THERMAL CONDUCTIVITY MEASUREMENT AT 40K DESIGNING A CRYOGENIC TEST BENCH

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ABSTRACT

The PLANCK telescope is designed for operating temperatures in the range of 40 K to 300 K. In order to characterise its interface behaviour under such a large temperature range, a dedicated test campaign has been performed in Alcatel Cannes premises, aiming at measuring the thermal conductivity of the interface.

These tests are based on the measurement of temperature gradient induced by power injection on the specimen during a thermal equilibrium.

For this purpose, two representative samples have been built and integrated in a dedicated test bench so-called C2. This facility is an under-vacuum cryostat with two temperature levels :

- 77 K achieved with liquid nitrogen shrouds
- 4.2 K with liquid helium shrouds and dedicated cooling support.

Thermal conductance measurements are thus performed under 10-7 HPa vacuum.

This paper presents the test configuration detailing the solution developed in order to optimise the thermal coupling between the specimen and its support. The difficulty is to stabilise the specimen at 40 K, when the test support and the radiative environment are closed to 4K.

The first test results are also presented and the total accuracy of this method is evaluated : 0.03 W/K measured at 40K with a maximum dispersion of +/- 0.5K and a stability of +/- 1K during 0.5 hour.

1. INTRODUCTION

The PLANCK satellite, a mission of the European Space agency due to be launched in 2007, is one of the most ambitious space mission.

Planck's large telescope will collect the light from the Cosmic Microwave Background and will focus it onto two arrays of radio detectors, which will translate the signal into a temperature.

The detectors have to be highly sensitive, since they will be looking for temperature variations of the cosmic background about a million times smaller than one degree.

A key requirement is that Planck detectors will have to be cooled down to temperatures very close to the coldest temperature reachable : absolute zero : 0 degree Kelvin (minus 273 degrees centigrade);

They have to be very cold to ensure that their own temperature does not swamp the signal from the sky. All of them will be cooled down to temperatures around or below 20 degrees Kelvin.

In the aim at isolating these arrays of detectors from the others parts of the satellite, which are maintained at about 300 degrees Kelvin, Planck is equipped with grooves.

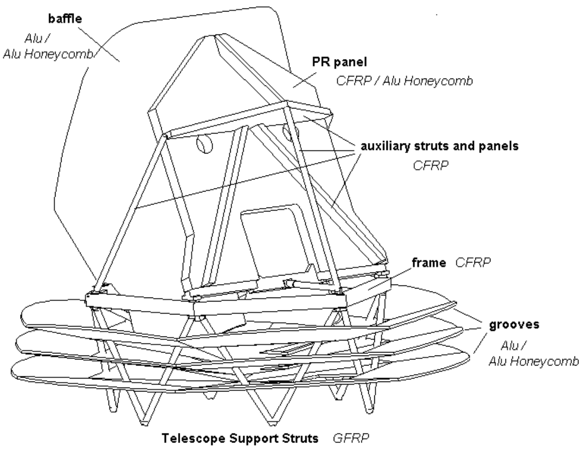

Figure 1 : Planck telescope environment configuration

These grooves have to radiatively "protect" detectors from the hot temperature of the baffle without disturbing or turning off the light flow coming from the telescope.

In this configuration, the lowest temperature reached by grooves is estimated at around 40 degrees Kelvin.

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The groove structure is made by Alu/alu Honeycomb panels joined by screwed interfaces.
The success of this radiative protection is based on the very good temperature homogeneity of these panels.

The knowledge of thermal conductance of these interfaces at 40 degrees Kelvin is then essential to ensure grooves performances.

Two interface samples, mechanically and thermally representative to flight interfaces, have been realised to perform some thermal vacuum tests to measure a thermal conductance value at 40 degrees Kelvin.

This paper first describes the bench used to perform these conductivity measurements at very low temperature. Secondly, it gives the results of conductivity measurement tests realised on two Planck interface samples.

2. PRINCIPLE OF CONDUCTION MEASUREMENT

In the case of heat, the transfer is always from a higher temperature to a lower temperature. Denser substances are usually better conductors; metals are excellent conductors.

The amount of heat transferred by conduction can be determined using Fourier's law:

$$Q = \frac{\lambda S}{L} \Delta T \qquad (1)$$

Where Q is heat transferred per unit time, S is the area perpendicular to the heat flow through which it is passing, L is the thickness of the specimen through which the heat is passing, λ is a conductivity constant dependent on the nature of the material and its temperature, and • T is the temperature difference between the hot and cold sides of the substance through which the heat is being transferred.

From equation (1), the conductivity constant λ could be expressed by :

$$\lambda = \frac{QL}{S\Delta T} \qquad (2)$$

So, the measurement incertitude on conductivity could be done with differentiation of equation (2) :

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta Q}{Q} + \frac{\Delta L}{L} - \frac{\Delta S}{S} - \frac{\Delta(\Delta T)}{\Delta T} \qquad (3)$$

(where for a quantity A, if $\frac{\Delta A}{A} = ^{+x}_{-y}$ then $-\frac{\Delta A}{A} = ^{+y}_{-x}$)

The measured conductivity error is most particularly linked to knowledge of :

- power applied in the sample and its environment,
- the sample's area throw which the power is conducted,
- the sample's, and its environment's temperatures

2.1 Case of multilayers

The reciprocal of conductance is resistance, equal to S• T/Q, and is additive when several conducting layers lie between the hot and cool regions, because S and Q are the same for all layers. In a multilayer partition, the total conductance is related to the conductance of its layers by:

$$\frac{L}{\lambda} = \frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3} \ldots \qquad (4)$$

So, when dealing with a multilayer partition, the following formula is usually used:

$$Q = \frac{A\Delta T}{\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} \ldots} \qquad (5)$$

2.2 Thermal conductance

For general scientific use, *thermal conductance* is the quantity of heat that goes in unit time through a plate of *particular area and thickness* when its opposite faces differ in temperature by one degree. For a plate of thermal conductivity •, area *A* and thickness *T* this is :

$$\text{Thermal conductance} = \frac{\lambda A}{T} \qquad (6)$$

measured in $W \cdot K^{-1}$.

3. SAMPLE INTERFACE DEFINITION

To be representative to the different flight interfaces, two samples have been realised :

- One internal/external interface sample,
- One external/external interface sample.

The test aim is to measure the thermal conductivity in the specimen height at very low temperature (lowest 40K).

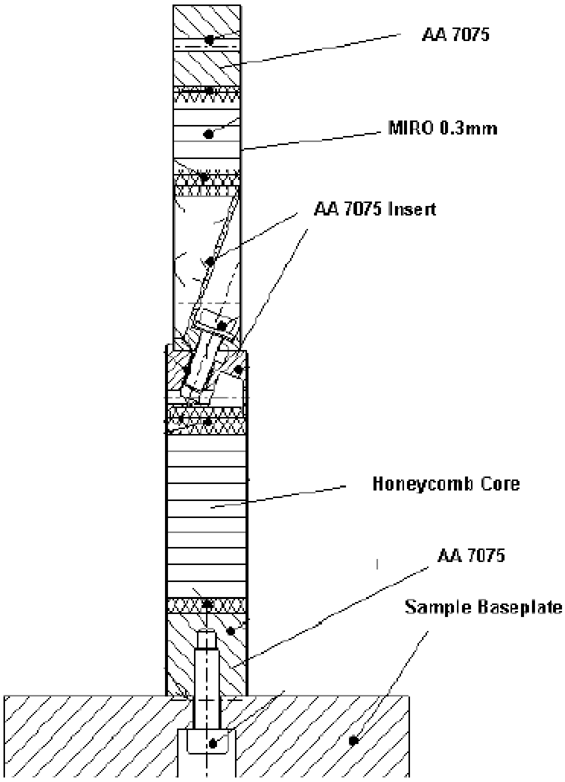

Figure 2 : Side view of internal/external I/F sample

Each sample is fixed on an aluminium base plate which will, by conductive exchanges with a cryogenic base plate, decrease the specimen temperature to reach objective temperature.

The base plate is equipped with 4 heaters which maintain the specimen in temperature tolerances.

The screwed link between two parts is supposed perfect.

To be representative to flight panels, interfaces samples are recovered by MIRO (thickness = 0.3 mm) on the two opposite side.

An other heater is fixed on the top part of specimen (head heater), it will provide required power to create temperature gradient in specimen to obtain its conductivity.

To avoid radiative exchange with close environment via specimen thickness, thermal aluminium scotch is applied on head heater.

All heaters are wired with 4 AWG 26 cables, 2 wires to supply heater and 2 wires to measure voltage and current.

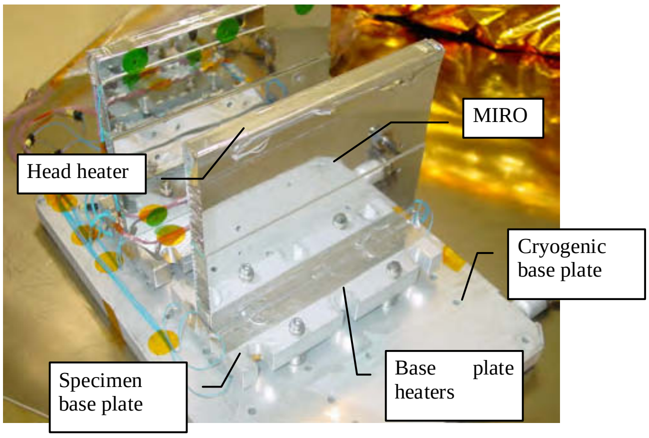

Figure 3 : Global view of 2 samples mounting

To perform the thermal vacuum tests, each specimen is equipped with 8/100 type T thermocouples. 10 thermocouples are used for gradient measurement.

6 thermocouples have been mounted in 3mm diameter holes in the sample and 4 thermocouples bounded on the Miro surface to allow double-check.

Finally 2 thermocouples have been bounded on the specimen base plate and 2 on the cryogenic base plate.

All specimen thermocouple wires are first rooted on specimen thickness and on specimen base plate to avoid conductive contribution via wires and so affect temperature measurement.

By considering 8/100mm diameter T type wires thermalised on 200mm (specimen base plate length) at 40K permit to reduce the heat flux leakage as more as it becomes negligible compared to the 3W power provided to the sample.

4. TEST BENCH CONFIGURATION

Sample's environment consists of a vacuum chamber equipped with two cold shrouds, respectively one liquid helium and a second, liquid nitrogen shroud that surrounds the first one and limits thermal exchanges between the 300 K chamber and the 4 K helium shroud. Such vacuum chamber features both primary and secondary pumping capable of vacuums on the order of 10-7 mbar.

Test principle is first to decrease specimen temperature via conductive exchanges between specimen base plate and cryogenic base plate until reaching objective temperature (the lowest is 40 degrees Kelvin). 4 heaters equip each specimen base plate to maintain it in temperature tolerance.

Secondly, the specimen head heater is turn on to create a gradient in the specimen height in the same time that the power of the base plate heater is minimise just to maintain the whole in objective temperature.

To preserve a good precision in temperature gradient measurement and so on conductivity value, the gradient must be at least 10 time better than accuracy measurement.

So, in the coldest case the difficulty is to apply enough power to obtain this gradient but not too much to maintain specimen temperature near 40K.

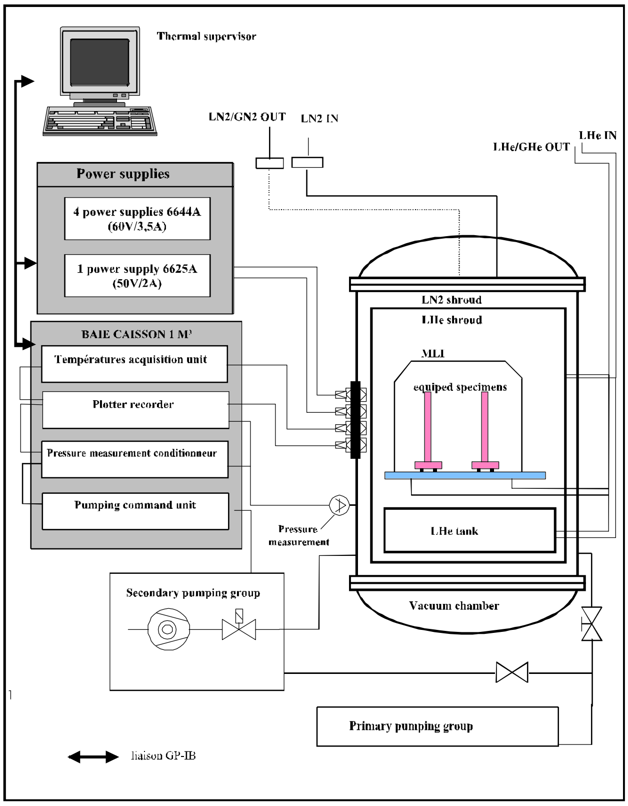

Figure 4 : Thermal vacuum configuration

The two specimens are tested in the same time and so not to disturb them each other, a multi layer insulation is fixed on the cryogenic base plate among the two specimens.

In the same way, to ensure that no power could be dissipated by cold environment, an other multi layer insulation is fixed all around the specimens.

Temperature sensors (T type thermocouples) are read out by a multi channel high precision voltmeter. Heaters are supplied by direct current precision power supplies. All machines are driven by a control-command-acquisition software.

5. SPECIMEN INTEGRATION

The liquid helium shroud also provides liquid to a liquid helium tank and to cryogenic base plate on which the two samples are screwed. Because of the low liquid capacity of cryogenic base plate and the small flow available, the maximum power applicable on each specimen base plate was estimated at about 3W (blank test previously performed confirmed this power).

So, the difficulty was to perform conductivity measurement on sample at 40 degrees Kelvin with maintain an environmental temperature (cryogenic base plate and shroud) at 4 degrees Kelvin.

Moreover, the measurement requires maintaining a gradient within the samples of about 10K. On one hand the gradient shall not be too low to allow sufficient precision, on the other hand it shall be kept minimum in order to estimate the interface performance at a realistic mean temperature (around 40K).

At first, to reduce conduction exchanges, 4 titanium bolts (with specific calculated dimensions) have been inserted between samples base plate and cryogenic base plate.

To avoid direct conduction link between samples base plate and cryogenic base plate via the inox screw, insulated PERMAGLASS washers , with two inox washers on each side to avoid flowing, have been added bellow each screw head.

Moreover to maintain good screwed pressure at low temperature and so to balance differential dilatation between aluminium plates, inox screws and titanium bolts, flexible copper/beryllium washers have been added in each link.

All mounted pieces have been assembly with thermal grease.

Mounting principle is shown in figure bellow :

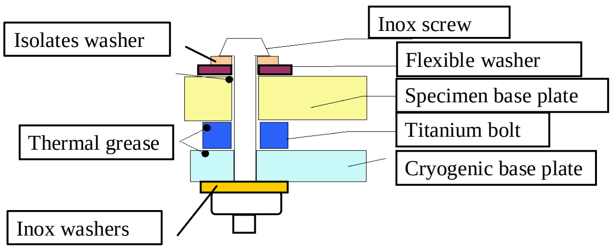

Figure 5 : Specimens mounting principle

6. TEMPERATURE DETERMINATION

6.1 Thermocouples accuracy

The thermocouples used for the tests come from the same wire group and have been previously calibrated on complete temperature range.

Moreover, during blank test two others calibration points have been added, one at liquid nitrogen temperature 77K and one at liquid helium temperature 4K.

In this way, the thermocouples provide a measurement of absolute temperature with a ± 1K accuracy, with a maximum temperature difference between the thermocouples better than 0.5K.

In worst case, the temperature relative precision is :

$$\frac{\Delta T}{T} = 0.05$$

6.2 Gradient temperature precision

The second step of test is to create a gradient in the specimen to compute conductivity. As shown in § 3, the gradient must be at least 10 time better than accuracy measurement that's mean higher than 5K.
In this case, the precision of gradient temperature can be :

$$\frac{\Delta(\Delta T)}{(\Delta T)} \leq 0.1$$

0.1 is the value obtained at temperature level of 40K with a temperature gradient of 5K. For higher temperature levels, the precision of gradient temperature will be better.

6.3 Acquisition chain precision

Acquisition chain consists of the temperature sensors and multimeter, which, cannot be selected independently of one another. One particular concern is compatibility of the temperature sensor's analogue signal with the multimeter's precision threshold. Choice for the sample's and thermalized wires' temperature sensors was type T (copper/constantan) thermocouples, whose 15 µV/K sensitivity at 40 K matches the multimeter's better than 1 µV sensitivity. The smallest detectable temperature variations lie around 0.07 K.

In this experiment's case, thermocouples offer quite a few significant advantages over thermistors or diodes. Apart from smaller size, they deliver a voltage and carry no current. Hence no need for the 4-wire configuration, and a useful wire cross-section that can be minimised (no Joule effect). Compared to thermistors, these thermocouples of, smaller-gage (diam.= 0.1 mm) wires entail less thermal leaks. And a nominative, thermocouple-by-thermocouple calibration throughout the acquisition chain (from sample to scanner) will achieve ± 0,5 K measuring accuracy.

7. POWER DETERMINATION

Measured power reflects the electric power dissipation in the heater, with measuring accuracy linked to:

- type of setup,
- measuring devices, whose sensitivities and accuracy shall match the measurements' orders of magnitudes.

As for first aspect, specimens have been wired with a very classic 4-wire set-up that measures power at the resistor's terminals and does away with on-line losses.

As for second aspect, the devices used on this experiment induced quite negligible errors (< 0.1 ‰). Electric power dissipation in the sample may be assimilated to the measured electric power.

8. KNOWLEDGE OF THE SAMPLE AREA

Absolute dimensions of specimen area can't be given, the measurement precision is essentially dependent of accuracy of measuring device.

And this is further, if slightly, compounded by a sample-contraction effect in cool-down phase.

Such contraction can be estimated (given the attendant uncertainties, especially on the sample's thermal expansion factors) and entered into the final error budget :

$$\frac{\Delta S}{S} < 0.002$$

9. GLOBAL CONDUCTIVITY MEASUREMENT ACCURACY

In account with all this precision data, the bench error estimated could be tabulated versus a variety of sample temperature levels and the gradient obtained at this temperature :

Sample temperature	Minimum temperature gradient obtained	Bench's estimated absolute measuring accuracy conductivity
40 K	5 K	± 0.1
100 K	10 K	± 0.05
150 K	11 K	± 0.04
300 K	5 K	± 0.1

10. MEASUREMENTS RESULTS

The two interface samples have been tested in the bench. Conductivity measurements have been done at temperatures of 40K, 100K, 150K and 300K.

The last temperature level, not directly related to the purposes of PLANCK program, enabled validation of the bench at a temperature at which this conductivity is better known.
Only 40K measurements on internal/external interface sample (sample n°2), the most interesting and the most difficult to reach, are described in paragraphs below.

10.1 Measurements at 40K

In the first step of the test, the aim is to decrease the specimen temperature until reach 40K ± 5K.

The base plate heater is then turned on to obtain a temperature stability of 2K/30mn during 30mn.

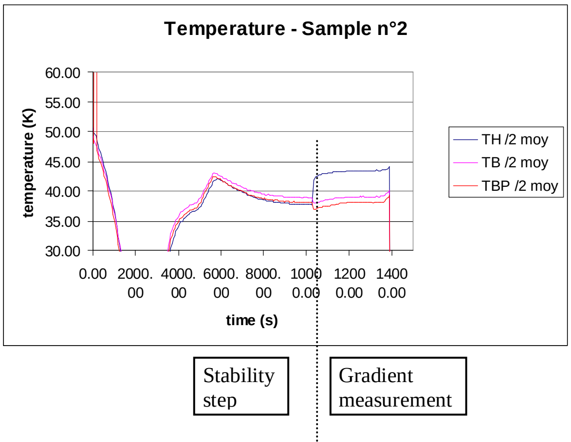

Figure 6 : Temperatures measurement at 40K

The power applied (1.2W) was sufficient to maintain the specimen temperature around 40K and also allow keeping cryogenic base plate (OSS) temperature around 15K.

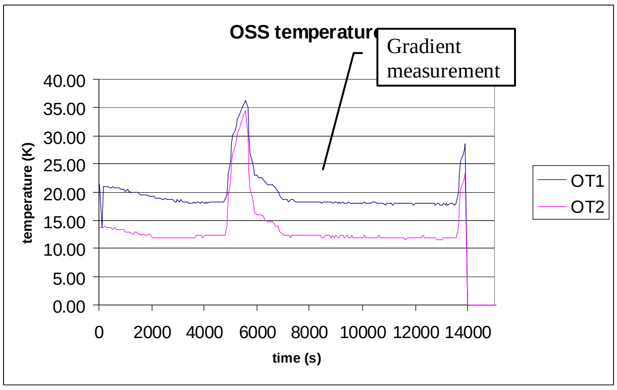

Figure 7 : Cryogenic base plate temperature evolution at 40K

The head heater was then turned on to create gradient in specimen of 5K ± 0.5K and stability of 2K/30mn during 30mn was obtained.

With all these data, a preliminary conductivity result for sample n°1 should be given at 40K :

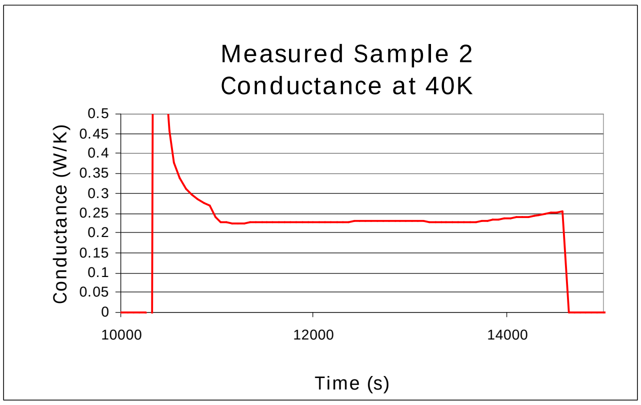

Figure 8 : Evolution of conductivity at 40K

After all temperature steps realised, a curve of evolution of conductivity could be graphed for each sample :

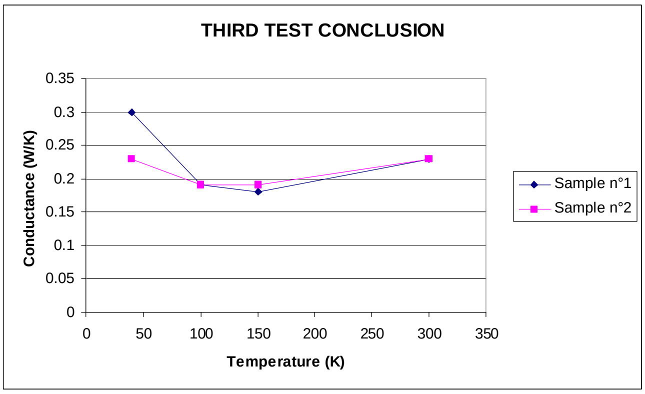

Figure 9 : Evolution of conductivity

11. CONCLUSION

The optical performances of today's observation satellites' request developments of cryogenic technologies, as the temperatures of some of the spacecraft's constituents may fall to liquid nitrogen's temperature or further below.

Accurate knowledge of thermophysical properties of materials is essential to thermal and optical engineers' designing, developing and operating the satellite systems' and subsystems' mathematical models (one example being PLANCK).

Measurements of conductivity at very low temperatures are getting crucial to the growth of new technologies.

The measurement solution proposed allows to measure conductivity of materials at very low temperature. At those temperature, a small inaccuracy of one parameter (temperature, power applied …) could have heavy consequences on result measurement accuracy.

For example, at 40K temperature step, this measurement bench could be more effective by using differential thermocouple. Then, it could give conductivity value with 2 times better accuracy measurement.

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Abbreviations and notations

λ	Conductivity
ASPI	Alcatel Space Industries
Lhe2	Liquid helium
LN2	Liquid nitrogen
P	Pressure
ΔT	Temperature difference