ESTIMATION OF TEMPERATURE FLUCTUATIONS HARSHNESS REGARDING STABILITY OF STRUCTURES IN THE NANOMETER RANGE

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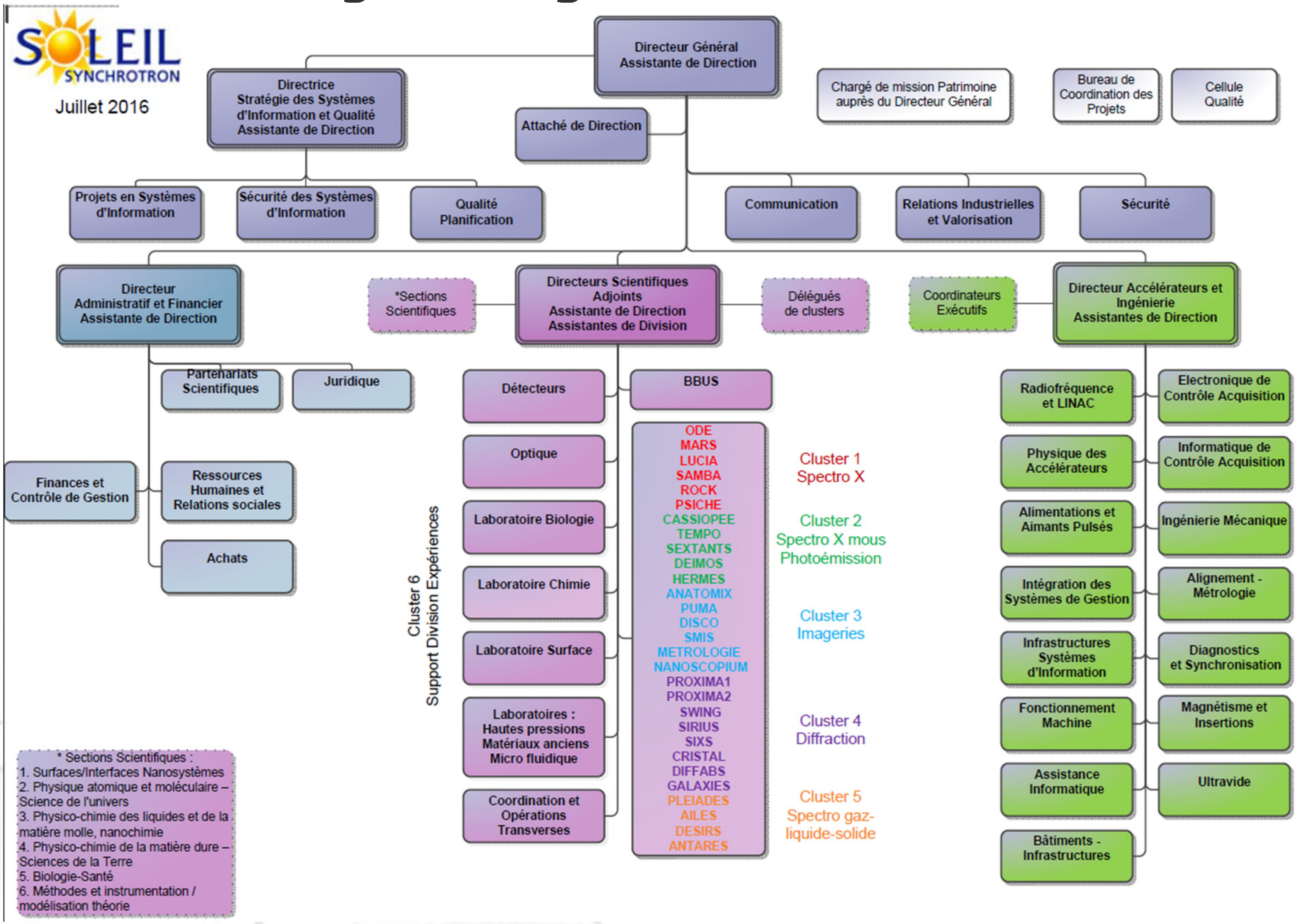
SYNCHROTRON SOLEIL

OUTLINE

- MECHANICAL ENGINEERING AT SOLEIL
- NANOMETER STABILITY: SOME CLARIFICATIONS
- DISTURBANCE SOURCES CLASSIFICATION
- THERMAL STABILITY IN NUMBERS
- THERMAL-MECHANICAL SUSCEPTIBILITY
  - MECHANISMS AT PLAY
  - PROPOSED PRACTICAL RULES FOR ESTIMATION
  - ILLUSTRATION AND VALIDATION
  - RELIABILITY ANALYSIS
- SUMMARY / CONCLUSION

SOLEIL SYNCHROTRON

Mechanical Engineering at SOLEIL



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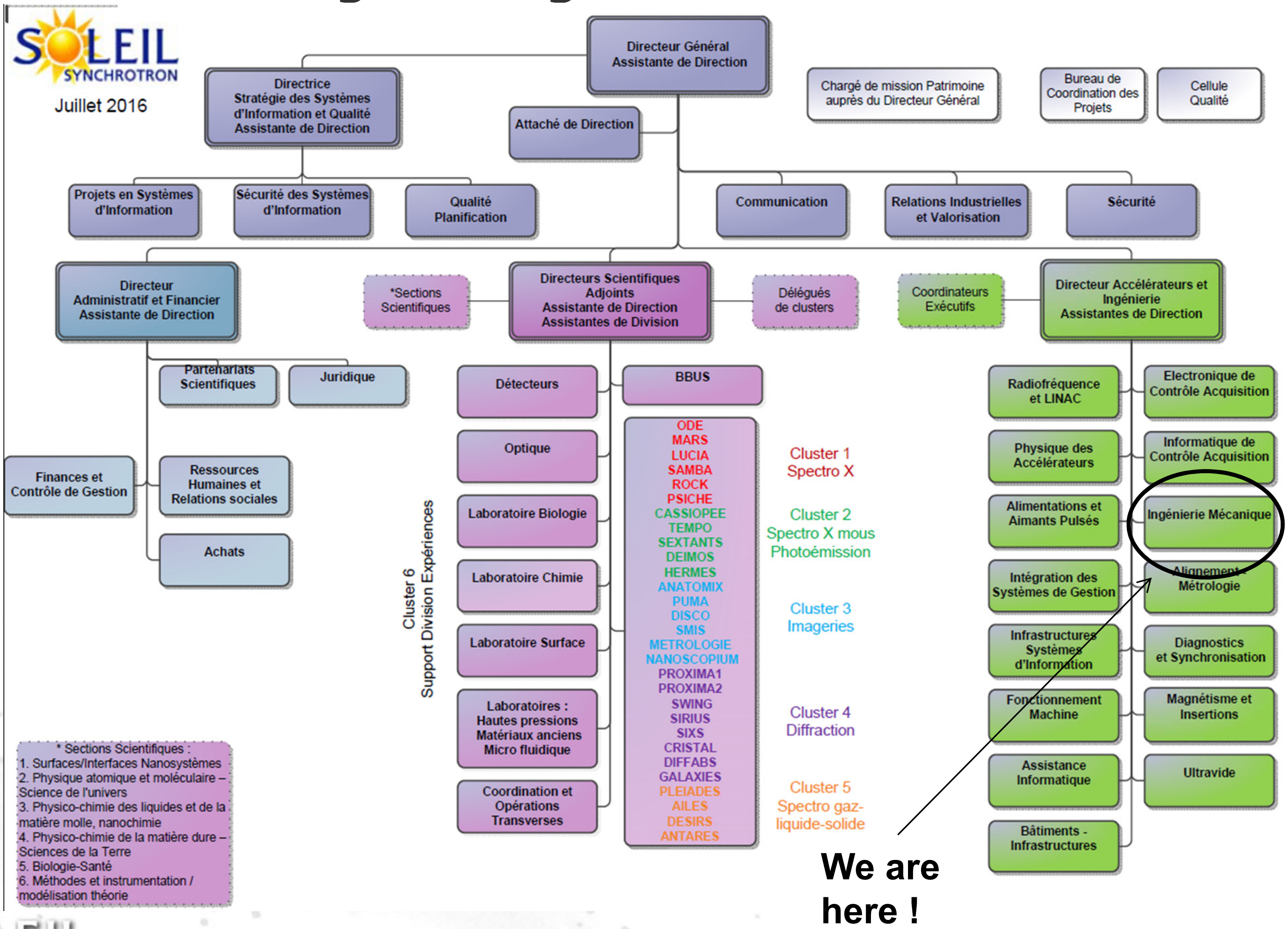
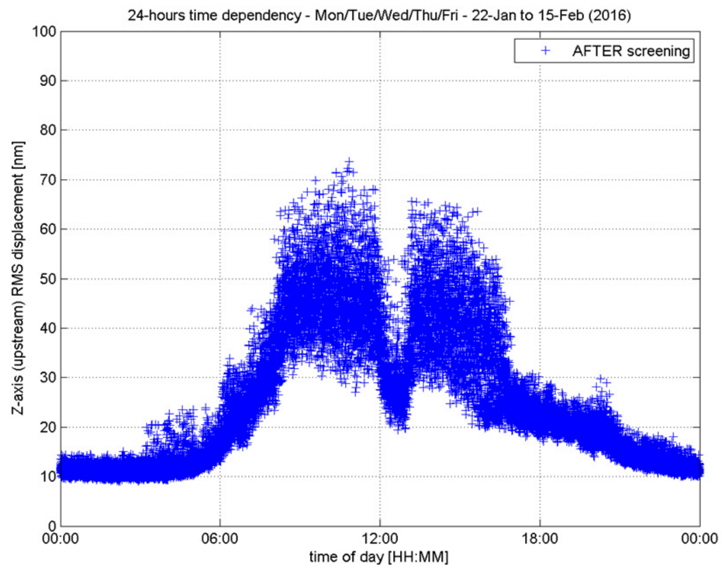
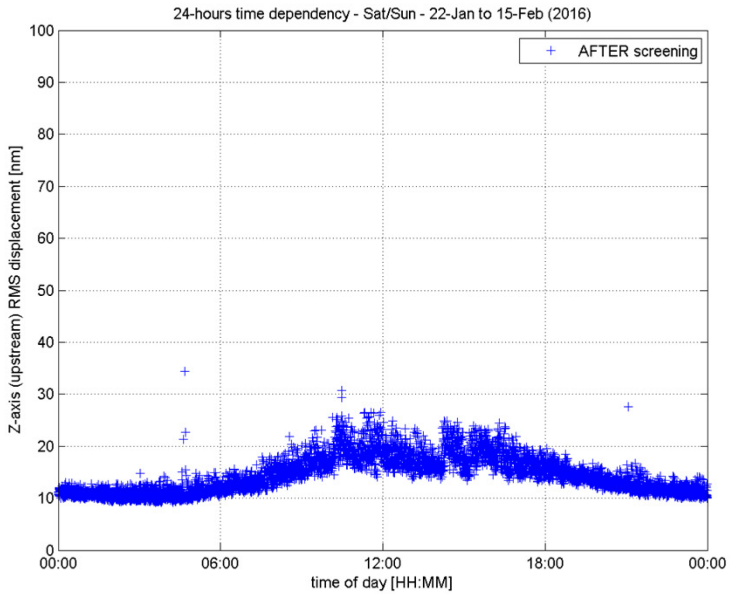


SOLEIL SYNCHROTRON

NANOMETER STABILITY: SOME CLARIFICATIONS

- Ground motion at SOLEIL = *dozens* of nm (RMS !)
- Absolute stability is <u>not</u> required, but
- Mis-alignment <u>is</u> critical
- Alignment preserved if:
  - Ground motion is uniform
  - Supports deflections are small





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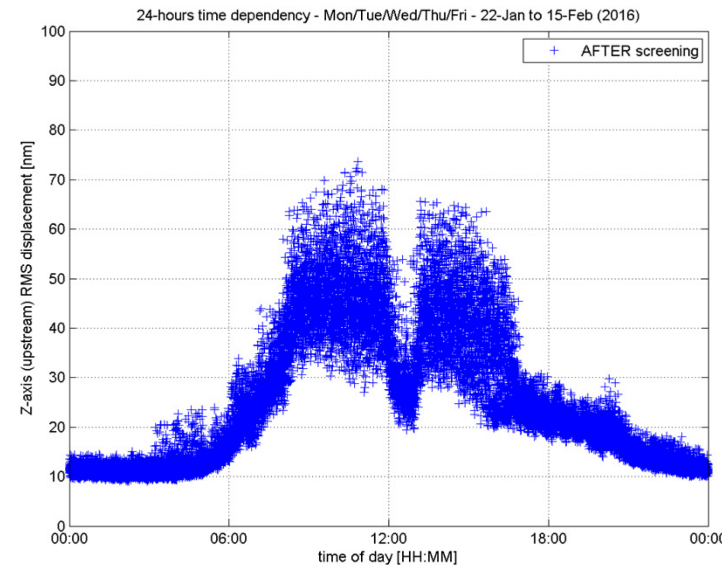
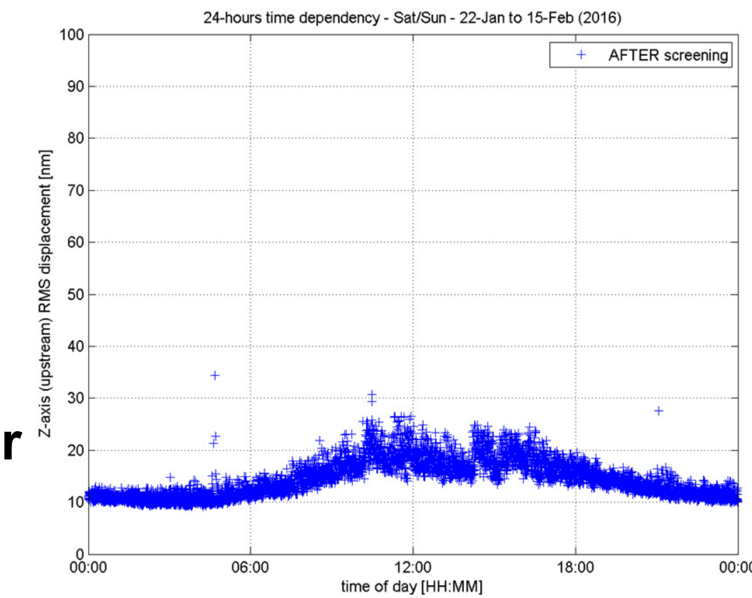
Compact & stiff support structures => dynamic relative motion << 10nm
BUT for long (1h+) observation time, thermally induced error can be WAY higher





DISTURBANCE SOURCES CLASSIFICATION

Thermal mechanical effects

Internal :

-beam heat load

-motors heat load

-coolant flow temp

External :

- hutch ambiant air

Dynamic effects

Internal:

- motors
- pressurized air
- coolant flow

External:

- ground transmitted
- acoustically transmitted

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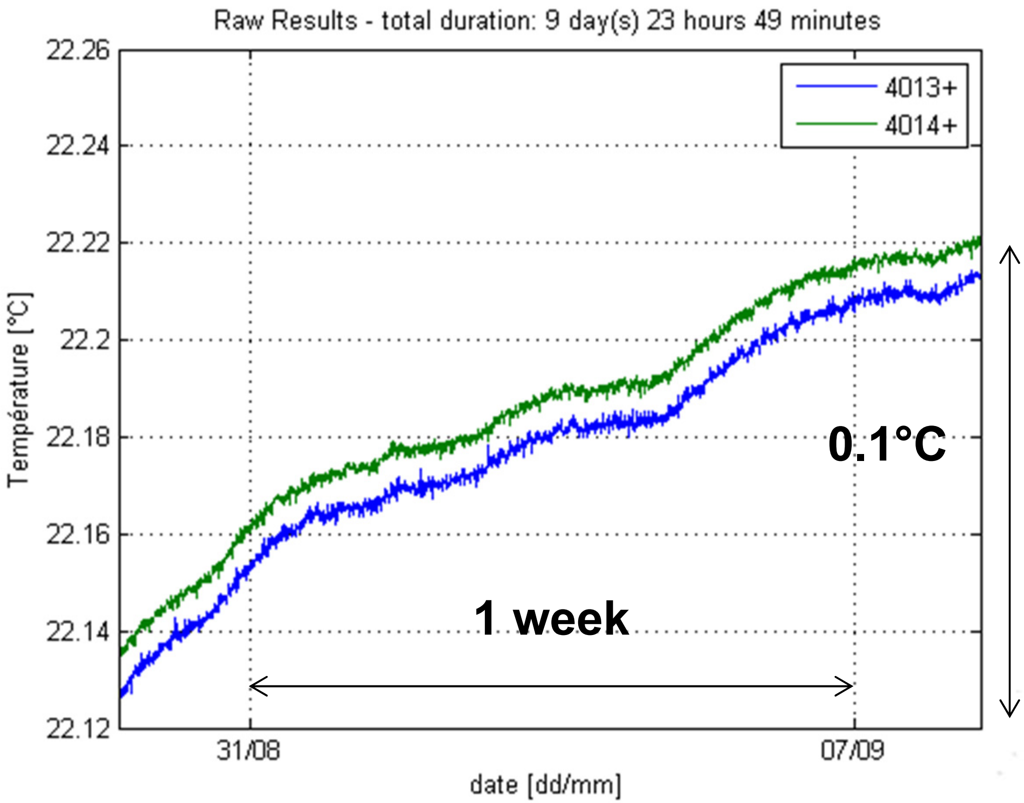
Design: no disturbance from heat sink
Reality: no perfect heat sink, non-zero perturbations

THERMAL STABILITY IN NUMBERS (1/2)

Common practice :

use peak-to-peak values



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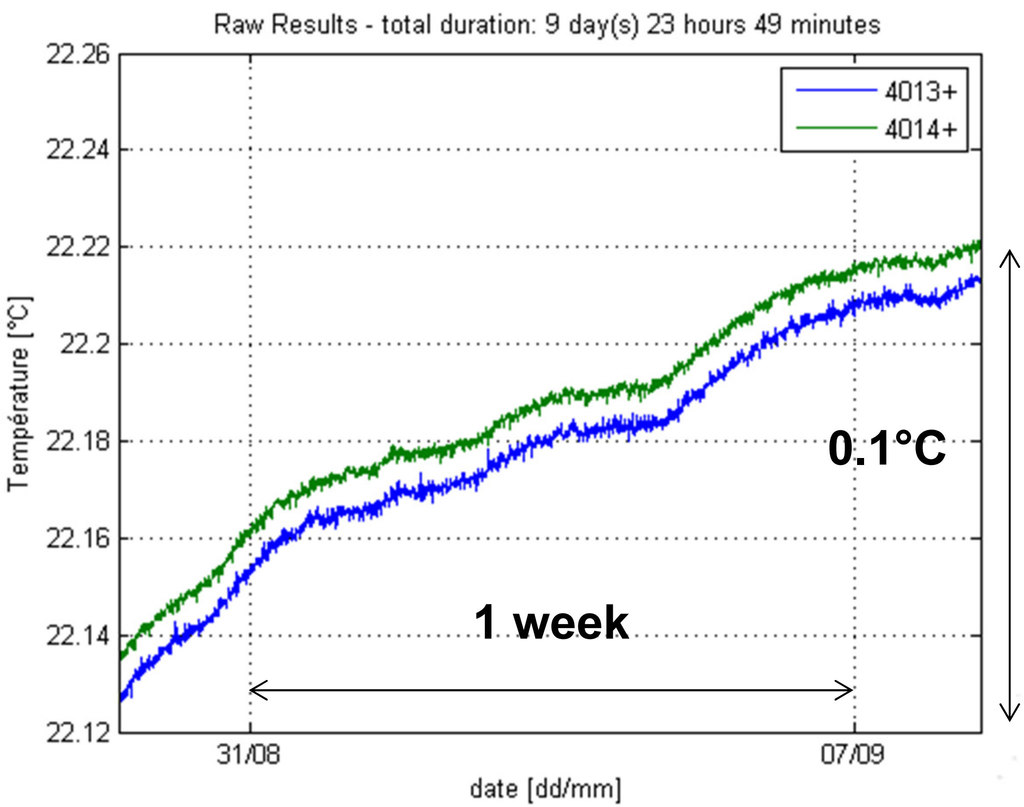

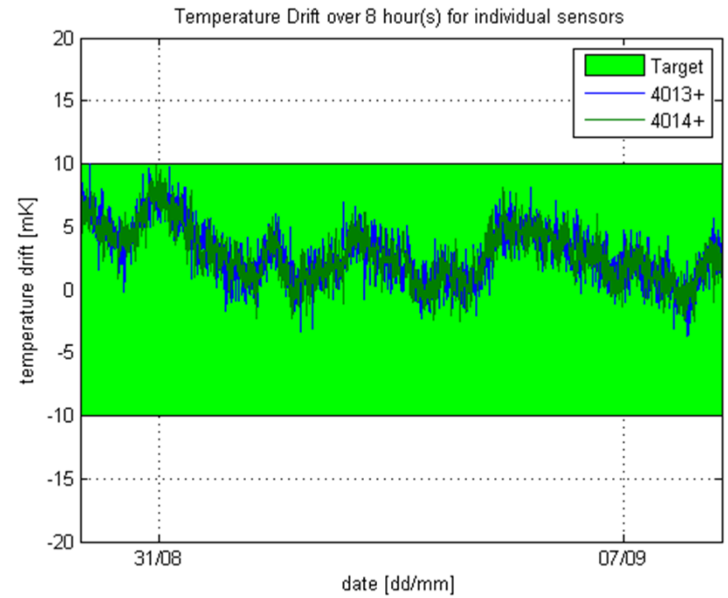

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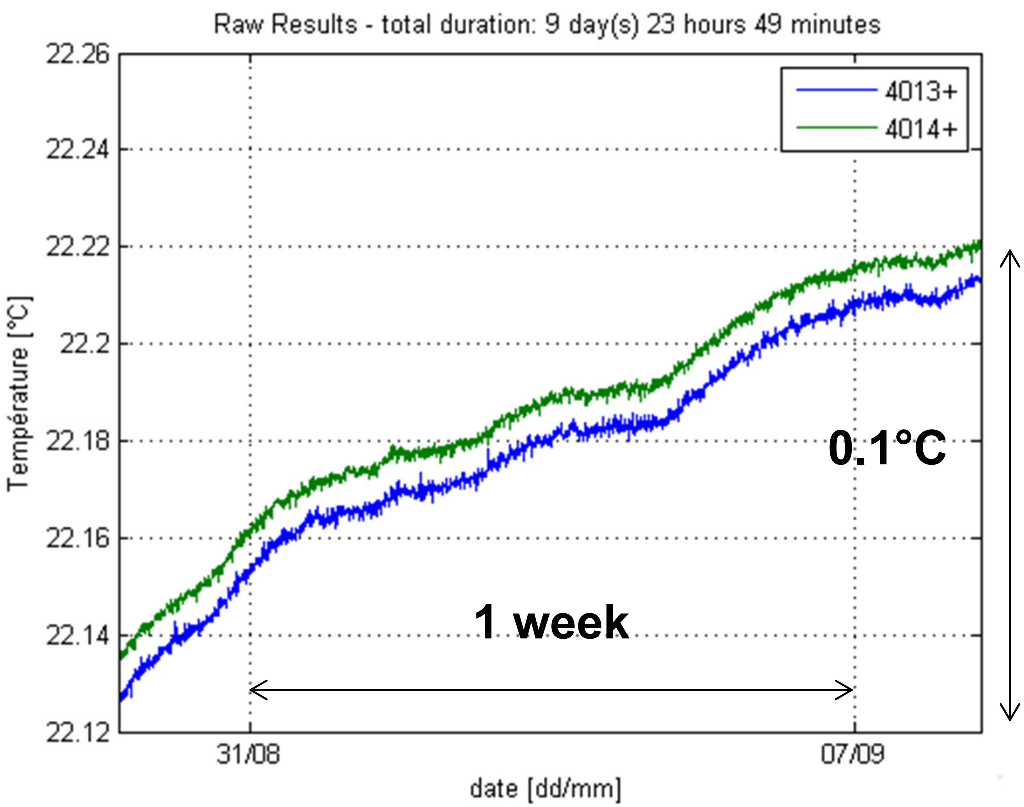

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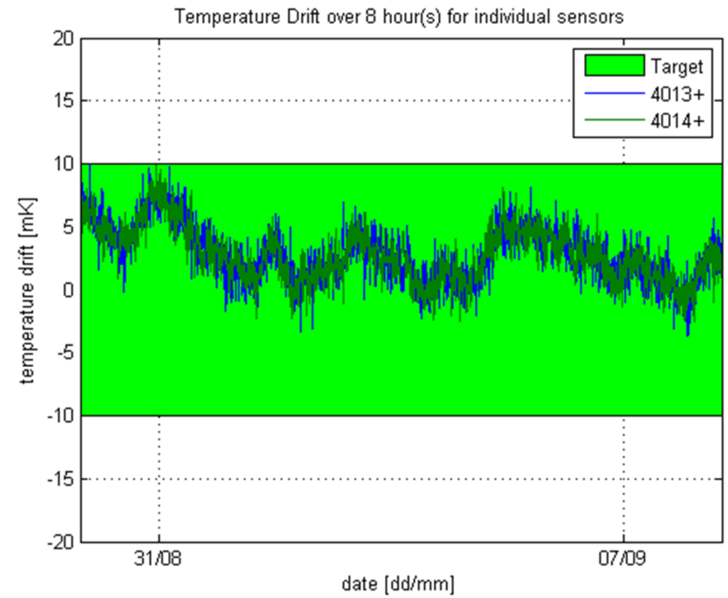

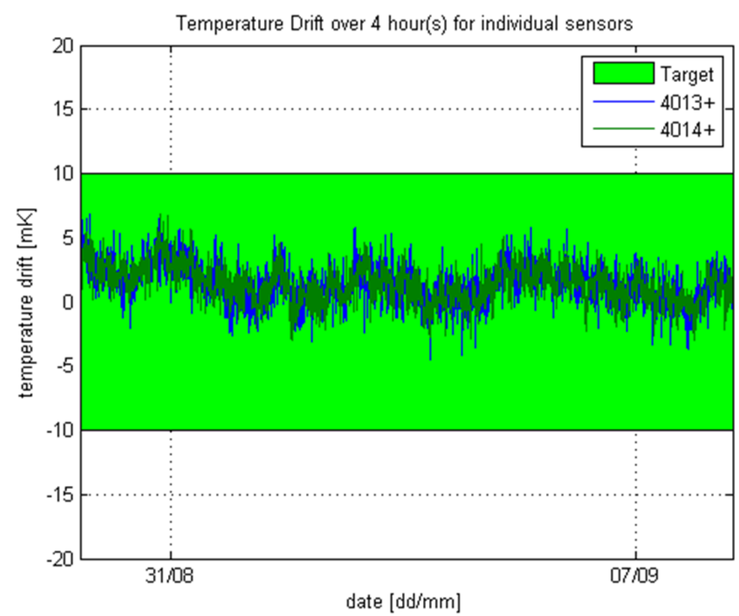

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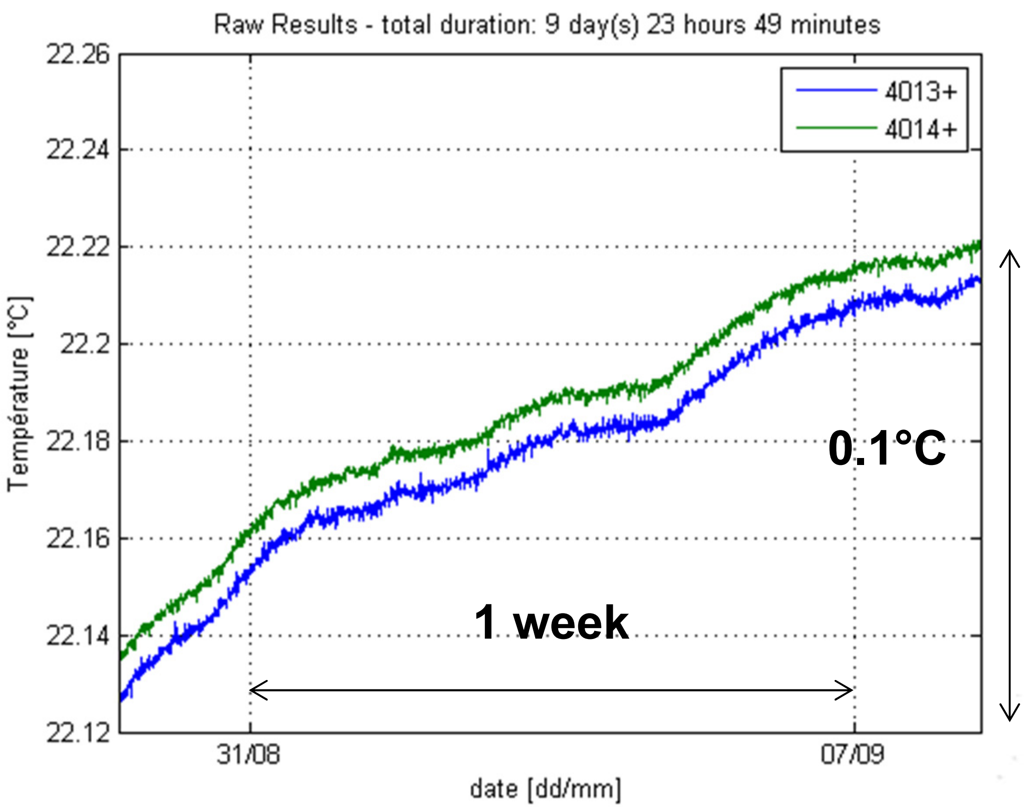

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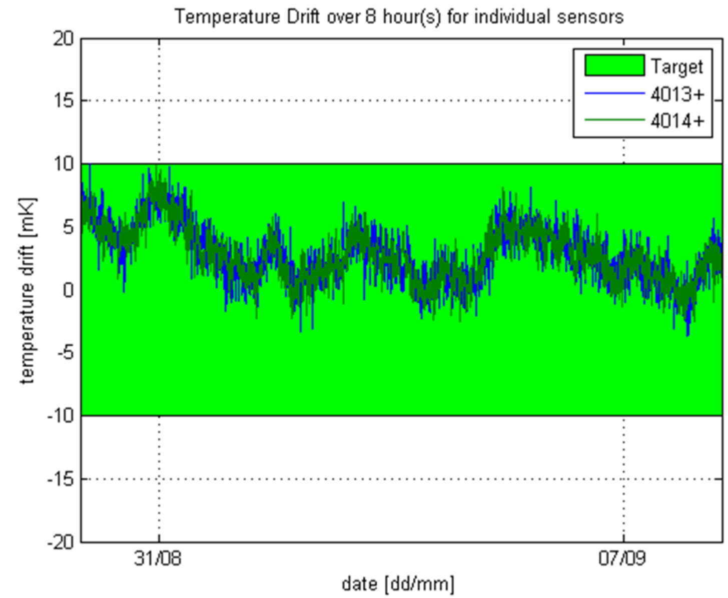

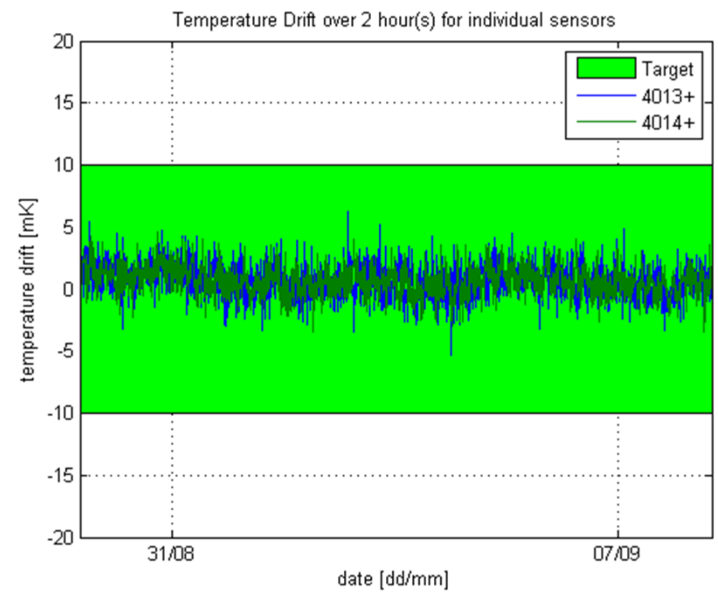

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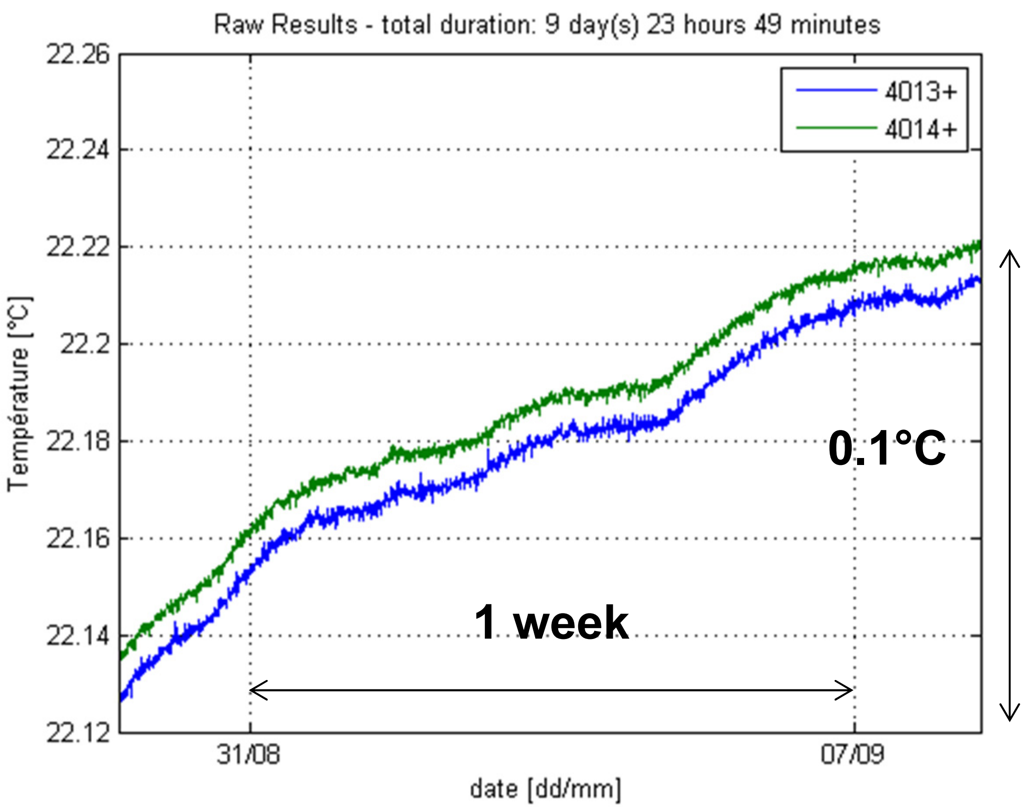

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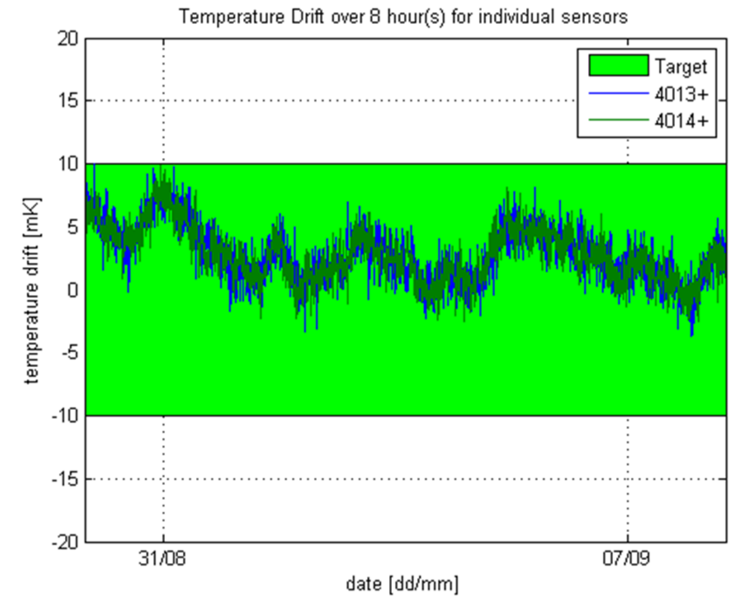

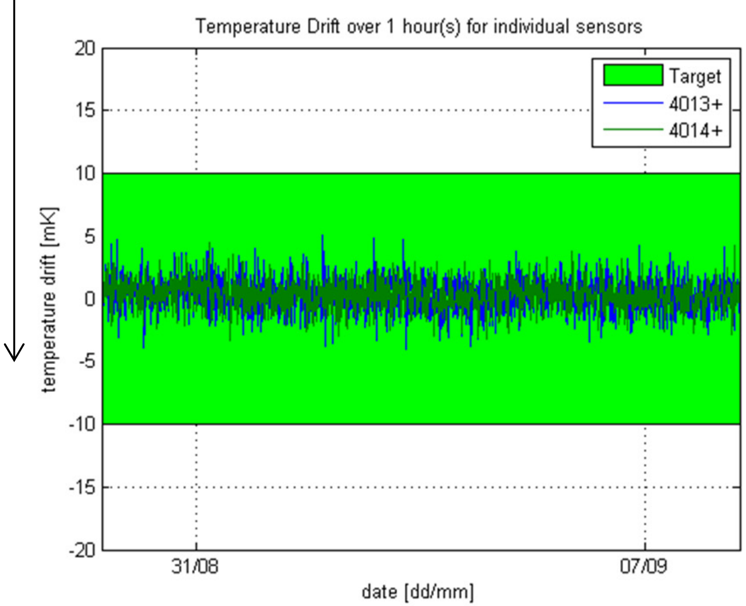

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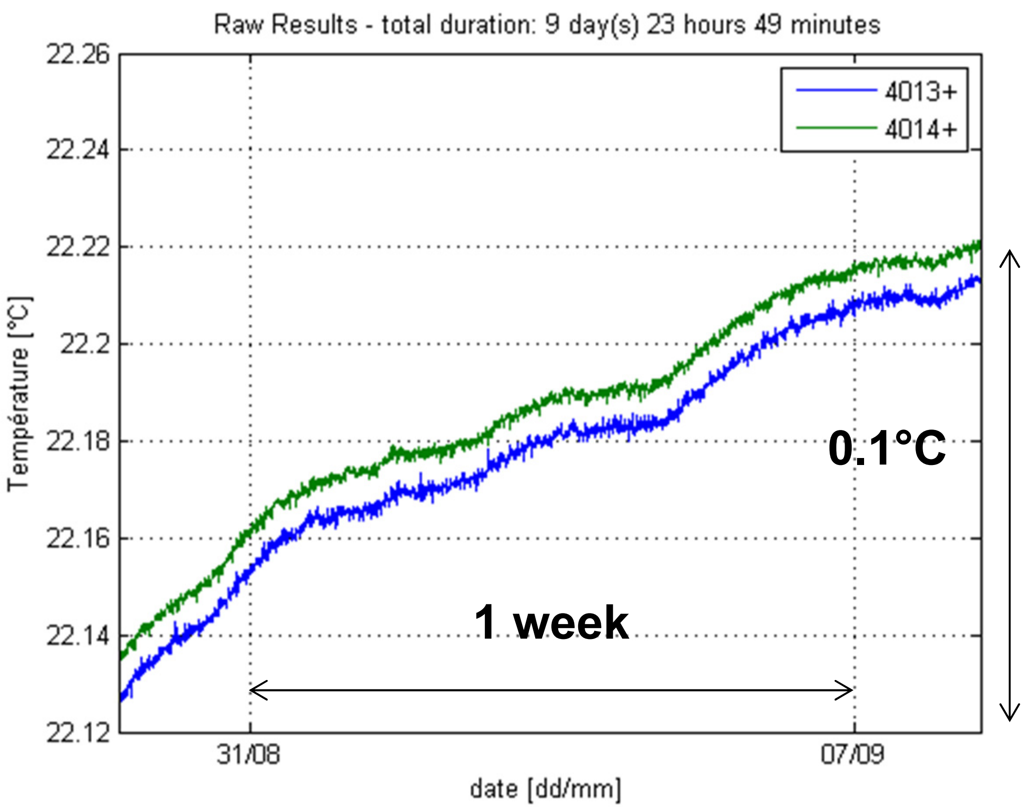

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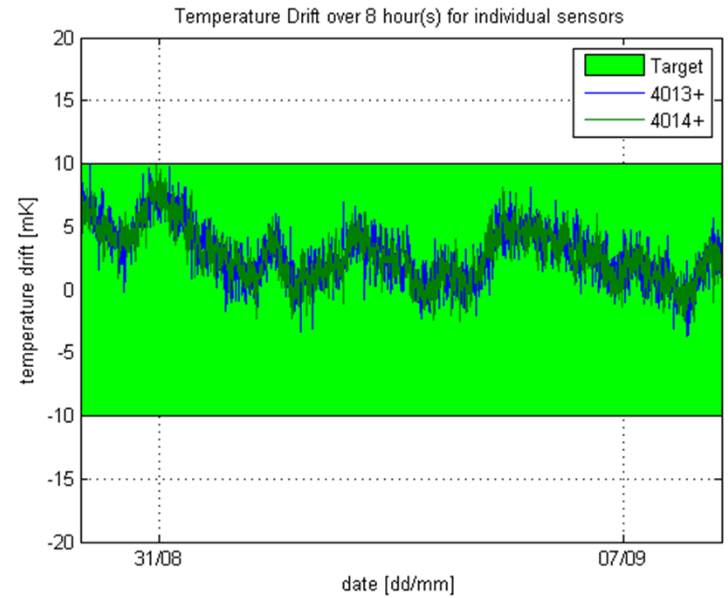

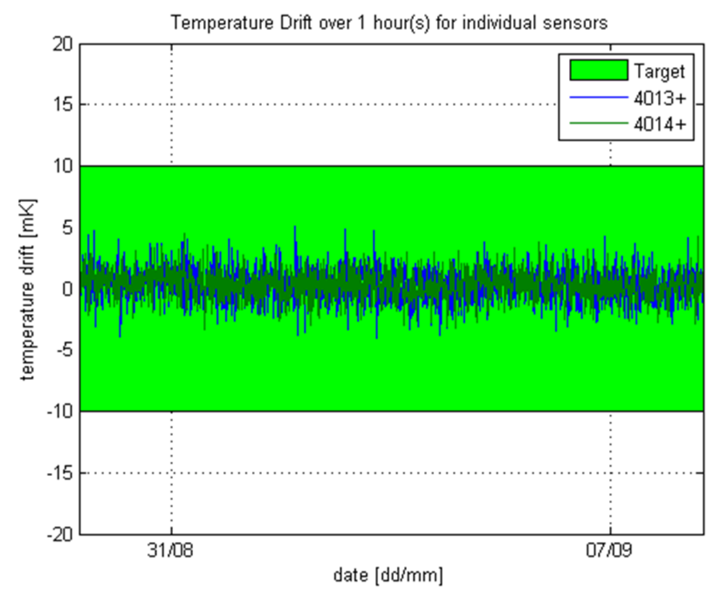

THERMAL STABILITY IN NUMBERS (2/2)

AMPLITUDE PP

(millidegree C)

- 9 days => 100mdeg
- 8 hours => 12 mdeg
- 4 hours => 10 mdeg
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SIGNAL TYPE

Steady trend

↓

No trend (random)

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Q: Where do we stand actually ?

SOLEIL SYNCHROTRON

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A1: our reference fluctuations are 50% of total error budget, it's a mess !

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SIGNAL TYPE

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No trend (random)

Q: Where do we stand actually ?

A1: our reference fluctuations are 50% of total error budget, it's a mess !

A2: random temperature fluctuations have no effect whatsoever so stop worrying: We're good !

THERMAL-MECHANICAL SUSCEPTIBILITY : MECHANISMS

Intuition: « fast » temperature oscillation do not propagate very far along support structure

$$\alpha = \boldsymbol{thermal\,diffusivity}\ [\boldsymbol{Length}^2/\boldsymbol{Time}]$$

$$\alpha[\frac{\boldsymbol{mm}^2}{\boldsymbol{s}}] \sim \boldsymbol{4}(\boldsymbol{Invar})\ \ldots \boldsymbol{100}(\boldsymbol{Al})$$

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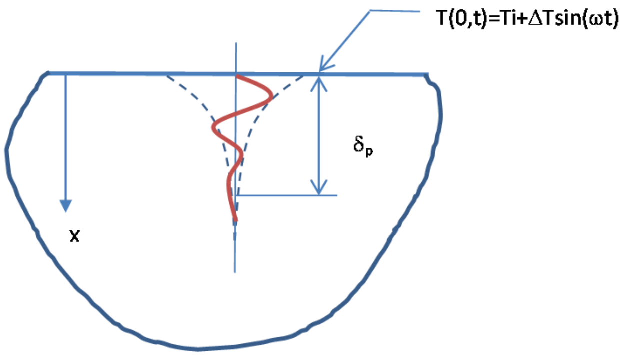

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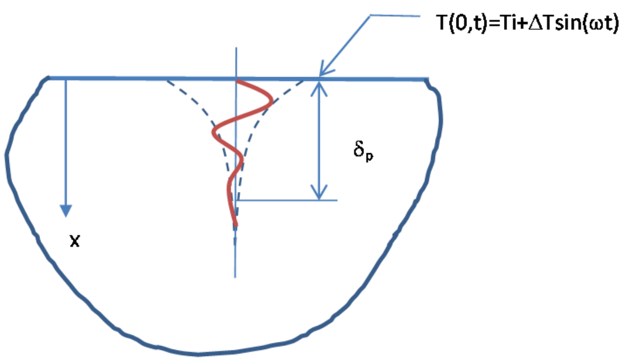

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$$T\mathrm{corner}[s] \sim 6.3\ \mathrm{L[mm]}^2/\alpha \quad \Leftarrow \quad \delta_{effective} = \sqrt{\frac{\alpha . T}{2\pi}}$$

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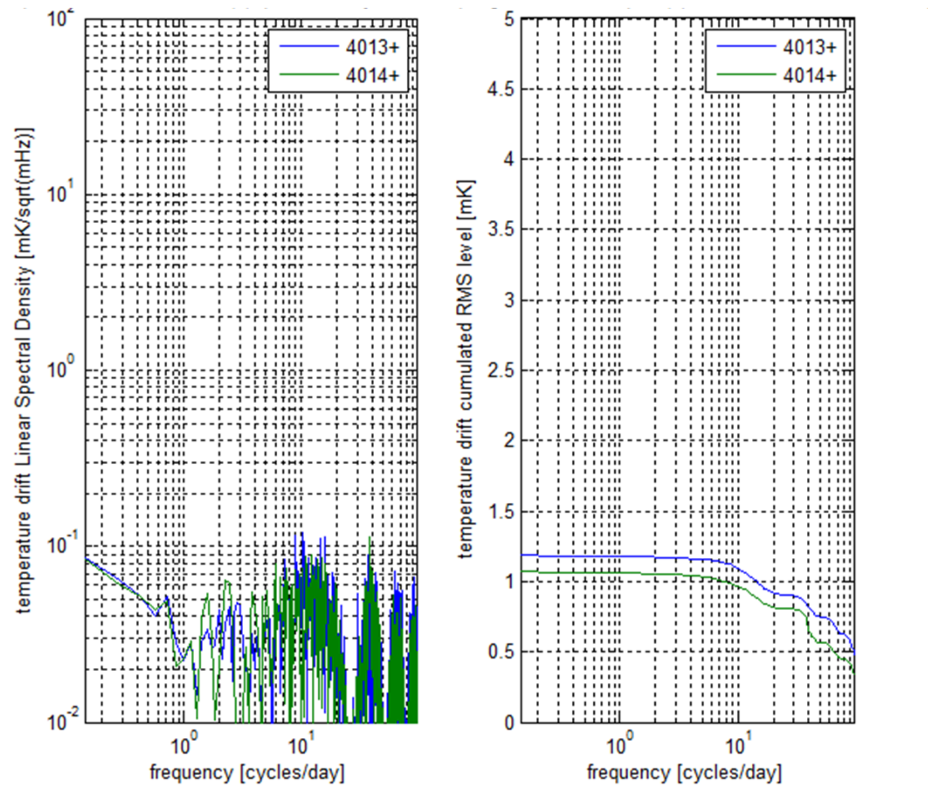
THERMAL-MECHANICAL SUSCEPTIBILITY : PRACTICAL ESTIMATION RULES (1/2)

- Random fluctuations ⇔ broadband spectral content
- Hence, harmonic formula not usable « as is »
- Need to SEPARETELY estimate severity of ALL frequency components
- Combine individual components into OVERALL harshness indicator

Need for a simple, automated procedure

EXAMPLE : SPECTRAL ANALYSIS OF 8 HOURS TEMPERATURE DRIFT



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THERMAL-MECHANICAL SUSCEPTIBILITY : PRACTICAL ESTIMATION RULES (2/2)

Estimate thermal mechanical « frequency response function »

$$H_{UTc}(f)$$

(structural response / unit temperature fluctuation)

Break down coolant temperature fluctuations into individual frequency components, i.e. « PSD analysis» $\widehat{\Phi}_{T_c T_c}(f)$ (degree²/unit frequency bandwith)

Combine to obtain into actual response level

$$\boldsymbol{U_{rms}} = \left(\int_0^{f_{maxi}} |H_{UT_c}(f)|^2 . \widehat{\Phi}_{T_c T_c}(f) df \right)^{1/2}$$

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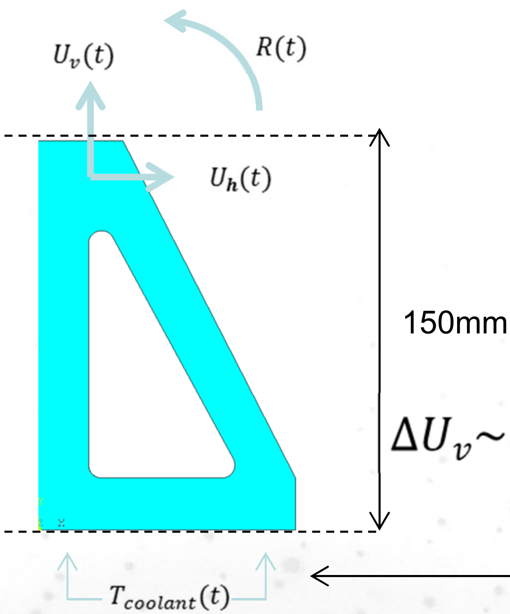
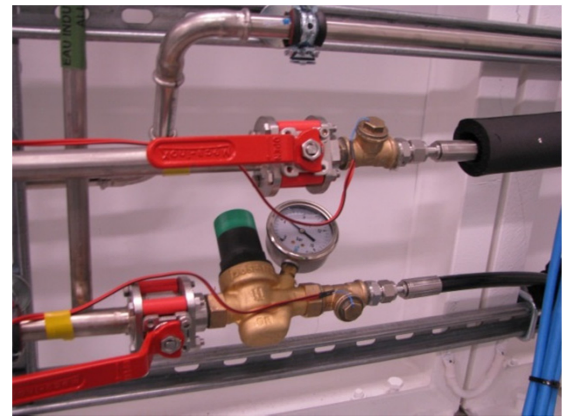
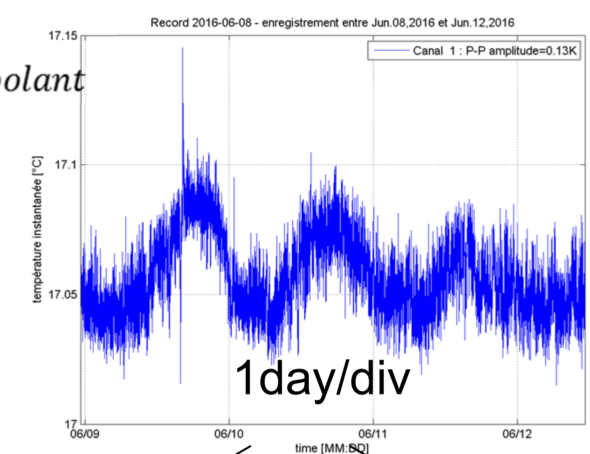
THERMAL-MECHANICAL SUSCEPTIBILITY : APPLICATION (1/2)

Application case: Aluminum (CTE=23ppm/K, diffusivity=100mm²/s)



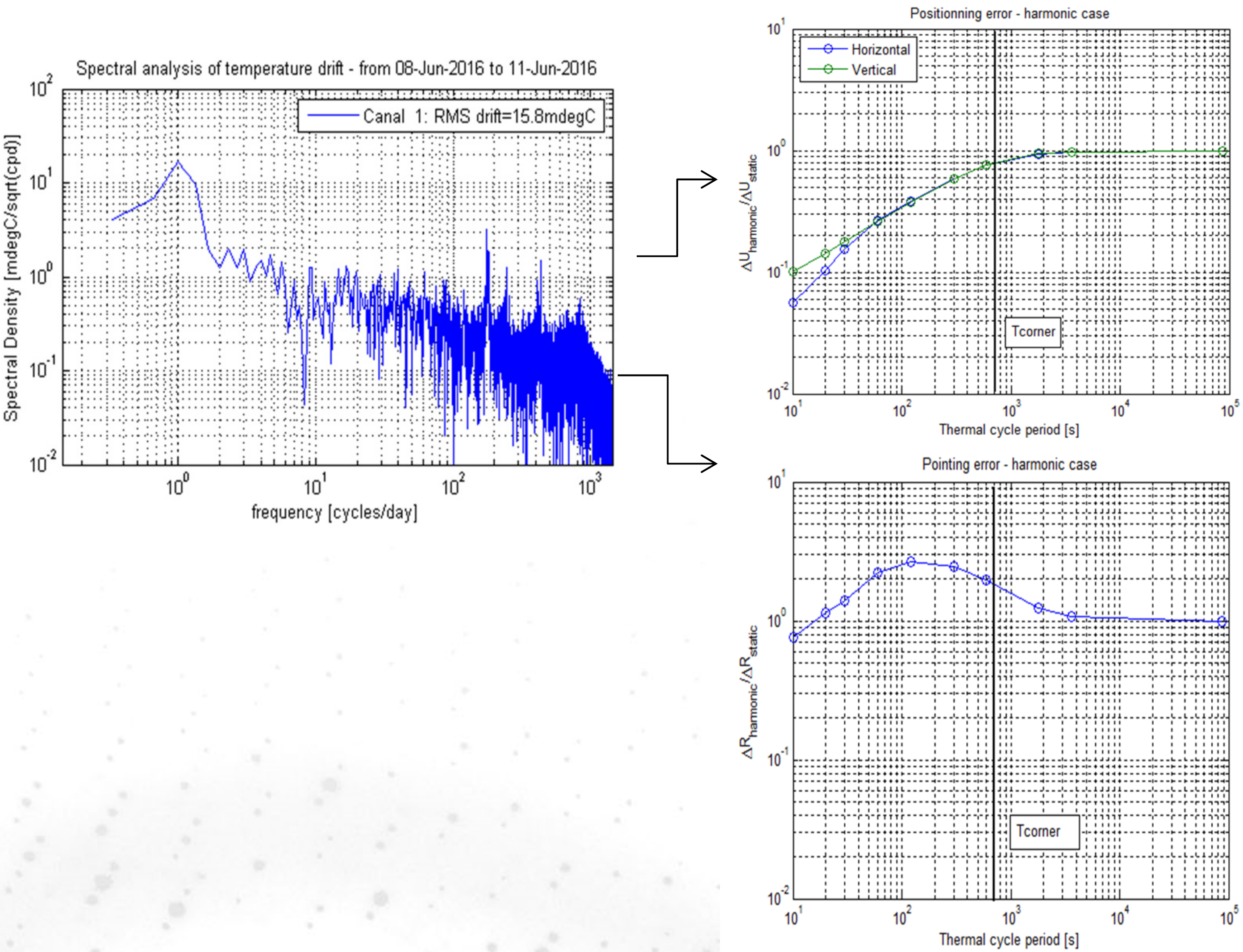
$$\Delta U_v \sim \boldsymbol{CTE}.Height.\Delta T_{coolant}$$





50mdeg/div

THERMAL-MECHANICAL SUSCEPTIBILITY : APPLICATION (2/2)



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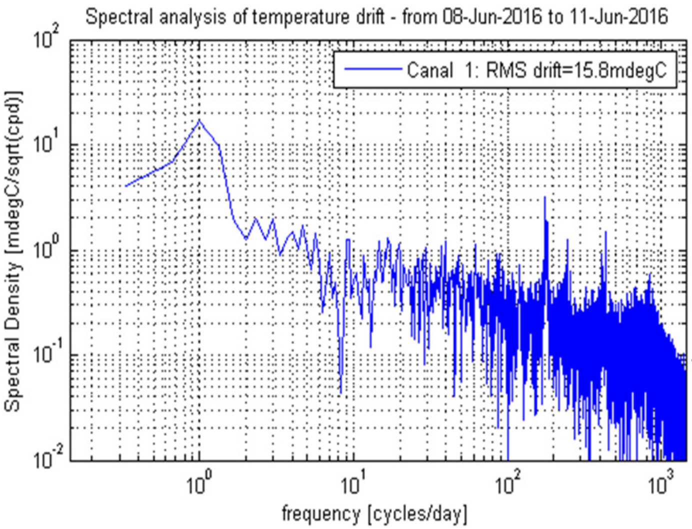

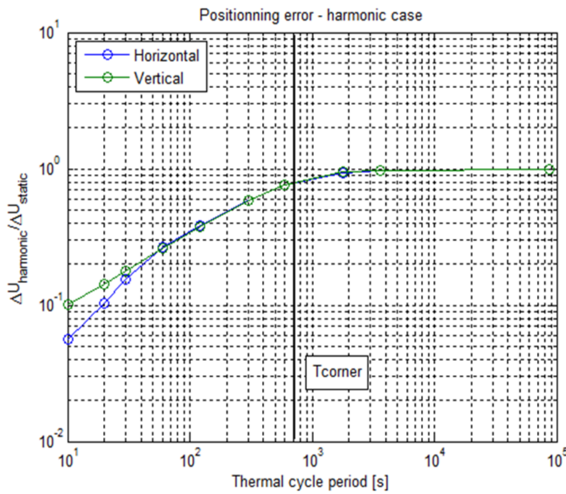

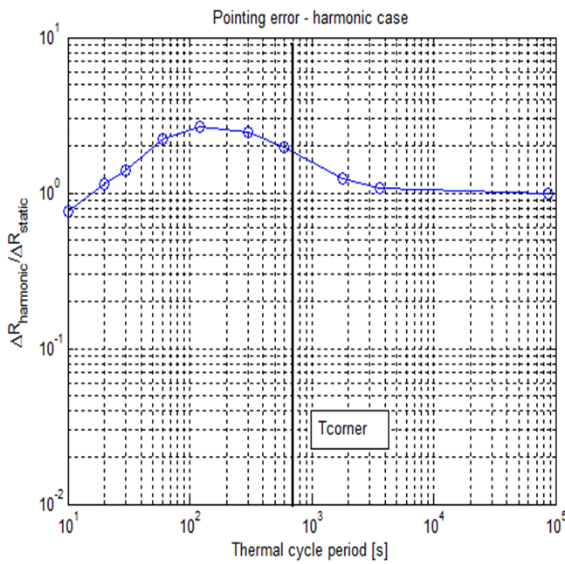

Corner period as predicted by hand calc's matchs FEM analysis results ☺ … except for pointing errors ☹ where AMPLIFICATION occurs

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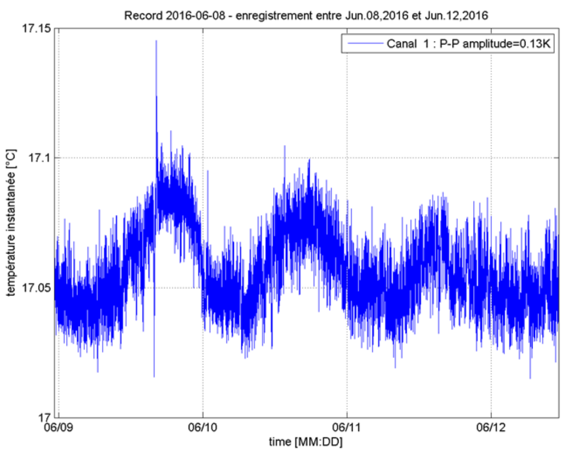
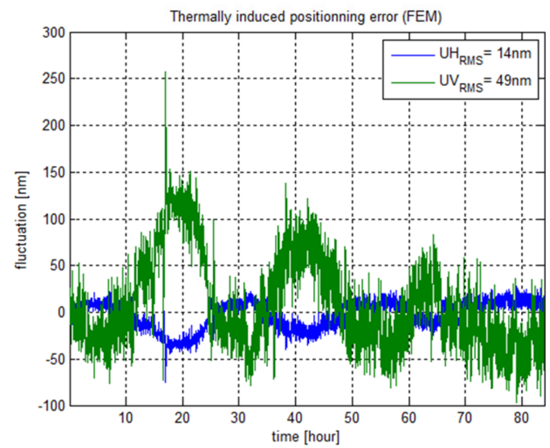
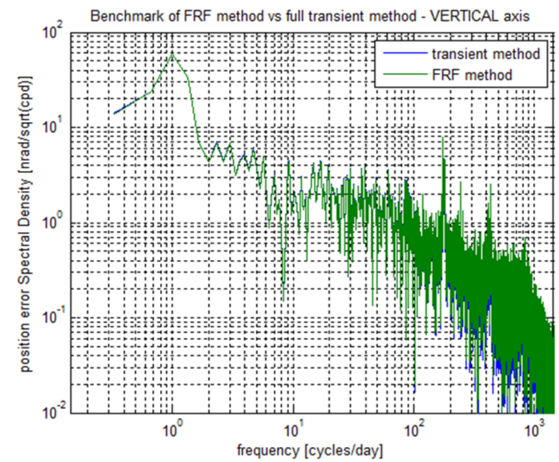
THERMAL-MECHANICAL SUSCEPTIBILITY : VALIDATION

- **Benchmark vs direct calculations**

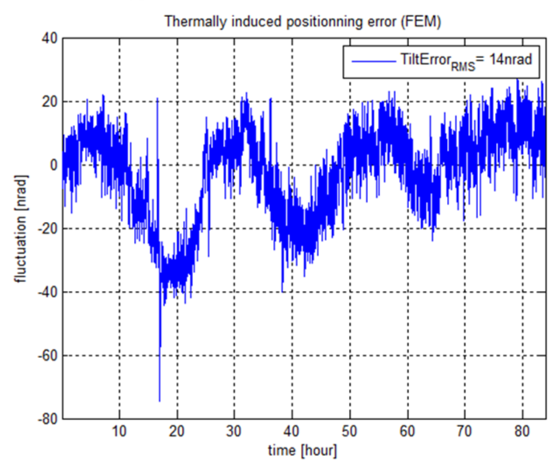


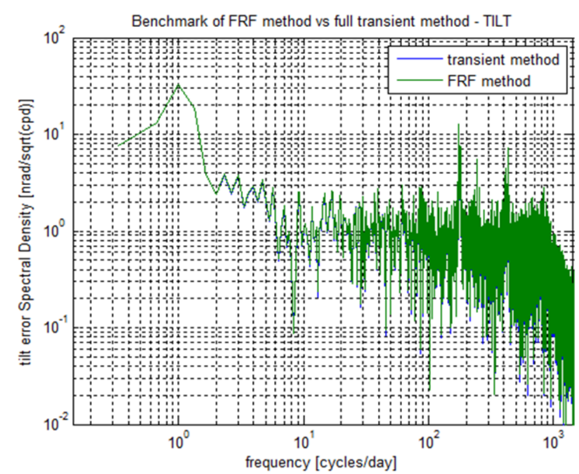




Near perfect agreeement

	Transient	FRF	Ratio
$U_{horizontal}$	15nm	14nm	0.99
$U_{vertical}$	50nm	49nm	0.99
$R_{transverse}$	43nrad	44nrad	1.02





SOLEIL SYNCHROTRON

PRACTICAL USAGE: RELIABILITY ANALYSIS

RANDOM FLUCTUATIONS

- Deterministic figures of merit (« Peak to peak ») amplitude meaningless
- Need to define amplitude into a probablistic sense
- Common practice at SOLEIL: Probability Of Exceedance For Given Allowable Drift (AD)

Need to know:

- RMS amplitude U_{RMS}
- Observation time T_s

$$P(|Drift(T_s)| > AD) = 1 - \text{erf}\left(\frac{AD}{\sqrt{2}U_{RMS}(Ts)}\right)$$

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NB: Other statistics (mean time between exceedances, etc..) could be estimated

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SUMMARY / CONCLUSION

For unstable environments, clear trends exist:

- « static rules » apply

BUT, for stabilized environments, fluctuations are mostly random

- need for *ad hoc* estimations procedures

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Severity of random temperature fluctuations cannot readily be assessed at face value.
Using the proposed procedure, a minimum analytical effort can provide reliable quantitative estimates of setup reliability

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THANK YOU FOR YOUR ATTENTION

QUESTION & COMMENTS ARE WELCOME

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