

Multi DOF Interferometer Measurements

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Agenda

-Dimensional Measurements

-Interferometer Basics

- Laser Head (split frequency & stage speed)
- Principle
- Single & dual pass interferometers, differential interferometer

-Configuration Examples

- How to measure a rotation?
- Examples of 2, 3 and 4 DOF interferometer configurations

- Multi axis interferometers

- Why a multi axis interferometer?
- Examples of 5 and 6 DOF interferometer configurations

-Variations in IFM Signal and Safety Budget

- Modulation Receiver Signal Modulation
- Doppler Shift
- Safety Budget

-Beam Delivery & System Alignment

- Balanced optical power distribution
- Beam manipulators for “perfect” alignment

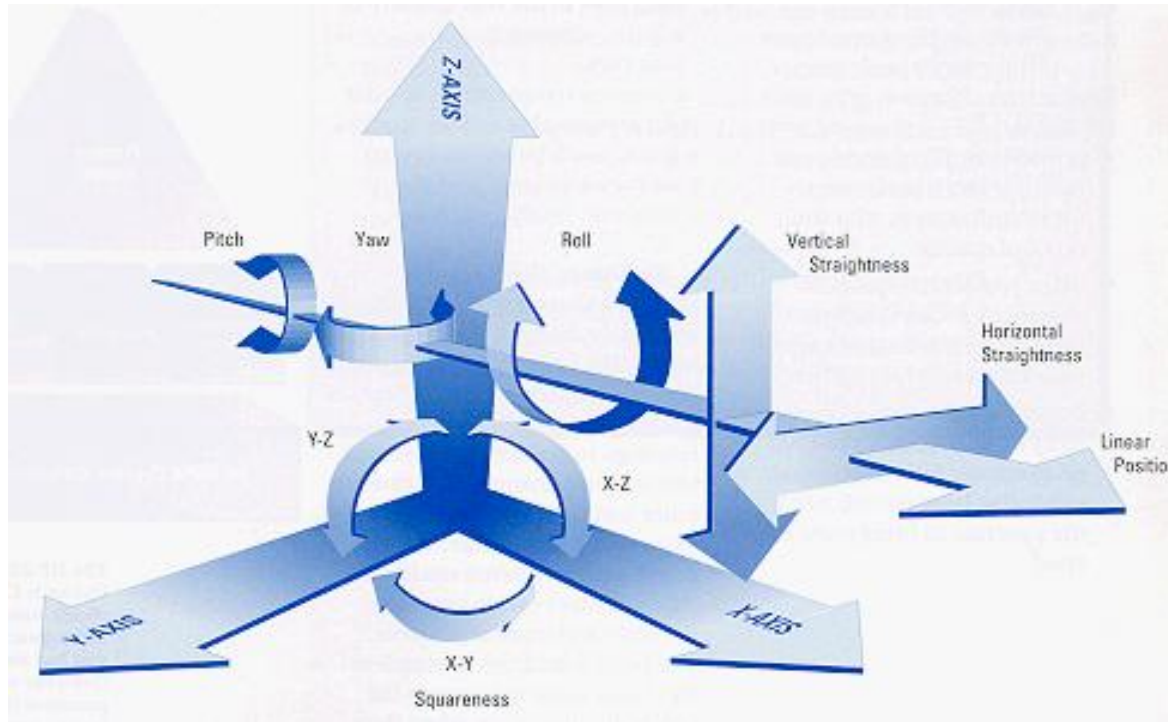
-System Design

-Electronics

-Accuracy & Repeatability

-Impact Environmental

Dimensional Measurements



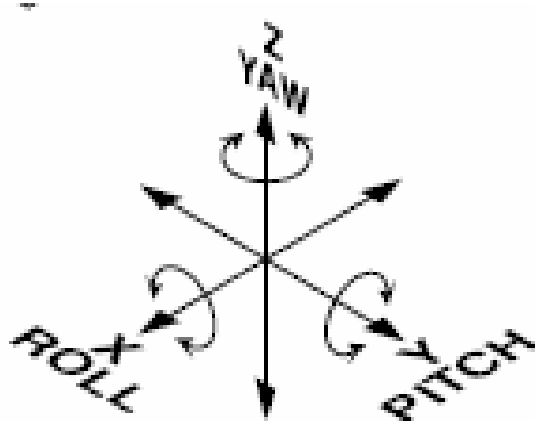
There are some 12 dimensional measurements:

-3x positions + 3x rotations

-3x squareness + 3x straightness

Multi-Dimensional Position Measurements

To control the stage position at high accuracy and resolution multi (6) DOF IFM measurements are required.



6 Degrees of Freedom (DOF):

- 3 translations along X, Y and Z axis
- 3 rotations around X,Y and Z axis

Note this presentation will deal with:

- *How to make 6 DOF measurements*
- *Factors to take into consideration*
- *Factors that impact accuracy*

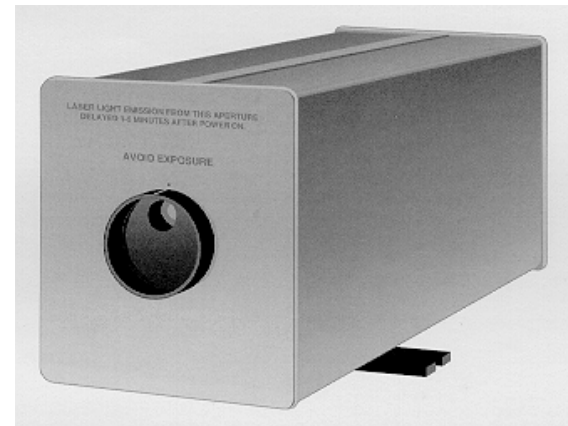
Principles of Interferometers

- Laser Heads (split frequency & stage speed)
- Principle Interferometer
- Single Pass Interferometer
- Dual Pass Interferometer
- Differential Interferometer
- Summary

Laser Head part 1

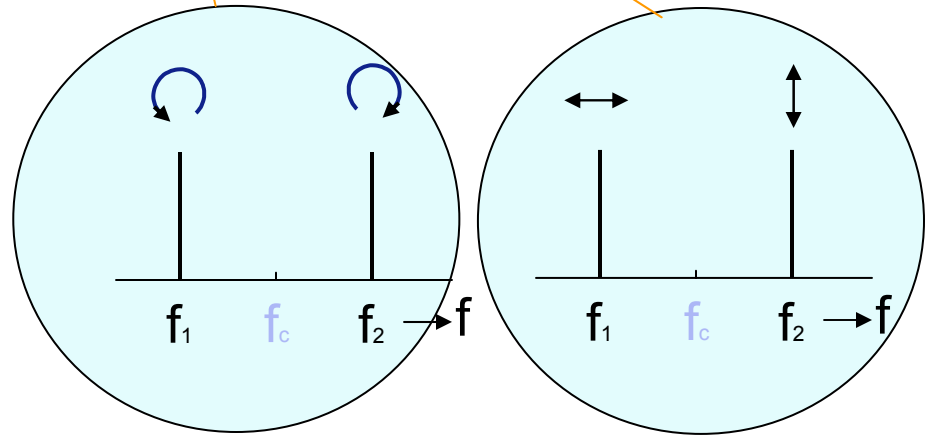
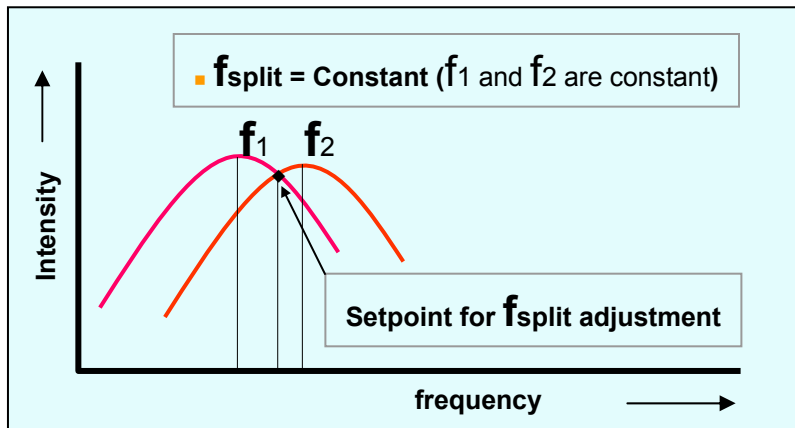
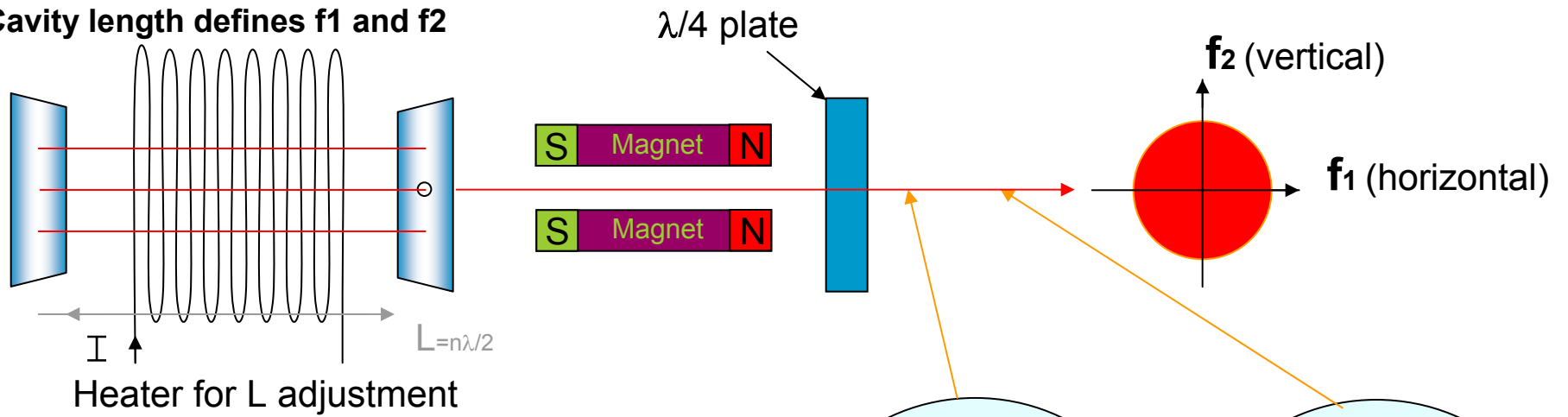
Agilent Laser Interferometry:

- Heterodyne System
- Uses Zeeman split at laser source
- Zeeman split → 2 frequencies
- Two frequencies (Reference & Measure)
- Doppler shift
- Split frequency → max. stage speed
- Several models
 - 5517B/C/D
 - Speed range 254, 356 or 500 mm/sec
- Higher split freq → lower output power



Laser Head part 2

Cavity length defines f_1 and f_2



Note: $f_1 - f_2$ is influenced by changing magnetic field (due to neighboring metal)

Principle Interferometer part 1

Principle:

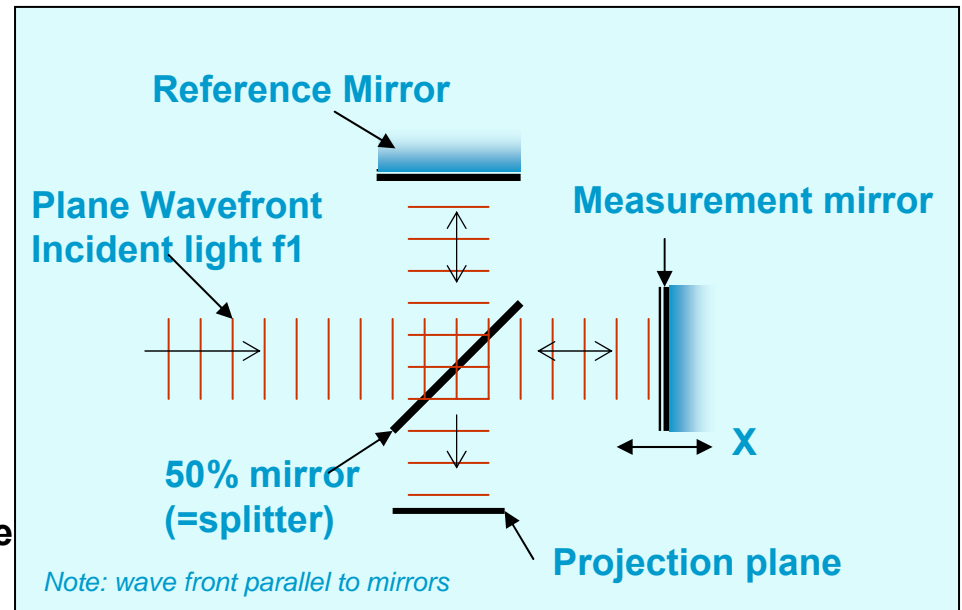
- Interference of light
- Δ Phase is indication for Δ Position (known wavelength & refractive index)

Michelson interferometer:

- Plane mirror interferometer
- Monochromatic light f_1

Displacement in $X \rightarrow$ Intensity deviation $\sim 2X/\lambda$

- Effective use of power 50%
- No signal change without position change
- +/- X direction is NOT defined



Principle Interferometer part 2

Principle:

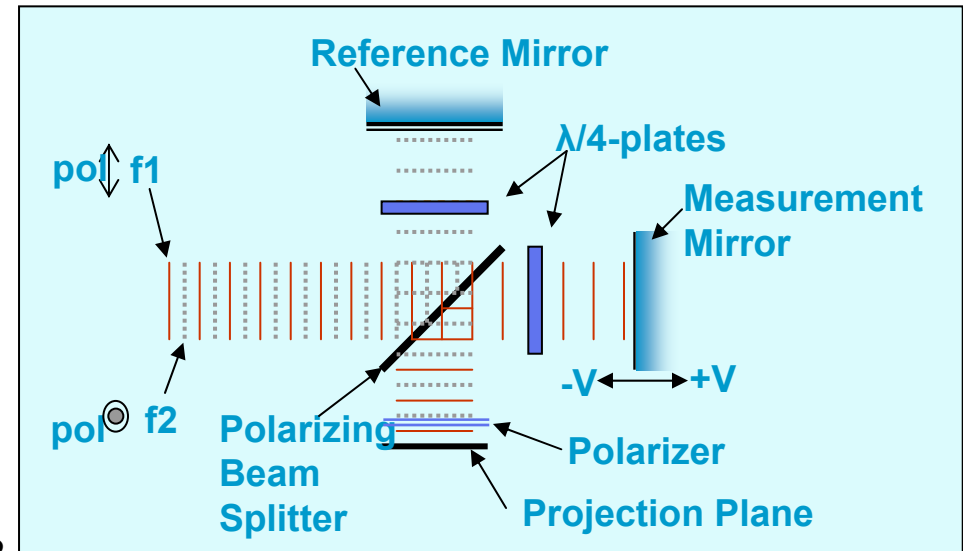
- Interference of light
- Δ Phase is indication for Δ Position (known wavelength & refractive index)

Two frequency Interferometer with PBS:

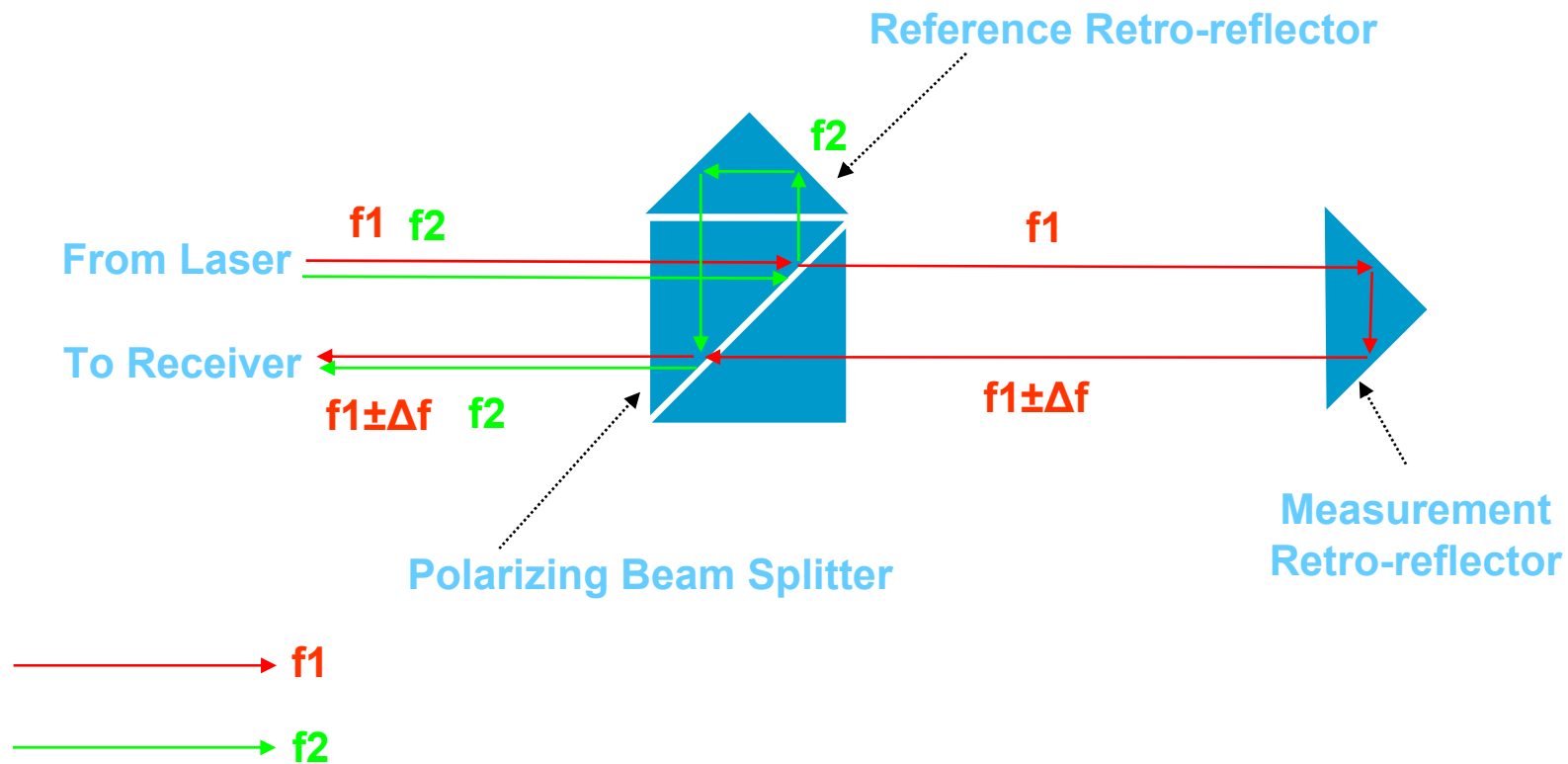
- Plane mirror interferometer
- Linear polarized light with freq's f_1 & f_2
- $\lambda/4$ plates act as optical switch

Displacement in $X \rightarrow \Delta$ Intensity $\sim 2X/\lambda$

- Effective power use 98%
- Continuous change in signal due to f_1 & f_2
- Direction defined

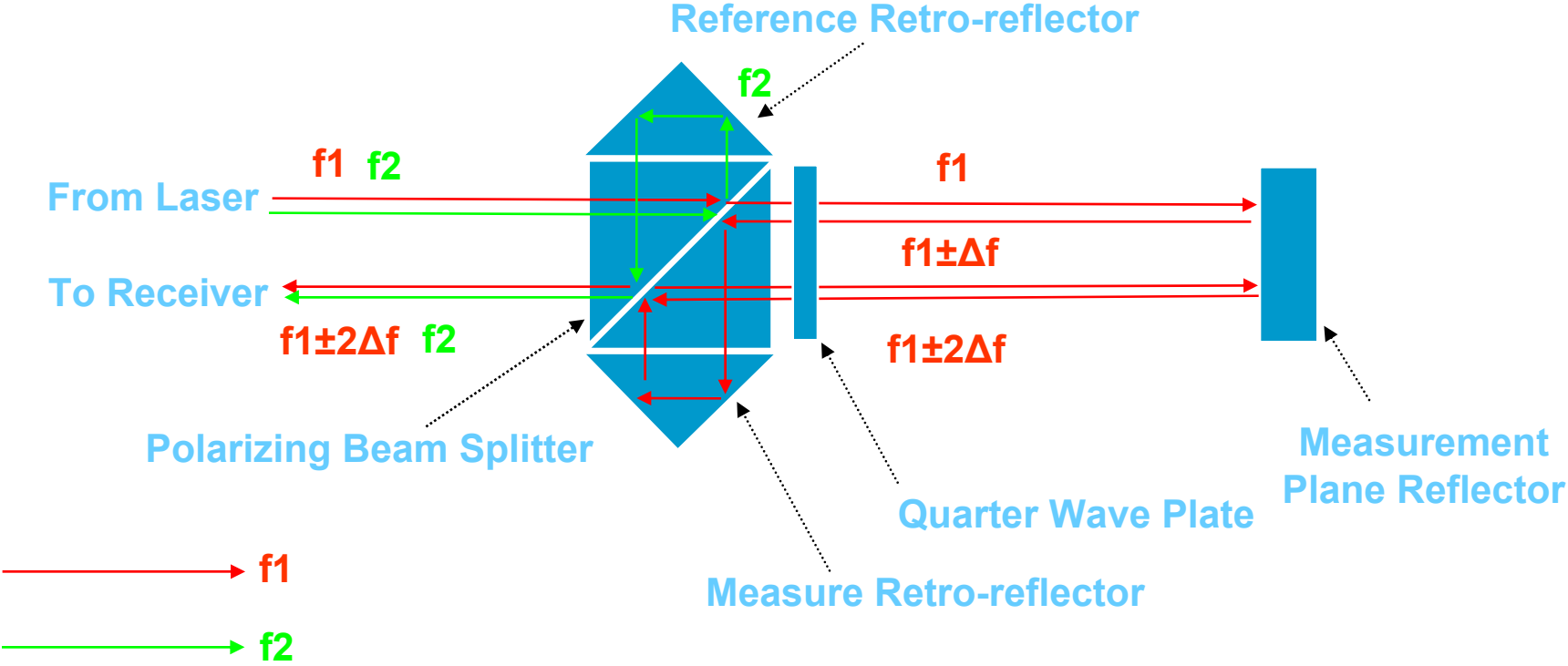


Principle single pass interferometer



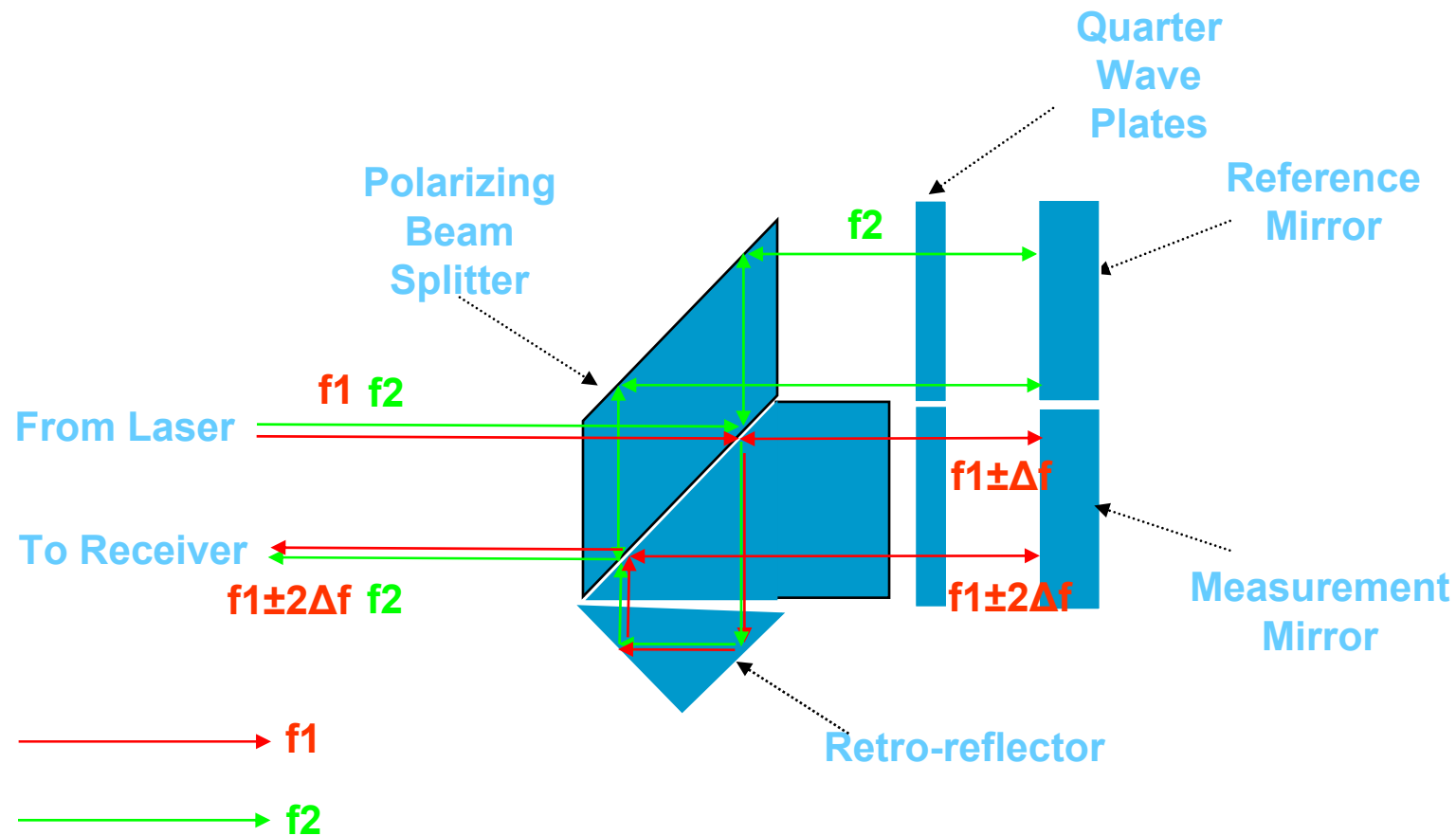
Single Pass \rightarrow optical resolution $\lambda/2$

Principle dual pass interferometer



Dual Pass → optical resolution $\lambda/4$

Principle differential interferometer



Differential Dual Pass \rightarrow optical resolution $\lambda/4$

Example Interferometers



10702A Linear Interferometer

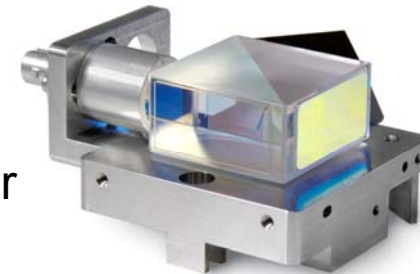


10706B High Stability Plane Mirror Interferometer



10719A Single Axis Differential Interferometer

E1826x Single Axis NGI Interferometer



Summary Interferometry

Laser Source

- Provides 2 frequencies: one for Reference and one for Measure
- Max stage speed determines the split frequency (Doppler Frequency)

Standard interferometer (IFM)

- Measures phase difference between reference and measurement path
- Phase difference translates into distance IFM – Measurement mirror
- Single path interferometer → optical resolution $\lambda/2$
- Dual path interferometer → optical resolution $\lambda/4$

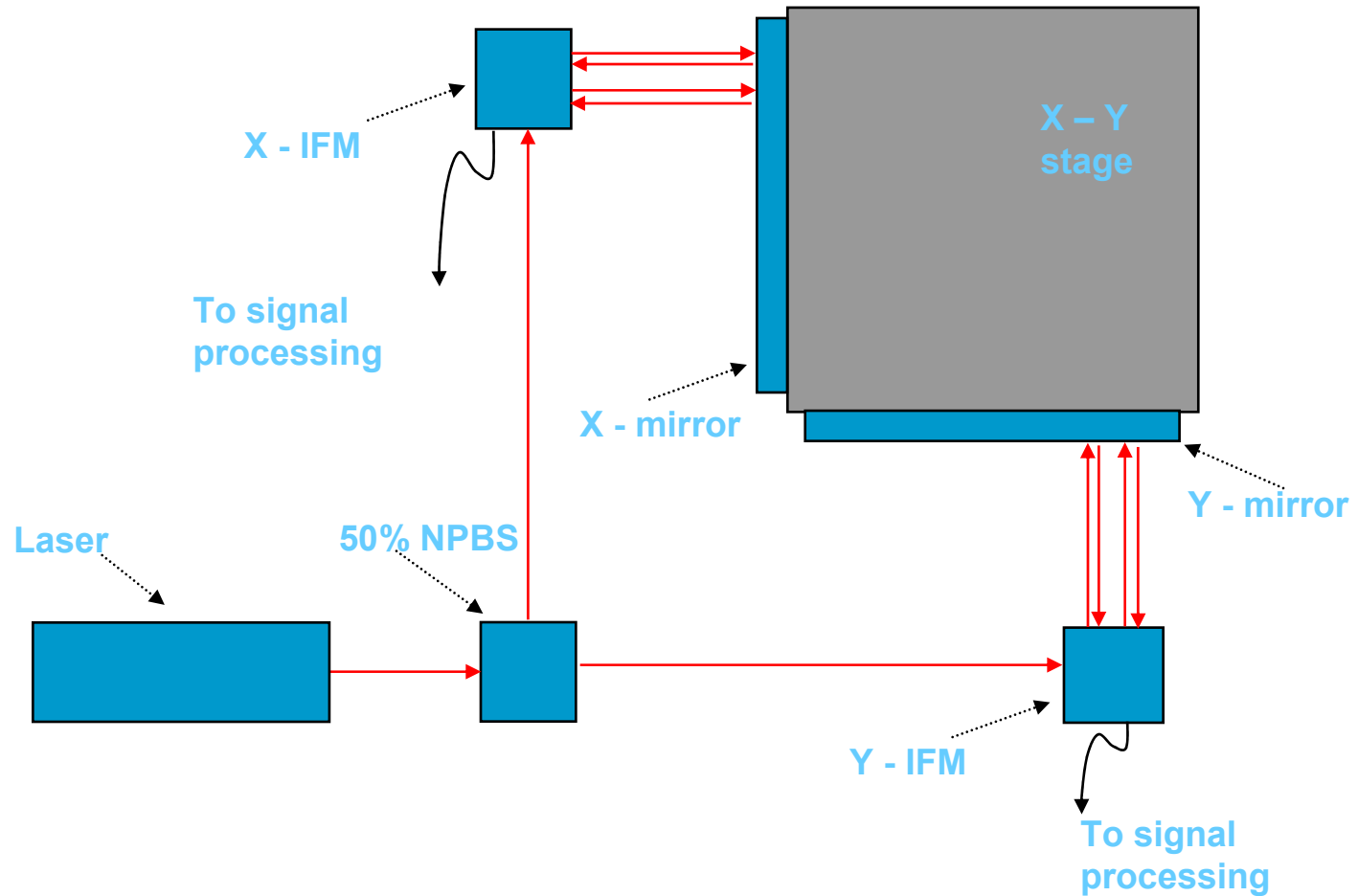
Differential interferometer

- Reference path is external instead of internal
- Measures the difference in position of measurement and reference mirror
- When reference and measurement mirror are the same → measurement can be translated into rotation

Configuration Examples multi DOF Interferometer Measurements (part 1)

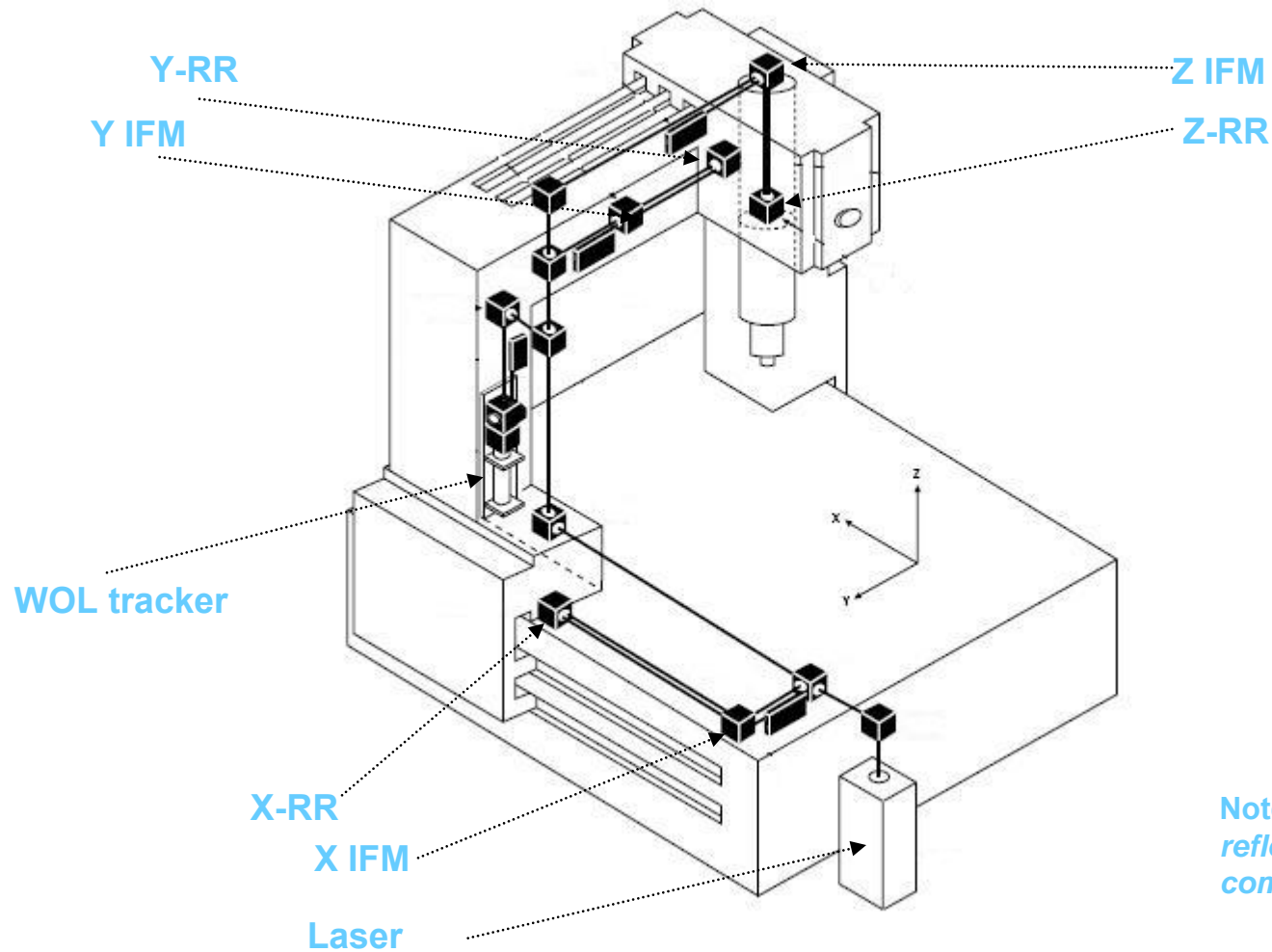
- 2 DOF (X-Y) measurement → 2 single axis interferometers
- 3 DOF (X-Y-Z) measurement → 3 single axis interferometers (CMM)
- Measurement of a rotation
 - 2 single axis interferometers – both IFM's pointing at the same mirror → 2 DOF's (X and R_z)
 - 1 differential interferometer – Ref & Meas arm pointing at the same mirror → 1 DOF (R_y)
- 3 DOF (X, Y and R_z) → 3 single axis interferometers

2 DOF (X-Y) Measurement



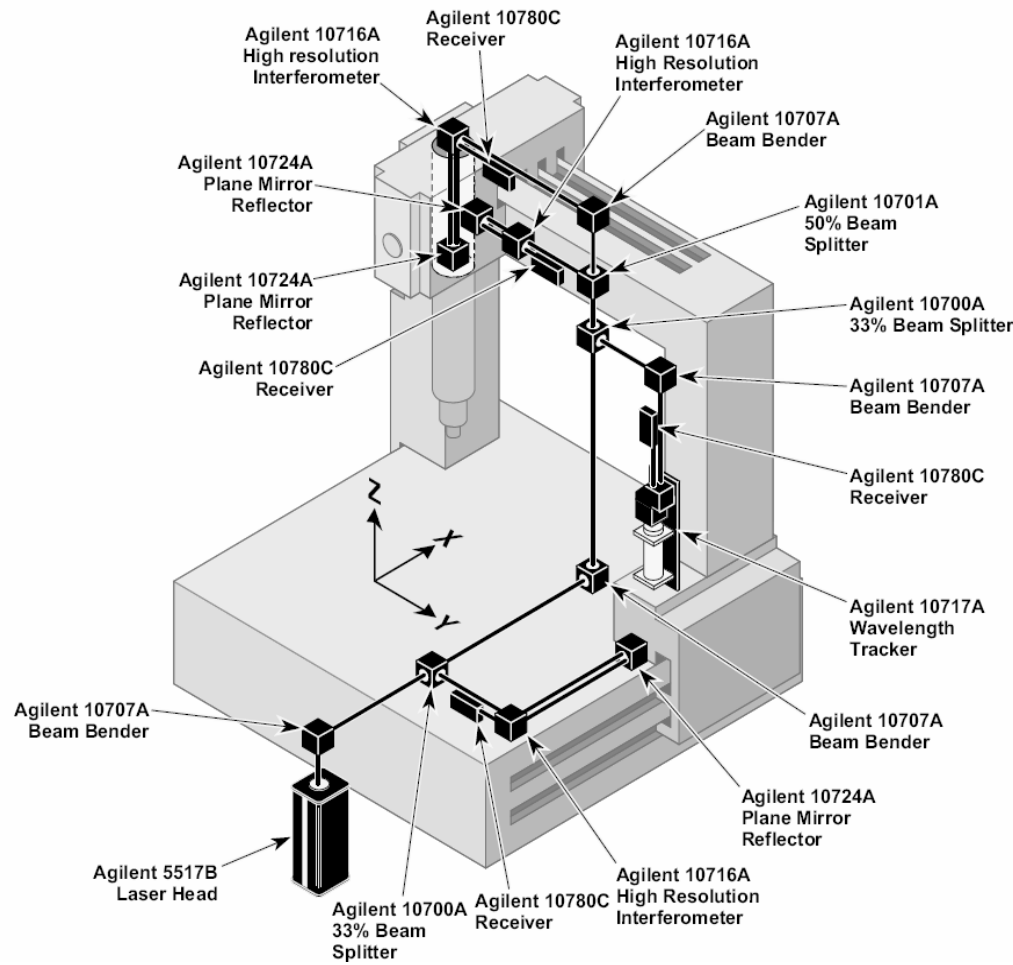
2 IFM measurements \rightarrow 2 DOF's \rightarrow X and Y position

3 DOF (X-Y-Z) Measurement with Gantry System



3 IFM measurements → 3 DOF's → X, Y and Z position

3 DOF (X-Y-Z) Measurement with Gantry System



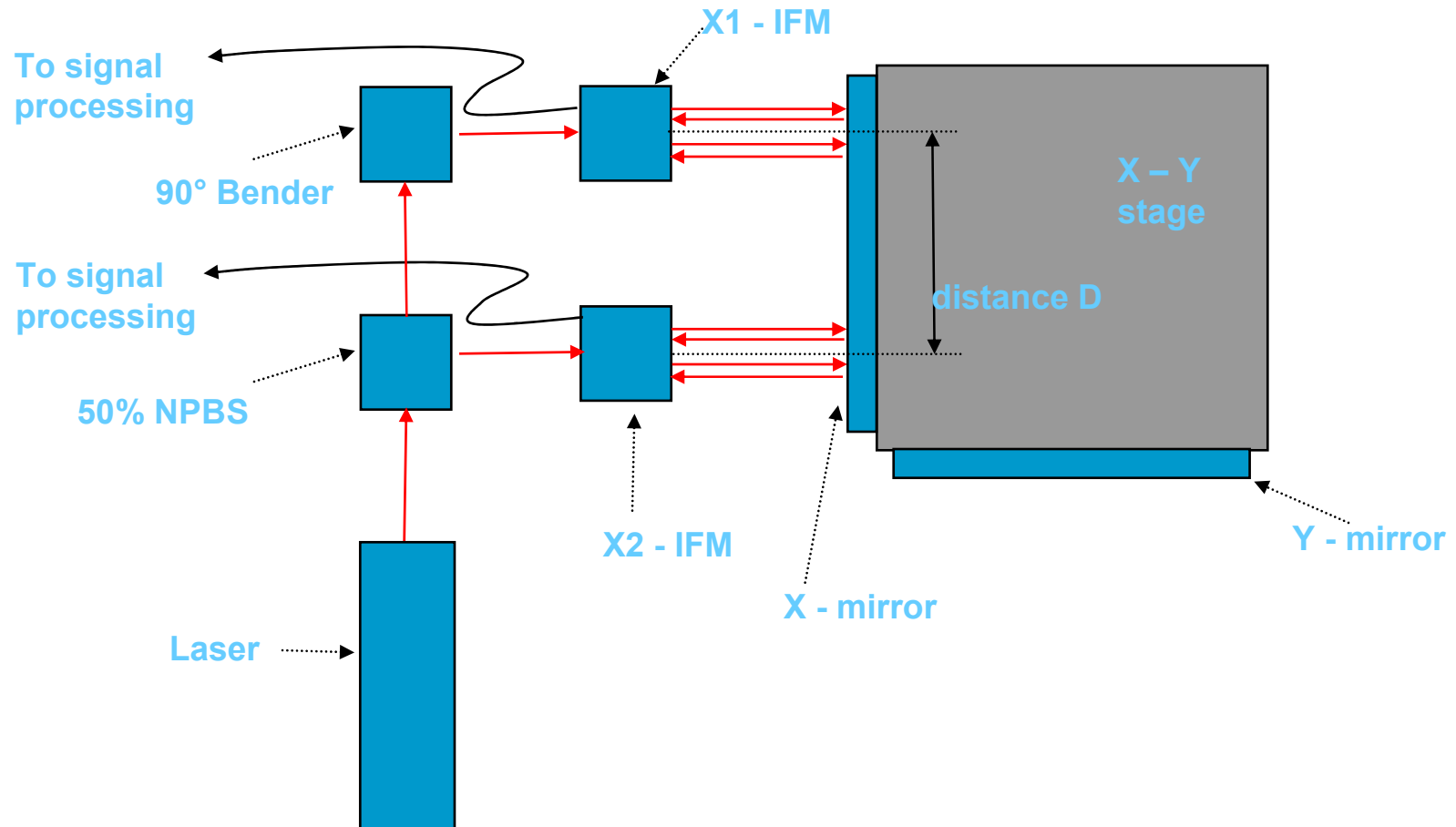
Note: version with 3 high resolution IFM's

3 IFM measurements → 3 DOF's → X, Y and Z position

Issues with Gantry Systems

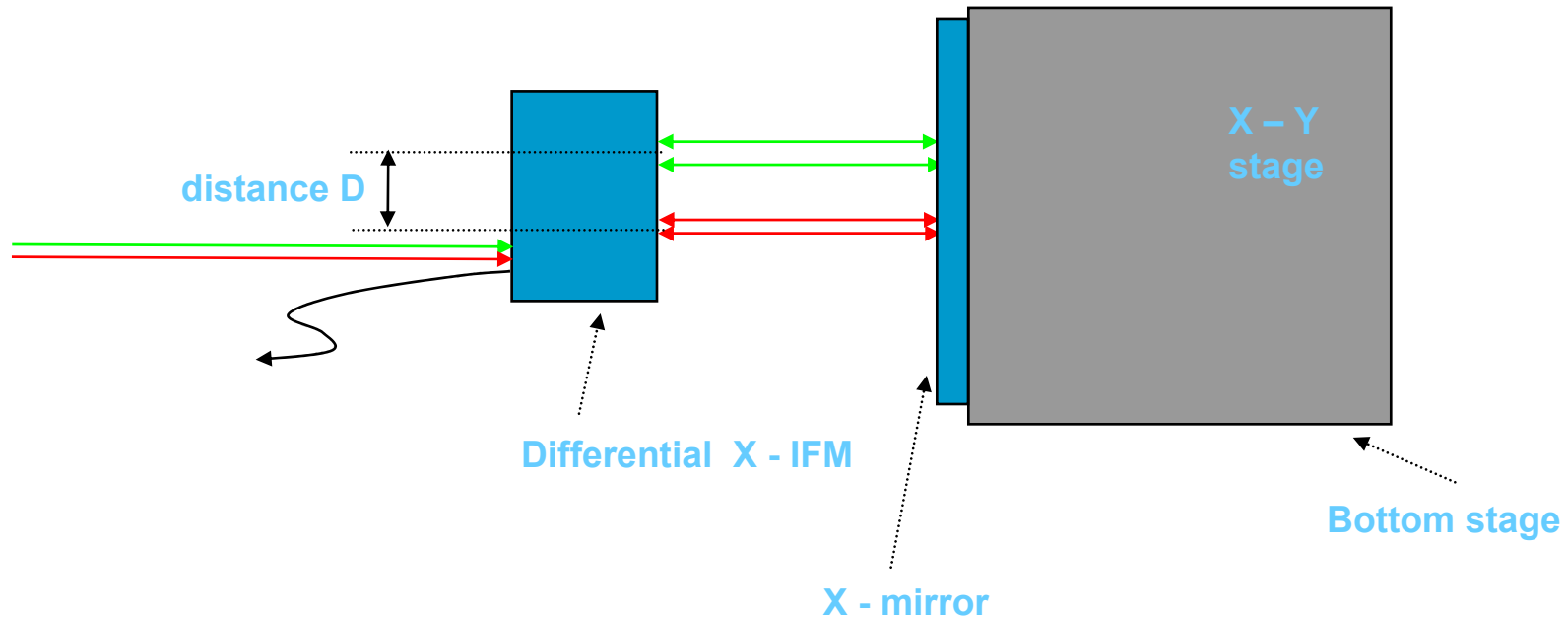
- 3 DOF's (X-Y-Z) do not reveal any rotations
- Large systems will experience rotations (stiffness)
 - Long stage travel combined with rotation → position error and BWO
 - Δx of 1mm combined with a height of 1000mm → 0.5 mrad at center
- Addition of 2nd X-measurement → yaw
- Addition of 2nd Y-measurement → pitch

Stage rotation measurement part 1



2 IFM measurements \rightarrow 2 DOF's \rightarrow X and R_z with
 $X = (x_1 + x_2) / 2$ and $R_z = \arctan((x_1 - x_2) / D)$

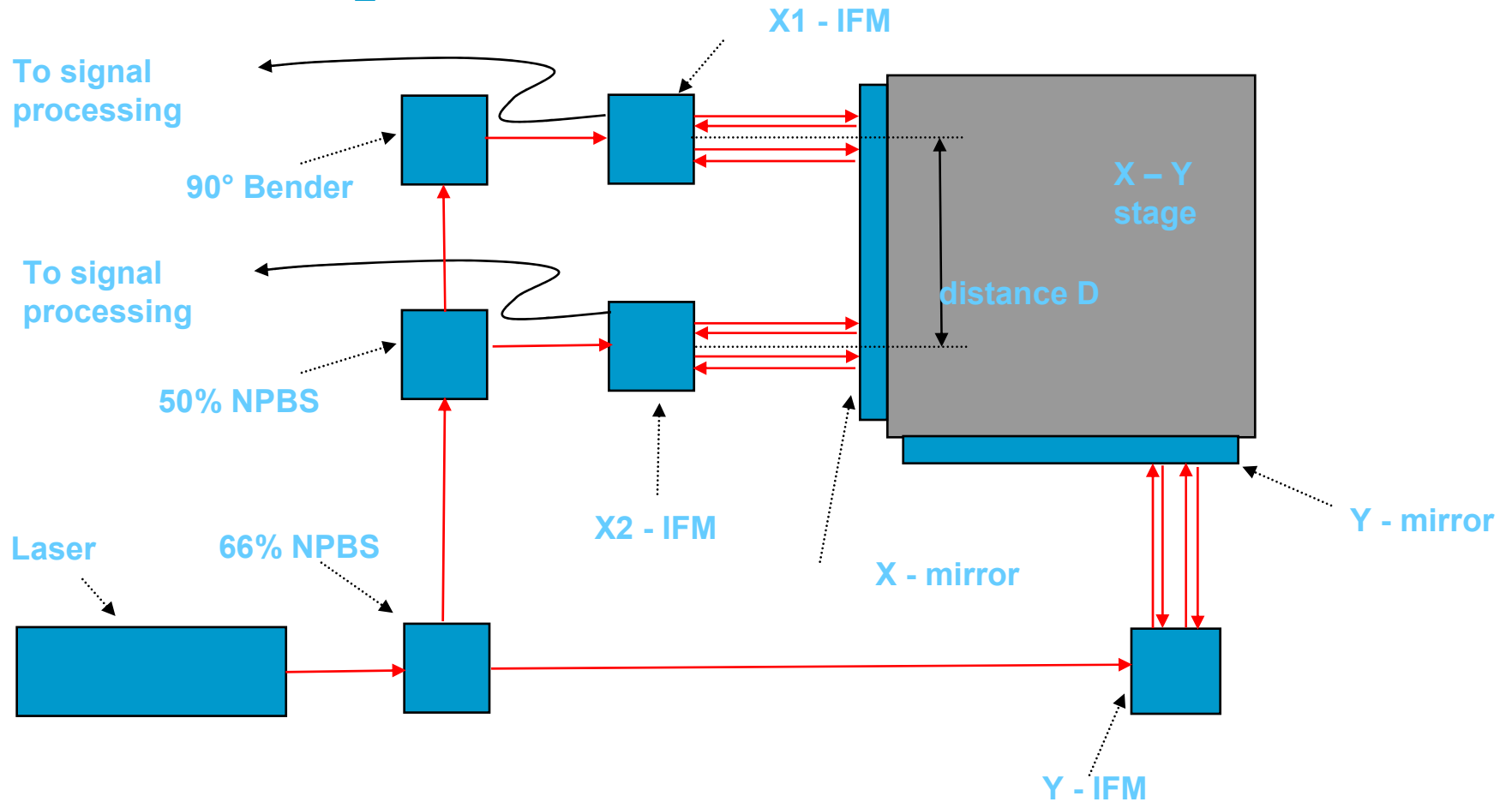
Stage rotation measurement part 2



Note: stage is seen from the side

1 IFM measurement \rightarrow 1 DOF \rightarrow delta Ref and Meas path plus distance D provides R_y (pitch)

3 DOF (X-Y-R_z) measurement



3 measurements → 3 DOF's X, Y and R_z

Configuration Examples multi DOF Interferometer Measurements (part 2)

- Why a multi-axes interferometer?
- Measurement with 3-axes interferometer
- 5 DOF's (X , Y , R_x , R_y and R_z) with:
 - 2 x 3-axes interferometer
- 6 DOF's (X , Y , Z , R_x , R_y and R_z) with:
 - 2 x 3-axes interferometer plus 1 x single axis interferometer

Why a multi-axis interferometer? (part 1)

Requirements for making a precise rotational measurement:

- All single axis interferometers must be in a single X-Y plane (=at the same level) relative to the stage mirror.
- All single axis interferometers must be in a single X-Z (or Y-Z) plane (=at same distance) relative to the stage mirror.
- The measurement beams from all interferometer must be parallel (without parallelism → cosine error).

These requirements results in:

- Tedious, time consuming and iterative alignments of all interferometer (incl. beam delivery).

Why a multi-axis interferometer:

- All axes in this type of interferometer operate from a single PBS.
- All axes are well aligned → better accuracy and reduction of alignment.
- Beam parallelism better than $50\mu\text{rads}$ (or 11 arcsec).

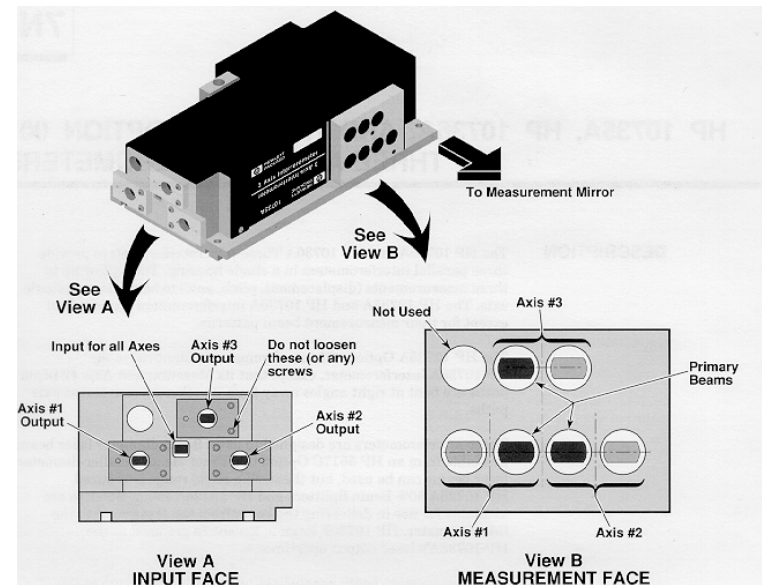
Why a multi-axis interferometer? (part 2)

Example multi-axes interferometer:

- 10735A a 3-axes interferometer
- Internal beam delivery to each axis
- Beam parallelism $< 50\mu\text{rads}$
- Non-linearity contribution $< 2.2\text{nm}$

Some specifications:

- Thermal drift $40\text{ nm}/^\circ\text{C}$
- Resolution (with resolution extension):
 - Position 0.62 nm
 - Angular 0.1 (pitch/roll) / 0.04 (yaw) μrads
- Angular range:
 - Pitch or Roll $\pm 2\text{ mrad}$ @ 150mm distance
 - Yaw $\pm 3\text{ mrad}$ @ 150mm distance



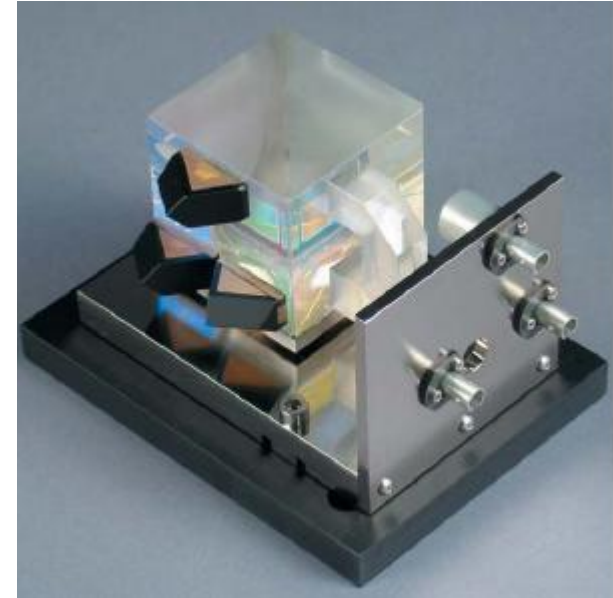
Why a multi-axis interferometer? (part 3)

Example multi-axes interferometer:

- NG (next generation) Z4399A 3-axes IFM
- Internal beam delivery to each axis
- Beam parallelism:
 - $< 25\mu\text{rads}$ primary beams
 - $< 15\mu\text{rads}$ secondary beams

Some specifications:

- Thermal drift $< 10 \text{ nm}/^\circ\text{C}$
- Resolution (with resolution extension):
 - Position: 0.62 nm
 - Angular 0.10 μrads
- Angular range:
 - Pitch, Yaw or Roll $\pm 4 \text{ mrad}$ @ 150mm distance



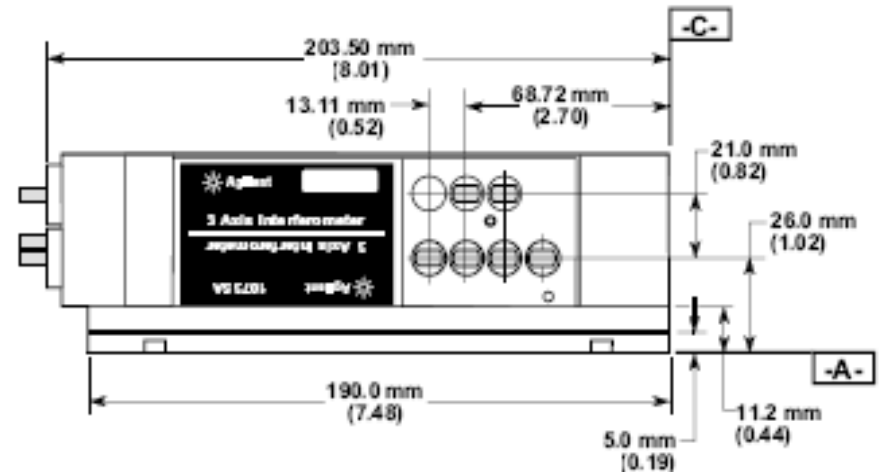
Measurement with 3-axes interferometer

Alignment:

- Interferometer must face stage mirror
- IFM face parallel to mirror
- All IFM beam perpendicular to mirror

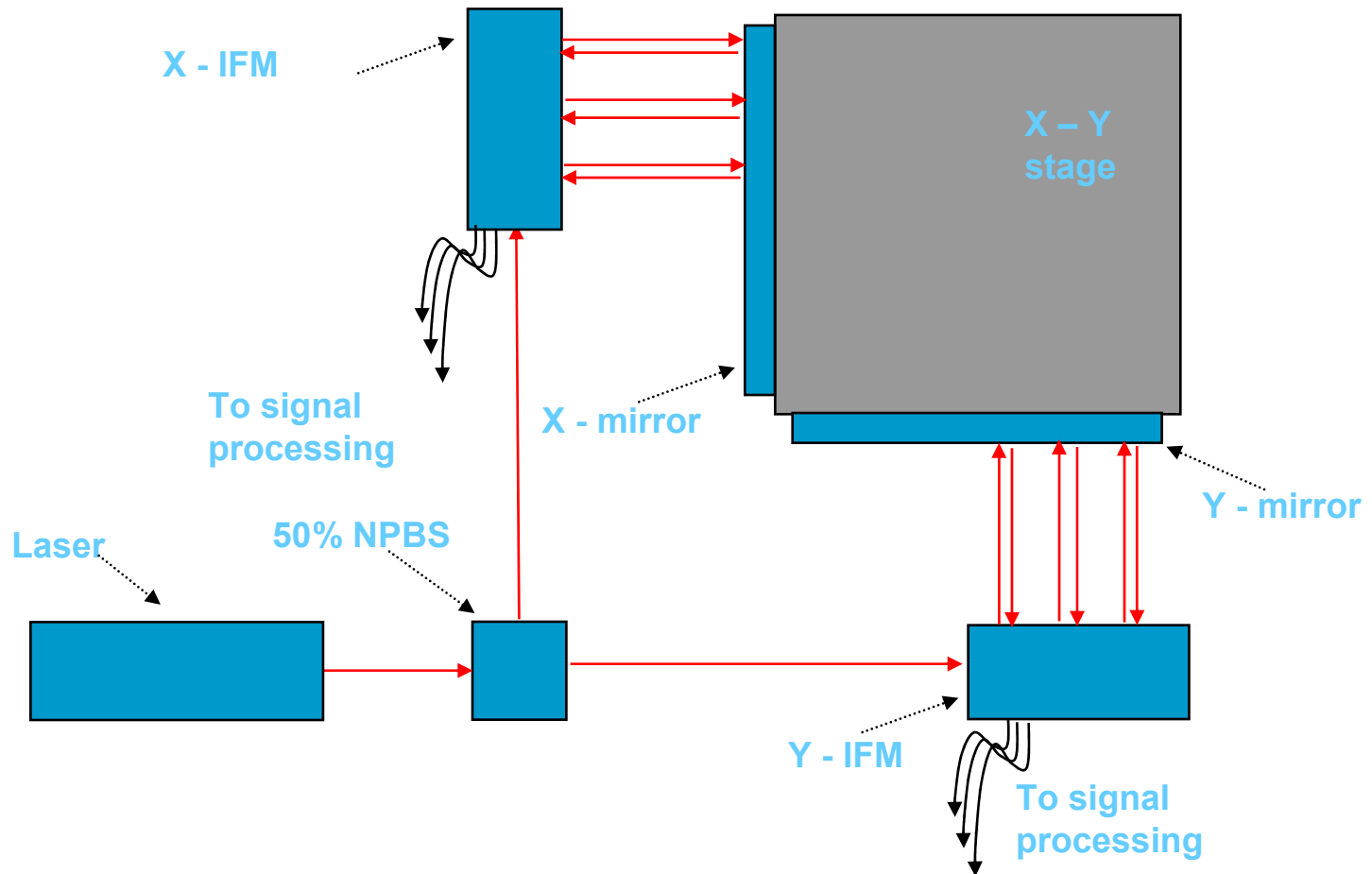
Measurement:

- Sample all axes at the same time
- Displacement $\rightarrow (\text{Axis \#1} + \text{Axis \#2})/2$
- Yaw (=Rz) $\rightarrow (\text{Axis \#1} - \text{Axis \#2})/26.22$ radians
- Pitch (=Ry) $\rightarrow (\text{Displacement} - \text{Axis \#3})/21.00$ radians



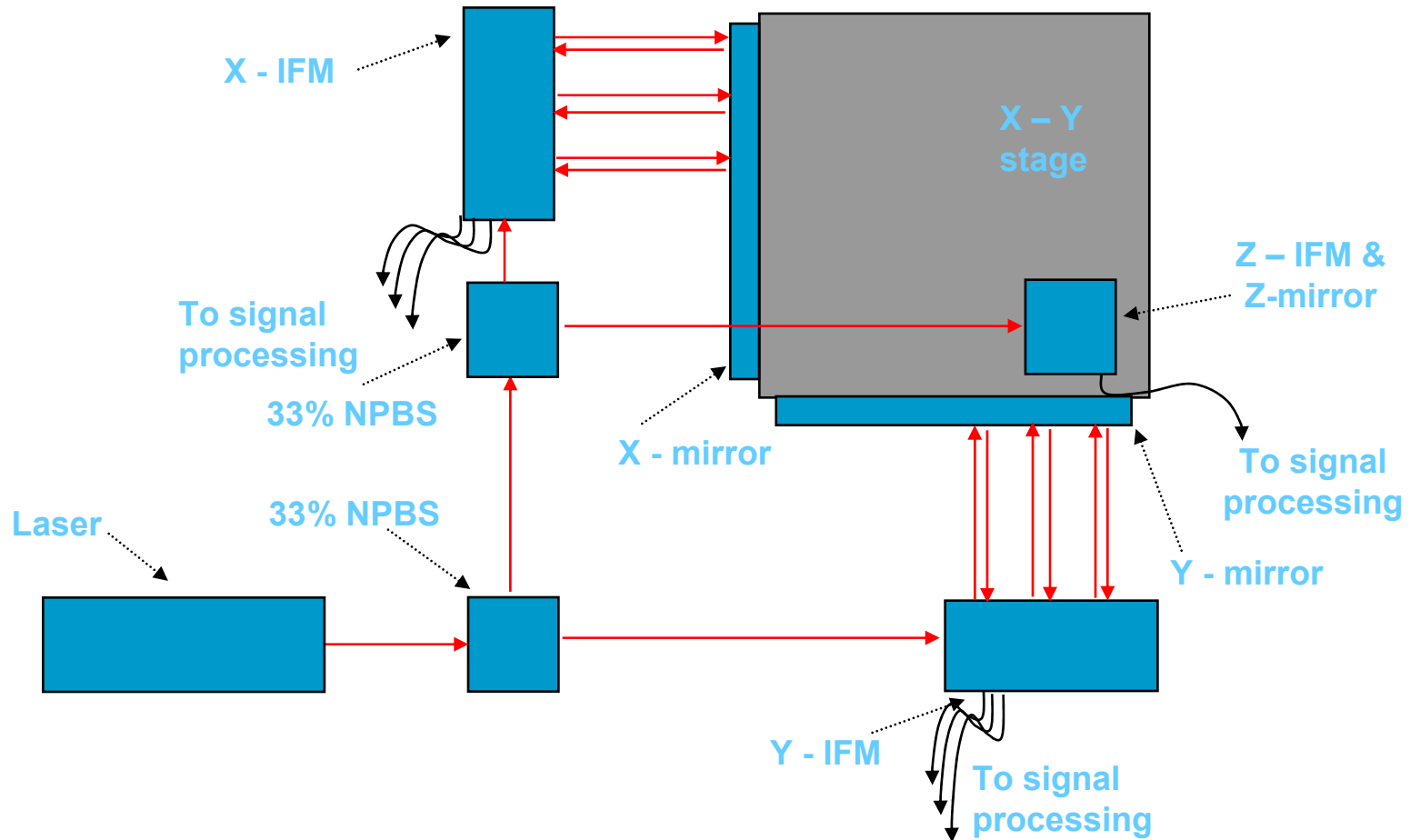
Note: the 2 distances (26.22 and 21.00mm) are derived from the IFM beam pattern

5 DOF (X-Y) Measurement



2 IFM measurements \rightarrow 6 axes \rightarrow 5 DOF's \rightarrow X, Y, Rx, Ry and Rz (2x)

6 DOF (X-Y) Measurement part 1

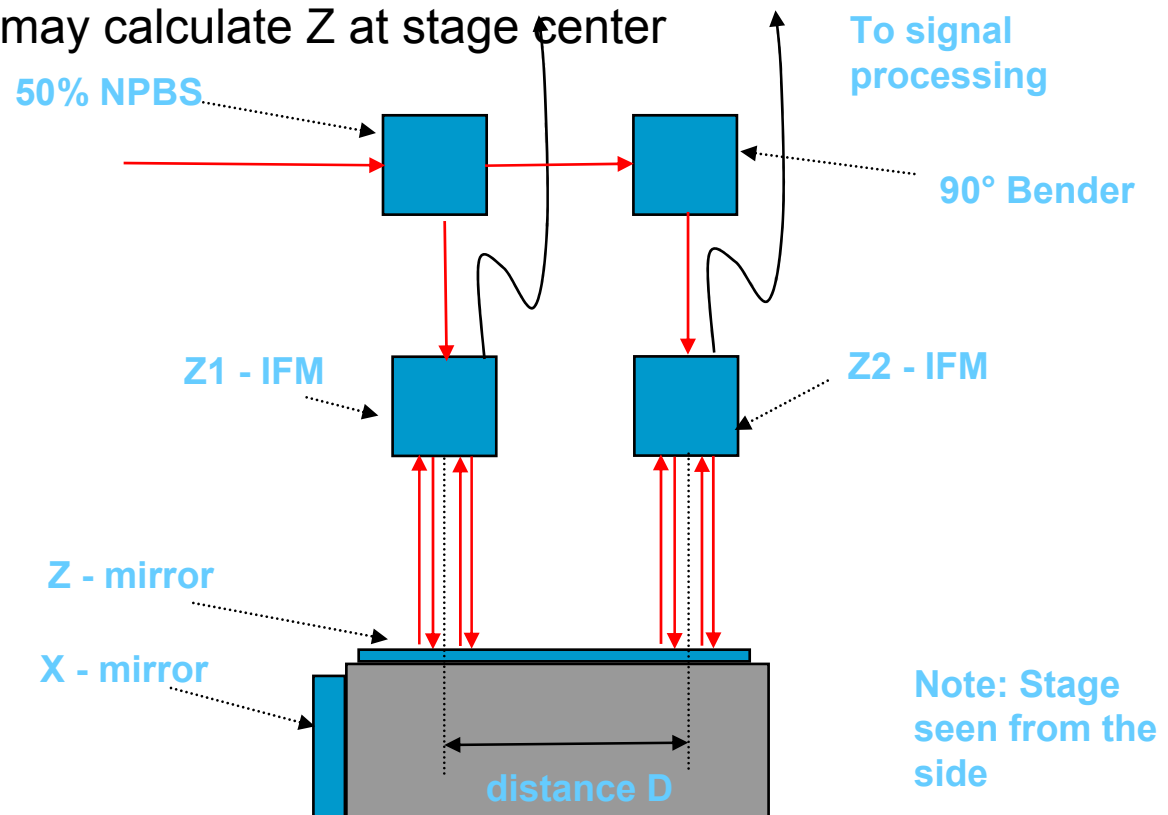


3 IFM measurements \rightarrow 7 axes \rightarrow 6 DOF's \rightarrow X, Y, Z, Rx, Ry and Rz (2x)

6 DOF (X-Y) Measurement part 2

Issue with Z-measurement:

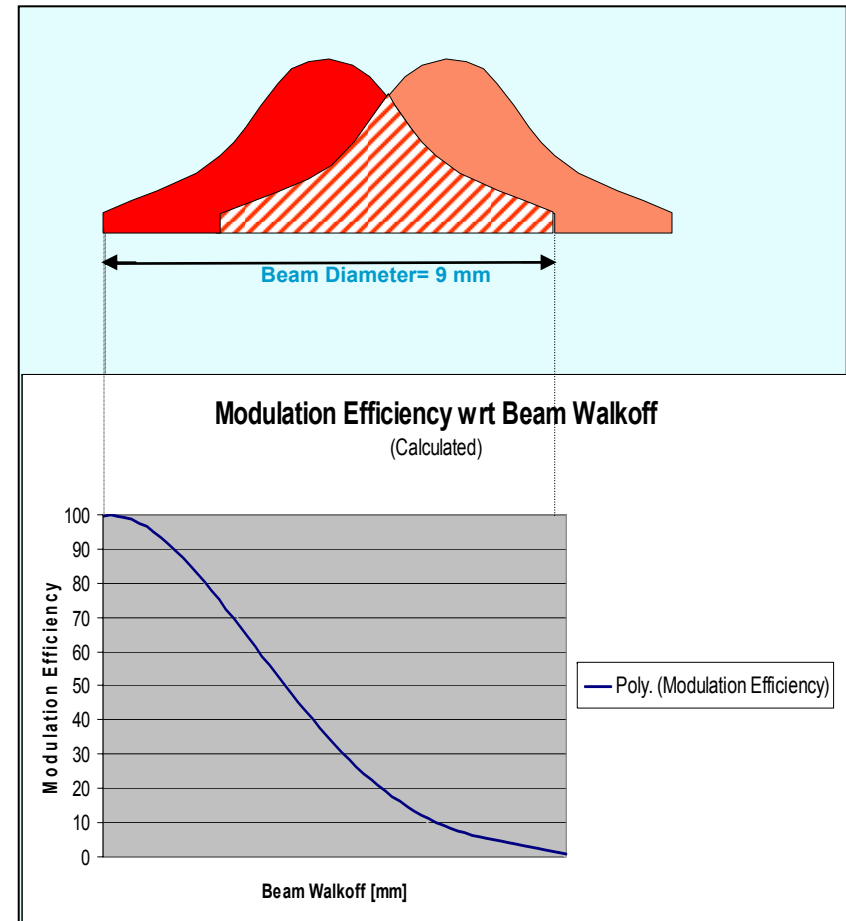
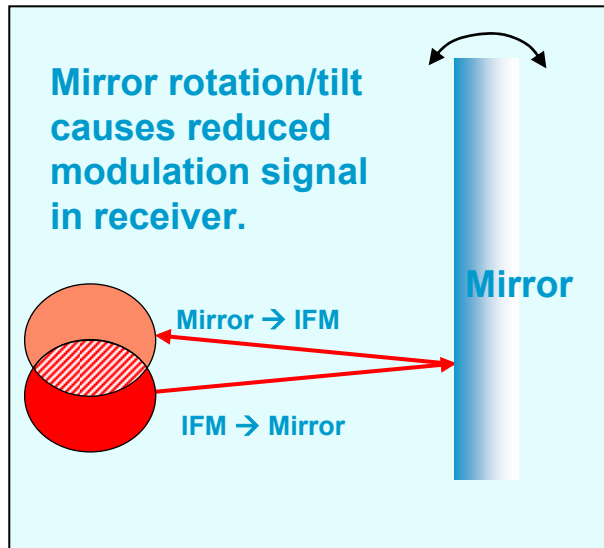
- In general top of stage is used for test-items or products in process
- In most cases space for Z-mirror on X-Y stage is limited
- Use of two IFM's helps
- With known geometry one may calculate Z at stage center



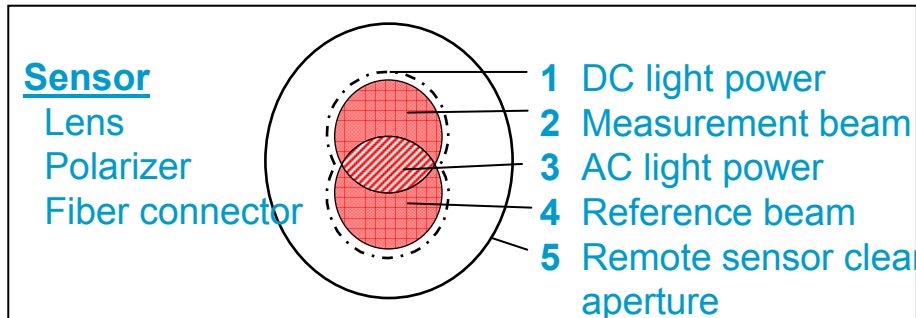
Variations in IFM Signal and Safety Budget

- Receiver Signal Modulation
 - Signal modulation due to stage rotation
- Doppler Shift
 - Maximum stage speed is limited by split frequency of laser
- Safety Budget
 - Determine efficiency for each IFM path/axis → multiply all (worst case) efficiencies of all optical components
 - Derive system safety factor (i.e. worst case of all axes)

Receiver Signal Modulation



Note: with beam diameter 9mm, max BWO = 9.0mm



Mirror rotation → beam walk-off → reduced overlap → smaller signal → limits measurement rotation range

Doppler Shift

Split frequency laser f_{split} (for 5517D 3.4 to 4.0 MHz)

Stage speed $\pm V$ leads to Doppler shift

$$f_{\text{doppler}} = \pm nV/\lambda \quad (\lambda \text{ actual wave length})$$

($n=2$ for linear and $=4$ for plane mirror IFM)

Stage moving at $+V$

$$f_{\text{sensor}} = f_{\text{split}} - (nV/\lambda)$$

Speed is limited by minimum f_{sensor} ($=200\text{kHz}$)

Stage moving $-V$

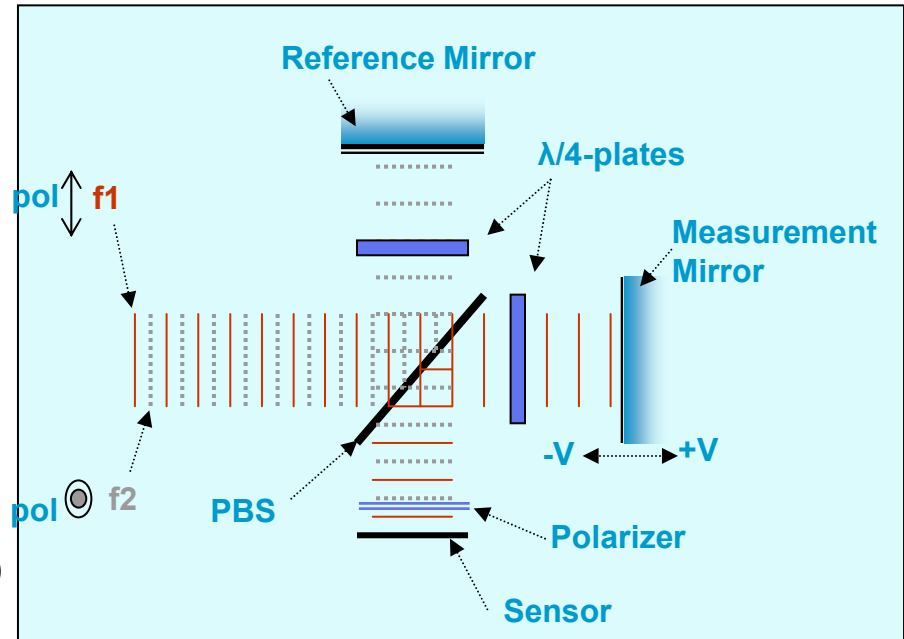
$$f_{\text{sensor}} = f_{\text{split}} + (nV/\lambda)$$

Speed is limited by receiver bandwidth ($\sim n \cdot f_s + x \text{ MHz}$)

Example

$$V = \lambda(f_{\text{split}} - f_{\text{sensor}})/n = 632 \cdot 3.2 \cdot 10^{-3} / 4 = 505 \text{ mm/s}$$

for 5517D in combination with plane mirror IFM



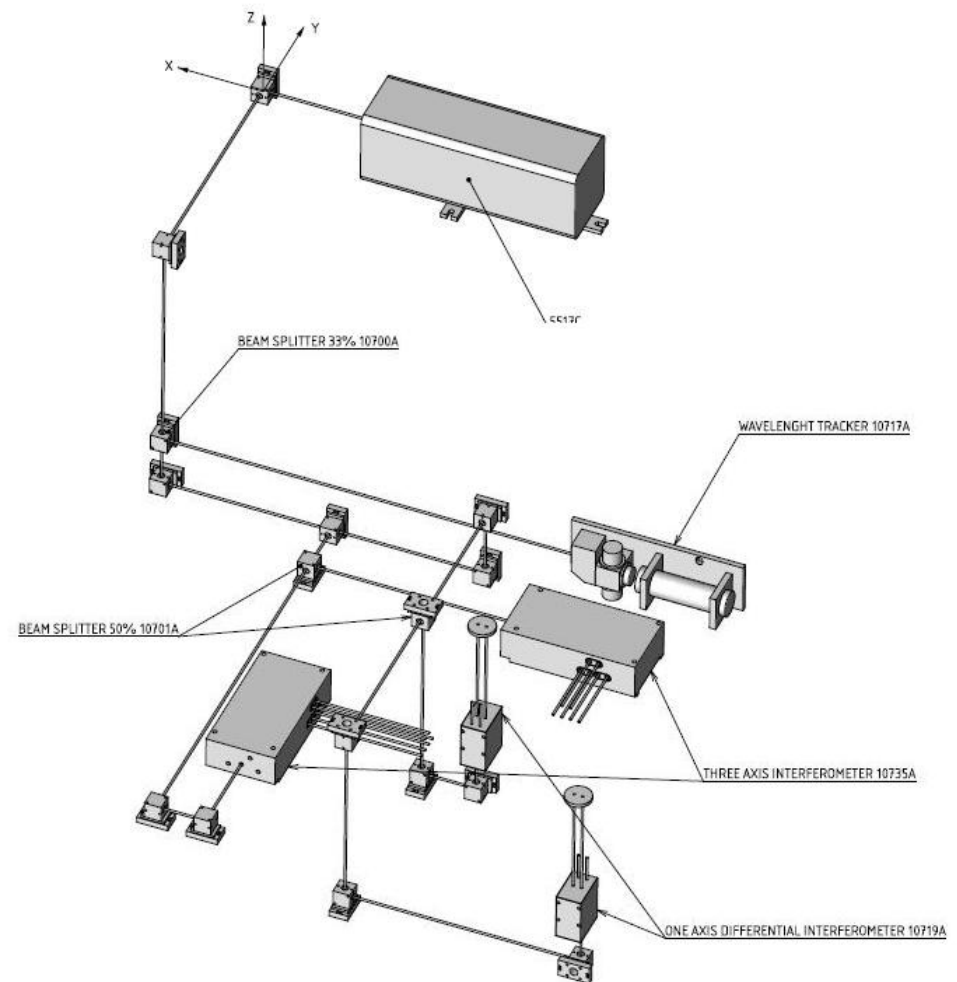
Speed moving stage \rightarrow Doppler shift \rightarrow limits stage speed

Safety Budget

- Laser output power will decrease over the years:
 - 5517C initial (minimum) power 250 μ W and typical after 3 years to 180 μ W
- Each optical system component (bender, splitter and interferometer) is characterized by nominal and worst case efficiency:
 - Efficiency = $100 * (\text{Output Power}/\text{Input Power})$
 - Bender \rightarrow ~ 99% (typical), 98% (worst case)
 - Splitter \rightarrow 50% splitter \rightarrow 45% (typical), 39% (worst case) per path
 - Note: *it's not the loss in a splitter, but the tolerance of the splitter*
 - Interferometers \rightarrow depending upon type (10735A \rightarrow 18 (typical), 10% (worst case) per axis
- Safety budget calculation:
 - Determine efficiency for each IFM path/axis \rightarrow multiply all (worst case) efficiencies of all optical components
 - Provides insight in optical power to each receiver
- System Safety Factor \rightarrow worst case of all IFM axes versus receiver sensitivity
 - Safety factor > 3 x relative to receiver sensitivity

Safety Budget Example part 1

- **6 DOF system with:**
 - 1x 5517C laser
 - 400 μ W power
 - 2x 3-axes IFM
 - 10% worst case/axis
 - 2x 1-axes diff IFM
 - 40% worst case
 - 1x 10717A WOL
 - 25% worst case
- **Splitters:**
 - 1x 33%
 - 27/61% worst case
 - 2x 50%
 - 39/39% worst case
- **Benders:**
 - 11x
 - 98% worst case



Safety Budget Example part 2

- 1st 10735A: 2x benders, 1x 33%, 1x 66% and 1x 50% splitters:
 - Per axis: $0.98^2 * 0.61 * 0.61 * 0.39 * 0.10 * 250 \mu\text{W} = 3.48 \mu\text{W}$
- 2nd 10735A: 4x benders, 1x 33%, 1x 66% and 1x 50% splitters:
 - Per axis: $0.98^4 * 0.61 * 0.61 * 0.39 * 0.10 * 250 \mu\text{W} = 3.45 \mu\text{W}$
- 1st 10719A: 6x benders, 1x33%, 166% and 1x 50% splitters:
 - Per axis: $0.98^6 * 0.61 * 0.27 * 0.39 * 0.40 * 250 \mu\text{W} = 5.69 \mu\text{W}$
- 2nd 10719A: 7x benders, 1x33%, 166% and 1x 50% splitters:
 - Per axis: $0.98^7 * 0.61 * 0.27 * 0.39 * 0.40 * 250 \mu\text{W} = 5.58 \mu\text{W}$
- 10717A WOL: 2x benders, 1x 33% splitter:
 - Per axis: $0.98^2 * 0.27 * 0.25 * 250 \mu\text{W} = 16 \mu\text{W}$
- Receiver E1709A sensitivity $0.8 \mu\text{W}$
- System Safety Factor \rightarrow worst case IFM axes \rightarrow 10735A @ $3.45 \mu\text{W}$
 - SF = 4.31 well above the limit of 3

Beam Delivery & System Alignment

-Beam Delivery

- Function
- Selection beam splitters

-System Alignment

- Alignment required to meet system specifications
- Define home position for stage
- Beam adjustments using manipulators

Beam Delivery part 1

- Function beam delivery → distribute main laser beam among all interferometers
 - Each interferometer has to meet specifications for the measurement ranges: both displacement and rotational range.
 - Each interferometer shall get “enough” power to operate properly
 - Balanced optical power distribution → power distribution to each IFM to meet measurement requirements.
 - Agilent offers the beam splitter with various percentages : 15, 33, 40, 50, 67%.
 - Start with IFM efficiency/axis (incl. beam walk-off)
 - Select beam splitter percentages.
 - Calculate Safety Factors/IFM axis
 - Re-visit power distribution and adapt splitter percentages.
-
- Note:
 - *Incorporate all benders in each delivery path.*

Beam Delivery part 2

- Illustrate with same example as used for safety factor calculation
- Function beam delivery → distribute main laser beam among the IFM
 - 1st 10735A and 2nd 10735A: 3.48 and 3.45 μW / axis
 - 1st 10719A and 2nd 10719A: 5.69 and 5.58 μW / axis
 - 10717A WOL: 16 μW
- 10717A monitors WOL length (no displacement, no rotation) → could do with less power
- Replace first 33% with 15% splitter:
 - 1st 10735A and 2nd 10735A: 4.57 and 4.39 μW / axis
 - 1st 10719A and 2nd 10719A: 7.46 and 7.31 μW / axis
 - 10717A WOL: 5.40 μW / axis
- Change from 33 to 15% splitter improves SF for IFM measuring stage position.

- Note:
 - *Put the power where it matters.*

Beam Alignment part 1

- **Define a stage home position** → position that can be reached accurately and repetitively.
- **IFM measurement beams to be perpendicular to the stage measurement mirror:**
 - IFM to be oriented properly in mounting plane and against defined datum A, B etc.
 - IFM to be mounted with the proper torque
- **Beam delivery (benders, splitters) bring the beam to the IFM.**
 - Each bender / splitter to be aligned → incident beam is at 45 degree (tol. 10 μ rad)
 - Each bender output beam to be aligned → output beam is at 90 degree relative to input beam (no rotation into other planes)
 - **Splitter output beams** →
 - Transmitted beam to be parallel to input beam
 - Reflected beam to be at 90 degree relative to input beam (no rotation)
- **Use beam manipulators:**
 - **Wedge manipulator at each IFM** →
 - Fine tune beam translation and rotation
 - Achieve beam at center of IFM input aperture and perpendicular to stage mirror

Beam Alignment part 2

- **Wedge manipulator**
- **2 adjustable wedges**
- **1 translator plate**
- **Aperture 16 mm**
- **Efficiency >95%**
- **Translation range $\pm 3\text{mm}$ radial**
- **Translation resolution $20\mu\text{m}$**
- **Max. Angular Deviation 18 milli-radians**
- **Angular Beam resolution $<30\ \mu\text{m}$**



Beam Alignment part 3

- **Beam Benders N1204C/N1207C**
 - Horizontal & Vertical versions
 - Precise beam bending around 90 degrees
 - No beam translation
 - Range around 90 degree:
 - Yaw ± 6 degrees
 - Pitch ± 3 degrees
 - Reduction of cosine error
- **Beam Translator N1203C**
 - Input/Output beam parallel
 - Translation ± 3 mm
 - Resolution $1\mu\text{m}$
 - Reduction Abbé errors
- **Thermal & Mechanical stability**
- **6 Access ports**
- **Adjustment Tools**



System Design

- Start with measurement (& control) requirements for the stage
- Design metrology frame
 - Stable frame holding beam delivery and interferometers
 - Same frame is used for other sensitive measurement systems
- Application (stage control) determines # DOF's
 - Synchronize position acquisition with motion control
 - Sampling speeds 5 to 20 kHz
- Maximum stage speed determines laser source
- Laser and # axes determine receiver sensitivity
- Laser axis boards:
 - phase measurement → position
 - resolution extension → 0.15 nm
- Compensation boards:
 - corrections for environmental changes (temperature, pressure & humidity)

System Design Hints

-Required accuracy can be achieved through:

- Perfect alignment of optical components
- Implement controlled environment
- Use laminar air flow (perpendicular to the laser beams)
- Cover all beam delivery paths (from laser to interferometer)
- Do NOT use beam benders in measurement path (IFM – stage mirror)
 - Causes potential polarization mixing → non-linearity
- Mirror mapping
 - Characterize surface of stage mirror
 - Apply correction during measurements

Electronics (part 1)

- Receivers (sensitivity & band-width):
 - E1708A Remote Dynamic: sensitivity 2.2 μ Watts, bandwidth 7.2 MHz
 - E1709A Remote Dynamic sensitivity 0.2 μ Watts, bandwidth 15.5 MHz
 - High stage speeds require large bandwidth
- Laser Axis boards:
 - Synchronized Multiple-axis Measurements for coordinated movements
 - 10897C Laser Axis Board (VME)
 - One axis per board / Data update rate up to 10 MHz
 - Data age: fixed 890 nsec (variable <800 psec and < 60 psec/degC)
 - 10898AC Dual Laser Axis Board (VME)
 - Two axis per board / Data update rate up to 10.0 MHz
 - Data age: fixed 890 nsec (variable <800 psec and < 60 psec/degC)
 - N1231A/B Triple Laser Axis Board (PCI)
 - Three axis per board / Data update rate up to 20.0 MHz

Electronics (part 2)

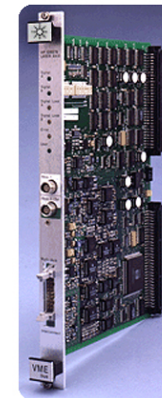
- 10896A Laser Compensation Board
- Environmental Sensors:
 - 10717A Wavelength Tracker
 - 10751 C/D Air Sensor
 - 10757 D/E/F Material Temperature Sensor
- Cables:
 - High performance cables (laser head & receiver)

Electronics (part 3)

- E1708A and E1709A Receivers



- 10897C and 10898A Laser Axis Boards



- 10896B Compensation Board



Electronics (part 4)

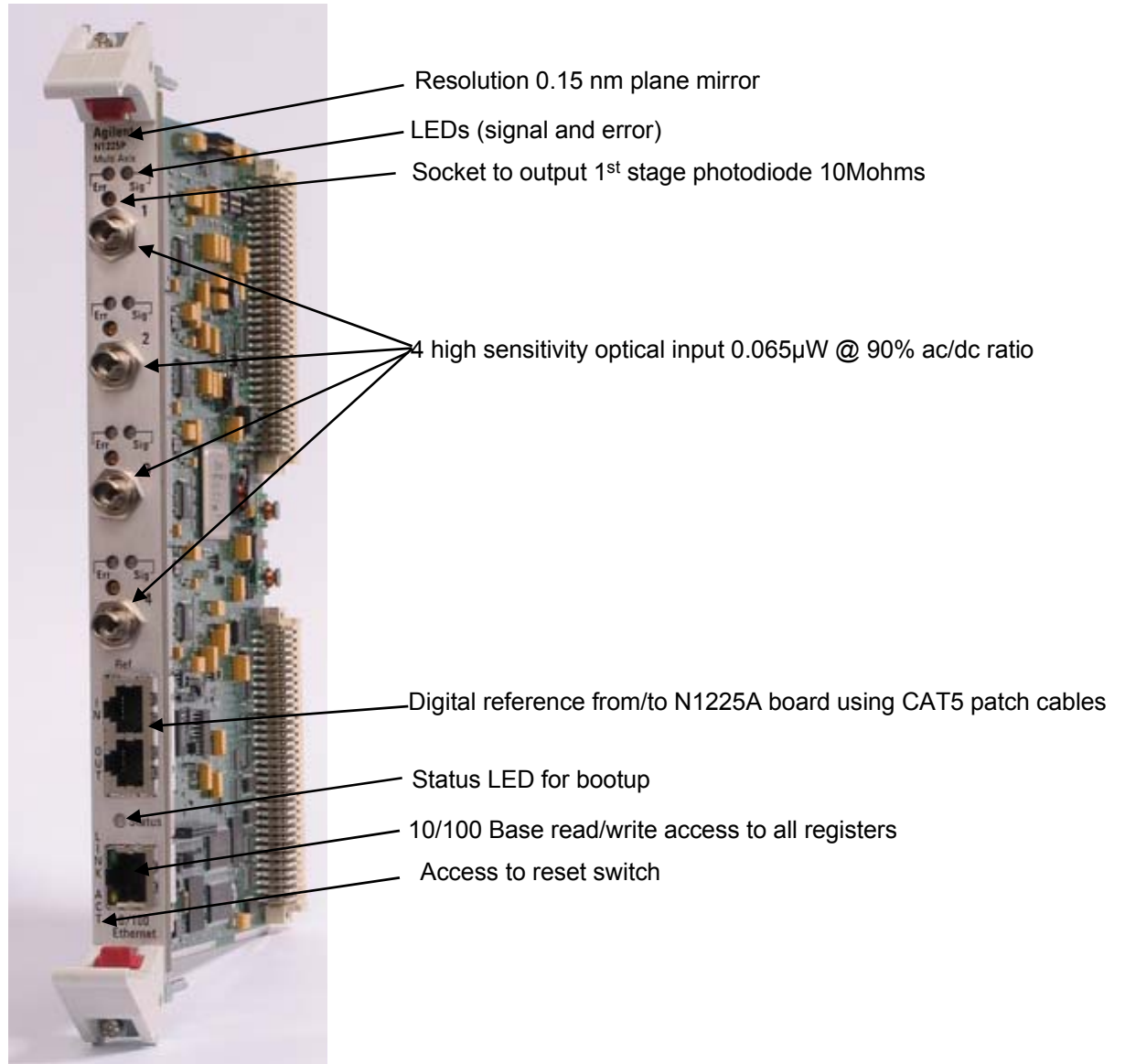
- N1231A/B Triple Laser Axis Board:
 - 0.15 nm resolution (plane mirror)
 - Flexible HW interface
 - External sample inputs
 - On-board programmable clocks
 - PCI compliant
 - PCI bus rates:
 - 200kHz 3 positions
 - 100kHz 3 position & velocity



Electronics (part 5)



- N1225A
- VME board
- 4 IFM axes
- High sensitivity
- Resolution 0.15nm
- VME & LAN I/F
- Improved algorithm



Electronics (part 6)

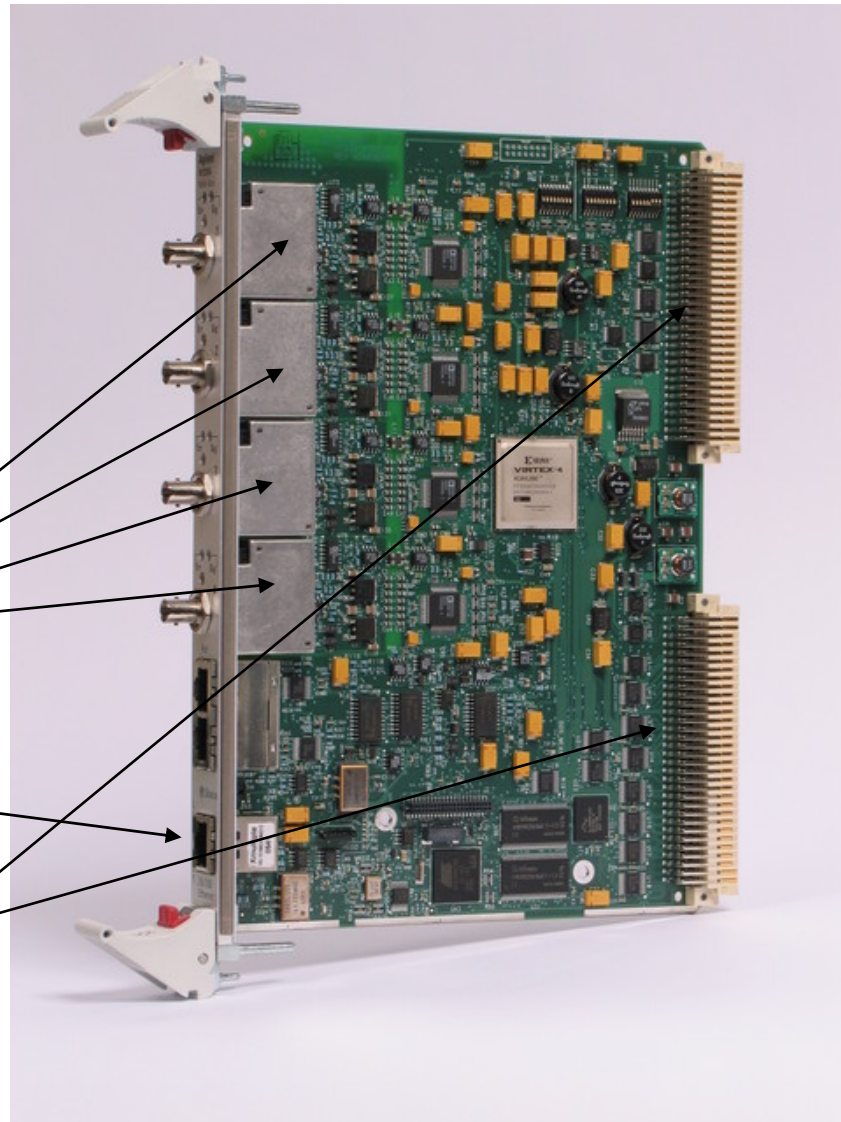


- 4 axes board N1225A

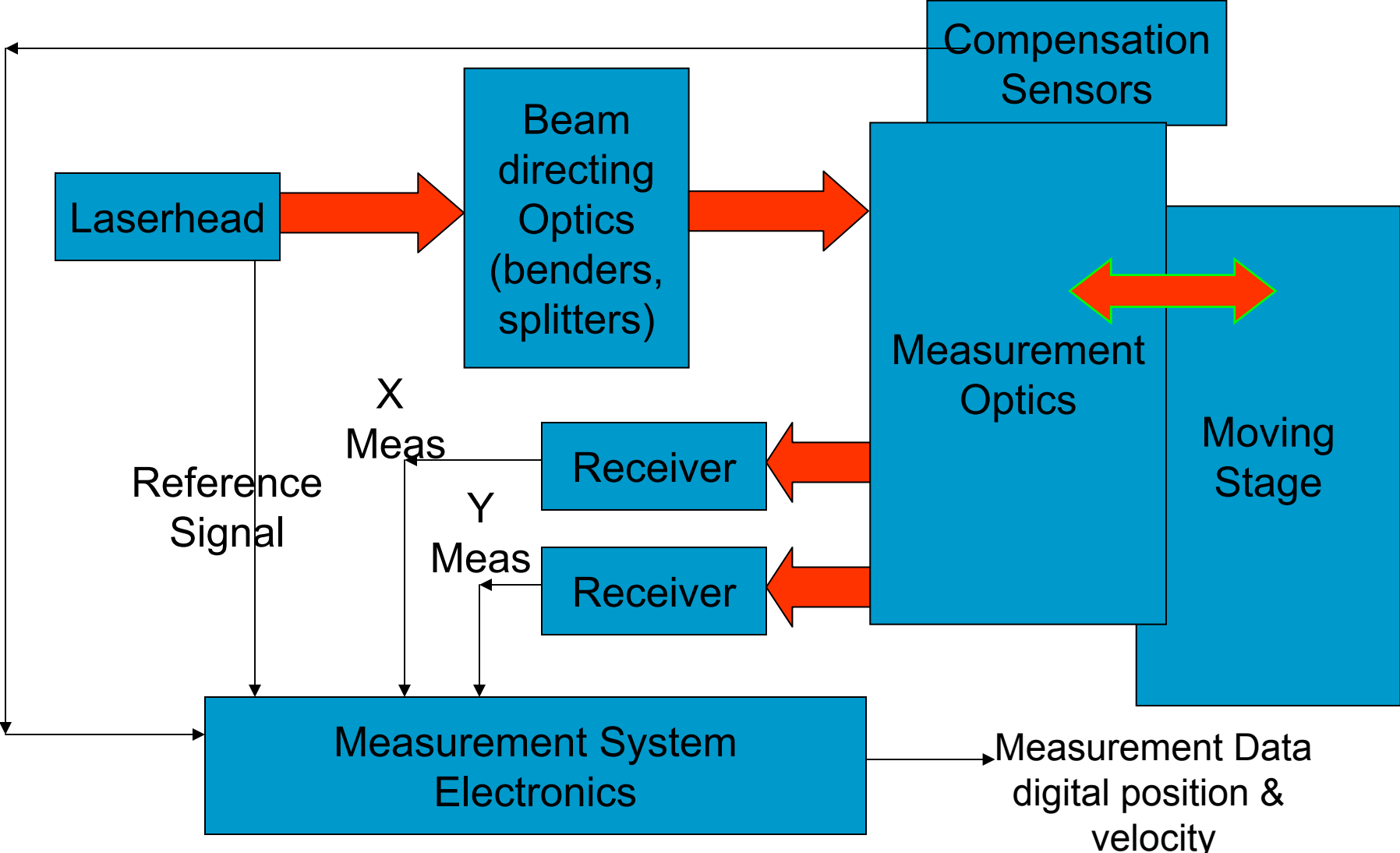
4 integrated receivers

10/100 Base LAN I/F

VME I/F



Putting System Components Together



Impact of Environment

Effect of variations in the environment of interferometer and stage mirrors:

Air-temperature

ΔT of 1.0 °C \rightarrow error 0.959 ppm in λ .

Air-pressure

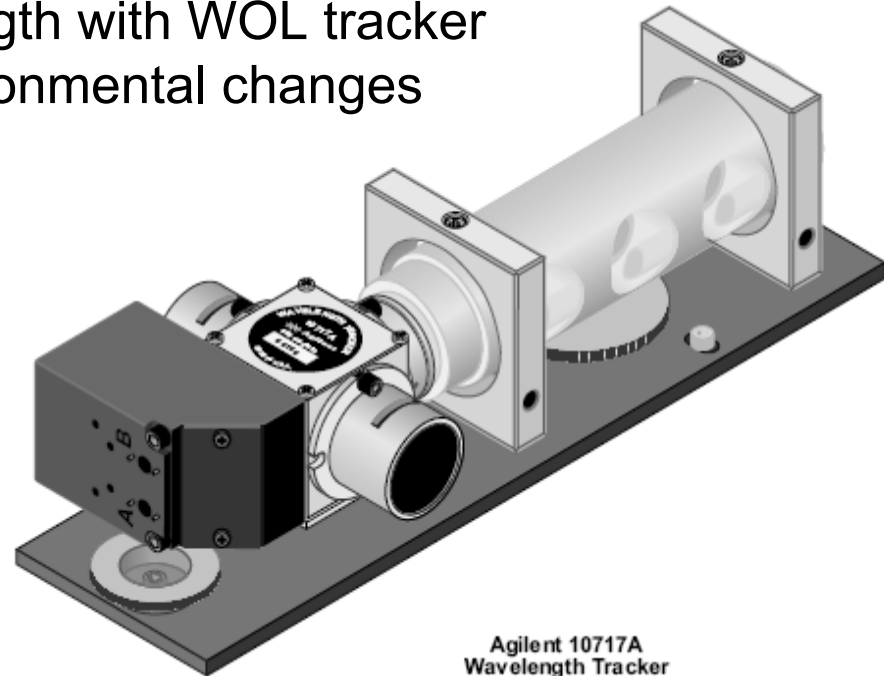
ΔP of 2.5 mm Hg \rightarrow error 0.894 ppm in λ .

Air-humidity

ΔH of 10% \rightarrow error 0.096 ppm in λ .

Environmental Issues part 1

- Changes in environment (temperature, pressure & humidity of air) affect wave length (λ)
 - $\Delta T, \Delta p \text{ \& } \Delta H \rightarrow \Delta \lambda \rightarrow$ IFM position measurement varies with environmental changes
- Continuous tracking of wavelength with WOL tracker
- Tracker \rightarrow monitors global environmental changes
- WOL tracker consists of:
 - Optical Ref. Cavity (etalon)
 - Differential IFM
- Etalon :
 - Build from Zerodur
 - 2 mirror at each end
 - Etalon has “constant” length
- WOL tracks $\Delta T, \Delta p \text{ \& } \Delta H$



Environmental Issues part 2

- However
 - WOL tracker requires initial p and T measurements
 - WOL tracker → monitors global environmental changes
 - Does not track environmental changes in measurement beams
- Improvements:
 - Track environmental changes at/around moving stage
 - Add high accurate thermal and pressure measurements
 - Monitor T and p-sensor
 - Update WOL with Edlin formulae
 - Apply compensation
- Note:
 - High accuracy barometric sensor p-sensor are available
 - Range 11-16 psi (atmospheric), $\pm 0.01\%$ full scale accuracy, good long-term accuracy
 - Update rate ~ 30 readings/sec.

Atmospheric Compensation

- Any change in refractive index of air affects WOL
- Without WOL compensation system accuracy and repeatability is degraded.
- WOL can be implemented with wave-length tracker or with high accuracy T, p and H sensors

However:

- To achieve high accuracy and resolution more is required such as
 - Set specifications for air quality
 - Reduce noise in the IFM system by:
 - Implement (closed) stage environment (with over-pressure)
 - Reduce air leakage to the minimum
 - Eliminate “hot” spots (remove sources of heat-dissipation)
 - Reduce any gradients (T & p) by laminar air flow
 - Follow strict operational procedure

Set Specifications for Air Quality

- **Conditioned air with narrow temperature specifications**
 - **Set-point range 20 – 24°C**
 - **Set-point tolerance $\pm 0.1^\circ\text{C}$**
 - **Stability of 0.0023°C over 5 minutes**
- **Monitor air-pressure**
 - **Rates of 1 to 10 (or more) readings/sec**
 - **Measurement accuracies 0.1 to 0.01 Pascal**
- **Conditioned air with respect to humidity**
 - **Range 35 to 60%**
 - **Stability better than 5%**
- **Air cleanliness:**
 - **Class 0.1**
 - **0.25 particles per cubic feet**
 - **Particle size $< 10 \mu$**

- **Note:**
 - Monitoring refractive index can be accomplished with WOL tracker
 - However:
 - Moving stages have their own air pressure dynamics (pressure variations while moving)
 - Heat sources close to the moving stage (motor, electronics or ...)

Reduction of Environmental Noise

- **Reduce local T & P disturbances**
 - Use closed environment for the stage (incl. IFMs & beam-delivery)
 - Use conditioned air → tightly thermal controlled air
 - Use overpressure in enclosure
 - Prevent leakage of “bad” air from outside in stage area
 - Cover all laser beams to the IFM’s
 - Reduce changes to laser beams in beam delivery to all IFM’s
 - Monitor air temperature and air pressure
 - Prevent air-pockets with slightly different temperature in the laser beams
 - Limit number of heat-sources in the enclosure or close to the laser beams
 - Set specification for maximum heat dissipation (10 to 20 Watts)
 - Remove “hot” spots
 - Apply low heat resistance material plus cooling device)
- **Air movement**
 - Application of continuous and homogeneous air-flow
 - Laminar flow is perpendicular to the laser beams
 - Air speed to be a magnitude above stage speed
 - Use tightly conditioned air
 - Implement air down-flow: supply on top, exhaust at bottom
 - Exhaust air can be re-circulated, but must be re-conditioned

Accuracy & Repeatability

- Accuracy → max. deviation of a measurement from a know standard
- Repeatability → max. deviation between measurements taken under same conditions and with same instrument
- Error Components :

Error Components by Category	System Error Budgets		
	Accuracy	Long-Term Repeatability	Short-term Repeatability
Intrinsic			
Laser Wavelength	X	X	X
Electronics Error	X	X	X
Optics Nonlinearity	X	X	X
Environmental			
Atmospheric Compensation	X	X	X
Material Thermal Expansion	X	X	
Optics Thermal Drift	X	X	
Installation			
Deadpath Error	X	X	X
Abbé Error	X	X	
Cosine Error	X		

Accuracy & Repeatability - Laser Wavelength

- Wavelength stability & accuracy of 5517 laser (1 hour):
 - Accuracy ± 0.02 ppm
 - Stability ± 0.02 ppm
- Stability environmental conditions (1 hour)
 - Temperature $\pm 0.1^{\circ}\text{C}$
 - Pressure ± 2.5 mm Hg

Accuracy & Repeatability – Electronics & Optics

-Electronics Error

- Basic resolution determined interferometer
- Resolution $\rightarrow \lambda/2$ for single and $\lambda/4$ for dual pass IFM
- Electronics \rightarrow resolution extension up to 0.15 nm (=error)

-Optics Non-linearity

- Determined by the optics \rightarrow optical leakage of one polarization component into the other (typical < 2.2 nm)
- Fixed term and typical each interferometer

Accuracy & Repeatability – Environmental

-Atmospheric Compensation

- Repeatability of compensation factor from wavelength tracker
 - Formula: $0.03 + 0.06 \Delta T (^{\circ}\text{C}) + 0.002 \Delta p (\text{mm Hg})$
 - Repeatability with given ΔT , ΔPT and $R=0.6 \rightarrow 0.041 \text{ ppm}$
 - Note: factor 0.03 determined by $R = \text{resolution, etalon length and non-linearity contribution}$

-Material Thermal Expansion

- Machine dimensions are function of temperature:
 - Material compensation $\rightarrow (1-\alpha)\Delta T$
 - With $\alpha = \text{thermal expansion coefficient}$. $\Delta T = \text{temperature change relative to } 20^{\circ}\text{C}$
 - Compensation with material temperature sensor (accuracy $\pm 0.1^{\circ}\text{C}$, repeatability $\pm 0.1^{\circ}\text{C}$)

-Optics Thermal Drift

- Thermal drift (xx nm/ $^{\circ}\text{C}$) is given by interferometer (and by axis)

Accuracy & Repeatability – Installation

-Deadpath

- Deadpath = difference in optical path length between Ref. and Meas. components at zero position
- Deathpath correction = Deathpath Length * WOL repeatability
- Required for each interferometer axis
- Abbé Error
 - Caused by offset between measurement and movement axis combined with unwanted angular motion
 - Compensation is possible when angular motion is measured by the system
- Cosine Error
 - Caused by misalignment of measurement and mechanical axis of motion
 - Error = $(1 - \cos \theta) \cdot 10^6$ ppm, where θ angle of mis-alignment
 - Use proper alignment techniques
 - Error for plane mirror interferometers ~ 0.05 ppm

Summary Accuracy & Repeatability

	Laser Interferometer System	
	Accuracy is the Sum of	Repeatability is the Sum of
Proportional Terms	Laser Wavelength Accuracy Atmospheric Compensation Material Thermal Expansion Cosine Error Deadpath Error	Laser Wavelength Stability Atmospheric Compensation Material Thermal Expansion not applicable Deadpath Error
Fixed Terms	Electronics Error (Resolution) Optics Non-Linearity Optics Thermal Drift Abbé Error	Electronics Error (Resolution) Optics Non-Linearity Optics Thermal Drift Abbé Error

Accuracy & Repeatability – Example (inputs)

Maximum distance measured (L) 200 mm

Deadpath distance (D) 20 mm

Cosine error ± 0.05 ppm

Non-linearity ± 2.2 nm

Optics Thermal Drift: 50nm/°C

Abbé error: none (assume zero offset)

Measurement resolution ± 0.31 nm

Temperature 20 ± 0.1 °C

Pressure 760 ± 2.5 mm Hg

Humidity $50\% \pm 10\%$

Accuracy & Repeatability – Example (results)

- Laser Wavelength Stability: $(\pm 0.02 \text{ ppm}) * L \rightarrow (\pm 0.02 * 10^{-6} * 0.2) = \pm 4 \text{ nm}$
- Laser Wavelength Accuracy: $(\pm 0.02 \text{ ppm}) * L \rightarrow \pm 4 \text{ nm}$
- Atmospheric Compensation ($\pm 0.1^\circ\text{C}$, $\pm 2.5 \text{ mm}$, $\pm 10\%$) $\rightarrow \pm 0.041 * 10^{-6} * 0.2 = \pm 8.2 \text{ nm}$
- Without atmospheric compensation $\rightarrow \pm 9 * 10^{-6} * 0.2 = \pm 1.8 \mu\text{m}$
- Material expansion (accuracy & repeatability): $(1-\alpha)\Delta T$ ($\alpha=10 \text{ ppm}$ for stainless steel and length 200mm) $\rightarrow \pm 0.2 \mu\text{m}$
- Deadpath error: $\pm 0.041 * 10^{-6} * 0.02 = \pm 0.82 \text{ nm}$
- Without atmospheric compensation $\rightarrow \pm 9 * 10^{-6} * 0.02 = \pm 0.18 \mu\text{m}$
- Measurement resolution: 0.31 nm
- Non-linearity: 2.2 nm
- Optics Thermal Drift: $\pm 50\text{nm}/^\circ\text{C} * \Delta T = \pm 5 \text{ nm}$
- Abbé error: none (assume zero offset)
- Cosine error: $\pm 0.05 \text{ ppm} * L \rightarrow \pm 5 \text{ nm}$

Accuracy & Repeatability – Example (summary)

	with compensation	without compensation	
Laser Wavelength Error	4.00	4.00	nm
Compensation Error	8.20	1800.00	nm
Material Thermal Expansion	0.00	0.00	nm
Deadpath Error	0.82	180.00	nm
Electronics Error	0.31	0.31	nm
Optics Non-Linearity	2.20	2.20	nm
Optics Thermal Drift	5.00	5.00	nm
Abbe Error	0.00	0.00	nm
Cosine Error	10.00	10.00	nm
Direct Sum	30.53	2001.51	nm
RSS	21.28	1990.01	nm

Conclusion:

- Worst Case Accuracy (direct summing):
-31 nm versus 2001 nm
- RSS Accuracy (root mean square):
-21 versus 1990 nm
- Repeatability (by leaving out Cosine Err)
-11.3 versus 1980 nm
- Largest contributors
 - Atmospheric compensation
 - Deadpath error

RSS = Square root(sum of squared independent terms+ square of sum of dependent terms) + offset