TECHNICAL NOTE

TITLE: FINE CONTROL LAW ANALYSIS

DRL Item or D.R.D. No: E4

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DOCUMENT CHANGE RECORD

ISSUE	DATE	REASON FOR CHANGE	AFFECTED PARAGRAPHS
01	June 30, 03	New document	All
02	March 31, 04	New paragraph	2
		Added fine control law subroutine	3
		New results	5
		Conclusions	6

TABLE OF CONTENTS

1. SCOPE

Scope of this document is to provide the analysis results of the fine control law designed to meet the HERSCHEL HIFI units temperature stability requirement of 0.3 mK/s (1 K/h to be intended as maximum slope following the H-P-ASP-CR-0423 “Implementation HIFI unit temperature stability”) in the frame of the HERSCHEL-PLANCK program.
A fine control law has been also designed to meet the temperature stability for the HERSCHEL STAR TRACKER at the mounting plate level.

1.1 APPLICABLE DOCUMENT

AD1	SVM TCS THERMAL ANALYSIS REPORT	H-P-RP-AI-0040
AD2	HERSCHEL / PLANCK SVM Thermal ICD	H-P-IC-AI-0002

2. REQUIREMENTS

The following requirements are applicable.

Unit/Item	Temp. operating range [°C]	Temp. stability req. [°C/s]	Max temp. gradient between the mounting feet [°C]	Max variation around any set-point [°C]
FHWOV	+5 / +15	0.0003	N/A	N/A
FHWOH	+5 / +15	0.0003	N/A	N/A
STR mount. plate	-20 / +40 (ref. to the unit)	0.0025	0.4	0.5 (ref. to the feet)

3. MODEL DESCRIPTION

Due to the high level of definition of the global TMM, approximately 150 thermal nodes for each HIFI panel and STR assembly (2000 thermal nodes globally), the first task was to reduce the model in order to have a more suitable thermal network good for the development of the algorithm.
The reduced model has been tested with ESATAN in order to keep a good correlation ($|T_{detailed} - T_{reduced}| \leq 3$ °C) between the detailed model and the reduced one.
The thermal network has been written in his characteristic differential equation.
The non-linear terms (e.g. radiative conductors) have been linearized around his equilibrium point using Taylor expansion.
The obtained linear system has been transformed into the state-space form, well suited for control analysis.

dx/dt = Ax + Bu
y = Cx + Du

with

x = […] state vector (all the temperatures considered in the system, dimension n)
u = […] command vector (heater power applied on the panel, dimension r)
y = […] output vector (unit temperature to be controlled, dimension p)
A = matrix of the dynamic of the states (dimension n x n)
B = matrix of the inputs (dimension n x r)
C = matrix of the outputs (dimension p x n)
D = matrix of the direct link between input and output (dimension p x r)

The approach followed was to consider the system as a SISO (=Single Input Single Output), the matrix D is null. To verify that each SISO system is enough decoupled (needed condition to design a good PI controller), a RGA (=Relative Gain Array) analysis has been performed, giving a positive answer.
After that for each SISO the appropriate PI regulator has been found and then discretized with the TUSTIN method with a sampling time of 10 seconds (the sampling characteristic of the data acquisition system).
The obtained algorithm to be implemented into the TMM and into the Application Software of the Spacecraft is:

$$P_k = -l\, P_{k-1} - d\, P_{k-2} + a\,(T_{ref} - T_k) + b\,(T_{ref} - T_{k-1}) + g\,(T_{ref} - T_{k-2})$$

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 the previous time $k-1$
T_{k-2} = measured temperature at the most previous time $k-2$
α, β, γ, λ, δ = coefficients of the discretized regulator.

The subroutine implemented into the TMM is:

DEFINITION OF THE PARAMETERS

Constants in PI algorithm	ALPHA, BETA, GAMMA, DELTA, LAMBDA ([W/°C] engineering units).
TREF	Temperature Set-Point ([°C] engineering units). It is a constant but TCS requires the possibility to change it during the mission.
QINST	Installed power (heater power dissipation) ([W] engineering units). It is a constant.
TIMEN	Simulation clock ([s] engineering units).
TACQUISITION	Routine/TMM clock counter ([s] engineering units).
TIMESTEP	Routine counter ([s] engineering units).
TK	Thermistor readout ([°C] engineering units).
PK	Heating power calculated by the algorithm ([W] engineering units).
AATK	Temperature history stored in the on-board computer memory ([°C] engineering units).
PPK	Heating power history stored in the on-board computer memory ([W] engineering units).
NIMPUL	Number of pulses (ON/OFF) to be provided.

ACTIONS TO BE PERFORMED EVERY 10 SECONDS

IF (TK < TREF – 3.0 °C) ISSUE 10 ON commands (1s pulse) EXIT Loop	If the read temperature is less then 3 °C below the Set-Point Temperature (TREF), keep ON the heater until the next acquisition cycle (10 s) and skip the fine control algorithm

IF (TK > TREF + 3.0 °C) ISSUE 10 OFF commands (1s pulse) EXIT Loop	If the read temperature is greater then 3 °C above the Set-Point Temperature (TREF), keep OFF the heater until the next acquisition cycle (10 s) and skip the fine control algorithm

IF (TREF –3.0 < TK < TREF + 3.0 °C) GO TO algorithm	If the read temperature is within a range of ±3 °C around the Set-Point Temperature (TREF), perform the PI algorithm calculation

PK = -LAMBDA * PPK[10] - DELTA * PPK[9] +ALPHA * (TREF – TK) +BETA * (TREF – AATK[10]) +GAMMA * (TREF - AATK[9])	PI algorithm for calculating the needed power PK

IF(PK < 0.0) THEN PK = 0.0	If the PI algorithm requires negative power, 10 OFF commands shall be released in the 10s interval
ELSE IF(PK > QINST) THEN PK = QINST ENDIF	Else if the PI algorithm requires more power than can be dissipated by the heater circuit, 10 ON commands shall be released in the 10s interval

DO I=2,10 AATK[I-1] = AATK[I] ENDDO	Updating of temperature history
AATK[10] = TK	

DO I=2,10 PPK[I-1] = PPK[I] ENDDO	Updating of power history
PPK[10] = PK	

IF(PK * 10.0 / QINST – AINT(PK*10.0/QINST) >= 0.5) THEN
    NIMPUL = INT(PK*10.0/QINST) + 1.0
ELSE
    NIMPUL = INT(PK*10.0/QINST)
ENDIF
	Calculation of the number of ON commands to be released in the 10s interval

ACTIONS TO BE PERFORMED EVERY 1 SECOND

TIMESTEP = INT(TIMEN-TACQUISITION+1.0)	Spreading of the ON/OFF commands in a homogenous fashion over the 10s interval

IF(PK > 0.0 AND NIMPUL > 0.0) THEN
    DO I=1,10
        IF(INT(1+10.0/NIMPUL*(I-1)) == TIMESTEP) THEN
            ISSUE ON command (1s pulse)
            EXIT Loop
        ELSE IF(INT(1+10.0/NIMPUL*(I-1)) > TIMESTEP) THEN
            ISSUE OFF command (1s pulse)
            EXIT Loop
        ENDIF
    ENDDO
ENDIF	

Concerning the approach described above the references are:

"Fondamenti di Automatica" – R. Vitelli, M. Petternella – Ed. Scientifiche SIDEREA

"Fondamenti di controlli automatici" – P. Bolzern, R. Scattolini, N. Schiavoni – Ed. McGraw-Hill

3.1 BLOCK DIAGRAM

The control is schematised in the following Fig. 3.1-1, where the block diagram is shown.
This block diagram has been properly translated in ESATAN format in order to be used for thermal analysis purposes.
The meaning of the terms used are the following:

“T set point” block = represents the temperature which the HIFI unit / STR mounting plate is maintained
“REGULATOR” block = represents the PI algorithm
“ACTUATOR” block = represents the heater installed on the panel operated by means of PWM
“ACTUATOR NOISE” block = represents the BUS voltage (useful to simulate the voltage fluctuation)
“SYSTEM” block = represents the relevant HIFI unit /STR mounting plate
“EXOGEN DISTURBANCES” block = represents the environment disturbances (e.g. the temperature variation due to the change of the S/C attitude and the HIFI/STR unit power fluctuation)
“TELEMETRY” block = represents the acquisition chain system
“TELEMETRY NOISE” block = represents the disturbances induced by the telemetry acquisition chain (analog error of the receiver and the quantization effect)

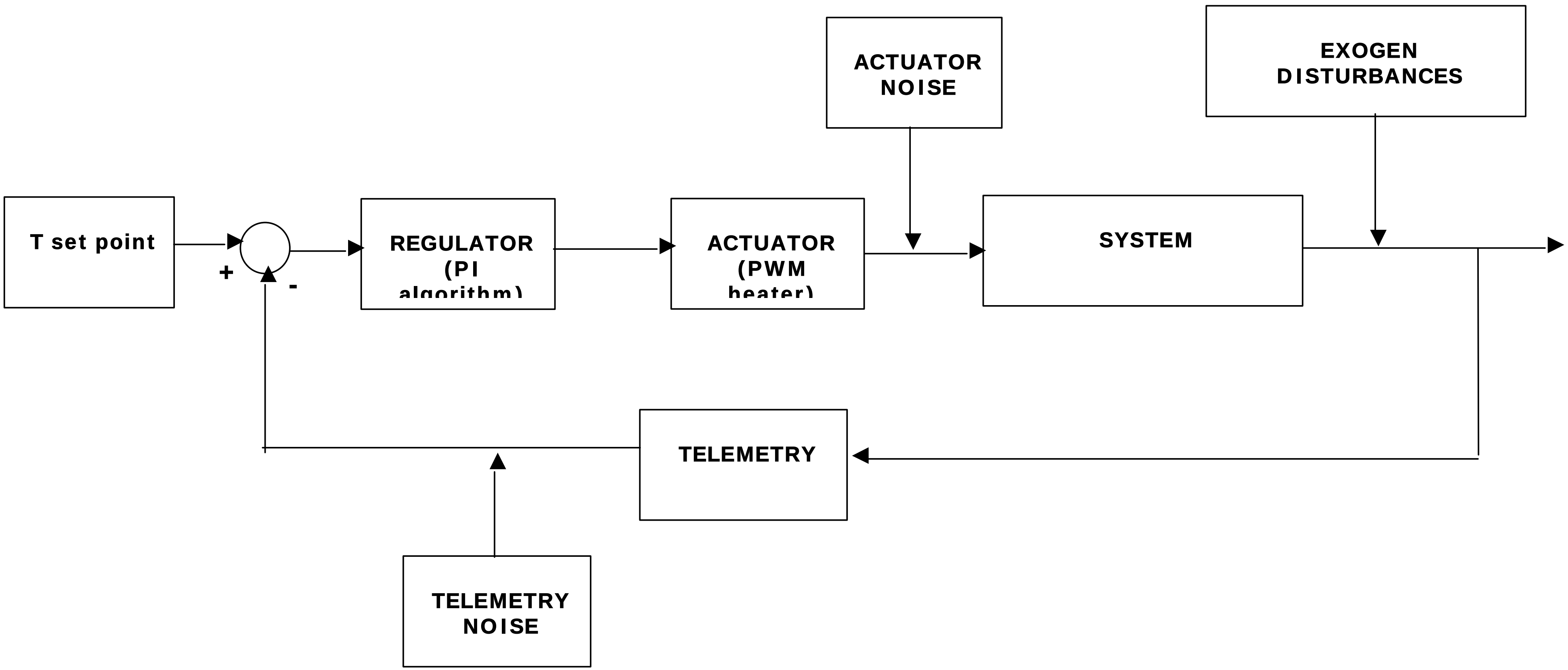
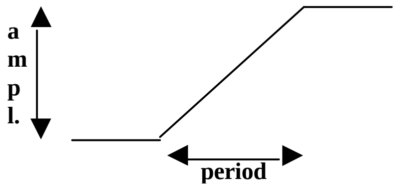
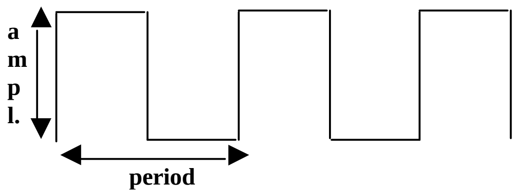
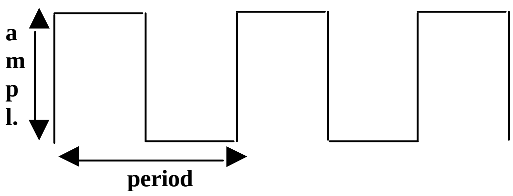


Fig.3.1-1: Block diagram

4. DISTURBANCES AND HARDWARE SIMULATION

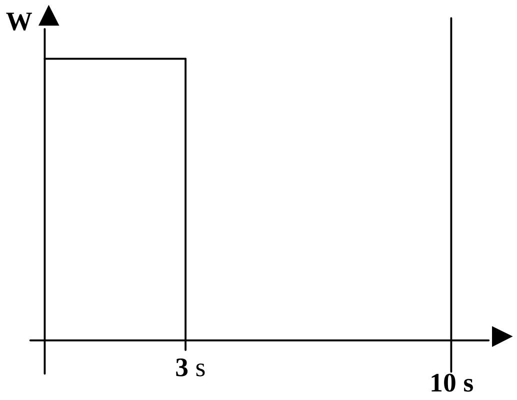
In the frame of this kind of analysis takes care to define all the possible sources of disturbances that are summarised in the following table 4-1. It represents the worst case condition for the error simulation.

Description	Period	Amplitude vs Period	Ampli.
Quantization (=LSB)	10 s	acquisition refresh time	0.05 °C (with an error of ½ LSB)
Telemetry analog error	random	N/A	± 0.05 °C
S/C attitude change	514 s (single event)		60 ° (a)
HIFI & STAR TRACKER unit dissipation power fluctuation. (b)	200 s		0.015 W
Heater BUS voltage fluctuation	200 s		0.125 V

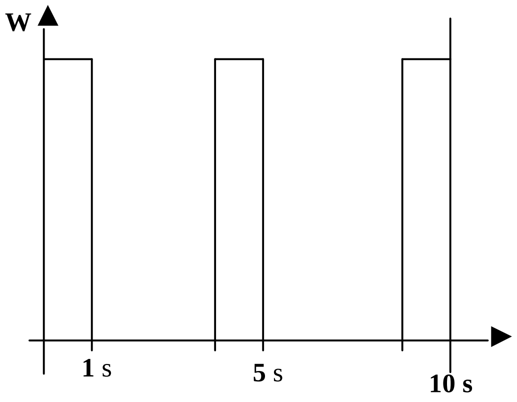
(a) = the satellite takes a time of 514 s to change his attitude from +30° to –30°	
(b) = ALS assumption is that the HIFI power is stable, this fluctuation is intended to be caused by the unregulated BUS	

Table 4-1: Sources of disturbances

Concerning the PWM simulation the following applies.
The PWM works as an ON/OFF command with a frequency of 1 Hz (this means to provide a command ON/OFF per second) for a power figured out every 10 seconds (the temperature acquisition frequency).
This leads to have a “train” of pulses to be provided for the next 10 seconds and it has been choice to send these pulses uniformly distributed along the whole 10 seconds (see SKETCH #2) to avoid energy spot that could affect negatively the temperature stability.
In the following two sketches, an example is shown: let’s take a “train pulses” of 3 seconds. In the SKETCH #1 all the pulses are provided in the first part of the frame, in the SKETCH #2 the 3 pulses are uniformly distributed in the whole frame.

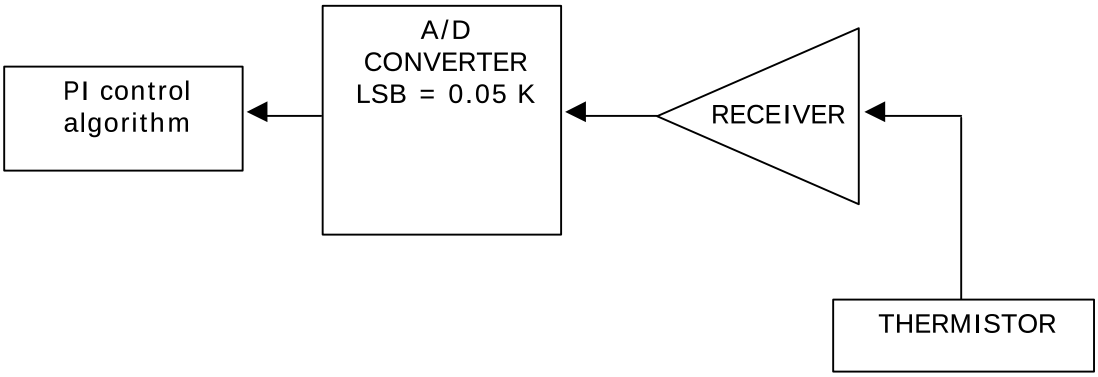


SKETCH #1



SKETCH #2

The telemetry acquisition chain has been simulated as follows.
Simplification of the CDMU interface is below sketched:



The BASELINE total error of this acquisition chain has been evaluated as follows, taking the into account the actual characteristics of the CDMU interface:

TOTAL ERROR = THERMISTOR ERROR + ANALOG ERROR + QUANTIZATION ERROR

With:

THERMISTOR ERROR = Negligible (=not taken into account)

ANALOG ERROR = ± 0.05 K (applied to the RECEIVER)

LSB = 0.05 K with a QUANTIZATION ERROR of ½ LSB (applied to the A/D CONVERTER)

So, the temperature, read by the THERMISTOR, enters into the RECEIVER and here the ANALOG ERROR is added. This “new” temperature enters into the A/D CONVERTER and it is converted in digital. Now, the converted temperature is used by the control algorithm.

5. ANALYSIS & RESULTS

Taking into account the considerations described in Para 4, the analysis has been performed and the results are shown in the following table 5-1 and plots in figures 5-4╕21.
The analysis has been performed both in COLD case and in HOT case.

The analysed cases are:

Cold Transient:
Starting from BOL case with Sun on +X -Y axis, SAA=+30°/-1° in Summer season
Ending to BOL case with Sun on -X -Y axis, SAA=-30°/-1° in Summer season
Power units dissipation: constant
Warm Units in MODE1
TT&C units: 21 hours Scientific Mode and 3 hours Telecom Mode
Nominal heater dissipation
Fine control law on Units: FHWOV, FHWOH, STR.
GYRO controlled within 1°C at set-point
Duration of change of attitude (7°/min): 514s
Overall duration of transient case: 500000 s
Change of attitude occurs after 150000 s

Hot Transient:
Starting from steady state EOL case with Sun on +X -Y axis, SAA=+30°/-1° in Winter season
Ending to steady state EOL case with Sun on -X -Y axis, SAA=-30°/-1° in Winter season
Power units dissipation: constant
Warm Units in MODE1
TT&C units: 21 hours Scientific Mode and 3 hours Telecom Mode
Nominal heater dissipation
Fine control law on Units: FHWOV, FHWOH, STR.
GYRO controlled within 1°C at set-point
Duration of change of attitude (7°/min): 514s
Overall duration of transient case: 500000 s
Change of attitude occurs after 150000 s

The set point temperature of the HIFI units is applied to thermistors (3 thermistors to be compliant with the majority-voting rule) that are located on the TRP of the unit itself.
Heaters layout of FHWOV and FHWOH are shown in figure 5-1/2 respectively.

The STR thermistors, which are the reference for the set-point temperature of the STAR TRACKERS, are located in the centre of the STR mounting plate, as shown in figure 5-3.
In the same figure 5-3 is also shown the location of the heaters.

The temperature stability of the STR mounting plate has been evaluated considering the average of the transient temperature of the mounting plate nodes on which the STR feet are attached (nodes 20014/20015/20022/20023 as per AD1).
The variation around any set-point has been evaluated for each foot and in table 5-1 is given the maximum variation.
Nodes 80027/80028/80029/80030 are referred to the STR feet as per AD1.

COLD CASE (BOL)				
UNIT	T set-point	Max ΔT/Δt [K/s]	Temp. gradient between the mounting feet [°C]	Max variation around any set-point [°C]
FHWOV	10 °C	0.000049	N/A	N/A

FHWOH	10 °C	0.000067	N/A	N/A
STR mount. plate	10 °C	0.001354	See fig. 5-11	80027 = 0.440 80028 = 0.454 80029 = 0.449 80030 = 0.455

HOT CASE (EOL)				
UNIT	T set-point	Max ΔT/Δt [K/s]	Temp. gradient between the mounting feet [°C]	Max variation around any set-point [°C]
FHWOV	10 °C	0.000059	N/A	N/A
FHWOH	10 °C	0.00006	N/A	N/A
STR mount. plate	10 °C	0.001375	See fig. 5-20	80027 = 0.812 80028 = 0.842 80029 = 0.828 80030 = 0.843

Table 5-1

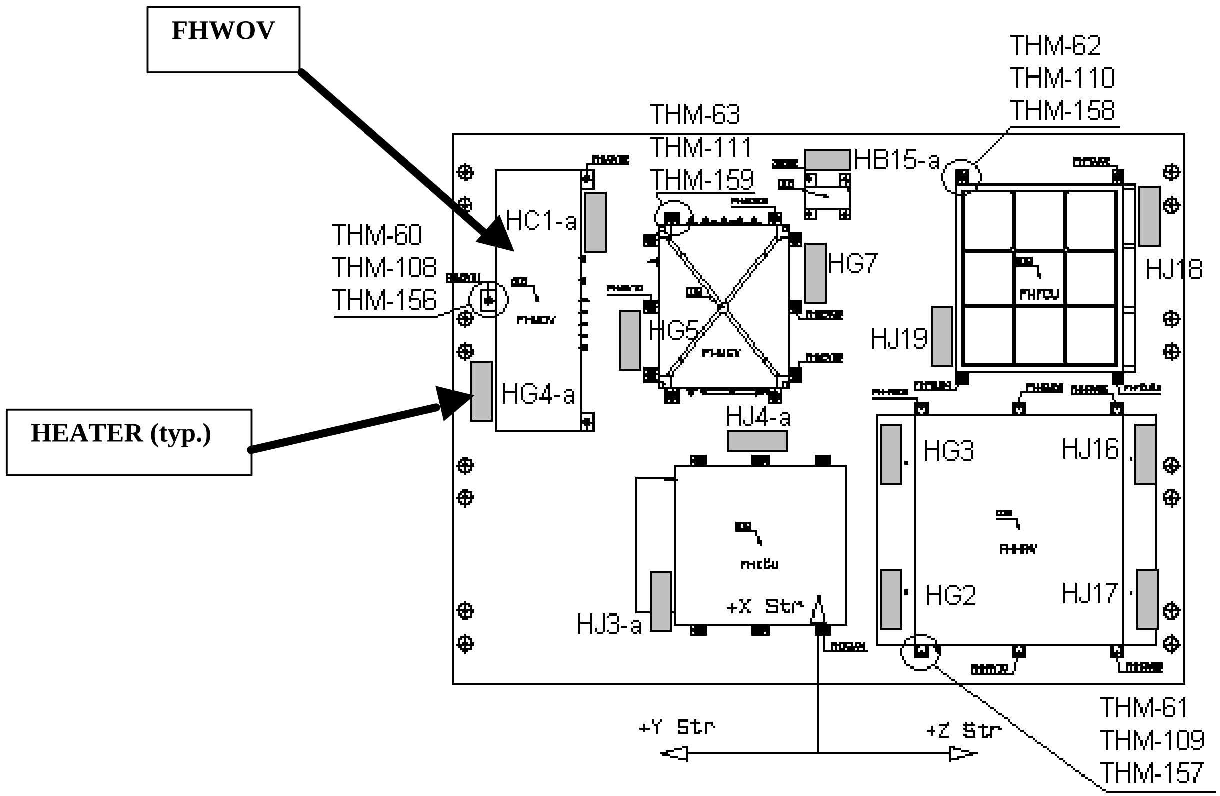


Figure 5-1: FHWOV: heaters and thermistors location

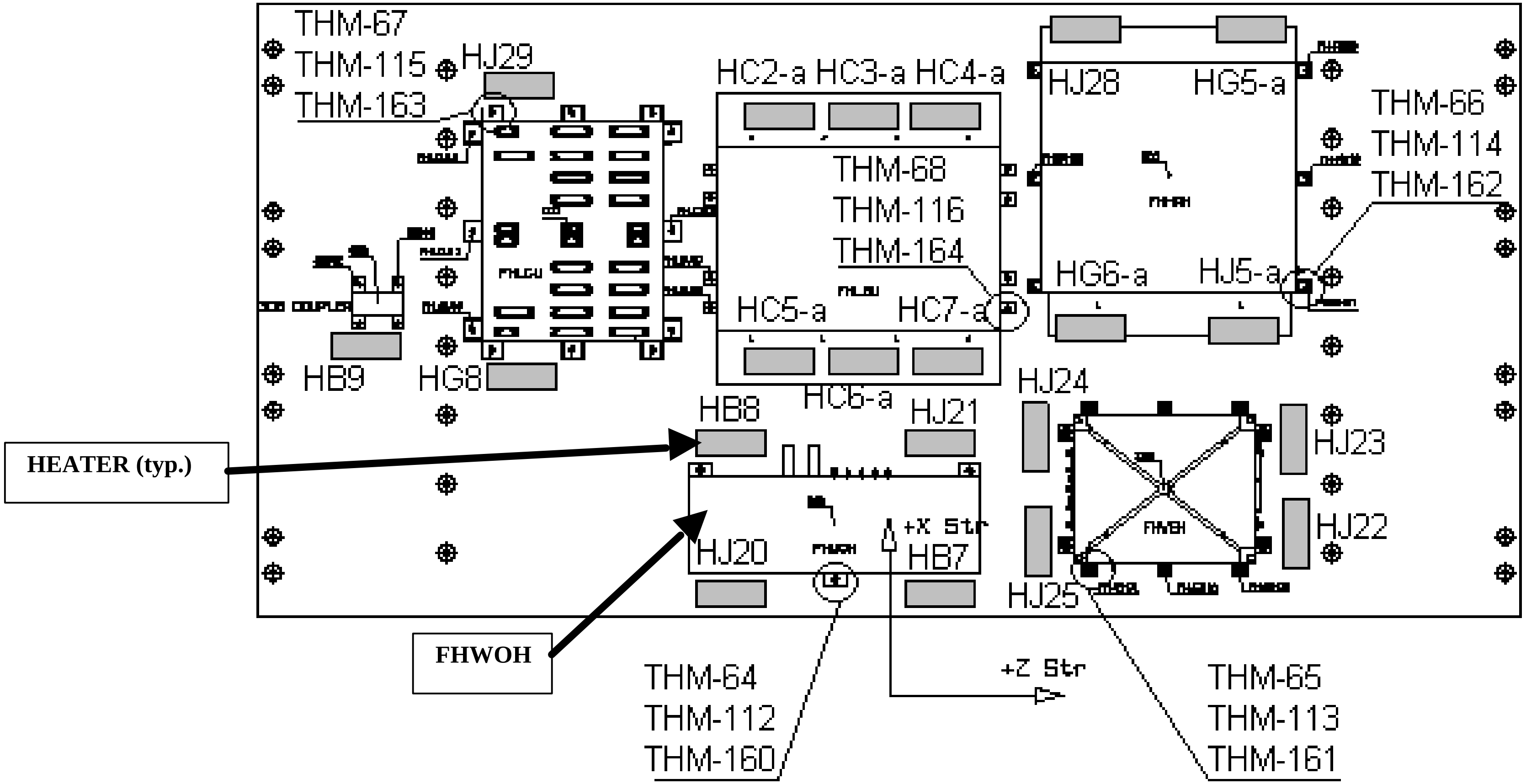


Figure 5-2: FHWOH: heaters and thermistors location

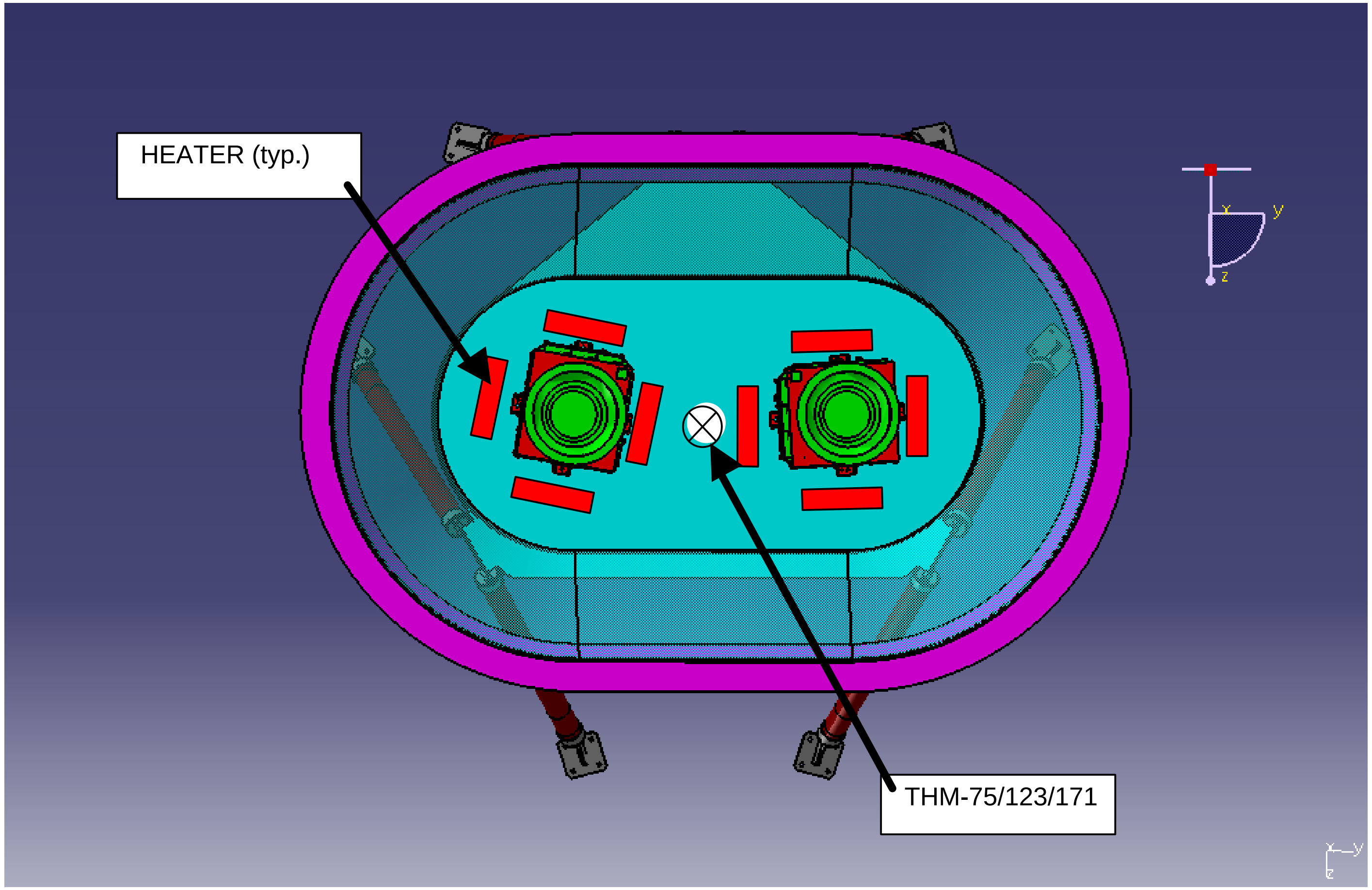


Figure 5-3: STAR TRACKERS: heaters and thermistors location (view from –X)

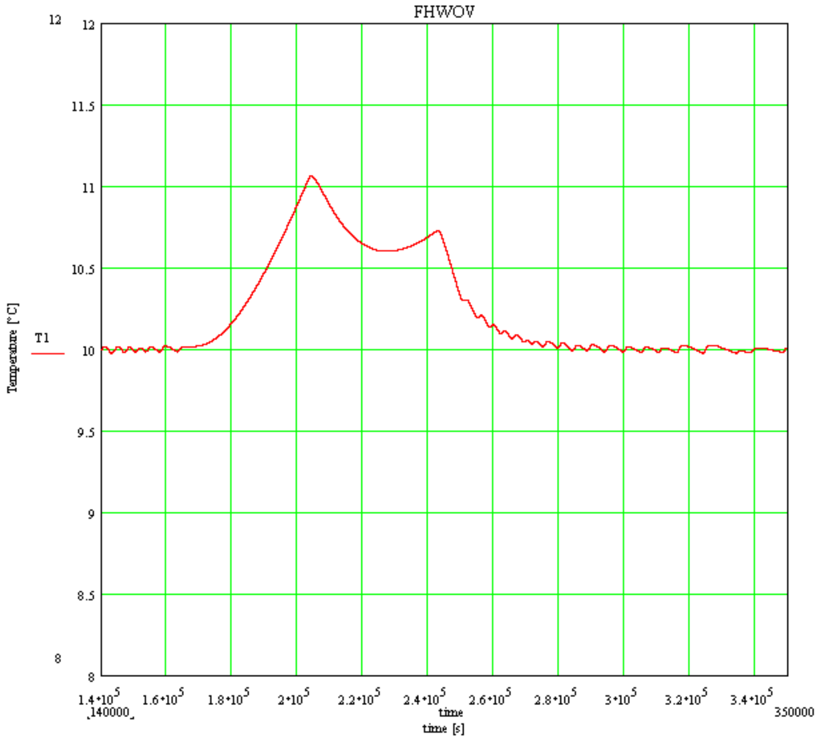


Fig. 5-4: FHWOV temperature profile (COLD CASE)

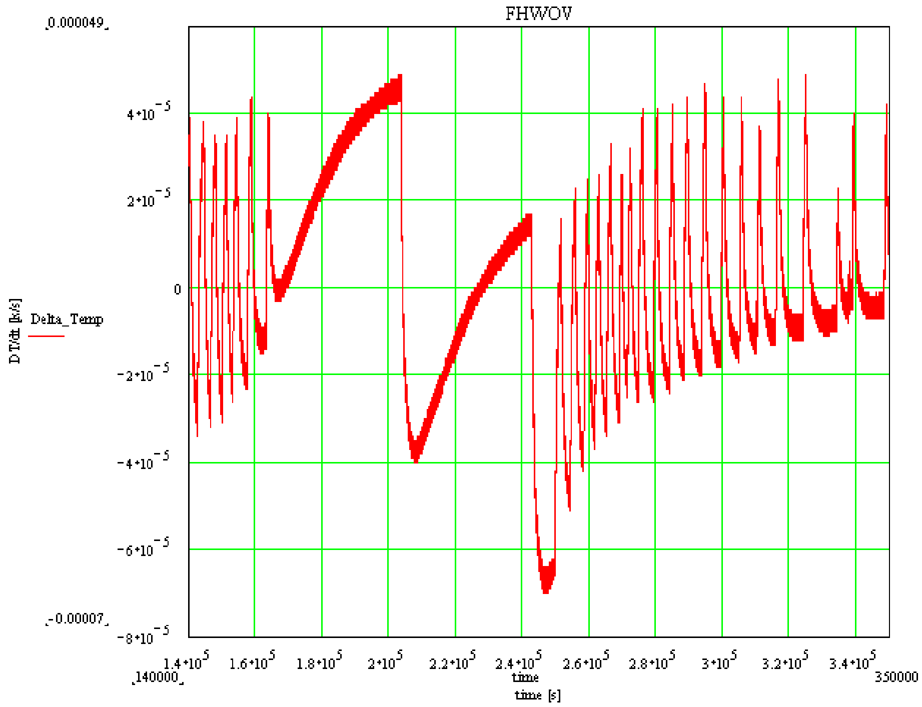


Fig. 5-5: FHWOV ΔT/Δt profile (COLD CASE)

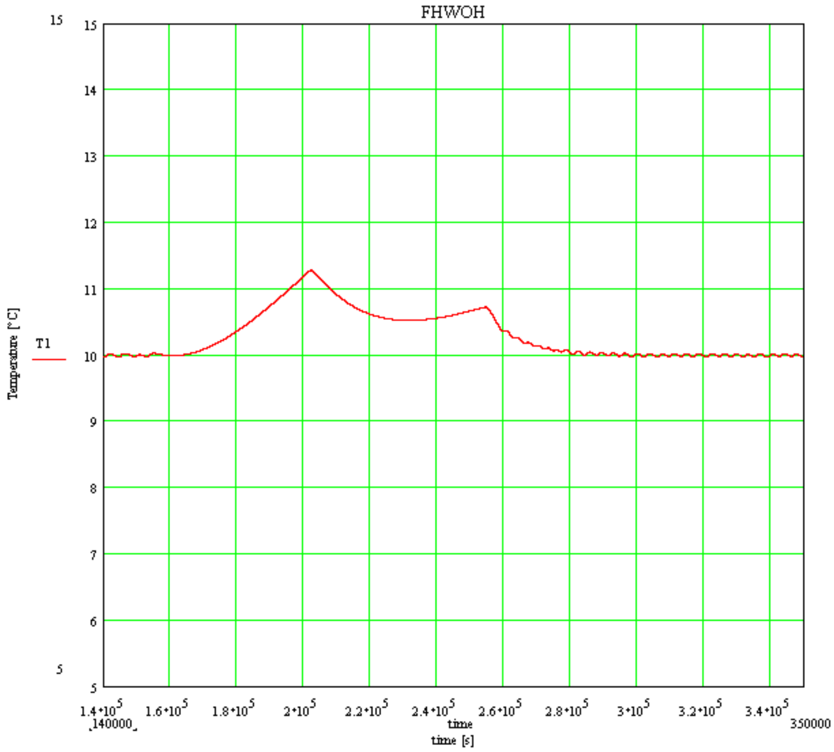


Fig. 5-6: FHWOH temperature profile (COLD CASE)

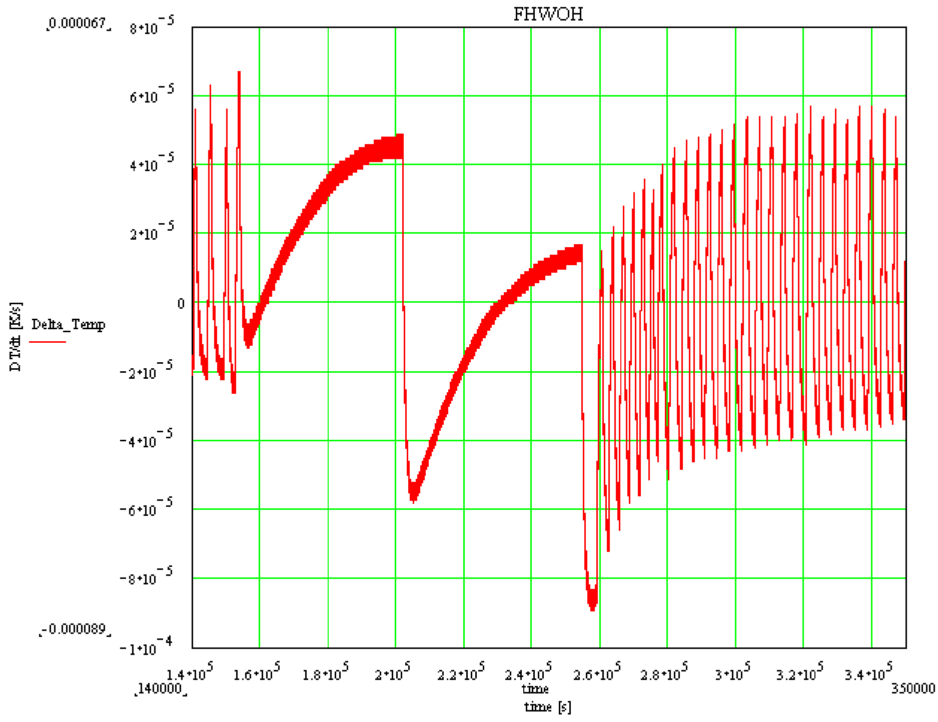


Fig. 5-7: FHWOH ΔT/Δt profile (COLD CASE)

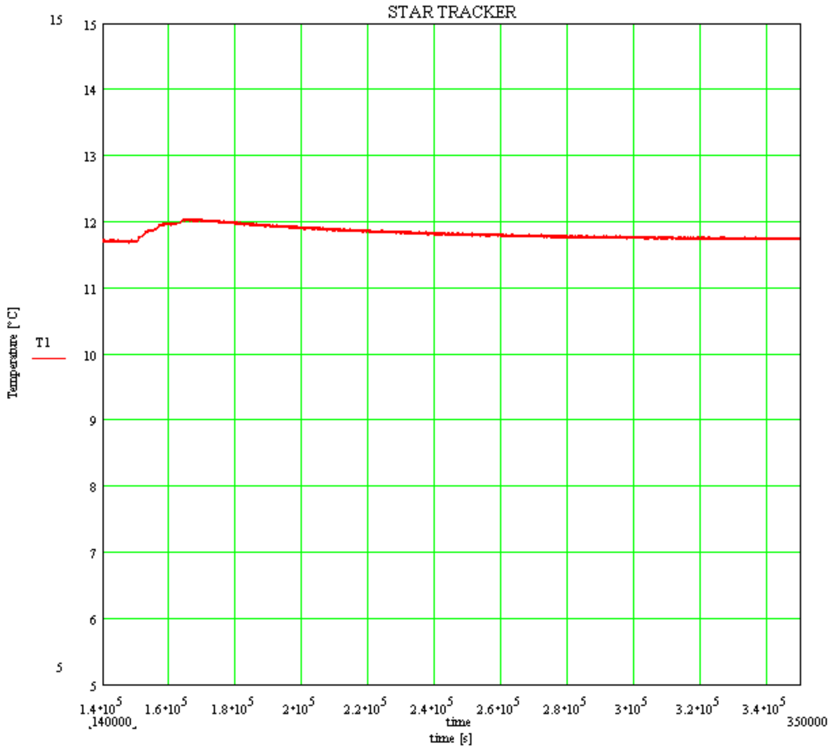


Fig. 5-8: STAR TRACKER mounting plate temperature profile (COLD CASE)

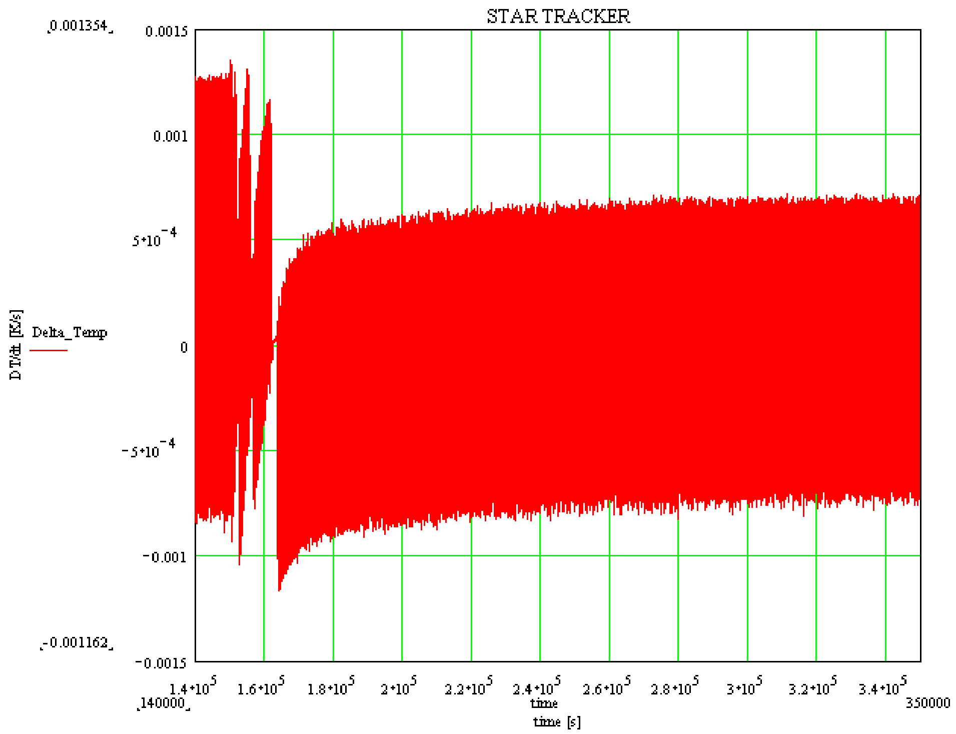


Fig. 5-9: STAR TRACKER mounting plate ΔT/Δt profile (COLD CASE)

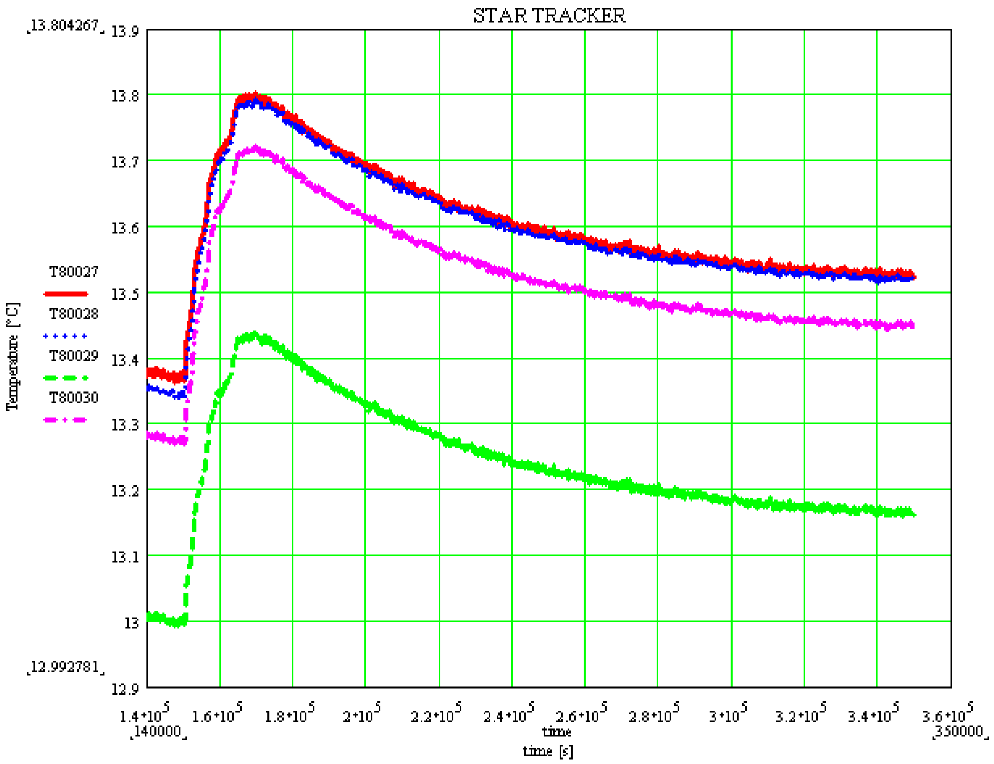


Fig. 5-10: STAR TRACKER FEET temperature profile (COLD CASE)

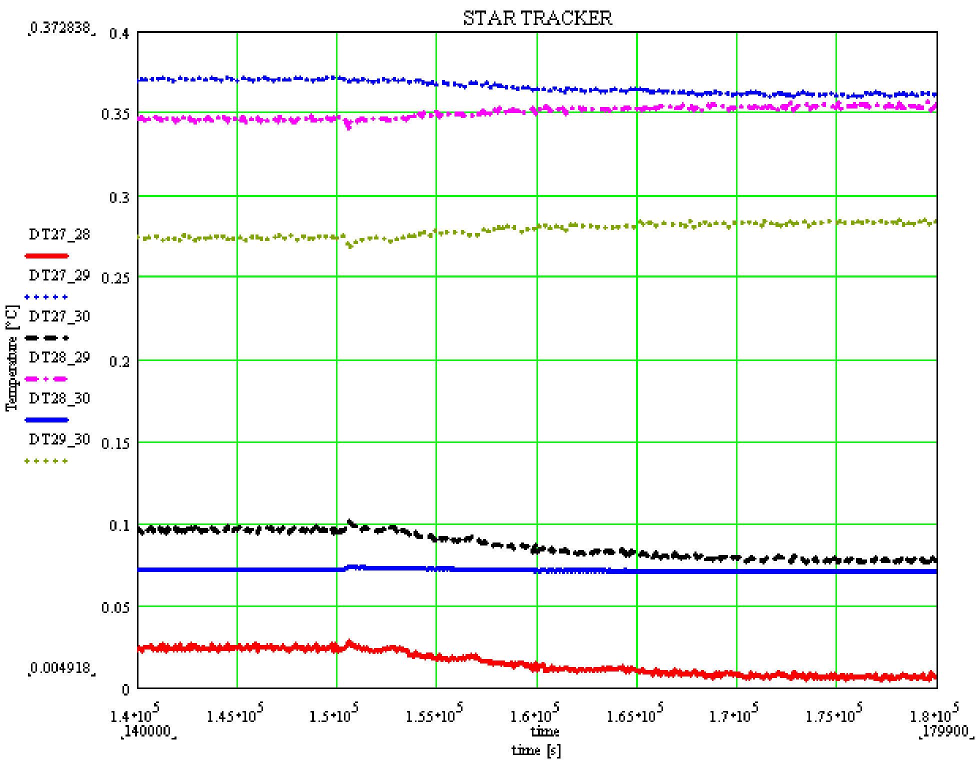


Fig. 5-11: STAR TRACKER FEET temperature gradient (COLD CASE)

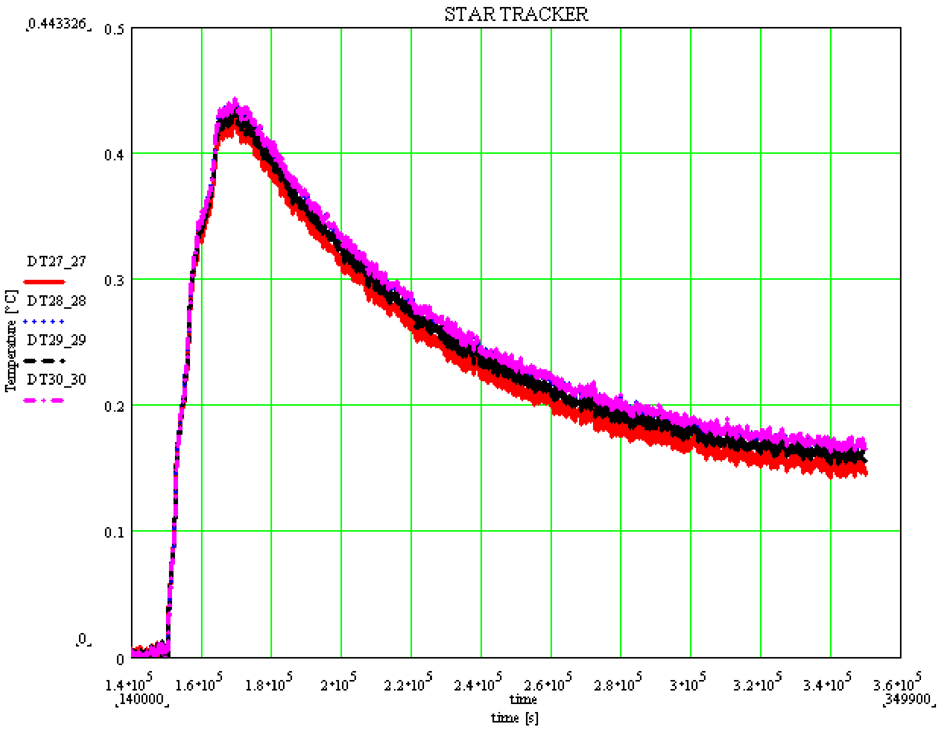


Fig. 5-12: STAR TRACKER FEET temperature variation around set-point (COLD CASE)

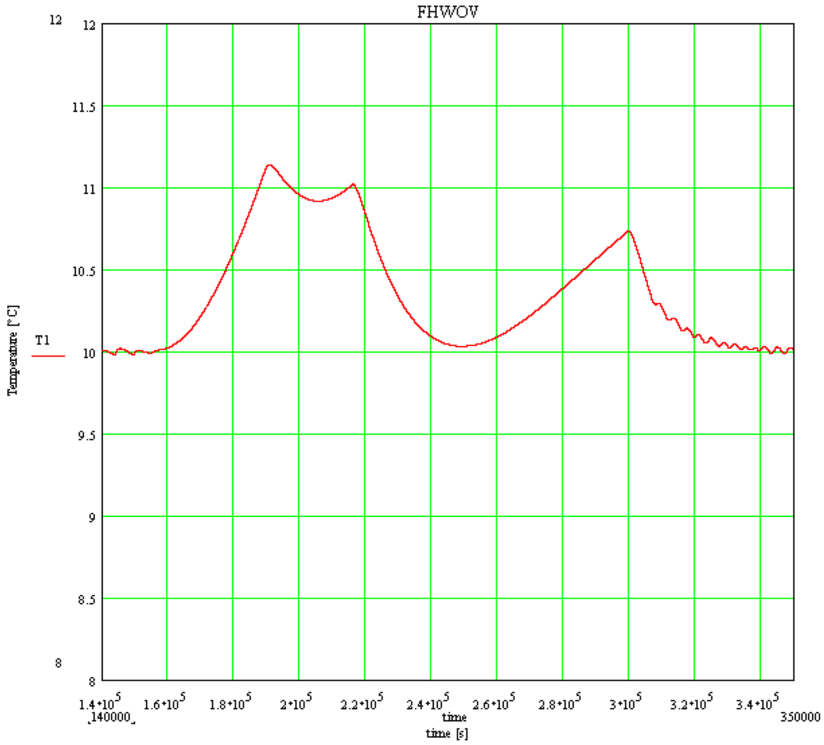


Fig. 5-13: FHWOV temperature profile (HOT CASE)

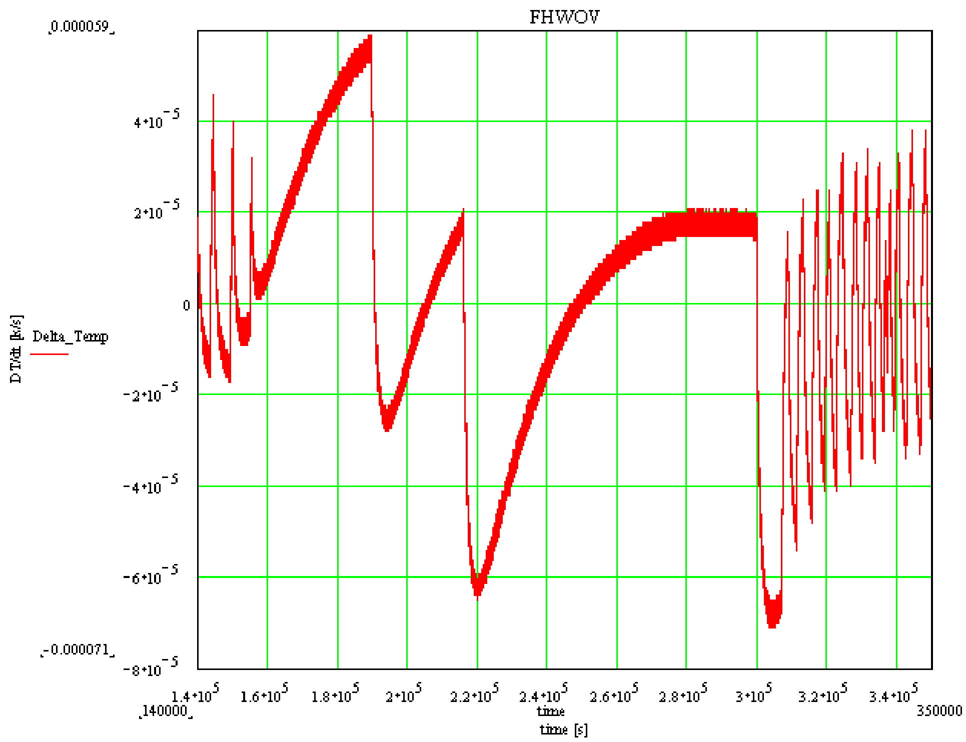


Fig. 5-14: FHWOV ΔT/Δt profile (HOT CASE)

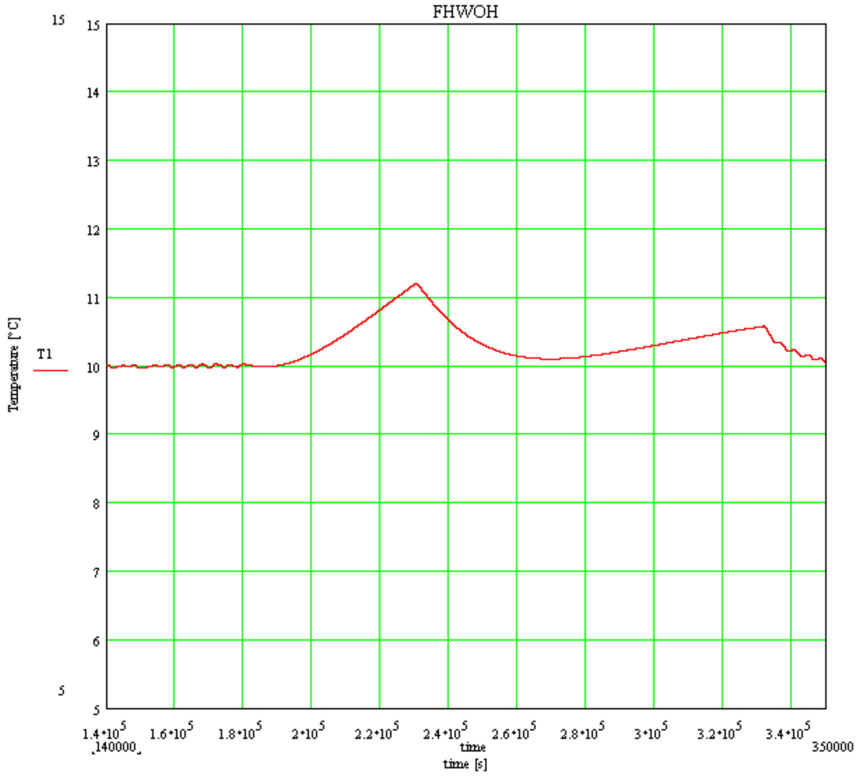


Fig. 5-15: FHWOH temperature profile (HOT CASE)

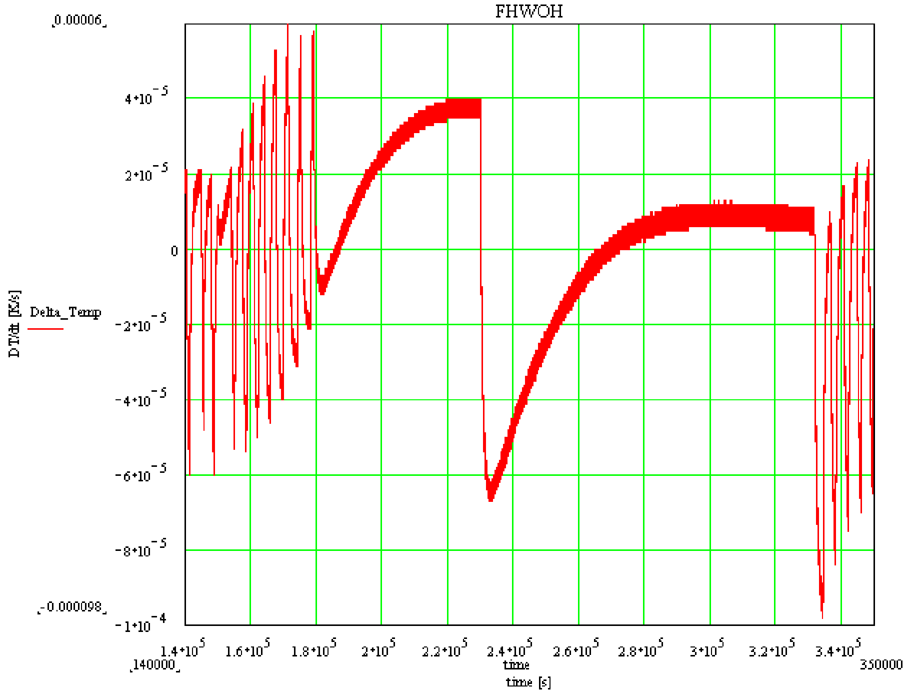


Fig. 5-16: FHWOH ΔT/Δt profile (HOT CASE)

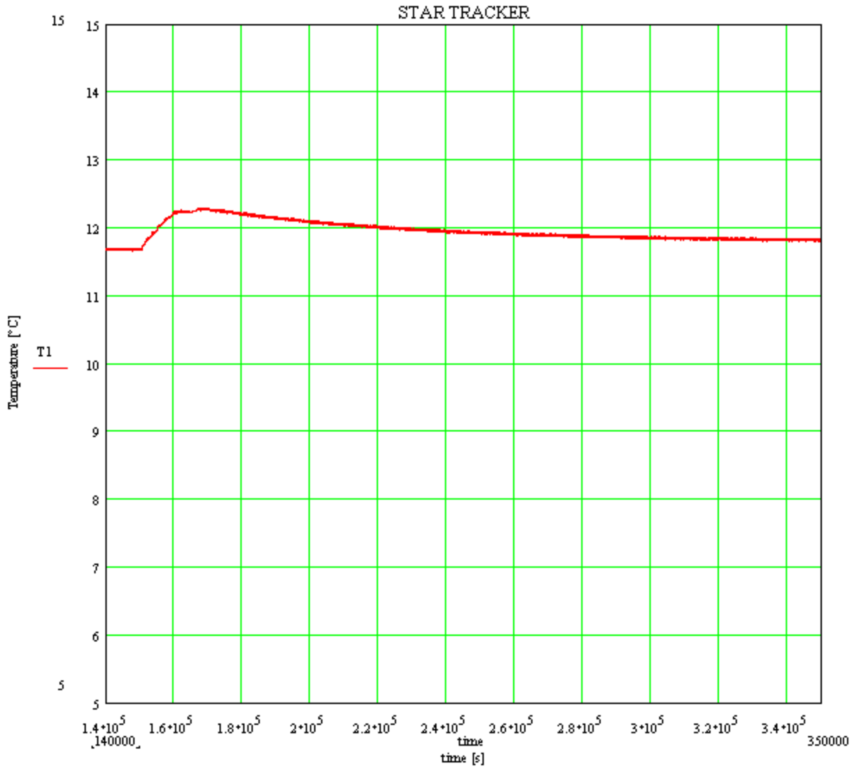


Fig. 5-17: STAR TRACKER mounting plate temperature profile (HOT CASE)

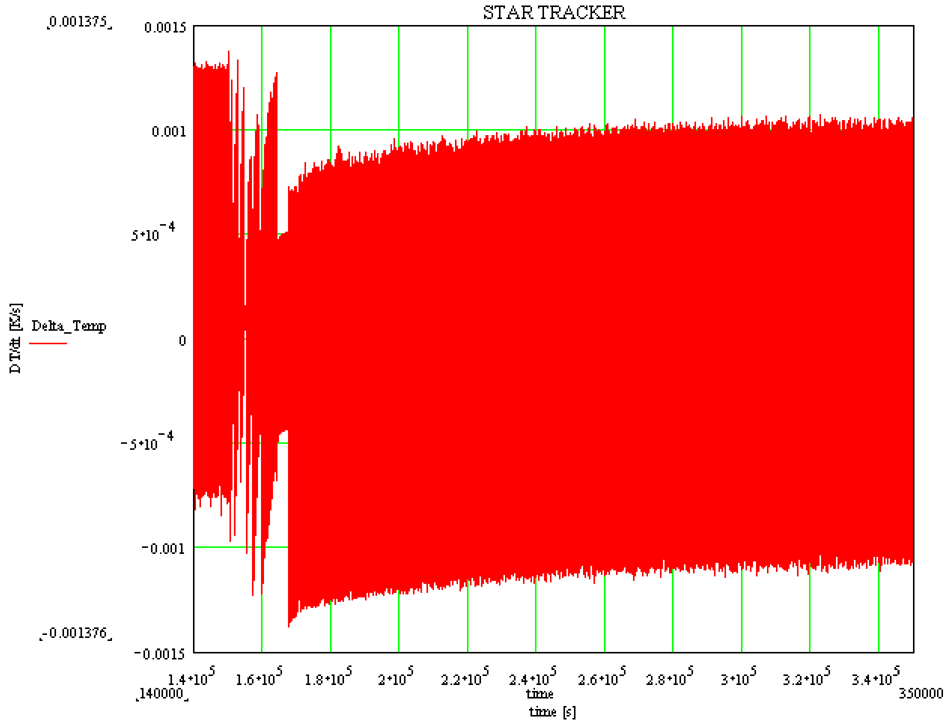


Fig. 5-18: STAR TRACKER mounting plate ΔT/Δt profile (HOT CASE)

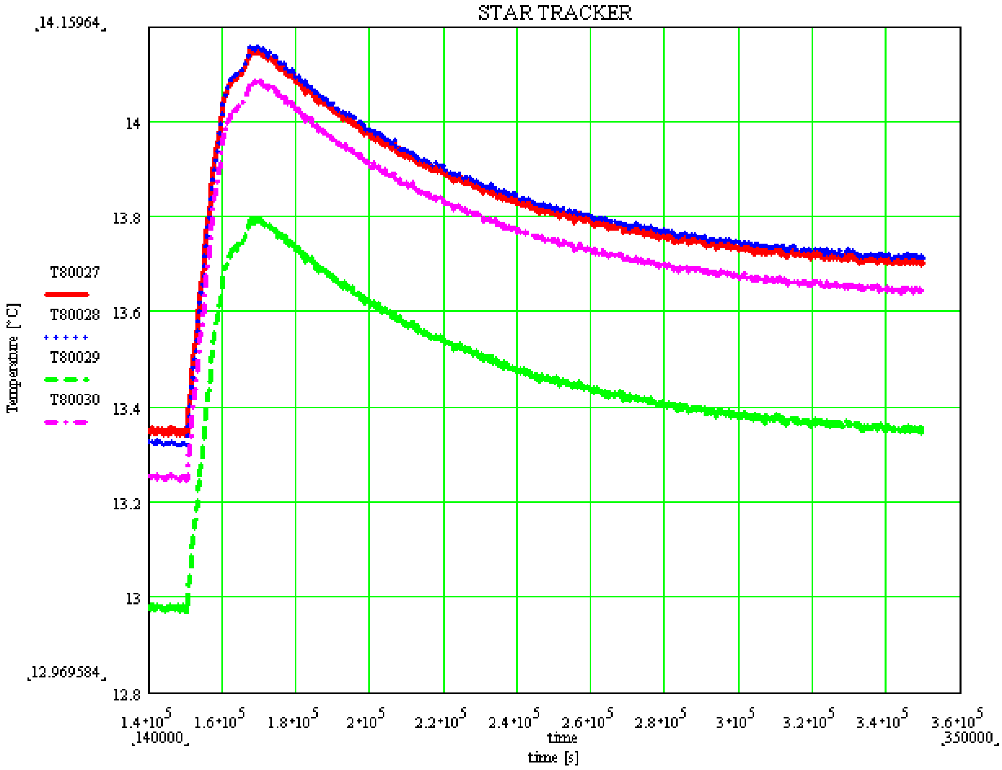


Fig. 5-19: STAR TRACKER FEET temperature profile (HOT CASE)

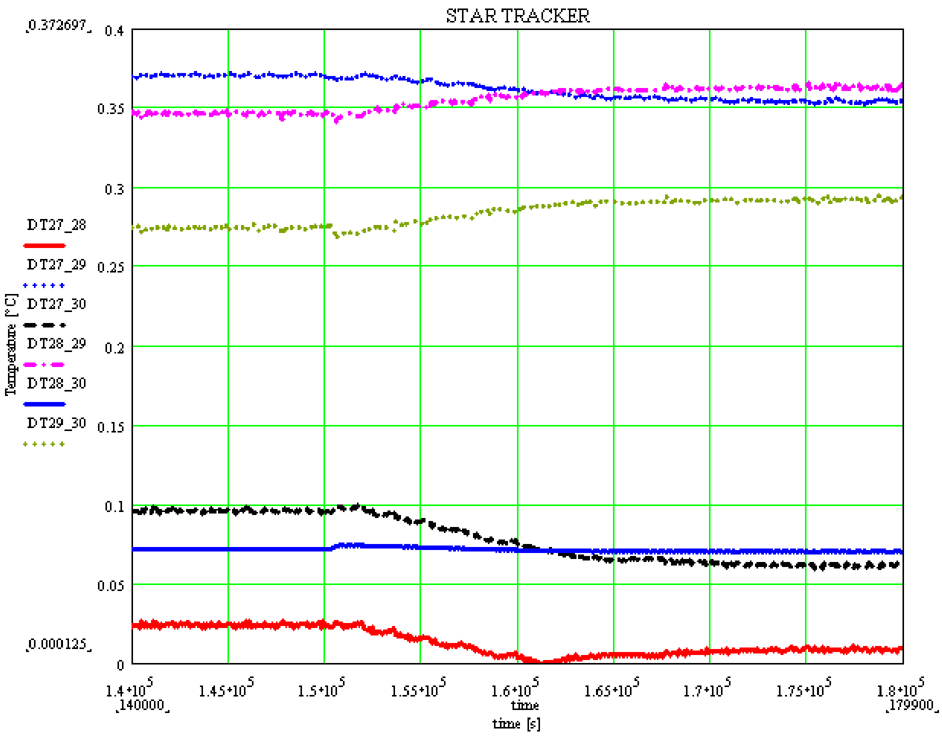


Fig. 5-20: STAR TRACKER FEET temperature gradient (HOT CASE)

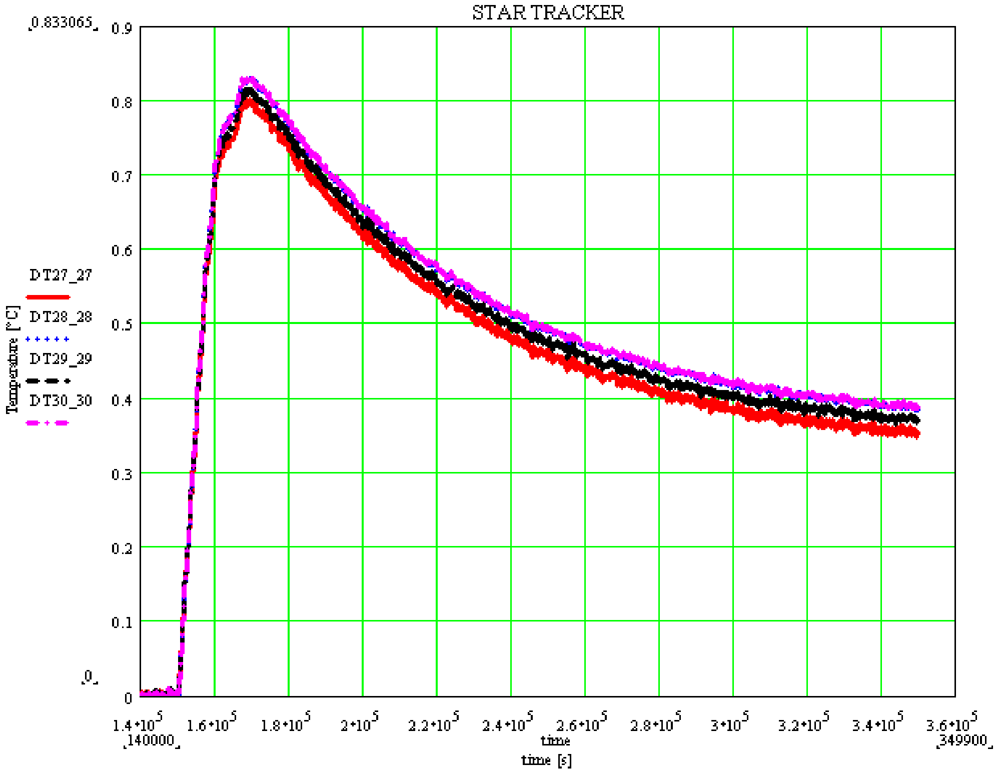


Fig. 5-21: STAR TRACKER FEET temperature variation around set-point (HOT CASE)

6. CONCLUSIONS

The results of the analysis reported in this document show that the thermal requirements achieved by means of a fine control law are always met.
One requirement only is not met and it is referred to the variation around set-point of the STR feet during the HOT CASE (EOL).
This out of requirement takes a time of about 28 hours after a S/C change of attitude.
A recovery action is to improve the proportional gain of the regulator to add “reactivity” to the control in order to keep under control the deviation from the set-point.
But this action leads to reduce the dumping effect at the high frequency (telemetry and actuator noises), affecting the temperature stability results.
TCS suggestion is, before acting on the design of the control, to ask at System level to evaluate the impacts on the STR performances with the not-complete fulfilment of this requirement.