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

- 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

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

Means:  

Point of view:

Sensors & instruments:
- Random & Bias (offset) $E_r$
- $\sigma$ & $B$

Mechanical units:
- Random & Bias (offset) $E_r$
- $\sigma$ & $B$

Stability $\sigma$

Angle-Length
- Effective length $\sigma$
- Metrology loop $\sigma$
- Lever arms $\sigma$
- Multi-Step Layout $B$ & $\sigma$
- Differential Meas. $B$

CAS 2009, Bruges, 15-26 June 2009: Metrology
Introduction

The four components of Design in Dimensional Metrology units:

Means:  Point of view:

Measure  Time

Mechanics  Space

Sensors & instruments: Random & Bias (offset) Er σ & B

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The sensor: We just consider it as an output value affected by a noise ($\sigma$) and a bias (or offset). The linearity error is supposed to be treated (calibration).
Random errors of sensors (type A errors)

- Normal distribution of random errors: standard deviation
- $\sigma$ 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…)

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

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

The four components of Design in Dimensional Metrology units:

Means: 

- Measure
- Time

Point of view: 

- Mechanics
- Space

Sensors & instruments: 
Random & Bias (offset) Er \( \sigma & B \)

Mechanical units: 
Random & Bias (offset) Er \( \sigma & B \)
Mechanics: positioning & measurements

- **Mechanics is a full component of the DM as a positioning system:**
  - As centring systems:
    - 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)
- $\sigma_a = \sigma/l$
- The $X$ uncertainty at the point $A$ is: $\sigma_X = L.\sigma_a$
- 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

Direct measurement

\[ h_\sigma = \text{offset} \]

With \( \sigma < \sigma_{tot} \)

\[ \sigma_{tot} = \sqrt{\sum_{i=1}^{n} \sigma_i^2} \]
Analogy between Measure and Mechanics

- 1) The least squares principle \( \sum v_i^2 \) 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
Introduction

- The four components of Design in Dimensional Metrology units:

- **Means:**
  - Measure
  - Mechanics

- **Point of view:**
  - Time
  - Space

- Sensors & instruments:
  - Random & Bias (offset) $E_r$
  - $\sigma$ & $B$

- Mechanical units:
  - Random & Bias (offset) $E_r$
  - $\sigma$ & $B$

- Stability $\sigma$
The stability of the set “Instrument-Object” should be better than the instrument precision.

STC is the acceptable duration $\delta t$ during which we do not want less than a parasitic displacement quantity $\delta d$:

$$STC = (\delta d, \delta t)$$

Whatever the origin of the disturbance of the system: mechanical, electronic, etc.

It’s common to consider $\delta d$ as a random error.
Stability Time Constant

- Stability analysis is mandatory to fit to the required accuracy
- For both, instrument and object 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**
  - $3.10^{-4} \text{deg}$ accuracy
  - $\delta t = 30 \text{mn}$ measurement duration

$STC_{0Z} = (3.10^{-4} \text{deg}; 30 \text{mn})$
Stability Time Constant

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

*(Synchrotron Soleil)*

*DOF: Degrees OF Freedom*
Introduction

The four components of Design in Dimensional Metrology units:

- **Means:**
  - **Measure**
  - **Time**

- **Point of view:**
  - **Mechanics**
  - **Space**

**Sensors & instruments:**
- Random & Bias (offset) Er \( \sigma \) & \( B \)

**Mechanical units:**
- Random & Bias (offset) Er \( \sigma \) & \( B \)

**Stability**
- Angle-Length \( \sigma \)
- Effective length \( \sigma \)
- Metrology loop \( \sigma \)
- Lever arms \( \sigma \)
- Multi-Step Layout \( B \) & \( \sigma \)
- Differential Meas. \( B \)
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

\[ \Delta \rightarrow \alpha \rightarrow dL \rightarrow \Delta \]

Theodolite

Laser-tracker
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

![Diode](image)

Effective Length

Extended EL ≈ 10mm
Stability Time Constant & Effective Length

- Structure to be motorized with the \( \mu \text{rad} \) level for a long time (\( \infty \))
- Any sub-part of the inclinometer should match to \( \text{STC} = (\mu \text{rad}, \infty) \)
- Especially the detection part which shows the Effective Length (EL)

\[ EL = 10\text{mm} \Rightarrow 10\text{nm for 1 } \mu \text{rad} \]

(in addition to electronic noise \( \Rightarrow \text{STC}_{\text{elec}} \))

Capacitive inclinometers:

\[ EL \approx \text{less than 1mm} \]
Stability Time Constant & Effective Length

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

\[
dZ = L'_1 - L'_2 = 0
\]

\[
dZ = L_1 - L_2
\]

\[
EL = 10m
\]

(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 \( 0.02/Y = 0.025 \text{ mrad} \), where \( Y = 786 \text{ mm} \), the width of yokes
  - The **Effective Length** for the electron beam is actually the width of the pole \( p = 128.6 \text{ mm} \)
    \[ 0.02/p = 0.156 \text{ mrad} \]

  - The drawings have to be checked (tolerance stack up)
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)

Metrology loop sensitive to errors (instrumental & instabilities) due to a cumulative effect.

(Hennebelle, ENSAM)
• Parallel layout: robust to errors, average influence

*Metrology loop*

(Lahousse, ENSAM)
• 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
• Decoupling the actuator & measuring loops is mandatory for high accuracy units
• Ex: Coordinate Measuring Machine (CMM):

(Hennebelle, ENSAM)
• 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

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Introduction

- The four components of Design in Dimensional Metrology units:

\[ \text{Means: } \quad \text{Point of view:} \]

- Sensors & instruments:
  - Random & Bias (offset) Er
  - \( \sigma \) & \( B \)

- Mechanical units:
  - Random & Bias (offset) Er
  - \( \sigma \) & \( B \)

- Stability
  - Angle-Length
    - Effective length \( \sigma \)
  - Metrology loop \( \sigma \)
  - Lever arms \( \sigma \)
  - Multi-Step Layout \( B \) & \( \sigma \)
  - Differential Meas. \( B \)
“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:**

\[ e_{\text{cos}} \approx \frac{l^2}{2d} \]

- \( l=1\text{mm}, \ d=100\text{mm} \Rightarrow e=5\mu\text{m} \)
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 Object or of the Measurement
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 $360^\circ/N$ 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”
• 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

\[ d = (L_2 + e) - (L_1 + e) = L_2 - L_1. \]

- **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.
Differential measurements

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

Detection Carriage

Stretched wire

Distance to be measured

Offset wire/fiducial

1\textsuperscript{st} offset

2\textsuperscript{nd} offset
Differential measurements

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

\[ dZ = L'_1 - L'_2 = 0 \]

\[ dZ = L_1 - L_2 = 0 \]

*(Fogale Nanotech)*
Differential measurements

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

\[
\begin{align*}
  h_1 &= L_1 + e_1 \\
  h_2 &= L_2 + e_2 \\
  de &= e_1 - e_2 \\
  dZ &= h_1 - h_2 = L_1 - L_2 + de
\end{align*}
\]

Measured with HLS

Measured with the tool

Stainless steel calibration tool

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Differential measurements

- **Superposition:**
  - Two opposite areas of a graduated circle are **superimposed**
  - Even for a bubble
  - MSL situation
Differential measurements

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

![Interferometer diagram]

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:

- 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

\[ dx \approx \frac{r_0}{2} \frac{B_1}{B_2} \]
\[ dz \approx -r_0 \frac{A_1}{2} \frac{B_2}{B_2} \]
\[ \tan(2\theta) = -\frac{A_2}{B_2} \]

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

<table>
<thead>
<tr>
<th>Nr</th>
<th>Component</th>
<th>Action</th>
<th>σ (µm)</th>
<th>Bias</th>
<th>STC=(µm,t)</th>
<th>STC=Easy/Diff</th>
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<tbody>
<tr>
<td>1</td>
<td>Bench</td>
<td>Mech</td>
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<td>(∞)</td>
<td>E</td>
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<tr>
<td>2</td>
<td>Tool Stand</td>
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<td>(m,M)</td>
<td>E</td>
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<td>D,E</td>
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<tr>
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<td>(∞)</td>
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<td>7</td>
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<td>Contact</td>
<td></td>
<td>(∞)</td>
<td>E</td>
<td></td>
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<tr>
<td>8</td>
<td>Coil Stand</td>
<td>Mech</td>
<td></td>
<td>(∞)</td>
<td>E</td>
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</tr>
<tr>
<td>1</td>
<td>Bench</td>
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</table>
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:**

<table>
<thead>
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<td>$(\infty)$</td>
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<td>Ball bearings</td>
<td>Contact</td>
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<td>8</td>
<td>Coil Stand</td>
<td>Mech</td>
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<td>(Tool1)</td>
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<tr>
<td>1</td>
<td>Bench</td>
<td>Mech</td>
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<td>$(\infty)$</td>
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<td>Bench Pin (surface)</td>
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<td>Qpole Yokes</td>
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<td>E</td>
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<td>Qpole Mag Axis</td>
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</table>

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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:

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<td></td>
<td>($30\text{\textmu}m$)</td>
<td>E</td>
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<tr>
<td>5</td>
<td>Coil Mag Axis</td>
<td>Rotat</td>
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<td>MSL</td>
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<tr>
<td>13</td>
<td>Dial gauge</td>
<td>Tool2 (14)</td>
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<td>($30\text{\textmu}m$)</td>
<td>E</td>
<td></td>
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<tr>
<td>15</td>
<td>QC structure</td>
<td>$X$: Mech, $Z$: Tool3</td>
<td>($30\text{\textmu}m$, $\text{days}$)</td>
<td>E</td>
<td>E</td>
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<td>Mech</td>
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</table>

Tool2: Wedge
Tool3: Z bench
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:

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<thead>
<tr>
<th>Nr</th>
<th>Component</th>
<th>Action</th>
<th>σ (μm)</th>
<th>Bias</th>
<th>STC=(μm,t)</th>
<th>STC=Easy/Diff</th>
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<tbody>
<tr>
<td>18</td>
<td>Laser beam</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>(2mn)</td>
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</tr>
<tr>
<td>19</td>
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<td>Meas</td>
<td>5</td>
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<td>MSL</td>
<td></td>
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<tr>
<td>17</td>
<td>Qpole Fiducials</td>
<td>Contact</td>
<td></td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>9</td>
<td>Qpole Mag Axis</td>
<td>Fiduc</td>
<td>10</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>11</td>
<td>Qpole shim</td>
<td>Bench</td>
<td>10</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>20</td>
<td>Girder pin (surface)</td>
<td>Contact</td>
<td>5</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>21</td>
<td>Girder</td>
<td></td>
<td></td>
<td></td>
<td>(∞)</td>
<td></td>
</tr>
</tbody>
</table>

◊: Common to all magnets on a girder
Fiduc: Fiducialization => offsets
Bench: Detection of the Qpole axis => Shim
Case study: The Qpole Alignment at SOLEIL

- **C mag**
  - 14*
  - Mag. sensor
  - **Mag. Meas.**
  - Bench stability
  - 3
  - shim
  - 7
  - Pos. yoke
  - 3
  - Thermal
  - 3
  - X pin
  - **X-Z Coupl.**
  - **Mechanical ref (girder)**
  - 8

- **C mag**
  - 3
  - Mag. sensor
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  - 3
  - X pin
  - **X-Z Coupl.**
  - 8

- **Magnet M**
  - 6*
  - Magnet M

CAS 2009, Bruges, 15-26 June 2009: Metrology
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: $\text{STC}_{\theta z} (3.10^{-4}\text{deg}, 10\text{mn})$ 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)

<table>
<thead>
<tr>
<th>Nr</th>
<th>Component</th>
<th>Action</th>
<th>$\sigma$ (µm)</th>
<th>Bias</th>
<th>STC = (µm, t)</th>
<th>STC = Easy/Diff</th>
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</thead>
<tbody>
<tr>
<td>12</td>
<td>Qpole yoke\textsubscript{TDA}</td>
<td>Mech</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Qpole Fiducials\textsubscript{TDA}</td>
<td>Contact</td>
<td>5</td>
<td>(10mm)</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>TDA centering</td>
<td>Mech</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Zero (Dist &amp; Angles)</td>
<td>Mech</td>
<td></td>
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</tr>
<tr>
<td>28</td>
<td>Air (Dist &amp; Angles)</td>
<td>Meas</td>
<td>0.12mm &amp; 3.10 deg</td>
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<tr>
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<td>Retroreflector</td>
<td>Contact</td>
<td>5</td>
<td>(10mm)</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Qpole Fiducials\textsubscript{ref}</td>
<td>Mech</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Qpole yoke\textsubscript{ref}</td>
<td>Mech *</td>
<td></td>
<td>(50,SA)</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Slab</td>
<td>Mech *</td>
<td></td>
<td>(50,SA)</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

* : 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):

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<tr>
<th>Nr</th>
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<th>σ (µm)</th>
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<tr>
<td></td>
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<td>Meas</td>
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<td>(&lt;10mn)</td>
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<tr>
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<td>Contact</td>
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<td></td>
<td>(&lt;10mn)</td>
<td>E</td>
</tr>
<tr>
<td>17</td>
<td>Qpole Fiducials</td>
<td>Fiduc</td>
<td>10</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>9</td>
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<td>Bench</td>
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<td></td>
<td>(∞)</td>
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<tr>
<td>11</td>
<td>Qpole shim</td>
<td>Contact</td>
<td>5</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>19</td>
<td>Girder pin</td>
<td>Contact</td>
<td>5</td>
<td></td>
<td>(∞)</td>
<td>E</td>
</tr>
<tr>
<td>21</td>
<td>Girder</td>
<td>Mech</td>
<td></td>
<td></td>
<td>(50,SA)</td>
<td>D</td>
</tr>
<tr>
<td>22</td>
<td>Concrete slab</td>
<td></td>
<td></td>
<td></td>
<td>(50,SA)</td>
<td>D</td>
</tr>
</tbody>
</table>

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):

<table>
<thead>
<tr>
<th>Nr</th>
<th>Component</th>
<th>Action</th>
<th>$\sigma$ ((\mu)m)</th>
<th>Bias</th>
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<td>$\Theta$</td>
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<td>$\Theta$</td>
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<td>($\infty$)</td>
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<td>E</td>
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<tr>
<td>24</td>
<td>HLS Zero sensor</td>
<td>10</td>
<td>($10, a year$)*</td>
<td></td>
<td>E</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contact</td>
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<td>($\infty$)</td>
<td></td>
<td>E</td>
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<td>25</td>
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<td>Laser</td>
<td>10</td>
<td>($\infty$)</td>
<td>E</td>
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<tr>
<td>17</td>
<td>Qpole Fiducials</td>
<td>Bench</td>
<td>10</td>
<td>($\infty$)</td>
<td>E</td>
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<td>Contact</td>
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<td>($\infty$)</td>
<td>E</td>
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<td>22</td>
<td>Girder surface</td>
<td>Mech</td>
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<td>($\infty$)</td>
<td>E</td>
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</tr>
<tr>
<td>20</td>
<td>Girder</td>
<td>Mech</td>
<td></td>
<td>($50, SA$)</td>
<td>D</td>
<td></td>
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<td>22</td>
<td>Concrete slab</td>
<td></td>
<td></td>
<td>($50, SA$)</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

* : With the calibration tool
Laser : Laser ecartomètre 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

Survey HLS (z, θs)

Survey (x, s)

TDA5005, Ecartometer

Ring shape calculation (s, x, z)

3D parameters of girders (5 DOF)

Calculation of displ. sensors reading

Reading of displ. sensors

Displacement (z, θs) then (x, s) blocking

Adjustment & control of: backlash, x-z coupling blocking effect

Survey

Calculations

Magnetic bench

Correction Shims

Machined references

Mounting

Qpoles / girder

Qpole

Girder

Magnet comp.

Survey HLS (z, θs)

Survey (x, s)

TDA5005, Ecartometer

Ring shape calculation (s, x, z)

3D parameters of girders (5 DOF)

Calculation of displ. sensors reading

Reading of displ. sensors

Displacement (z, θs) then (x, s) blocking

Adjustment & control of: backlash, x-z coupling blocking effect
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):

  • $\Rightarrow \ 0.015\text{mm on girder (1}\sigma)$
  $\ 0.050\text{mm/girders (1}\sigma)$
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)
The limit of the error elimination:

- The real physical phenomena are essentially complex & non-linear
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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

Case study: The Qpole Alignment at SOLEIL
• Thank you for your attention!