

Herschel Heaters Control Modeling and Correlation

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ABSTRACT

Herschel and Planck satellites have recently undergone the thermal vacuum and thermal balance (TVTB) test which was performed in the ESA-ESTEC Large Space Simulator for Herschel and in Centre Spatial de Liège (CSL) for Planck. One of the specific targets of the Herschel test was the verification of the thermal stability of two HIFI units (required to be better than $3 \cdot 10^{-4}$ °C/s) and of the Star Tracker mounting plate (required to be better than $2.5 \cdot 10^{-3}$ °C/s), with particular attention on the performance of the relevant feedback control loops. Control system design and model predictions are presented and compared against the test results. Further discussion on the requirement verification is provided.

INTRODUCTION

Herschel and Planck are two European Space Agency (ESA) scientific satellites for astronomical observation and survey in the infrared and sub-millimeters wavelength ranges. The industrial consortium is composed by ThalesAlenia Space (France) as prime contractor for the development of the two satellites and of the Planck payload, Astrium for the development of the Herschel payload and ThalesAlenia Space (Italy) for the development of the service module (SVM) of both satellites.

Herschel is designed for high and medium resolution spectroscopy, imaging and photometry over the sub-millimeters and far-infrared range, with a 3.5 m telescope that will focus the incoming radiation on the Focal Plane Units of three instruments named Heterodyne Instrument for the Far infrared (HIFI), Spectral Photometer Imaging REceiver (SPIRE) and Photoconductor Array camera and Spectrometer (PACS).

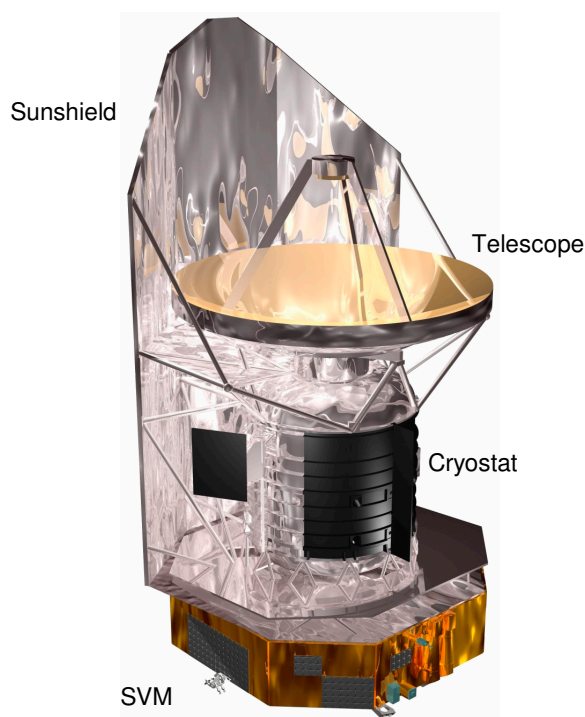


Figure 1 – Herschel Satellite overview

Planck goal is to provide a high-angular resolution map of the cosmic microwave background anisotropies over at least 95% of the sky and over a wide frequency range, with a smaller telescope of 1.5 m that will focus the incoming radiation on the focal plane shared by the two instruments named LFI and HFI.

Thermal balance tests were performed in year 2008 on both satellites, completing the qualification campaign under full flight representative conditions. The two satellites, to be launched together by Ariane 5 on mid 2009, will operate in Lissajous orbits around the Lagrange point L2 of the Sun-Earth system.

This paper focuses on the Herschel service module thermal control developments, with particular attention to the actively controlled units. After a quick view to the satellites, the SVM is introduced, providing a deeper view to the active control system currently implemented, test results and control performance verification.

HERSCHEL SVM

The two main units of the Herschel satellite (Figure 1) are the Payload Module (PLM), comprising the telescope, the cryostat, the focal plane and the instrument units, the sunshield with the solar arrays and Herschel Service Module (SVM), comprising the conventional spacecraft subsystems, the “warm” instrument units and the sunshield.

The SVM Thermal Control was designed to withstand the following requirements:

- Temperature design limits of avionics and warm units on the SVM → $[-20; +40^{\circ}\text{C}]$
- Temperature design limits of the hydrazine units (piping, thrusters, valves...) → $[10; +50^{\circ}\text{C}]$
- 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 over 100 s
- Radiative flux to the PLM limit → 10 W
- Conductive flux to the PLM limit → 150 mW

The thermal design was achieved by combining classical thermal control techniques (MLI, coatings etc.) together with specific thermal control provisions and in particular:

1. Heater circuits commanded by a fine control law (PI regulation) to ensure requested temperature stability on the wide band spectrometer optics FHWOV and FWHOH (the two HIFI units) and STR. For each unit temperatures are acquired by three thermistors and mean temperature is used for control purpose.
2. Specific accommodation of the STR in a dedicated cavity combined with an extensive passive isolation using very low conductive GFRP struts, particular

MLI shaping (so-called pool design because of the cavity shape) and solar baffle inside the SVM to damp the change of attitude effects

3. Highly resistive blankets to support the extreme temperature of 390°C during launch separation (combination of sun and friction heat loads)

The SVM Structural Thermal Model (STM) was tested at ESTEC facilities (Netherlands) in May, 2005 [1].

Thermal Vacuum and Thermal Balance (TVTB) test was performed on November/ December 2008 at the ESTEC LSS facility in Noordwijk on the Flight Model unit (Figure 2).



Figure 2 – Herschel FM in ESTEC clean room

In the following particular attention is devoted to the PI regulator design and verification performed during the TVTB test performed at ESTEC

FINE CONTROL LAW

The very stringent thermal stability requirements on the two HIFI units required a dedicated thermal design of the supporting panels, which were thermally decoupled to the maximum extent by the rest of SVM, conductively by means of Titanium brackets and radiatively by aluminized MLI covering all the warm units.

In addition dedicated fine control law (Proportional Integrative control with low pass filter) implemented in the Central Data Management Unit (CDMU) software. Each 10 s the algorithm reads the sensors temperatures and compute the power input for the heaters as:

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

where:

- 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 $k-2$
- $\alpha, \beta, \gamma, \lambda, \delta$ = coefficients of the discretized regulator.

The heater power profile is then delivered by means of a Pulse Width Modulation (PWM), which provides on/off command every second to the heater system for the power figured. In order to reduce to the minimum the discretization effects, the pulse train is uniformly distributed along the whole 10 seconds. As an example, on next Figure 3 is shown the time distribution of three pulses over the 10 s.

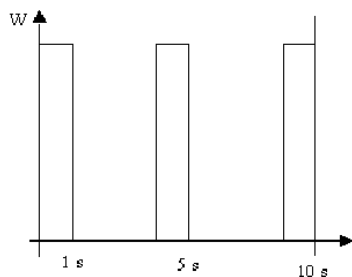


Figure 3 – Example of pulse modulation

After STM test [1] the algorithm was further refined introducing the so called residual logic. This logic keeps the history of the difference between the power computed by the PI algorithm (P_k in the formula above) and the real (mean) power injected via PWM. When the cumulated difference reaches the equivalent of one pulse, the pulse is injected.

PLANT TRANSFER FUNCTION

For the computation of control law coefficients $\alpha, \beta, \gamma, \lambda$, and δ , the transfer function of controlled chain must be derived, i.e., the influence of power input to the measured temperature in terms of Linear Time Invariant (LTI) model, also known in the control theory as the "plant" model.

For the STM test prediction and correlation, the plant models were derived directly in terms of space state models in the form

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

Matrixes and vectors were derived directly from the Thermal Mathematical Models (TMM) by means of linear conductance matrix GL, radiative conductance matrix GR etc. in a similar fashion as described in [3] and Laplace transfer function computed with the well known formula

$$G(s) = C(sI - A)^{-1}B + D$$

Control chains de-coupling were verified by means of Relative Gain Array (RGA) analysis. At that time the size of the model was limited to about 150 thermal nodes and reduced models were used for plant computation activity.

Approaching the FM TVTB it was clear that design updates occurred since the STM test required also an updates in the plant models. FM TMM size is in the order of about 4000 nodes and the task of deriving the new FM transfer functions $G(s)$ from reduced models and space state model approach was any more feasible, due to model complexity and limited time available. For FM the new transfer function $G(s)$ models were then derived directly using the System Identification (SI) approach applied to the FM TMM: starting from a nominal steady state condition, transient simulations were run in which the only disturbance applied were step variation in the controlled heater chain. TMM transient results were then provided to the System Identification Toolbox in Matlab, which computed the Laplace transfer functions best fitting the TMM results. On Figure 4 to Figure 6 are shown the transient step responses of the LTI models (blue lines) vs original TMM transient response (red lines).

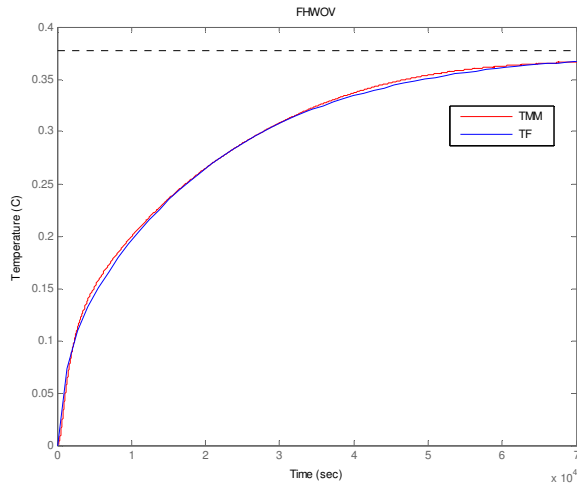


Figure 4 – FHWOV Identification

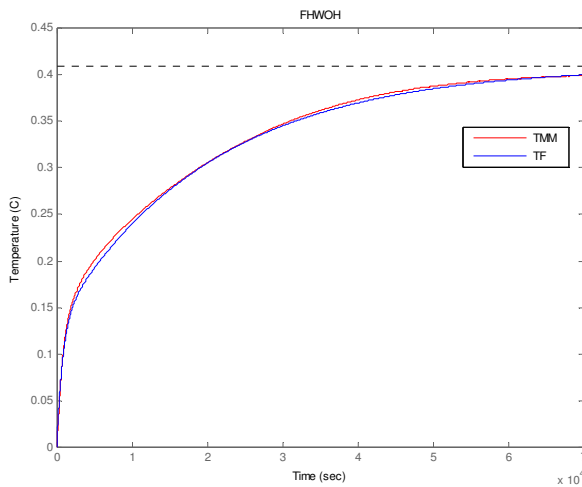


Figure 5 – FHWOH Identification

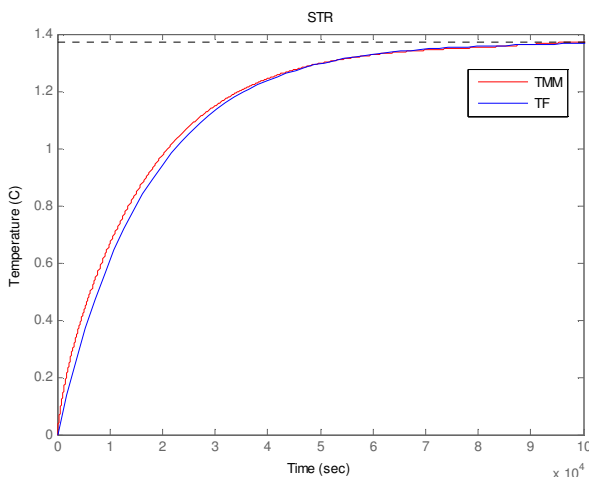


Figure 6 – STR Identification

CONTROL TUNING

For the FM control tuning the same approach applied in [2] was adopted, working with the computed plant model. Control law coefficient were designed in the continuous time domain working with the open loop transfer function taking into account the disturbances source (see next Table 1). Continuous time domain parameters of the control block were then discretized with the Tustin method with a sampling time of 10 seconds, obtaining the formula of P_k already introduced.

Stability (not the absolute stability but the requirement previously defined) verification is based on TMM implementing the control logic already described, modeling all type of known disturbances. Some of them, considered also in the PI tuning process, are listed on Table 1. The other disturbances, implemented only at TMM level, are those induced by heat loads variation on all other units mounted on the satellite.

Once control parameter set are computed with LTI models, this are further verified through TMM simulations in flight conditions.

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

Table 1 – Disturbances considered for PI tuning

TVTB TEST CASES

Among the classical tests performed in a TVTB, for the control law verification it was planned to perform some transients to verify the active controls performance on HIFI and STR units, for stability requirement verification and control model tuning. Starting from stabilized conditions, for each unit, in hot and cold phases, step changes of 1°C in the control set-points were given producing the required transient response.

In the following, after a brief description of the data filtering on the test data, two main representative phases named TB Cold 1 and TB Cold 2 are presented and discussed.