Appendix K

Herschel experience on modelling and verification of active heater control

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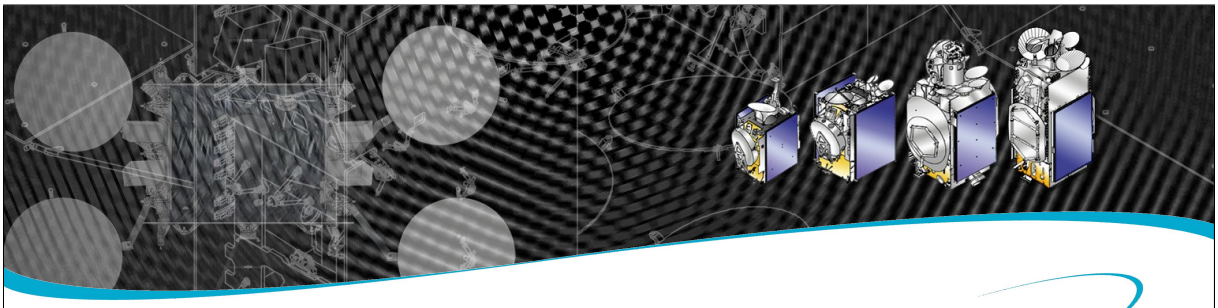
Abstract

Herschel satellite was launched on May 14th, 2009 and is currently orbiting 1.5 million kilometres away from the earth on the second Lagrange point (L2) of the Sun-Earth system.
Main objective of the active thermal control system is the thermal stability of two HIFI instrument units ($3 \cdot 10^{-4}$ °C/s) and of the Star Tracker mounting plate ($2.5 \cdot 10^{-4}$ °C/s). After a brief introduction of the satellite, the presentation provides a general view on the lesson learnt from the thermal vacuum and thermal balance (TVTB) test performed in the ESA-ESTEC Large Space Simulator (LSS), control system design, thermal modelling and the current status of the ESA telescope.



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HERSCHEL EXPERIENCE ON MODELING AND VERIFICATION OF ACTIVE HEATER CONTROL

Savino DE PALO, Marco COMPASSI - ThalesAlenia Space

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- CONTROL TUNING
- TVTB TEST
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INTRODUCTION

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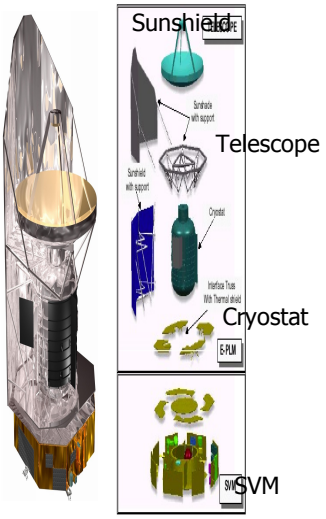
Herschel ESA Satellite was launched on 14th May 2009

Working in L2 orbit, investigating over the sub-millimeters and far-infrared range

Main instruments on board:

- 3.5 m Telescope
- Heterodyne Instrument for the Far Infrared (HIFI)
- Spectral Photometer Imaging REceiver (SPIRE)
- Photoconductor Array Camera & Spectrometer (PACS)



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SVM

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SVM Thermal Control Design objectives:

- Avionics and warm units → [-20;+40°C]
- Hydrazine units → [10;+50°C]
- Star tracker (STR) thermal stability
  - 250 mK over 100 s
  - feet gradients smaller than 0.4 K
  - variation amplitude +/-0.5 K
- HIFI and warm units thermal stability → 30 mK/100 s
- Radiative flux to the PLM limit → 10 W
- Conductive flux to the PLM limit → 150 mW

STM test performed on May 2005 in ESTEC

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FINE CONTROL LAW

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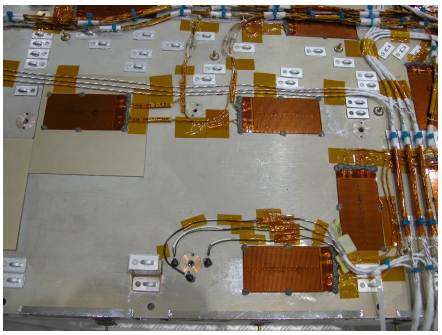
Temperature stability required for:

- FHWOV (HIFI unit)
- FHWOH (HIFI unit)
- STR



Control the mean temperature of 3 thermistors placed close to units

Heater circuits commanded by PI control

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FINE CONTROL LAW

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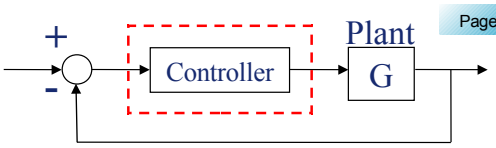

Control Algorithm

$$P_k = -\lambda P_{k-1} - \delta P_{k-2} + \alpha(T_{ref} - T_k) + \beta(T_{ref} - T_{k-1}) + \gamma(T_{ref} - T_{k-2})$$

P_k = heating power at current time *k*

P_{k-1} = heating power at the previous time *k-1*

P_{k-2} = heating power at the most previous time *k-2*

T_{ref} = reference temperature (set-point)

T_k = measured temperature at the current time *k*

T_{k-1} = measured temperature at time *k-1*

T_{k-2} = measured temperature at time *k-2*

α, β, γ, λ, δ = coefficients of the discretized regulator

Sampling frequency / command = 10s

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FINE CONTROL LAW

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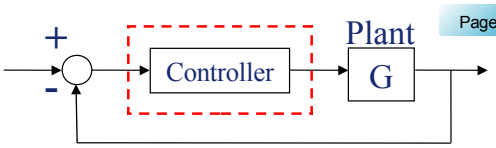
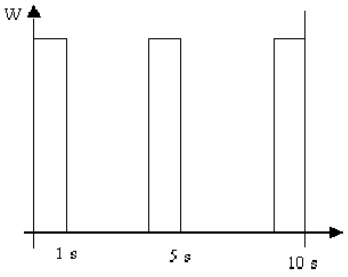


Pulse Width Modulation (PWM)

- P_k commanded every second as pulse train
- Pulse train uniformly distributed to reduce discretization disturbances
- Residual logic implemented after STM test

P_k computed – P actually injected

Cumulated residuals for additional pulses



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PLANT TRANSFER FUNCTION

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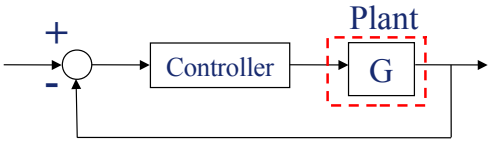
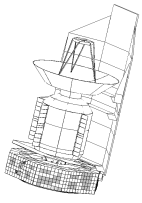
- Plant Model required to tune PI (α, β, γ, λ, δ)



- STM test → Space State model from Reduced TMM



ESATAN

→ *GL, GR, T, C...* →

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \rightarrow G(s) = C(sI - A)^{-1}B + D$$

- FM huge TMM (~ 4000 nodes) → System Identification (MATLAB)

PLANT TRANSFER FUNCTION

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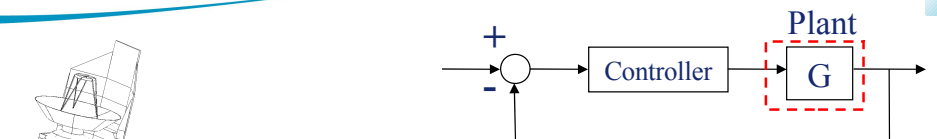
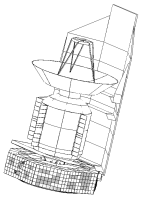


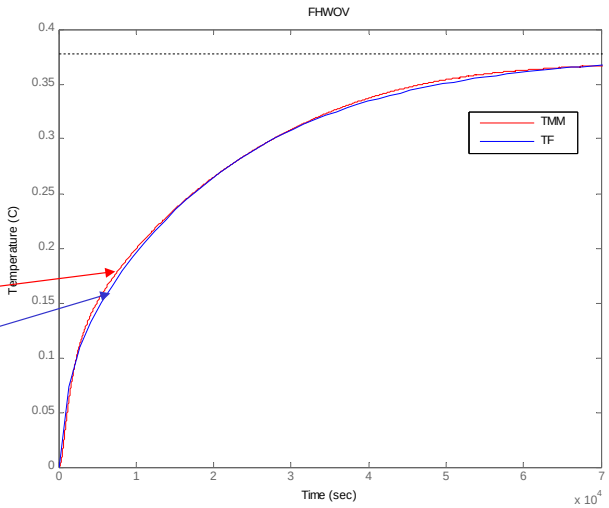


ESATAN TMM

Step P variation

T response to System Identification Toolbox

G



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CONTROL TUNING

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- Control law coefficients designed in the continuous time domain (open loop transfer function)
- Tustin method (sampling =10 s)

Disturbance	Period	Amplitude vs Period	Amplitude
Quantization (=LSB)	10 s	acquisition refresh time	0.05 °C
Telemetry analog error	random	N/A	± 0.05 °C
S/C attitude change	514 s (single event)	Ramp	60 ° (a)
Unit dissipation power fluctuation	200 s	Square wave	0.015 W
Heater BUS voltage fluctuation	200 s	Square wave	0.125 V

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TVTB TEST

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FM TVTB was performed on Nov./Dec. 2008 in ESTEC

- Control law performance on HIFI and STR units → stability requirement verification

- Step changes of 1°C in the control set-points were given producing the required transient response

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TVTB TEST

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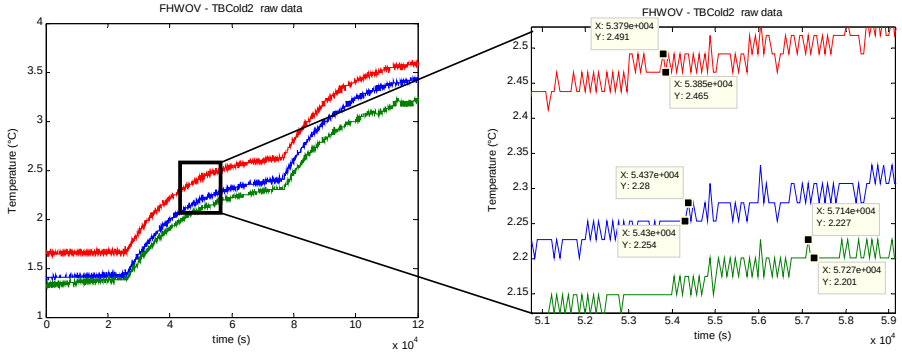
Sampling Rate = 64s ; ΔT min = 0.026°C

Minimum ΔT gradient between two samples
0.026°C / 64s = $4.026 \cdot 10^{-4}$ °C/s > 0.03°C/100s

Raw data noise overcomes the rqmt ! → Filter the data



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TVTB TEST

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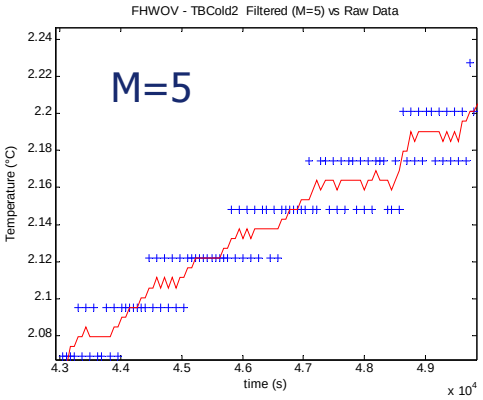
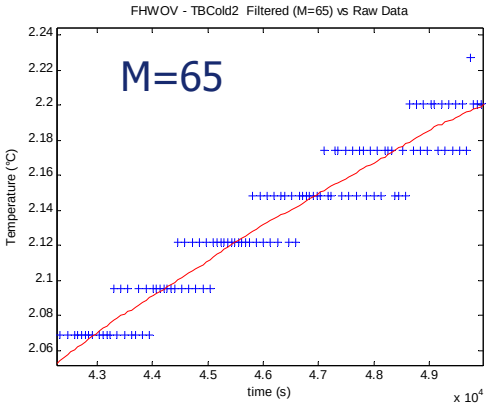
Moving Average Filter (MAF) as suggested by DSP theory

$$tfilt(i) = \frac{1}{M} \sum_{j=-(M-1)/2}^{(M-1)/2} traw(i+j)$$





Lowest span (M=5) selected to reduce to the minimum MAF weight on requirement verification

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TVTB TEST

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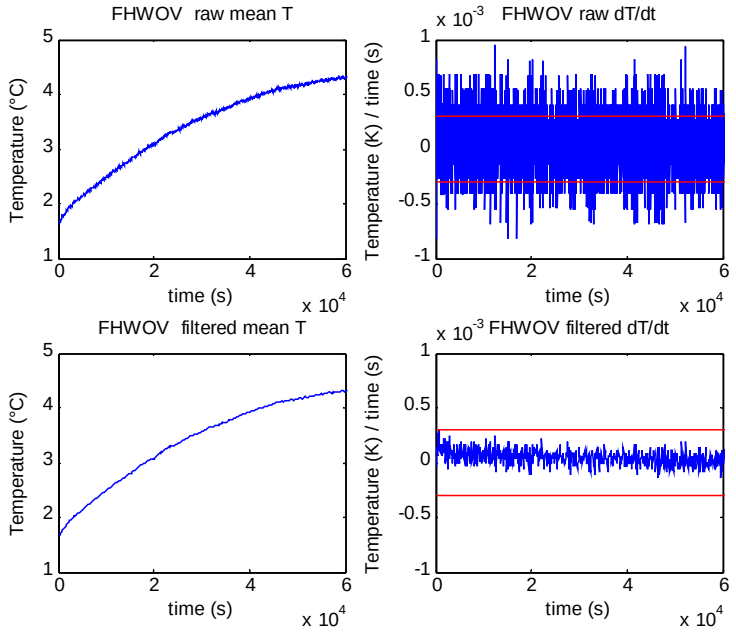

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STABILITY VERIFICATION

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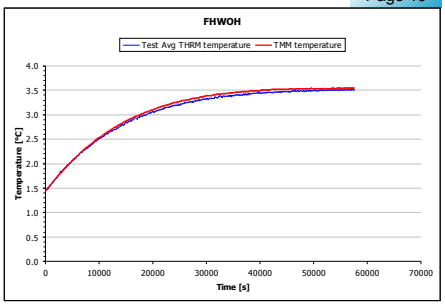
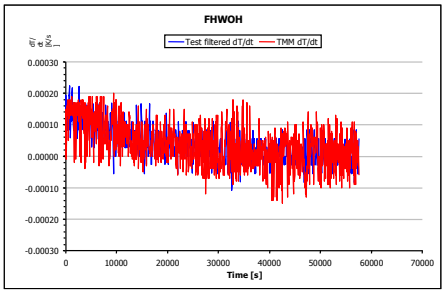
- TMM correlated for TVTB Predictions compared with test results
- TMM was able to reproduce with good fidelity the transient response providing even conservative values for stability verification
- TMM was used to verify stability requirements in Flight conditions





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FLIGHT

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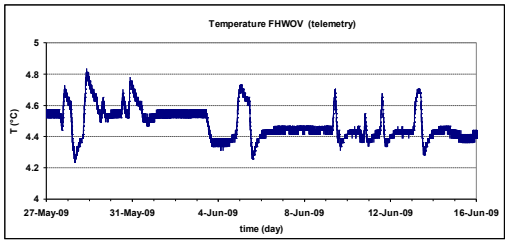

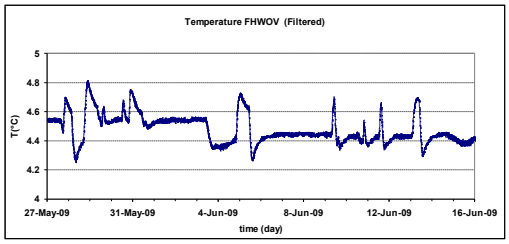

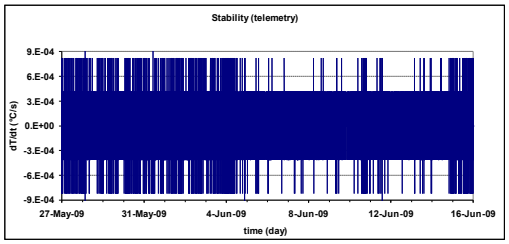

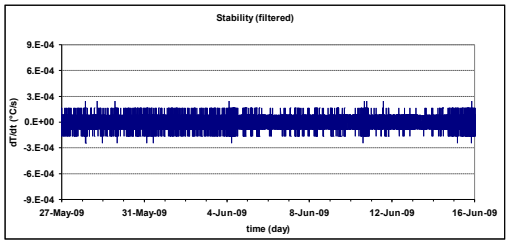

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CONCLUSIONS

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◇ Herschel active control loop performance vs thermal stability requirements verified at test/flight level

◇ TMM (ESATAN) was used for validation before flight

◇ System Identification played a key role for fast plant modeling (LTI) from huge TMM

◇ Test/flight data filtering (MAF) for correct verification of the requirement