Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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Design, implementation and installation of a new TEMPerature Data Acquisition System (TEMPDAS) for the ESTEC Large Space Simulator (LSS)

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Abstract

The ESTEC Large Space Simulator (LSS) provides close simulation of in-orbit environmental conditions. The LSS is equipped with a two-axis Motion System, which permits a test article to be placed within the LSS in any position relative to the angle of incidence of solar radiation axis. Temperature measurement signals generated by thermocouples fixed on the rotating test article are connected to the main data handling system through a Slip-Ring Unit. A high-accuracy multi-channel Temperature Data Acquisition System (TEMPDAS) has been developed for specific use in the LSS.

The concept of TEMPDAS is to multiplex, condition and measure the signals from the thermocouple sensors inside the LSS and send the digital measurement data to the data-handling unit. The National Aerospace Laboratory NLR designed, manufactured and tested two Data Collection Units, enabling TEMPDAS to measure 864 thermocouple signals.

This paper presents a full description of the main project phases and their outcomes from unit prototyping to final unit verification and installation. Special attention is paid to address some critical design and manufacturing items encountered in the course of the development and to highlight the technical solutions implemented to surmount the difficulties.

Abbreviations

ADC	Analogue to Digital Converter
DCU	Data Collection Unit
EMF	Electro-Mechanical Force
ESTEC	European Space Research and Technology Centre
FPGA	Field Programmable Gate Array
LSS	Large Space Simulator
NLR	National Aerospace Laboratory NLR
SRU	Slip Ring Unit
TC	Thermocouple
TCMB	Thermocouple Multiplexer Board
TEMPDAS	Temperature Data Acquisition System
VTR	Variable Temperature Reference

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(17 pages in total)

1 Introduction

Measurement of temperatures on a spacecraft inside ESTEC's Large Space Simulator (LSS) is generally done with thermocouples. The thermocouples are connected to a Variable Temperature Reference (VTR), which forms the cold junction. In the current situation 144 channels of the Slip Ring Unit (SRU) are used to measure 576 (compensated) thermocouple signals. The low-level signals from the thermocouples are multiplexed by mechanical relays and measured by the Data Handling System outside the Large Space Simulator [ref. 1].

A new Temperature Data Acquisition System (TEMPDAS) has been conceived [ref. 2] in order to:

- extend the thermocouple channel capacity up to 2000 channels;
- drastically reduce the required number of SRU channels from 144 to fewer than 20;
- have a system less prone to data corruption;
- have a system with self compensating capabilities.

TEMPDAS is made up of Data Collection Units (DCUs), placed in the LSS, and a Data Handling Unit located in the control room. Each DCU is characterised by a modular architecture and takes care of analogue thermocouple signal conditioning, digitisation and multiplexing over a MIL-STD-1553B data bus. For the realisation of the new system the National Aerospace Laboratory NLR has designed, manufactured and tested two DCUs. The absolute measurement accuracy of the system must be better than ±1 °C in all LSS operational conditions.

Besides the Data Collection Unit for the measurements of thermocouples, TEMPDAS is currently also capable of measuring Platinum sensors (Pt-DCU). ESTEC is developing a multifunctional system [ref. 3] that combines the measurement of these sensors together with thermistor sensors. This paper focuses on the thermocouple measurements only and presents the project phases and their outcomes from unit prototyping to final unit verification. Special attention is paid to address some critical design and manufacturing items encountered in the course of the development and to highlight the technical solutions implemented to surmount the difficulties.

2 TEMPDAS design

The “Specification for the Design and Manufacturing of a prototype Data Collection Unit” [ref. 4] forms the functional baseline for the system design. This document translates the overall accuracy requirement of ±1°C into specifications for the DCU in terms of volts, taking into account the error introduced by the sensor itself and the cold junction (VTR). The major performance specifications for the DCU are:

- Input range from –10 mV to +10 mV
- Repeatability: $3\sigma < 4{,}2\ \mu V$
- Offset between any two channels:
  - Steady-state temperature condition: < 5,7 μV
  - Transient temperature condition: < 15 μV
- Remaining System Error
  - Steady-state temperature condition: < 4,5 μV
  - Transient temperature condition: < 7,5 μV

Other design specifications are:

- Operating in vacuum between –40 °C and +50 °C
- Powered by a +28VDC external supply
- Communication via a MIL-STD-1553B bus
- Electromagnetic Compatibility in accordance with MIL-STD-461C – part3.

Figure 1 depicts the architectural design of TEMPDAS. The system is set-up to be modular extensible (up to five complete units inside the LSS). The Data Handling Unit controls the DCUs via a redundant MIL-STD-1553B bus. The software on the Data Handling Unit runs under Windows 95 and consists of Application Software (developed by ESTEC) to interface with the Data Handling System and DCU Control Software (developed by NLR).

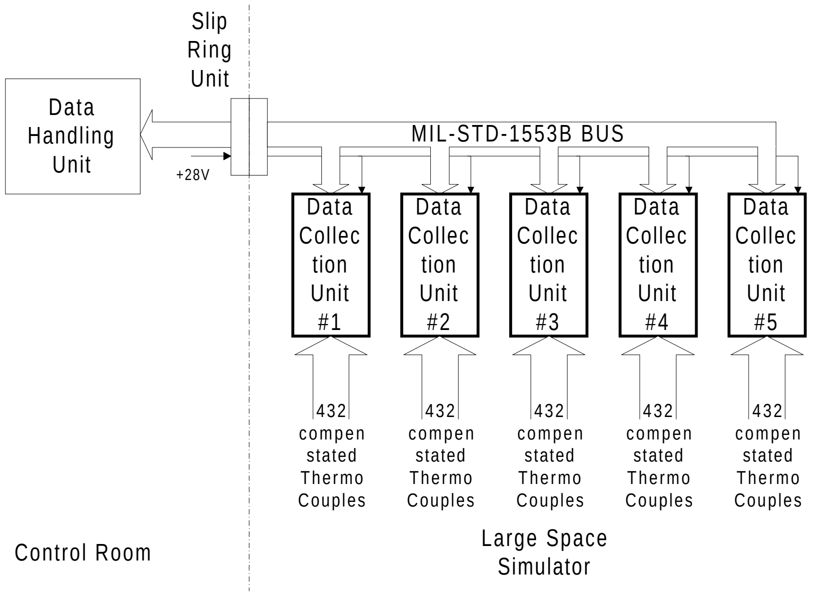


Figure 1: TEMPDAS Architectural Design

Figure 2 shows the block diagram of the DCU. Each DCU is equipped with redundant power supplies to convert the external +28 V into internal +5 V/±15 V.

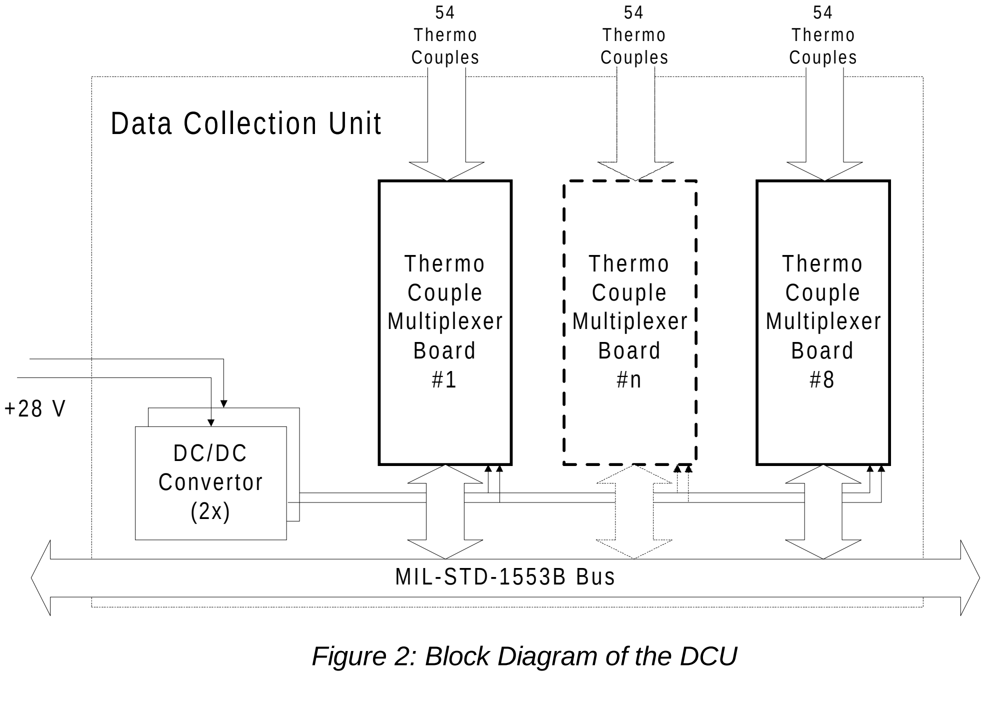


Figure 2: Block Diagram of the DCU

The actual measurements are performed on a Thermocouple Multiplexer Board (TCMB). The TCMBs work independently and are capable of measuring 54 thermocouples each. A block diagram of the TCMB is shown in figure 3.

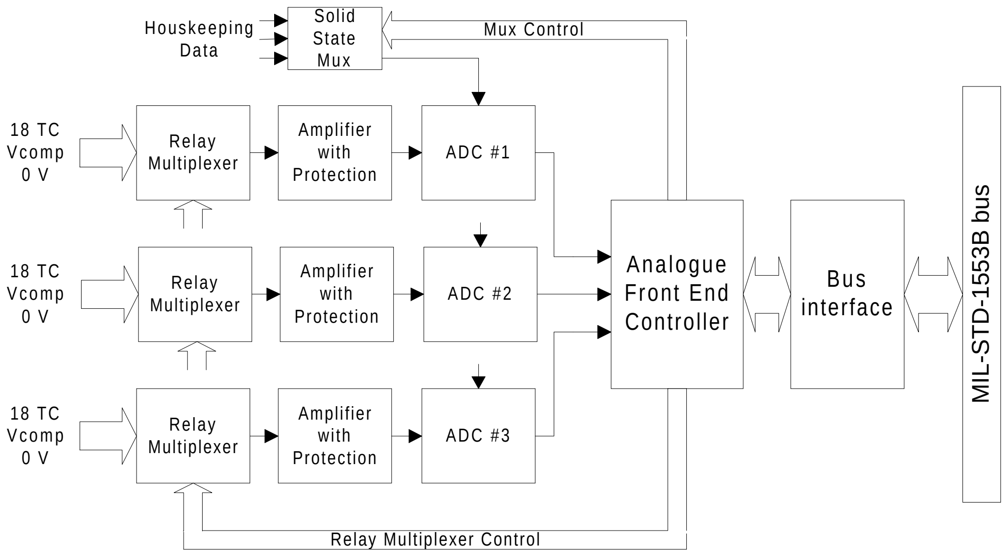


Figure 3: Block Diagram of a Thermocouple Multiplexer Board (TCMB)

The heart of the TCMB consists of an analogue front-end controller which is implemented in a Field Programmable Gate Array. Its functions are to control the multiplexers and the Analogue to Digital Converters (ADCs), store the last measurement data and provide communication with the Data Handling Unit.

Multiplexing of the low-level thermocouple signals is done with electromechanical relays because of the overall superior performance [ref. 5**]**. In comparison with the solid state multiplexers, relays have a lower leakage current and “on”-resistance. In the “off”-state relays also offer a protection against high common mode voltages that could be induced during isolation tests of solar panels.

A single TCMB measures 54 thermocouple signals in three parallel groups that measure 18 channels sequentially. To compensate for the offset and gain error in the amplifier and in the ADC, a measurement cycle also samples two well-known voltages; a short circuit (V_0) and a compensation voltage (V_{comp}) of about 20 mV. The compensation voltage is derived from a stable 2,5 V reference source with a 1:125 precision resistor divider. This derived voltage needs to be very stable and its value is assessed during the calibration. Each group has its own source for the compensation voltage. The compensation for the offset and gain is performed in the DCU Control Software on the Data Handling Unit according to the following formula:

$$V_{measured,TCx} = \frac{(C_{ADC,V_{TCx}} - C_{ADC,V_0})}{(C_{ADC,V_{comp}} - C_{ADC,V_0})} * V_{comp} \quad (1)$$

Where:

$C_{ADC,VTCx}$ is the ADC code while TCx was connected to the input
$C_{ADC,Vcomp}$ is the ADC code while V_{comp} was connected to the input
$C_{ADC,V0}$ is the ADC code while V_0 was connected to the input
V_{comp} is the well-known on-board compensation voltage

Housekeeping data is measured by the less accurate inputs of the ADC. Each board monitors the differences between the on-board precision voltages (V_{comp}) and four temperatures to get a good thermal overview of the board. Additional inputs are used to measure the power supply output voltages and some temperatures of the DCU housing.

TEMPDAS has been designed to minimise the effects of single point failures [ref. 6]. The MIL-STD-1553B bus has built-in features to ascertain communication in case of a single point failure in the bus hardware. The MIL-STD-1553B bus is therefore implemented as a primary bus A and a secondary bus B (redundant). This makes it possible to connect all boards in the DCU directly to the busses without jeopardising reliable operation. The power supplies of the DCU are hot redundant. At TCMB level the three independent groups have their own reference voltage, with an option to use one of another group.

3 Assembly

All components and materials used for the assembly of the DCU and the TCMBs were selected to have low outgassing. If available on the market, MIL-STD-883B qualified components were used. If not, the extended temperature range (-55 °C to +125°C) was selected. Due to these selection criteria the delivery times of most components was in the order of 15 to 30 weeks.

As a result of the thermal analysis [ref. 7] the layers of the PCB contained as much copper as possible to optimise thermal distribution. During the assembly of some components the boards needed to be warmed up in order to achieve good solder junctions.

Figure 4 shows the DCU with one TCMB installed and one TCMB at the front. On top of the DCU the connectors for the power supply are visible. Each TCMB has three flying wires (black cables), each for 18 TC inputs, with standard sub-D connectors. Clearly visible on the TCMB are the relay area (on top of the board) and the FPGA (on the bottom-centre). The dimensions of the housing are 217,1 mm x 180,4 mm x 156,3 mm (H x D x W).

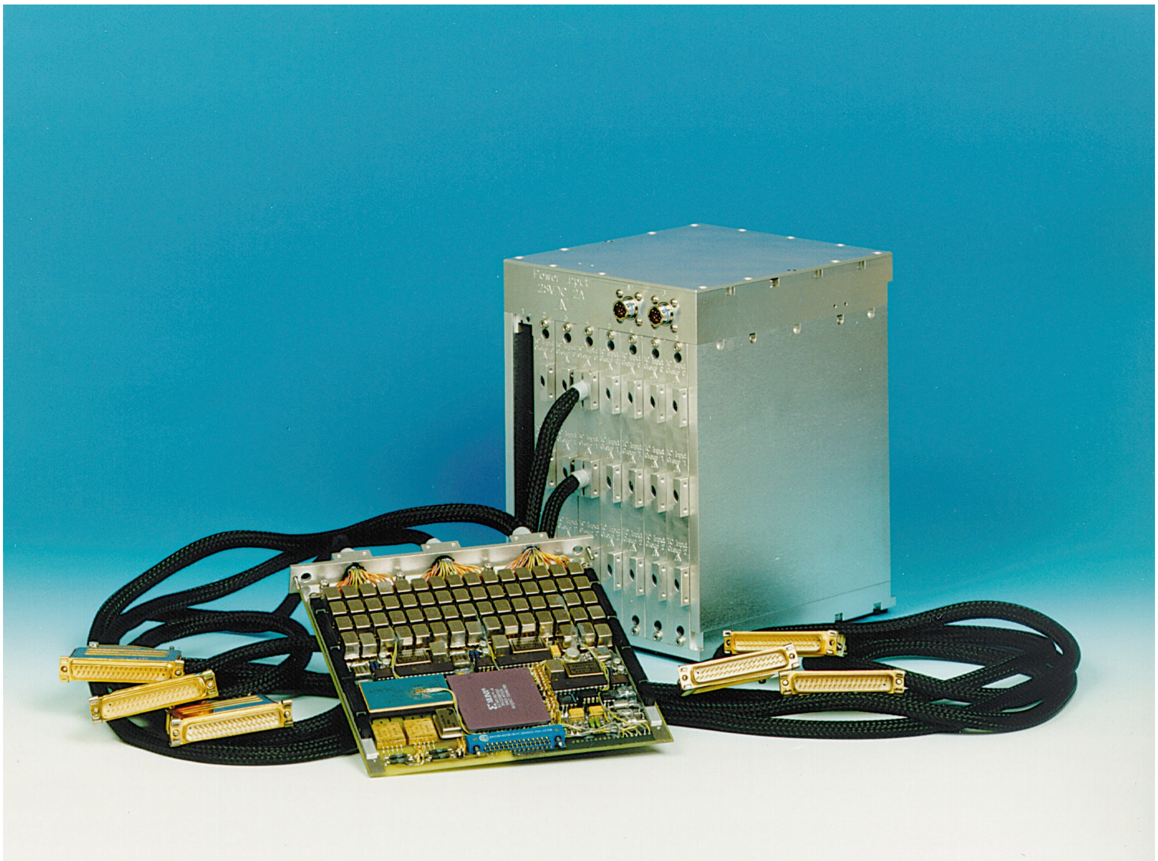


Figure 4: DCU with component side view of a TCMB at the front

4 Calibration

After assembly and functional check, the two DCUs were powered on for about one month in order to have a burn-in period for the on-board derived precision voltages. Next, the value of these compensation voltages was determined in NLR's calibration facility, for which the set-up is depicted in figure 5. After temperature stabilisation of the DCU a stable input voltage in the order of 20 mV (i.e. 200 mA for the current source) is applied to the TC inputs of the TCMB. The same voltage is measured with a Keithley model 181 nanovolt meter. The magnitude of compensation voltages is derived from the measurements of the DCU and the Keithley 181, using equation 1 in the reversed way.

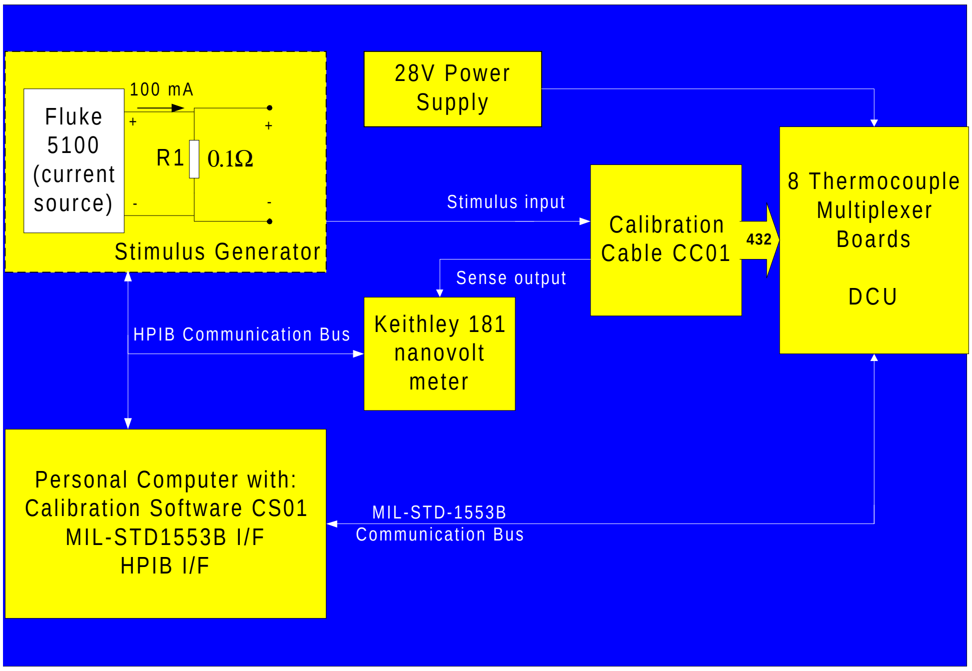


Figure 5: Calibration set-up

In order to minimise the source loading by the input impedance of the TCMBs, the output impedance of the stimulus generator has to be as low as possible. A practical value of 0,1 Ω was chosen, resulting in a stimulus current between –100 mA and +100 mA to cover the specified input range. The process is automated by a personal computer that is able to control the stimulus generator, the DCU and the Keithley 181 nanovolt meter. The results of the seven-point calibration (-10 mV, -5 mV, -2 mV, 0 mV, +2 mV, +5 mV, +10 mV) of DCU#1 is shown in figure 6. The black centre portion indicates the deviation with respect to the generated voltage of the average values measured (minimum to maximum) over all TCMBs, the red (outer) bars add the maximum two-sigma (2σ) to these values. It is shown that all measurements of the DCU are within 1μV from the generated voltage. The absolute accuracy of the Keithley 181 nanovolt meter is better than $3 \cdot 10^{-6}$ V in the range from –10 mV to +10 mV.

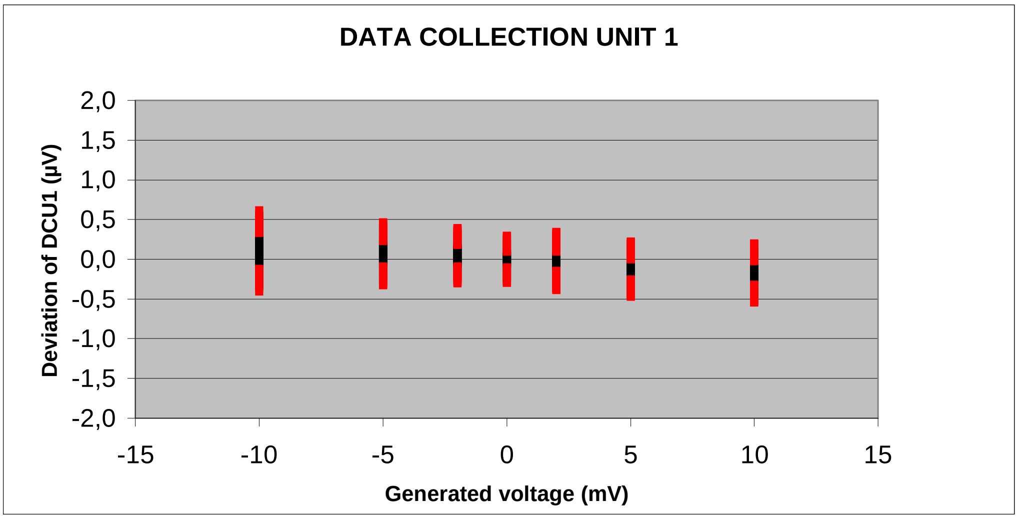


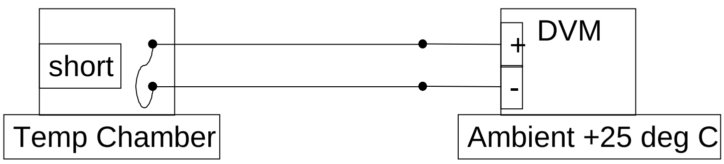
Figure 6: Calibration result of DCU#1

5 Environmental test results

The two DCUs were subjected to EMC and Thermal Vacuum (TV) tests. The EMC tests were carried out at the facilities of the NLR EMC Laboratory according to MIL-STD-461C, part3 cat. A2c. With the exception of one susceptibility test (RS03 100 MHz – 1000 MHz) the units were found to be compliant. Susceptibility was however found to be less than 2 μV when the radiated field levels were halved.

The thermal vacuum tests revealed some interesting issues. A prototype DCU with only three TCMB was tested at IABG in Ottobrunn, Germany [ref 8]. Mainly the observed Offset Between Channels was out of specification. The following causes were identified for the large offset voltages:

1. **Flying Wires**: The TCMBs are equipped with flying wires, made of silver plated copper, to connect to thermocouple signals. To ease assembly, three different production batches (colours) were used. Because the connector temperature differs from the DCU temperature, a thermal Electro-Mechanical Force (EMF) is introduced as is indicated in figure 7. The voltage is larger than the specification for the complete unit. Ref 9 lists a table with values for thermo-electric potentials for several materials, which shows that Cu-Cu junctions can result in up to 0,2 μV/°C. The maximum thermal EMF in figure 7 is about 0,1 μV/°C. In the final two DCUs the wires all come from a single batch to minimise the thermal EMF effects. The same is applicable for the Test Cable Harness used for the calibration and the environmental tests; all wires between the TCMB input connectors, the stimulus generator and the Keithley 181 nanovolt meter are from a single production batch.



Wire Combination		Measurements (uV) at delta T of	
+	-	+75 deg C	-65 deg C
Orange	Yellow	-7	7
Yellow	Grey	5	-6
Orange	Grey	-1	1
Orange	Orange	0	0
Yellow	Yellow	0	0
Grey	Grey	0	0

Figure 7: Offset voltage due to material differences of flying wires

2. **Thermal distribution:** Figure 8 shows a thermal image of a DCU under vacuum conditions. The left side of the housing was removed to visualise the heat distribution on the TCMB. The relay area is situated on the right half of the TCMB, where also the connected flying wires are visible.
A steep temperature transient near the edges of the relay multiplexer area (right top of the TCMB in figure 8) introduced an offset voltage in the order of 10 – 20 μV in the prototype DCU. This is mainly caused by heat flow between the flying wires and the housing through the PCB. The effect is reduced by thermally isolating the relay multiplexer area from the housing as much as possible.

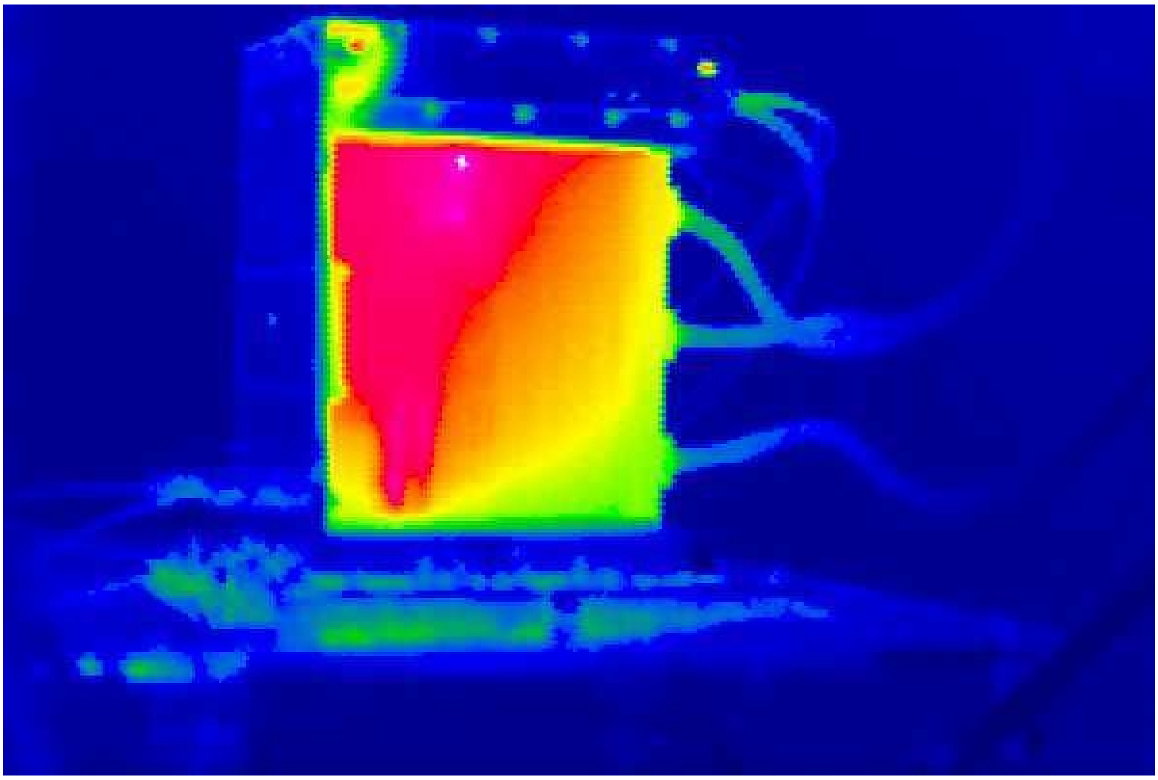


Figure 8: Thermal image of a DCU in a vacuum chamber (left side view)

The two DCUs went through a total of three thermal cycles under vacuum conditions [ref. 10]. Figure 9 shows the temperature profile of the heatsink and shrouds during the TV test. The test set-up was basically the same as used for the calibration (See Figure 5: Calibration set-up).

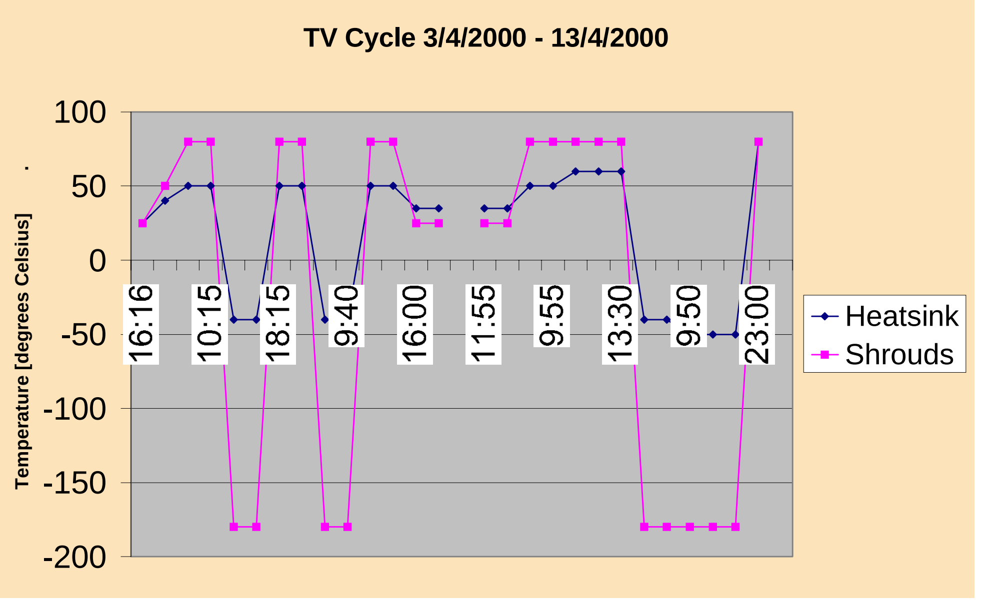


Figure 9: Temperature cycle of the thermal vacuum test

The temperature transients took place in about 2 hours. The units were continuously scanning during the cycles. The time needed for temperature stabilisation inside the DCU after a transient takes more than 8 hours.

In the first two temperature cycles a large deviation was found between the voltage of the stimulus generator and the feedback signal from the test cable harness inside the chamber. Apparently the feedthrough connector introduced a thermal offset voltage in the order of several tens of microvolts. For the investigation the test cable harness was shorted inside the chamber and the stimulus current disabled. In the last cycle the voltages on the wires coming from the feedthrough connector were measured to quantify the distortion. The offset voltage in the stimulus input lines varied between 0,4 μV and 2,3 μV while the feedback signal ranged between +31,6 μV and –62,5 μV.

To determine the accuracy of the DCU measurements, the results were corrected with the findings of the investigation on the behaviour of the feedthrough connector. Table 1 shows the overall results of the two DCUs. The repeatability and the remaining system error show to be well within specification. The offset between channels is however outside the specification.

Table 1: Results of the TV test

		Requirement	Test Result
Repeatability (3σ)		4,2 μV	1 μV (max) <0,5 μV (general)
Offset Between Channels	Steady-state	5,7 μV	10,5 μV
	Transient	15 μV	25 μV
Remaining System Error	Steady-state	4,5 μV	-1,6 μV
	Transient	7,5 μV	-2,3 μV

In the third thermal cycle the temperature limits were extended by 10 degrees. In these periods the DCUs were powered-off and powered-on after about two hours. The system started without any problem.

During the testing of the system, problems were encountered with relays that did not properly function. In the prototype DCU more than 20% of the relays failed to properly close the contacts one or more times. The failure normally showed to be intermittent; after a failure the relay would subsequently function normally for multiple consecutive scans. ESTEC and the manufacturer of the relays, Teledyne Relays, have investigated the problem. It was concluded that the problem could very likely be attributed to contamination of the contact surfaces with silicone; a problem which was related to the production batches used.
The functional and EMC tests of the two final DCUs were conducted without failing relays. The intermittent switching problem was, however, again seen in the results of thermal vacuum test. A new kind of failure was also detected; a few relays were switched on continuously for a longer period of time. Investigation of the test data showed that the number of channels with failures (about 5%) was within the specification of the relay when related to the number of unit cycles performed.

6 Conclusions

The test results show that the DCUs work within their specification, except for the offset between channels and the EMC specification RS03. If the measurement errors were converted to temperatures, the excess offset would be in the order of 0,25 degrees (10 μV) for the temperature transient situation and 0,12 degrees (5 μV) for steady state. Susceptibility is found to be within the margins when the field levels are halved.

The temperature distribution over the relay area on the TCMB shows to have a large effect on the on the measurements. Although the board is designed for optimal thermal conductivity (without the use of a thermal frame), there will always be a small temperature gradient over the footprint of the relay. An effective improvement could be achieved by a redesign of the housing, where the boards are mounted horizontally instead of vertically.

The failures in the measurements due to the malfunctioning of the relays used make their application arguable. The accuracy that is achieved with the relays is, however, very high; the standard deviation is generally less than 200 nV. The results of future operational tests with the DCU will enable a better judgement on whether to use relays or not.

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