted target through a software look-up table.

Cosine error results from an angular misalignment between the measurement axis and the axis of motion.

Target uniformity represents the error caused by uncompensated surface figure variation in the target mirror.

Abbé error results from an offset between the plane of the measurement axis and the axis of motion of the part under test.

Typically, target mirror non-uniformity is the largest geometrical error source.



Optical Alignment

- Beam overlap
  - Alignment goal = 100% overlap
  - Runout of measurement beam during motion indicates cosine error

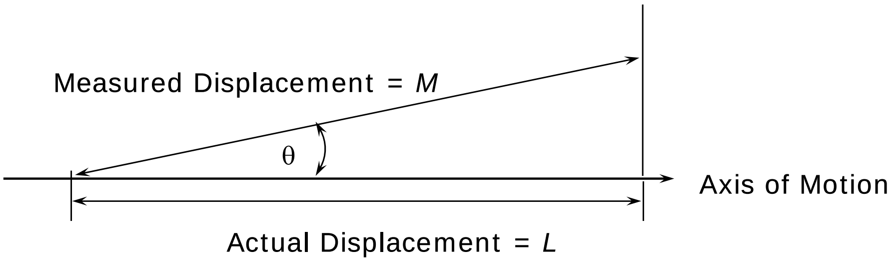
In a single axis system the beam overlap can be minimal and still yield a sufficient measurement signal (minimum overlap is approximately 50%). As the number of axes increase and the efficiency of the interferometers decrease, the overlap must be near 100%.

Misalignment of the measurement beam to the axis of motion can be visualized by observing the return beam of the measurement beam with respect to the reference beam. As the stage is moved, the reference signal will remain fixed and any angular error (cosine error) of the measurement beam shows up as runout in the beam overlap.

For example; Observing a 1 mm runout over a 1 m motion yields a 0.5 mrad alignment error.

$$a = \text{beam runout} / (2 \cdot \text{range of motion})$$

Cosine Error



$$M = L\cos\theta$$

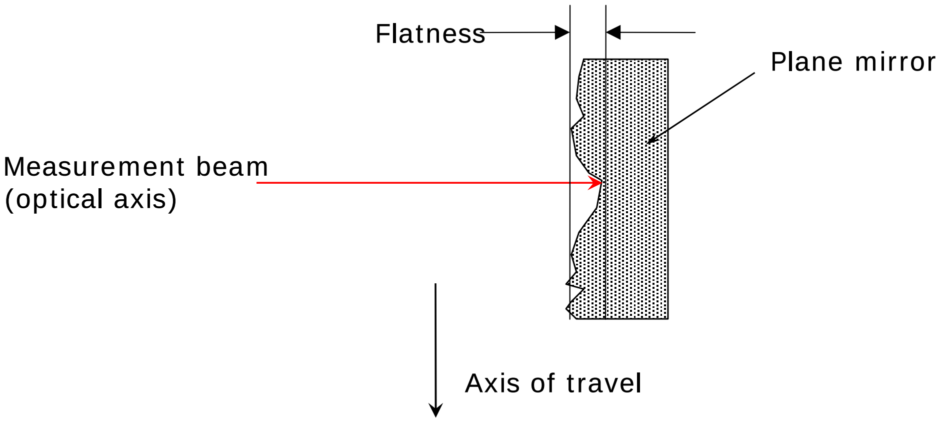
$$\text{Cosine error} = L(\cos\theta - 1)$$

A cosine error results from an angular misalignment between the measurement laser beam and the axis of motion. For optimum alignment of a DMI system the optical path and axis of motion must be parallel. Cosine error is generally negligible until the angle becomes quite large.

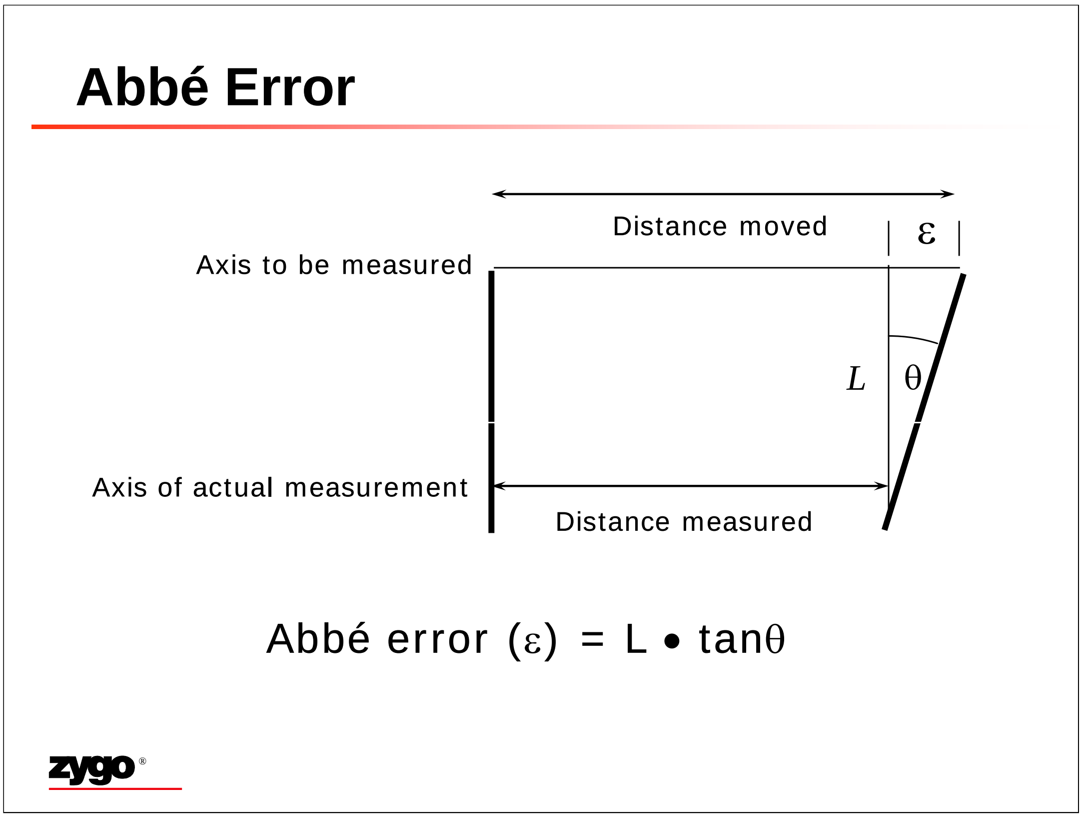
A cosine error will cause the interferometer to measure a displacement shorter than the actual distance traveled.

As cosine error occurs the measurement and reference beams will shear resulting in a loss of signal efficiency.

Target Uniformity



The target mirror must be flat to fractions of a wavelength in applications that require multiple axes of travel. A target mirror with a surface figure of λ/10 can contribute up to 63 nanometers of error as the stage travels along the axis parallel to the clear aperture of the mirror. In a measurement configuration where the beam reflects from the same location on the target mirror this error source will be zero.



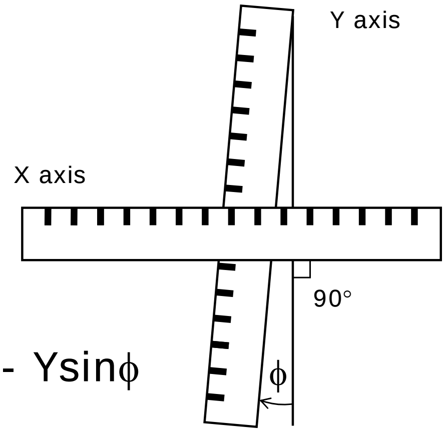
Abbé Error

$$\text{Abbé error } (\varepsilon) = L \bullet \tan\theta$$

When the axis of measurement is offset from the axis of interest, Abbé errors will occur. As first described by Dr. Ernst Abbé of Zeiss:

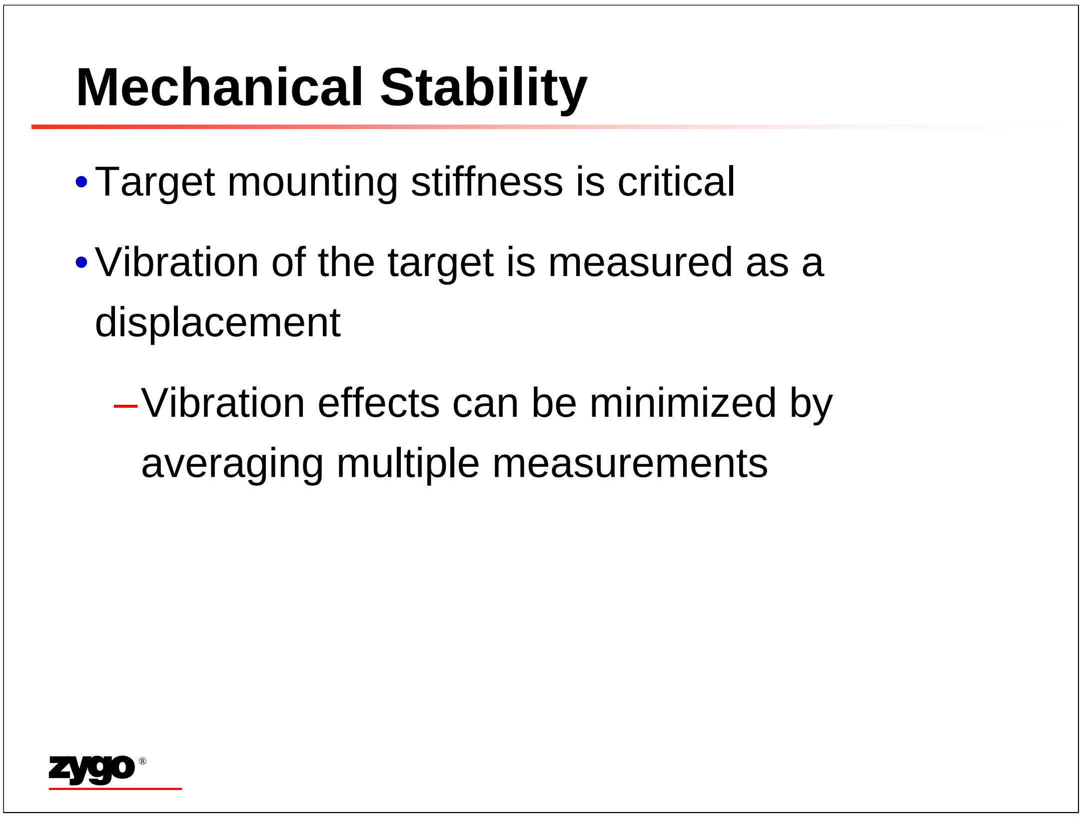
“If errors of parallax are to be avoided, the measuring systems must be placed coaxially to the line in which displacement is to be measured on the workpiece.”

Opposite Axis Error



True X = X - Y$\sin\phi$

Opposite axis errors are often present in mechanical measuring systems. An opposite axis error is caused when perpendicular axes are not truly orthogonal to each other. This error is typically eliminated when a standard DMI system alignment procedure is followed.



Mechanical Stability

- Target mounting stiffness is critical
- Vibration of the target is measured as a displacement
  - Vibration effects can be minimized by averaging multiple measurements

Stiffness of the mechanical assembly is critical. If the physical relationship between the target optic and the point of interest changes during the measurement time, this is indistinguishable from actual motion.

Vibration effects can be minimized by taking several measurements at one position and averaging them together.

Instrumentation Errors

• Laser		1.6nm
• Electronics		0.4nm
• Interferometer		2.0nm
• Data age uncertainty		0.2nm
Total	(sum)	*4.2nm*
	(rss)	*2.6nm*

Instrumentation errors are not under the users control. These errors are based on the suppliers system parameters.

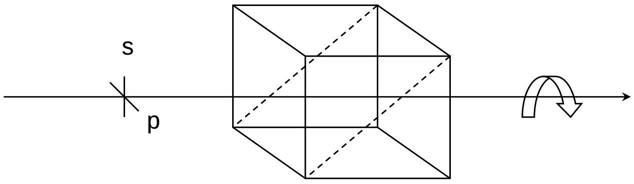
The basis of a DMI is the wavelength of the laser source. Stability circuitry within the laser head is designed to control the output frequency of the laser tube at a fixed value.

The contribution of the electronic uncertainty to the error analysis is a product of the electronic accuracy of the measurement board and the optical resolution of the interferometer.

Polarization mixing errors are caused by imperfections in the optical components and their coatings. This error can be minimized by optimizing the rotation of the interferometer about the optical axis. The magnitude of the polarization mixing error will increase if the optical alignment causes the incident beam not to lie perpendicular to the plane of incidence. Optical components with dielectric coatings are very polarization sensitive and can induce additional errors if not aligned properly.

Polarization Leakage Error

- Polarization leakage causes frequency mixing
- Minimize leakage by maintaining square beam path



Polarization mixing of the laser’s frequency components within the interferometer causes a nonlinear relationship between the measured displacement and the actual displacement. To minimize errors caused by polarization mixing, a perpendicular relationship must be maintained between the two frequency components of the laser head and the orientation of the polarization-sensitive optical components.

The angular rotation of the interferometer about the optical axis should be limited to less than 1 degree to minimize polarization errors.

Data Age Uncertainty

- At fast slew rates, knowledge of data age is critical
  - Fixed component (data age)
  - Variable component (uncertainty)
- Synchronization required to minimize uncertainty between axes

Error = velocity x data age uncertainty

1 m/sec x 10nsec = 10nm error

To accurately control precision motion it is necessary to provide not both position and time data. Data age is defined as the difference in the time between when the object of interest is measured and when the user control system gets the position information. Data age uncertainty is defined as the maximum variation in the data age in a multi-axis system, due primarily to process variation in the electronics.

Having minimum data age and data age uncertainty is critical for multi-axis high velocity applications.

Environmental Errors

Index change (measurement)		363.3nm
Index change (deadpath)		16.8nm
Interferometer thermal		18.0nm
Substrate expansion		0.0nm
Turbulence		9.4nm
Total	(sum)	*407.5nm*
	(rss)	*364.3nm*

Environmental errors are usually the largest contributor to a DMI error budget. Variations in the index of refraction of the air alter the wavelength of the laser source and change the apparent length of the optical path. The index of refraction changes with deviations in the temperature, pressure and humidity. Controlling or monitoring the environment or minimizing the measurement time will reduce environmentally induced errors.

Wavelength of Light

- Measurement beam travels through air
- Changes in the refractive index of the air will change the wavelength of the source

$$\lambda = \frac{\lambda_{vac}}{n_{air}}$$

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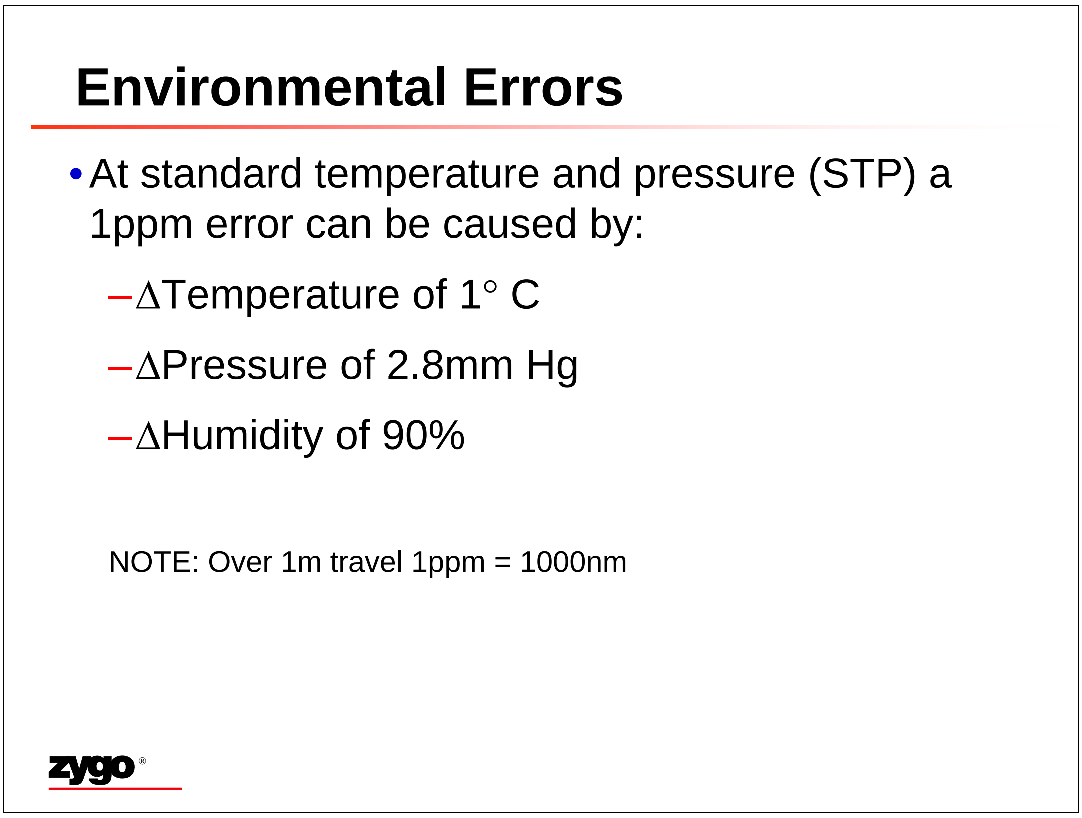
Unless measurements are taken in a vacuum the accuracy of a displacement measurement will be limited by the change in the environmental conditions and the time it takes to complete the measurement. To compensate for changes in the air temperature, pressure and humidity, the vacuum wavelength of the measurement beam, λ_{vac}, is divided by the index of refraction of air, n_{air}.

For nominal conditions (pressure = 760 mm Hg, temperature = 20°C.



Environmental Errors

- At standard temperature and pressure (STP) a 1ppm error can be caused by:
  - ΔTemperature of 1° C
  - ΔPressure of 2.8mm Hg
  - ΔHumidity of 90%

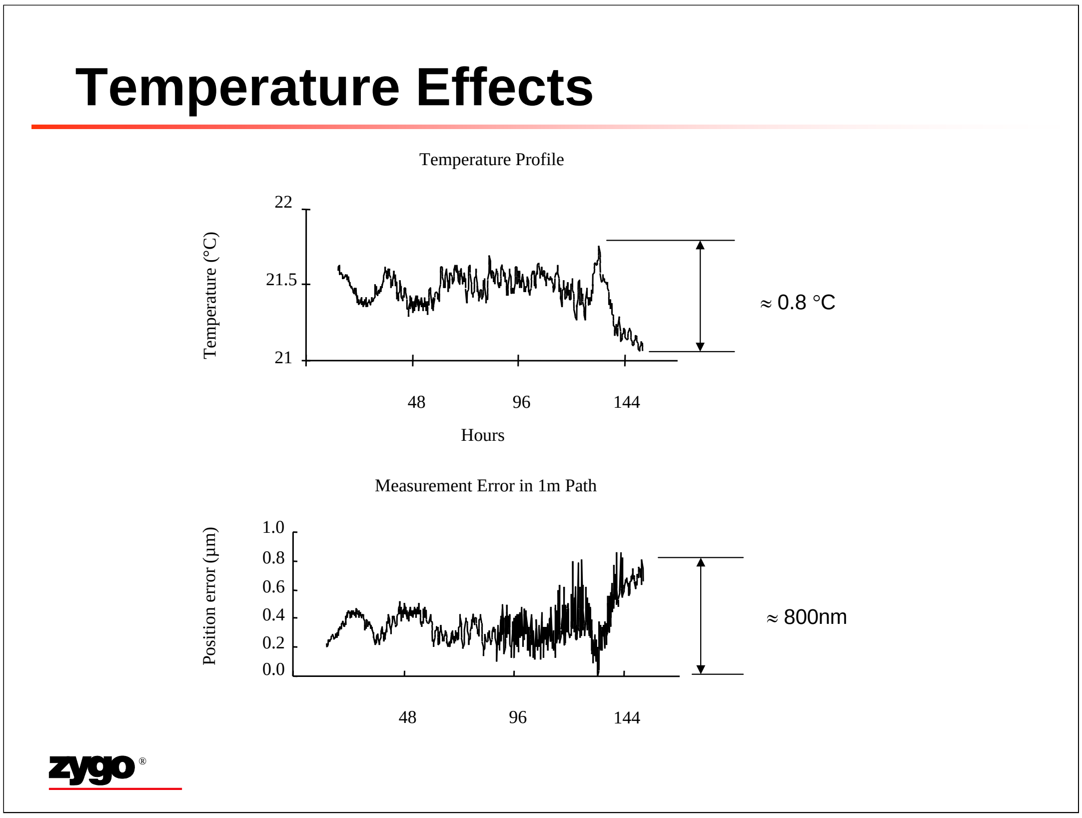
NOTE: Over 1m travel 1ppm = 1000nm

STP = Standard Temperature and Pressure

T = 20°C

P = 760 mm Hg

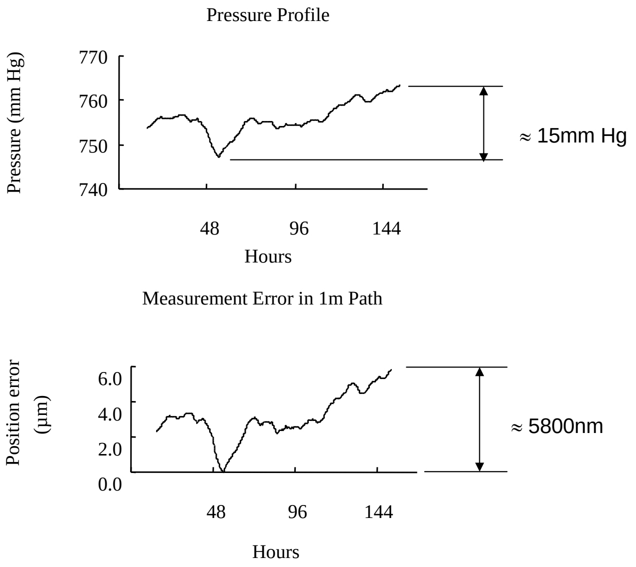
RH = 50%



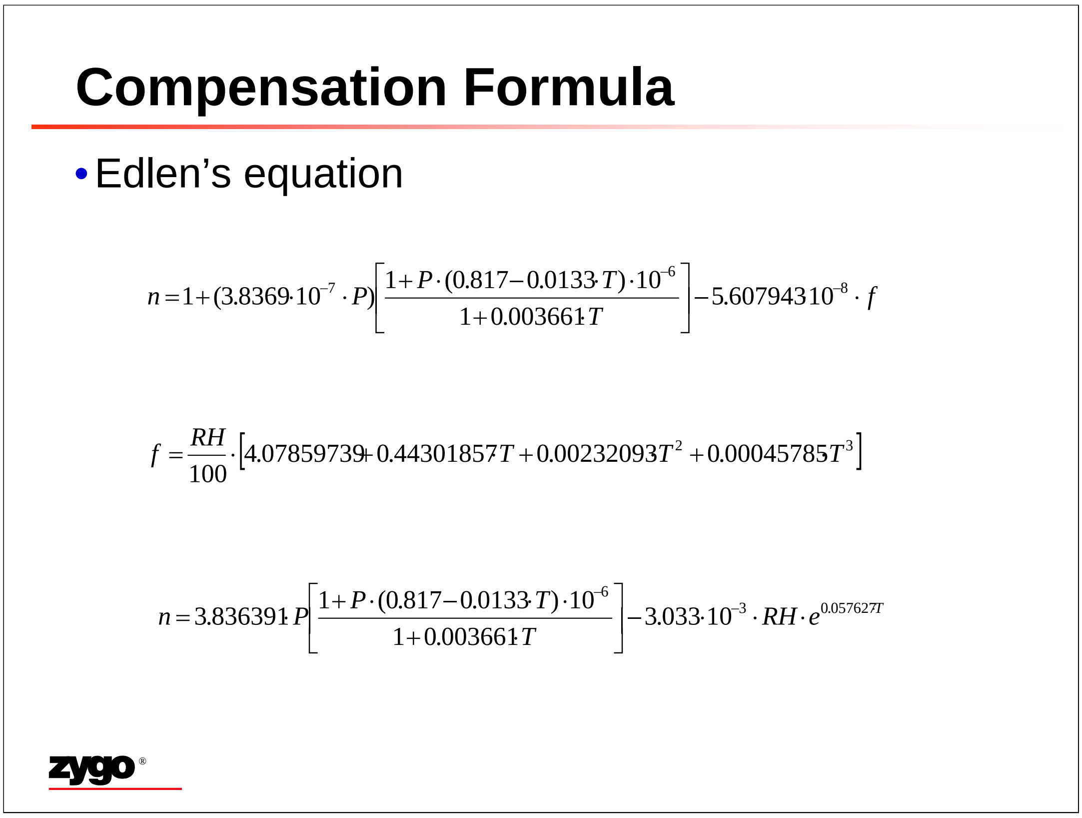
Temperature Effects

In this example the temperature was monitored for a period of six days. Edlèn's equation was used to calculate the error in a test setup with a one meter optical path difference between the measurement and reference beams. The pressure was assumed constant at 760 mm Hg and the relative humidity was taken as 50%.

Pressure Effects



In this example the pressure was monitored for a period of six days. Edlèn's equation was used to calculate the error in a test setup with a one meter optical path difference between the measurement and reference beams. The temperature was assumed constant at 20°C and the relative humidity was taken as 50%.



Compensation Formula

- Edlen’s equation

$$n = 1 + (3.8369 \cdot 10^{-7} \cdot P)\left[\frac{1 + P \cdot (0.817 - 0.0133 \cdot T) \cdot 10^{-6}}{1 + 0.003661 \cdot T}\right] - 5.607943\,10^{-8} \cdot f$$

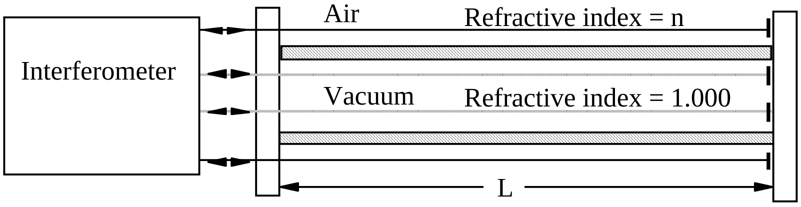
$$f = \frac{RH}{100} \cdot \left[4.07859739 + 0.44301857 \cdot T + 0.00232093 \cdot T^2 + 0.00045785 \cdot T^3\right]$$

$$n = 3.836391 \cdot P\left[\frac{1 + P \cdot (0.817 - 0.0133 \cdot T) \cdot 10^{-6}}{1 + 0.003661 \cdot T}\right] - 3.033 \cdot 10^{-3} \cdot RH \cdot e^{0.057627 \cdot T}$$

Changes in the environment over the time of measurement are typically the largest error source in a DMI metrology system. Controlling the climate, monitoring the pressure, temperature and humidity changes and/or reducing the measurement time will minimize these errors.

Edlèn published the first paper detailing wavelength compensation calculations. Shown above is Edlèn's formula with a power series expansion for the water vapor pressure term and an alternate formulation using an exponential fit. Other versions of Edlèn's formula exist. For more precise work, it is possible to incorporate molecular concentrations of the air, such as the partial pressure of CO_2, into the calculation.

Refractometry



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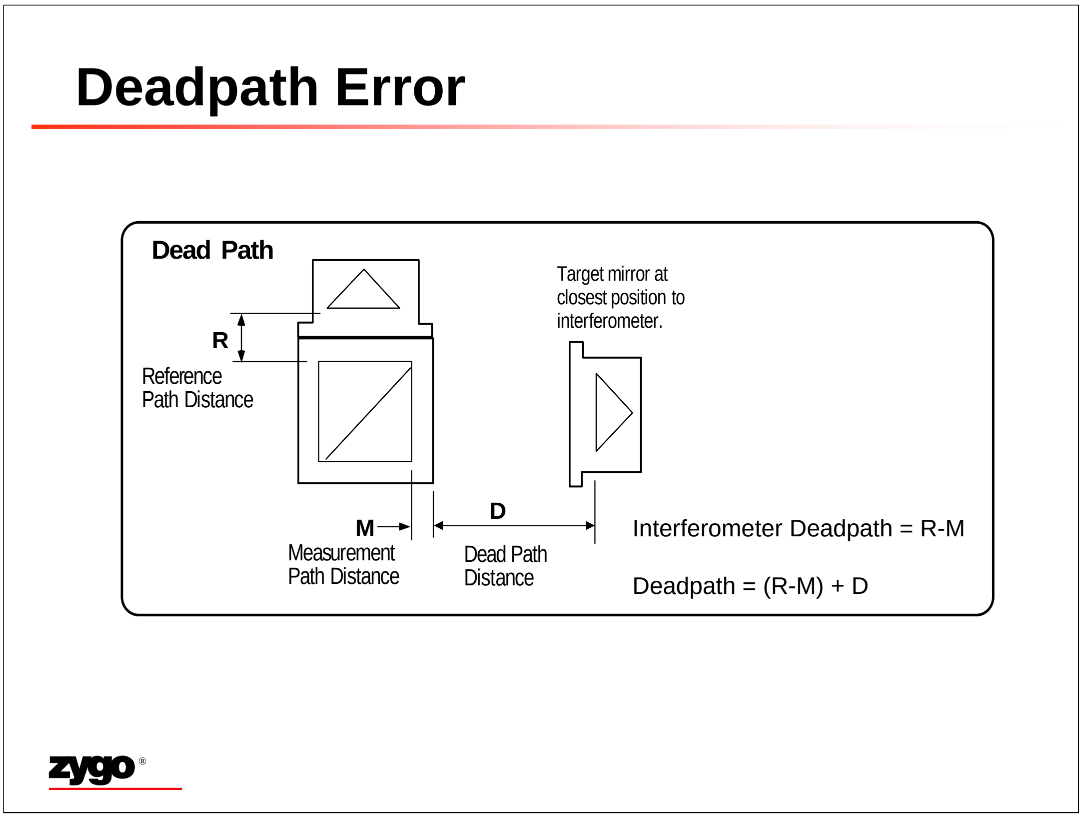
An optical wavelength compensator (refractometer) measures the change in the refractive index of air. Since it measures relative change, it is important to know the index of refraction at the start of the measurement. This may be accomplished using Edlèn's equations and taking initial measurements of the temperature, pressure and humidity.

In a refractometer the measurement and reference beams travel across the same nominal distance; the reference beam travels through a pair of vacuum sealed tubes while the measurement beam travels through air. The difference between the two represents the change in the index of refraction over the time of the measurement.



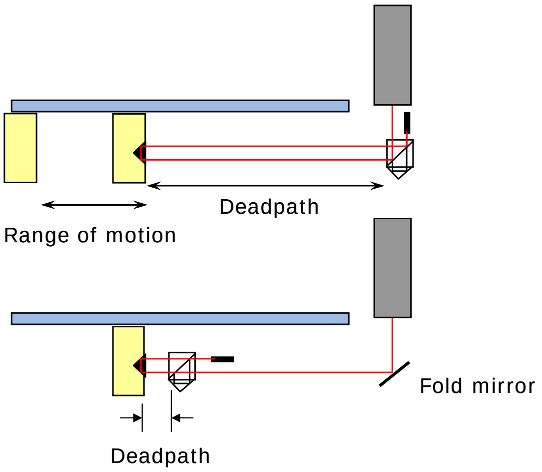
Deadpath Error

Interferometer Deadpath = R-M

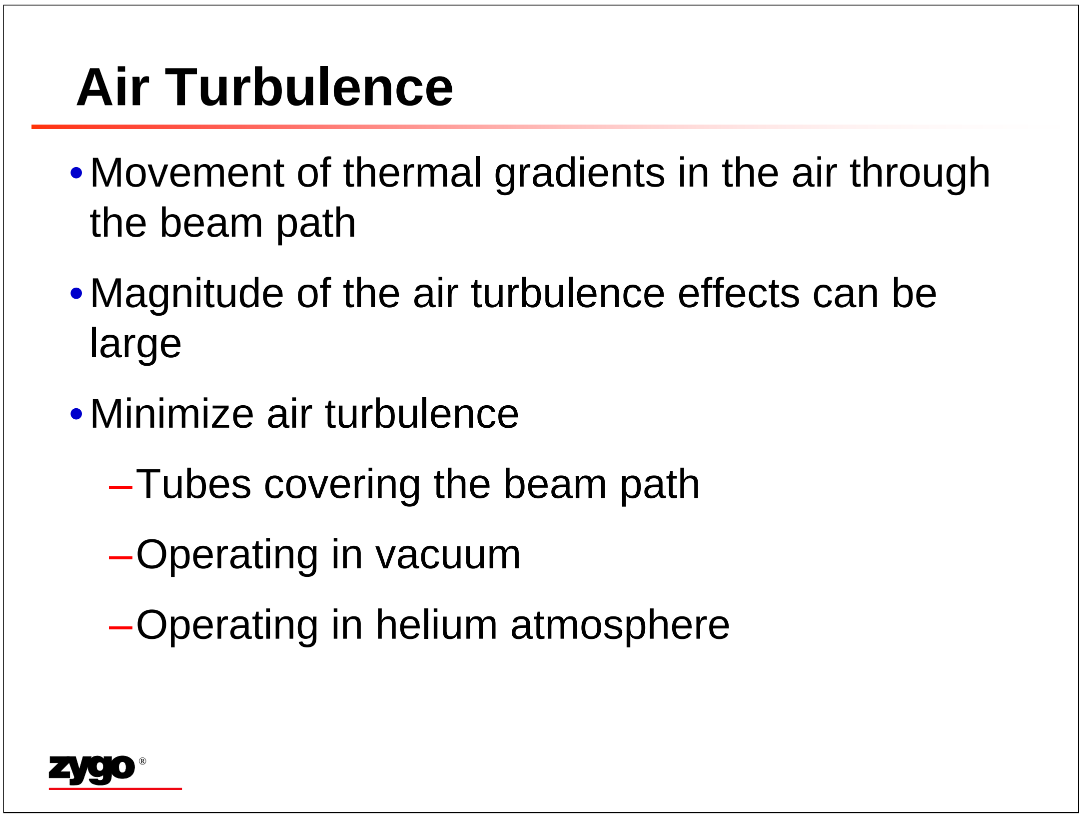
Deadpath = (R-M) + D

Deadpath is the difference in distance in air between the reference and measurement paths of an interferometer configuration. The deadpath error is caused by a change in the environment during the measurement. To minimize deadpath distance, locate the interferometer as close to the target mirror as possible. Minimizing environmental changes during the time of the measurement also reduces the deadpath error.

Minimizing Deadpath



The upper example is using a right angle configured interferometer that is positioned a long distance from the target's travel. The lower example shows how adding a fold mirror and changing the interferometer to a straight thru configuration can minimize the potential deadpath error.



Air Turbulence

- Movement of thermal gradients in the air through the beam path
- Magnitude of the air turbulence effects can be large
- Minimize air turbulence
  - Tubes covering the beam path
  - Operating in vacuum
  - Operating in helium atmosphere

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Air turbulence is movement of thermal gradients in the air through the beam path. The magnitude of the air turbulence effects can be large if precautions are not taken. The simplest precaution is to place tubes along the beam path, except where there is actual motion. More extreme, and effective, methods include operating in a helium atmosphere or operating in a vacuum.

Summary

- Error associated with refractive index typically dominate in uncompensated system
- Setup related contributions can usually be reduced by careful alignment
  - Abbé error
  - Deadpath
  - Beam alignment to direction of motion
- Capability of a measurement technique should be judged in the context of the measurement uncertainty