Dimensional Metrology

And

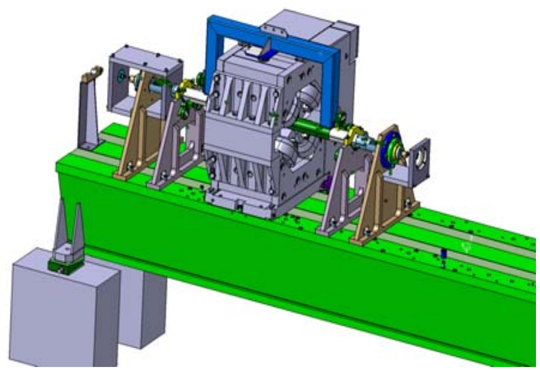
Positioning Operations

(Alain LESTRADE, Synchrotron SOLEIL)

Frame of the lecture

- **Theoretical tools for designers in the field of the measure:**
  - Magneticians who need Metrology: bench for magnetic measures, magnet (positioning)
  - Mechanical engineering

Mechanics ↔ ***Metrology*** ↔ Magnetism



  - To take the opportunity to introduce the basis an extended approach of DM & Alignment
  - In addition of what already exists on the topic
  - To present a case study: from the rotating coil to the beam orbit definition
  - Examples & case study are oriented “Synchrotron facility”

Frame of the lecture

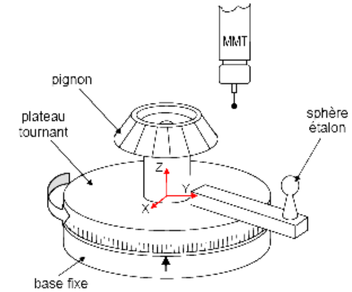
- **Theoretical tools for designers in the field of the measure:**
  - To reach the necessary accuracy
  - with a good reliability

  - Common forgetting about reliability:

- **Micrometers or nanometers from sensors are nothing without reliability, redundancy is necessary but sometimes difficult (costly).**

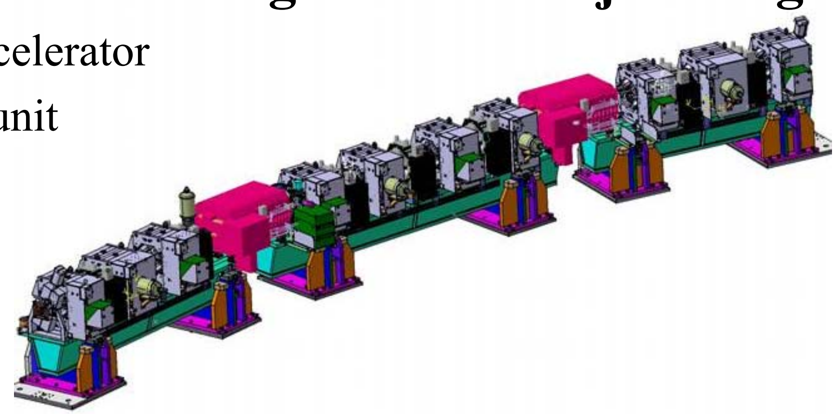
Introduction

- **Dimensional Metrology: measuring the "shape" of an object:**
  - Dimensions (length)
  - Relative coordinates of 2 points (W.R. to a referential)
  - Displacements
  - Shapes (roundness, straightness)
  - Angles



Gear measured by CMM

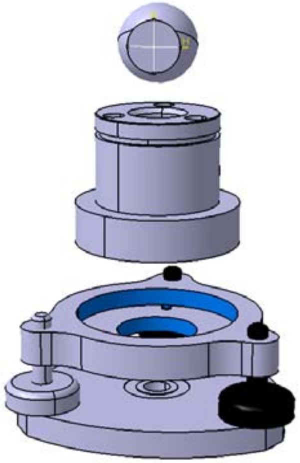
- **Positioning Operations: alignment of objects together:**
  - Magnets of an accelerator
  - Any mechanical unit

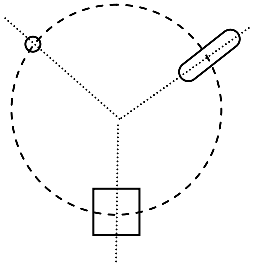


Introduction

- **Sensors & Instruments: deliver a measurement:**
  - Distances : Caliper, Electronic Distancementer (total station, laser tracker), etc.
  - Angles : Theodolite, inclinometer, autocollimator, etc.
  - Displacement: Interferometer → Distance & Angle measurements
  - (Magnetism : Rotating coils)

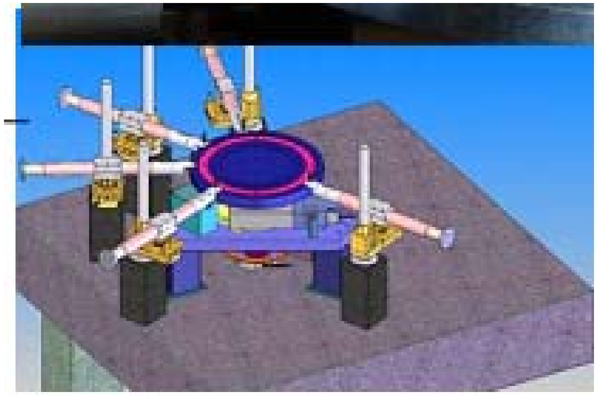
- **Mechanics: delivers a "position":**
  - Links & contacts:
    - Shaft-bore
    - Sphere-cone
    - Kinematic mount (line-dot-plane), etc.

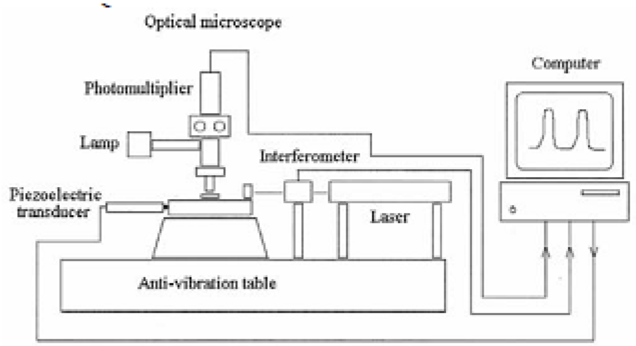




Introduction

- **Time dependence of electronics & mechanical units:**
  - Any structure is subject to tiny shape modification, stress or displacement (ex: thermal dependence) due to influence quantities and varying with time
  - *Metrology depends on time*
- **Spatial layout (design):**
  - spatial analysis of any measurement system
  - *Metrology depends on space*





Martin, ESRF

Introduction

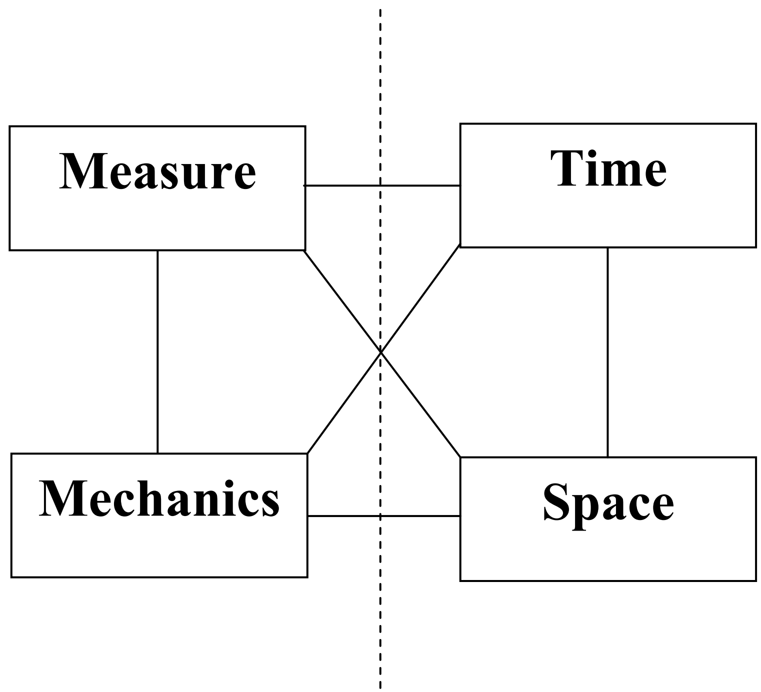
- **The four components of Design in Dimensional Metrology units:**

Means: *Point of view:*

Sensors & instruments:

Random & Bias (offset) Er

σ & B



Mechanical units:

Random & Bias (offset) Er

σ & B

Stability	σ
Angle-Length	
Effective length	σ
Metrology loop	σ
Lever arms	σ
Multi-Step Layout	*B & σ*
Differential Meas.	*B*

Introduction

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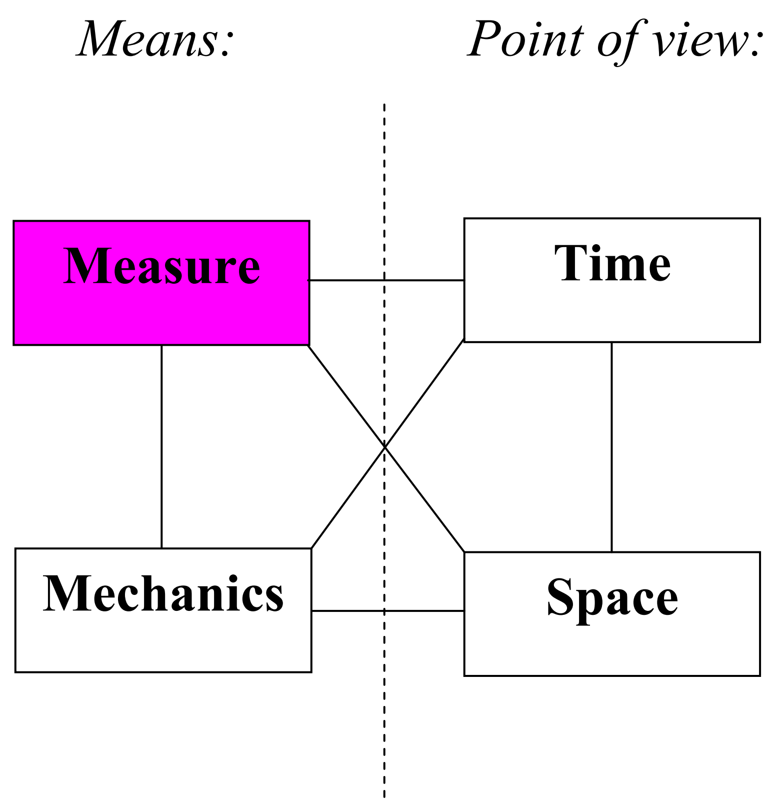
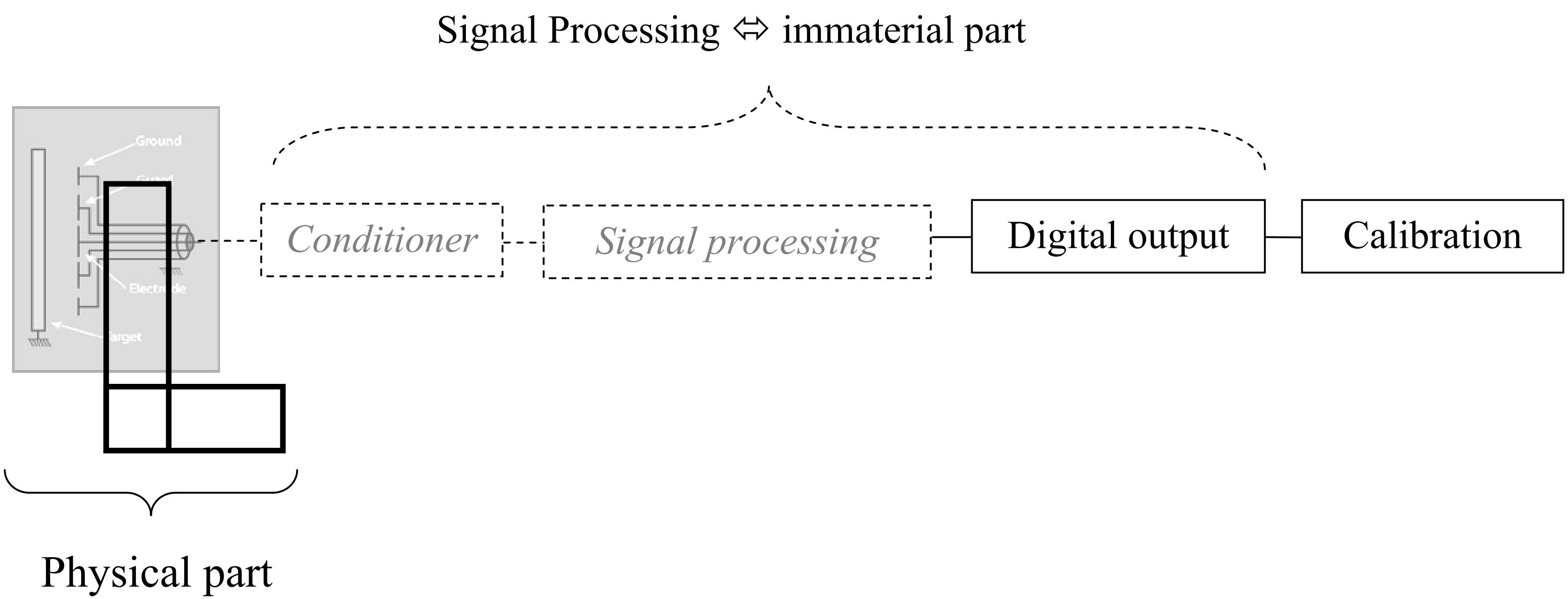
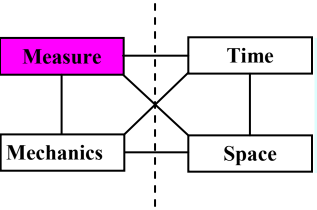


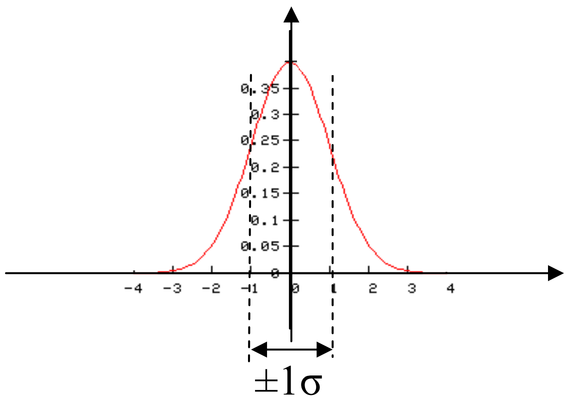
Measurements

- **The sensor: We just consider it as an output value affected by a noise (σ) and a bias (or offset). The linearity error is supposed to be treated (calibration)**





Random errors of sensors (type A errors)



$$M = \frac{1}{n}\sum_{i=1}^{n} m_i$$

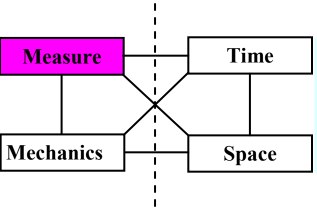
$$\sigma = \frac{1}{n-1}\sum_{i=1}^{n} m_i^2$$

- **Normal distribution of random errors: standard deviation**
- σ **is used as the definition of the accuracy (precision) of a measurement**

- **Law of random errors combination (n independent random variables) :**

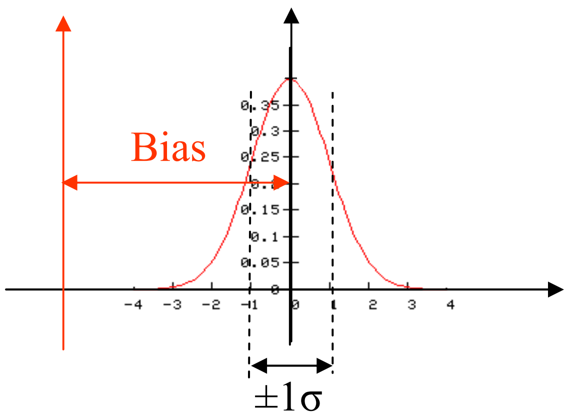
$$\sigma_{tot} = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$$

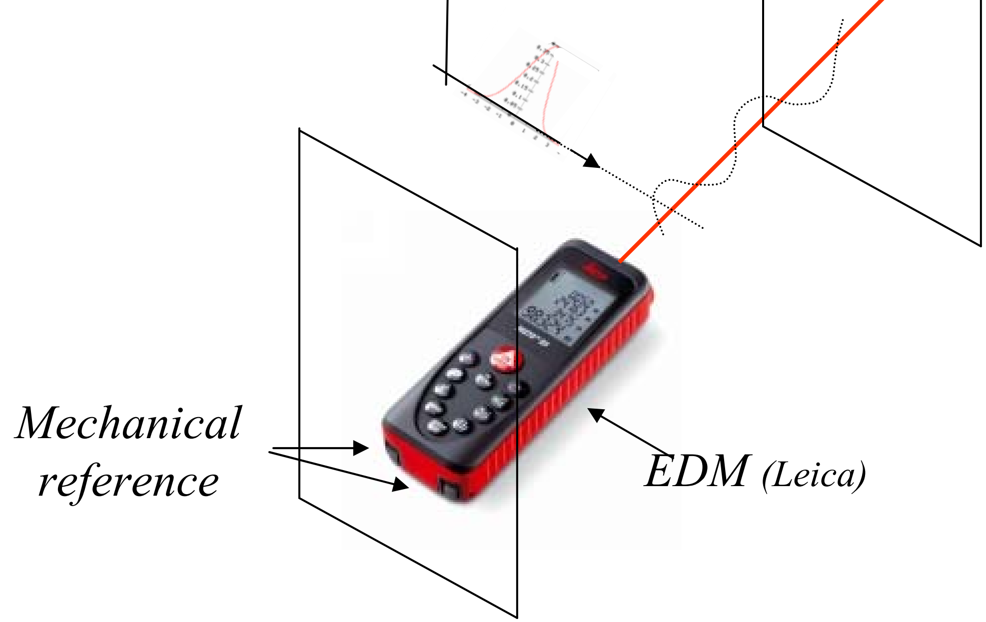
- **It leads to an error budget**
- **Not exhaustive but the main statistical terms (Ki² test, LLSC ,etc…)**



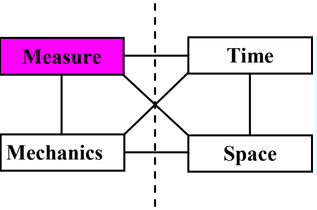
Bias errors of sensors (type B errors)

- the zero value of a sensor not known / mechanics (offset)
- Linearity errors of sensors: → calibration





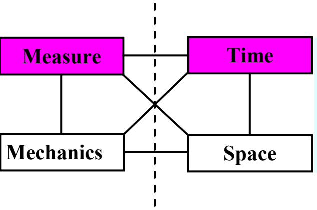
- The bias errors do not depend on time and their magnitude can be important



Errors depending on the external sources

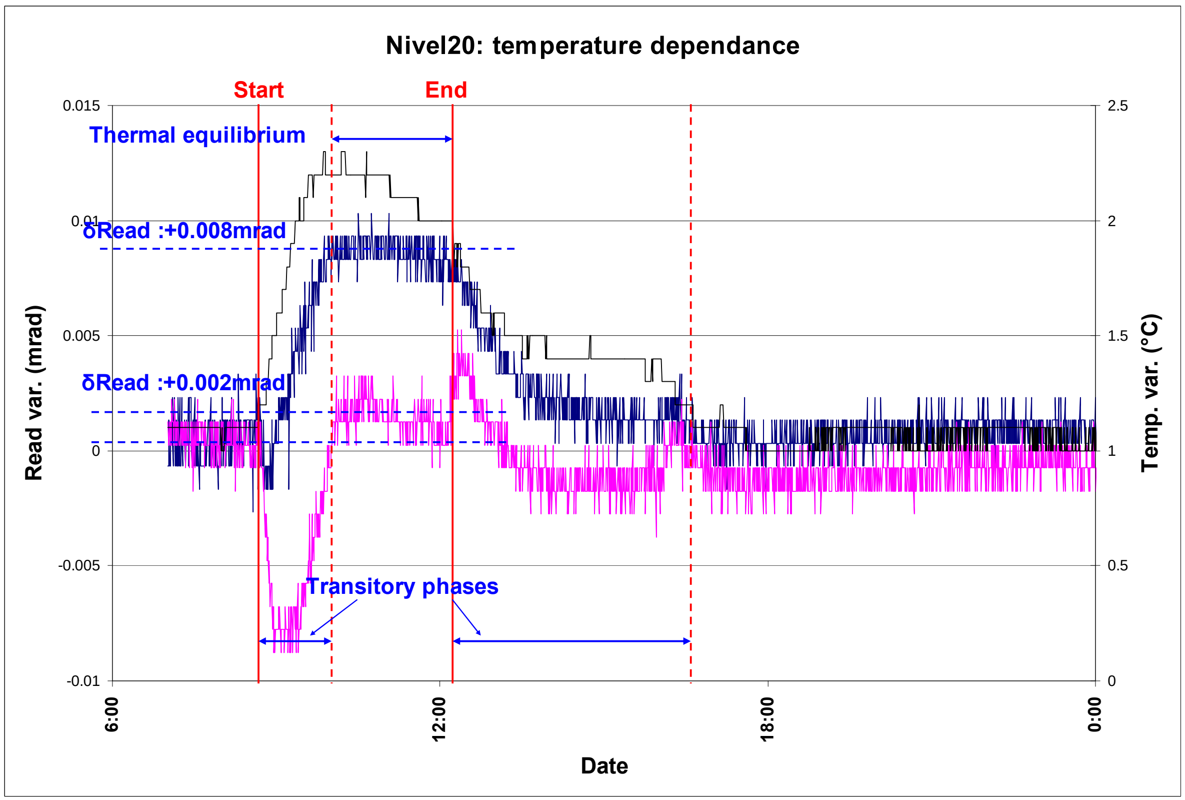
- **Also called “influence quantities”**
  - Vibrations
  - Slow drifts of mechanical units
  - Or of the ground

- **The main influence quantity is the thermal parameter:**
  - Electronic components
  - Mechanical unit

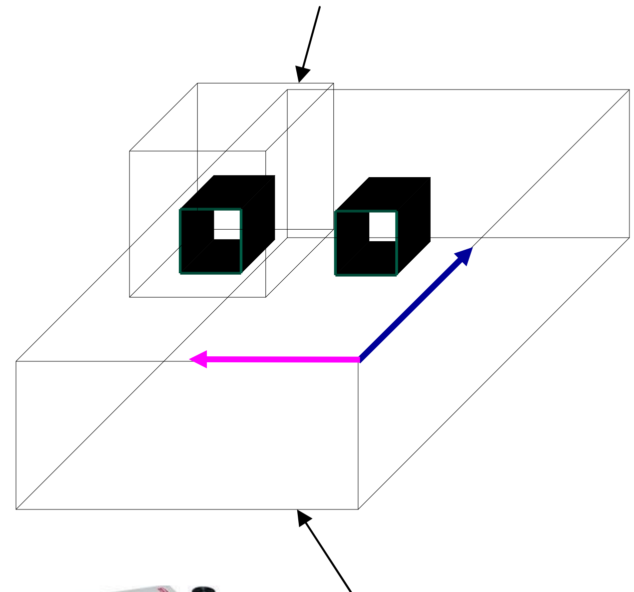


Thermal dependence

- 2 inclinometers on a marble
- Difference of readings versus temperature



Thermal cover



Marble

Leica Nivel20

Introduction

- **The four components of Design in Dimensional Metrology units:**

Means: *Point of view:*

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Random & Bias (offset) Er

σ & B

Mechanical units:

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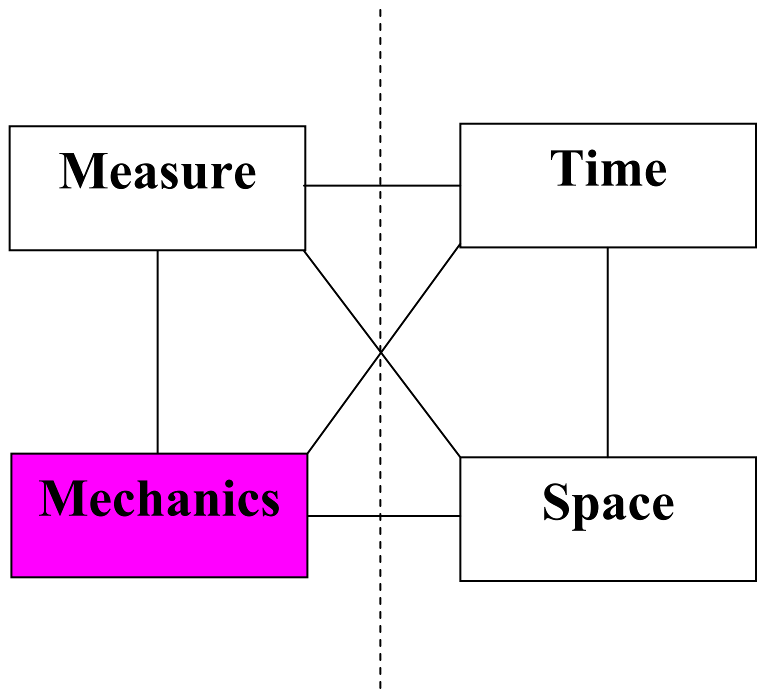
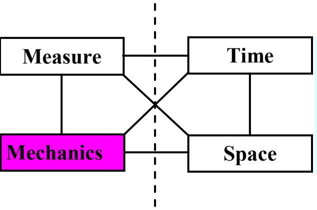
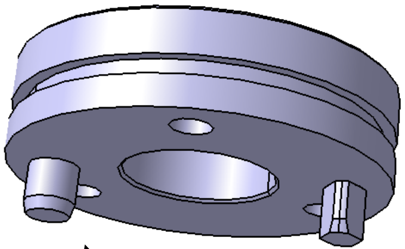
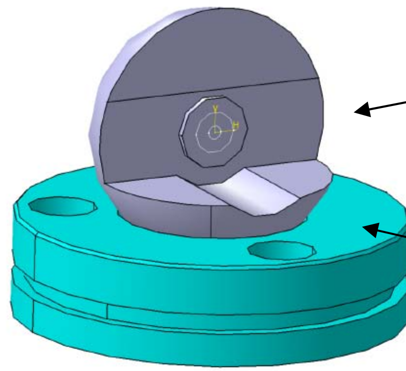




Mechanics: positioning & measurements

- **Mechanics is a full component of the DM as a positioning system:**
  - As centring systems:





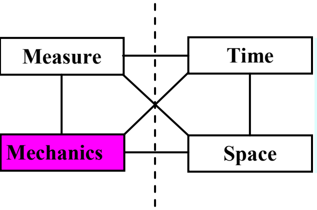
Target / Sphere

Sphere / Cone

Cone / pins

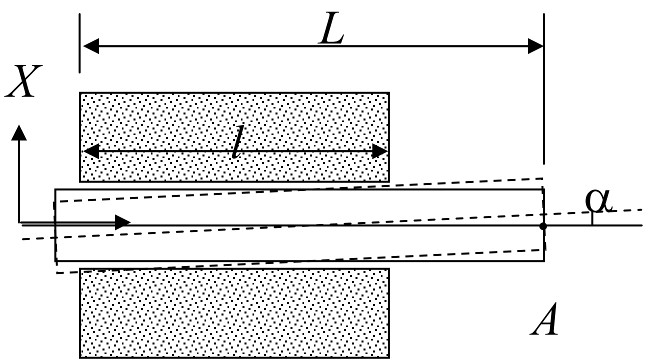
pins / magnetic axis

- **Mechanics can deliver a dimensional quantity: gage block "Johnson"**

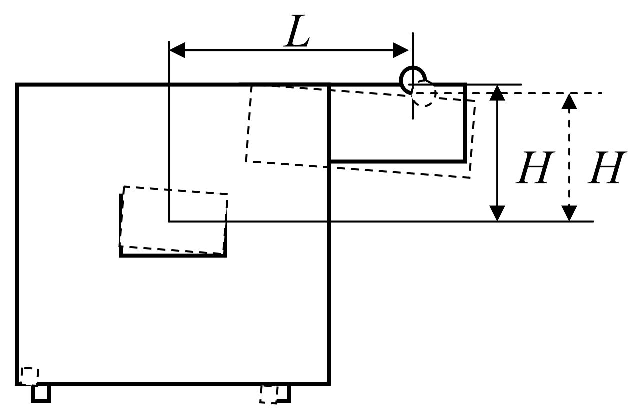


Random errors in Mechanics

- **Accuracy of machining is equivalent to random errors in the field of measurements**
- **Clearance $\sigma=10\mu m$ (do not confuse with the tolerance)**
- $\sigma_\alpha = \sigma/l$
- **the X uncertainty at the point A is:** $\sigma_X = L.\sigma_\alpha$
- **The H accuracy depends on the rotation one**



Clearance of a unit shaft-bore

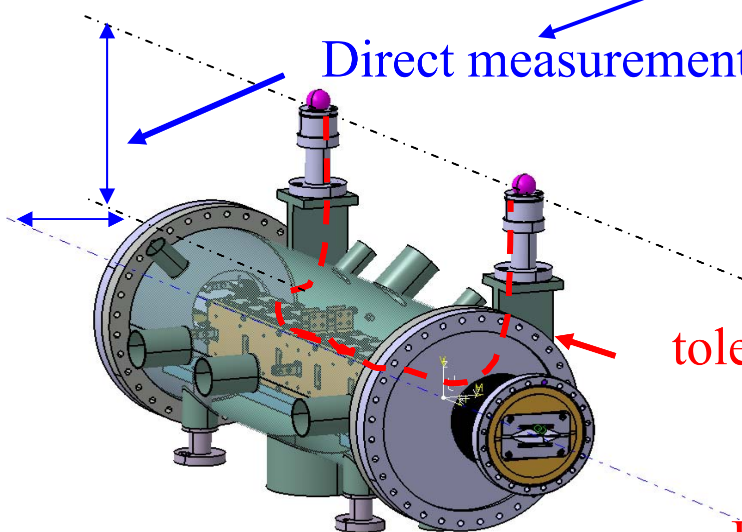


Dependence from lever arm

Offsets in Mechanics

- **Mechanical unit measured after having being machined; the difference with respect to the nominal dimension is called “offset”, and is similar to a bias error.**

Fiducialization ⇔shunt of the assembly



$h_\sigma = offset$

With $\sigma < \sigma_{tot}$

tolerance stack-up

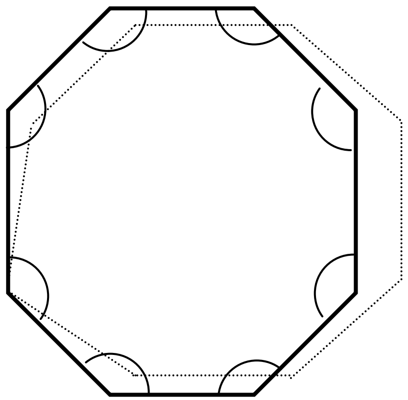
⇔

Error budget

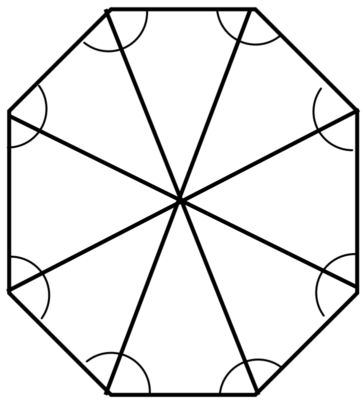
$$\sigma_{tot} = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$$

Analogy between Measure and Mechanics

- **1) The least squares principle ($\sum \upsilon_i^2$ minimum), in the field of measures corresponds to a minimum of energy of a mechanical system at equilibrium.**
- **2) Strengthening a geodetic network with additional measurements:**



Sensitive to errors



The network is more rigid

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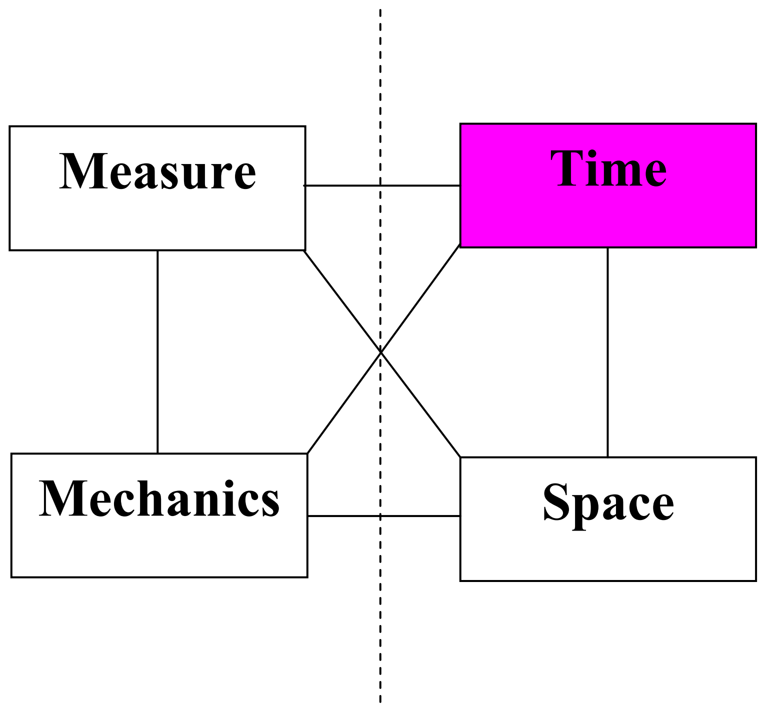
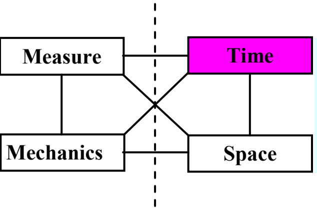


Stability σ

Mechanical units:

Random & Bias (offset) Er

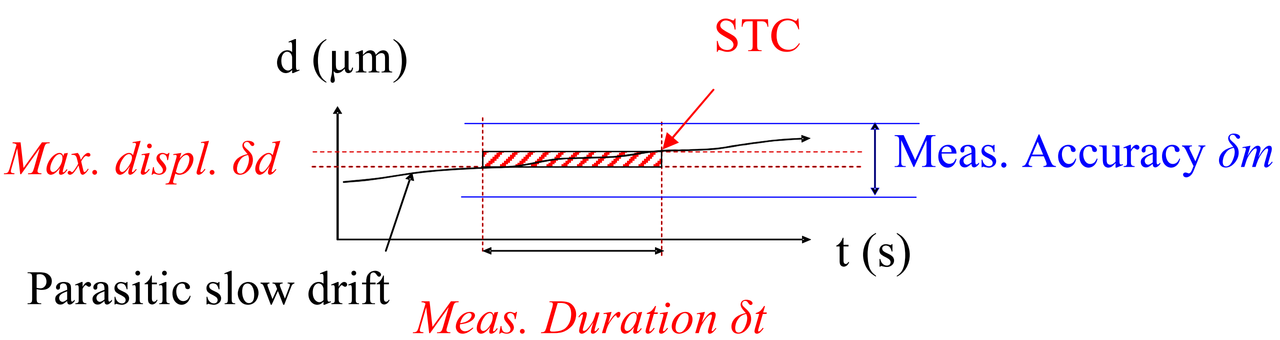
σ & B



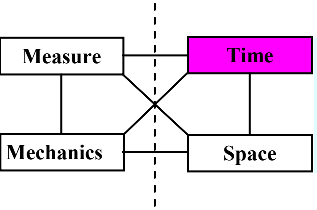
Stability Time Constant

- **The stability of the set "Instrument-Object" should be better than the instrument precision**
- **STC is the acceptable duration δt during which we do not want less than a parasitic displacement quantity δd :**

  - ***STC = (δd, δt)***



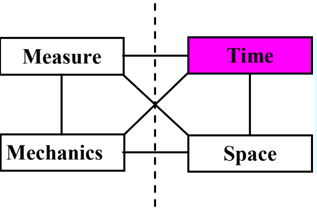
- **whatever the origin of the disturbance of the system: mechanical, electronic, etc.**
- **It's common to consider δd as a random error**



Stability Time Constant

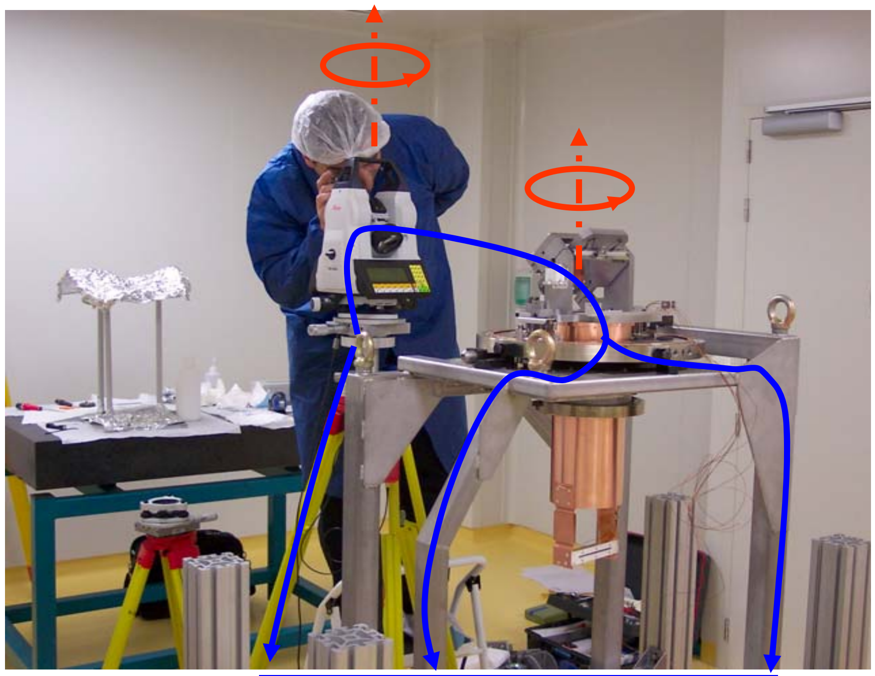
- **Stability analysis is mandatory to fit to the required accuracy**
- **For both, <u>instrument</u> and <u>object</u> to be measured**

(Synchrotron Soleil)



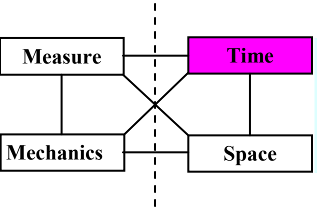
Stability Time Constant

- **differential DOF * has to be considered: R_z**



(Synchrotron Soleil)

* *DOF: Degrees OF Freedom*

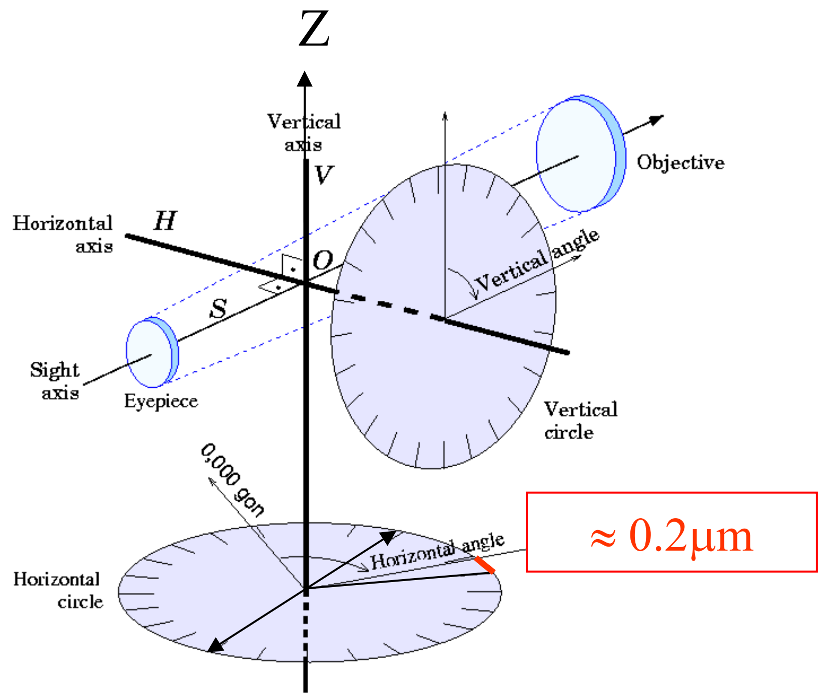


Stability Time Constant

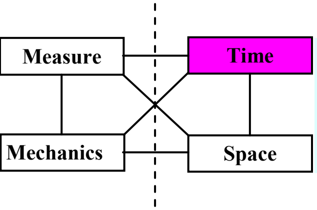
- **Theodolite**
  - $\underline{3.10^{-4} deg}$ accuracy
  - $\underline{\delta t = 30mn}$ measurement duration

$$STC_{\theta Z} = (3.10^{-4} deg;\ 30mn)$$

Leica TDA5005, TM5100A

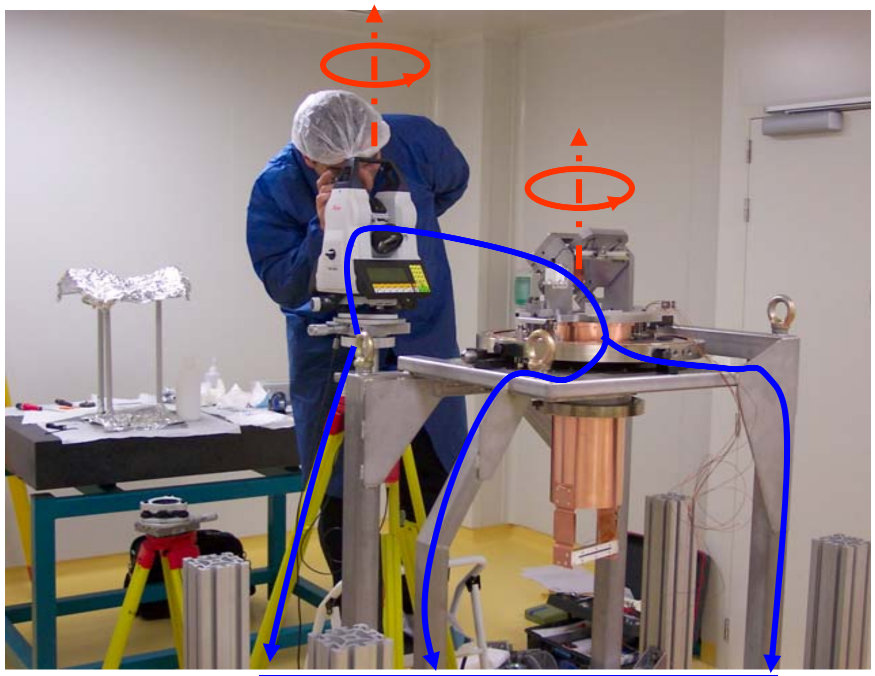


ø70mm



Stability Time Constant

- **One solution is: re-measuring periodically the angle between the 2 mirrors ⇔ *$STC_{\theta Z}$ = (3.10^{-4}deg; 2mn)***

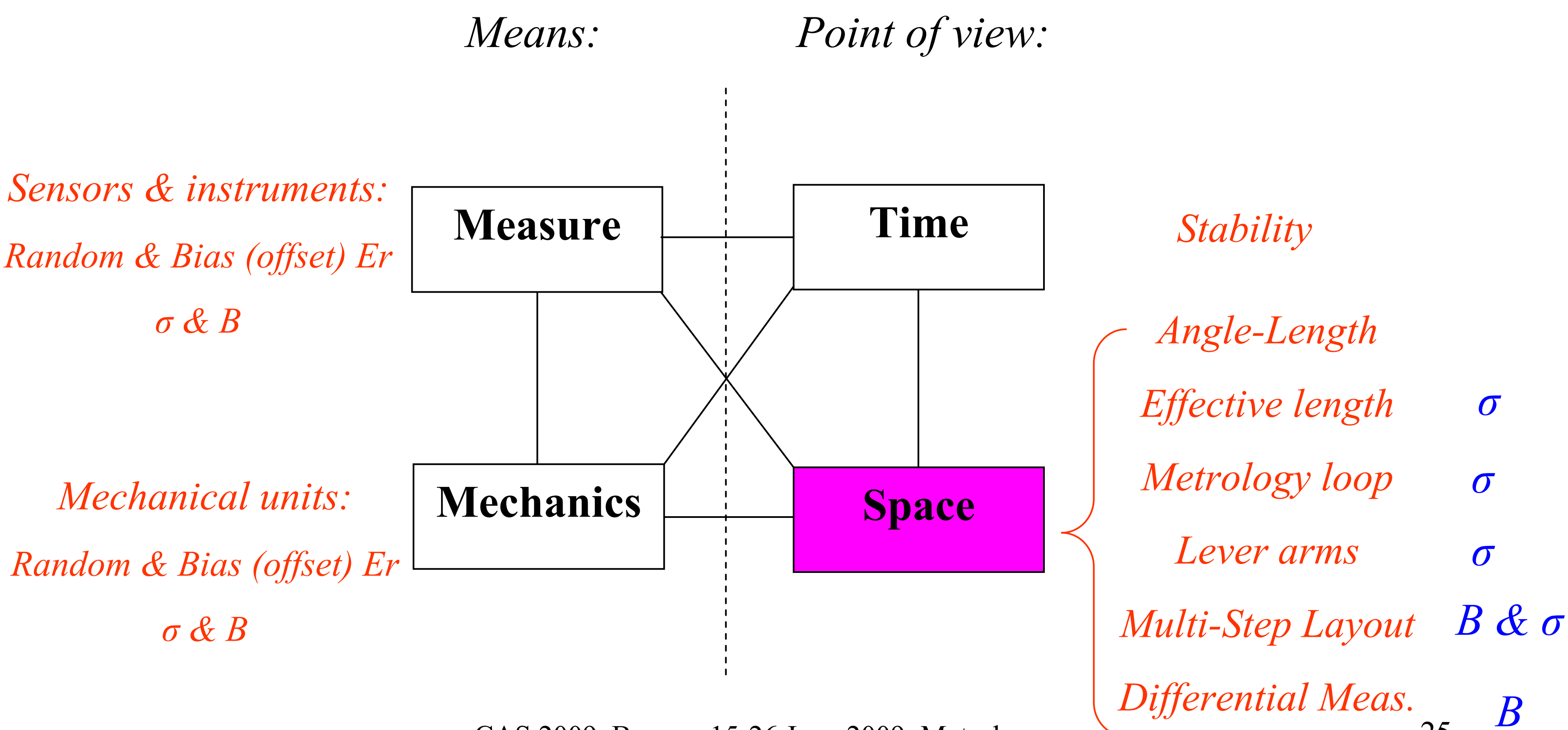


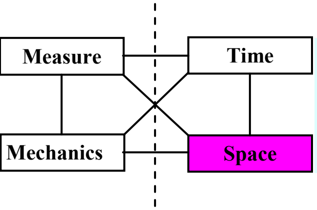
(Synchrotron Soleil)

** DOF: Degrees OF Freedom*

Introduction

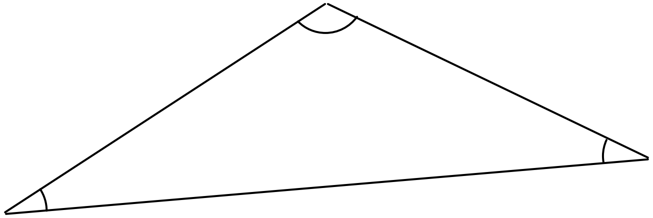
- **The four components of Design in Dimensional Metrology units:**



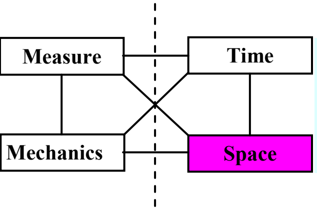


Spatial aspect of DM: Affine Space

- **The physical space is mathematically modelled by an Affine Space with 3 dimensions:**
  - The Length: "quantity **with** a dimension and with a unit", the meter
- **The angles are define by a ratio of two lengths:**
  - The Angle, "quantity **without** dimension and with a unit", the radian

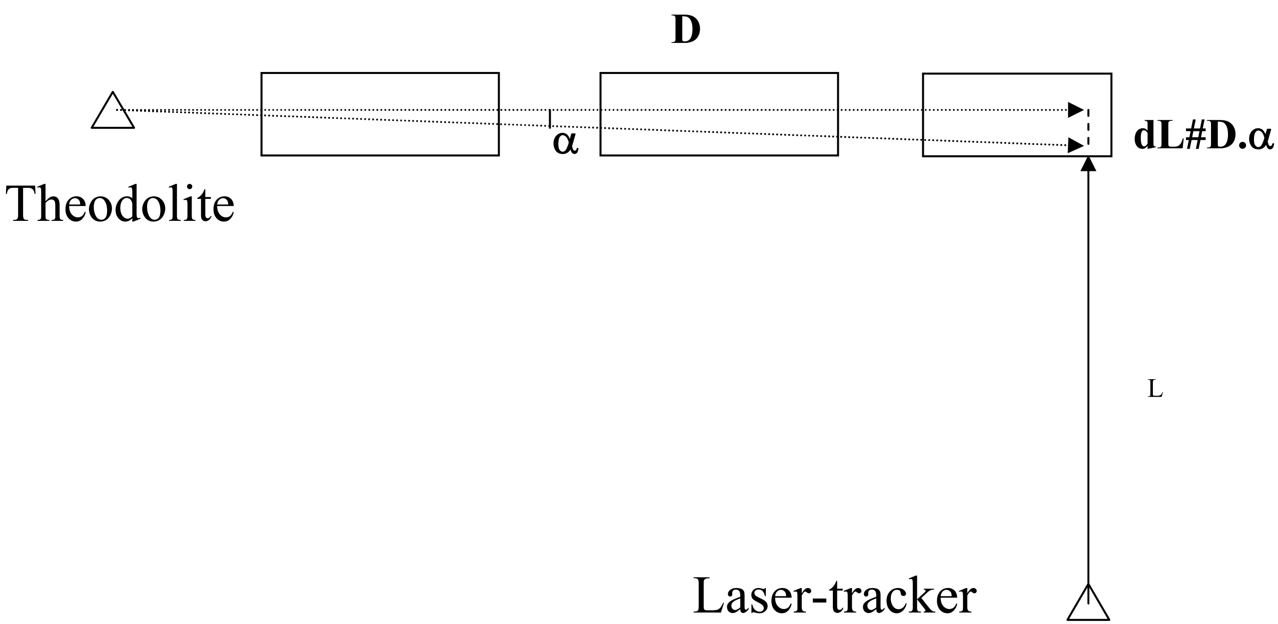


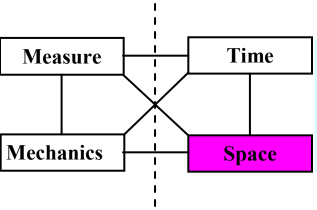
- **3 quantities are enough to define a triangle**
- **Case of 3 angles known: we can only define its shape and not its dimension**



Spatial aspect of DM: Affine Space

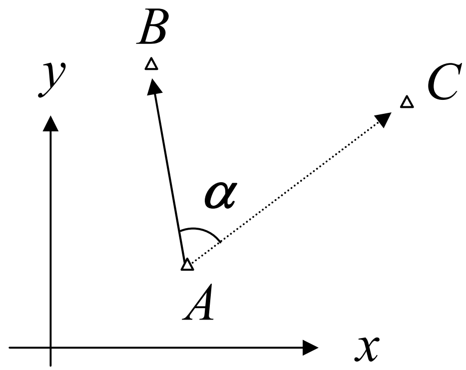
- **The small angles are often assimilated to a length:**
  - duality “angle-length”
- **Alignment on linear structure: Angle or length approach**



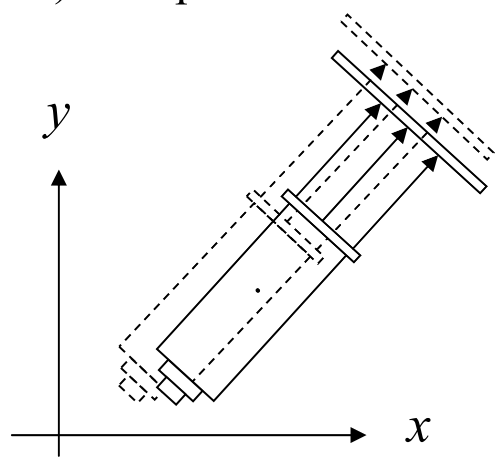


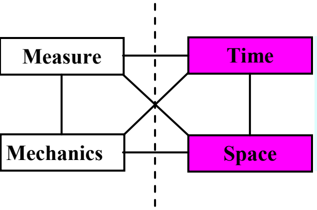
The Angles: Affine & Vector Spaces

- **Affine Space:**
  - Theodolite



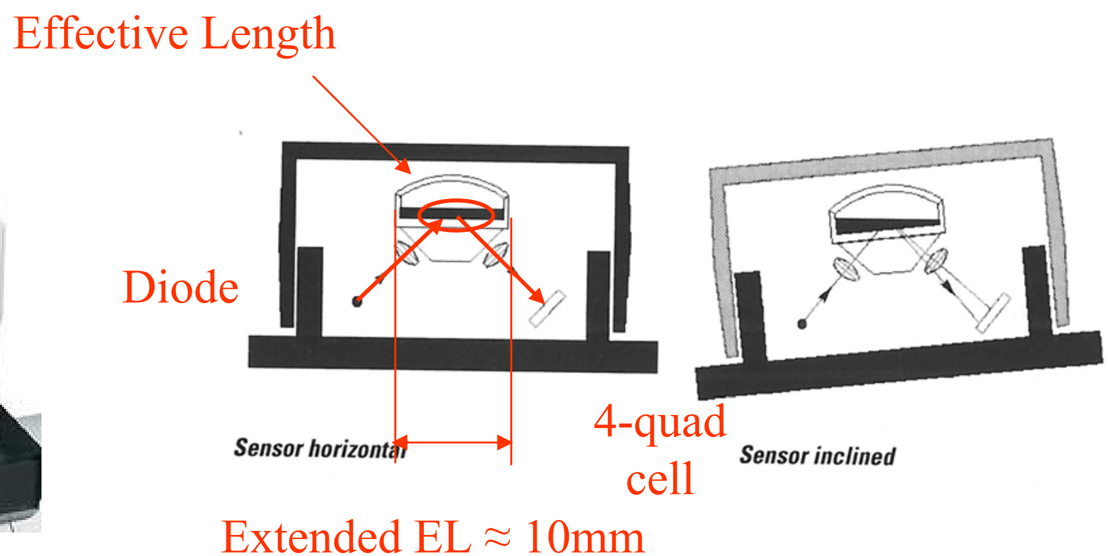
  - Vector Space:
  - Autocollimator (theodolite) on a plane mirror
  - Inclinometre

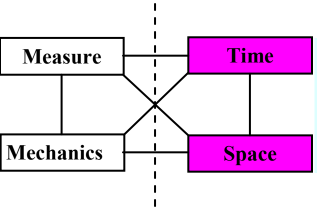




Stability Time Constant & Effective length

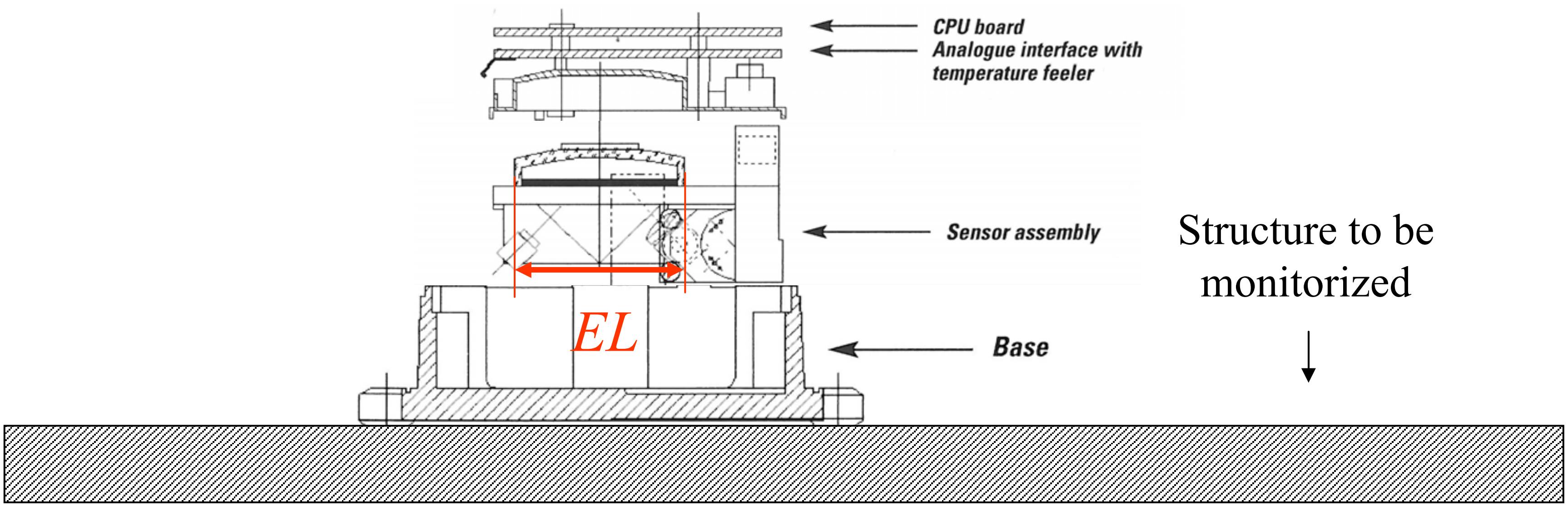
- **Inclinometer: Instrument for small angle measurement around the horizontal (tiny slopes); Accuracy ≈ few µrad**
- **The effective length (EL) is the one of the detection part**





Stability Time Constant & Effective Length

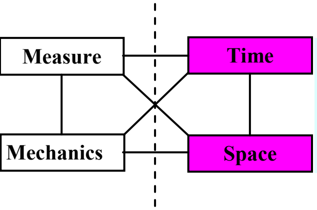
- **Structure to be motorized with the μrad level for a long time (∞)**
- **Any sub-part of the inclinometer should match to STC = (μrad, ∞)**
- **Especially the detection part which shows the Effective Length (EL)**



***EL* = 10mm => 10nm for 1 μrad**
(in addition to electronic noise→ $\mathbf{STC_{elec}}$)

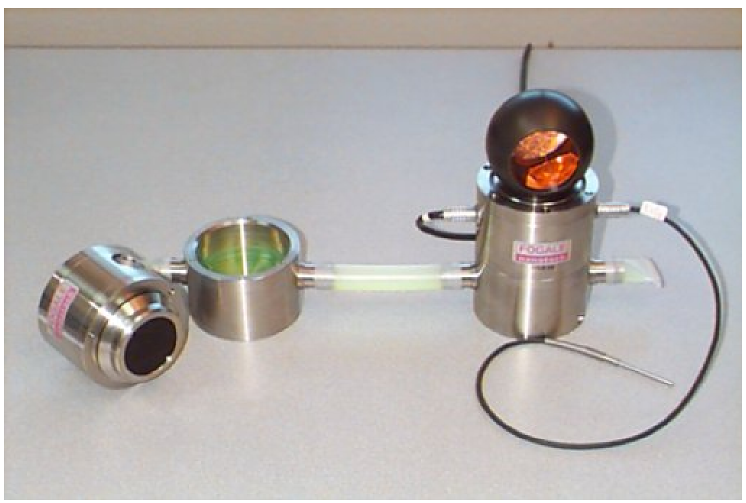
Capacitive inclinometers:

EL ≈ less than 1mm

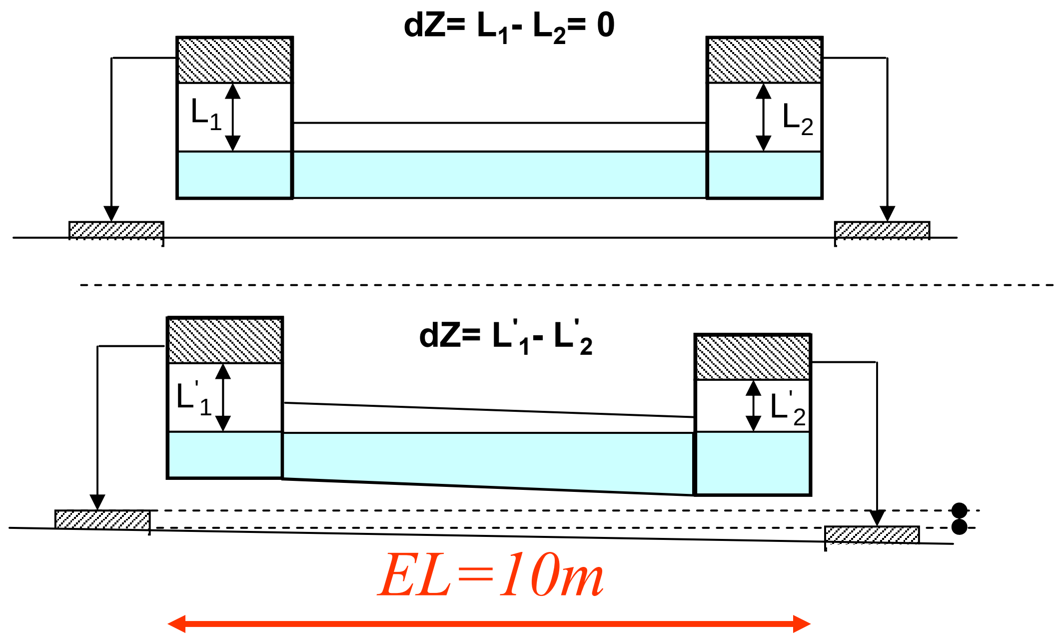


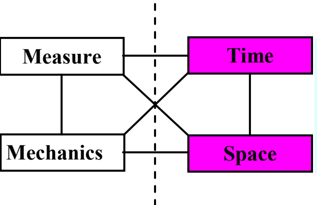
Stability Time Constant & Effective Length

- **Hydrostatic Leveling System (HLS):** **10nm, 10m => 1nrad**



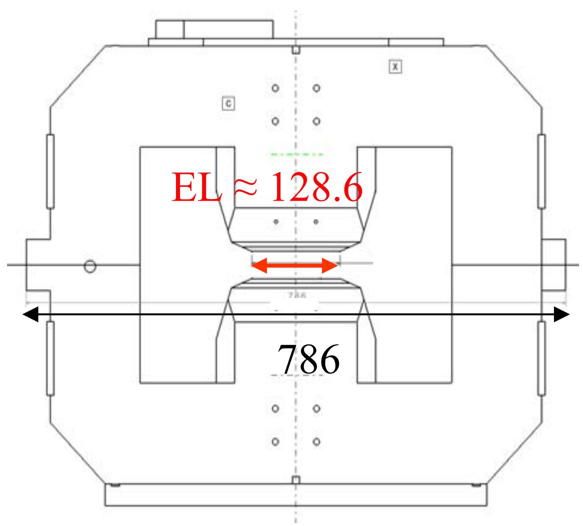
(Fogale Nanotech)



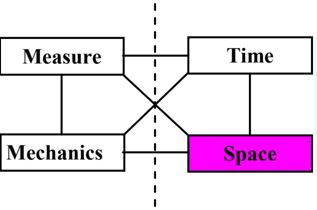


Effective Length

- **Machining Dipole laminations:**
  - Shape or size tolerance is typically ±*0.02mm*
  - A usual confusion is to believe that the accuracy of the mechanical tilt (rotation around the beam) of the magnet *is 0.02/Y=0.025mrad* , where *Y=786mm,* the width of yokes
  - The Effective Length for the electron beam is actually the width of the pole *p=128.6mm* → *0.02/p=0.156mrad*

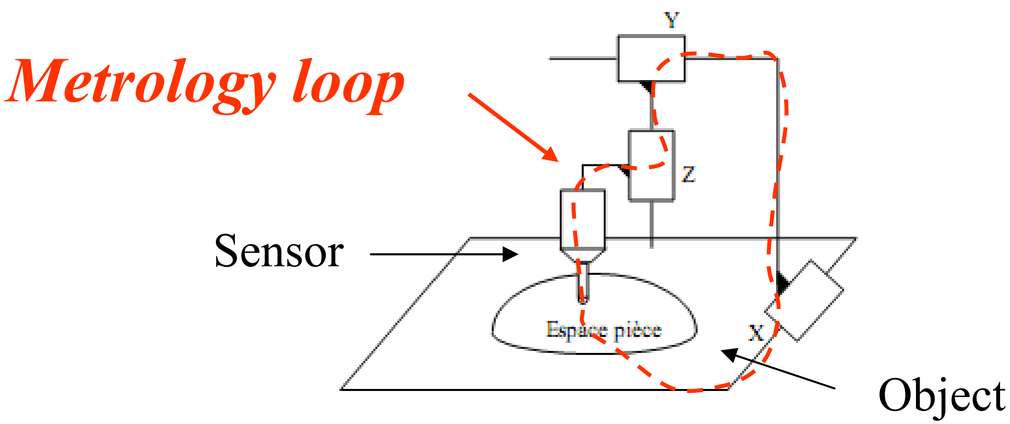


  - The drawings have to be checked (tolerance stack_up)



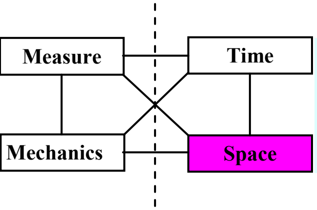
Metrology loop

- **Any system dedicated to positioning or requiring a positioning operation, consists of a succession of mechanical parts and/or of sensors**
- **It is the support of the positioning information transmission *(Lahousse)***
- **Ex: Coordinate Measuring Machine (CMM)**



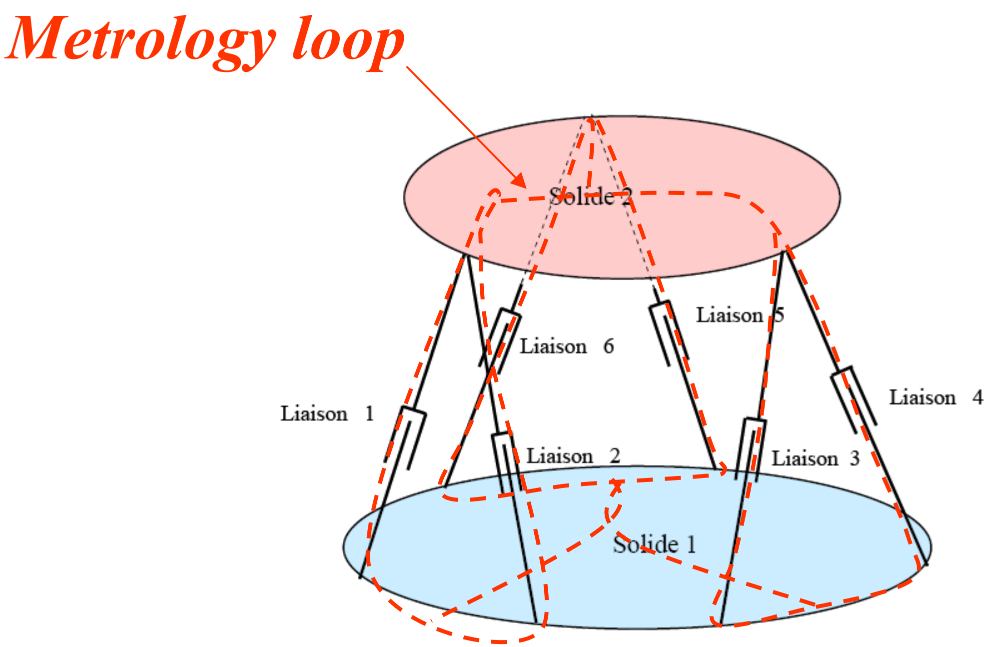
(Hennebelle, ENSAM)

- **Serial layout sensitive to errors (instrumental & instabilities) due to a cumulative effect**

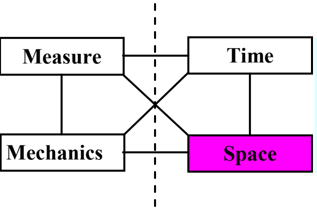


Metrology loop

- **Parallel layout: robust to errors, average influence**

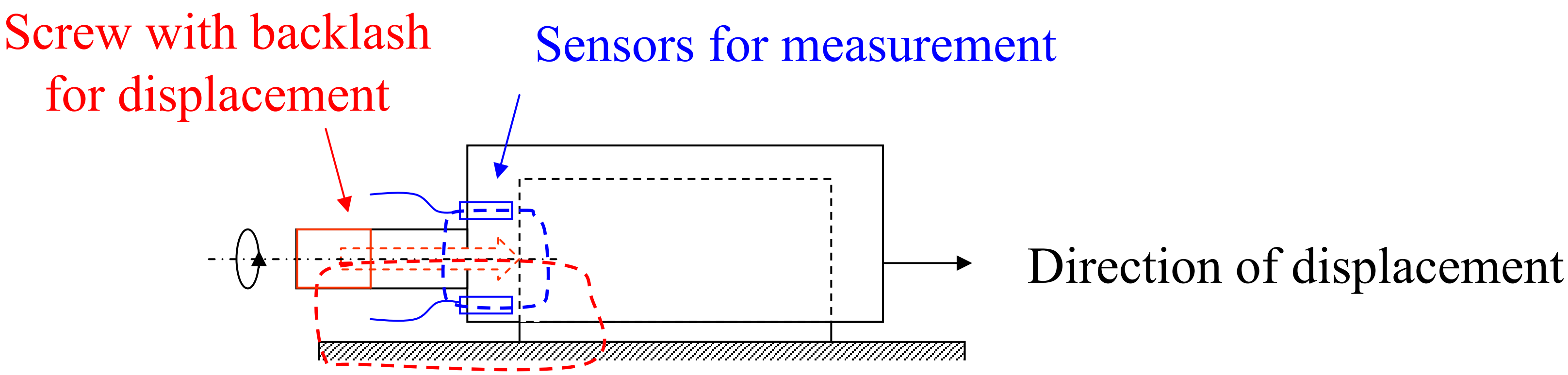


(Lahousse, ENSAM)

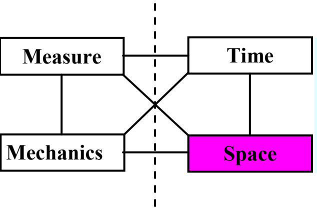


Metrology loop

- **Translation stage with coaxial micrometer:**
  - Micrometer (screw) with backlash
  - The backlash is « seen » by the measure
  - Not transmitted to the displacement

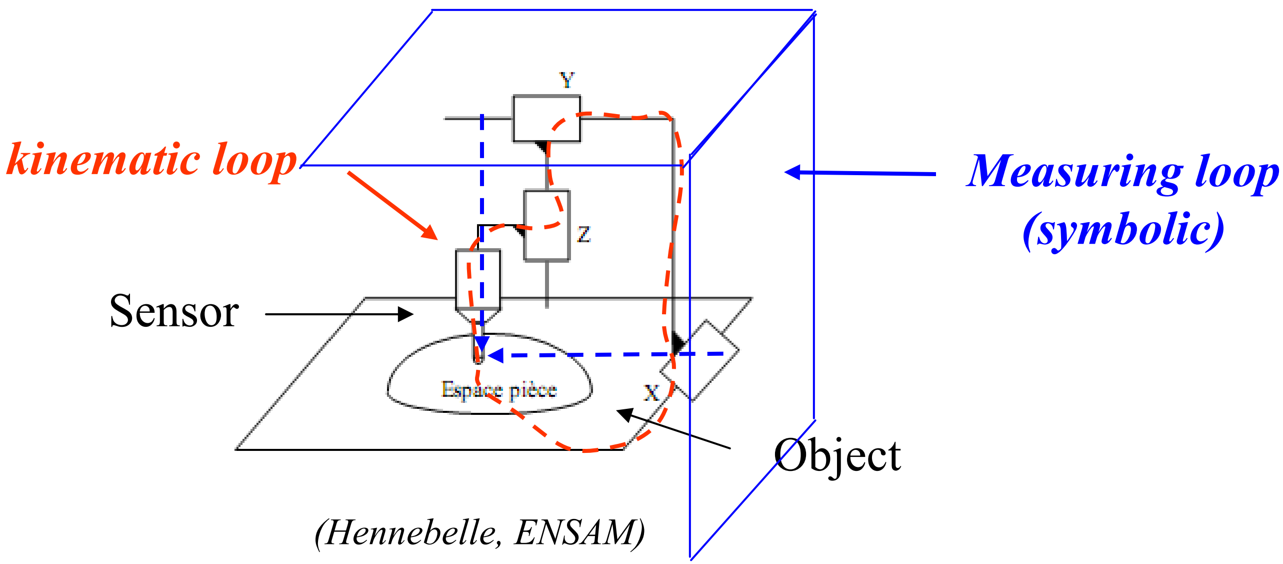


- **Measuring & mechanical loops are not independent**

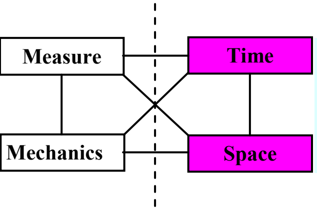


Metrology loop

- **Decoupling the actuator & measuring loops is mandatory for high accuracy units**
- **Ex: Coordinate Measuring Machine (CMM):**

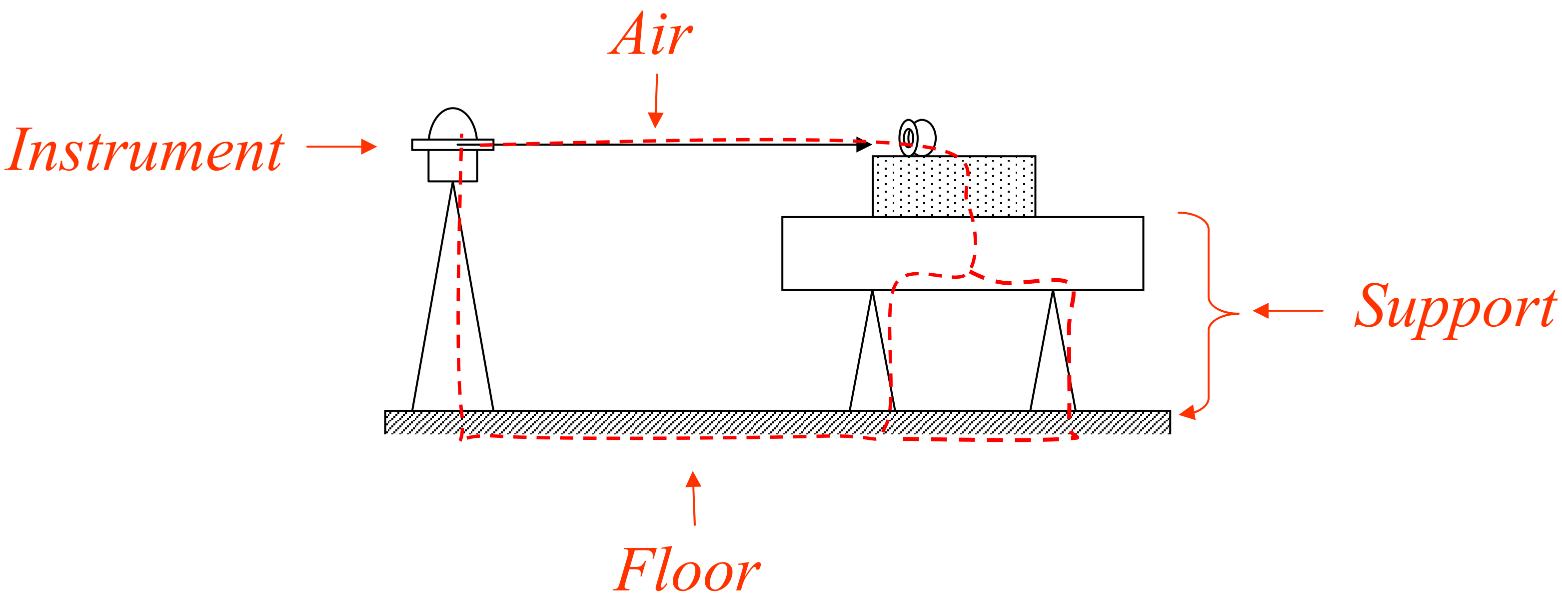


(Hennebelle, ENSAM)

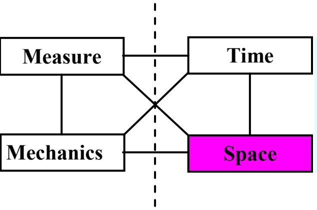


Metrology loop

- **Optical measurements:**

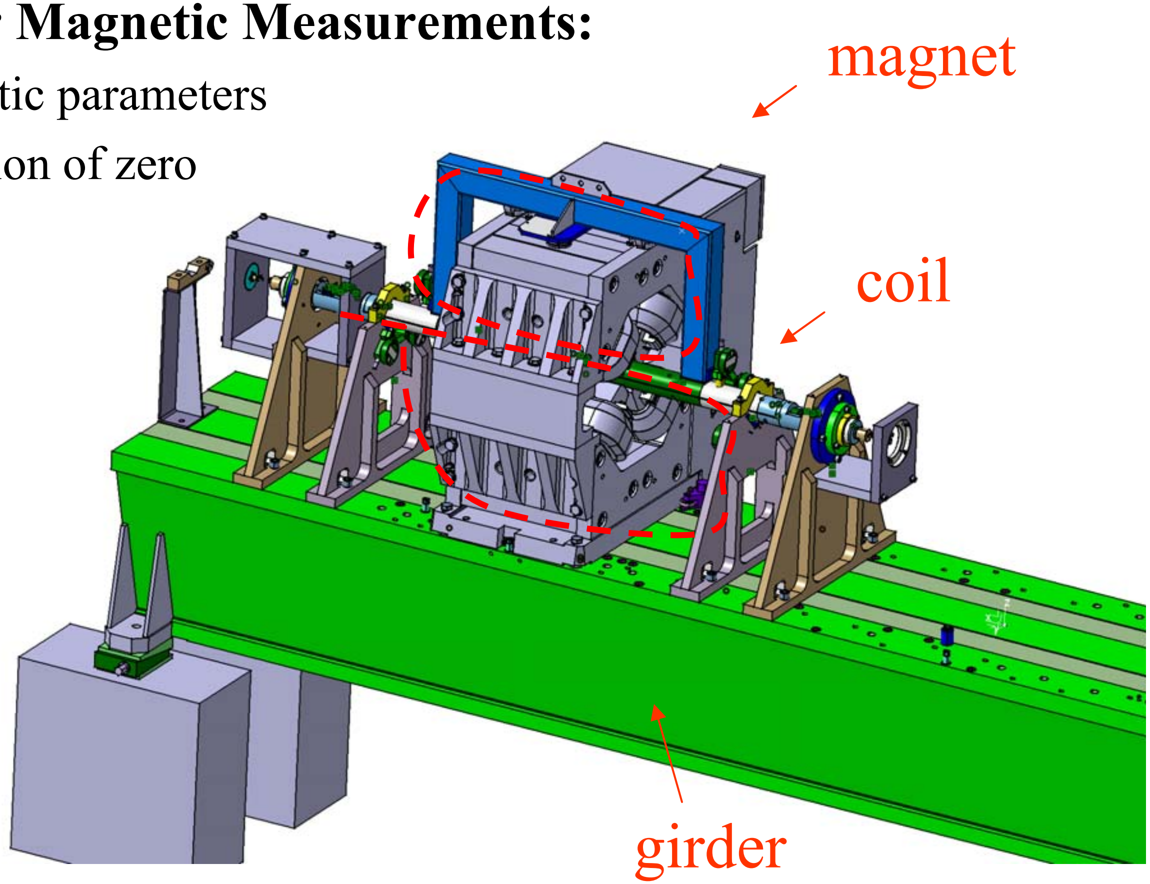


- Interferometry is affected by errors due to refractive index of the air on its path: Vacuum condition required for high accuracy or
- “cale à gradins” for CMM



Metrology loop

- **Bench for Magnetic Measurements:**
  - Magnetic parameters
  - Detection of zero



Introduction

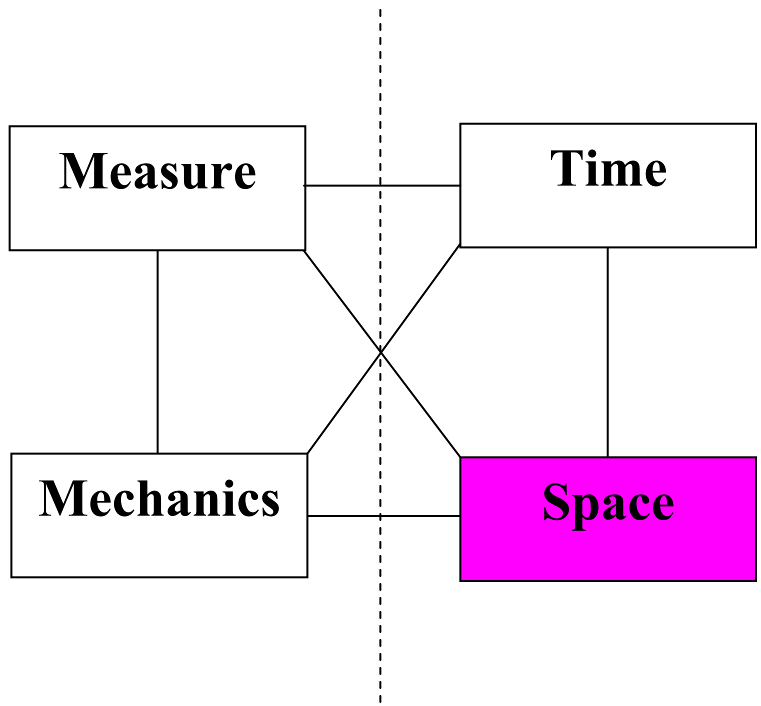
- **The four components of Design in Dimensional Metrology units:**

Means: *Point of view:*

Sensors & instruments:

Random & Bias (offset) Er

σ & B



Stability

Mechanical units:

Random & Bias (offset) Er

σ & B

Angle-Length

Effective length *σ*

Metrology loop *σ*

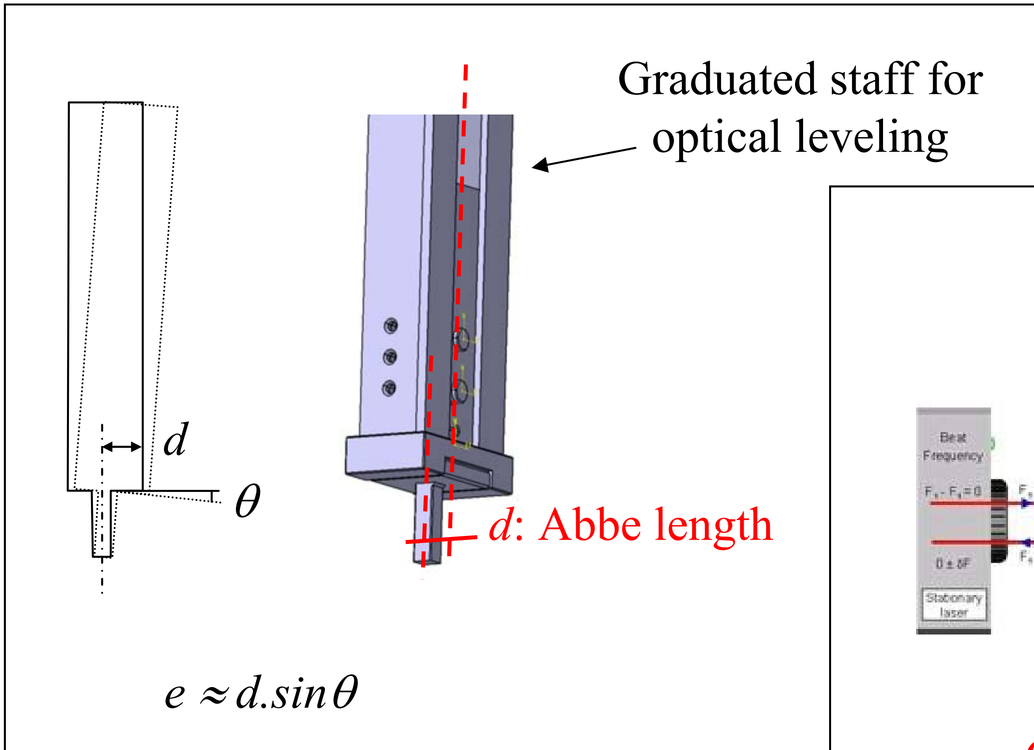
Lever arms *σ*

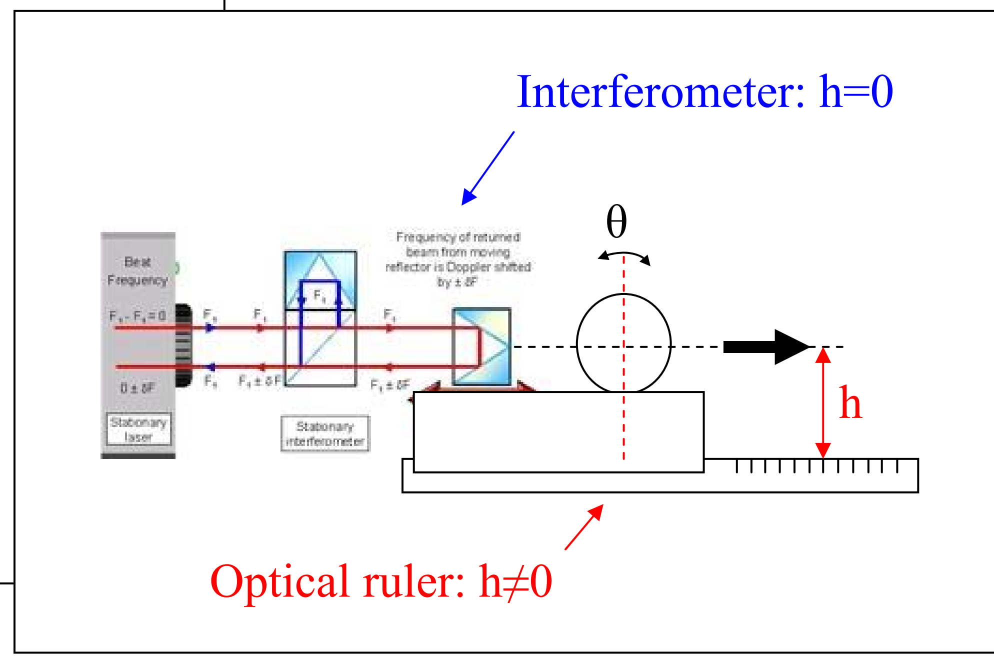
Multi-Step Layout *B & σ*

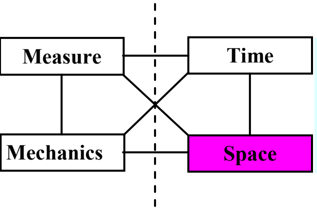
Differential Meas. *B*

Abbe error & lever arms

- **“Carrying out a good measure needs the measurement standard being placed in the same line as the dimension to be checked”**



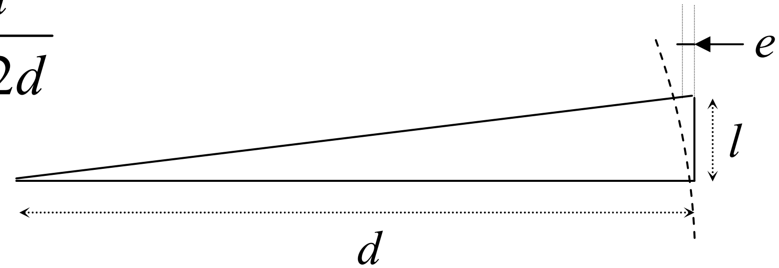


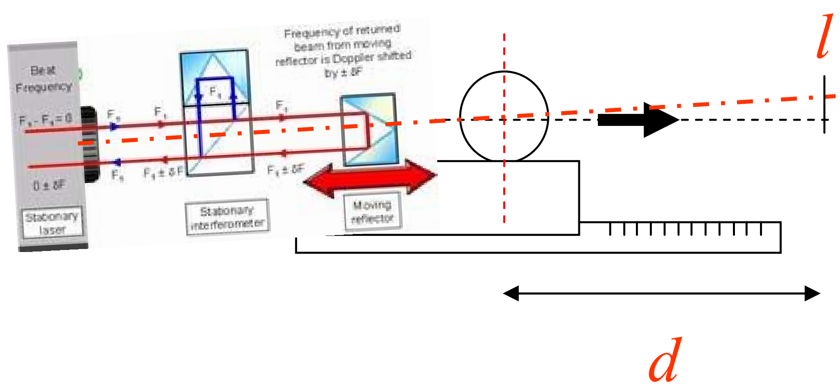


Abbe error & lever arms

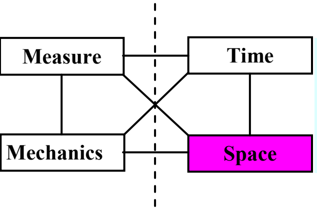
- **Cosine error:**

$$e_{\cos} \approx \frac{l^2}{2d}$$



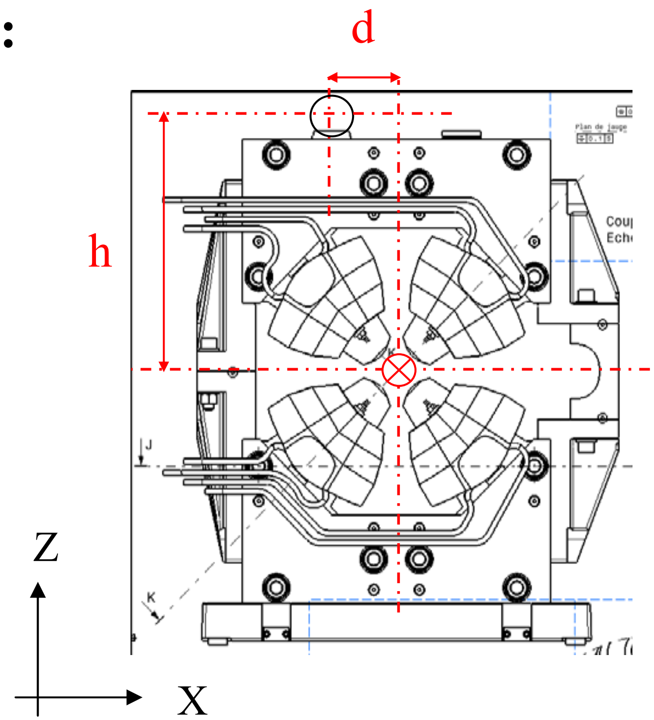


- **l=1mm, d=100mm => e=5µm**

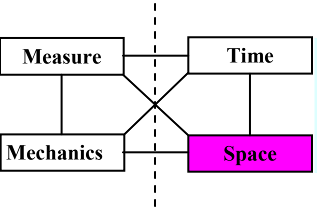


Abbe error & lever arms

- **Qpole Fiducialization lever arms:**

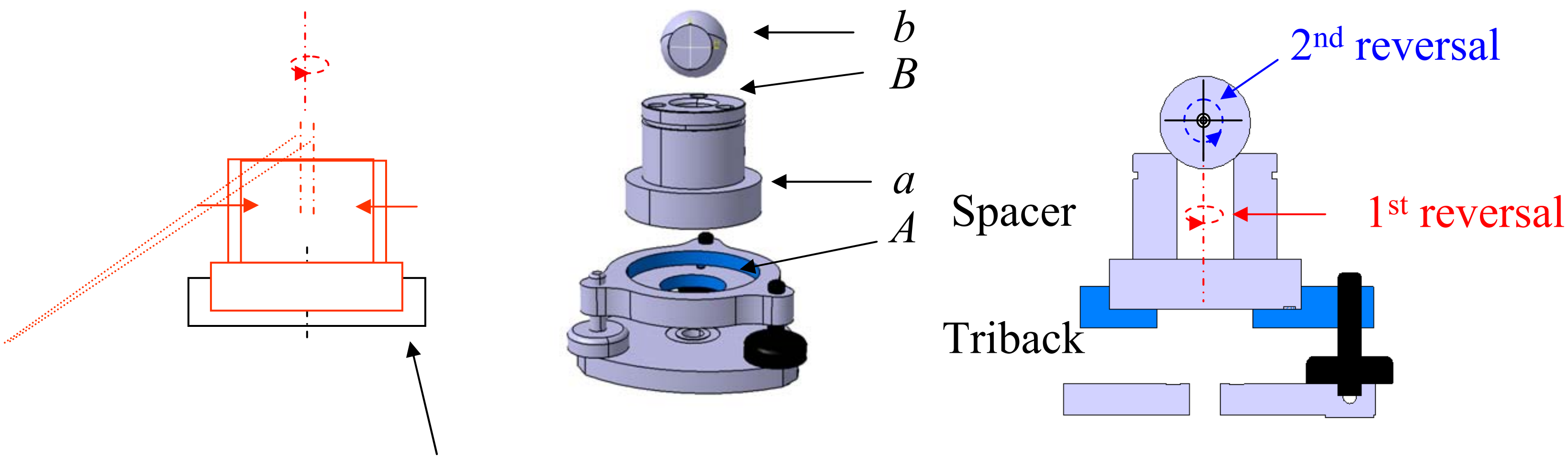


- **The complete description of lever arms stays the matrix of rotation: 2D or 3D**

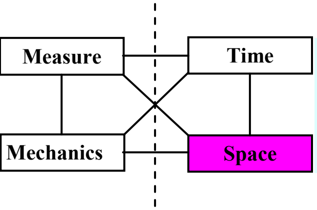


Multi-Step Layout

- **Reversal method for centring systems:** $$l = \frac{l_1 + l_2}{2}$$



  – The arrow represents the orientation of the **O**bject or of the **M**easurement



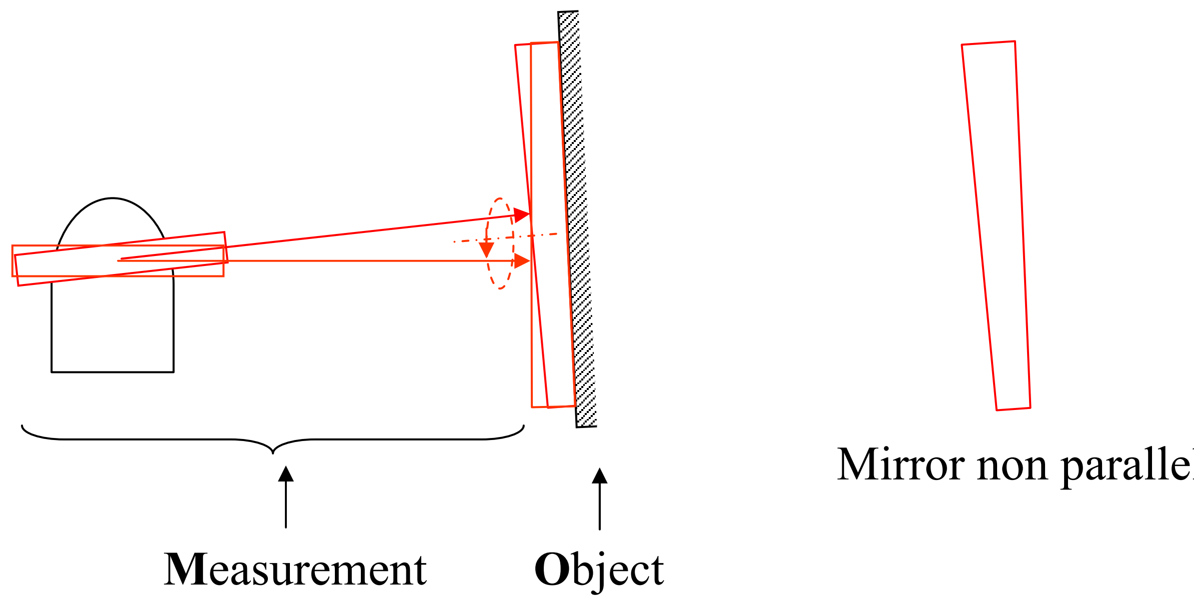
Multi-Step Layout

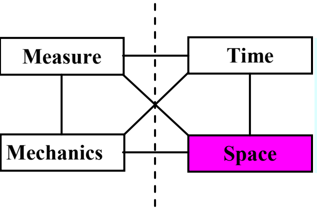
- **Autocollimation on mirror:**
  - Measurement:

$$m = \frac{l_1 + l_2}{2}$$

  - Mirror error:

$$e = \frac{l_1 - l_2}{2}$$





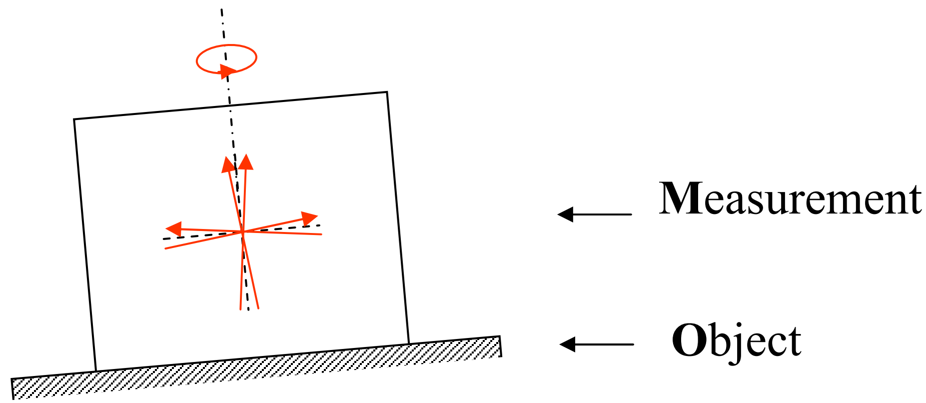
Multi-Step Layout

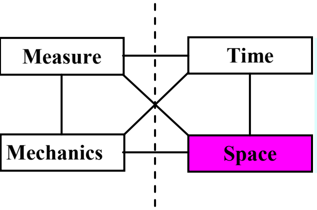
- **Inclinometer:**
  - Measurement:

$$m = \frac{l_1 - l_2}{2}$$

  - Inclinometer error:

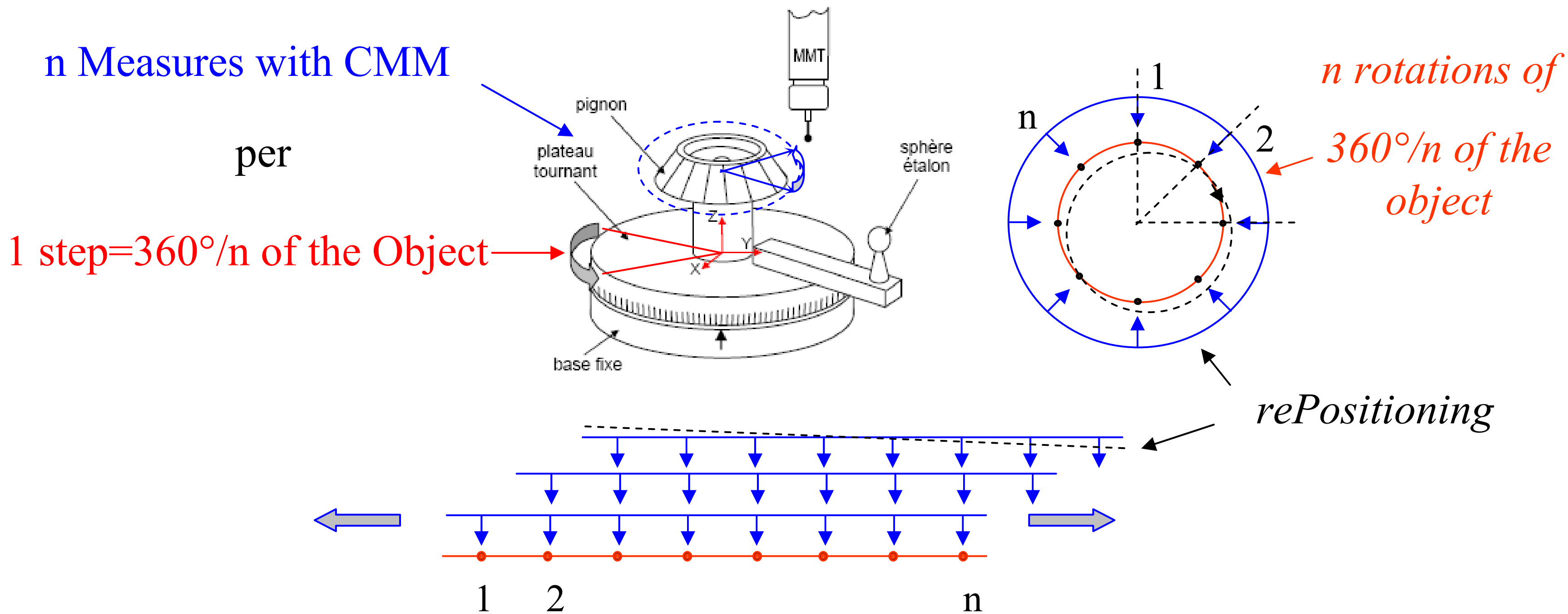
$$e = \frac{l_1 + l_2}{2}$$

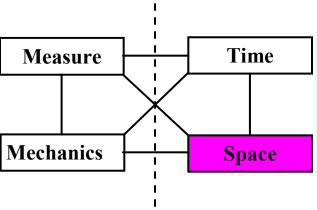




Multi-Step Layout

- **Multi-reversal method: roundness error of a circular piece:**
- The object is entirely measured n times by a Coordinate Measuring Machine (CMM) in the *n* positions of the object after each rotation of *360°/n* around its axis of symmetry. At each step of rotation of the object corresponds a full rotation of the CMM head for measuring the object.

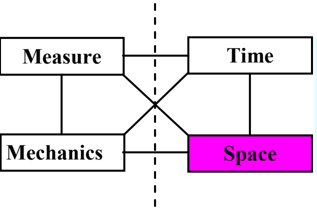




Multi-Step Layout

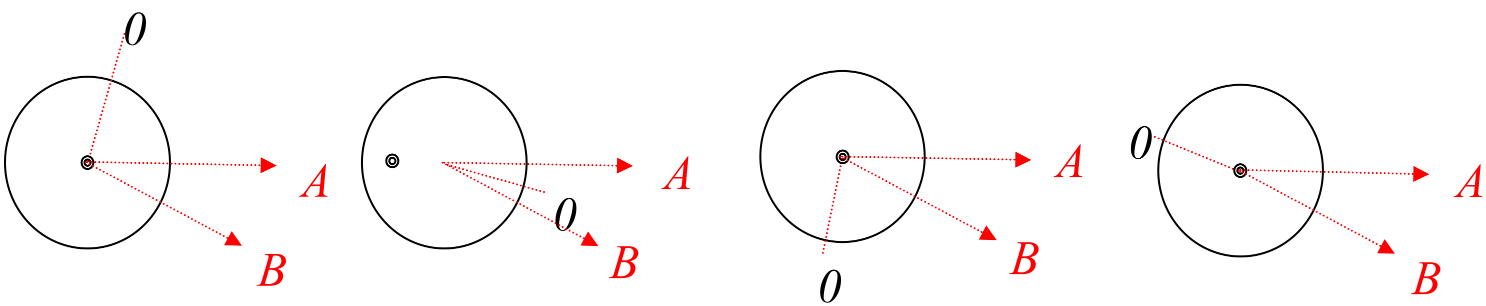
- **Multi-Step Layout (MSL):**
  - Each point of the Object “sees” successively the defects of the Measurement system (+rePositioning)
  - Each position of measurement of the CMM “sees” successively the defects of the Object (+rePositioning)
  - After calculation, Object, Measurement & rePositioning errors are known
  - MSL (O,M,P): → Least Square Calculation: LLSC or NLLSC

  - Literature:
    - Multi-probe error separation
    - Donaldson Reversal
    - Etc.



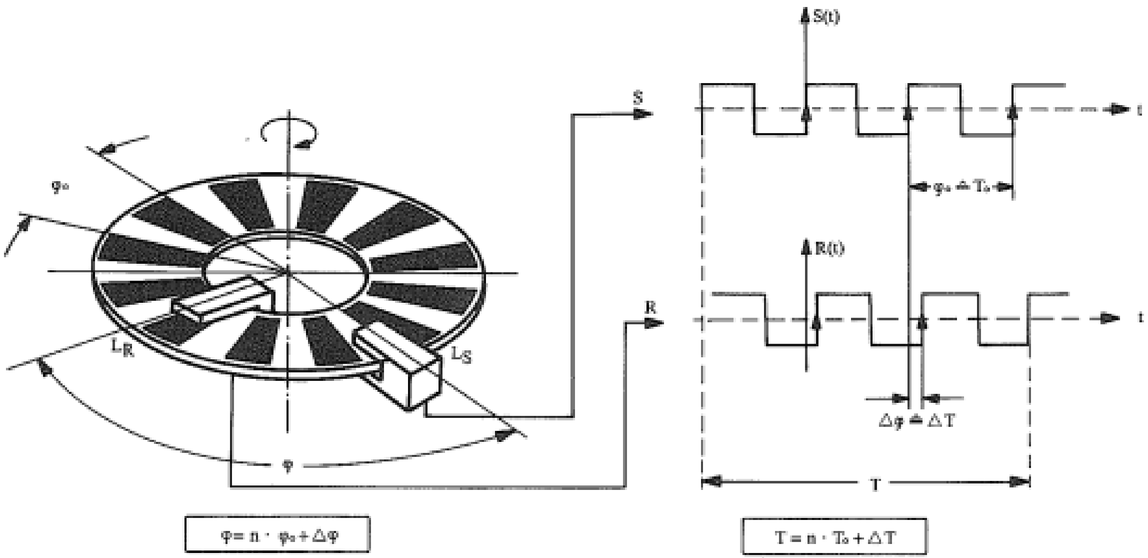
Multi-Step Layout

- **The general case:**
  - Any kind of measurement can be involved: radial, tangential, etc.
  - Any kind of layout: circular, linear, etc.
  - Any kind of sensor, even a rotating coil for magnetic measurements or a theodolite
- **The theodolite case:**
  - tangential as graduation errors of a theodolite circle
  - Iterating the measurements with a 360°/N step, eliminates the Fourier coefficients of the error function until order n-1



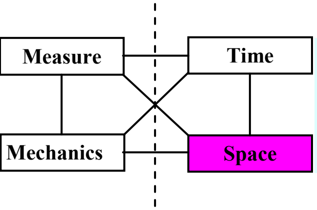
Multi-Step Layout

- **N should be as great as possible: N$\rightarrow\infty$**
  - Continuous measurements, dynamic encoder



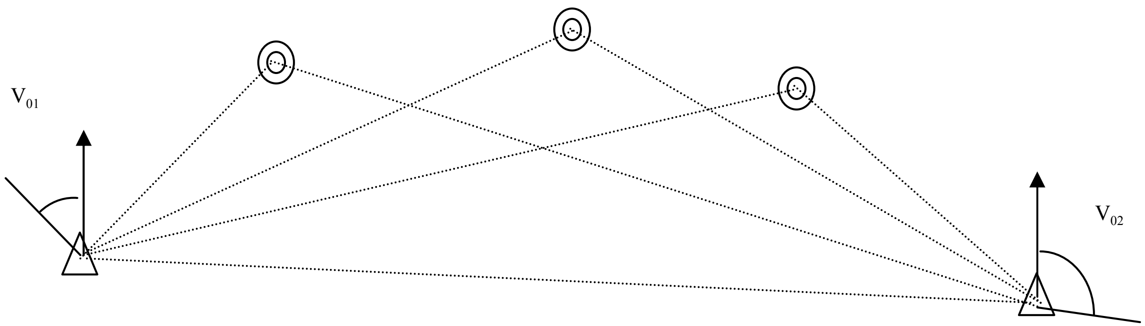
Dynamic angular encoder of Wild T2000

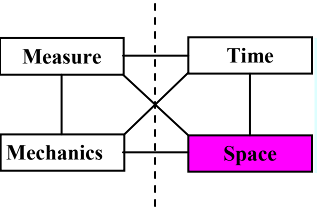
- **Precise rotating tables with two encoders in juxtaposition to each other: 0.01''**



Multi-Step Layout

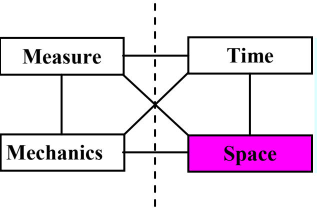
- **Geodetic network measurement:**
  – Presents a Multi-Step layout: MSL(O,(M),(P))





Multi-Step Layout

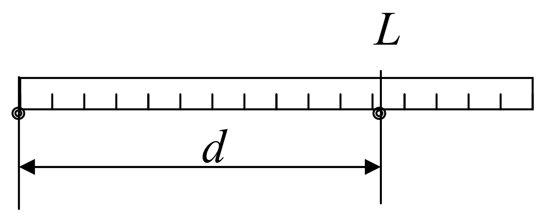
- **The most important with the concept of MSL:**
  - It is first of all, a qualitative approach, just to feel:
    - A wider approach of the “simple” reversal method
    - to keep in mind that all the errors can be detected (O,M,P) in any kind of such situation
    - A capability to quantify the redundancy
    - A capability to quantify the number of unknowns of a set “Measurements-Object”



Differential measurements

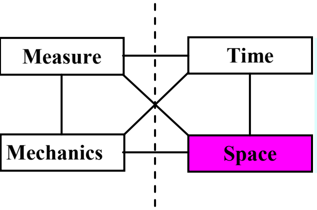
- **Very common in Metrology**

- **Direct measurement: applying an extremity to a point and by reading the graduation in correspondence of the other**



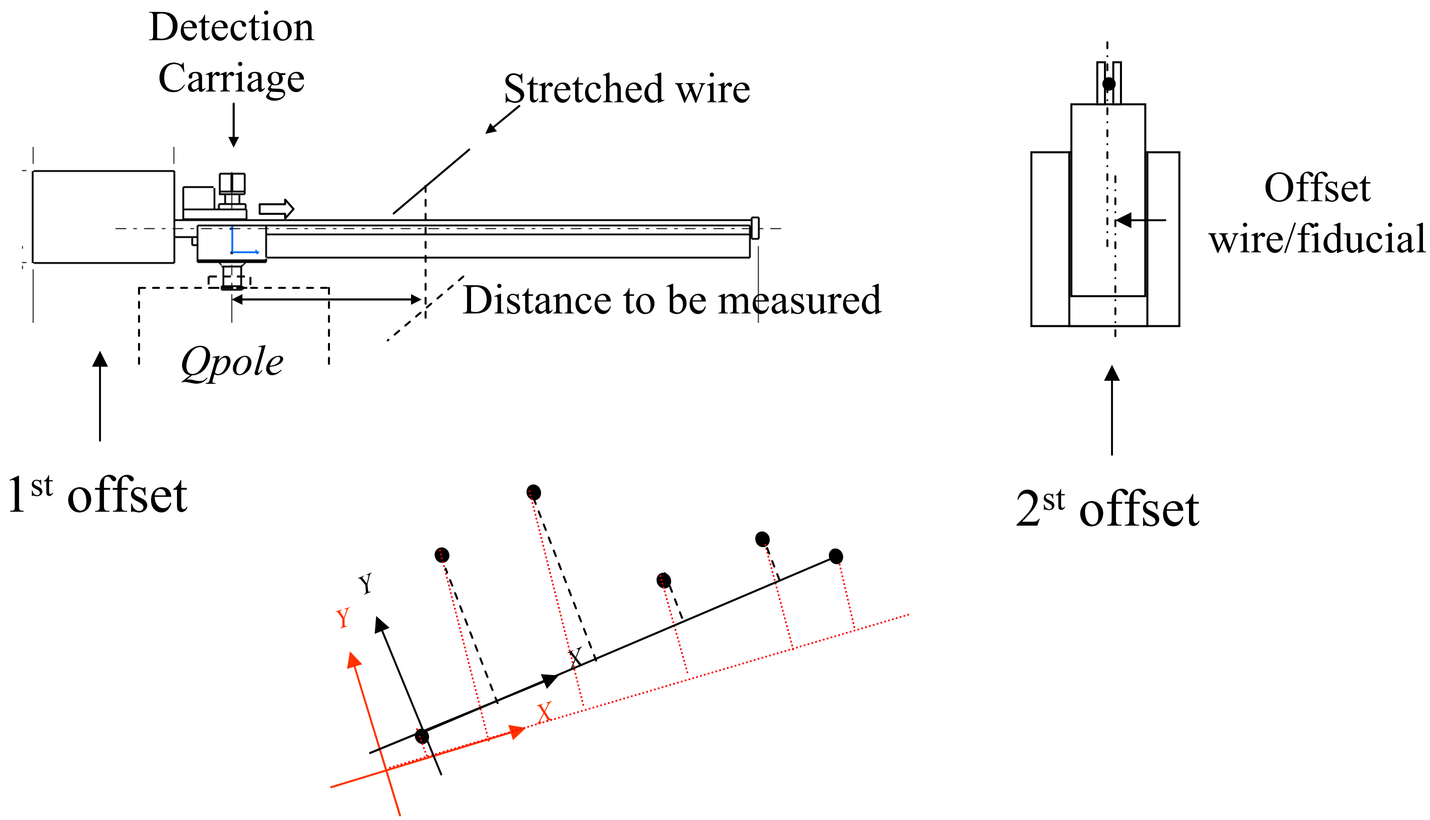
- **Differential method: the rule is shifted and two readings on the rule are carried out in front of the two points. The length is the difference of the readings.**

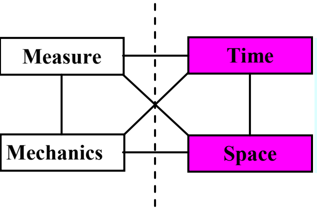
$$d = (L_2+e) – (L_1+e) = L_2-L_1.$$



Differential measurements

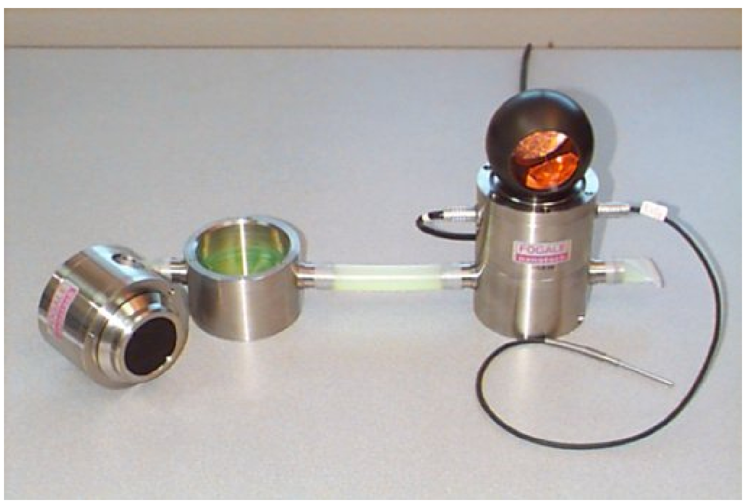
- **Wire Ecartometre: zero error, offset wire / fiducial:**



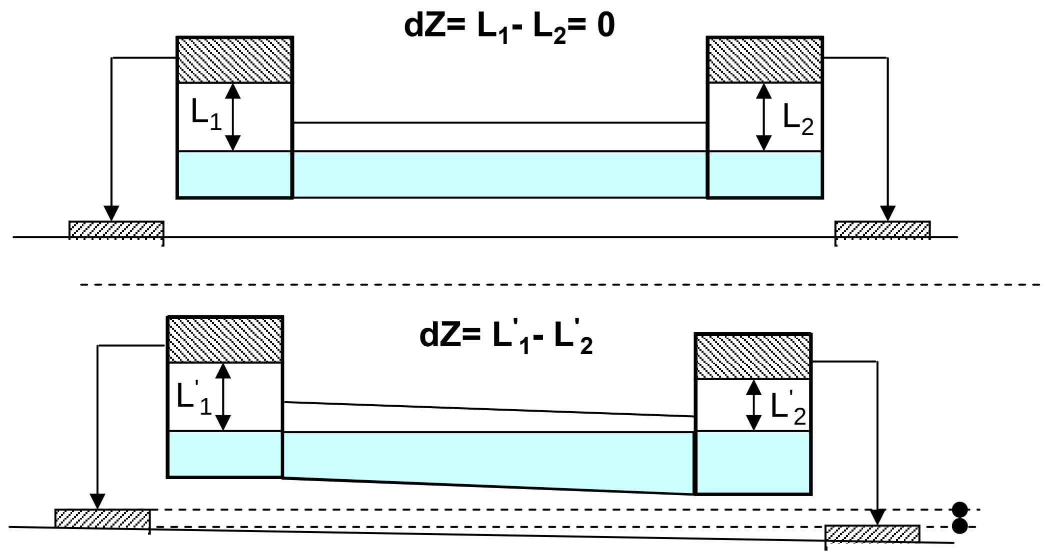


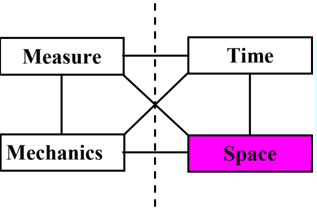
Differential measurements

- **Hydrostatic Leveling System (HLS):**



(Fogale Nanotech)





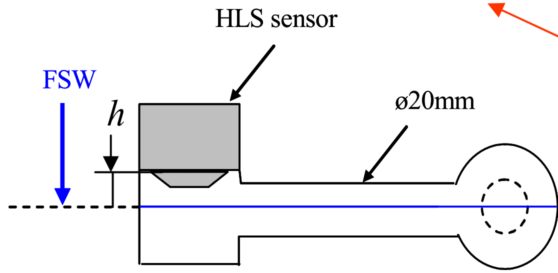
Differential measurements

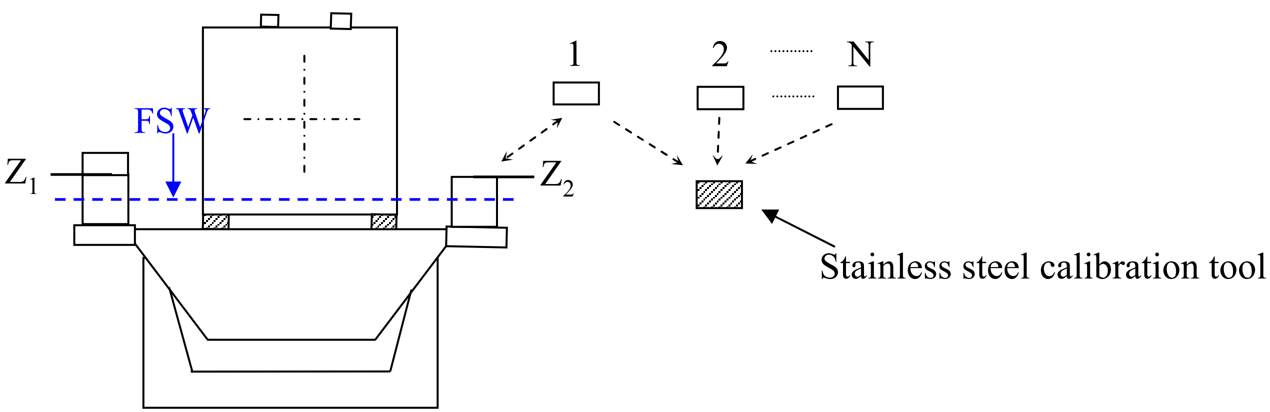
- **HLS network: use of calibration tool to compare all the zero errors**

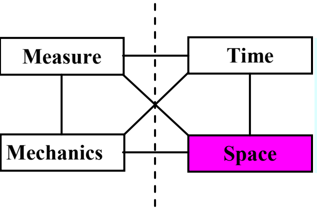
$\boxed{h_1 = L_1 + e_1}$ $\boxed{h_2 = L_2 + e_2}$ $\boxed{de = e_1 - e_2}$ $\boxed{dZ = h_1 - h_2 = L_1 - L_2 + de}$

Measured with HLS

Measured with the tool

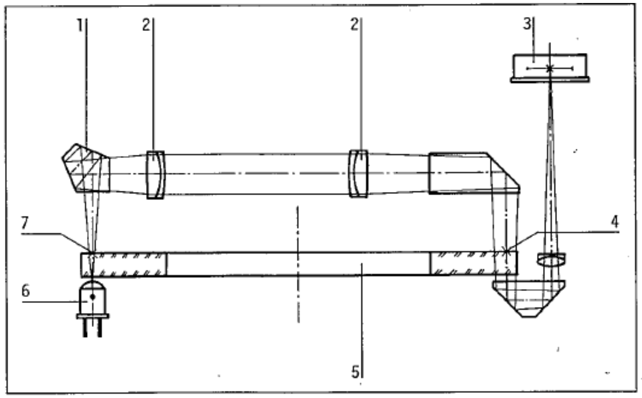


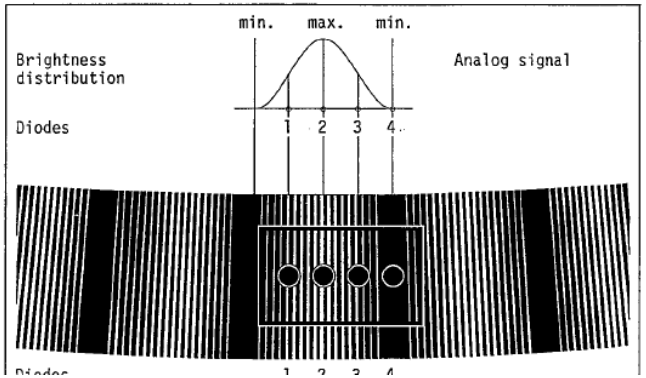


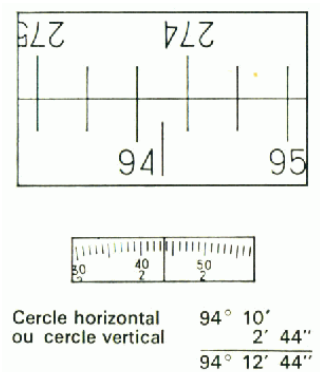


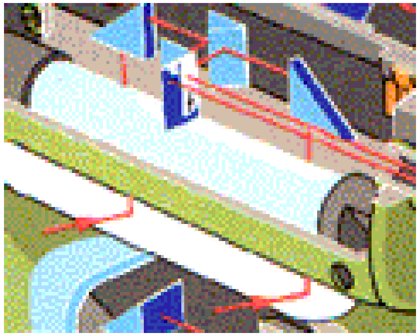
Differential measurements

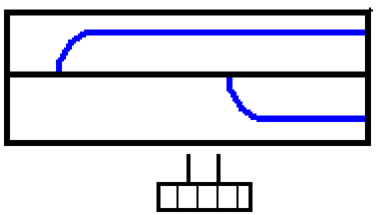
- **Superposition:**
  - Two opposite areas of a graduated circle are **<u>superimposed</u>**
  - Even for a bubble
  - MSL situation





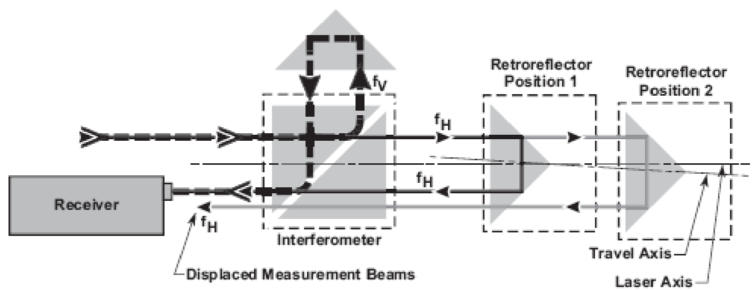


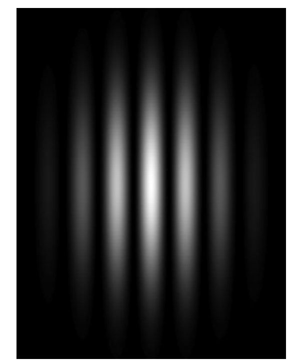




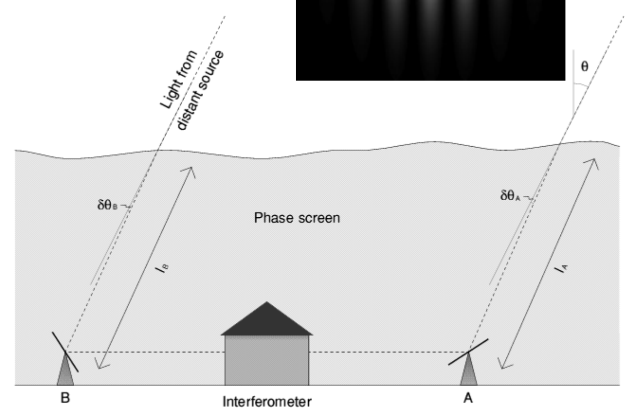
Differential measurements

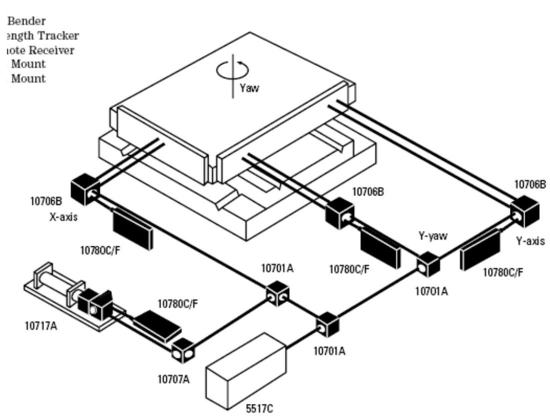
- **Interferometry:**
  - Physical system of differential measurement
  - At the level of the wave length, idea of **<u>superimposition</u>**
  - A wide range of applications: from astronomy to microscopy (VLTI, LiDar, etc.)
  - In Dimensional Metrology: distance measurement by counting the fringes





quasar

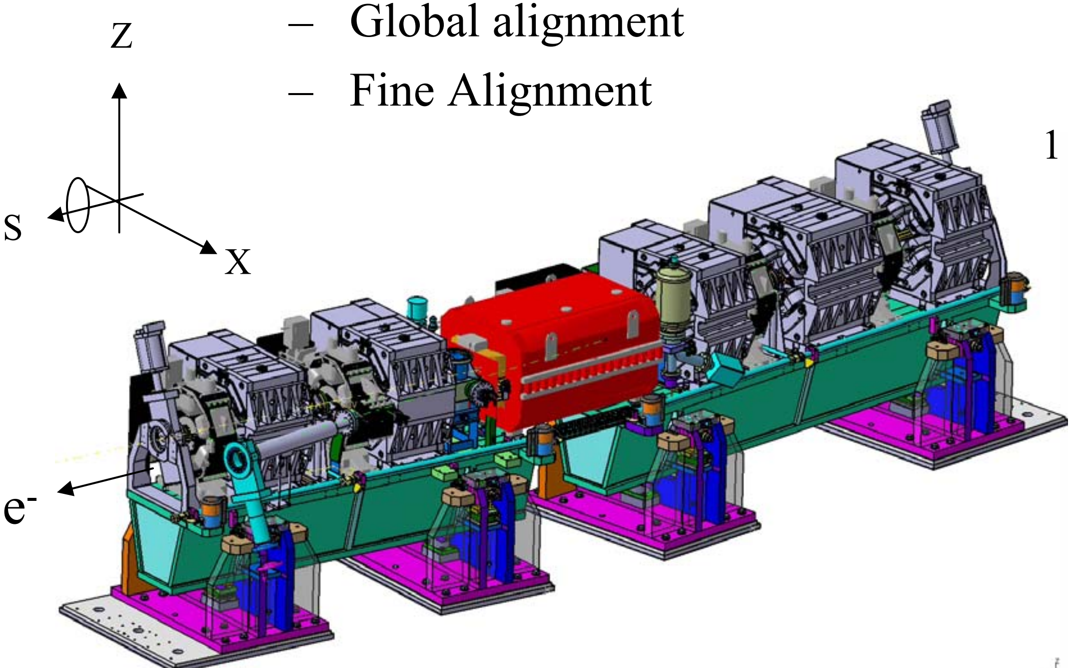


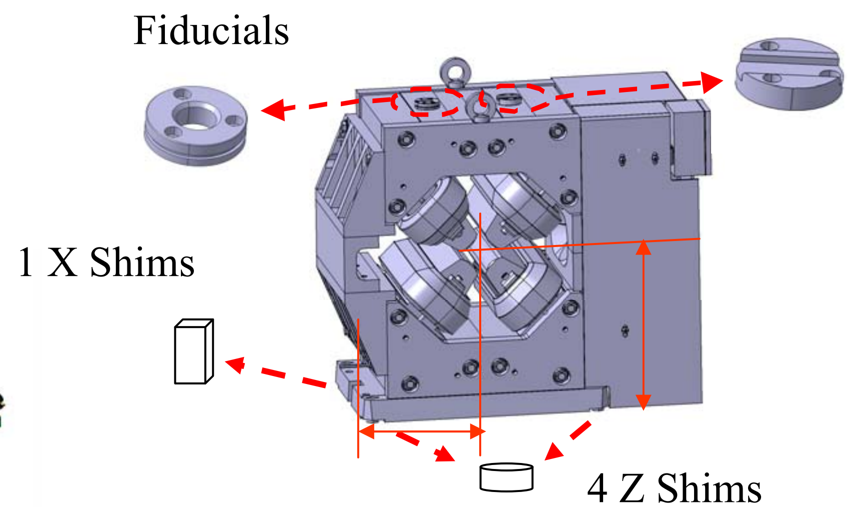


- Case study: The Qpole Alignment at SOLEIL

Case study: The Qpole Alignment at SOLEIL

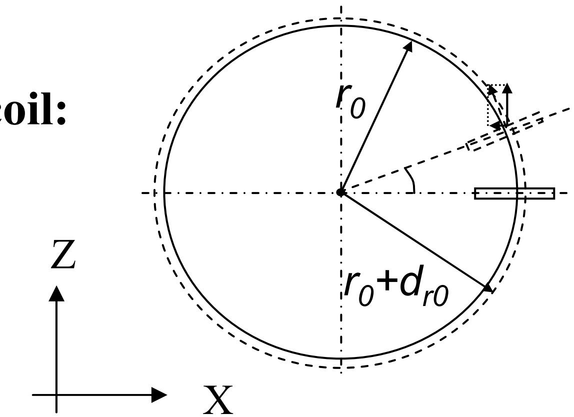
- **The beam orbit of Storage Ring is fully defined by the location of its quadrupole magnets:**
  - The magnetic axis detection of the Qpoles
  - Fiducialization
  - Mechanical alignment on girder
  - Global alignment
  - Fine Alignment

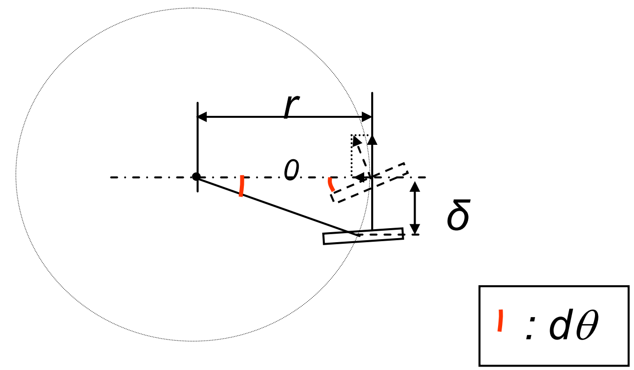




Case study: The Qpole Alignment at SOLEIL

- **Rotating coil:**

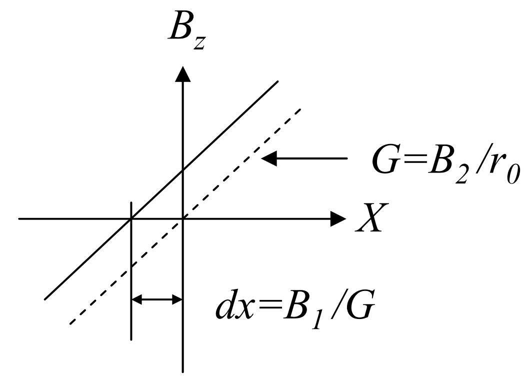




$$dx \approx \frac{r_0}{2}\frac{B_1}{B_2}$$

$$dz \approx -\frac{r_0}{2}\frac{A_1}{B_2}$$

$$\tan(2\theta) = -\frac{A_2}{B_2}$$

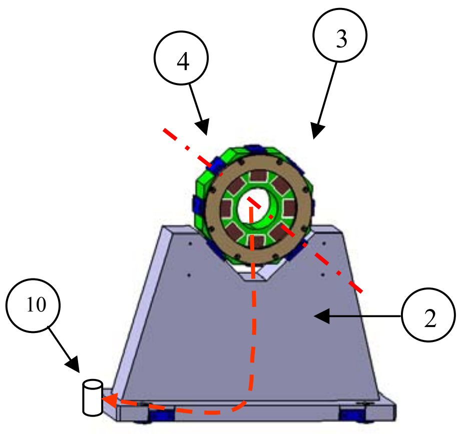


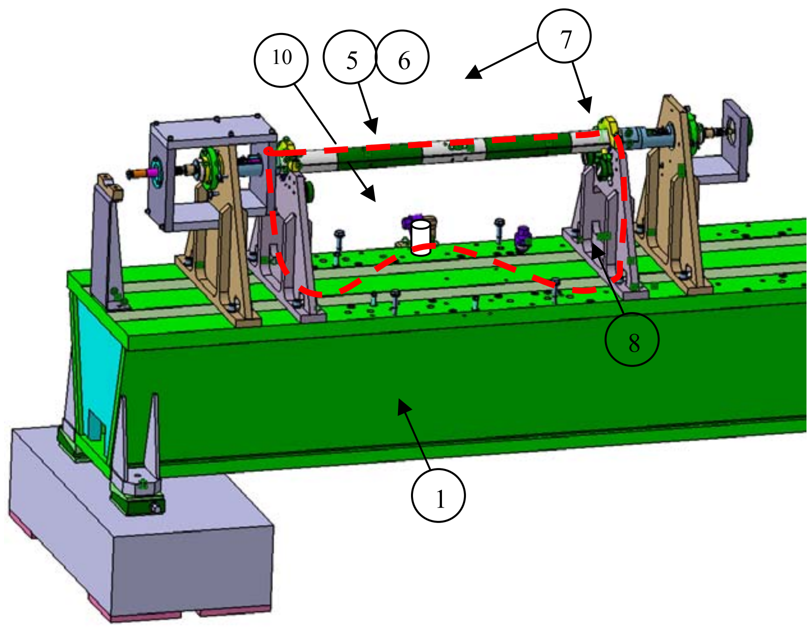
Bi , *Ai,* being the i^{th} real & imaginary harmonics of the flux

- **Hypothesis: the true axis of rotation is fixed and confused with the geometrical axis of the coil. There is no radial runout due to bearings**

Case study: The Qpole Alignment at SOLEIL

- **The bench for magnetic measurements, calibration tool:**
  - Link the coil axis to the bench to avoid STC = (10µm,∞)
    - A permanent Qpole tool with 8 faces
    - The tool is accurately measured
    - Multi-Step Layout





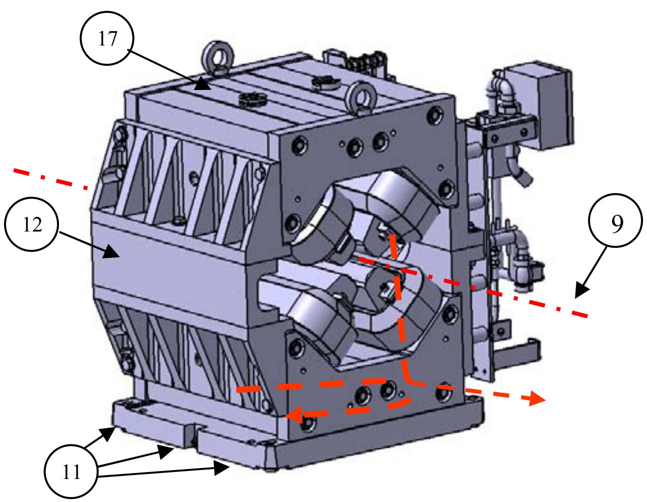
Case study: The Qpole Alignment at SOLEIL

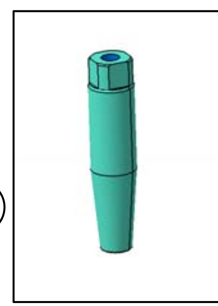
- **The magnetic axis detection:**
  - Calibration magnetic tool

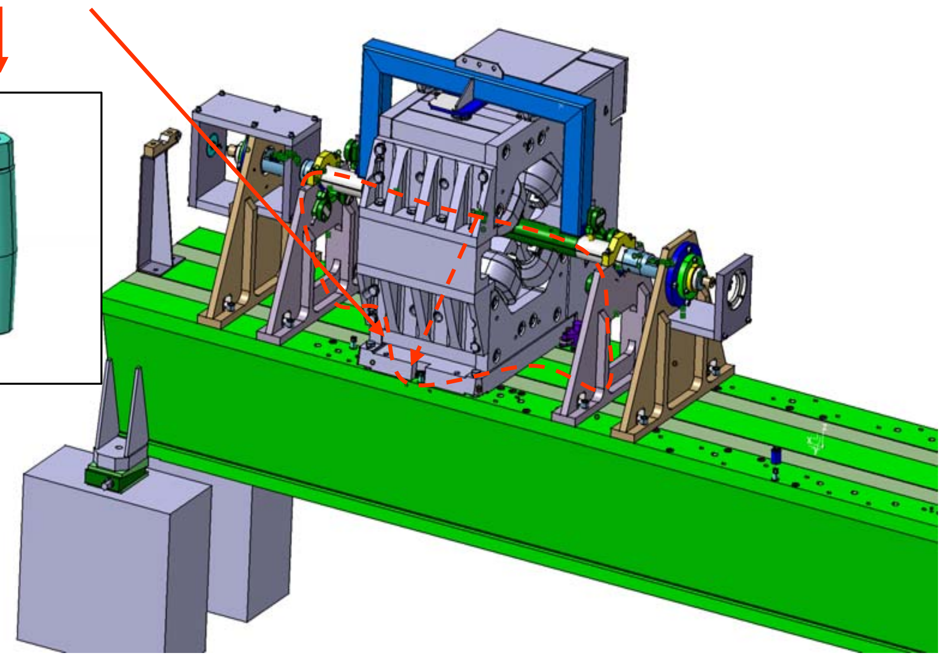
Nr	Component	Action	σ (µm)	Bias	STC=(µm,t)	STC=Easy/Diff
1	Bench					
		Mech			(,∞)	E
2	Tool Stand					
		Contact		MSL	(,mn)	E
3	Tool Ext Face					
		Mech			(,∞), (,mn)=MSL	D,E
4	Tool Mag Axis					
		Meas	5			
5	Coil Mag Axis					
		Mech			(,∞)	E
6	Coil Rotat Axis					
		Rotat	5		(,∞)	E
7	Ball bearings					
		Contact			(,∞)	E
8	Coil Stand					
		Mech			(,∞)	E
1	Bench					

Case study: The Qpole Alignment at SOLEIL

- **Zero detection:**
  - Each Qpole is measured by the bench: differential measurements
  - A set of shims are chosen for having the zero on the axis of the coil
  - The shims are in contact with bench references: X pin & Z surface
  - STC = (10µm,∞) for the whole metrology loop
  - The weak point is the **pin** STC = (10µm,∞): 200 times in contact with 300-500kg!







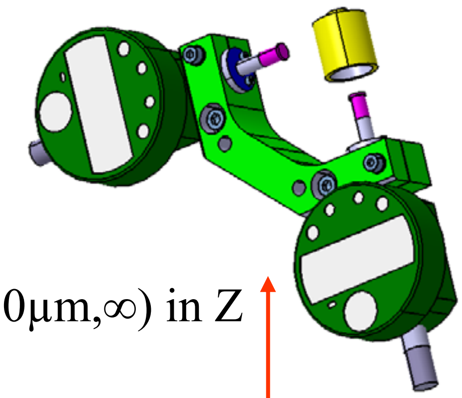
Case study: The Qpole Alignment at SOLEIL

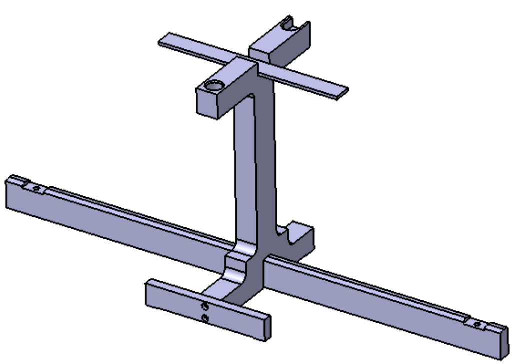
- **Zero detection:**

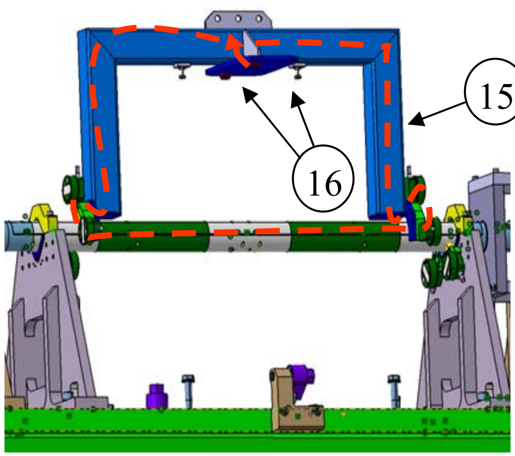
Nr	Component	Action	σ (μm)	Bias	STC=(μm,t)	STC=Easy/Diff
9	Qpole Mag Axis					
		Meas	5			
5	Coil Mag Axis					
		Rotat	5		(,∞)	E
7	Ball bearings					
		Contact			(,∞)	E
8	Coil Stand				(,Tool1)	
		Mech			(,∞)	E
1	Bench					
		Mech	5		(,∞)	D
10	Bench Pin (surface)					
		Contact			(,∞)	E
11	Qpole Shim(s)					
		Mech	5		(,∞)	E
12	Qpole Yokes					
		Mech			(,∞)	E
9	Qpole Mag Axis					

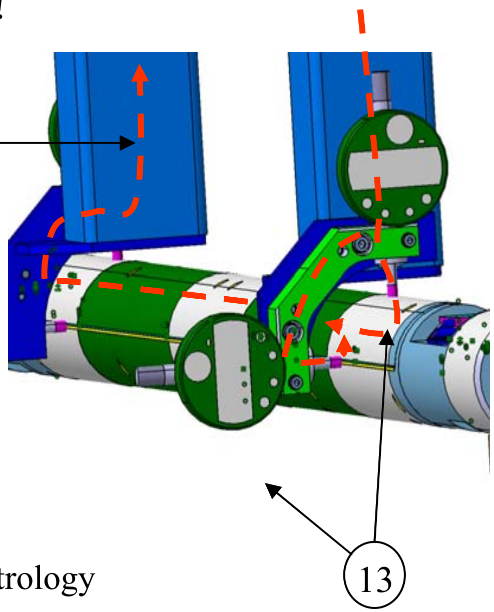
Case study: The Qpole Alignment at SOLEIL

- **Fiducialization:**
  - When zero detection is OK: store the axis
  - Qpole Comparator: 4 electronic dial gages + 1 inclinometer
  - Contact on the coil support in rotation
  - Multi-Step Layout: reversal for X direction & tilt, **not for Z!**
  - STC = (10µm,30mn) in X thanks to the MSL, STC = (10µm,∞) in Z
  - A dedicated bench is necessary for Z
  - Dial gage zero: for practical reason on Z, not necessary on X (reversal)
  - The metrology loop does not include the bench!









Case study: The Qpole Alignment at SOLEIL

- **Fiducialization :**

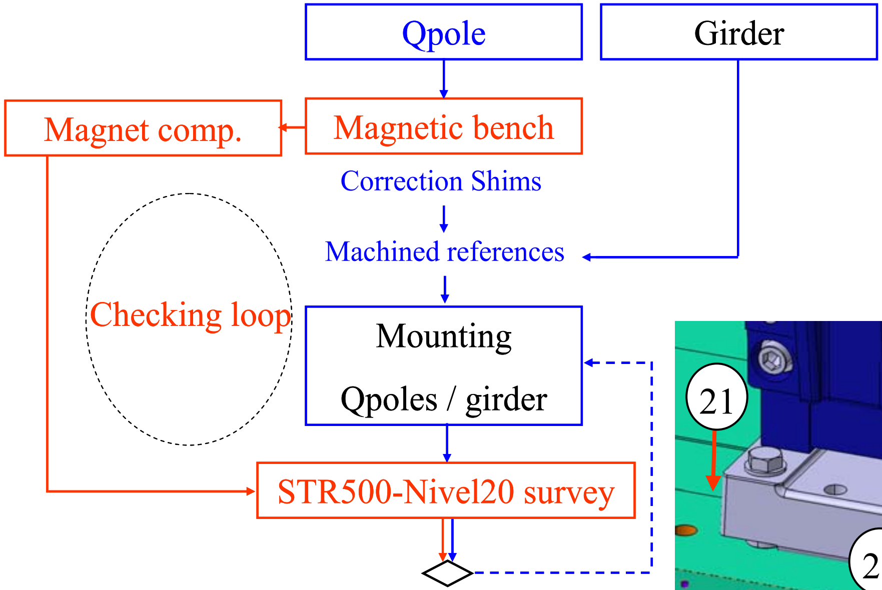
Nr	Component	Action	σ (µm)	Bias	STC=(µm,t)	STC=Easy/Diff
9	Qpole Mag Axis					
		Meas	5		(,30mn)	E
5	Coil Mag Axis					
		Rotat	5	MSL		
13	Dial gage					
		Tool2(14)	5		(,30mn)	E
15	QC structure					
		X: Mech *Z: Tool3*			(,30mn) (,days)	E E
16	Trunc. spheres					
		Contact	5		(,30mn)	E
17	Qpole Fiducials					
		Mech			(,∞)	E
12	Qpole Yoke					
		Mech			(,∞)	E
9	Qpole Mag Axis					

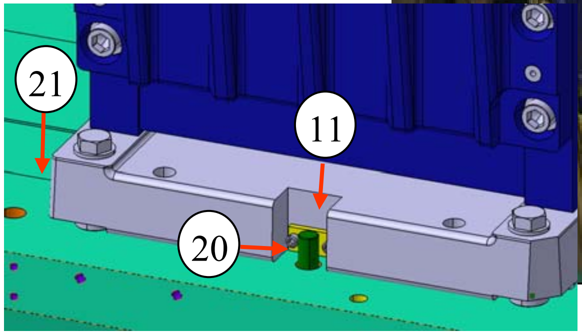
Tool2: Wedge
Tool3: Z bench

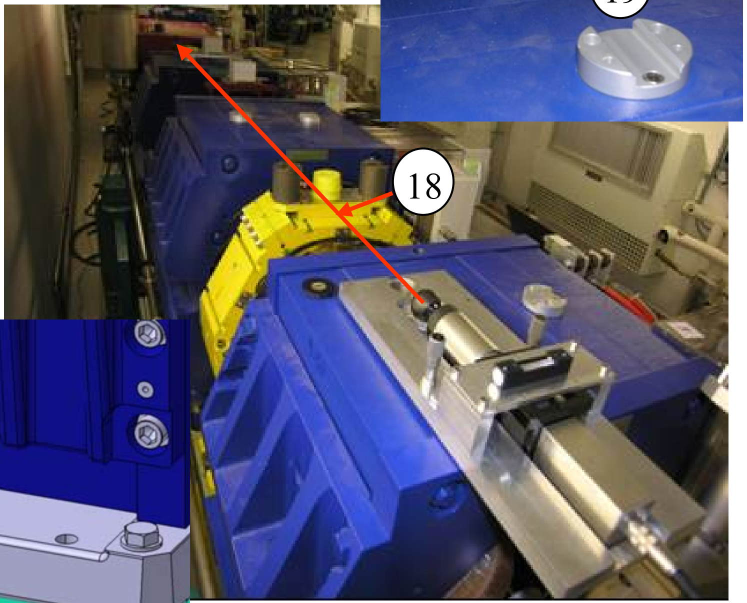
Case study: The Qpole Alignment at SOLEIL

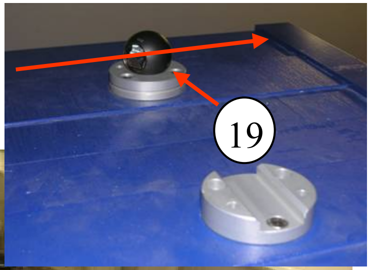
Laser ecartometry of Qpoles on a girder :

- Qpoles are mechanically aligned by the contact of their shims with the girder references: X pin & Z surface
- checking of the previous steps, results (X,Z) at SOLEIL : 15µm
- MSL: reversal of the laser position WR to the girder
- Beam stability is easy: STC = (5µm,2mn)









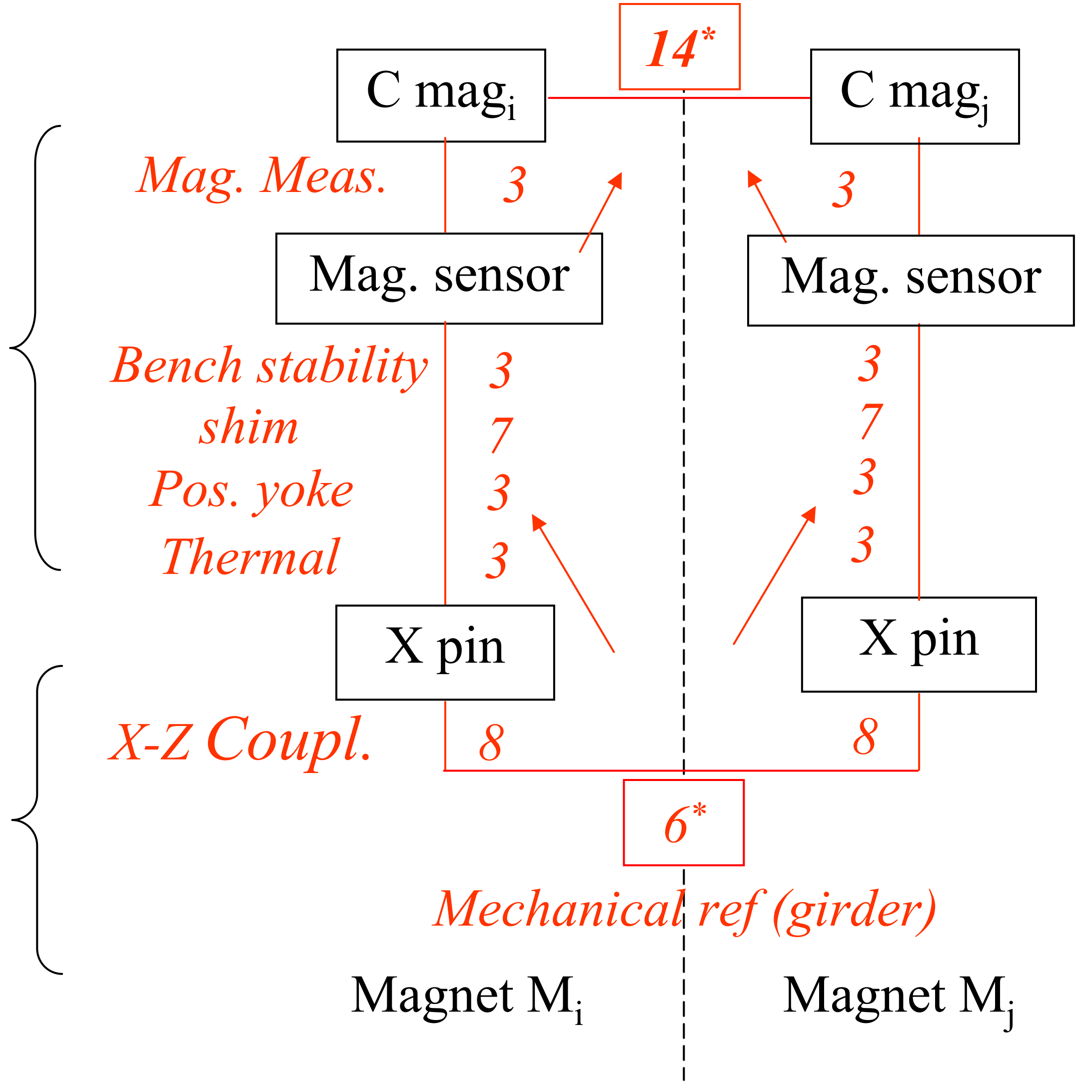
Case study: The Qpole Alignment at SOLEIL

Laser ecartometry of Qpoles on a girder :

Nr	Component	Action	σ (µm)	Bias	STC=(µm,t)	STC=Easy/Diff
18	Laser beam	⇔	⇔	⇔	(,2mn)* ⇔	⇔
		Meas	5	MSL		
19	Retroreflector					
		Contact			(,∞)	E
17	Qpole Fiducials					
		Fiduc	10		(,∞)	E
9	Qpole Mag Axis					
		Bench	10		(,∞)	E
11	Qpole shim					
		Contact	5		(,∞)	E
20	Girder pin (surface)					
		Mech	5		(,∞)	E
21	Girder	⇔	⇔	⇔	(,∞)⇔	⇔

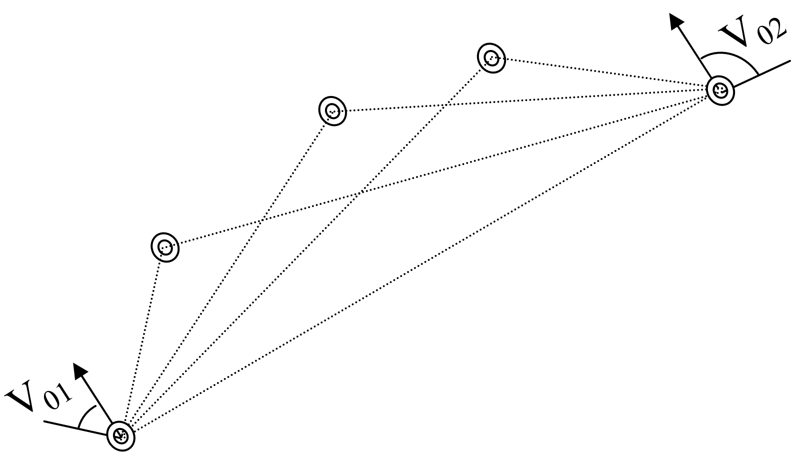
⇔ : Common to all magnets on a girder
Fiduc : Fiducialization => offsets
Bench : Detection of the Qpole axis => Shim

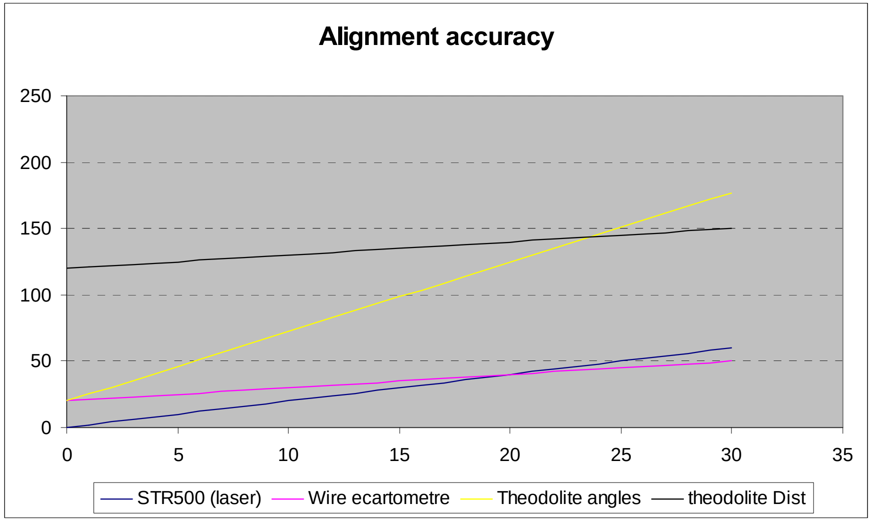
Case study: The Qpole Alignment at SOLEIL



Case study: The Qpole Alignment at SOLEIL

- **Planimetric Alignment with precise tacheometer (orbit definition) :**
  - The general shape has to be controlled
  - Theodolite equipped with an Electronic DistanceMeter (EDM)
  - Leica TDA5005: to measured the network of points defined by all the Qpole fiducials: $STC_{\theta z}$ (3.10^{-4}deg, 10mn) difficult to reach
  - bundle adjustment based on least square calculation: similar to MSL
  - STC= (50µm,SA) for slab & mechanics: SA is the period between to realignment campaigns.





Case study: The Qpole Alignment at SOLEIL

- **Planimetric Alignment with precise tacheometer (orbit definition)**

Nr	Component	Action	σ (µm)	Bias	STC=(µm,t)	STC=Easy/Diff
12	Qpole yoke$_{TDA}$					
		Mech				
17	Qpole Fiducials$_{TDA}$					
		Contact	5		(,10mn)	E
26	TDA centering					
		Mech				
27	Zero (Dist & Angles)				(,10mn)	D_θ**
28	Air(Dist & Angles)	Meas	0.12mm & 3.10^{-4}deg			
19	Retroreflector					
		Contact	5		(,10mn)	E
17	Qpole Fiducials$_{refl}$					
		Mech				
12	Qpole yoke$_{refl}$					
		Mech *			(50,SA)	D
22	Slab				(50,SA)	D
		Mech *			(50,SA)	D
12	Qpole yoke$_{TDA}$					

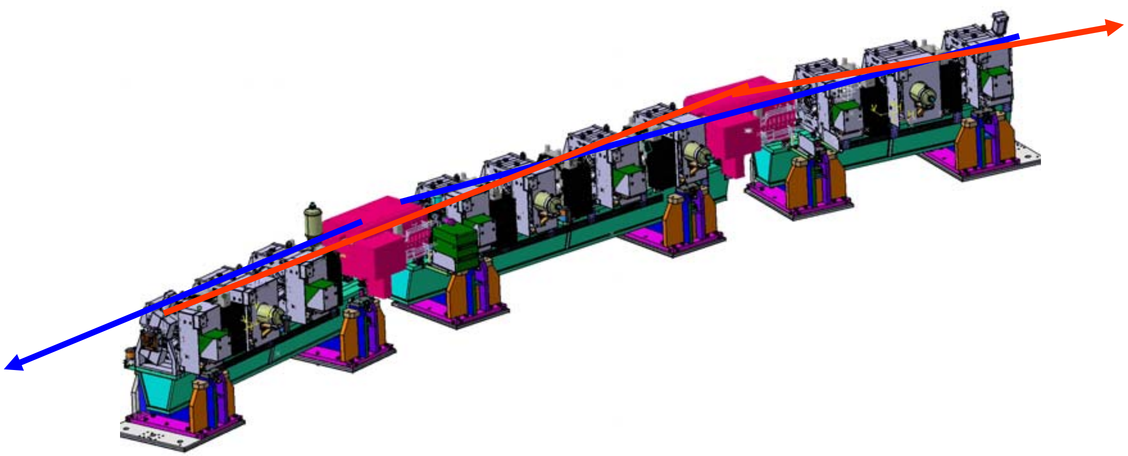
* : Including girders and stands

** : Difficult for Angle zero

SA : Period between two Survey & Alignment operations

Case study: The Qpole Alignment at SOLEIL

- **Planimetric Alignment with wire ecartometry (orbit definition):**
  - Final step for accurate alignment
  - A Kevlar wire is stretched to include the Qpoles of 2 adjacent girders
  - Differential measurements to eliminate offsets
  - The final least square calculation includes also STR500 & TDA5005
  - STC= (10µm, 10mn): measurements
  - STC= (50µm,SA) for slab & mechanics: SA is the period between to realignment campaigns.



Case study: The Qpole Alignment at SOLEIL

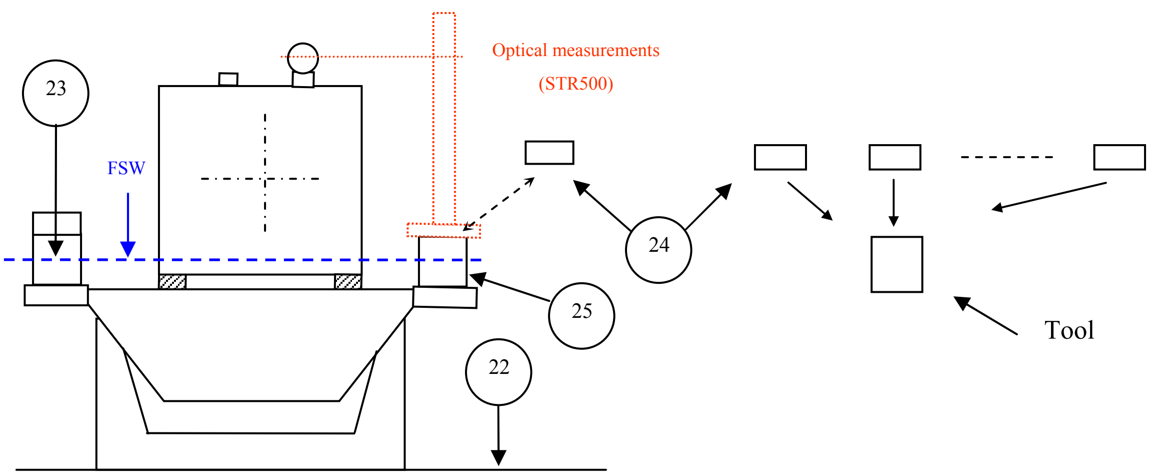
- **Planimetric Alignment with wire ecartometry (orbit definition):**

Nr	Component	Action	σ (µm)	Bias	STC=(µm,t)	STC=Easy/Diff
	Wire	⇔	⇔	⇔	(,10mn) ⇔	⇔
		Meas	10			
22	Ecartometre centering					
		Contact	5		(,10mn)	E
17	Qpole Fiducials					
		Fiduc	10		(,∞)	E
9	Qpole Mag Axis					
		Bench	10		(,∞)	E
11	Qpole shim					
		Contact	5		(,∞)	E
19	Girder pin					
		Contact	5		(,∞)	E
21	Girder					
		Mech			(50,SA)	D
22	Concrete slab	⇔	⇔	⇔	(50,SA)	D

SA : Period between two Survey & Alignment operations

Case study: The Qpole Alignment at SOLEIL

- **Altimetric Alignment with HLS (orbit definition):**
  - Free surface of water available all along the Storage Ring
  - Linking the Qpole Magnetic axis to that surface is very sensitive
  - Altimetric measurements from fiducials to HLS vessels
  - Linking all the zero sensors together: a stainless steel tool for calibration
  - STC = (5 µm, 1 year), differential measurement to eliminate the common part of sensor offsets



Case study: The Qpole Alignment at SOLEIL

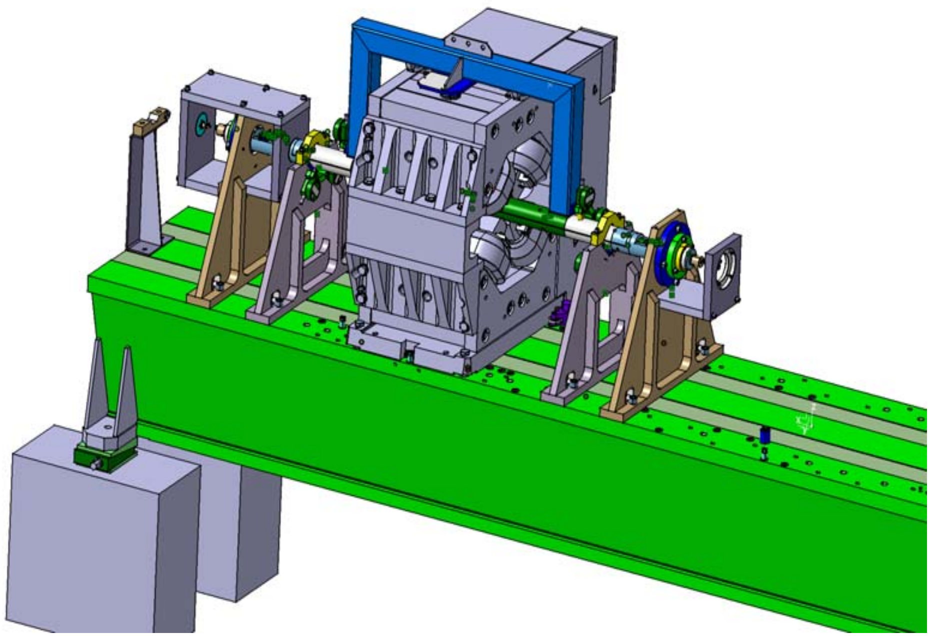
- **Altimetric Alignment with HLS (orbit definition):**

Nr	Component	Action	σ (μm)	Bias	STC=(μm,t)	STC=Easy/Diff
22	Water	⇔	⇔	⇔	⇔	⇔
		Meas	5		(,∞)	E
24	HLS Zero sensor		10		(10,a year)*	E
		Contact			(,∞)	E
25	HLS vessel					
		Laser	10		(,∞)	E
17	Qpole Fiducials					
		Bench	10		(,∞)	E
11	Qpole shims					
		Contact	5		(,∞)	E
22	Girder surface					
		Mech	5		(,∞)	E
20	Girder					
		Mech			(50,SA)	D
22	Concrete slab	⇔	⇔	⇔	(50,SA)	D

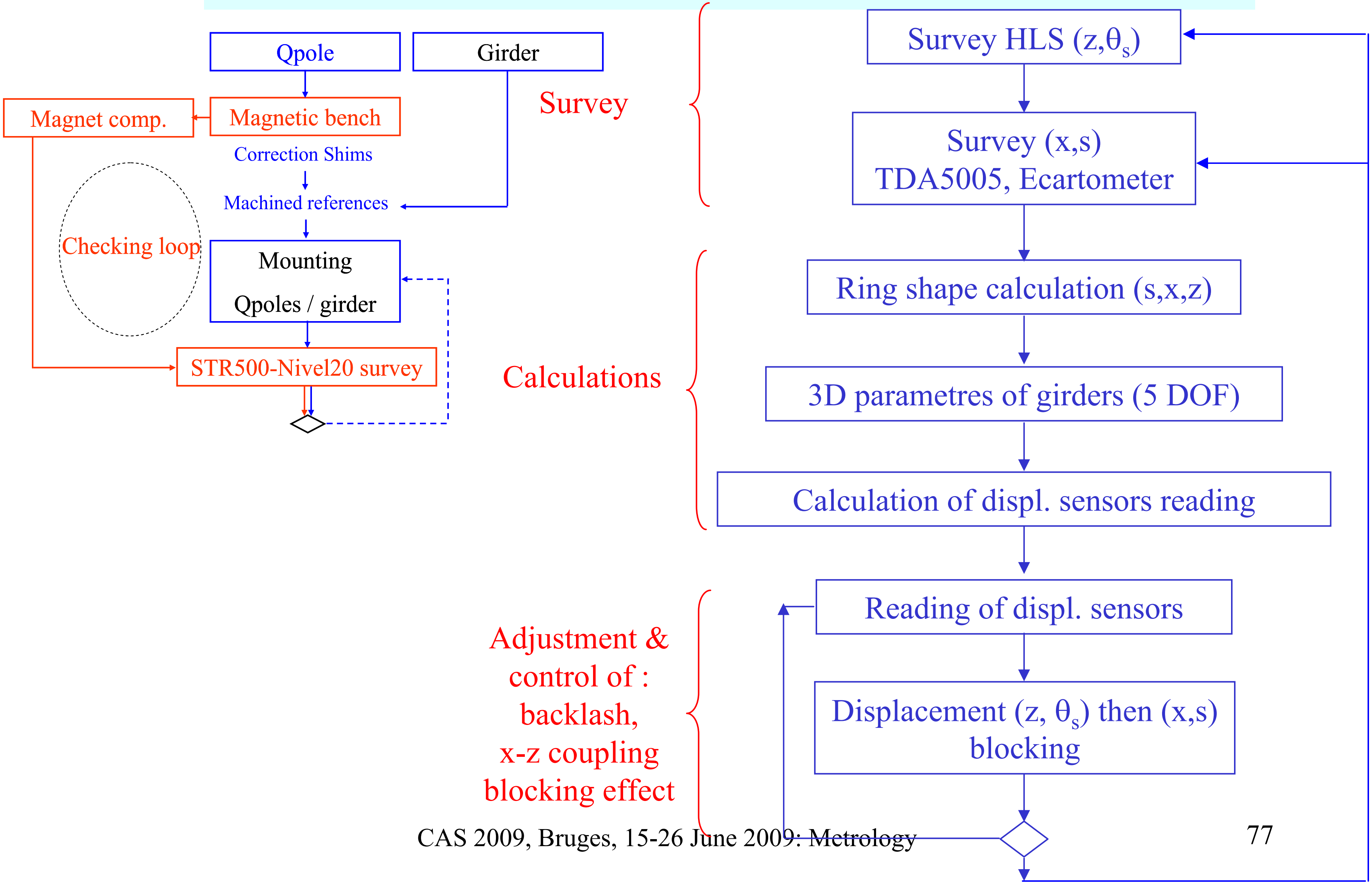
* : With the calibration tool
Laser : Laser ecartometre measurements between HLS vessels and fiducials (not described here).
SA : Period between two Survey & Alignment operations

Case study: The Qpole Alignment at SOLEIL

- **The limit of Differential Measurement:**
  - Each Qpole is measured by the bench: differential measurements
    - It can be applied at the girder scale because any other component requires biggest accuracy of alignment → bench & Magnet comparator
    - Take care of components on straight sections (outside girders) with the magnet comparator: it has to be known in an "absolute way".



Case study: The Qpole Alignment at SOLEIL



Case study: The Qpole Alignment at SOLEIL

- **The achieved results (must not be considered as the ultimate accuracy):**
- **However, they are excellent according to the machine physics results (BPM readings):**

- **=> 0.015mm on girder (1σ)**
  0.050mm/girders (1σ)

Case study: The Qpole Alignment at SOLEIL

- **The limit of the error elimination:**
  - The real physical phenomena are essentially complex & non-linear
  - True for the existing errors, especially for random errors

  - Try to limit the size of errors with the layout design because it allows:
    - Small displacement torsors (commutativity of 3D rotations)
    - Linearization of Least Square calculation (matrix)

Case study: The Qpole Alignment at SOLEIL

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  - Try to limit the size of errors with the layout design because it allows:
    - Small displacement torsors (commutativity of 3D rotations)
    - Linearization of Least Square calculation (matrix)

- **Repeating a set of measurement decreases random errors but does not affect bias errors**
- **MSL will eliminate bias errors and decreases random errors**

- **Thank you for your attention!**